ESA Climate Change Initiative Phase-II

Sea Surface Temperature (SST)

www.esa-sst-cci.org

SST Retrieval Methods in the ESA Climate Change Initiative

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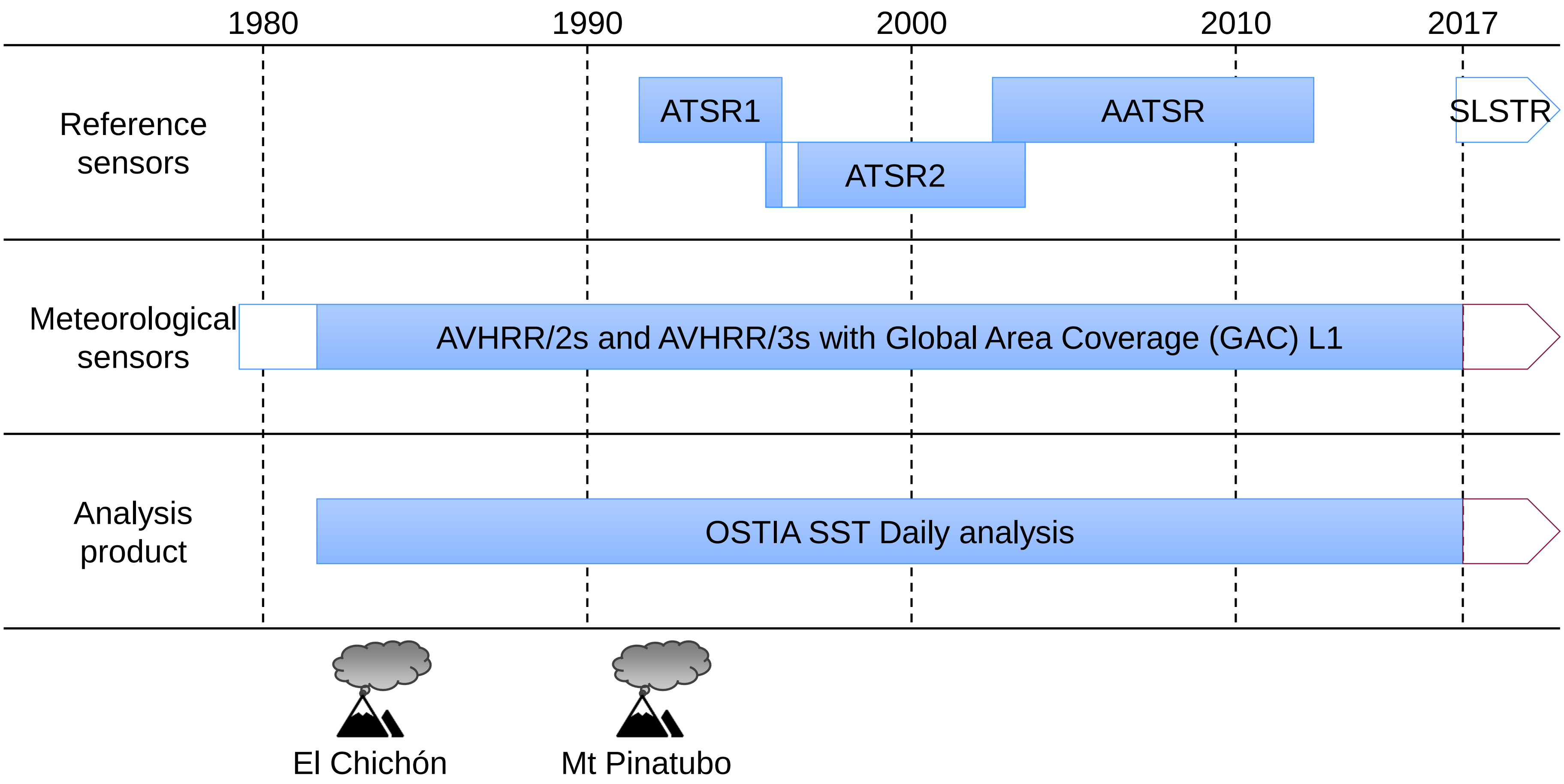
Climate Change Initiative

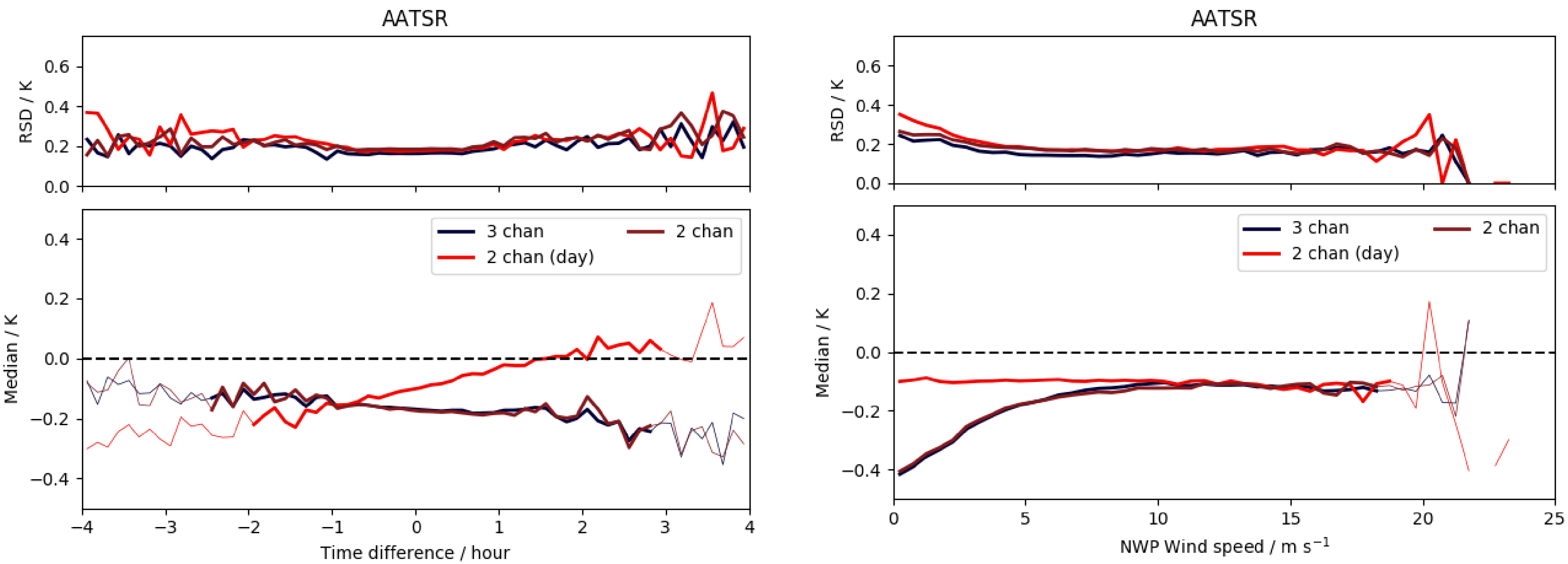
- ESA Climate Change Initiative (CCI)
  - Programme to produce satellite-based Climate Data Records (CDR)
  - Targeting 13 Essential Climate Variables (ECVs) including SST
  - Running since 2009
- Climate Data Record is:
  - A time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change
- Aims for SST-CCI CDR:
  - **INDEPENDENT** of in situ SST measurements
  - Of useful, quantified **ACCURACY** and **SENSITIVITY**
  - With context-sensitive **UNCERTAINTY** estimates (at all spatio-temporal scales)
  - Harmonised to provide useful **STABILITY**
  - Able to be linked to the longer **HISTORICAL RECORD**
  - Generated by a **ROBUST**, **SUSTAINABLE** processing system in short delay mode

SST-CCI


1980
1990
2000
2010
2017
Reference sensors
ATSR1
AATSR
SLSTR
ATSR2
Meteorological sensors
AVHRR/2s and AVHRR/3s with Global Area Coverage (GAC) L1
Analysis product
OSTIA SST Daily analysis
El Chichón
Mt Pinatubo

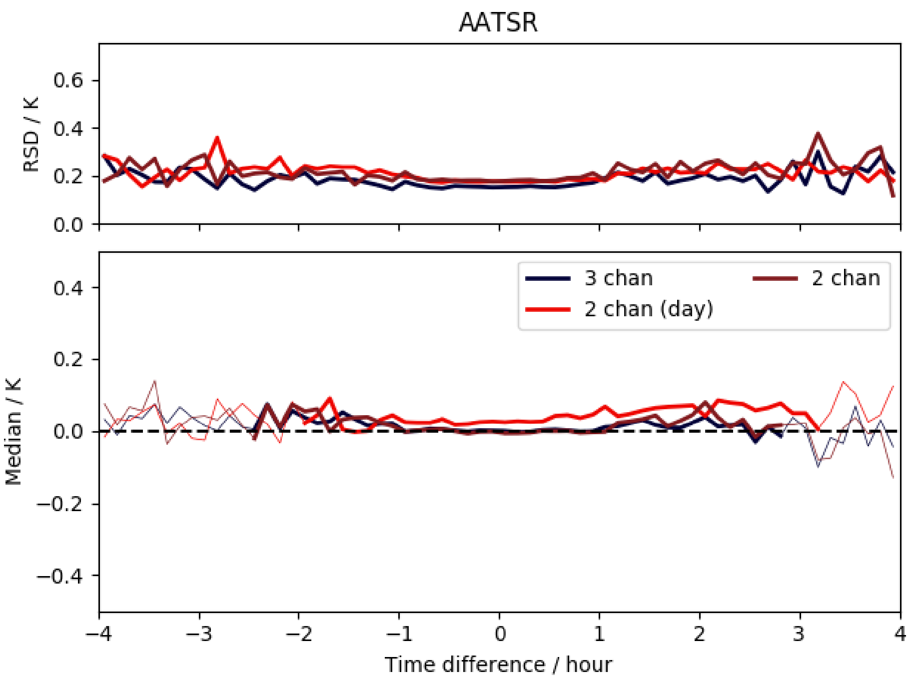
Skin-to-depth adjustment

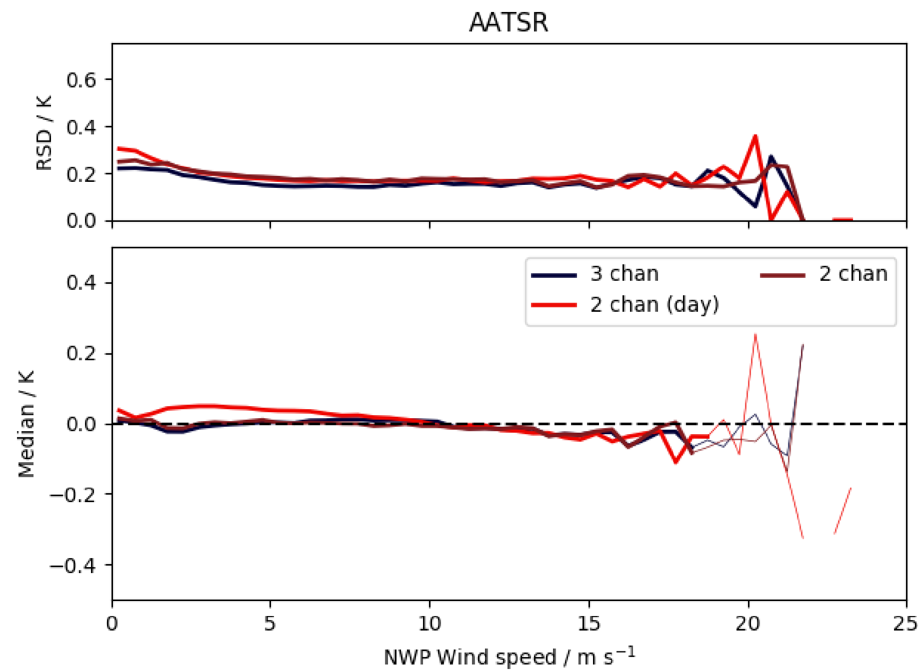
- Primary retrieval is skin-SST – expect differences to in situ depth-SST
- Examine difference from in situ drifter as a function of satellite-in situ time difference and wind speed
- Can clearly see diurnal cycle and skin effect



Skin-to-depth adjustment

- Use Fairall Kantha-Clayson model (UKMO code)
- Correct for time/depth differences in in situ comparisons
- To correct for satellite overpass time in CDR





ATSR SST Retrieval

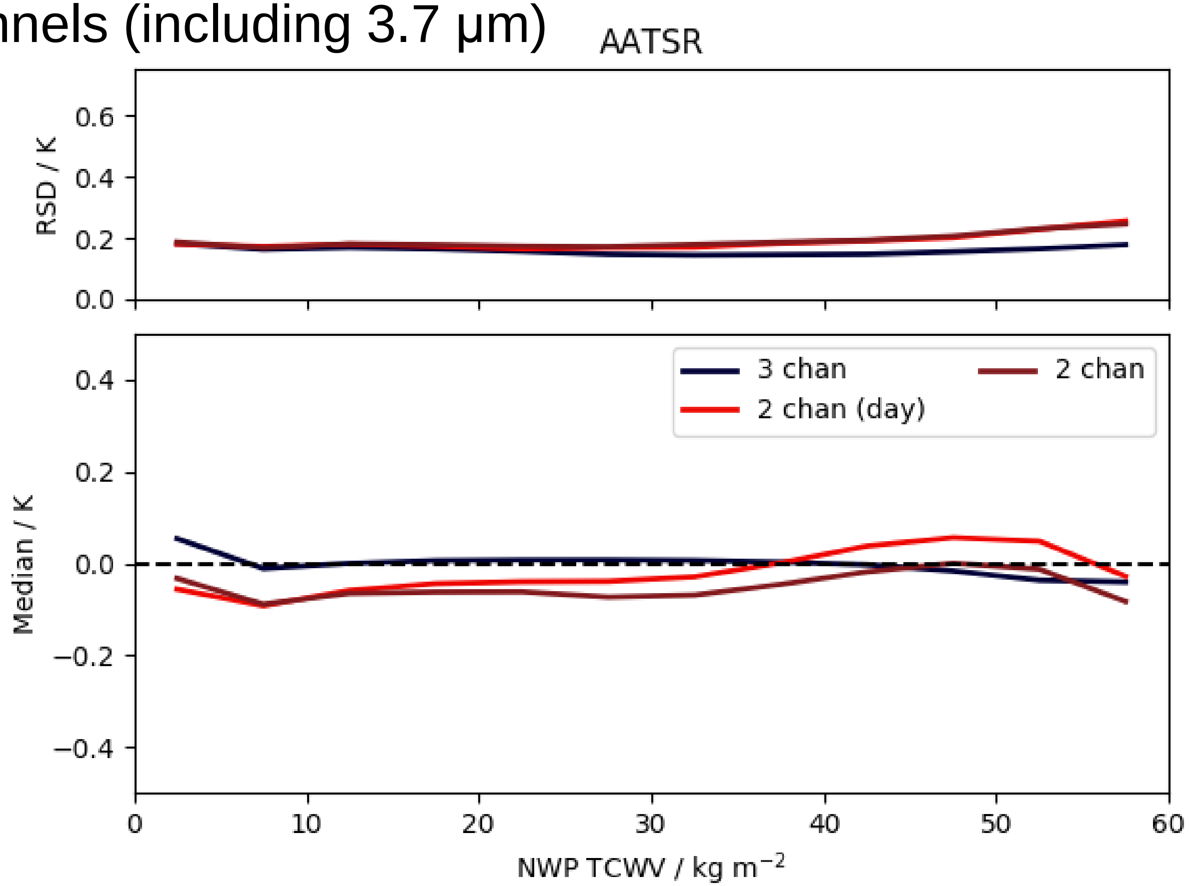
- Update from ATSR Reprocessing for Climate (ARC) project
- Linear regression based on Radiative Transfer (RT) simulation
  - $\widehat{SST} = a_0 + \sum a_i BT_i$
  - Coefficients a_0 , a_i
    - Banded by: TCWV, nadir path, forward path, year
    - Interpolate between bands as required
- Accurate RT simulations
  - Line-by-line model: LBLRTM
  - Atmospheric data: 2100 profiles extracted from ERA-40 (Chevallier 2002)
  - Variable trace gases: CO_2, HNO_3, N_2O, CH_4, CFC-11, CFC-12
  - Aerosol scattering calculate using RTTOV and DISORT
- Retrieval coefficients
  - Independent of in situ SST
  - Aerosol-robust (Merchant et al. 1999) formulation used for ATSR1
  - No requirement for aerosol-robustness for ATSR2/AATSR

AATSR 12 micron anomaly

- After launch AATSR 12 µm BTs were ~0.2 K colder than expected
- During ARC and SST-CCI Phase-I projects
  - Could not use 12 µm channel in reference SST retrieval
  - Used dual-view 3.7 µm and 11 µm combination as reference
  - Adjusted other channel combinations to match
- Issue investigated by AATSR 12 micron Anomaly Review Board
  - Biases consistent with:
    - Small error in non-linearity adjustment
    - 40 nm shift in Spectral Response Function (SRF)
- SST-CCI Phase-II
  - Includes ARB recommendations in RT simulations and processing
  - Uses D3: dual-view 3.7, 11, and 12 µm retrieval as reference

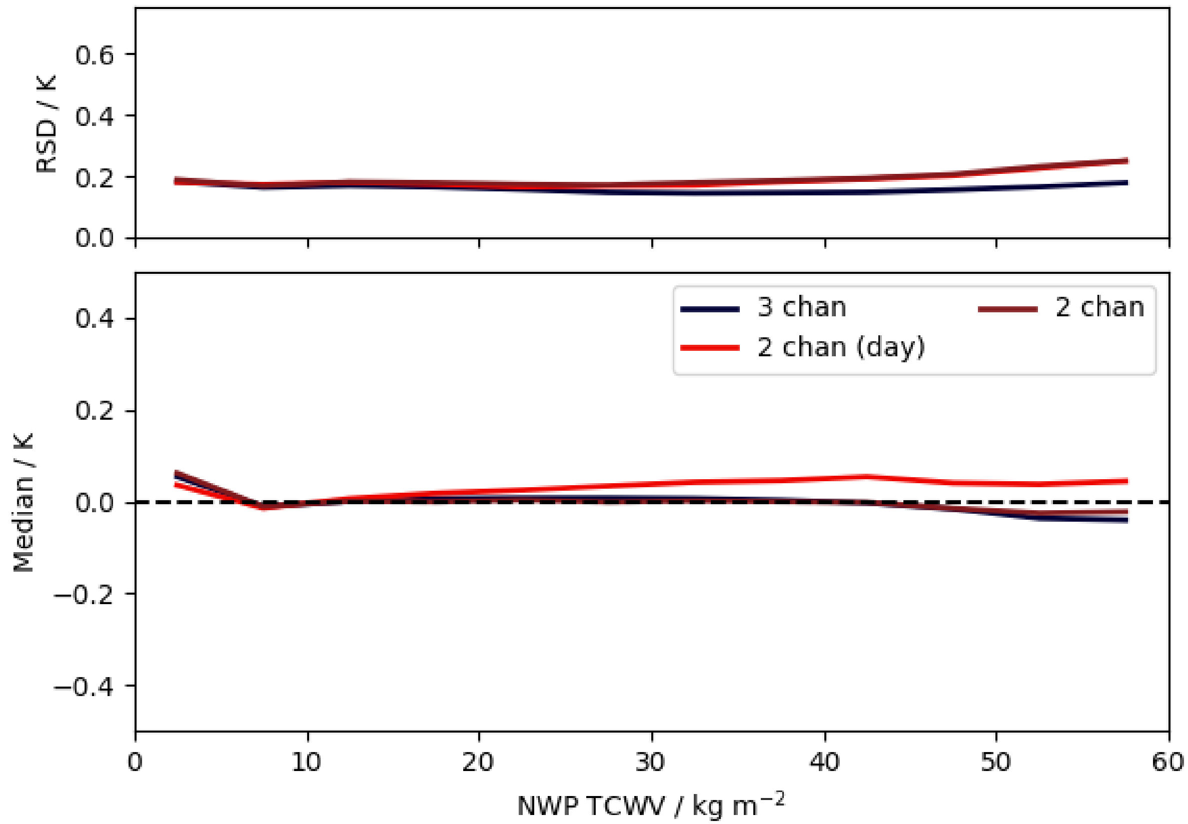
AATSR before inter-algorithm adjustment

- D3 biases are small; D2 biases ~0.1 K
- D3 expected to be best retrieval due to higher information content from more channels (including 3.7 μm)



AATSR after inter-algorithm adjustment

- Use D3 as reference and correct D2 to match D3
  - Offset coefficient is corrected for each TCWV bin
- Note – biases shown relative to in situ drifters. But no in situ used for adjustment



Comparison vs drifters

Validation of skin SST + depth adjustment

	Matches	N2	N3	D2	D3
AATSR					
Day	166218	0.015 (0.280)		0.026 (0.178)	
Night	135129	0.005 (0.291)	0.004 (0.164)	-0.002 (0.182)	0.001 (0.156)
ATSR2					
Day	33996	-0.042 (0.313)		-0.001 (0.246)	
Night	30898	-0.001 (0.308)	0.006 (0.203)	0.006 (0.235)	0.006 (0.197)
ATSR1					
Day	13229	-0.052 (0.401)		0.042 (0.406)	
Night	9160	-0.104 (0.414)		0.002 (0.421)	
3.7 µm	721		-0.503 (0.374)		0.003 (0.256)

- Median (Robust Standard Deviation) of satellite – drifter difference
- N = Nadir-only retrieval. D = Dual-view retrieval

Comparison vs GTMBA

Validation of skin SST + depth adjustment, in tropics

	Matches	N2	N3	D2	D3
AATSR					
Day	10312	-0.006 (0.362)		0.007 (0.180)	
Night	12590	-0.009 (0.379)	0.004 (0.139)	-0.011 (0.181)	-0.001 (0.129)
ATSR2					
Day	5342	-0.040 (0.324)		-0.009 (0.194)	
Night	4835	-0.024 (0.336)	-0.004 (0.113)	-0.024 (0.183)	-0.013 (0.110)
ATSR1					
Day	2950	-0.068 (0.437)		0.046 (0.411)	
Night	2122	-0.144 (0.410)		-0.051 (0.394)	
3.7 µm	109		-0.884 (0.333)		0.001 (0.114)

- Median (Robust Standard Deviation) of satellite – drifter difference
- N = Nadir-only retrieval. D = Dual-view retrieval

Comparison vs Radiometers

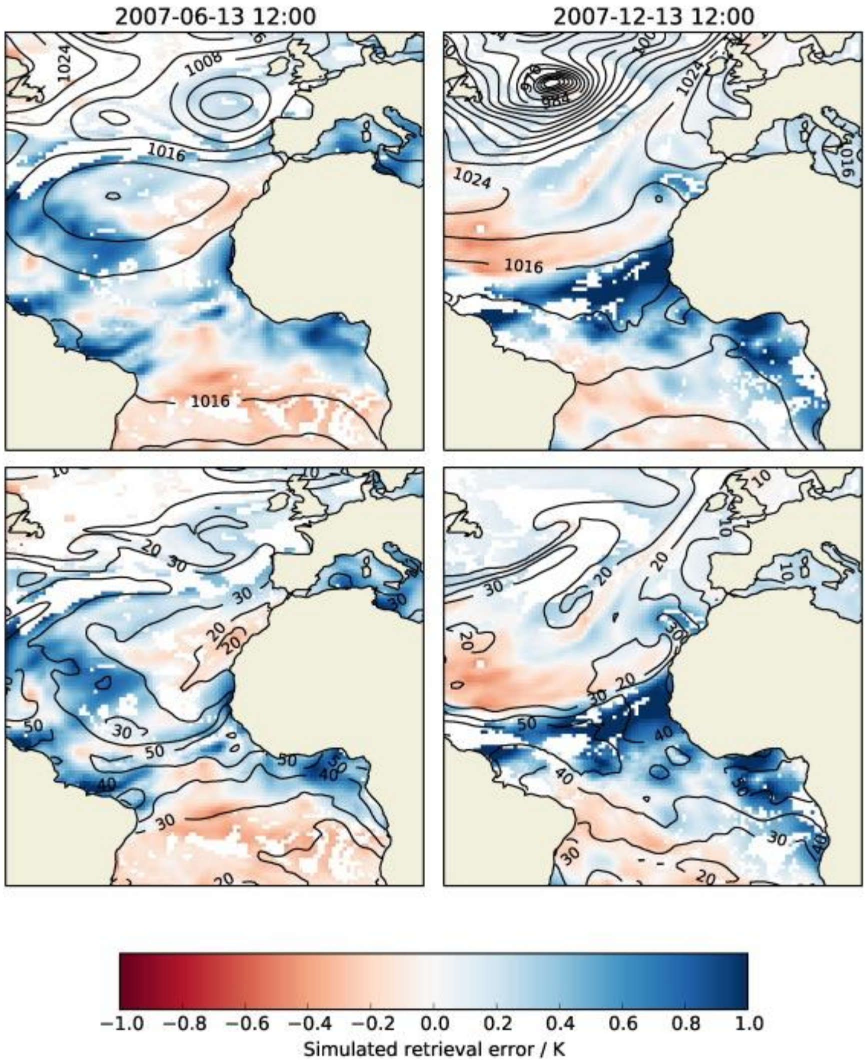
Validation of skin SST against skin SST

	Matches	N2	N3	D2	D3
AATSR					
Day	273	0.054 (0.290)		-0.000 (0.200)	
Night	302	0.056 (0.289)	0.031 (0.212)	0.013 (0.217)	0.003 (0.187)
ATSR2					
Day	62	0.008 (0.419)		0.040 (0.274)	
Night	101	0.009 (0.298)	-0.065 (0.185)	-0.044 (0.203)	-0.039 (0.156)
ATSR1					
Day					
Night					
3.7 µm					

- Median (Robust Standard Deviation) of satellite – drifter difference
- N = Nadir-only retrieval. D = Dual-view retrieval

ATSR SST Uncertainties

- Uncertainty due to correlated effects
- Can study in RT simulations:
  - Take NWP SST + atmosphere
  - Simulate ToA BTs
  - Retrieve SST
  - Compare retrieved with "true" SST
- For uncertainty estimate
  - Use same simulations as regression
  - Standard error of regression
    - i.e. fitting error

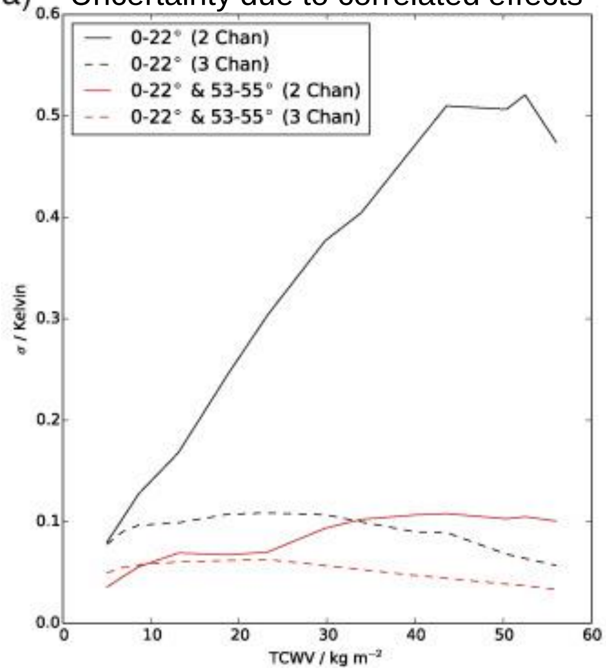


Simulated retrieval errors (2-channel single-view). Plots in upper panels show pressure contours (hPa), and lower panels show TCWV contours (kg m^{-2})

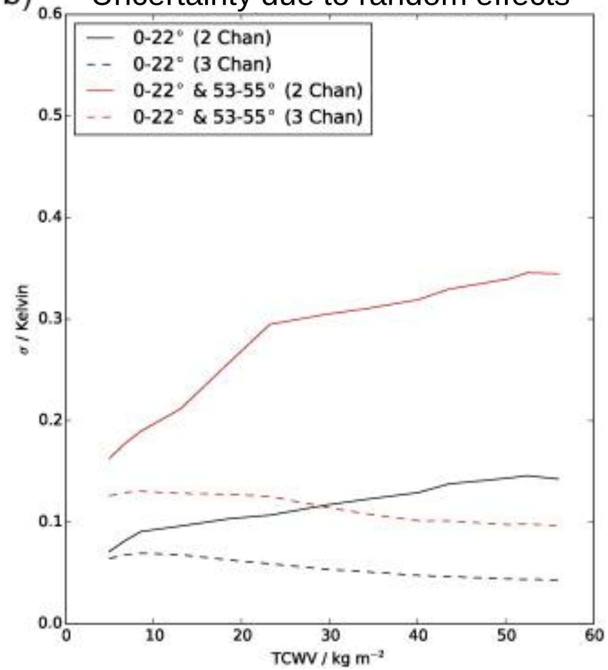
ATSR SST Uncertainties

- Uncertainty due to correlated effects
  - Estimate with standard error of regression
- Uncertainty due to random BT noise
  - Calculate per-pixel from the instrument noise $u_{random} = \sqrt{\sum a_i^2 \mathrm{NeDT}_i^2}$

a) Uncertainty due to correlated effects

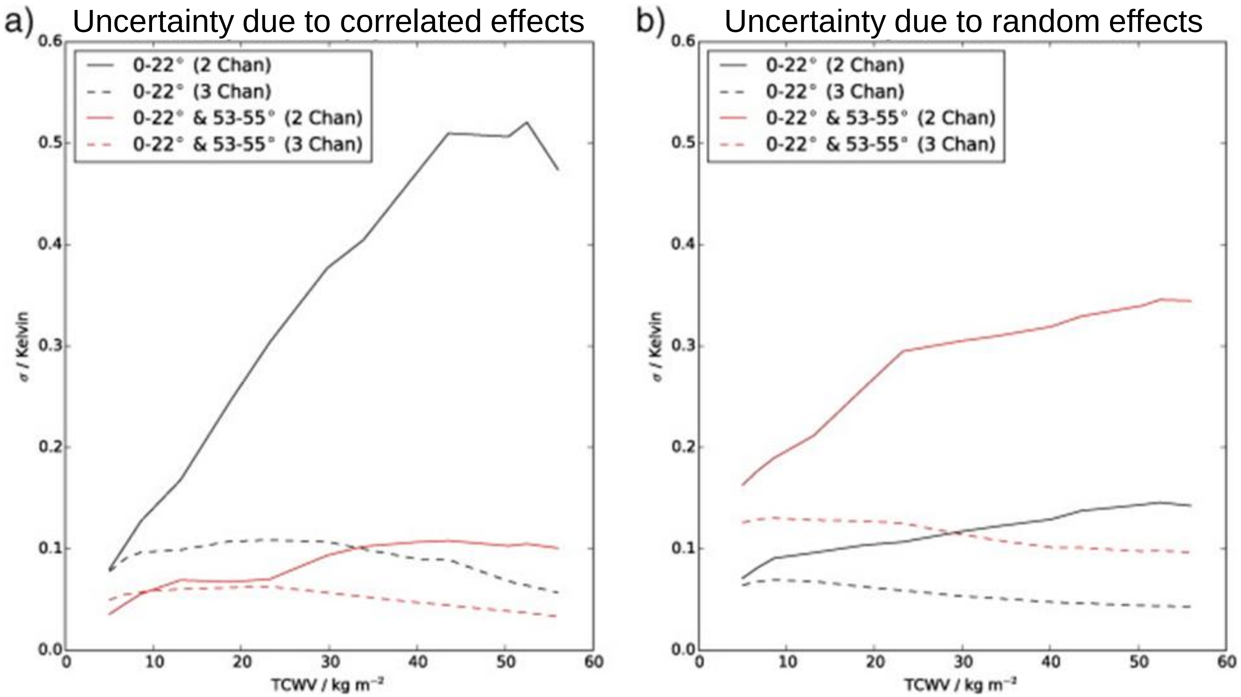


b) Uncertainty due to random effects



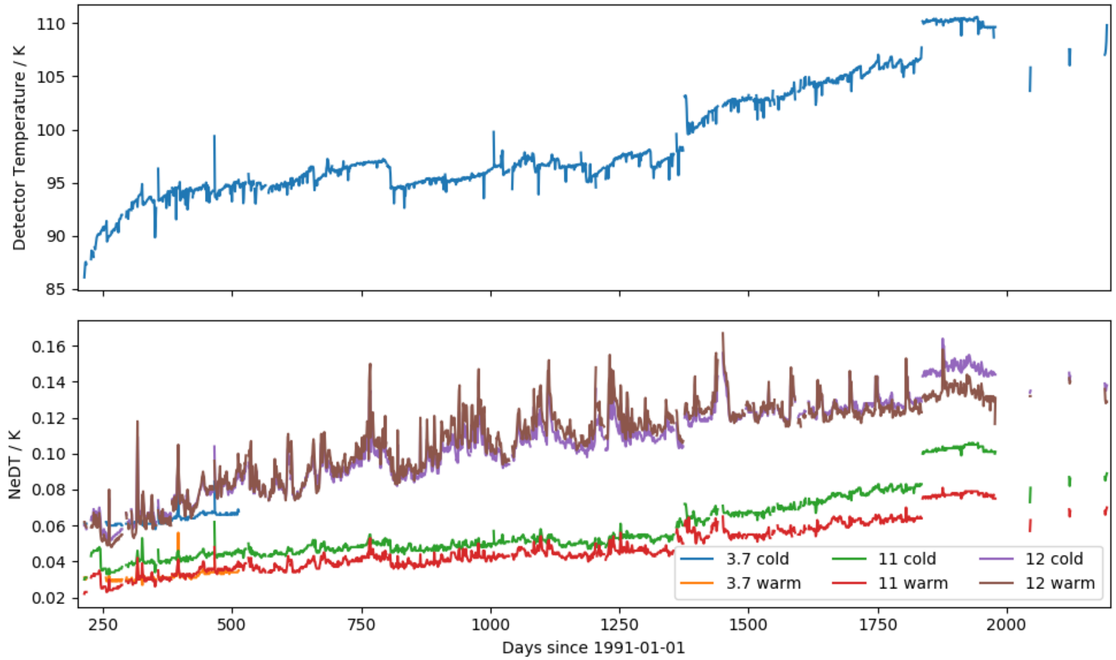
Atmospheric Correction Smoothing

- ATSR SST retrieval based on RT simulations
  - Regression will minimise fit error – i.e. local correlated uncertainty
  - u_{random} tends to be larger for dual-view retrievals
  - u_{random} generally not important for gridded L3 / L4 as it reduces via averaging

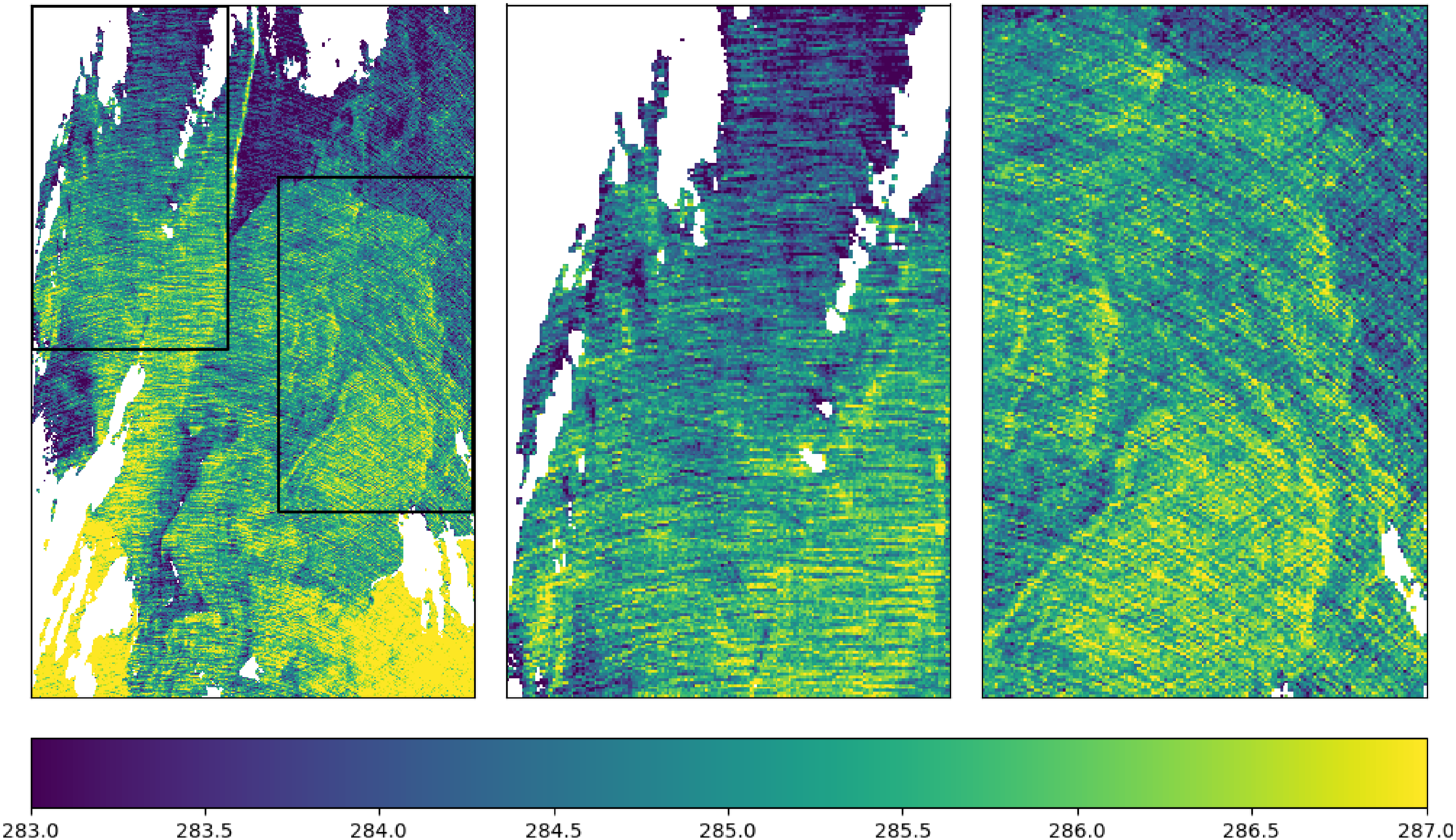


Atmospheric Correction Smoothing

- ATSR SST retrieval based on (noise-free) RT simulations
  - Regression will minimise fit error – i.e. local correlated uncertainty
  - u_{random} tends to be larger for dual-view retrievals
  - u_{random} generally not important for gridded L3 / L4 as it reduces via averaging
  - Significant for L2P – especially for ATSR1 where NeDT can reach 0.1 K



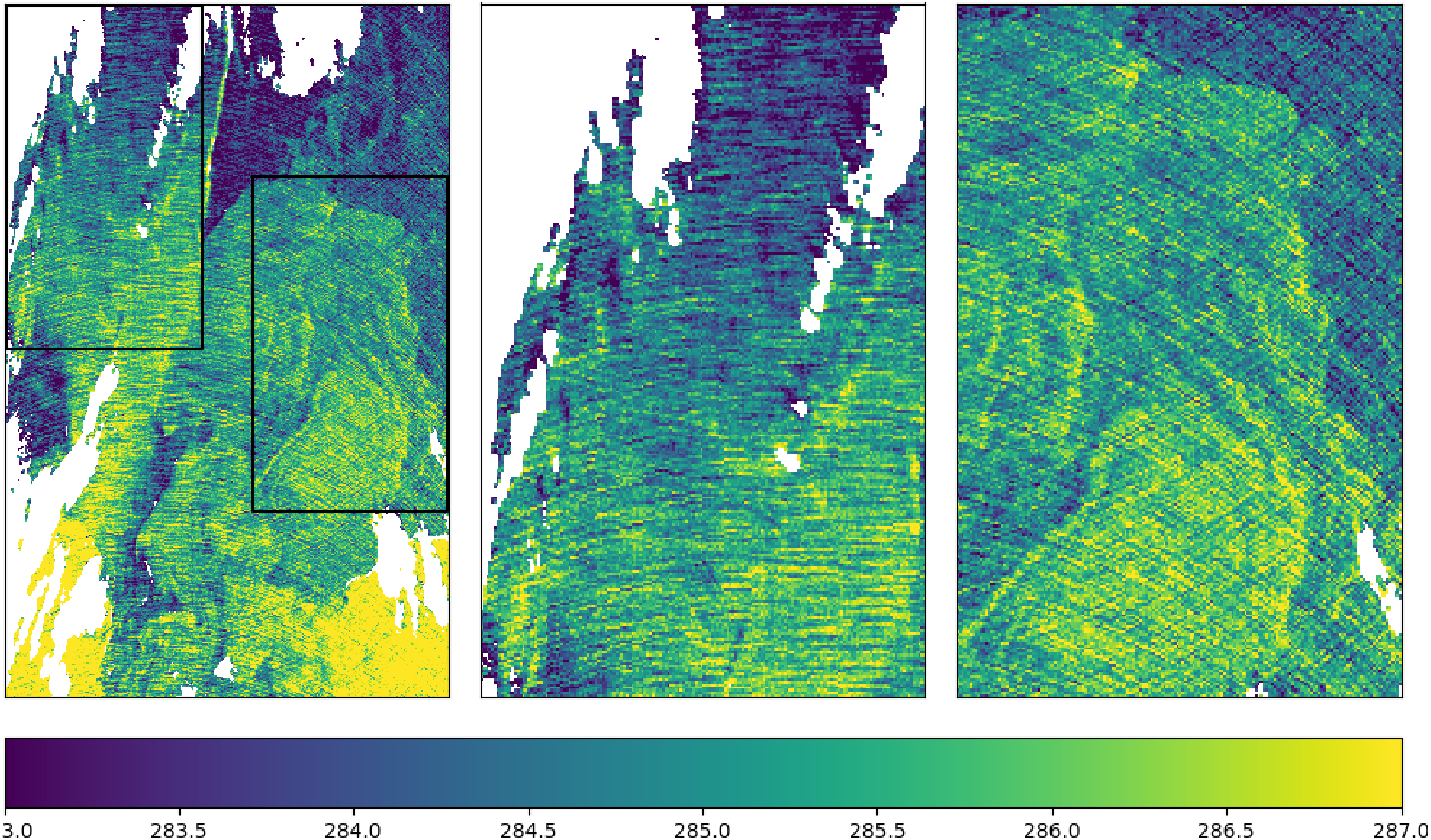
ATSR1 scene affected by high NeDT



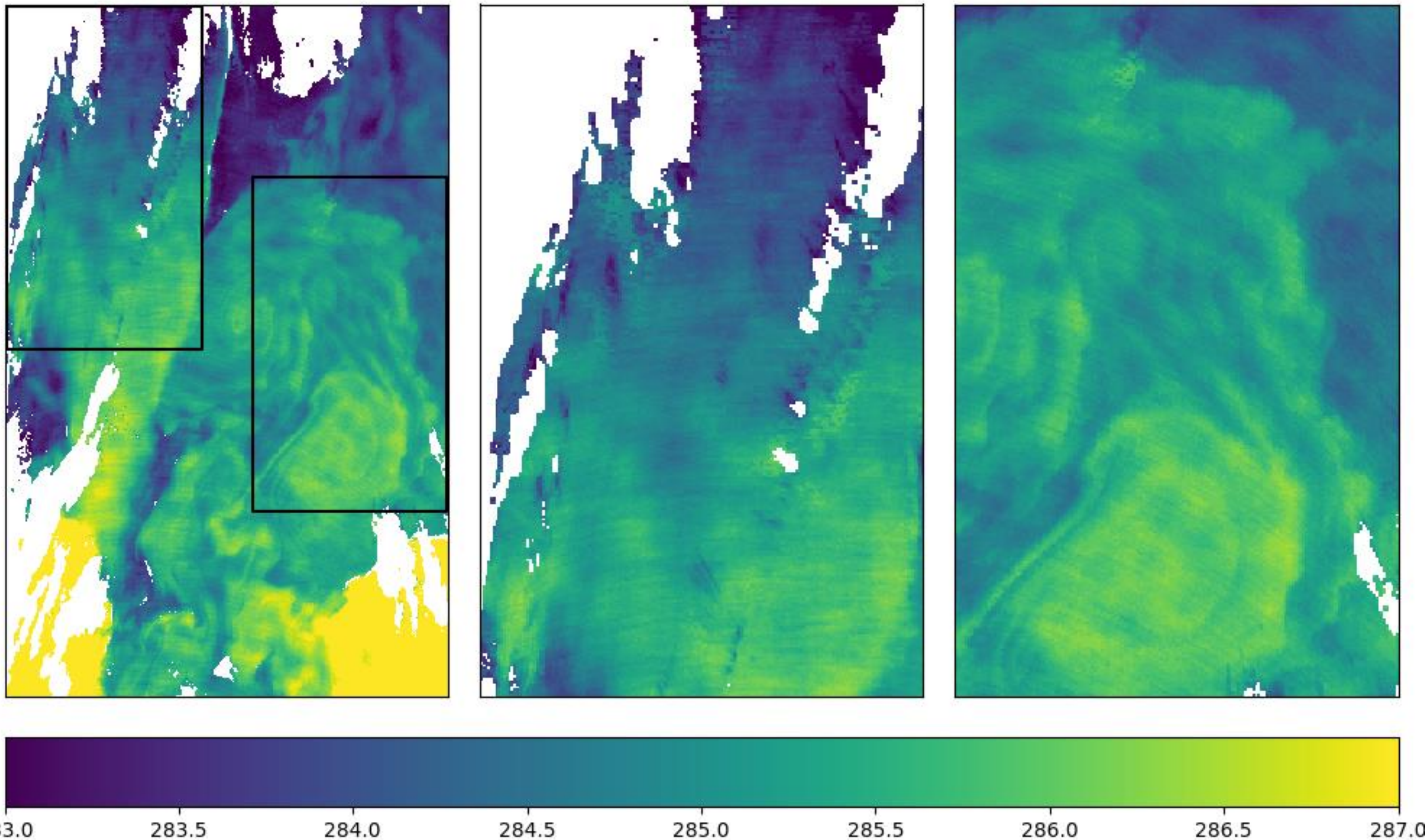
Atmospheric Correction Smoothing

- Smoothing the SST field would reduce feature resolution
  - Need to reduce noise without reducing feature resolution
- Consider atmospheric correction parameter δ
  - $\delta = x - y_{11}$
  - Where x is the SST, y_{11} is the 11 µm BT
- δ is a function of atmospheric state, correlated from pixel to pixel
- We can replace δ with the NxN average $\langle \delta \rangle = \langle x \rangle - \langle y_{11} \rangle$
- This gives noise-reduced SST:
  - $\tilde{x} = \langle x \rangle + y_{11\mu m} - \langle y_{11\mu m} \rangle$
- With general form we can choose:
  - Single channel, simple mean, noise weighted, sensitivity weighted etc.
- Note – this does introduce correlated uncertainties, so L3 SSTs are calculated from **unsmoothed** SSTs

ATSR1 scene – no smoothing



ATSR1 scene – atmospheric correction



AVHRR SST Retrieval

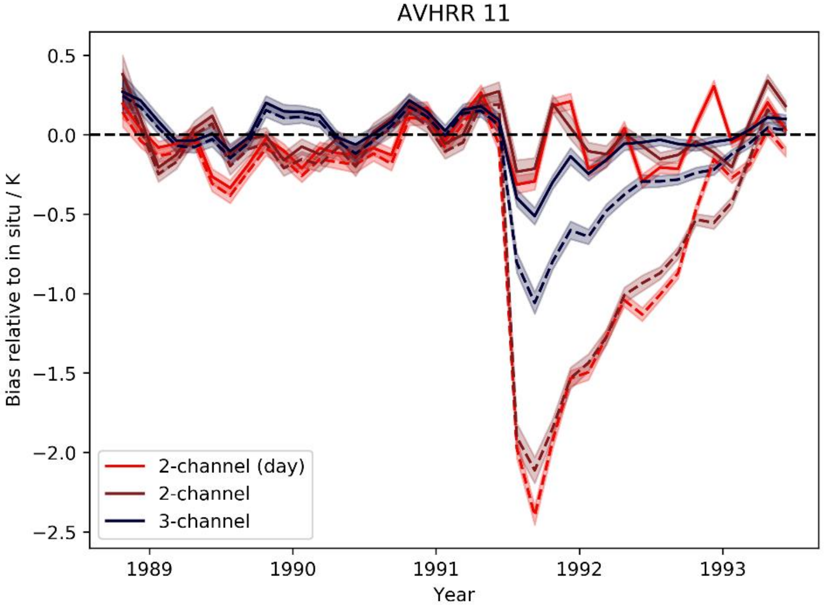
- Optimal Estimation (OE)
- $\hat{x} = x_a + G\left(y - F(x_a)\right)$
  - $\hat{x}$ is the retrieved state; x_a is the prior state
  - y is the observation vector
  - F is the forward model (RTTOV)
  - $G = S_a K^T (K S_a K^T + S_\varepsilon)^{-1}$ is the gain matrix
  - S_a, S_ε are the error covariance matrices
  - K is the tangent linear matrix
- Uncertainties:
  - $u_{random} = \sqrt{G S_{NeDT} G^T}$
  - $u_{correlated} = \sqrt{G S_{ffm} G^T}$
  - SST sensitivity ($d\widehat{SST}/dSST$) from averaging kernel $A = GK$

AVHRR BT level improvements

- For full details see Chris Merchant’s talk
- Quick summary:
- Improved AVHRR L1b reader
- Consistent AVHRR BT calibration based on Walton et al. 1998 with new calibration coefficients
- New solar contamination algorithm
- Per-pixel NeDT calculated from space view counts

AVHRR Stratospheric Aerosol

- Stratospheric aerosol from El Chichón and Mount Pinatubo causes significant cold biases in SST retrieval
- AVHRR is not capable of ATSR-style aerosol robust retrieval
- Can include aerosol in forward model and *a priori*
- For details see poster:
  - "Stratospheric Aerosol and Impacts on Infrared SST Retrievals"

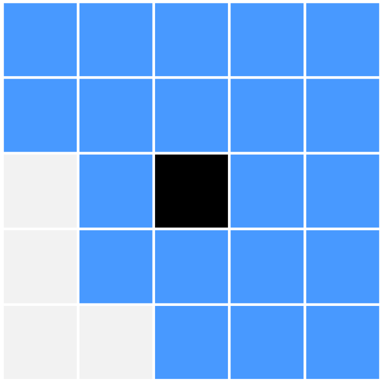


Including aerosol prior reduces retrieval biases

Retrieval without aerosol prior is biased cold. Approx 1 K for 3 channel retrieval, and over 2 K for 2 channel retrieval

AVHRR Smoothed Optimal Estimation

- Extend smoothed OE implementation from Merchant et al. 2013
- Simple overview:
  - Include average (of surrounding pixel) BTs in observation vector
  - Include surrounding average SST in state vector
  - Atmospheric state is the same for centre pixel and surrounding pixels
  - Retrieve centre-pixel SST



- central pixel for retrieval
- surrounding clear-sky pixels for average
- non-clear pixels are not used

AVHRR Smoothed Optimal Estimation

- $x^T = (\mathrm{SST} \quad \overline{\mathrm{SST}} \quad \mathrm{TCWV})$
- $y^T = (y_{3.7} \quad y_{11} \quad y_{12} \quad \bar{y}_{3.7} \quad \bar{y}_{11} \quad \bar{y}_{12})$
- $$\mathbf{K}^{\mathrm{T}} = \begin{pmatrix} \frac{\partial y_{3.7}}{\partial \mathrm{SST}} & \frac{\partial y_{11}}{\partial \mathrm{SST}} & \frac{\partial y_{12}}{\partial \mathrm{SST}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{\partial \bar{y}_{3.7}}{\partial \overline{\mathrm{SST}}} & \frac{\partial \bar{y}_{11}}{\partial \overline{\mathrm{SST}}} & \frac{\partial \bar{y}_{12}}{\partial \overline{\mathrm{SST}}} \\ \frac{\partial y_{3.7}}{\partial \mathrm{TCWV}} & \frac{\partial y_{11}}{\partial \mathrm{TCWV}} & \frac{\partial y_{12}}{\partial \mathrm{TCWV}} & \frac{\partial \bar{y}_{3.7}}{\partial \mathrm{TCWV}} & \frac{\partial \bar{y}_{11}}{\partial \mathrm{TCWV}} & \frac{\partial \bar{y}_{12}}{\partial \mathrm{TCWV}} \end{pmatrix}$$
- Atmospheric state is common to centre and surrounding pixels
- Surrounding pixel SST is independent of centre-pixel

SST CCI Retrievals Summary

- ATSR
  - Linear retrieval based on ARC heritage
  - Aerosol robust for ATSR-1 (no volcanic eruptions during ATSR-2/AATSR)
  - L2/L3 product generation ongoing
- AVHRR
  - Optimal Estimation retrieval
  - Includes stratospheric aerosol in prior and forward model
  - Inter-satellite harmonisation of BT and SST ongoing
- Atmospheric correction smoothing to reduce noise in pixel-level L2P
- Uncertainties
  - Random
  - Locally correlated
  - Systematic
  - Depth adjustment
  - (L3) Sampling