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SST and cloud mask algorithms in reprocessing of 1981-2002 NOAA AVHRR data with ACSPO

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Objective

- NOAA AVHRR GAC Reanalyzes ("RANs") project is aimed at creating time series of global SST from 1981-on by reprocessing NOAA AVHRR GAC data with the Advanced Clear-Sky Processor for Oceans (ACSPO) system.
- The ACSPO AVHRR GAC RAN1 covered the period from 2002-2015 *(Ignatov et al., 2016)*.
- The ongoing RAN2 will extend AVHRR GAC SST time series to 1981-2018.
- At this time, the initial "beta" (RAN2 B01) data set has covered years 1981-2002.
- Several issues complicate SST retrievals during the RAN2 B01 period:
    - Performance problems in the earlier NOAA AVHRR instruments
    - Contaminations of the atmosphere after volcanic eruptions
    - Scarcity of *in situ* SST data from drifters and tropical moored buoys
- The ACSPO training, SST retrieval and cloud-masking algorithms were modified to mitigate the above issues.
- This presentation describes modifications to the ACSPO L2P processing algorithms made during RAN2 B01, demonstrates their effects on retrieved SST and outlines problems yet to be solved.

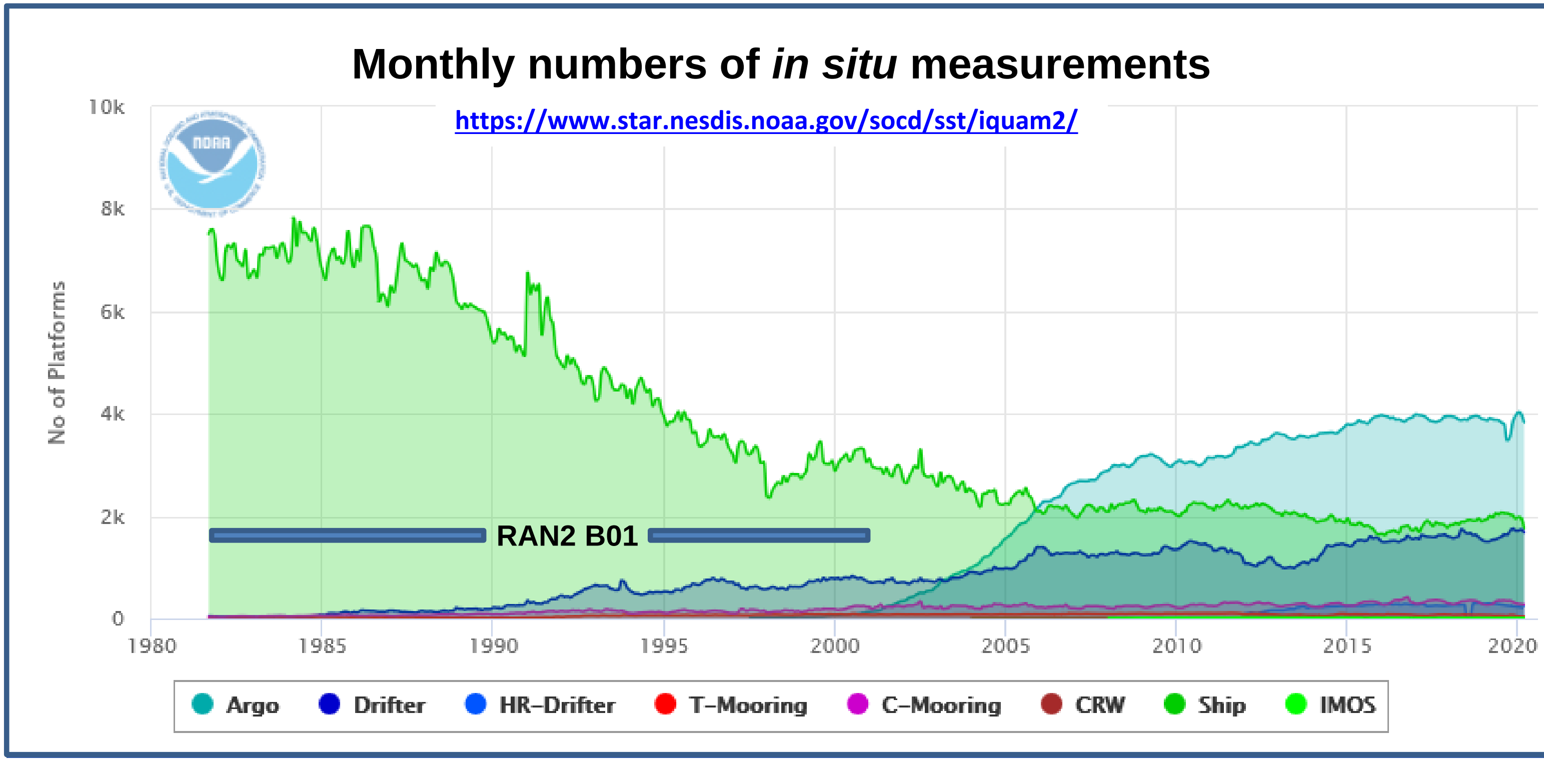
Satellites Involved in RAN2 B01

Satellite	Type of orbit	Type of AVHRR	L1B data available	Used in RAN2 B01	AVHRR bands used for SST
NOAA-7	Afternoon	AVHRR-2	09.01.1981- 02.02.1985	09.01.1981- 02.02.1985	Day and night: Bands 4 and 5
NOAA-9	Afternoon	AVHRR-2	02.25.1985- 11.07.1988	02.25.1985- 11.07.1988	Day: Bands 4 and 5 Night: Bands 3/3b, 4 and 5
NOAA-11	Afternoon	AVHRR-2	11.08.1988- 12.31.1994	11.08.1988- 09.13.1994	
NOAA-12	Morning	AVHRR-2	09.16.1991- 12.14.1998	09.16.1991- 12.13.1998	
NOAA-14	Afternoon	AVHRR-2	01.01.1995- 10.08.2002	01.20.1995- 10.31.2001	
NOAA-15	Morning	AVHRR-3	11.01-1998- 12.31.2018	11.01.1998- 07.22.2000; 01.24.2001- 10.26.2003	
NOAA-16	Afternoon	AVHRR-3	01.01.2001- 08.22.2009	01.02.2001- 12.31.2002	

- ❑ AVHRR IR bands, used for SST: 3/3b (3.7 μm), 4 (10.8 μm) and 5 (12 μm)
- ❑ Day and night SST and cloud mask algorithms are switched at solar zenith angle SZA=90°
- ❑ Failure of band 3 in September 1982 prevented its using for NOAA-7

(source: NOAA 3s system, www.star.nesdis.noaa.gov/socd/sst/3s/)

In situ data in RAN2



- ❑ Customarily, the ACSPO SST is trained on *in situ* SST from drifters (D) + tropical moorings (TM)
- ❑ In 1981-2002, the numbers of D+TM data were small, especially in 1981 - mid 1990s
- ❑ The ships' SST measurements (S) were much more numerous, although less accurate
- ❑ SST algorithms were trained:
  - NOAA-7, NOAA-9, NOAA-11: using S + D + TM
  - NOAA-12, NOAA-14, NOAA-15, NOAA-16: using D + TM

L4 analyses in RAN2

- The following L4 SST analyses were used as the “first guess” in NLSST equations and in the Clear-Sky mask:
- ESA Climate Change Initiative, v.2.1 (CCI):
  - Available since 09.1981
  - Produced from CCI L2P “skin” SST
  - In RAN2 B01, CCI is used for NOAA-7, NOAA-9 and NOAA-11
- Canadian Meteorological Center 0.2° (CMC):
  - Available since 09.1991
  - Produced from ESA ATSR-1 and -2; RSS TMI and NAVO NOAA-16 SSTs
  - In RAN2 B01, CMC is used for NOAA-12, NOAA-14 and NOAA-15 and NOAA-16

ACSPO SST products

- Global Regression (GR) SST:
  - Two sets of coefficients (one for day and one for night)
  - Trained on global datasets of matchups (MDS)
  - Sensitive to “skin” SST
  - Unbiased wrt *in situ* SST within training MDS; may be biased wrt “skin” SST
  - <u>Denominated as ACSPO “sub-skin” SST</u>

- Piecewise Regression (PWR) SST:
  - Uses multiple sets of coefficients
  - Each set of coefficients is trained on a separate subset of the global MDS
  - The coefficients are selected by regressors’ values at a given pixel
  - Less sensitive to “skin” SST
  - More accurate and precise wrt *in situ* SST (i.e., “depth” SST)
  - <u>Denominated as ACSPO “depth” SST</u>

SST Equations Employed in RAN2 AVHRR

2-band equation (Daytime for all satellites, Nighttime for NOAA-07):

$$T_S=a_0+a_1T_{11}+a_2(T_{11}-T_{12})+a_3T_{11}S+a_4(T_{11}-T_{12})S+a_5(T_{11}-T_{12})T_0+a_6S \quad (1)$$

3-band equation (Nighttime for all satellites except NOAA-07):

$$T_S=b_0+b_1T_{11}+b_2(T_{11}-T_{3.7})+b_3(T_{11}-T_{12})+b_4T_{11}S+b_5(T_{11}-T_{3.7})S+$$
$$+b_6(T_{11}-T_{12})S+b_7(T_{11}-T_{3.7})T_0+b_8(T_{11}-T_{12})T_0+b_9S \quad (2)$$

$T_{3.7}$, T_{11} and T_{12}	brightness temperatures (BTs) in bands 3b, 4 and 5
T_0	"first guess" SST from L4 analysis
$S=sec(VZA)-1$	VZA is satellite view zenith angle
a_i and b_i	regression coefficients

- Equations include more terms than customarily, to extract more information from measurements
- Both equations include "first guess" SST
- The coefficients estimation method preserves stability of coefficients and sensitivity to T_{SKIN}
- Having more terms and stable coefficients estimation are <u>especially important for PWR SST</u> because:
  - PWR coefficients are derived from limited subsets of matchups
  - The information content of regressors may change within different subsets

The method for training regression coefficients

- Compensates for calibration trends:
  - Regression coefficients are recalculated daily
  - Matchups are collected within 1±45 days for GR SST and 1±180 days for PWR SST
  - The offsets are adjusted using shorter windows containing at least 100 matchups

- Preserves sensitivity to T_{SKIN} and limits the sensitivity to the “first guess” SST:
  - GR coefficients: trained under constraint on mean sensitivity to T_{SKIN} over MDS, $<\mu>$
    - Two-band equation: $<\mu>=0.94$; tree-band equation: $<\mu>=0.98$
    - The mean GR sensitivity to the “first guess” SST is limited at ~0.06 (day) and ~0.02 (night).
  - PWR coefficients: Trained without constraint first. If $<\mu> < 0.4$, retrained under constraint $<\mu>=0.4$.

- Helps extract maximum information from observations while keeping the coefficients’ estimates stable:
  - The increased number of regressors in Eqs. (1-2) helps extract more information from satellite observations, but may cause the instability of coefficients’ estimates.
  - This instability is prevented by cutting off the least informative dimensions in the space of regressors.

ACSPO Clear-Sky Mask

Filters using thermal bands only:

1. **SST filter (Static +Adaptive)**
2. **Warm SST filter for low stratus**
3. **Low stratus filter**
4. **SST Uniformity filter**
5. **Warm Outliers filter (added in RAN2 B01 - night only)**

Filters using reflectance bands (daytime only):

6. **Reflectance Relative Contrast filter (RRCT)**
7. **Reflectance "Gross" Contrast filter (RGCT)**
8. **SST/Reflectance Cross-Correlation filter**

All filters are binary, i.e., the output is either "Clear" or "Cloudy"

2-bit ACSM output	Meaning	Conditions
0	Clear	All filters show "clear" (QL=5 –recommended)
1	Probably clear	Filters 1-3 and 5-7 show "clear" Filter 4 or 8 show "cloudy"
2	Cloudy	At least one of Filters 1-3,5-7 show "cloudy"
3	Invalid	Land, ice etc.

In RAN2 B01:

- ❑ The SST filter is set more conservative for NOAA-11 from 05-1991 to 12-1992 and for NOAA-12 from 09-1991 to 12-1992, to mitigate the effect of volcanic dust (as a temporary solution)
- ❑ The new Warm Outliers filter (specific for each sensor) has been added – see next slide

“Warm Outliers” filters

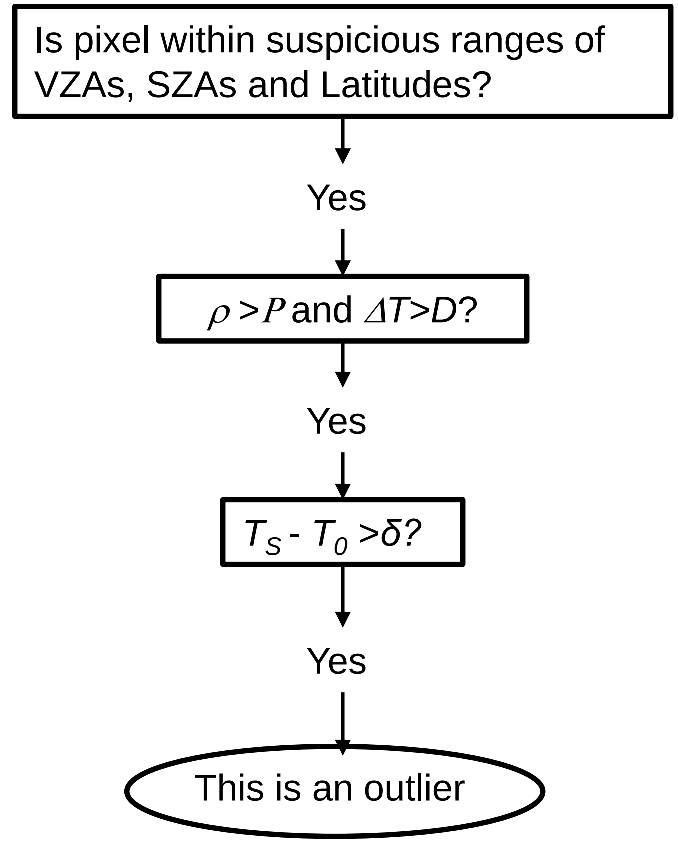
- Nighttime SST from earlier AVHRRs is often contaminated with warm outliers due to illumination of the band 3/3b sensor with direct solar light.
- Locations of such outliers are different for different satellites.
- The “Warm Outliers" filters screen out the warm outliers using the following predictors within specified ranges of VZA, SZA and latitude:

- ΔT Differential part of Eq. (2), depending on BT differences:

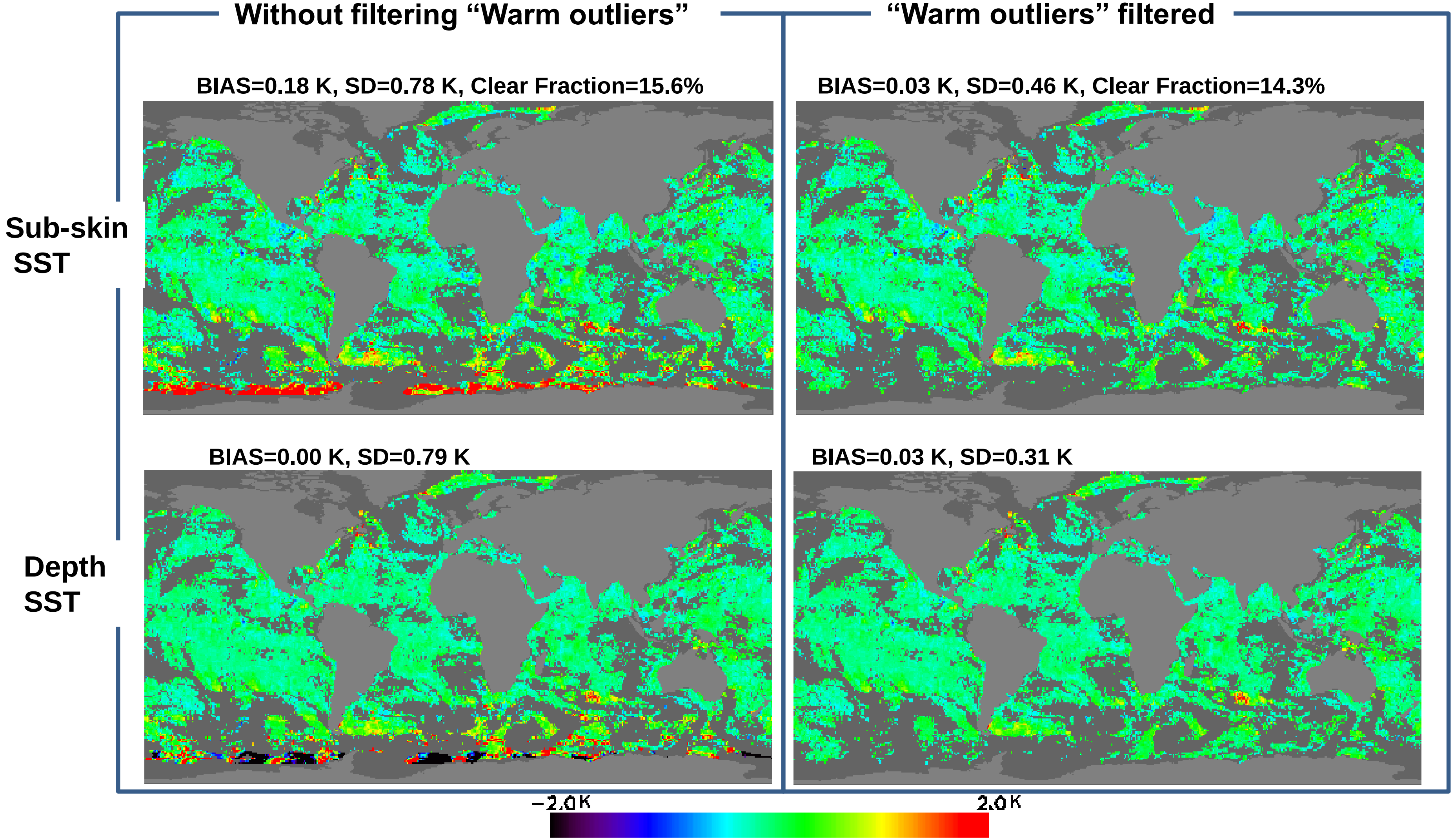
$$\Delta T= b_2(T_{11}-T_{3.7})+b_3(T_{11}-T_{12})+b_5(T_{11}-T_{3.7})S+ \\ + b_6(T_{11}-T_{12})S+b_7(T_{11}-T_{3.7})T_0+b_8(T_{11}-T_{12})T_0.$$

- ρ Fisher distance - the measure of consistency of a regressors’ vector with a global training MDS.
- $T_S - T_0$ Deviation of GR SST from “first guess” SST.

- Tested ranges of VZA, SZA and latitude, as well as thresholds P, D and δ, are empirically set for each satellite

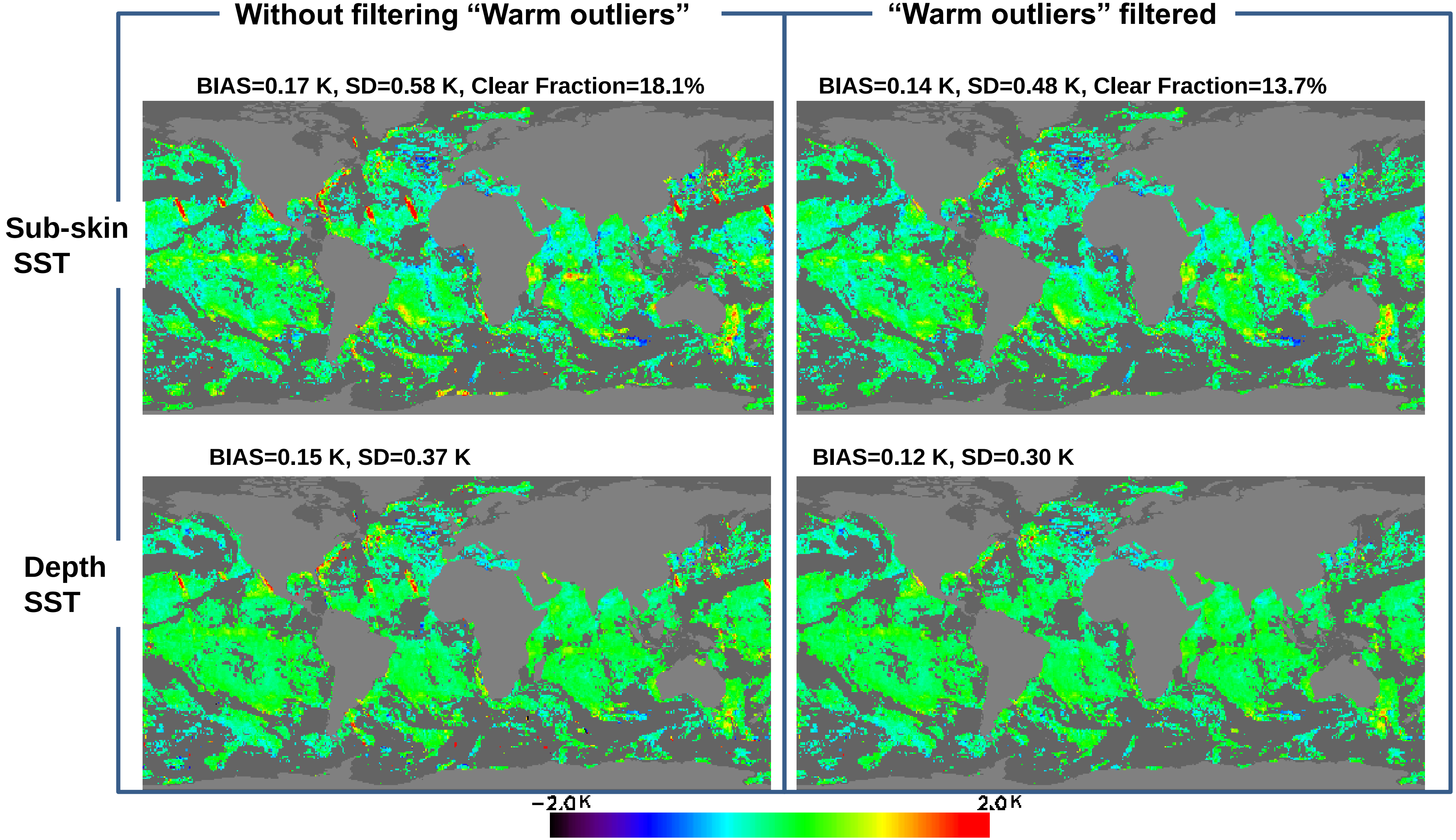


Filtering warm outliers in NOAA-14 SST, 01-20-1996 (Night)



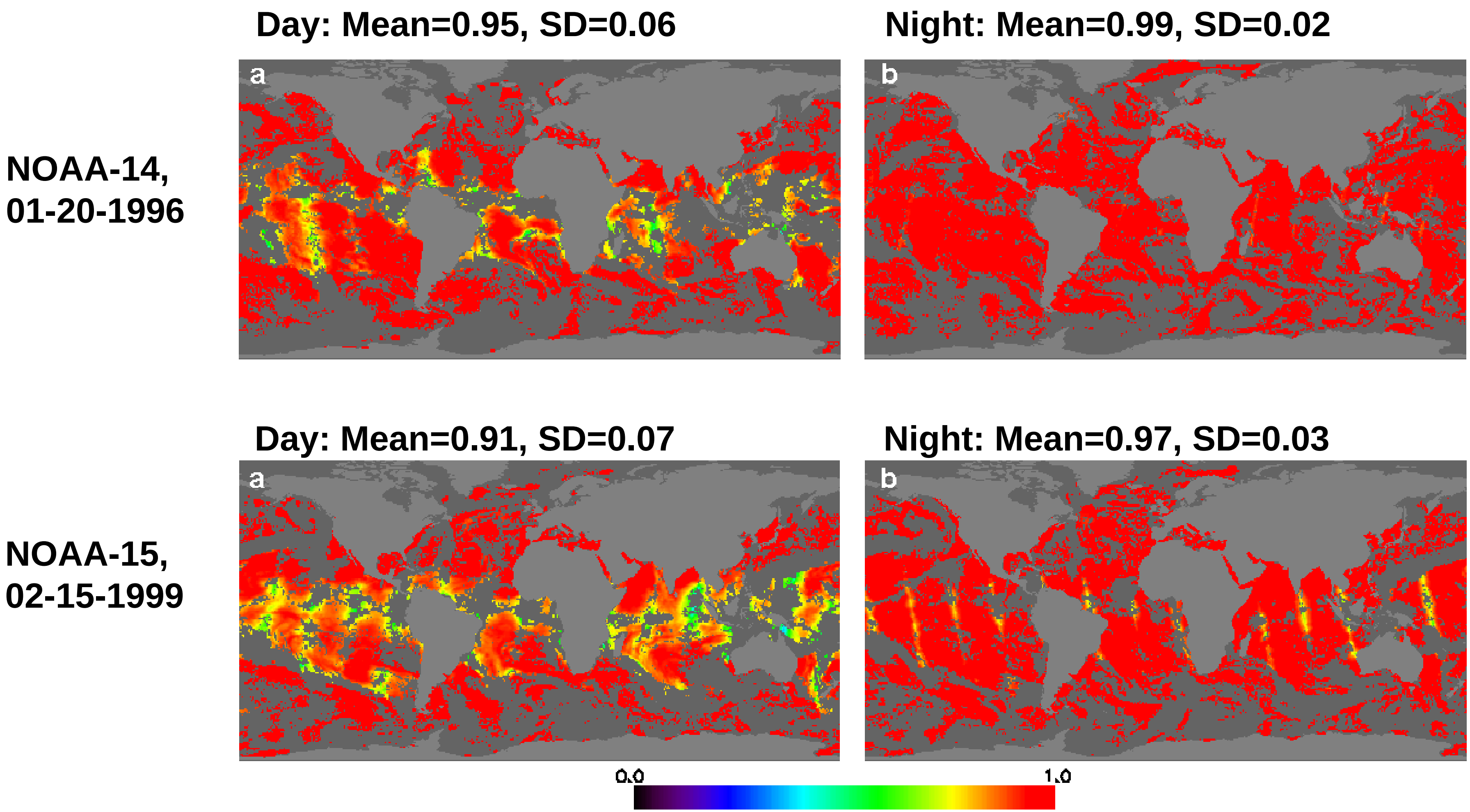
- ❑ In NOAA14, warm outliers occur at Latitude < -40°
- ❑ Filtering outliers is efficient and significantly improves the statistics wrt CMC

Filtering warm outliers in NOAA-15 SST, 02-15-1999 (Night)



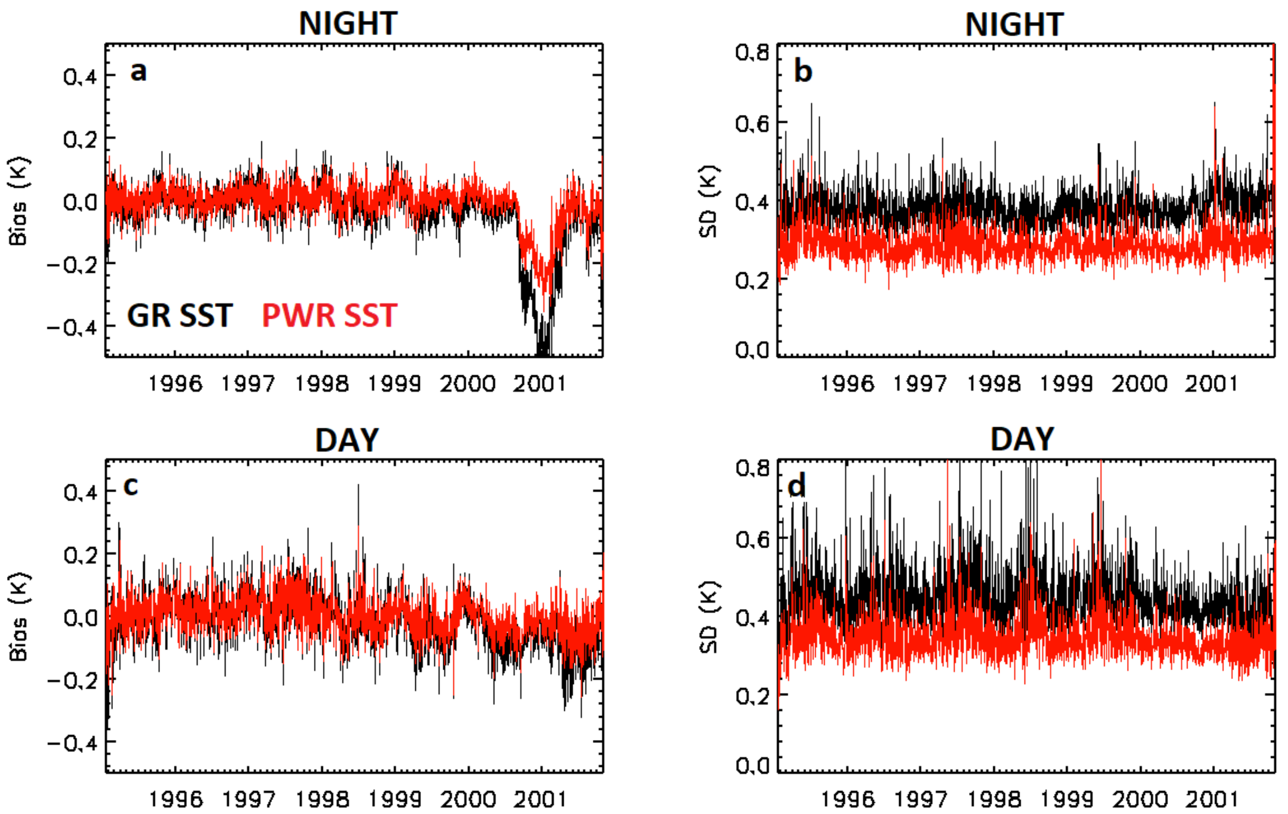
- In NOAA15, warm outliers occur at SZA < -120° and VZA < -40°, at western swaths' edges
- Filtering outliers is efficient and significantly improves the statistics wrt CMC

Sensitivities of “sub-skin” SST



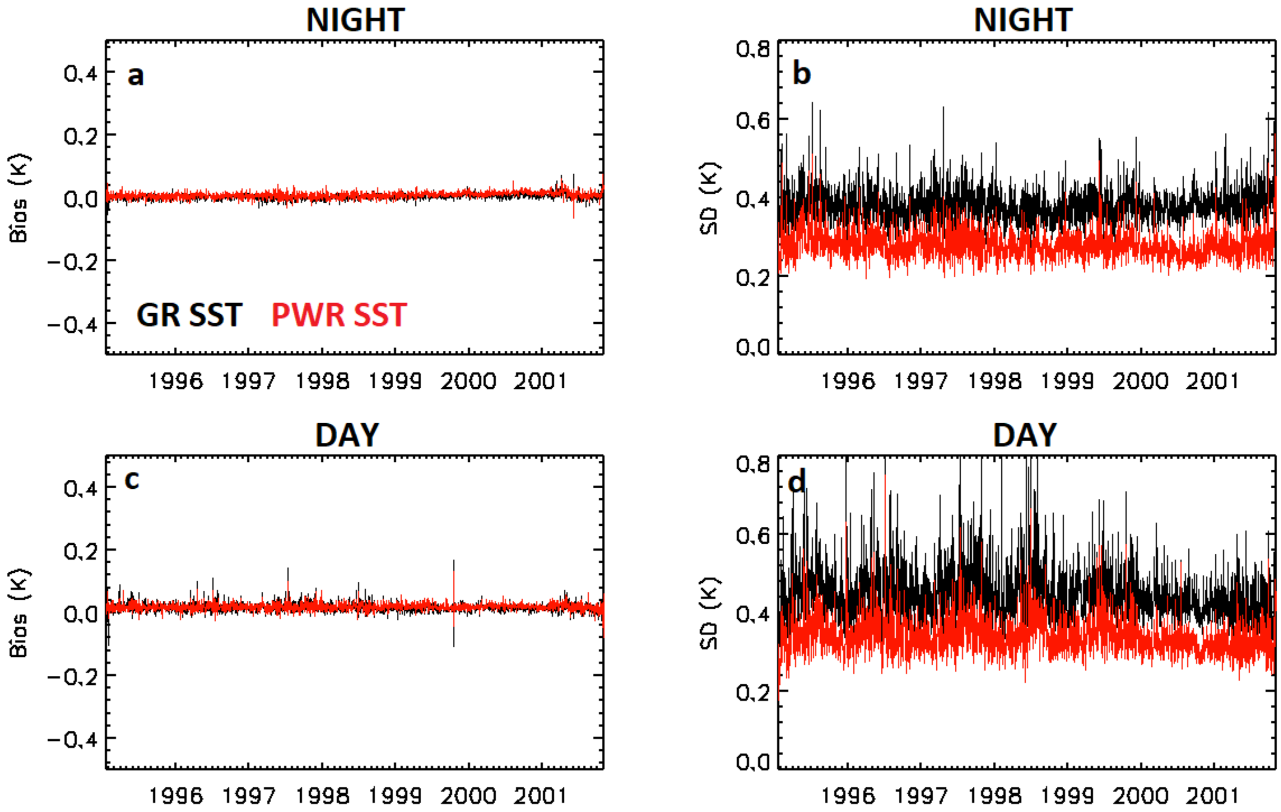
- Global mean sensitivity may deviate from constrained mean over the MDS
- The nighttime sensitivities are closer to 1, and more uniform
- The GR sensitivity degrades in the Tropics at large VZAs (especially during the daytime)

NOAA-14: Time series of bias and SD of GR and PWR SSTs wrt in situ SST (fixed coefficients)



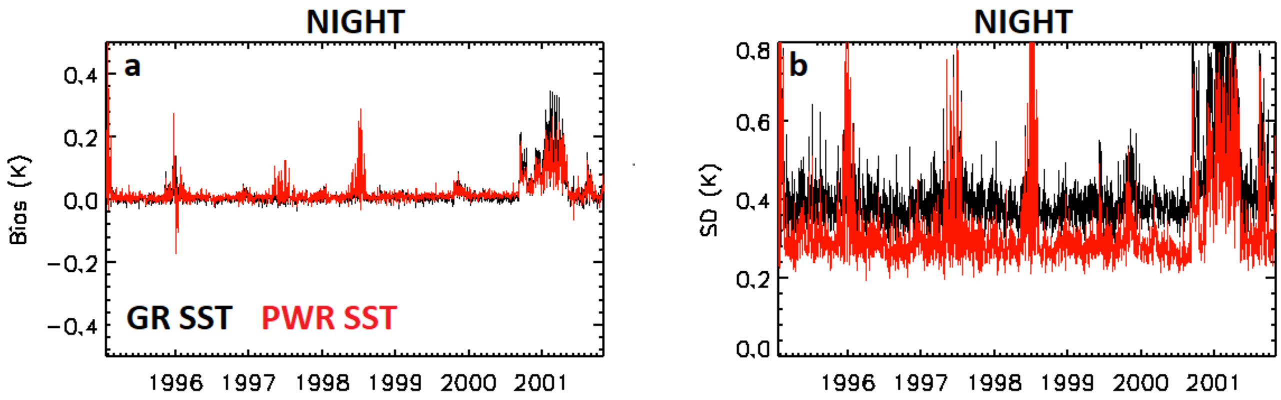
- Fixed coefficients were trained using matchups collected during the whole 1996 year
- Daytime biases usually vary within ±0.2 K
- Nighttime biases vary within ±0.1 K and drop to -0.5 K (GR) and – 0.2 K (PWR) in 2000-2001

NOAA-14: Time series of bias and SD of GR and PWR SSTs wrt in situ SST (variable coefficients)



- Variable coefficients are trained using matchups within sliding windows of 91-day size (GR) and 361-day size (PWR); offsets are adjusted by at least 100 matchups closest to a given day
- This flattens out time series of biases wrt *in situ* SST
- SDs only slightly reduced compared with the ones for fixed coefficients

NOAA-14: Time series of bias and SD of GR and PWR SSTs wrt in situ SST (no “Warm Outliers” filter)



- Positive outliers, if not filtered, substantially deteriorate the statistics wrt *in situ* SST

Future work: Mitigation of cold SST biases

- In RAN2 B01, we have efficiently eliminated nighttime warm biases in retrieved SST, caused by Sun impingement on the band 3/3b sensor
- The future work will be focused at cold biases in AVHRR SSTs.
- The cold biases may be caused by several reasons, and, among them:
  - Volcanic eruptions:
    NOAA-7: Mt. El Chichon, Mar-Apr 1982;
    NOAA-11 and -12: Mt. Pinatubo, Jun 1991; Mt. Hudson, Aug-Oct 1991
  - Sun impingement on the blackbody calibration target
- In many cases, the cold biases have well-expressed latitudinal dependencies
- We will try to mitigate cold biases in two ways:
  - By accounting for latitudinal dependencies of biases in the Clear-Sky mask
  - By correction of AVHRR brightness temperatures using calibration parameters, available in L1B data

Summary

- The initial “B01" version of RAN2 AVHRR SST dataset, covering 1981-2002 has been created from data of NOAA-7, -9, -11, -12, -14, -15 and -16.
- The dataset includes two SST products:
  - “Sub-skin” Global Regression SST (more sensitive to T_{SKIN})
  - “Depth” Piecewise Regression SST (more precise with respect to T_{DEPTH})
- In both products:
  - Calibration trends are corrected by daily recalculation of regression coefficients
  - Contaminations of the nighttime AVHRR band 3/3b with direct solar light are filtered out.
- Mean sensitivity of GR SST to T_{SKIN} is maintained at ~0.98 (night) and ~0.94 (day).
- The future development of RAN2 SST algorithms will be aimed at:
  - Mitigation of cold regional biases in retrieved SST, including those caused by contaminations of the atmosphere with volcanic dust
  - Exploring the potential of correction of AVHRR brightness temperatures based on calibration parameters, available in L1B data.

THANK YOU