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Key Points:

- SST trend in the past decade is as large as that in the past 34 years
- SST trends do not reduce significantly when satellite-based observations are included
- The biases of satellite observations should be corrected

Correspondence to:
B. Huang,
boyin.huang@noaa.gov

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Assessing the impact of satellite-based observations in sea surface temperature trends

Boyin Huang[1], Chunying Liu[2], Viva F. Banzon[1], Huai-Min Zhang[1], Thomas R. Karl[1], Jay H. Lawrimore[1], and Russell S. Vose[1]

[1]National Centers for Climate Information (NCEI), Asheville, North Carolina, USA, [2]ERT, Inc., Laurel, Maryland, USA

Abstract Global trends of sea surface temperature (SST) are assessed for the existing and new experimental SST analyses that incorporate advanced very high resolution radiometer (AVHRR) observations from NOAA polar-orbiting satellites. These analyses show that globally and annually averaged SST trends over the 21st century (2000–2015) are similar to the trends for the full satellite record period (1982–2015), regardless of whether AVHRR data are included in the analyses. It is shown that appropriate bias correction is an important step to remove discontinuities of AVHRR data for consistent time series and trend analysis.

1. Introduction

Global surface temperature trends in various time scales have been widely studied in climate research literature in terms of long-term climate change as well as contributions from decadal variations (e.g., the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report [*IPCC*, 2013; *Fyfe et al.*, 2016, and citations therein]). The objective of our study is to assess the impact of satellite observations on sea surface temperature (SST) trends in the most recent decades (such as in 2000–2015) in the satellite SST observation era (1982–2015). *Karl et al.* [2015] reported that global SST since 2000 has continued to exhibit a significant warming trend based on the Extended Reconstructed SST version 4 (ERSSTv4) [*Huang et al.*, 2015a]. Notably, the trend since 2000 was shown to be as large as that in the previous 50 year period. The study of *Rajaratnam et al.* [2015] found that the conclusion of *Karl et al.* [2015] was statistically robust. However, *Roemmich et al.* [2015] found that there was no significant trend in a different SST product, the weekly Optimum Interpolation SST (OISST) (WOISST) [*Reynolds et al.*, 2002]. This discrepancy with ERSSTv4 (and also the Daily OISST version 2; DOISST hereafter) is investigated here. The WOISST used in *Roemmich et al.* [2015] included SSTs from the advanced very high resolution radiometer (AVHRR) on NOAA polar-orbiting satellites. Therefore, it was suspected whether the above discrepancy was caused by the inclusion of the satellite-based SSTs. In this paper, we demonstrate that the cause for the above discrepancy lies in the offsets between ship and buoy SSTs, which were corrected in the ERSSTv4 and DOISST but not in the earlier WOISST. When the ship-buoy offsets are corrected, satellite and in situ SSTs produce consistent trends in the existing and experimental analyses and data sets (Table 1).

2. Existing and Experimental Analyses

2.1. ERSSTv4

ERSSTv4 [*Huang et al.*, 2015a] is a monthly 2° × 2° analysis that uses in situ SSTs from the International Comprehensive Ocean-Atmosphere Dataset (ICOADS) R2.5 (1854–2007) [*Woodruff et al.*, 2011] and the Global Telecommunications System (GTS) (2008–2015) receipts collected by the National Centers for Environmental Prediction (NCEP). ERSSTv4 contains corrections for in situ data biases: (a) ship SST biases associated with different instruments (i.e., buckets and engine room intakes) are corrected using Nighttime Marine Air Temperature (NMAT) and (b) to be consistent with the long historical ship records as a reference baseline, buoy SSTs are corrected according to a systematic ship-buoy SST offset of 0.12°C based on observations from 1990 to 2012. The bias-corrected ship and buoy SSTs are merged according to their relative weights of 1.0 and 6.8, respectively, determined by their random errors [*Reynolds and Smith*, 1994]. In ERSSTv4, satellite AVHRR SSTs are not included because they introduce a data discontinuity in the 1980s and because the biases are difficult to correct in regions with sparse in situ data in the early time period (e.g., the high latitudes).

Table 1. SST Products and Their Data Sources[a]

SST Data Sets	Resolution	Ship-Buoy Cor.	Ship Instr. Bias Cor.	In Situ Obs.	AVHRR Obs. and Bias Cor. Timescale	Weights
(a) ERSSTv4	Monthly 2° × 2° from 1854	0.12°C added to buoys	UK Hadley NMAT2	ICOADS R2.5, NCEP GTS	None	1.0 and 6.8
(b) ERSSTv4SAT	Monthly 2° × 2° from 1982	0.12°C added to buoys	UK Hadley NMAT2	ICOADS R2.5, NCEP GTS	*Banzon et al.* [2016], 30 days	1.0, 6.8, 5.9, and 18.8
(c) ERSSTv3b	Monthly 2° × 2° from 1854	0°C	UKMO NMAT before 1941; zero after 1941	ICOADS R2.4, NCEP GTS	None	1.0 and 6.8
(d) DOISST	Daily 0.25° × 0.25° from 1982	0.14°C subtracted from ships	0°C	ICOADS R2.4, NCEP GTS	*Banzon et al.* [2016], 15 days	1.0, 15.1, 15.1, and 15.1
(e) WOISST	Weekly 1° × 1° from 1982	0°C	0°C	COADS	*Kilpatrick et al.* [2001], 7 days	1.0, 6.8, 6.8, and 18.8
(f)–(i) Org/cor day/night SAT	Daily 4.4 km except for MetOp-A (1.1 km)	N/A	N/A	N/A	*Banzon et al.* [2016]	N/A

[a]Weights in the last column are in the order of ship, buoy, daytime, and nighttime AVHRR SSTs when they are merged together. The abbreviations of obs, org, cor, day, night, and instr represent observation, original, correction, daytime, nighttime, and instrument, respectively.

2.2. ERSSTv4SAT

To assess the impact of AVHRR observations, an experimental analysis (called ERSSTv4SAT herein) was developed based on ERSSTv4 [*Huang et al.*, 2015a] but with satellite data included. The satellite-based AVHRR observations consisted of Pathfinder (PF) v5.1 (NOAA-7, 1982–1985) and v5.0 (NOAA-9, 1985–1988; NOAA-11, 1988–1994; NOAA-9, 1994–1995; NOAA-14, 1995–2000; NOAA-16, 2000–2002; NOAA-17, 2003–2005; NOAA-18, 2005–2006), together with the operational SSTs produced by the U.S. Navy (NOAA-17, 2006–2008; MetOp-A, 2009–2015; NOAA-18, 2007 to August 2011; NOAA-19, August 2011–2015) [*Banzon et al.*, 2016]. These AVHRR SSTs were also used in DOISST, discussed in section 2.5. The AVHRR observations are separated into daytime and nighttime SSTs. Note that PF SSTs may not appear continuous near 2006 when NOAA-18/19 SSTs from the U.S. Navy are introduced, and two sensors are used at a time. Therefore, the SSTs from PF v5.0/5.1, NOAA-17, and MetOp-A are combined (SAT, hereafter) to estimate the trends of original AVHRR SSTs, but both SAT and NOAA-18/19 SSTs are included in ERSSTv4SAT analysis.

Several studies indicated that AVHRR SSTs can contain residual biases due to cloud contamination, noise amplification at high satellite zenith angles, instrument degradation, imperfect correction for atmospheric water vapor and aerosols, etc. [*Kilpatrick et al.*, 2001; *Zhang et al.*, 2004; *Merchant et al.*, 2009, 2014]. The PF retrieval algorithm computes regression coefficients from brightness temperature and high quality buoy SST matchups per satellite, so any temporal changes are not corrected. The early AVHRR satellites also experienced significant orbit drift. The biases of AVHRR SSTs are therefore corrected according to the monthly patterns of in situ and AVHRR observations [*Smith et al.*, 2008; *Huang et al.*, 2015b]. There are five basic steps in this process. First, the ship and buoy SSTs are merged with relative weights of 1.0 and 6.8, respectively, as in ERSSTv4. Second, the merged in situ and AVHRR SSTs are analyzed by decomposition and summation of a maximum of 130 common spatial modes that can be represented by both in situ and AVHRR SSTs. Third, the difference between the analyzed in situ and AVHRR SSTs is defined as the bias of AVHRR SST. The biases are calculated separately for daytime and nighttime AVHRR SSTs. Fourth, the bias-corrected daytime/nighttime AVHRR SSTs are generated by subtracting their biases from original daytime/nighttime AVHRR SSTs. Finally, the bias-corrected daytime and nighttime AVHRR, ship, and buoy SSTs are merged with relative weights of 5.9, 18.8, 1.0, and 6.8, respectively, according to their random error statistics [*Reynolds and Smith*, 1994; *Smith et al.*, 2008]. A higher weight is given to the nighttime AVHRR SSTs due to their lower error in comparison with daytime AVHRR SSTs. The original spatial resolution of AVHRR is 4.4 km except for MetOp-A whose resolution is 1.1 km. In this paper and for comparison purposes, the daily satellite SST anomalies (SSTAs) are first derived from the 1971 to 2000 base period climatology and then averaged into monthly 2° × 2° as in ERSSTv4.

2.3. ERSSTv3b

ERSSTv4 was developed from ERSSTv3b. ERSSTv3b [*Smith et al.*, 2008] is a monthly 2° × 2° analysis that uses in situ SSTs from ICOADS R2.4 (1854–2007) and NCEP GTS (2008–2015). In contrast to ERSSTv4, the ship-buoy

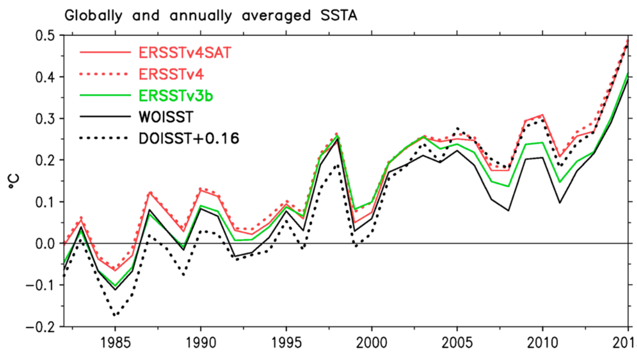

Figure 1. Globally and annually averaged SSTAs in ERSSTv4SAT (solid red line), ERSSTv4 (dotted red line), ERSSTv3b (solid green line), WOISST (solid black line), and DOISST (dotted black line). The DOISST is shifted by adding a constant of 0.16°C throughout the entire time series.

offset correction is not applied, and the ship SST bias correction is set to zero after 1941. Ship and buoy SSTs are merged according to their relative weights of 1.0 and 6.8, respectively. Satellite SSTs are not included.

2.4. Weekly OISST

The WOISST is an earlier generation of OISST. The WOISST analysis [*Reynolds et al.*, 2002] uses AVHRR SSTs and in situ SSTs from the Comprehensive Ocean-Atmosphere Data Set (COADS) before 1998 [*Woodruff et al.*, 1998] and from the NCEP GTS collection after 1998. The AVHRR SSTs [*Kilpatrick et al.*, 2001] are from the operational Navy algorithms and from NOAA-7 (1982–1985), NOAA-9 (1985–1988), NOAA-11 (1988–1994), NOAA-14 (1995–2000), NOAA-16 (2001–2004), NOAA-17 (2004–2008), NOAA-18 (2008–2010), and NOAA-19 (2010–2015). In the WOISST, AVHRR SST biases are corrected using the Poisson equation within a data window of 7 days [*Reynolds et al.*, 2002]. The ship-buoy offset and ship SST bias correction are not applied. The bias-corrected data are merged using signal-to-noise fields, which produce average weights of about of 6.8, 18.8, 1.0, and 6.8, for daytime and nighttime AVHRR, ship, and buoy SSTs, respectively [*Reynolds et al.*, 2002]. In this paper and for comparison purposes, data are averaged into monthly 2° × 2° boxes from the original weekly 1° × 1° fields.

2.5. Daily OISST

The DOISST [*Reynolds et al.*, 2007] is a new generation of OISST with daily rather than weekly resolution as in WOISST. DOISST uses the in situ SSTs from ICOADS R2.4 between September 1981 and December 2006 [*Woodruff et al.*, 2011] and NCEP GTS data thereafter. It uses the same AVHRR SSTs as in ERSSTv4SAT. AVHRR SST biases are corrected using the patterns of 15 day averaged in situ SSTs. The ship-buoy offset is set to 0.14°C based on observations from 1982 to 2000 [*Reynolds et al.*, 2007]. The ship SST bias correction relative to NMAT is not applied [*Huang et al.*, 2015b]. The bias-corrected daytime and nighttime AVHRR, ship, and buoy SSTs are merged based on noise-to-signal ratio maps for each data type, which have averaged weights of 15.1, 15.1, 1.0, and 15.1, respectively [*Reynolds et al.*, 2007]. In this paper and for comparison purposes, data are averaged into monthly 2° × 2° boxes from the original daily 0.25° × 0.25° fields.

Note that the DOISST has been systematically shifted in Figure 1 by adding a constant of 0.16°C, the averaged difference between ERSSTv4 and DOISST in 1982–2015. With all input SSTs adjusted to buoys rather than ships, DOISST is cooler. There are systematic differences between ship and buoy measured SSTs, with ship SSTs generally being warmer than buoy SSTs [*Reynolds et al.*, 2007; *Huang et al.*, 2015a]. For the satellite era DOISST (1982 to present), ship SSTs are corrected toward the more accurate buoy SSTs by subtracting 0.14°C [*Reynolds et al.*, 2007]. In contrast, for the century-scale (1854 to present) ERSSTv4, buoy SSTs are corrected toward ship SSTs by adding 0.12°C for the long historical consistency [*Huang et al.*, 2015a]. Thus, for this comparison study and for the DOISST and ERSSTv4 to be comparable, the DOISSTs are added 0.16°C to make up the systematic offsets.

2.6. Daytime and Nighttime SAT SSTs

These data sets contain SSTs from PF v5.0/5.1 and operational Navy NOAA-17, and MetOp-A. In this paper and for comparison purposes, data are averaged into monthly 2° × 2° boxes.

2.7. Bias-Corrected Daytime and Nighttime SAT SSTs

These data sets are the same as those in section 2.6 except that the SSTs are bias-corrected using in situ observations [*Huang et al.*, 2015b].

Table 2. SSTA Trends (°C Decade^{-1}) and Their Uncertainties (95% Confidence Level) for 1982–2015, 2000–2015, and 2000–2014

SST data sets	1982–2015 Trends	2000–2015 Trends	2000–2014 Trends
(a) ERSSTv4	0.11 ± 0.03	0.13 ± 0.08	0.10 ± 0.07
(b) ERSSTv4SAT	0.11 ± 0.03	0.13 ± 0.09	0.10 ± 0.07
(c) ERSSTv3b	0.10 ± 0.03	0.07 ± 0.09	0.03 ± 0.07
(d) DOISST	0.14 ± 0.03	0.15 ± 0.08	0.12 ± 0.07
(e) WOISST	0.09 ± 0.03	0.09 ± 0.10	0.04 ± 0.08
(f) Daytime SAT	0.13 ± 0.04	0.18 ± 0.14	0.12 ± 0.12
(g) Nighttime SAT	0.21 ± 0.05	0.34 ± 0.09	0.31 ± 0.08
(h) Corrected daytime SAT	0.13 ± 0.03	0.16 ± 0.09	0.12 ± 0.06
(i) Corrected nighttime SAT	0.12 ± 0.03	0.15 ± 0.08	0.11 ± 0.07

3. SSTA Trends

3.1. SSTA Trends in Five SST Analyses

The SSTAs were area weighted globally and annually averaged, and linear trends were computed for 1982–2015 (satellite era) and 2000–2015 (21st century) using least squares fitting. The trend for 1982–2015 (the satellite data era) is used as a reference to determine whether recent SST warming (2000–2015/2014) [*Karl et al.*, 2015] has become stronger, weaker, or remained the same. Tests show that the selection of recent periods other than 2000–2014/2015 will not affect the overall conclusion [*Karl et al.*, 2015]. Trend uncertainties (95% confidence level) were estimated using effective sampling numbers determined by an AR1 process [*von Storch and Zwiers*, 1999]. Note that the trend uncertainties in the present study do not include the contributions from parametric uncertainty—i.e., due to changes in internal parameters [*Liu et al.*, 2015; *Huang et al.*, 2016]. However, as indicated in *Huang et al.* [2016], the contribution of parametric uncertainty to the SST trend is very small in the recent period and is much smaller for the long-term trend (0.01°C decade^{-1}; their Figure 7c). Therefore, the parametric uncertainty has been ignored in the present study.

Figure 1 shows the globally and annually averaged SSTAs in ERSSTv4SAT, ERSSTv4, ERSSTv3b, WOISST, and DOISST. SSTAs exhibit a clear warming tendency from 1982 to 2015 in all analyses in addition to consistent interannual variability in all analyses. The magnitude of SSTA trends ranges from 0.09°C to 0.14°C decade^{-1} (Table 2; rows (a)–(e), second column). The strongest trend (0.14°C decade^{-1}) is in DOISST and the weakest trend (0.09°C decade^{-1}) is in WOISST. ERSSTv4SAT, ERSSTv4, and ERSSTv3b have comparable trends for 1982–2015 (0.10°C to 0.11°C). Notably, the trends in ERSSTv4SAT and ERSSTv4 are about the same, indicating that the addition of AVHRR SSTs has no impacts on trend at the global scale for this period.

As seen in Table 2, WOISST exhibits less warming than DOISST for 1982–2015. This difference is largely associated with (a) using different in situ and AVHRR SSTs and (b) using different bias corrections in both in situ and AVHRR SSTs. Ship SST biases are corrected by subtracting 0.14°C in the new generation DOISST, while such a correction is not applied in the old generation WOISST (Table 1). Since the number of ship observations has decreased since the 1980s while the number of buoy observations has increased rapidly [*Huang et al.*, 2015a], the application of the ship-buoy offset correction in DOISST results in a larger trend [*Huang et al.*, 2016]. Furthermore, on average, the weights in merging the bias-corrected daytime AVHRR and buoy SSTs are higher in DOISST (15.1) than that in WOISST (6.8). The higher weights, particularly in buoy SSTs, may contribute to the higher SSTA trend in DOISST, since the trend in the bias-corrected daytime AVHRR SST is higher than that in the in situ SST as indicated in ERSSTv4 (Table 2; rows (a), (h), and (i), second column).

ERSSTv4SAT also exhibits slightly less warming than DOISST for 1982–2015. This trend difference is likely associated with different bias correction algorithms. The biases in AVHRR SSTs are corrected with a data window of 15 days in DOISST versus one month in ERSSTv4SAT [*Huang et al.*, 2015b]. The ship-buoy offset is higher in DOISST (0.14°C) than in ERSSTv4SAT (0.12°C), and the weight for buoy SST is higher in DOISST (15.1 on average) than in ERSSTv4SAT (6.8 fixed). The weight in merging the bias-corrected daytime AVHRR SST is higher in DOISST (15.1) than ERSSTv4SAT (5.9). As indicated in *Huang et al.* [2016], the higher the ship-buoy offset and the greater the weight assigned to daytime AVHRR, the higher the SSTA trend in the analysis.

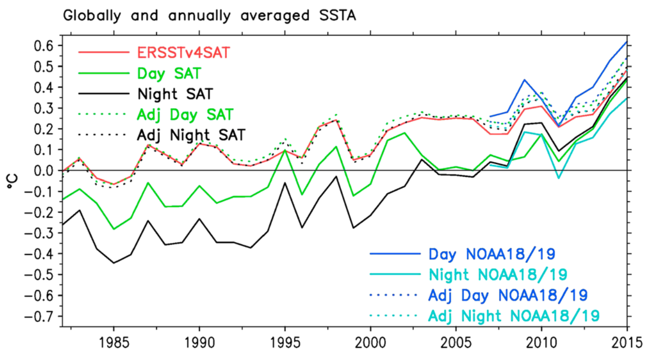

Figure 2. Globally and annually averaged SSTAs from ERSSTv4SAT (solid red), daytime SAT (solid green), nighttime SAT (solid black), corrected daytime SAT (dotted green), corrected nighttime SAT (dotted black), daytime NOAA-18/19 (solid blue), nighttime NOAA-18/19 (solid light blue), corrected daytime NOAA-18/19 (dotted blue), and corrected nighttime NOAA-18/19 (dotted light blue). Note that the SAT data include PF v5.0/5.1, NOAA-17, and MetOp-A.

SSTA trends for 2000–2015 in ERSSTv4SAT, ERSSTv4, and DOISST range from 0.13°C to 0.15°C decade^{-1} (Table 2; rows (a), (b) and (d), third column). This is roughly comparable to the range for 1982–2015 (0.11°C to 0.13°C). In other words, the globally averaged SSTA trend since 2000 exhibits no warming hiatus or slowdown, consistent with *Karl et al.* [2015]. It should be noted that the SSTA trend since 2000 is slightly higher in DOISST than in ERSSTv4SAT for the reasons described earlier.

SSTA trends for 2000–2015 in the earlier version ERSSTv3b and WOISST, however, are small and not statistically significant (0.07°C to 0.09°C decade^{-1}; Table 2, rows (c) and (e), third column) as indicated in *Karl et al.* [2015] and *Roemmich et al.* [2015]. As shown earlier, the smaller trends are associated with the lack of key bias corrections (i.e., ship-buoy offset and ship instrumental biases correction are neglected in ERSSTv3b and WOISST [*Huang et al.*, 2015b]). These problems have been addressed in the new generation ERSSTv4 and DOISST, which results in improved trend estimates.

3.2. SSTA Trends in ERSSTv4SAT

Figure 2 shows the globally and annually averaged SSTAs in ERSSTv4SAT, the original daytime and nighttime SAT, and bias-corrected daytime and nighttime SAT. The original AVHRR SSTs clearly exhibit cold biases that increase going back in time. The averaged cold biases of daytime and nighttime SSTs in SAT (measured by the deviation between bias-corrected and original series) are approximately 0.3°C before 1995, 0.2°C between 1995 and 2010, and 0.1°C after 2010. The magnitude of the bias is consistent with *Huang et al.* [2015b]. The original daytime and nighttime SAT trends are 0.13°C and 0.21°C decade^{-1} for 1982–2015 (Table 2; rows (f) and (g), second column) and 0.16°C and 0.34°C decade^{-1} for 2000–2015 (Table 2; rows (f) and (g), third column). In contrast, the trends in bias-corrected AVHRR SSTs decrease to 0.12°C to 0.13°C decade^{-1} for 1982–2015 and 0.15°C to 0.16°C decade^{-1} for 2000–2015 (Table 2; rows (h) and (i)). In other words, SAT SSTs have higher trends, and the bias corrections by the in situ SSTs actually reduce the trend in the AVHRR SSTs, which directly contributes to a similarly lower trend in ERSSTv4SAT. However, the trend in ERSSTv4SAT remains significant and is close to the SSTA trends of 0.10°C decade^{-1} in both periods in ERSSTv4 (Table 2; rows (a) and (b)). Thus, the global SST warming hiatus in the past decade cannot be identified by either including the bias-corrected AVHRR SSTs in ERSSTv4 or in the original AVHRR SST time series themselves. Note that the larger trends in original nighttime AVHRR SST (Table 2; row (g)) are associated with the reduced daytime-nighttime SST differences after 2003 (Figure 2; solid green and solid black lines) due to drifts in the equator-crossing times of the satellite.

4. Conclusions and Discussion

Our study finds that the SST trends are significant in the in situ based ERSSTv4, the ERSSTv4 with satellite AVHRR SSTs included (ERSSTv4SAT), and the new generation OISST (DOISST) over the periods of 1982–2015 and 2000–2015. In comparison, the SSTA trends in the earlier generation ERSSTv3b and WOISST are smaller and the warming trends are insignificant in the recent decade (2010–2015); this is because the recently revealed ship-buoy offset and ship SST instrumental bias corrections were not applied in ERSST v3b and WOISST but implemented in the improved and updated version ERSSTv4 and DOISST.

The SSTA time series in the new generation ERSSTv4, ERSSTv4SAT, and DOISST consistently show that the warming trends since 2000 were as strong as those in the past 34 years of the satellite era. Particularly, the

SSTA trends in DOISST and ERSSTv4SAT are very close to those in ERSSTv4, indicating that the inclusion of satellite-based observations do not alter the conclusion that there is no warming hiatus or slowdown from the beginning of the 21st century to present (2000–2015) as compared to the 34 year satellite observation period (1982–2015).

One may argue that the SSTA trends of 2000–2015 are larger because of the strong 2015–2016 El Niño. However, our conclusions remain the same for the SSTA trends for 2000–2014 (Table 2; fourth column). It is important to remember that the biases of AVHRR SSTs need to be corrected before they are merged with in situ SSTs. If these biases are not corrected, the warming trends become even larger but biased.

It is noteworthy that the data sets used in our comparisons are not completely independent including the satellite retrieved SSTs. However, some of these data sets are used to compute and analyze SST trends and disagreements were discovered, as in *Roemmich et al*. [2015]. The purpose of this study is to understand the cause for the above discrepancies. We further note that the reconstruction methodologies are independent between OISST and ERSST. The data interdependency also exists when comparing with data sets from the UK Met Office and Japanese Meteorological Agency [*Huang et al*., 2015a]. We note that data sets such as those from the Along-Track Scanning Radiometer (1997–2011; refer to *Huang et al*. [2015a]) and Argo floats (after 1999) can be regarded as independent from the data sets used in our study. However, the above two independent data sets are limited by short time periods in both and low spatial coverage in Argo data set (less than 20% of global 2° × 2° grid cells with data prior to 2005). These hinder their use in comparison to our SST trend analysis in this study.

The objective of our study is to assess the impact of satellite observations on SST trends in the most recent decades (such as in 2000–2015) in the context of the satellite SST observation era (1982–2015). These trends are used to measure the climate change in recent years as done by the IPCC Fifth Assessment Report [*IPCC*, 2013]. However, readers need to be cautious in interpreting the statistical significance of SST trends over short time periods. These SST trends may directly be associated with SST variabilities at decadal timescales [*Fyfe et al*., 2016]. Traditionally, SST trends have been assessed over periods longer than 30 years for stable climate signals beyond decadal variabilities. Nevertheless, according to the study of *Weatherhead et al*. [1998], we estimate the length of time needed for a significant trend using $N = \left[\frac{2T\sigma}{\omega}\sqrt{\frac{1+\phi}{1-\phi}}\right]^{2/3}$, where T is the T value for a specific significance test (1.96 for 95% significance level), σ is the standard deviation, ϕ is the AR1 autocorrelation, and ω is the trend. In ERSSTv4, for example, σ, ϕ, and ω are 0.062°C, 0.47, and 0.13°C decade^{-1}, respectively, in 2000–2015 time period. The required data length for the SST trend to be statistically significant is approximately 10 years. Based on this criterion, the estimated SST trend of 0.13°C decade^{-1} is statistically significant.

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