Evaluation of aqua MODIS thermal emissive bands stability through radiative transfer modeling

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Abstract. Moderate Resolution Imaging Spectroradiometer (MODIS) on Aqua has been in operation providing continuous global observations for science research and applications since 2002. The long-term stability of thermal emissive bands (TEBs) of Aqua MODIS was monitored through inter-comparisons with measurements by hyperspectral or multi-spectral infrared sensors or through vicarious monitoring over cold targets such as Dome-C and deep convective clouds. The radiative transfer modeling (RTM)-based simulation models are developed to perform the long-term monitoring of the stability of Aqua MODIS TEBs. Long-term European Centre for Medium-Range Weather Forecasts global atmospheric reanalysis data are used as inputs to the RTM simulation. By confining ocean in low to middle latitudes as the area of interest, the long-term stabilities of Aqua MODIS TEBs are monitored through observation minus background (O-B) brightness temperature (BT) bias between MODIS measurements and simulations from the RTM. In general, the RTM-based O-B analysis shows that the long-term stability of Aqua MODIS TEBs are maintained well. It is shown that Aqua MODIS surface bands are all radiometrically stable with yearly BT bias drifts <0.005 K/year for B20, B22, and B23 and ~ 0.01 K/year for B31 and B32. The carbon dioxide (CO_2) absorption channels of Aqua MODIS, e.g., B33 to B36, are stable with a BT bias drift <0.005 K/year. It is also found that after accounting for the long-term growth of greenhouse gas N_2O, the O-B bias trends for B24 and B25 are quite stable with yearly BT bias drifts around 0.0002 and 0.0055 K/year, respectively. The stabilities of the moisture-sensitive channels B27 to B29 and the ozone channel B30 of Aqua MODIS are also evaluated and the remnant small variations in the O-B bias trending of these channels are further discussed. The RTM-based inter-comparison of MODIS TEB measurements with global atmospheric and climate re-analysis data provides validation of the long-term radiometric stability of Aqua MODIS TEBs. The analysis in this paper also demonstrates that the comparison of well-calibrated MODIS TEB measurements with RTM simulation helps quantify the long-term impacts of global greenhouse gas concentration growth on the BT decreases in the MODIS greenhouse gas-sensitive channels. © *2021 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JRS.15.024502]

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1 Introduction

The Moderate Resolution Imaging Spectroradiometer (MODIS) is one of the key instruments on-board National Aeronautics and Space Administration's (NASA) Terra and Aqua spacecraft

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*Address all correspondence to Tung-Chang Liu, tcliu@umd.edu and have been in operation since 1999 and 2002.[1–7] MODIS is a cross-track, whiskbroom, and scanning radiometer-based imager that uses a double-sided scan mirror (SM) to obtain nearly continuous Earth observations in 36 spectral bands. Among the 36 bands, channels 1 to 19 and 26 with wavelengths from 0.41- to 2.2-μm cover visible (VIS), near-infrared (NIR), and shortwave infrared (SWIR) ranges, and channels 20 to 25 and 27 to 36 with wavelengths from 3.7 to 14.5 μm are the thermal emissive bands (TEBs). The continuous global observations by MODIS instruments enable a wide range of science data products with applications in the Earth's land, ocean, and atmosphere studies.[8–12]

The MODIS Earth view (EV) sector data are obtained with a scan angle of ±55 deg from instrument nadir. All MODIS TEBs have 1-km resolution at nadir. To ensure sensor data quality through the entire mission, the MODIS TEBs are calibrated on-orbit on a scan-by-scan basis by observing a large aperture V-grooved blackbody (BB) target at a fixed scan-angle. During each scan, the space view (SV) provides the background offset for the calibration. The calibration of MODIS TEBs is based on a quadratic calibration algorithm using the observations of the BB and SV. Although Aqua MODIS has been in operation well beyond its design lifetime, the Aqua MODIS TEBs have been relatively stable with long-term detector gain change within 2%.[1–6]

Previous studies track the long-term stability of Aqua MODIS TEBs through inter-comparisons with co-located measurements by hyperspectral infrared sensors, such as Atmospheric Infrared Sounder (AIRS) on Aqua and Infrared Atmospheric Sounding Interferometer (IASI) on MetOp satellite,[13,14] or with SNPP and NOAA-20 Visible Infrared Imaging Radiometer Suite (VIIRS) after correcting the spectral response function (SRF) difference using the measurements by Cross-track Infrared Sounder on SNPP and NOAA-20 spacecraft.[15,16] These intercomparison studies can only cover limited number of MODIS channels due to either finite spectral coverages of hyperspectral sounder or limited matching bands between MODIS and VIIRS. Alternatively, cold invariant vicarious sites such as Dome-C[17] or stable deep convective clouds (DCC)[18,19] have also been used to track long-term stability of MODIS TEBs. The brightness temperature (BT) of these cold targets is typically outside the MODIS BB calibration range. The *in-situ* sea surface temperature (SST) measurements were used to provide useful references for MODIS over typically higher scene temperatures.[20] Such comparisons within situ measurements cover mostly the MODIS surface channels and need to account for the light transmission through the atmosphere in the bias analysis.

In this paper, radiative transfer modeling (RTM)-based simulation models using community radiative transfer model (CRTM) and moderate resolution atmospheric transmission (MODTRAN) are developed to monitor the long-term radiometric stability of Aqua MODIS TEBs. The CRTM simulation tool is computationally efficient but the available model setup could not incorporate effects of time-varying greenhouse gas concentration such as methane (CH_4) and dinitrogen oxide (N_2O). On the other hand, MODTRAN can incorporate more comprehensive gas types into the simulation than the CRTM, but it is much more computationally intensive. The uses of two RTM modeling tools complement each other and enable us to address different aspects of the stability evaluation for Aqua MODIS TEBs.[21]

In the RTM simulations in this study, the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA) global atmosphere data are used as inputs. The RTM-based simulations cover all bands of interest and are first principal physics-based scene simulation. The simulated top of atmosphere (TOA) BT data from RTM using ECMWF data as inputs for MODIS channels are referred as the background BT from modeling. The bias between observed BT and simulated BT is called observation minus background (O-B) bias. Long-term trending of mean O-B biases for MODIS TEBs provides alternative independent validations of MODIS TEBs stability.

In the following, we first introduce the calibration of Aqua MODIS TEBs and their characteristics in terms of associated gas absorptions and weight functions in Sec. 2. In Sec. 3, we introduce the methodology of RTMs with the CRTM and MODTRAN to derive O-B bias trending for Aqua MODIS stability monitoring. In Sec. 4, the consistency and relative stability between Aqua MODIS and ECMWF reanalysis data are evaluated with long-term O-B BT bias derived from the RTM simulations. In addition, we performed an impact analysis of greenhouse gas concentration growth on BT variations of Aqua MODIS CO_2 absorption channels. In Sec. 5, the stability performance of the MODIS TEBs is summarized and discussed.

2 Aqua MODIS Thermal Emissive Band Calibration and Characteristics

Among the 36 bands of Aqua MODIS, 16 TEBs cover the mid-wave infrared (MWIR) (B20 to B25) and long-wave infrared (LWIR) (B27 to B36) spectral regions. All MODIS TEB detectors are located on two cold focal plane assemblies (FPAs) for SWIR/MWIR and LWIR bands, respectively. Both FPAs are nominally controlled at 83 K with a passive radiative cooler. The MODIS TEB calibration uses an onboard BB as the primary calibration source together with the SV, which provides the instrument background reference. The sensor background-subtracted digital response to calibration source dn_{BB} can be converted to calibration radiance L_{cal} through a quadratic calibration algorithm:[5,22,23]

$$L_{\mathrm{cal}} = a_0 + b_1 dn_{BB} + a_2 dn_{BB}{}^2, \tag{1}$$

where a_0, b_1, and a_2 are the offset, linear, and quadratic calibration coefficients, respectively. When viewing the onboard BB, the calibration radiance also includes contributions from the SM and the cavity emission reflected from the BB,

$$L_{\mathrm{cal}} = RVS_{BB}\varepsilon_{BB}L_{BB} + (RVS_{SV} - RVS_{BB})L_{SM} + RVS_{BB}(1 - \varepsilon_{BB})\varepsilon_{cav}L_{\mathrm{cav}}, \tag{2}$$

where RVS_{SV} and RVS_{BB} are the response-versus-scan-angle at SV and BB scan angle, respectively. ε_{BB} and ε_{cav} are the emissivity of the BB and the scan cavity (CAV), respectively. Both the terms RVS and ε are determined pre-launch. L_{BB}, L_{SM}, and L_{cav} are the spectral radiances of the BB, SM, and scan cavity, respectively, which can be calculated with the corresponding temperature data monitored by the onboard thermistors. During nominal operation, the BB is set at 285 K for Aqua MODIS.

Combing Eqs. (1) and (2), the linear calibration coefficient b_1 of MODIS TEB can be derived as

$$\begin{aligned} b_1 = [&RVS_{BB}\varepsilon_{BB}L_{BB} + (RVS_{SV} - RVS_{BB})L_{SM} + RVS_{BB}(1 - \varepsilon_{BB})\varepsilon_{cav}L_{\mathrm{cav}} - a_0 \\ &- a_2 dn_{BB}{}^2]/dn_{BB}, \end{aligned} \tag{3}$$

where the nonlinear coefficient a_2 and offset a_0 are read from a pre-developed look-up-table (LUT). The linear coefficient b_1 is calibrated scan-by-scan for each detector of MODIS TEB and for each side of the SM. The EV radiance L_{EV}, is then calculated using the following expression:

$$L_{EV} = [a_0 + b_1 dn_{EV} + a_2 dn_{EV}{}^2 - (RVS_{SV} - RVS_{EV})L_{SM}]/RVS_{EV}, \tag{4}$$

where dn_{EV} is the background-subtracted sensor's EV response.

In MODIS on-orbit calibration, the offset a_0 and the nonlinear response coefficient a_2 are updated (if needed) based on quarterly on-orbit BB warm up-cool down (WUCD) calibration activities. During each WUCD, the calibration coeffcients a_0 and a_2 are derived from the onboard BB measurements with BB temperature varying from 270 to 315 K. These coefficients are delivered as operational LUTs on an as needed basis. More information about the MODIS TEB calibration algorithms can be found in references.[1,2,22]

The RTM-based stability analysis covers all the Aqua MODIS TEB channels listed in Table 1. Figure 1 shows the SRFs of 16 MODIS TEBs overlaid onto the spectral transmittance of various gases such as water vapor (H_2O), ozone (O_3), and greenhouse gases: CO_2, CH_4, and N_2O, which are derived from MODTRAN. Table 1 lists the gases affecting MODIS TEBs with absorption >10%, which is calculated by integrating the MODIS TEB SRFs with the transmittance curve shown in Fig. 1. It can be seen that MODIS B20, B24 to B29, and B32 to B36 channels are water vapor-sensitive. The MODIS bands B24 and B33 to B36 are affected by the atmospheric CO_2 concentration. The MODIS B24 and B25 are N_2O-sensitive channels while MODIS B28 is affected by atmospheric CH_4 absorption. The MODIS B30 is an ozone-sensitive channel. The RTM simulations will evaluate the absorption effects by these gases for satellite sensors.

Table 1 Aqua MODIS TEB channel properties and primary applications.

MODIS band	Central wavelength (μm)	Sounding peak height (km)	Water vapor, greenhouse gas, and ozone absorption	Application
B20	3.780	Surface	H_2O	Surface/cloud temperature
B21	3.982	Surface	—	Fire detection
B22	3.972	Surface	—	Surface/cloud temperature
B23	4.062	Surface	—	Surface/cloud temperature
B24	4.448	10.68	H_2O, CO_2, and N_2O	Atmospheric temperature
B25	4.526	5.35	H_2O and N_2O	Atmospheric temperature
B27	6.789	8.06	H_2O	Cirrus cloud/water vapor
B28	7.350	4.73	H_2O and CH_4	Cirrus cloud/water vapor
B29	8.555	Surface	H_2O	Cloud properties
B30	9.725	22.36	O_3	Ozone
B31	11.026	Surface	—	Surface/cloud temperature
B32	12.042	Surface	H_2O	Surface/cloud temperature
B33	13.365	1.48	H_2O and CO_2	Cloud top altitude
B34	13.686	3.72	H_2O and CO_2	Cloud top altitude
B35	13.923	6.20	H_2O and CO_2	Cloud top altitude
B36	14.216	9.68	H_2O and CO_2	Cloud top altitude

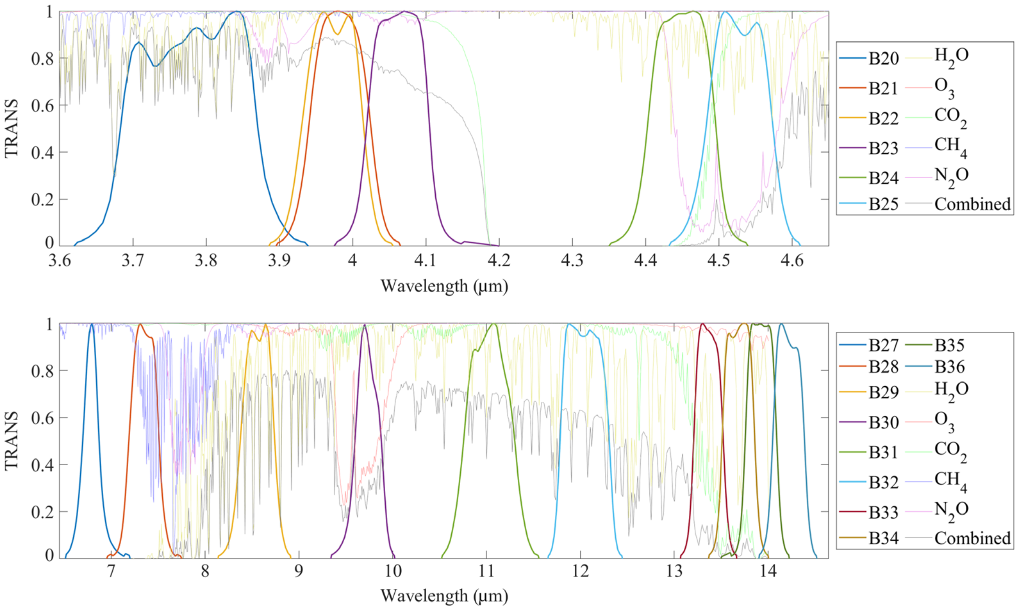
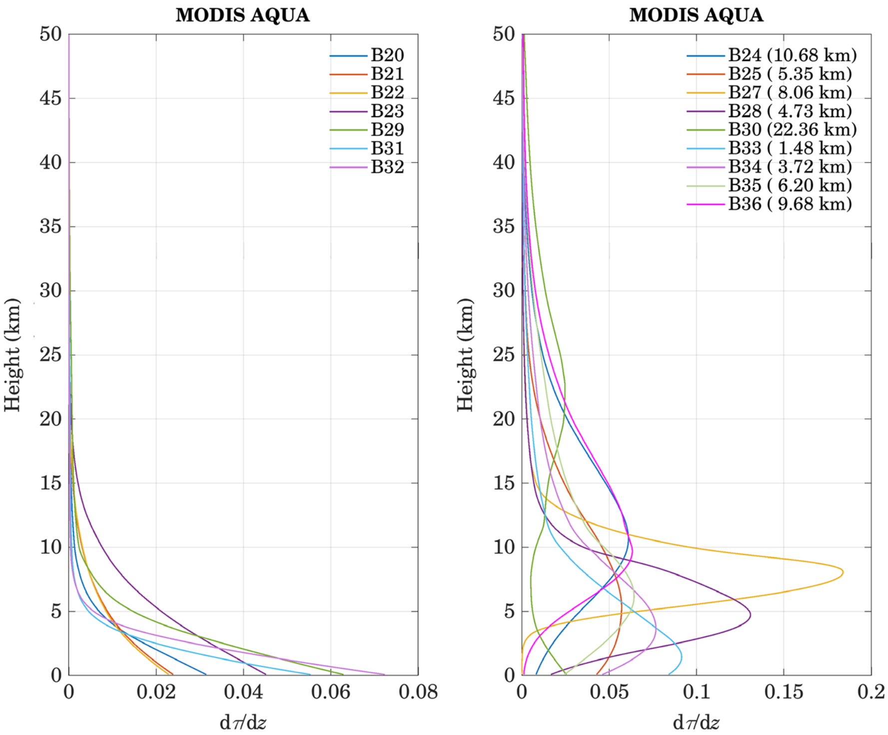


Fig. 1 Aqua MODIS SRFs overlaid with spectral transmittances of various gas types.



(a) (b)

Fig. 2 Weighting function profile of Aqua MODIS TEB channels, where (a) shows the surface channels and (b) shows the sounding channels with their peak sounding positions displayed in the legends.

Figure 2 shows the weighting function profiles, defined as the derivative of light transmittance τ, i.e., $d\tau/dz$, of the 16 MODIS TEBs with respect to height, which is derived from 1976 US standard atmosphere model. In Fig. 2, we separate these 16 channels into two groups according to the peak position of the weighting function: the channels B20 to B23 and B29 to B32 shown in Fig. 2(a) whose peak weighting function positions are on the surface, and the sounding channels B24, B25, B27 to B30, and B33 to B36 shown in Fig. 2(b) whose peak sounding positions vary from 1.48 (B33) to 22.36 (B30, ozone channel) km. Table 1 lists the peak sounding height values of theses Aqua MODIS sounding channels.

3 Simulation Methods and Scene Selection Scheme

3.1 *Radiative Transfer Modeling*

In this study, two RTM simulation models, namely, CRTM and MODTRAN, have been used to evaluate O-B biases of Aqua MODIS TEBs. Both simulations use long-term ECMWF reanalysis data as inputs. The advantage of the CRTM simulation is that it is much more computationally efficient than MODTRAN while MODTRAN simulation can incorporate more gas types into the simulation than the CRTM. Both tools have been used in our study to address different aspects of the O-B bias trending-based stability evaluation for Aqua MODIS TEBs. Details of these two RTM tools are introduced as follows.

3.1.1 *CRTM*

The CRTM (V2.1.3) has been used to perform monthly RTM simulations for trending the stability of Aqua MODIS TEBs. The CRTM was developed and maintained by US Joint Center for Satellite Data Assimilation and can be downloaded from Ref. 24.[25] The CRTM is a fast sensor-channel-based RTM tool for simulating TOA satellite-measured radiances for VIS, infrared, or microwave radiometers by quantitatively accounting for reflection and emission of radiation by the Earth surface, gaseous absorption in the atmosphere, and scattering and absorption of radiation by clouds and aerosols. It has been widely used in calibration and assimilation of infrared and microwave sensor data and remote sensing applications.[26,27] Given the spectral response data of a new sensor, spectral and transmittance coefficient parameter files need to be created to make the CRTM ready for the new sensor. The CRTM package provides comprehensive functions such as forward, adjoint, tangent-linear, and K-matrix to meet users' modeling need. The inputs to the CRTM include atmospheric profile of water vapor, temperature, pressure, CO_2, ozone, and other variable gas concentrations at layers defined by user; aerosol-related characteristic parameters; cloud types and cloud parameters; and surface property parameters, such as skin temperature, emissivity, wind speed, and direction.

Figure 3 shows the simulation setup with the CRTM as the simulator for long-term O-B bias evaluation of MODIS TEBs. Simulation coefficients for Aqua MODIS TEBs were first trained with line-by-line radiative transfer model and then fed into CRTM. In this study, the atmospheric absorption effects of CO_2 and ozone are included in the trained coefficient data set. We did retraining of the CRTM simulation coefficient table for Aqua MODIS TEB channels to account for the growth of CO_2.

The RTM simulations were carried out with time-varying surface data and atmospheric profile data from ECMWF reanalysis data as inputs. ERA global atmospheric and climate reanalysis dataset are from 4DVAR data assimilation, which uses a fixed version of a numerical weather prediction (NWP) system [integrated forecast system, cycle 31r2 (IFS-Cy31r2)] to produce the re-analyzed data. The NWP system blends or assimilates observations with a previous forecast to obtain the best fit to both. The results of this blending serve as the starting point for the next forecast. The fixed version in ERA dataset ensures that no spurious trends are caused by an evolving NWP system since the changing observing system can create such trends.

The long-term global atmospheric data from ERA such as temperature and water vapor profiles, and CO_2 and ozone profiles are used as inputs to the CRTM simulation. Surface parameters including skin temperature, wind speed, and wind direction are obtained from ECMWF's ERA-Interim reanalysis model, which is based on 6-h increments. The data from ECMWF were collected with 0.75-deg spatially gridded resolution which is equivalent to a spatial resolution of ~80 km at equator. Ozone, water vapor, and temperature profiles from ECMWF are coordinated at 37 mandatory pressure levels and are available from ground to up to ~0.1 hPa. Global atmospheric CO_2 concentrations profiles are inferred from atmospheric inversion carried out at Copernicus Atmosphere Monitoring Service (CAMS) and recorded at 40 pressure levels.

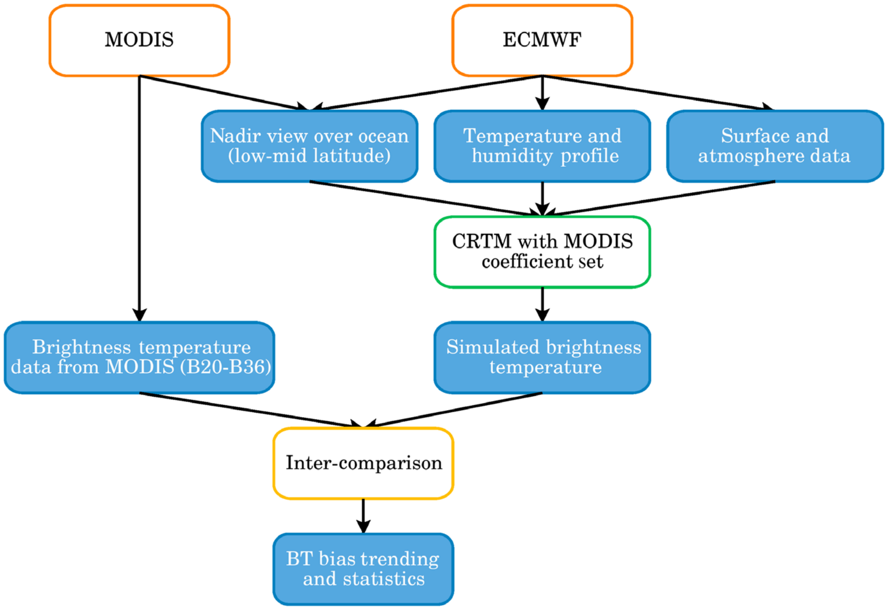


Fig. 3 RTM simulation setup with CRTM as the simulator for long-term O-B bias evaluation of MODIS TEBs.

Aqua MODIS orbital nadir locations over oceans and corresponding times are collected and fed to process the global ECMWF data. Spatial and temporal interpolations of ECMWF surface and profile parameters at the MODIS observation location and time are performed to derive the input parameters for the CRTM. The CRTM simulations in this study are focused over ocean surface and effects from cloud or aerosols are not considered in the simulation. Simulated TOA BT data from CRTM over Aqua MODIS nadir are compared with corresponding MODIS TEB measurements (MODIS Standard Collection 6.1) for O-B BT bias evaluation. The surface emissivity model used in the CRTM simulation is based on the default CRTM oceanic surface model at MODIS channel frequencies.

3.1.2 *MODTRAN simulation*

The simulation coefficient setup for the CRTM simulation of Aqua MODIS TEBs is limited to account for the growth of CO_2 and could not account for the impacts of other greenhouse gases such as CH_4 and N_2O. As shown in Fig. 1 and Table 1, MODIS B24, B25, and B28 are affected by these greenhouse gaseous absorption. On the other hand, the MODTRAN software[23] is capable of simulating optical measurements through the atmosphere by accounting for absorption effects of a more comprehensive set of gas types. The MODTRAN computes line-of-sight atmospheric spectral transmittances and radiances over the ultraviolet through LWIR spectral regime. Under the assumption of horizontally homogeneous atmospheres, the MODTRAN simulation accounts for the constituent vertical atmospheric profiles defined by either built-in models or user-specified data. To set up MODTRAN simulation, in addition to the time-varying surface data and atmospheric profile data fed into the CRTM simulation, we also include the spatial and time-varying greenhouse gases including CH_4 and N_2O. The global atmospheric CH_4 and N_2O concentration profiles are both collected from CAMS. Other direct inputs to the MODTRAN simulation include SRF of Aqua MODIS TEBs and geometric parameters such as solar and satellite zenith angles and relative azimuth angle between solar and view azimuth angles. The surface emissivity model used in the MODTRAN simulation is the default MODTRAN oceanic surface model. The MODTRAN simulation is physics-based and quite computationally intensive. Therefore, the MODTRAN simulations carried out in this study were limited to be over valid 1000 pixels on one selected day in each year.

3.2 *Scene Selection and Long-Term O-B BT Bias Trending*

The evaluation of MODIS TEB stability is carried out through comparison of Aqua MODIS measurements with the RTM-modeled BT data to derive O-B biases, i.e., O-B analysis. In this study, Aqua MODIS nadir view data are collected, and the areas of interest (AOIs) are confined to be over low to mid-latitude (−60 to 60 deg in latitude) ocean, which are warm temperature targets. Areas with solar zenith angles between 80 and 100 deg are excluded to avoid the terminator region.

For CRTM–based O-B analysis, both MODIS and ECMWF data on the 15’th day of each month from 2003 to 2018 are collected. The ending year in 2018 for the O-B analysis is due to the availability of ECMWF data at the time when this study was conducted. For each O-B BT bias comparison, about 100 data points around the center of the target location at satellite nadir are collected. The only constraint on the target type of interest in this study is over ocean under MODIS nadir. We do not specify any target with fixed location. The 10×10 (100) data points are chosen over the 10 along scan lines closest to nadir track for each MODIS TEB as Aqua MODIS moves along the track direction over ocean. Over this 100 point-region, the mean and standard deviation of pixel BT are recorded. To remove measurements due to scene non-uniformity, only scenes with standard deviation of BT <0.5 K are kept for all MODIS TEBs analyzed. The AOIs with cloud contaminations are screened out with three sigma filtering using MODIS surface channel B20 data. After the uniformity and cloud contamination screening, the number of remaining valid pixels for O-B comparison is about 30,000 each day, which solidifies the statistical advantages of the CRTM-based stability analysis. The O-B bias data derived from CRTM simulation for the day of interest are used for further mean O-B bias, uncertainty, and trending analysis.

For MODTRAN–based inter-comparison, due to computational limitation, only one day data on December 15 in each year from 2003 to 2017 is used for the MODTRAN simulation. The ending year is set at 2017 due to that the long-term global atmospheric N_2O profile data from CAMS are only available up to 2017. Over the day of interest, MODTRAN simulations were carried out over 1000 nadir pixels from MODIS observations, which have passed the uniformity check and cloud screening and have been sampled equally over time. The MODTRAN-simulated BT data for MODIS TEBs are compared with Aqua MODIS measurements to produce RTM-based O-B BT biases for further statistical analysis.

The ensemble of O-B BT biases over valid scenes during each day of interest is used to characterize the monthly O-B BT bias (mean) and its uncertainty (standard deviation) for each MODIS TEB analyzed. The time series of CRTM-based monthly O-B BT biases over 16 years and MODTRAN-based yearly O-B BT biases over 15 years are further analyzed to evaluate the long-term radiometric stability of the MODIS TEBs.

4 Results from Evaluation of Aqua MODIS TEB Stability with RTM

4.1 *Long-Term Stability of MODIS Surface Channels*

The first set of Aqua MODIS TEBs to be evaluated for long-term stability monitoring includes the MODIS surface channels B20 to B23, B31, and B32 [see Fig. 2(a)]. Figure 4 shows the long-term (16-year) trending of O-B (ECMWF model) BT bias derived from CRTM simulation for these TEBs of Aqua MODIS along with their uncertainties. The time series of O-B biases in Fig. 4 show that the surface channels (B20 to B23, B31, and B32) of Aqua MODIS are in general stable and consistent with ECMWF reanalysis data. Figure 5 shows the dependences of O-B BT biases on the scene temperature measurement of Aqua MODIS for the MODIS channels of interest. Since the AOIs in this study are over low to mid-latitude ocean surfaces, the scene BT data are mostly within the range between 290 and 300 K, which are warm scene targets. The mean O-B BT biases versus scene temperature shown in Fig. 5 suggest that there are no significant scene temperature dependences for the O-B biases of B21 to B23, B31, and B32. For

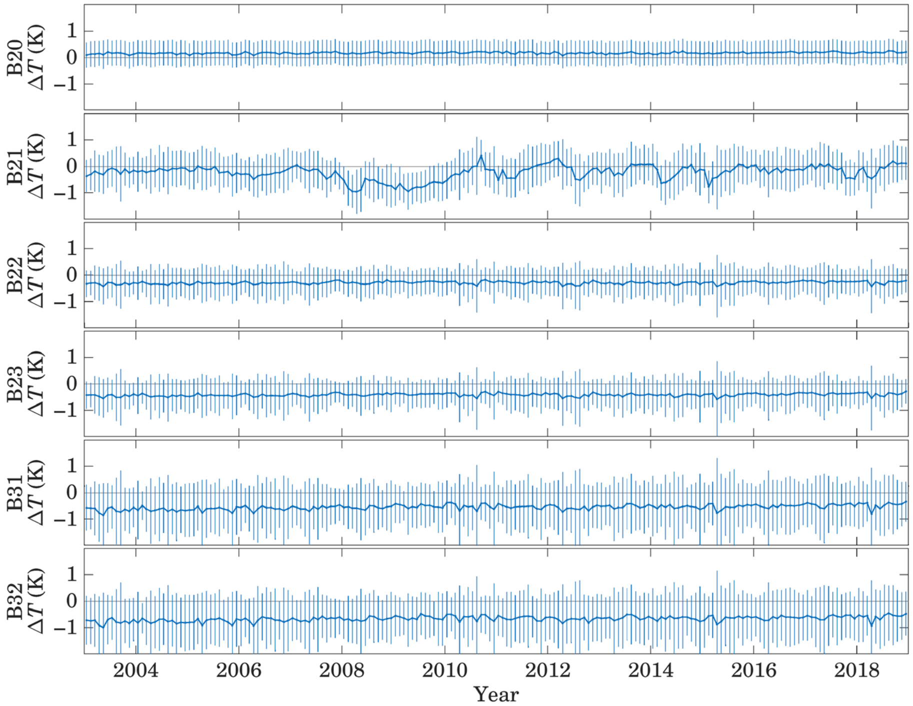


Fig. 4 Long-term monthly trending of O-B (ECMWF model) BT biases from CRTM simulation for surface channels of Aqua MODIS (B20 to B23, B31, and B32) along with their uncertainties.

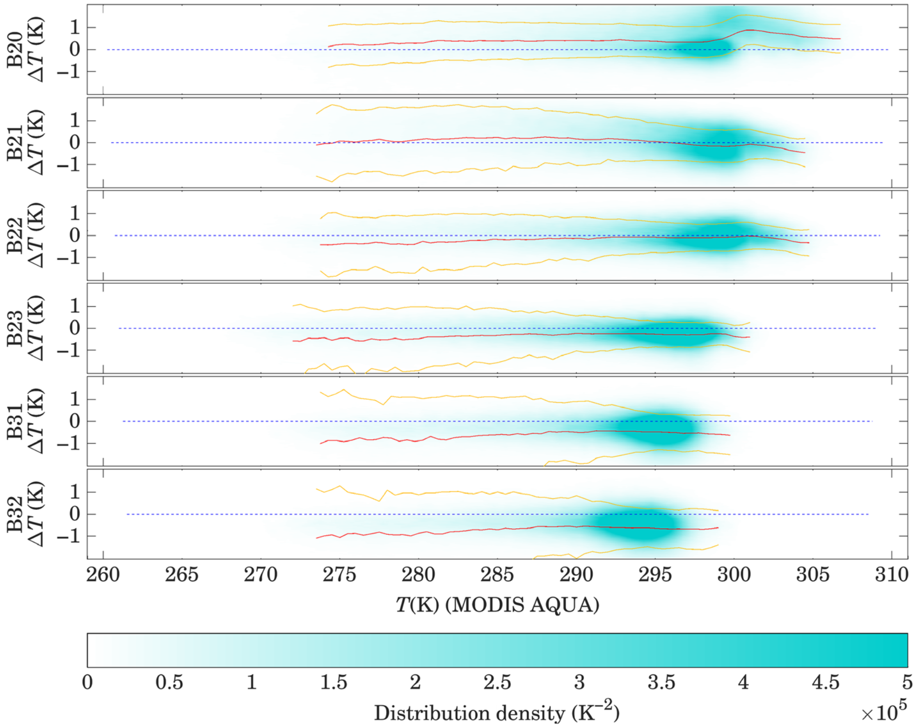


Fig. 5 The dependence and distribution of O-B BT bias with respect to the BT measurement of Aqua MODIS for MODIS surface channels. The O-B distribution statistics are derived from CRTM-simulation of 2003 to 2018 MODIS data. The curves overlayed with the distribution density plot show the mean (red) and one standard deviation from mean (yellow) of O-B BT biases in each BT bin.

B20, the mean O-B BT bias curve consists of two parts: the low-temperature part where the temperature dependence is insignificant and the high-temperature part where there is a transition to higher O-B bias and then trend downward with the increase of scene temperature. The residual absolute O-B bias (<1 K) in Fig. 4 between MODIS observation and CRTM simulation results for these channels can be due to the uncertainties in the RTM simulation setup such as the surface emissivity model. Since the RTM simulation is better suited for sensor stability analysis than absolute bias evaluation, we focus on the evaluation of the stability of MODIS TEBs with the O-B bias analysis.

The long-term time series of O-B BT biases shown in Fig. 4 are further trended with linear regression to derive the yearly BT drift rate for each MODIS TEB. The trending results are listed in Table 2 together with 95% confidence interval (CI), which enables quantitative evaluation of the stability of MODIS TEBs. It can be seen that Aqua MODIS surface channels B20, B22, and

Table 2 Yearly BT drifts ±95%CI (K/year) of Aqua MODIS surface TEBs (B20 to B23, B31, and B32) derived from O-B analysis with CRTM simulation.

MODIS bands	Wavelength (μm)	Yearly drift (K/year)
B20	3.780	0.0027 ± 0.0010
B21	3.982	0.0120 ± 0.0078
B22	3.972	0.0029 ± 0.0015
B23	4.062	0.0036 ± 0.0016
B31	11.026	0.0105 ± 0.0025
B32	12.042	0.0107 ± 0.0026

B23 are all radiometrically stable with the yearly O-B BT bias drift <0.004 K/year. For B31 and B32 of Aqua MODIS, the yearly O-B BT bias drift is around 0.01 K/year.

In the TEB bias and stability analysis through inter-comparison between MODIS and AIRS,[13] Aqua MODIS B20 was completely excluded from the analysis because the spectral overlap between the two sensors was insufficient. Our analysis in Fig. 4 and Table 2 show that Aqua MODIS B20 is quite stable with the yearly O-B BT bias drift about 0.0027 ± 0.0010 K/year.

MODIS B21 and B22 have very similar SRFs and about the same center wavelength. Figure 4 and Table 2 show that MODIS B21 has larger bias fluctuations with larger yearly O-B BT bias drift than MODIS B22. The estimated O-B BT bias drift of B21 has five-time larger CI than MODIS B22, which suggests that the yearly O-B BT bias drift of MODIS B21 has much larger uncertainties, as B21 is for fire detection and specification is low. This is due to that MODIS B21 is specifically designed for the detection of fire scenes with high temperature and its quality assurance (QA) for non-fire scenes is very low.[5] Our analysis confirms that Aqua MODIS B22 is more reliable than B21 for typical Earth surface temperature scene observation.

For the surface channels B31 and B32 of Aqua MODIS, their radiometric stabilities after 2012 have been extensively monitored and validated through inter-comparison with NPP VIIRS matching channels in Li et al.[15,16] Our long-term O-B BT bias analysis confirmed that the surface channels B31 and B32 of Aqua MODIS have maintained their stabilities with yearly BT bias drift around 0.01 K/year over all 16 years. In Shrestha and Xiong[17] and Chang et al.,[18,19] the stability of MODIS surface TEBs was validated with long-term measurements over cold targets such as Dome-C and DCC. Our RTM-based simulation analysis independently validates the stability of these MODIS surface channels over ocean surfaces with more representative higher temperatures.

4.2 *Evaluation of Aqua MODIS CO_2 Channel Stability and the Impacts of Global CO_2 Concentration Growth*

The B24 and B33 to B36 channels of Aqua MODIS are infrared troposphere sounding channels and are largely affected by the atmospheric CO_2 absorption (see Fig. 1 and Table 1) as the thermal radiation transmitting through the atmosphere. During the lifetime of Aqua MODIS, global carbon concentration continues to increase (Fig. 6).[28] The CRTM simulation has the flexibility of

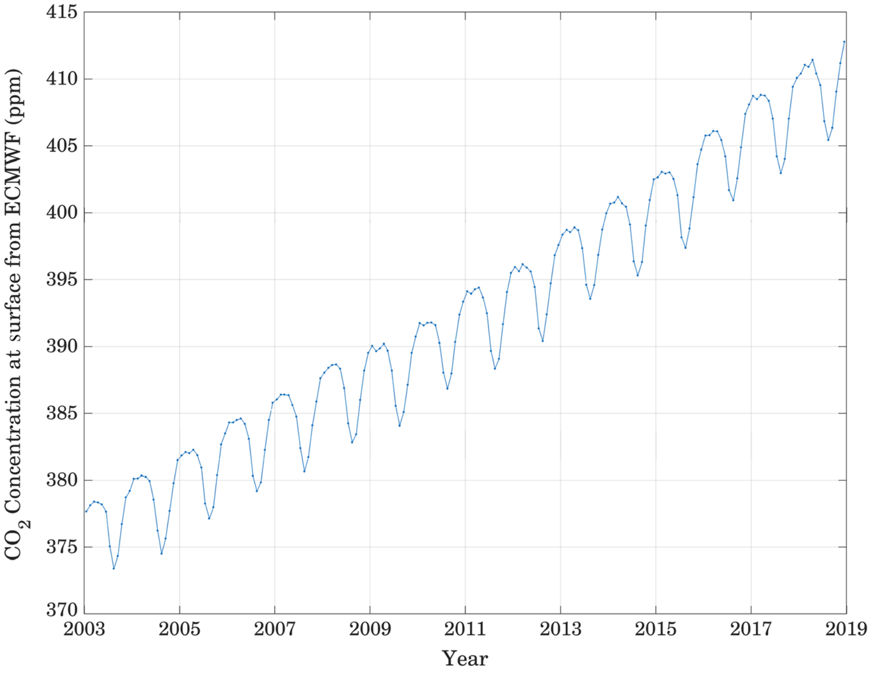
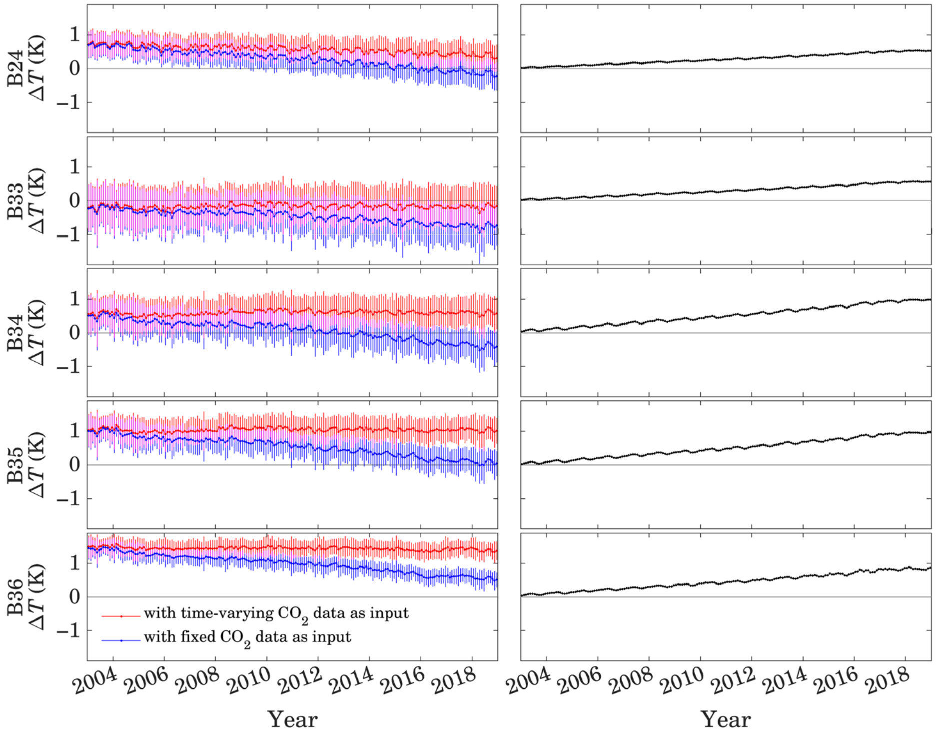


Fig. 6 Time series of monthly global CO_2 concentration (ppm) at surface from ECMWF.

using either fixed initial global CO_2 profile or time-varying global CO_2 profiles collected from ECMWF reanalysis data as the simulation input. By comparing the long-term O-B bias from simulations with fixed and time-varying global CO_2 profiles (Fig. 7), the impacts of global CO_2 concentration growth on Aqua MODIS B24 and B33 to B36 calibration can be quantified.

Figure 7 shows that after accounting for the growth of global CO_2 concentration, the long-term O-B BT bias variations (red curves) of Aqua MODIS B33 to B36 become very stable. More quantitatively, Table 3 shows the yearly O-B BT bias drifts of MODIS CO_2 channels derived from the linear regression fitting of time series of O-B BT bias data shown in Fig. 7. The yearly BT bias drifts of Aqua MODIS CO_2 absorption channels, e.g., B33 to B36, are all <0.005 K/year. There remains a downward slope in O-B BT bias of MODIS B24 after accounting for the CO_2 concentration growth in the CRTM simulation. This can



(a) (b)

Fig. 7 (a) Comparison of long-term O-B BT bias (K) variation and uncertainties derived from inter-comparison with CRTM simulations with fixed (blue) and time varying (red) CO_2 profiles for B24 and B33 to B36 of Aqua MODIS. (b) Time series of difference (K) between O-B biases of simulations with fixed and time-varying CO_2 profiles shown in (a).

Table 3 Yearly O-B BT bias drift ±95%CI (K/year) of MODIS CO_2 channels (B24 and B33 to B36) derived from inter-comparison with CRTM simulations with fixed and time-varying CO_2 profiles as inputs and ending BT difference between two inter-comparisons.

MODIS bands	Wavelength (μm)	Yearly drift with fixed CO_2 profile (K/year)	Yearly drift with time varying CO_2 profile (K/year)	Ending ΔT (K) between two simulations
B24	4.448	-0.0550 ± 0.0019	-0.0215 ± 0.0020	0.54
B33	13.365	-0.0352 ± 0.0023	0.0005 ± 0.0020	0.58
B34	13.686	-0.0574 ± 0.0023	0.0039 ± 0.0019	0.99
B35	13.923	-0.0599 ± 0.0020	0.0008 ± 0.0016	0.97
B36	14.216	-0.0568 ± 0.0014	-0.0049 ± 0.0011	0.86

be attributed to the unaccounted absorption in the CRTM simulation by the growing greenhouse gas N_2O concentration, which will be addressed in Sec. 4.3 with MODTRAN simulation.

The well-calibrated infrared detectors of MODIS B33 to B36 maintain long-term stability with yearly O-B BT bias being <0.005 K/year or equivalently <0.08 K over16 years as shown in Fig. 7 and Table 3. Long-term MODIS CO_2 channel data also provide the opportunity to reveal the impacts of global CO_2 concentration growth on the variation of global mean BT of these CO_2 channels. Figure 7 also shows the time series of O-B BT bias (blue curves in Fig. 7) between Aqua MODIS measurements and CRTM simulation with fixed initial CO_2 profiles as input. There are long-term decreasing trends in the O-B BT bias from CRTM simulation with fixed CO_2 profiles in comparison with the results (red curves in Fig. 7) derived from simulation with time-varying ECMWF reanalysis data. The difference between O-B BT bias time series (red versus blue curves in Fig. 7) from two inter-comparisons shows the global mean BT decreases in these infrared channels due to the long-term growth of global CO_2 concentration. Table 3 also listed the ending difference between O-B BT biases of simulations with fixed and time-varying CO_2 profiles. The impacts of CO_2 growth over 16 years on BT decrease of these Aqua MODIS TEBs are more significant in B34 to B36 (0.86 to 0.99 K) than B33 (0.58 K) since the CO_2 absorption coefficient is smaller for B33 than the other three channels. The growth of atmospheric CO_2 concentration over Aqua MODIS lifetime induced more absorptions of infrared radiation in these MODIS CO_2 bands such that the observed infrared radiation of these channels by Aqua MODIS decrease as shown from the O-B bias analysis. These absorbed energy by CO_2 are not transmitted back to space and trapped in the atmosphere which may affect the energy conversion, balance and transportation in the atmosphere and Earth's environment. This analysis shows that combining the well-calibrated MODIS TEB measurements with RTM simulation helps quantify the long-term impacts of global CO_2 concentration growth on the BT decreases in MODIS CO_2 absorption channels.

4.3 *Evaluation of Stability of MODIS N_2O-Sensitive Channels B24 and B25*

Over the lifetime of Aqua MODIS, the greenhouse gas N_2O concentration also grows steadily from 316 ppb to ∼332 ppb at a rate of 0.88 ppb/year as shown in Fig. 8. From Fig. 1, the growth of N_2O concentration has direct impact on the MOIDS N_2O-sensitive channels B24 and B25.

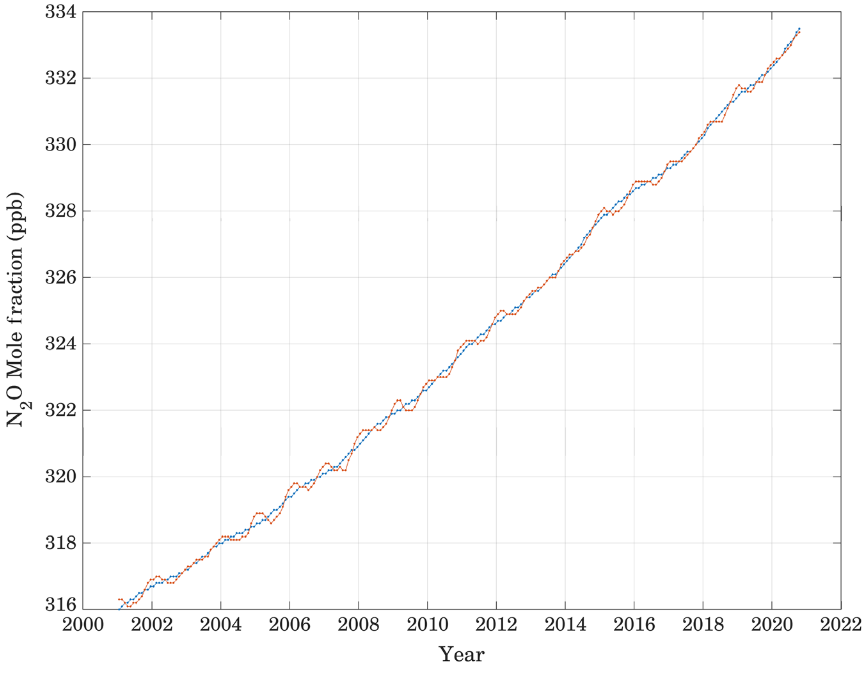


Fig. 8 Growth of monthly mean of global N_2O concentration (ppb) over the lifetime of Aqua MODIS. (data from Ref. 29).

However, the absorption by varying N_2O concentration is not accounted in CRTM simulation for multi-band spectral sensors. The CRTM simulation is set up with trained input parameters such that effects of time-varying CO_2 profiles are accounted for while the absorption effects by N_2O concentration is fixed in the simulation. Figure 9 shows the O-B bias (red curve) and uncertainties between Aqua MODIS measurements and CRTM simulations for the MODIS N_2O sensitive channels B24 and B25. As expected, there are long-term downward trends at -0.0238 and -0.0252 K/year in the O-B BT biases of MODIS B24 and B25, respectively, due to the unaccounted-for growth of N_2O concentration in the CRTM simulation.

To account for the effects of major greenhouse gas concentration growths in the RTM simulation, we carried out MODTRAN simulation with time varying CO_2, CH_4, and N_2O gas profiles collected from long-term ECMWF reanalysis data. Since the MODTRAN simulation is computationally intensive, we limited the simulation to be over 1000 ocean pixels (-60 to 60 degrees in latitude) in one selected day in each year from 2004 to 2017. The ending year of the simulation is set at 2017 due to that the long-term global N_2O profile data from ECMWF reanalysis model are only available up to 2017 at the time of this study. Figure 9 shows the comparison of O-B bias trending between CRTM (red curve, with fixed N_2O concentration) and MODTRAN (blue curve, with time-varying global N_2O profiles from ECMWF) simulations for MODIS N_2O-sensitive channels B24 and B25. It can be seen that the downward slope of O-B bias trending in the CRTM simulation results is corrected in the MODTRAN simulation. The O-B bias trends derived from MODTRAN simulation are nearly flat with yearly drift $= 0.0002$ and 0.0055 (K/year) for B24 and B25, respectively. From Figs. 7 and 9, the step-by-step flattening of the O-B bias trending for MODIS B24 can be clearly seen when the time varying CO_2 profile is first accounted for in the CRTM simulation and then the more comprehensive greenhouse gas types such as CO_2, CH_4, and N_2O are accounted for in the MODTRAN simulation. MODIS B24 is a channel sensitive to both CO_2 and N_2O absorptions. Figure 7(a) shows that by accounting for CO_2 growth in CRTM simulation, the download trend of B24 bias can be reduced to some extent, but not fully. On the other hand, the MODTRAN simulation accounts for both CO_2 and N_2O growth in the simulation and the trending of Aqua MODIS B24 O-B bias (Fig. 9) is essentially flat, i.e., very stable. Our O-B bias analysis with MODTRAN simulation confirms that the long-term stabilities MODIS B24 and B25 are well maintained. Furthermore, the impacts

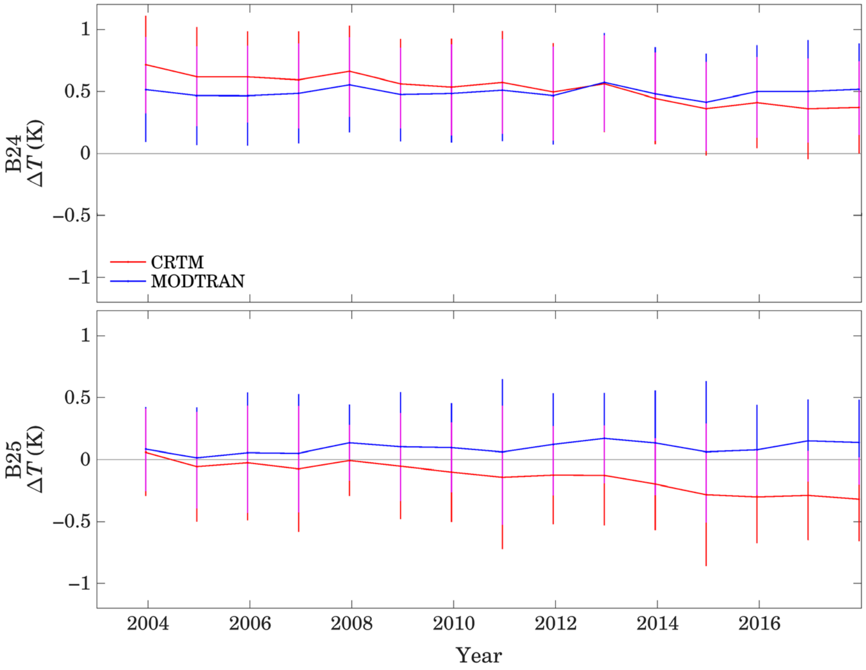


Fig. 9 Comparison of O-B bias trending between CRTM (with fixed N_2O concentration) and MODTRAN (with varying N_2O concentration) simulations for MODIS N_2O sensitive channels B24 and B25.

of the growth of global N_2O concentration on these two MODIS channels can be evaluated by calculating the difference between the O-B BT biases derived from the CRTM and MODTRAN simulations. From Fig. 9, it is estimated that the growth of N_2O from 2003 to 2017 can cause the decreases of BT by ~0.35 and ~0.43 K for MODIS B24 and B25, respectively.

4.4 *Stability of Aqua MODIS B27 to B30*

The stability of the remaining TEB channels of Aqua MODIS, i.e., B27 to B30, is analyzed in this section. The B27 to B29 of MODIS with center wavelengths 6.715, 7.315, and 8.55 μm, respectively, are moisture-absorption channels for cloud and water vapor measurements. MODIS B28 is also affected by the absorption due to the CH_4 gas concentration in the atmosphere. The B27 and B28 of MODIS have moisture sounding peak heights at 8.06 and 4.73 km, respectively, in the troposphere. The trending results of O-B biases for these three channels from the CRTM simulation are shown in Fig. 10 with the corresponding yearly drift of O-B bias listed in Table 4 (Table 5). There are apparent downward drifts after 2013 in the O-B biases of B27 and B28 shown in Fig. 10. For MODIS B29, the upward drift of O-B bias continues over the period of interest.

To further investigate whether the drift in O-B biases shown in Fig. 10 is due to the unaccounted growth of greenhouse gas concentration in the atmosphere, the yearly O-B biases from

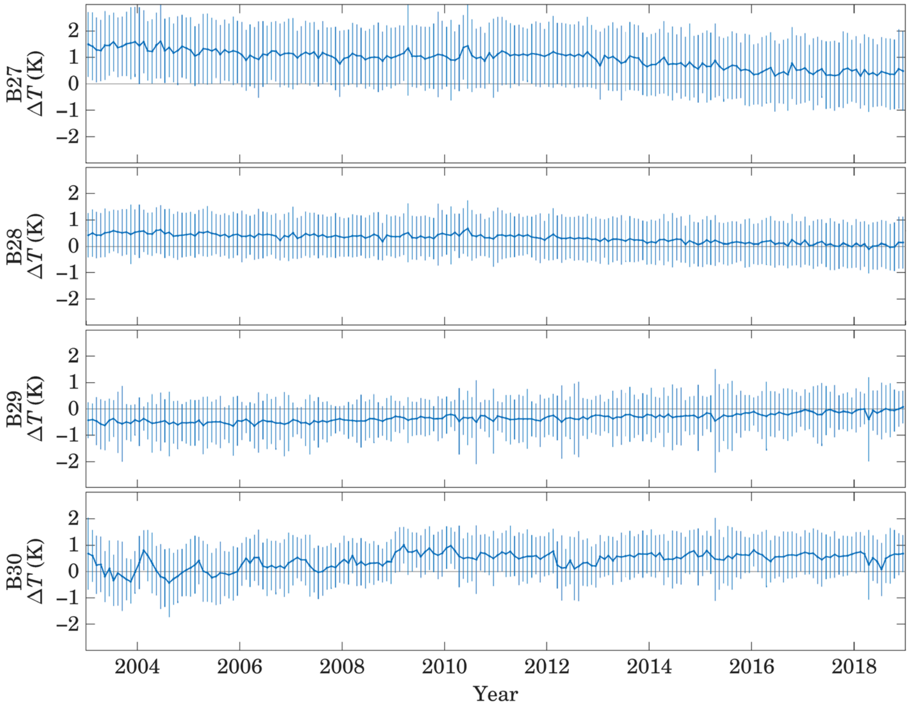


Fig. 10 Long-term monthly trending of O-B (ECMWF model) BT biases from CRTM simulation for Aqua MODIS B27 to B30 along with their uncertainties.

Table 4 Yearly O-B BT bias drift ±95%CI (K/year) of Aqua MODIS N_2O-sensitive channels B24 and B25 derived from CRTM with time-varying and MODTRAN simulations.

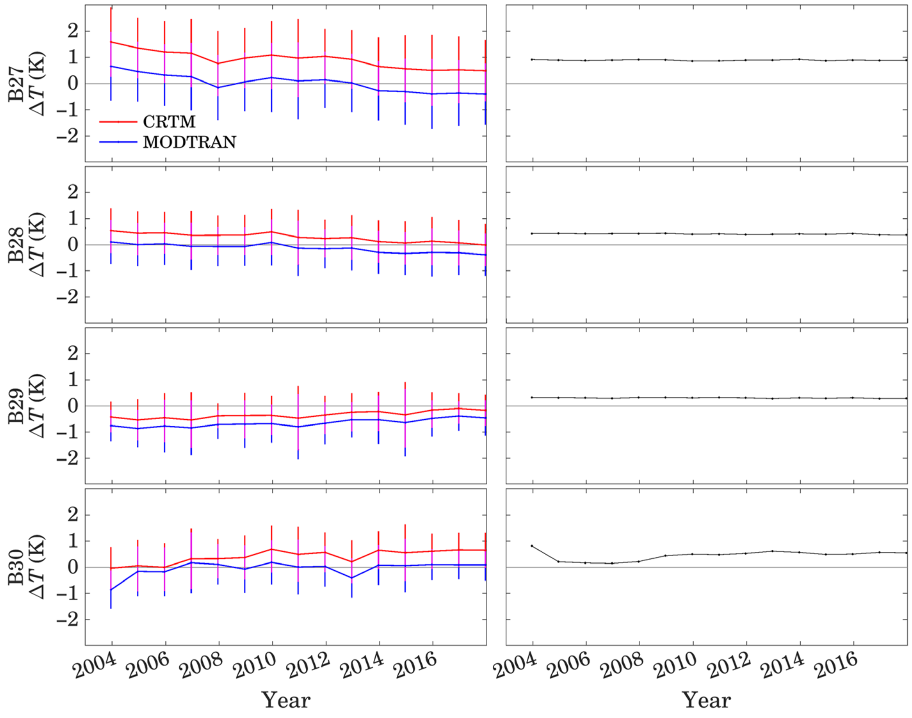
MODIS bands	Yearly drift from CRTM (with CO_2)	Yearly drift from MODTRAN (with CO_2, N_2O, and CH_4)
B24	−0.0237 ± 0.0056	0.0002 ± 0.0052
B25	−0.0250 ± 0.0051	0.0055 ± 0.0050

Table 5 Yearly BT drifts ±95%CI (K/year) of Aqua MODIS TEBs (B27 to B30) derived from O-B analysis with CRTM simulation.

MODIS bands	Yearly drift from O-B (K/year)
B27	-0.0620 ± 0.0048
B28	-0.0305 ± 0.0024
B29	0.0289 ± 0.0024
B30	0.0368 ± 0.0074

MODTRAN simulation accounting for time-varying greenhouse gases such as CO_2, CH_4, and N_2O are compared to the O-B biases derived from the CRTM simulations. As shown in Fig. 11, trending of O-B bias from CRTM and that from the MODTRAN simulations are consistent for B27 to B29 with the difference between the two O-B biases being almost flat [Fig. 11(b)]. This indicates that the inclusion of CH_4 growth data in MODTRAN simulation does not have noticeable impacts on the bias trending of B28. The consistency between MODTRAN and CRTM simulation results shown in Fig. 11 also rules out the possible cause of the downward trends in the O-B biases of B27 and B28 and the upward trend in the O-B BT bias of B29 due to the unaccounted time varying greenhouse gas absorption in the CRTM simulation.

In Chang et al.,[18] DCC, one of the most invariant Earth targets for calibration assessment, measurements were used to evaluate the long-term stability of MODIS TEB products for both Aqua and Terra from 2003 to 2019. DCC is one of the coldest targets and observations of DCC from space have minimal impact from water vapor. It is shown in the paper of Chang et al.[18] that the monthly trending of B27 and B28 bias from DCC analysis both show a downward trending while B29 bias shows an upward trend. The directions of the bias trending of these three bands



(a) (b)

Fig. 11 (a) Comparison of yearly O-B BT bias (K) and uncertainty trending of Aqua MODIS B27 to B30 between CRTM and MODTRAN simulations. (b) Time series of difference (K) between O-B biases from CRTM and MODTRAN simulations shown in (a).

are consistent with our CRTM-based O-B BT bias analysis. But the magnitudes of the bias drift in the paper of Chang et al.[18] are all less than what we see in Table 5. Li et al.[14] observed similar trends of bias drift, e.g., downward trends for MODIS B27 to B28 and slight upward trend for B29, from the inter-comparison between Aqua MODIS and IASI measurements. On the other hand, in the DCC trending analysis in the paper of Chang et al.,[18] there are noticeable drops of BT biases of magnitude ∼0.6 and ∼0.3 K for B27 and B28, respectively, in the 2014 to 2017 time frame. This time period seems to be overlapped with the occurrence of the downward trends of O-B bias shown in Fig. 10. As an estimation, a 1.5% gain change can result in ∼0.5 K bias at 250 k for MODIS B27 with central wavelength at 6.715 μm.

Since MODIS B27 to B29 are all water vapor sensitive channels with sounding peaks from surface to 8 km as seen in Fig. 2. The inputs of long-term water vapor profiles to the RTM simulation play an important role in the O-B bias assessment. In Fig. 10, it can be seen that for all of the three moisture-sensitive channels (B27 to B29), the drifts of the O-B bias all cause the O-B bias to be reduced (approaching the zero line). Such bias reduction trend may also come from the change of the moisture profile bias in ECMWF reanalysis model over time as more observational data are assimilated into the ECMWF model.

The MODIS B30 channel with center wavelength 9.73 μm is an ozone sensitive channel as shown in Fig. 1. In the study by Veglio et al.[13] through inter-comparison of Aqua MODIS data with co-located hyperspectral infrared sensor IASI measurement, it is shown that the bias of MODIS B30 fluctuates significantly. Our O-B analysis also shows more fluctuations over years for this channel in comparison with other MODIS TEBs. In the paper of Veglio et al.,[13] there is step transitions around 2009 in the bias trending between Aqua MODIS and IASI measurements. In Fig. 10, we also observe such step transition for MODIS B30. In Fig. 11, it also shows that there are differences between the O-B biases from MODTRAN and CRTM simulations. It is shown that the O-B bias trend of B30 from MODTRAN simulation appears to be mostly flat after 2005 while the O-B bias from CRTM simulation has a step transition in 2009. However, both simulations show the dip in the O-B bias in 2013. Since MODTRAN simulation is constrained by the computational cost and carried out with limited number of pixels in one day of each year, the derived trending for MODIS B30 has larger uncertainties.

5 Discussion and Summary

The MODIS on Aqua has been in operation providing continuous global observations for science research and applications since 2002. In the past, the long-term stability of Aqua MODIS TEBs was monitored through inter-comparisons with hyperspectral and multi-band sensors measurements such as from AIRS on Aqua,[13] IASI on MetOp and VIIRS on SNPP and NOAA-20,[15,16] or through long-term vicarious monitoring over stable cold targets such as Dome-C[17] or DCC.[18,19] In this paper, the RTM-based simulation models using CRTM or MODTRAN are developed to perform the long-term monitoring of the stability of TEBs of Aqua MODIS. The model is based on O-B BT bias analysis through inter-comparison of BT measurements by infrared sensors with the RTM-modeled BT using the atmosphere and surface reanalysis data from ECMWF. The area of interest in this study is confined to be over ocean in low to middle latitudes. Long-term ECMWF global atmospheric reanalysis data such as temperature, humidity, CO_2, and ozone profiles, and surface temperature and wind data are used as inputs to the CRTM simulation. The ECMWF reanalysis data have global coverage and are continuous in time. The RTM-based simulation has comprehensive spectral coverage. Therefore, the O-B bias analysis is not limited by spatial and temporal availability of global atmosphere data or spectral coverage of the reference sensors. There are about 30,000 MODIS measurements daily that can be used for O-B analysis after applying the uniformity and cloud contamination filtering, which can be efficiently processed with the CRTM simulation. Such a large amount of matched MODIS measurements significantly reduce the uncertainty in the O-B BT bias calculation. The limitation of limited gas types supported in CRTM is addressed with much coarsely sampled MODTRAN simulations which allow the incorporation of additional long-term global atmospheric profiles of greenhouse gases such as CH_4 and N_2O. Therefore, the uses of two RTM modeling tools, e.g., CRTM and MODTRAN, in this study enable us to address different aspects of the stability evaluation for

Table 6 Summary of Aqua MODIS TEB stability from RTM-based O-B analysis.

MODIS channels	Final yearly drift (K/year)	RTM model and note
CH20	0.0027 ± 0.0010	CRTM
CH21	0.0120 ± 0.0078	CRTM (fire detection channel with low QA)
CH22	0.0029 ± 0.0015	CRTM
CH23	0.0036 ± 0.0016	CRTM
CH24	0.0002 ± 0.0052	MODTRAN (very stable after accounting for N_2O and CO_2 growth)
CH25	0.0055 ± 0.0050	MODTRAN (very stable after accounting for N_2O growth)
CH27	−0.0620 ± 0.0048	Trending from both CRTM and MODTRAN show similar results with downward trend after 2013.
CH28	−0.0305 ± 0.0024	
CH29	0.0289 ± 0.0024	CRTM and MODTRAN both show small upward trend.
CH30	0.0368 ± 0.0074	CRTM and MODTRAN (ozone channel with larger uncertainty in trending.)
CH31	0.0105 ± 0.0025	CRTM
CH32	0.0107 ± 0.0026	CRTM
CH33	0.0005 ± 0.0020	CRTM (accounting for CO_2 growth is essential for stability assessment with the CRTM simulation.)
CH34	0.0039 ± 0.0019	
CH35	0.0008 ± 0.0016	
CH36	−0.0049 ± 0.0011	

Aqua MODIS TEBs. The long-term radiometric stability evaluation results from the O-B bias analysis for all the 16 Aqua MODIS TEBs are summarized in Table 6.

In general, the RTM-based O-B analyses show that the long-term stability of Aqua MODIS TEBs is maintained well. In particular, the CRTM simulation shows that Aqua MODIS surface channels are all radiometrically stable with yearly BT bias drift <0.004 K/year for B20, B22, B23, and ∼0.01 K/year for B31 and B32 over the 16 years studied in this paper. The CO_2 absorption channels of Aqua MODIS, e.g., B33 to B36, are stable with BT bias drift <0.005 K/year. The well-calibrated Aqua MODIS CO_2 TEB channels also enable the evaluation of the impacts of global CO_2 concentration growth on the trending of mean BT for these channels. The growth of atmospheric CO_2 concentration is expected to induce more absorptions of infrared radiation in these MODIS CO_2 bands. Through the comparison of the O-B BT bias from simulations with fixed and variable CO_2 profiles as inputs, the long-term impact of global CO_2 concentration growth has shown to cause the mean BT to decrease ∼0.58 to 1 K over 16 years from 2003 to 2018 for Aqua MODIS B33 to B36 channels.

For Aqua MODIS B24 and B25, their TOA radiance measurements are affected by the absorption due to the N_2O concentration in the atmosphere. MODTRAN simulation is carried out to account for the growth of N_2O concentration over 2003 to 2017. Our analysis confirms that the long-term stabilities of MODIS B24 and B25 are maintained well with yearly drift 0.0002 and 0.0055 K/year, respectively. Furthermore, the impacts of the growth of global N_2O concentration on these two Aqua MODIS channels are estimated to reduce the mean BT ∼0.35 and ∼0.43 K for MODIS B24 and B25, respectively, over 15 years.

From O-B bias trending analysis of moisture-sensitive channels B27 to B29 of Aqua MODIS, it is found that there are downward drifts after 2013 in the O-B biases of B27 and

B28. For MODIS B29, the upward drift of O-B bias continues from 2003 to 2018. The trending analysis of MODIS TEBs with DCC[18] shows similar trending directions for Aqua MODIS B27 to B29, but with much smaller magnitudes. On other hand, the trending results of these three moisture-sensitive channels (B27 to B29) all show that the O-B biases have been reduced and are approaching the 0 K line over the lifetime of Aqua MODIS. For these moisture-sensitive channels, the inputs of long-term water vapor profiles from ERA to the RTM simulation play an important role in the O-B bias assessment. The observed bias reduction trend may also come from the improvement of the moisture profile in the ECMWF reanalysis data as more observational data are assimilated into the ECMWF model over time. The drifts of O-B bias of Aqua MODIS B27 to B29 need further investigations such as through comparisons with other independent hyperspectral infrared sensor measurements or with atmospheric temperature and moisture profiles retrievals from radio occultation measurements, which can be traced to SI-traceable Global Positioning Satellite data. The MODIS B30 is an ozone sensitive channel. Our O-B analysis also shows more fluctuations over years for this channel in comparison with other MODIS TEBs.

The inter-comparison of MODIS TEB measurements with global atmospheric and climate reanalysis data through RTM provides validation of the radiometric stability of Aqua MODIS TEBs with Weather Forecasting model and other space-borne and ground-based observations. The analysis in this paper also demonstrates that combining the well-calibrated MODIS TEB measurements with RTM simulation helps quantify the long-term impacts of global greenhouse gas concentration growth on the BT decreases in the greenhouse gas-sensitive channels. The RTM-based inter-comparison method developed in this paper can be extended to evaluate the stability of other infrared sensors such as MOIDS on TERRA, VIIRS on SNPP and NOAA-20, and Advanced Baseline Imager (ABI) on Geostationary Operational Environmental Satellite satellites.

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References

1. W. L. Barnes, T. S. Pagano, and V. V. Salomonson, "Prelaunch characteristics of the moderate resolution imaging spectroradiometer (MODIS) on EOS-AM1," *IEEE Trans. Geosci. Remote Sens.* **36**(4), 1088–1100 (1998).
2. X. Xiong et al., "MODIS on-orbit calibration and characterization," *Metrologia* **40**(1), S89–S92 (2003).
3. X. Xiong et al., "Status of MODIS instrument and radiometric calibration," in *IEEE Int. Geosci. and Remote Sens. Symp.*, pp. 4419–4422 (2013).
4. X. Xiong et al., "Moderate resolution imaging spectroradiometer on terra and aqua missions," in *Optical Payloads for Space Missions*, S. Qian et al., Ed., pp. 53–89, John Wiley & Sons, Ltd., Oxford (2015).
5. X. Xiong et al., "Terra and aqua MODIS thermal emissive bands on-orbit calibration and performance," *IEEE Trans. Geosci. Remote Sens.* **53**(10), 5709–5721 (2015).
6. X. Xiong et al., "Updates of moderate resolution imaging spectroradiometer on-orbit calibration uncertainty assessments," *J. Appl. Remote Sens.* **12**(3), 034001 (2018).
7. X. Shao et al., "Orbital variations and impacts on observations from SNPP, NOAA 18-20, and AQUA sun-synchronous satellites," *Proc. SPIE* **10764**, 107641U (2018).
8. C. L. Parkinson, "Summarizing the first ten years of NASA's aqua mission," *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **6**(3), 1179–1188 (2013).
9. H. Yue et al., "The brightness temperature adjusted dust index: an improved approach to detect dust storms using MODIS imagery," *Int. J. Appl. Earth Obs. Geoinf.* **57**, 166–176 (2017).
10. S. Skakun et al., "Transitioning from MODIS to VIIRS: an analysis of inter-consistency of NDVI data sets for agricultural monitoring," *Int. J. Remote Sens.* **39**(4), 971–992 (2018).

11. P. Gupta et al., "Validation of MODIS 3 km land aerosol optical depth from NASA's EOS Terra and Aqua missions," *Atmos. Meas. Tech.* **11**(5), 3145–3159 (2018).
12. R. C. Levy et al., "The collection 6 MODIS aerosol products over land and ocean," *Atmos. Meas. Tech.* **6**(11), 2989–3034 (2013).
13. P. Veglio et al., "Long-term assessment of Aqua MODIS radiance observation using comparisons with AIRS and IASI," *J. Geophys. Res. Atmos.* **121**(14), 8460–8471 (2016).
14. Y. Li, A. Wu, and X. Xiong, "Assessment of MODIS collection 6.1 thermal emissive band calibration using hyperspectral IASI observations," *Proc. SPIE* **11530**, 1153019 (2020).
15. Y. Li, A. Wu, and X. Xiong, "Inter-comparison of S-NPP VIIRS and aqua MODIS thermal emissive bands using hyperspectral infrared sounder measurements as a transfer reference," *Remote Sens.* **8**(1), 72 (2016).
16. Y. Li et al., "Comparison of the MODIS and VIIRS thermal emissive band radiometric calibration," *IEEE Trans. Geosci. Remote Sens.* **58**(7), 4852–4859 (2020).
17. A. Shrestha and X. Xiong, "Tracking long-term stability of MODIS thermal emissive bands response versus scan-angle using Dome C observations," *Proc. SPIE* **10986**, 109861W (2019).
18. T. Chang, X. Xiong, and A. Shrestha, "Assessment of MODIS thermal emissive bands calibration performance using deep convective clouds," *J. Appl. Remote Sens.* **13**(4), 044526 (2019).
19. T. Chang et al., "Methodology development for calibration assessment using quasi-deep convective clouds with application to aqua MODIS TEB," *Earth Space Sci.* **7**(1), e2019EA001055 (2020).
20. C. P. Díaz, X. Xiong, and A. Wu, "MODIS thermal emissive bands calibration stability using in-situ ocean targets and remotely-sensed SST retrievals provided by the group for high resolution sea surface temperature," *Proc. SPIE* **11014**, 110140P (2019).
21. T.-C. Liu et al., "Long term stability monitoring of aqua MODIS thermal emissive bands through radiative transfer modeling," *Proc. SPIE* **11501**, 115011K (2020).
22. X. Xiong et al., "Multiyear on-orbit calibration and performance of terra MODIS thermal emissive bands," *IEEE Trans. Geosci. Remote Sens.* **46**(6), 1790–1803 (2008).
23. A. Berk et al., "MODTRAN6: a major upgrade of the MODTRAN radiative transfer code," *Proc. SPIE* **9088**, 90880H (2014).
24. Joint Center for Satellite Data Assimilation, "Community radiative transfer model 2.1.3," 2013, ftp://ftp.emc.ncep.noaa.gov/jcsda/CRTM/REL-2.1.3/ (accessed March 2021).
25. Y. Han et al., "Current status of the JCSDA community radiative transfer model (CRTM)," in *Proc. 17th Int. ATOVS Study Conf.*, Monterey, CA (2010).
26. Y. Chen et al., "Assessment of shortwave infrared sea surface reflection and nonlocal thermodynamic equilibrium effects in the community radiative transfer model using IASI data," *J. Atmos. Oceanic Technol.* **30**(9), 2152–2160 (2013).
27. Q. Liu and S. Boukabara, "Community radiative transfer model (CRTM) applications in supporting the Suomi national polar-orbiting partnership (SNPP) mission validation and verification," *Remote Sens. Environ.* **140**, 744–754 (2014).
28. M. Collins et al., "Long-term climate change: projections, commitments and irreversibility," Climate Change 2013—The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 1029–1136, Cambridge University Press (2013).
29. Ed Dlugokencky, "Trends in atmospheric nitrous oxide," https://www.esrl.noaa.gov/gmd/ccgg/trends_n2o/ (accessed March 2021).

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