Determination of high latitude SST algorithms for NOAA-18

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1 Introduction

This document presents the work done in preparing SST algorithms for high latitude conditions for the AVHRR instrument on board the NOAA-18 satellite. These algorithms have been developed by the Ocean and Sea Ice Satellite Application Facility (O&SI SAF) team.

The algorithms have been developed as described in Andersen et al. (1998). In brief, this is done by calculating simulated NOAA-18 temperatures from a database of simulated radiances and then derive algorithms by regression analysis on these simulated temperatures. The steps are further described in the next chapters. No validation of these SST algorithms against in situ observations have yet been done for this satellite since NOAA-18 has just recently been declared operational.

2 Simulated temperatures

In the O&SI SAF a database of cloud free radio-soundings for high latitudes has been built. These radio-soundings have been used as input to the radiative transfer model MODTRAN 3.5 for calculating radiances for each wavenumber (steps of 1 cm^{-1}) covering the wavelength intervals of the three infrared channels on the AVHRR instruments. The conditions under which the simulations with MODTRAN where made are summarized below:

- Temperature and water vapour profiles where selected from the radio-soundings, while ozone and other gas profiles where taken from the MODTRAN standard atmospheres.
- There are no aerosols present in the simulations.
- For each radio-sounding, 5 different satellite zenith angles where considered: 0, 37, 48, 55 and 60 degrees. These values correspond to secant values of 1.00, 1.25, 1.50, 1.75 and 2.00, respectively.
- For each radio-sounding, 3 surface temperatures have been considered: T0-3^{o}C,

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T0 and T0+3ºC, where T0 is the observed sea surface temperature.

- The surface emissivities used are those in Table 1.

Satellite zenith	***T3, 3.7um***	***T4, 11um***	***T5, 12um***
1.00 (0.00)	0.9749	0.9919	0.9879
1.25 (36.87)	0.9703	0.9895	0.9841
1.50 (48.19)	0.9595	0.9831	0.9745
1.75 (55.15)	0.9421	0.9714	0.9580
2.00 (60.00)	0.9276	0.9615	0.9442

Table 1: Surface emissivities for different satellite zenith angles for the three infrared AVHRR channels. The satellite zenith angle is given in secant of value and in degrees in brackets. These are interpolated values from Masuda et al. (1988).

The results from the MODTRAN simulations are organized in a simulated radiances database. When the response functions for an instrument are known, these simulated radiances can be integrated over the response function and the corresponding simulated temperature can be calculated.

The response functions for the AVHRR instrument on board NOAA-18 have been provided by NOAA. They are shown in Appendix A. The simulated radiances have been integrated over the three infrared channels 3B, 4 and 5 to produce simulated tempeatures. Each case was checked to remove unrealistic values using these tests:

$$\begin{aligned} T_s - T_4 &> 0.0 \\ T_s &> -2^oC \end{aligned} \qquad (1)$$

where T_s is the sea surface temperature and T_4 is the channel 4 temperature.

This gave a dataset with 1690 cases of simulated temperatures for AVHRR channels for NOAA-18. Each case contains the surface temperature, the three simulated temperatures for channel 3B, 4 and 5, the satellite zenith angle, the integrated water vapour content as well as the date and position of the profile.

3 Algorithm formalisms

The dataset with simulated temperature can be used to derive algorithms for estimating the sea surface temperature (SST) from AVHRR derived temperatures. This can be done using multi linear regression analysis on different algorithm formalisms combining different parameters. The algorithm formalisms that have been tested in this work are shown below. The resulting coefficients for these algorithms are given in Table 2 together with the standard deviation of the residuals from the regression analysis.

T4_1: $SST = A_0 \cdot T_4 + C_0$

T4_2: $SST = A_0 \cdot T_4 + C_0 + C_1 \cdot S$

T4_3: $SST = (A_0 + A_1 \cdot S) \cdot T_4 + C_0 + C_1 \cdot S$

MC_1: $SST = A_0 \cdot T_4 + B_0 \cdot (T_4 - T_5) + C_0$

MC_2: $SST = A_0 \cdot T_4 + (B_0 + B_1 \cdot S) \cdot (T_4 - T_5) + C_0$

MC_3: $SST = A_0 \cdot T_4 + (B_0 + B_1 \cdot S) \cdot (T_4 - T_5) + C_0 + C_1 \cdot S$

MC_4: $SST = (A_0 + A_1 \cdot S) \cdot T_4 + (B_0 + B_1 \cdot S) \cdot (T_4 - T_5) + C_0 + C_1 \cdot S$

WVC_1: $SST = A_0 \cdot T_4 + (B_0 + B_1 \cdot S + B_3 \cdot wvc) \cdot (T_4 - T_5) + C_0$

WVC_2: $SST = A_0 \cdot T_4 + (B_0 + B_1 \cdot S + B_3 \cdot wvc) \cdot (T_4 - T_5) + C_0 + C_1 \cdot S + C_2 \cdot wvc$

QUAD: $SST = A_0 \cdot T_4 + (B_0 + B_1 \cdot S + B_4 \cdot (T4 - T5)) \cdot (T4 - T5) + C_0 + C_1 \cdot S$

NL_1: $SST = A_0 \cdot T_4 + (B_1 \cdot S + B_2 \cdot T_{guess}) \cdot (T4 - T5) + C_0$

NL_2: $SST = A_0 \cdot T_4 + (B_0 + B_1 \cdot S + B_2 \cdot T_{guess}) \cdot (T4 - T5) + C_0$

NL_3: $SST = A_0 \cdot T_4 + (B_0 + B_1 \cdot S + B_2 \cdot T_{guess}) \cdot (T4 - T5) + C_0 + C_1 \cdot S$

NL_4: $SST = (A_0 + A_1 \cdot S) \cdot T_4 + (B_0 + B_1 \cdot S + B_2 \cdot T_{guess}) \cdot (T4 - T5) + C_0 + C_1 \cdot S$

T3_1: $SST = A_0 \cdot T_3 + C_0 + C_1 \cdot S$

TRI_1: $SST = (A_0 + A_1 \cdot S) \cdot T_3 + (B_0 + B_1 \cdot S) \cdot (T_4 - T_5) + C_0 + C_1 \cdot S$

TRI_2: $SST = (A_0 + A_1 \cdot S) \cdot T_4 + (B_0 + B_1 \cdot S) \cdot (T_3 - T_5) + C_0 + C_1 \cdot S$

TNL_1: $SST = A_0 \cdot T_3 + (B_0 + B_1 \cdot S + B_2 \cdot T_{guess}) \cdot (T_4 - T_5) + C_0 + C_1 \cdot S$

TNL_2: $SST = A_0 \cdot T_4 + (B_0 + B_1 \cdot S + B_2 \cdot T_{guess}) \cdot (T_3 - T_5) + C_0 + C_1 \cdot S$

where

T_{guess} = first guess SST (observed SST is used here)
$S = (1/\cos(\theta)) - 1$, θ = satellite zenith angle
$wvc = wvc0/\cos(\theta)$, $wvc0$ = vertical water vapour content

Name	A_0	A_1	B_0	B_1	B_2	B_3	B_4	C_0	C_1	C_2	***std***
T4_1	1.03433							1.35769			0.848
T4_2	1.05175							0.28258	1.88802		0.529
T4_3	1.05107	0.00136						0.28774	1.87831		0.530
MC_1	1.00860		2.09701					-0.25420			0.242
MC_2	1.02233		1.25392	0.74651				-0.01765			0.174
MC_3	1.02183		1.40705	0.45504				-0.14132	0.29262		0.170
MC_4	1.00562	0.03028	1.50388	0.34700				-0.07716	0.13933		0.162
WVC_1	1.00089		1.15175	0.45828		0.19447		0.06746			0.102
WVC_2	1.00645		1.04298	0.15756		0.30186		0.14689	0.44330	-0.14698	0.090
QUAD	1.02176		1.39711	0.44620			0.00872	-0.13851	0.29872		0.167
NL_1	0.96466			1.06347	0.07073			0.72971			0.185
NL_2	0.98703		0.81004	0.75000	0.03870			0.29877			0.152
NL_3	0.98255		0.97537	0.34520	0.04284			0.16074	0.40679		0.141
NL_4	0.98310	-0.00527	0.93359	0.35765	0.04532			0.16703	0.44005		0.141
T3_1	1.02247							0.72484	1.40813		0.193
TRI_1	1.00334	0.01563	0.40263	0.26898				0.69582	0.66953		0.088
TRI_2	1.00404	0.01805	0.72311	0.13456				0.46687	0.68293		0.082
TNL_1	1.01458		0.37153	0.34836	-0.00307			0.64937	0.72902		0.092
TNL_2	1.01160		0.66469	0.17117	0.00229			0.42420	0.79872		0.087

Table 2: Coefficients for the SST algorithms for NOAA-18 AVHRR. The first column gives the abbreviation used to identify the algorithm. The last column gives the standard deviation of the regression residuals.

In Eastwood (1998) and Francois (1999) it is shown that introduction of noise on the simulated temperatures before the regression analysis is performed can improve the performance of the algorithms on real data. The satellite instruments have radiometric noise and algorithms that are developed on data that have been added similar noise, may be more resistant to such noise.

The coefficients for the NL-algorithms[3] were also calculated with "noisy" simulated temperatures. This was done by adding random noise of +/- 0.12 ºC to the T4 and T5 temperatures. The resulting coefficients are given in Table 3.

Name	A_0	A_1	B_0	B_1	B_2	B_3	B_4	C_0	C_1	C_2	***std***
NL_1n	0.97292			1.09553	0.06192			0.71912			0.251
NL_2n	0.98416		0.39177	0.94481	0.04595			0.51035			0.245
NL_3n	0.98018		0.54779	0.55754	0.04964			0.37577	0.39789		0.239
NL_4n	0.98306	-0.02172	0.39155	0.60517	0.05906			0.39246	0.53426		0.237

Table 3: Coefficients for noise resistant SST algorithms for NOAA-18 AVHRR. The formalisms are the same as for the corresponding NL algorithms in Table 2. The last column gives the standard deviation of the regression residuals.

3 NL: Non-Linear algorithm, reflecting the non-linear term T_{guess}.

4 NL, the selected algorithm

From the initial tests with NOAA-14, it has been shown that the algorithm performing best at high latitudes is the NL algorithm (Eastwood, 1998). It is called NL algorithm because it has the non linear term, T_{guess}. The TRI and TNL algorithms using the T3 channel have shown to perform good at nighttime at low and mid latitudes (ie. Brisson et al., 1998), but at high latitudes they did not show any better results than the NL algorithm. At high latitudes the NL algorithm is therefor used both at day and nigh.

Four different formalisms have been tested for the NL algorithm, NL_1 - NL_4. For NOAA-14 the NL_4 algorithm showed best results (Eastwood, 1998) on both simulated temperatures and in situ observations, but only slightly better than NL_3. From Table 2 no difference can be seen between NL_3 and NL_4. NL_3 is therefor chosen as the SST algorithm for high latitudes, as given in (2). Plots of the residuals of the NL_3 algorithm for NOAA-18 are given in Appendix B.

$$SST = 0.98255 \cdot T_4 + (0.97537 + 0.34520 \cdot S + 0.04284 \cdot T_{guess}) \cdot (T_4 - T_5) + 0.16074 + 0.40679 \cdot S \qquad (2)$$

The noise resistant algorithms will be considered for operational use when the NOAA-16 algorithms have been validated and the benefit of using noise resistent algorithms have been documented for high latitudes.

To test the effect of having satellite specific algorithms, the NOAA-16 NL_3 algorithm was used to calculate the SST from the NOAA-18 simulated temperatures. The result was a standard deviation of 0.148 and a bias of 0.097. So the standard deviation would be expected to be slightly higher and the bias negative if the NOAA-16 algorithm were to be used on NOAA-18 data.

5 Comparison with mid latitude algorithm

To check for consistency the selected algorithm developed for high latitudes has been compared with the algorithm developed for mid latitudes (ML) at CMS, Meteo-France within the O&SI SAF project. The development of the mid latitudes algorithm is described in Brisson et al. (2002). For mid latitudes this report recommends using a NL algorithm with the formalism of NL_1 and noise resistent coefficients. The ML algorithm is given in (3).

$$SST = 0.96163 \cdot T4 + (0.89572 \cdot S + 0.07080 \cdot T_{guess}) \cdot (T4 - T5) + 0.92201 \qquad (3)$$

This algorithm has been compared with the selected NL algorithm for high latitudes, NL_3. The results are shown in Illustration 1. The mid latitude algorithm shows an overall positive bias of 0.08ºC. This difference is decreasing with both increasing temperature and satellite zenith angle.

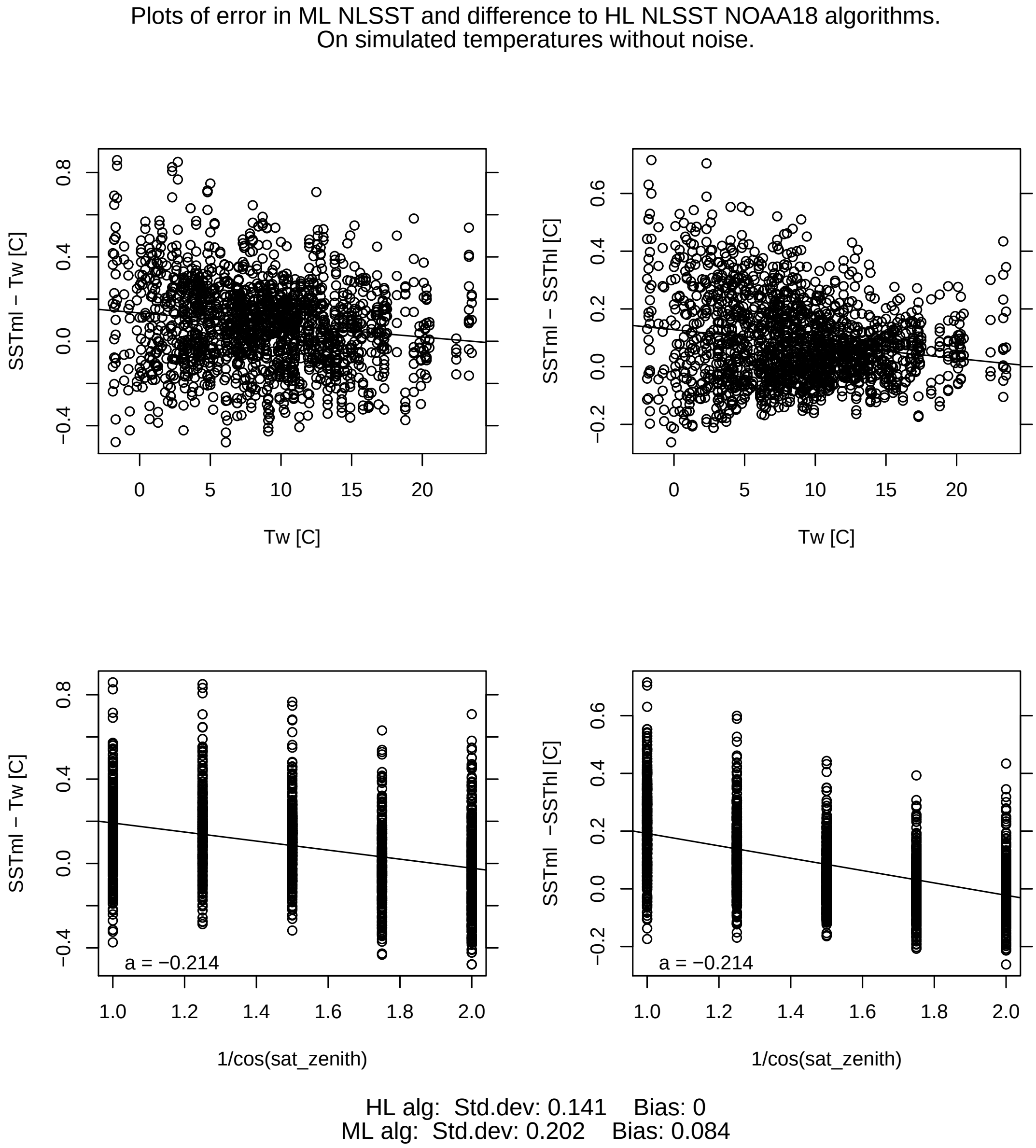

Illustration 1: Comparison of mid latitude and high latitude NL SST algorithms for NOAA-18 on simulated radiances without noise.

Compared to the high latitudes algorithm this means that the mid latitudes algorithm is expected to give slightly warmer temperatures than the high latitudes algorithm, with the largest difference and low temperatures and low satellite zentih angles. The HL NL_1 algorithm was also compared with the ML algorithm, as they have the same formalism. The mean difference and how the difference varied with temperature and satellite zenith angle was similar for the comparison between HL NL_3 and ML.

References

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Appendix A: Response functions for NOAA 16, 17 and 18.

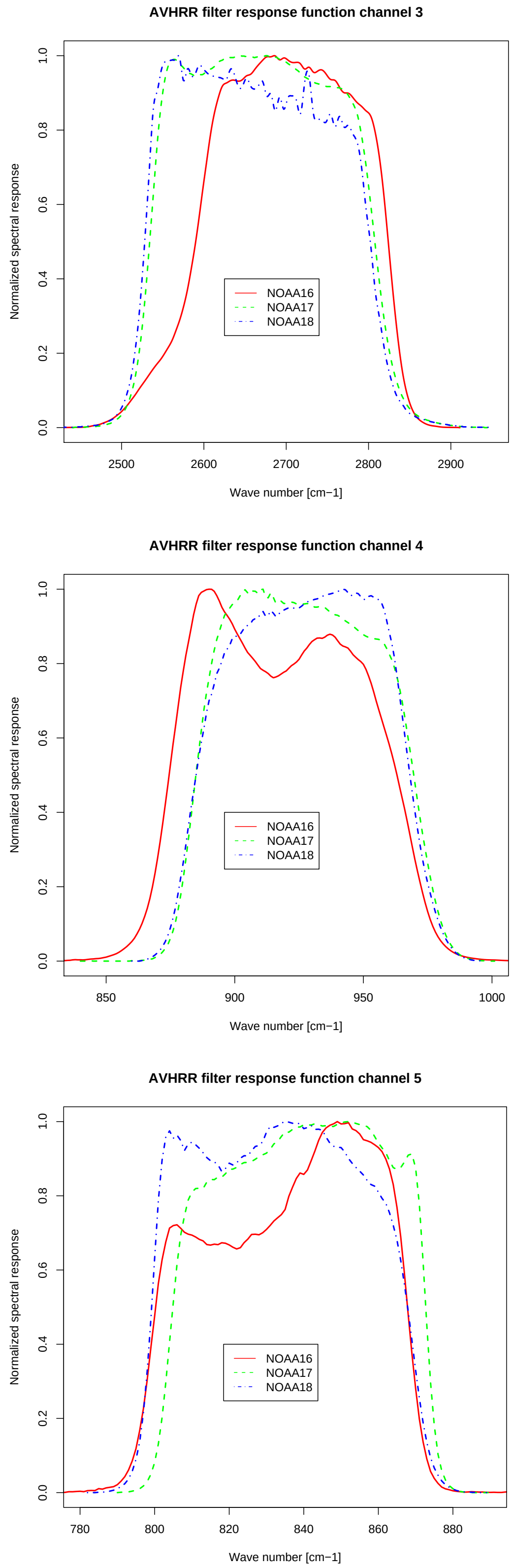

Illustration 2: AVHRR response functions.

Appendix B: Regression residuals for the selected NL algorithm for NOAA-18 at high latitudes.

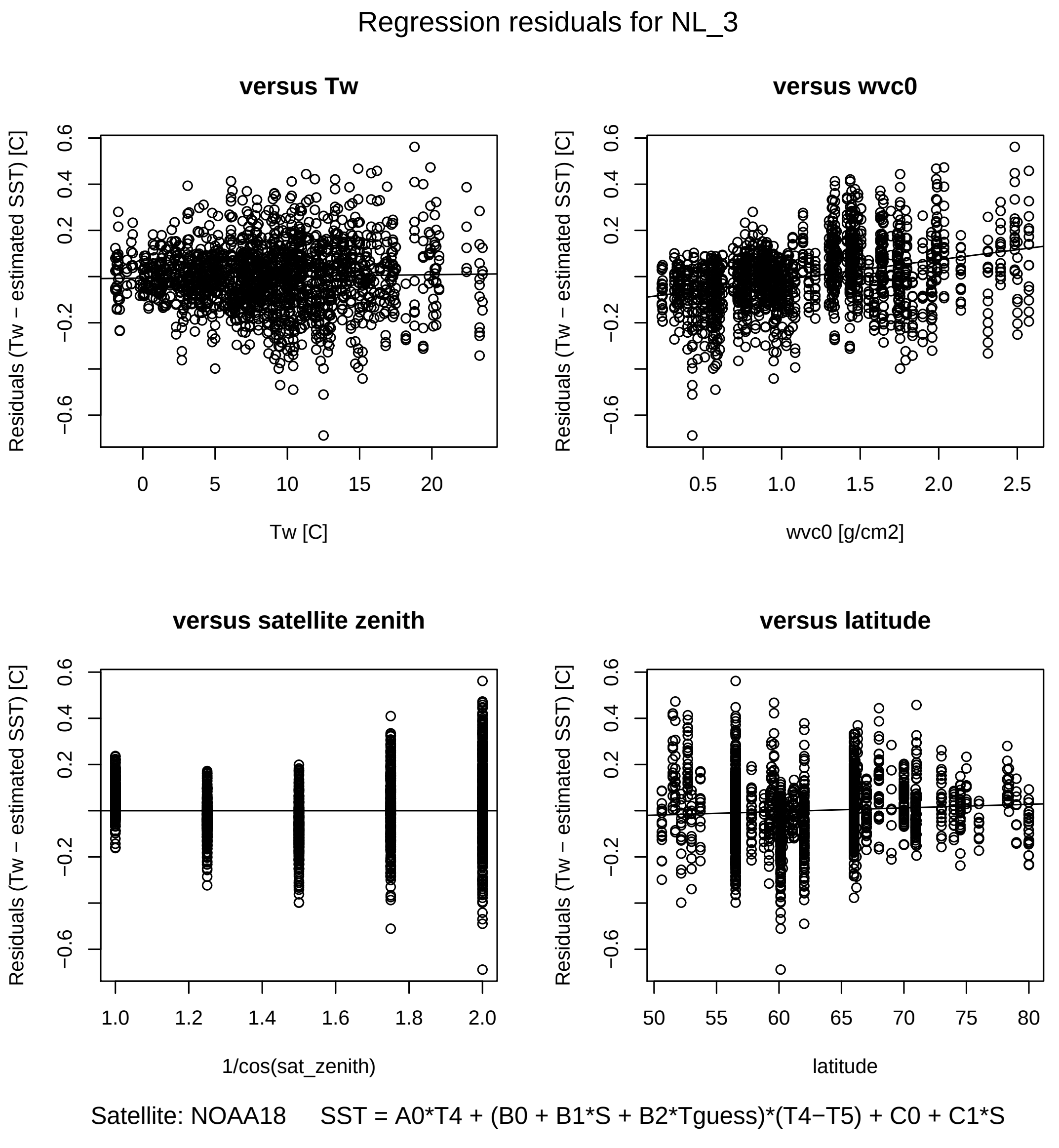

Illustration 3: Plots of the residuals from the regression analysis of the NL_3 algorithm for NOAA-18.