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Deriving the operational nonlinear multichannel sea surface temperature algorithm coefficients for NOAA-15 AVHRR/3

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Abstract. The National Oceanic and Atmospheric Administration (NOAA) currently uses Nonlinear Sea Surface Temperature (NLSST) algorithms to estimate sea surface temperature (SST) from NOAA satellite Advanced Very High Resolution Radiometer (AVHRR) data. In this study, we created a three-month dataset of global sea surface temperature derived from NOAA-15 AVHRR data paired with coincident SST measurements from buoys (i.e. called the SST match-up dataset) between October and December 1998. The satellite sensor SST and buoy SST pairs were included in the dataset if they were coincident within 25 km and 4 hours. A regression analysis of the data in this matchup dataset was used to derive the coefficients for the operational NLSST equations applicable to NOAA-15 AVHRR sensor data.

An independent matchup dataset (between January and March 1999) was also used to assess the accuracy of these day and night operational NLSST algorithms. The bias was found to be 0.14°C and 0.08°C for the day and night algorithms, respectively. The standard deviation was 0.5°C or less.

1. Introduction

Global sea surface temperature (SST) products have been produced operationally from National Oceanic and Atmospheric Administration (NOAA) satellite Advanced Very High Resolution Radiometer (AVHRR) data since 1979 (McClain *et al.* 1985, Pichel 1991, Walton *et al.* 1998). The AVHRR/2 instruments, flown on the NOAA-7, 9, 11–14 satellites, have two visible channels (channels 1 and 2 at 0.6 and 0.9 μm, respectively), one short-wavelength infrared channel (channel 3 at 3.7 μm), and two long-wavelength infrared channels, the split window channels (channels 4 and 5 at 11 and 12 μm, respectively). The AVHRR/3 on board the recently launched NOAA-15 satellite has spectral and gain changes to the visible channels that allow low energy/light detection and carries a sixth channel, called 3A, at 1.6 μm for snow and ice discrimination. On NOAA-15, the AVHRR channel 3A is only used experimentally; but on NOAA-16 it will be time shared with the 3.7 μm channel, named channel 3B. Detailed documentation on the modified AVHRR/3 visible and infrared channels can be found at http://www2.ncdc.noaa.gov/docs/intro.htm.

To estimate SST from AVHRR channel data, dual window (channels 3 and 4), split window (channels 4 and 5), and triple window (channels 3, 4 and 5) methods

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are widely used to correct for absorption and re-emission of radiation by atmospheric gases, predominantly water vapour (McMillin 1975, Barton 1983, Llewellyn-Jones *et al.* 1984, McClain *et al.* 1985, Brown *et al.* 1985, Walton 1988, Barton 1995, Walton *et al.* 1998). The coefficients in these algorithms are calculated after satellite launch by matching the first few months' worth of NOAA satellite AVHRR data with global drifting buoy observations.

In this study, we first created a dataset of global sea surface temperature derived from NOAA-15 AVHRR sensor data paired with coincident SST measurements from buoys (i.e. called the SST matchup dataset) between October and December 1998. We then performed a regression analysis to calculate coefficients for the NOAA National Environment Satellite Data and Information Service (NESDIS) operational SST estimation algorithm applicable to NOAA-15 AVHRR data. The buoys used in this study are both global drifting buoys and Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE) moored buoys located in the tropical Pacific. Since the matchup dataset contains the global range of SST and atmosphere moisture content, these NESDIS operational equations and their coefficients can be used by High Resolution Picture Transmission (HRPT) station operators all over the world. In §2, a description of the SST matchup dataset is given, followed by an introduction to the NLSST algorithms in §3. In §4, the assessment of SST accuracy using an independent dataset between January and March 1999 is presented. Conclusions are in §5.

2. SST matchup dataset preparation

NOAA-15 was launched on 13 May 1998, into the Sun synchronous polar orbit with equator crossing times of 13:43 pm local time (ascending) and 01:43 am (descending). AVHRR/3 sensor data are processed into orbital dataset, referred to as level 1b data (Kidwell 1997), containing digitized instrument sensor output along with appended information useful for navigation, calibration, and quality control. The procedure for calculating SST is as follows: (1) Preprocessing—AVHRR data of good quality are used to construct an 11×11 array of 4 km pixels centred on each High Resolution Infrared Sensor (HIRS) field of view; (2) Land masking—Pixels over land are eliminated with a land/ocean tag database; (3) Cloud detection—Various 2×2 'unit' arrays within the 11×11 array are tested using multichannel cloud tests; (4) Calibration—The cloud-free unit-array channel counts are averaged to 8 km, converted to albedo or equivalent blackbody temperature (correcting for non-linearity in the calibration of channels 4 and 5, see Planet 1998) and assigned the latitude and longitude of the centre of the unit array; (5) SST calculation—Nonlinear SST equations are employed to calculate SST from the 8 km averaged radiometric data.

The drifting buoy and TOGA COARE moored buoy data are received by NOAA/NESDIS and quality controlled by NOAA's National Weather Service (NWS). The buoy data are incorporated into six-hour synoptic marine observation dataset for use as input to the NWS forecast models. We also use the buoy SST information from this six-hour synoptic marine observation dataset. All SST derived from NOAA-15 AVHRR data are paired with buoy SST measurements coincident within 25 km and 4 hours and extracted to form a SST matchup dataset.

3. NOAA/NESDIS operational SST algorithms

NOAA/NESDIS uses a global NLSST algorithm rather than regional algorithms to estimate SST. This avoids the problems of possible discontinuities at the regional boundaries as well as any need for seasonal adjustments within regions (Walton *et al.* 1998). The early multichannel SST (MCSST) algorithm (McClain *et al.* 1985) assumes that there is a linear relationship between the difference of the actual SST and an AVHRR infrared channel equivalent black body temperature and the temperature difference between sensor data from two AVHRR infrared channels. Therefore, the actual SST can be estimated using brightness temperatures obtained from AVHRR channels 4 and 5. Walton (1988) considered a nonlinear term in the further development of MCSST algorithm and developed the cross product SST (CPSST) algorithm. A simple version of the CPSST algorithm, called the Nonlinear SST (NLSST) algorithm, was implemented at NOAA/NESDIS for operational use in April 1991. NOAA/NESDIS uses the split window NLSST algorithm for daytime SST education and the triple window NLSST algorithm for night-time SST estimate. The NLSST equations used in the NOAA global SST operation are given below:

The daytime operational split window NLSST algorithm:

$$\mathrm{NLSST(day)} = A_1 \times T_{11} + A_2 \times T_{\mathrm{sfc}} \times (T_{11} - T_{12}) + A_3 \times (T_{11} - T_{12}) \times (\sec\theta - 1) + A_4 \tag{1}$$

The night-time operational triple window NLSST algorithm:

$$\mathrm{NLSST(night)} = B_1 \times T_{11} + B_2 \times T_{\mathrm{sfc}} \times (T_{3.7} - T_{12}) + B_3 \times (\sec\theta - 1) + B_4 \tag{2}$$

Where, $T_{3.7}$, T_{11} and T_{12} are the equivalent blackbody temperatures in Kelvin for the AVHRR 3.7, 11 and 12 μm channels, respectively; T_{sfc} is an *a priori* estimate of the SST derived from the closest NESDIS global analysed 100 km SST field value (1° latitude/longitude grid) in degrees Celsius; θ is the satellite zenith angle; NLSST is the nonlinear multichannel SST, in degree Celsius; T_{sfc} is restricted to the range − 2°C to 28°C. The NESDIS global analysed 100 km SST field value is a time and space objective analysis temperature derived predominantly from AVHRR data from the previous day, i.e. not a near real-time temperature. It is also possible to use other sources for the T_{sfc} value, such as climatological SST estimate (Walton *et al.* 1998). In the NOAA CoastWatch operational NLSST algorithms (high resolution SST estimate at 1.1 km resolution), the SST estimated by split window MCSST algorithm is used as the T_{sfc} value (Li *et al.* 2001). A_1–A_4 and B_1–B_4 are coefficients. The coefficients for equations (1) and (2) derived from the regression analysis are given in table 1.

Table 1. NOAA-15 NLSST algorithm coefficients derived from regression analysis of a matchup dataset of AVHRR SST estimates paired with SST measurements obtained from buoys from October to December 1998.

NOAA-15 day split window NLSST coefficients

A_1	A_2	A_3	A_4	Number of observations	R^2	Bias	Standard deviation
0.913116	0.0905762	0.476940	− 246.877	2840	0.99	0.00	0.48

NOAA-15 night triple window NLSST coefficients

B_1	B_2	B_3	B_4	Number of observations	R^2	Bias	Standard deviation
0.970141	0.0358449	1.04688	− 262.991	5671	0.99	0.00	0.58

4. SST accuracy assessment

In this study, an independent SST matchup data set was used to assess the SST accuracy of SST calculated using the above operational algorithms. This dataset covered a three-month time series of SST matchup from January to March 1999. The bias (i.e. the average difference between AVHRR derived SST and buoy SST) and standard deviation of differences between SST estimated from AVHRR data and SST measured by buoy sensors is given in figure 1. For the daytime split window algorithm, there were 2788 AVHRR SST estimates and buoy pairs in the global ocean. The bias was 0.14°C with a standard deviation of 0.4°C. For the night-time triple window algorithm, there were 7080 pairs. The bias was 0.08°C with standard deviation of 0.5°C.

For the global AVHRR SST estimates, Strong and McClain (1984) found that the root mean square (rms) error of the temperature difference between MCSST estimates and *in situ* measurements was between 0.6°C and 1.8°C. Pichel (1991) used three months of a NOAA-11 AVHRR SST and drifting buoy SST matchup data set between March and May 1990 to assess the accuracy of the CPSST algorithm (the first operational nonlinear SST algorithm used at NESDIS), and found the accuracy had increased. The global mean AVHRR-buoy difference (or bias) was −0.12°C during the day and −0.10°C at night, with a standard deviation of 0.56°C during the day and 0.4°C at night. With the afternoon NOAA-14 satellite (since 20 March 1995) using the NLSST algorithm, the accuracy has been remarkably consistent on a monthly basis with a day and night bias less than 0.1°C and a standard deviation less than 0.58°C during the day and 0.56°C at night (Walton *et al.* 1998). There has been a general improvement in accuracy of global satellite SST measurements since the AVHRR was introduced into the SST operation in January 1979. This improvement is a consequence of developments in the SST algorithms, but can be attributed also to refinements in the cloud tests, improvements in satellite navigation and enhanced calibration techniques. Interruptions in this general increase in accuracy can be attributed to AVHRR instrument calibration problems or the effects of stratospheric aerosols, principally from eruptions of the El Chichón (April 1982) and Mt. Pinatubo (June 1991) volcanoes. Since NESDIS has had little experience with using the morning satellite for global SST (NOAA-6 was used for a year and a half, and NOAA-12 was used for six months), it is encouraging to note that the accuracy of NOAA-15 AVHRR SST estimates is comparable to that obtained with NOAA-14.

5. Conclusion

The NOAA/NESDIS operational split window and triple window NLSST SST equation coefficients were derived by performing a regression analysis on buoy SST measurements and AVHRR infrared channel data between October and December 1998. Using an independent matchup data set of SST derived from global drifting and TOGA COARE moored buoys paired with coincident NOAA-15 AVHRR SST estimates globally from the first three months in 1999, we assess the accuracy of the NOAA-15 daytime and night-time SST algorithms. The bias is very small (0.08°C to 0.14°C) with a standard deviation of 0.50°C or less for both the day and night algorithms.

The NLSST algorithm for NOAA-15 produces SST estimates with accuracy compared to that of the NOAA-14 algorithms. There is no significant variation in accuracy with satellite zenith angle or atmospheric water vapor content.

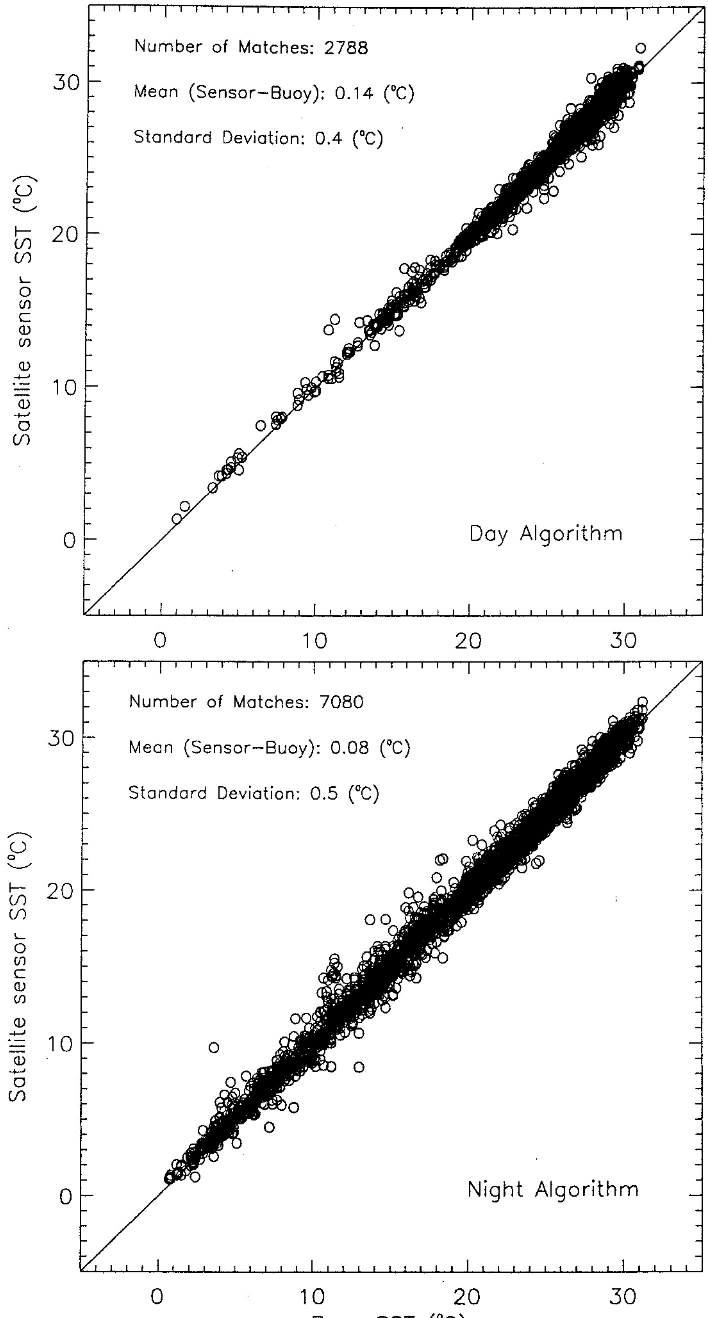

Figure 1. Scatter plots of NOAA-15 NLSST algorithms derived GAC AVHRR SST versus buoy measurements between January and March 1999. The numbers of matches, mean sensor-buoy SST difference, and standard deviation of the difference are given.

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References

Barton, I., 1983, Dual channel satellite measurements of sea surface temperature. *Quarterly Journal of the Royal Meteorological Society*, **109**, 265–378.

Barton, I., 1995, Satellite-derived sea surface temperature: Current status. *Journal of Geophysical Research*, **100**, 8777–8790.

Brown, O. B., Brown, J. W., and Evens, R. H., 1985, Calibration of advanced very high resolution radiometer infrared observations. *Journal of Geophysical Research*, **90**, 11 667–11 677.

Kidwell, K., 1997, *NOAA Polar Orbiter Data Users Guide*, January 1997 Version (US Department of Commerce, NOAA/NESDIS, Washington DC).

Li, X., Pichel, W. G., Clemente-Colón, P., Krasnopolsky, V., and Sapper, J., 2001, Validation of coastal sea and lake surface temperature measurements derived from NOAA/AVHRR data. *International Journal of Remote Sensing*, in press.

Llewellyn-Jones, D. T., Minnett, P. J., Saunders, R. W., and Zavody, A. M., 1984, Satellite multichannel infrared measurements of sea surface temperature of the NE Atlantic Ocean using AVHRR/2. *Quarterly Journal of the Royal Meteorological Society*, **110**, 613–631.

McClain, E. P., Pichel, W. G., and Walton, C. C., 1985, Comparative performance of AVHRR-based multichannel sea surface temperatures. *Journal of Geophysical Research*, **90**, 11 587–11 601.

McMillin, L. M., 1975, Estimation of sea surface temperature from two infrared window measurements with different absorption. *Journal of Geophysical Research*, **80**, 5113–5117.

Pichel, W. G., 1991, Operational production of multichannel sea surface temperatures from NOAA polar satellite AVHRR data. Palaeogeography, Palaeoclimatology, *Palaeoecology*, **90**, 173–177.

Planet, W. G., 1998, Data extraction and calibration of TIROS-N/NOAA radiometers, *NOAA Technicval Memorandum NESS 107—Rev. 1*. US Department of Commerce, NOAA/NESDIS, Washington DC, 105.

Strong, A. E., and McClain, E. P., 1984, Improved ocean surface temperatures from space—comparisons with drifting buoys. *Bulletin of the American Meteorological Society*, **65**, 138–142.

Walton, C. C., 1988, Nonlinear multichannel algorithms for estimating sea surface temperature with AVHRR satellite data. *Journal of Applied Meteorology*, **27**, 115–124.

Walton, C. C., Pichel, W. G., Sapper, J. F., and May, D. A., 1998, The development and operational application of non-linear algorithms for the measurement of sea surface temperatures with the NOAA polar-orbiting environmental satellites. *Journal of Geophysical Research*, **103**, 27 999–28 012.