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The quality of Sea Surface Temperature observations from drifting buoys and the role of the natural variability

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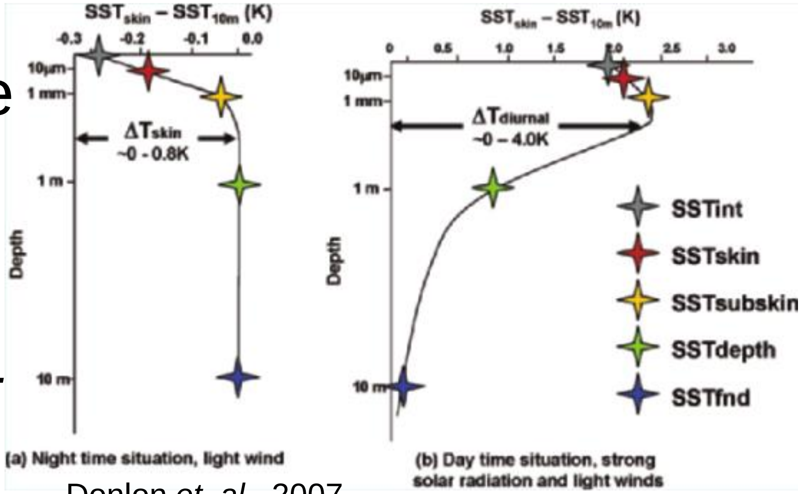
Sea Surface Temperature (SST)

• Consists the lower boundary condition for NWP and climate models (e.g. OSTIA, HadISST).
• Climate monitoring with observations since ~1850 (e.g. HadSST3).
• Determines the exchange of fluxes in the interface ocean/atmosphere.

• *Note the variation of SST with measurement depth.*



Donlon *et. al.*, 2007

SST observation methods

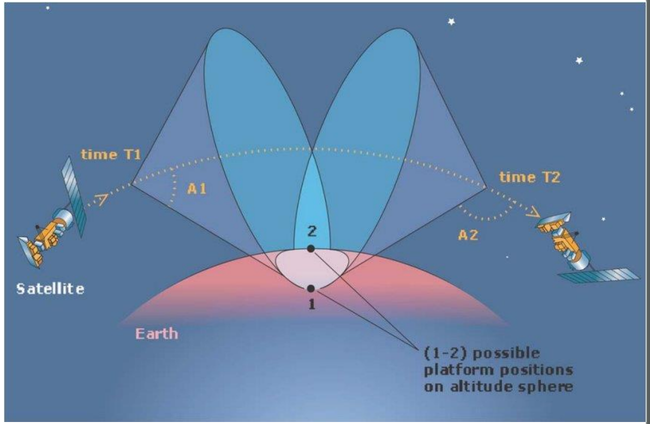
- Satellite retrievals based on infrared (IR) and microwave (MW) observations.

Sensor Type	Spatial resolution	Limitations	Depth penetration
IR radiometer	1-4 km (nadir)	Cloud-free scenes, impact from aerosols	~10-20 μm
MW radiometer	25-50km	Precipitating clouds	~1-1.5 mm

- Ships (Ships of Opportunity Programme [SOOP] or research vessels).
- Moored and drifting buoys.
- Argo profilers.

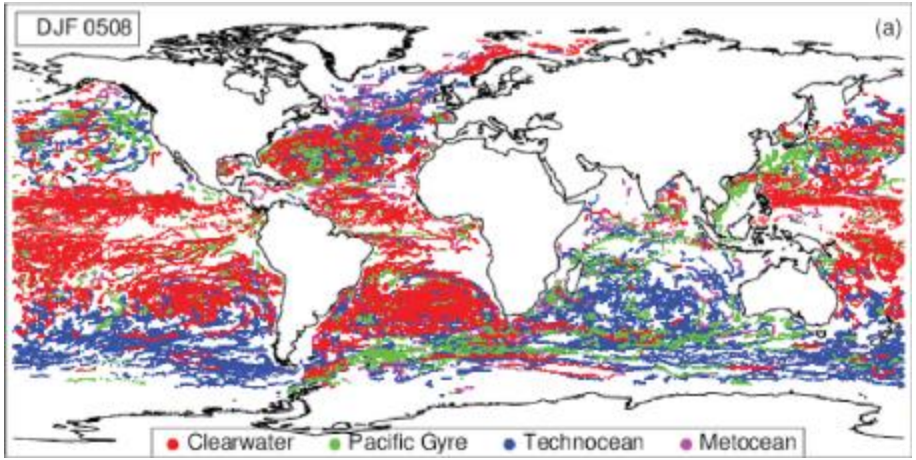
A closer look to drifting buoys

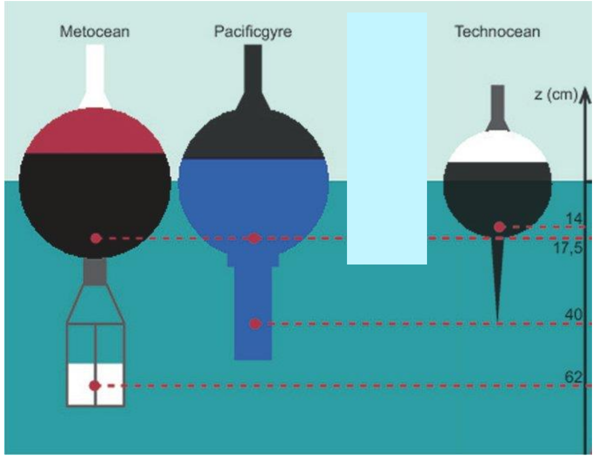
- Positioning using mainly Argos system, with accuracy ~500 m (Lopez et al., 2014).



- SST is sampled continuously with a 15-minute repeat cycle (DBCP, 2009).
  - Interval between samples = 60 s.
  - Number of samples averaged = 15.
  - SST updated every 15 minutes.
  - Number of thermistors monitored = 1 (YSI 44018 or equivalent).

One or more types of drifting buoys?





- AMSR-E and NAVOCEANO analysis SST do not show significant difference (Castro et al., 2012).
- Use of limited number of pairs indicate non-negligible differences (Reverdin et al., 2013).

Rationale

- Drifting buoys are the backbone of the SST observational array providing global coverage (vs. moored buoys) and better quality observations (vs. ships).
- They are used extensively for the calibration and/or validation of SST retrievals from satellite instruments.
- It is widely believed that the random uncertainty of SST observations from drifting buoys is ~0.2 K.

Is it correct?

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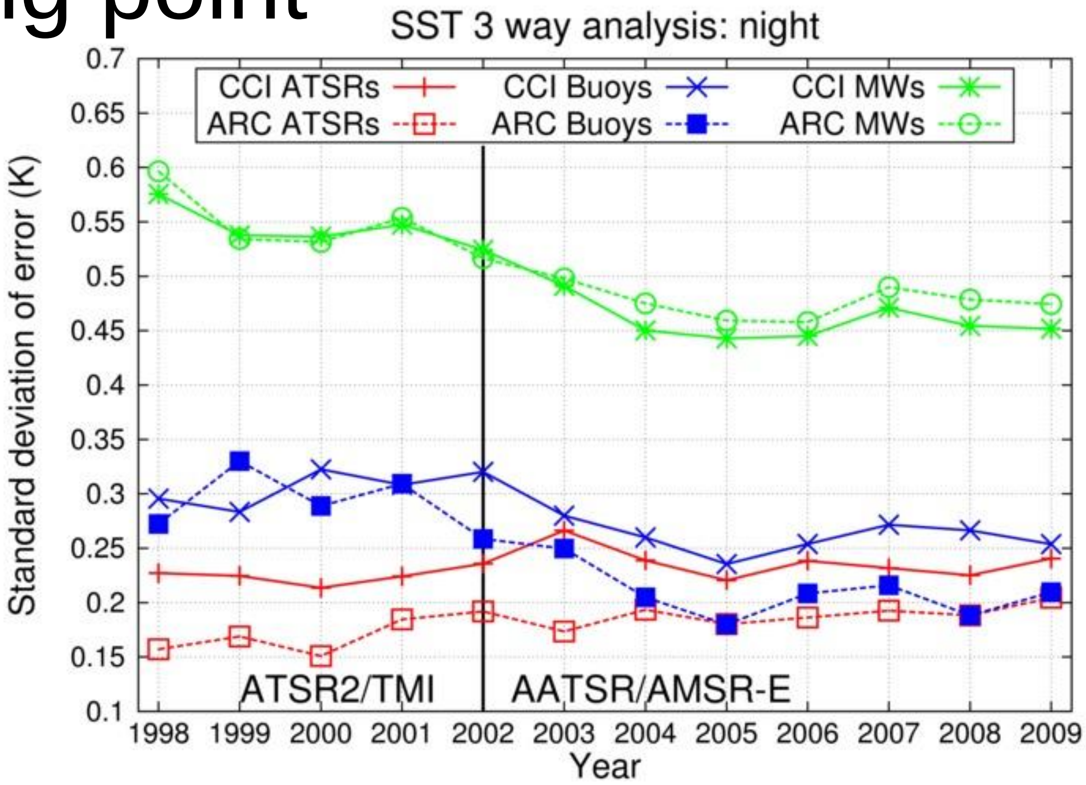
The starting point

- Triple collocation (O'Carroll et al., 2008)
- Same datasets for MW and drifting buoys.



What is going on with drifting buoys??

Uncertainty model

- An instrument (X) with systematic uncertainty (b_X) and random uncertainty (e_X) makes observations of the measurand T:

$$X = T + b_X + e_X$$

$$E[b_X] = \beta_X, \qquad E[e_X] = 0, \qquad Var[e_X] = \sigma_X^2$$

- For another instrument (Y) located “nearby” similar equations hold, with ΔT denoting the change of T with space (Δ**r**) and/or time (Δt):

$$Y = T + \Delta T + b_Y + e_Y$$

Mean value of the difference

$$\mu \equiv E[Y - X] = E[\Delta T + b_Y - b_X + e_Y - e_X]$$
$$= E[\Delta T] + E[b_Y] - E[b_X] + E[e_Y] - E[e_X]$$
$$= \mu_{\Delta T} + \beta_Y - \beta_X$$
$$= \beta_Y - \beta_X$$

$\mu_{\Delta T}$ stands for the mean value of ΔT, which is expected to be 0 at least on global scale.

Variance of the difference

$$\sigma^2 \equiv Var[Y - X] = Var[\Delta T + b_Y - b_X + e_Y - e_X]$$

$$= Var[\Delta T] + Var[b_Y - b_X] + Var[e_Y - e_X] \qquad \text{I.}$$

$$= \sigma^2_{\Delta T} + \sigma^2_{\Delta\beta} + Var[e_Y] - 2Cov[e_Y, e_X] + Var[e_X]$$

$$= \sigma^2_{\Delta T} + \sigma^2_{\Delta\beta} + \sigma^2_Y + \sigma^2_X \qquad \text{II.}$$

Assumptions

I. No correlation between ΔT and uncertainties and between uncertainties.

II. The random uncertainties are uncorrelated.

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One equation – 4 unknowns

$$\sigma^2 = \sigma_{\Delta T}^2 + \sigma_{\Delta\beta}^2 + \sigma_Y^2 + \sigma_X^2$$

- For every one of the right hand terms the following inequality holds, because all terms are quadratic (e.g. for ΔT):

$$\sigma_{\Delta T}^2 \le \sigma^2 \Rightarrow \sigma_{\Delta T} \le \sigma$$

- Given that ΔT depends on Δ**r** and Δt, when space and time differences are sufficiently small (i.e. for the measuring standards of the instruments) then:

$$\sigma_{\Delta T} \xrightarrow{\Delta r, \Delta t \to 0} 0$$

Application to drifting buoys (DB)

Both X and Y are DB i.e.:

$$\beta_X = \beta_Y = \beta_{DB} \Rightarrow \boxed{\mu = 0}$$

Ideally for mean

$$\sigma_Y = \sigma_X = \sigma_{DB} \Rightarrow \sigma^2 = \sigma^2_{\Delta T} + \sigma^2_{\Delta\beta} + 2\sigma^2_{DB}$$

$$\boxed{\sigma^2_{DB} = \frac{\sigma^2 - \sigma^2_{\Delta\beta} - \sigma^2_{\Delta T}}{2}}$$

$$\sigma^2_{\Delta\beta} = Var[b_Y - b_X] = Var[b_Y] - 2Cov[b_Y * b_X] + Var[b_X]$$

$$= \sigma^2_\beta - 2 * \rho_\beta * \sigma_\beta * \sigma_\beta + \sigma^2_\beta = 2 * \sigma^2_\beta (1 - \rho_\beta)$$

Application to DB (continuing)

- Ideally the correlation of the systematic uncertainty is totally correlated [assumption III].

$$\sigma_{\Delta\beta}^2 = 2 * \sigma_{\beta}^2 (1 - \rho_{\beta}) = 0$$

$$\sigma_{DB}^2 = \frac{\sigma^2 - \sigma_{\Delta\beta}^2 - \sigma_{\Delta T}^2}{2} \Rightarrow \boxed{\sigma_{DB}^2 = \frac{\sigma^2 - \sigma_{\Delta T}^2}{2}}$$

$$\xrightarrow{\Delta r, \Delta t \to 0 \Rightarrow \sigma_{\Delta T} \to 0} \sigma_{DB}^2 = \frac{\sigma^2}{2}$$

Assumption IV: Negligible natural variability

$$\sigma_{DB} = \frac{\sigma}{\sqrt{2}}$$

Semivariogram!

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Importance of the model

- Both semivariogram and tiple collocation (3-way error analysis) make *de facto* these four assumptions!!!
  In reality it's not a new model, just reveals the limitations/assumptions.

$$\sigma_{DB} = \frac{\sigma}{\sqrt{2}}$$

- The standard deviation is the upper bound for natural variability (representetativeness), random uncertainties and **variance of the systematic uncertainties** (under two assumptions).

Not accounted generally!

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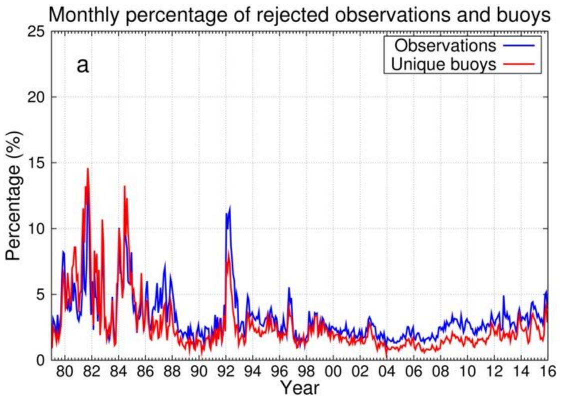
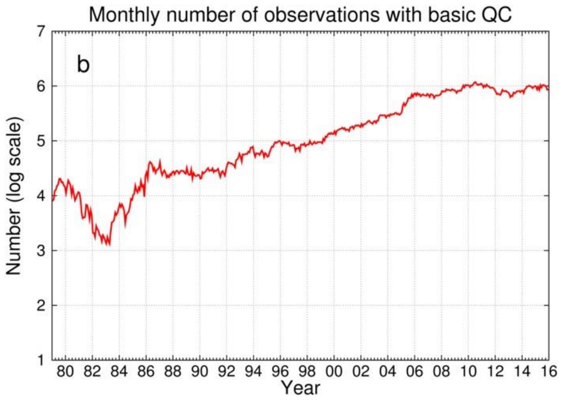
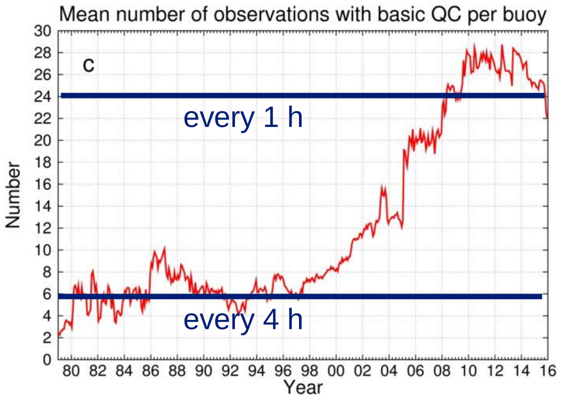
Dataset

- HadIOD1.2.0.0 (Atkinson et al., 2013, 2014)
- Drifting buoys from 1979 to 2015.
- 3 options/2 quality control (QC) flags:
  - **Basic QC** i.e. these used in HadSST2 (Rayner et al., 2006)
  - **Basic QC + Tracking** i.e. using OSTIA reanalysis SST, available only after 1985
  - **Basic QC + Tracking + Night time**

Monthly numbers

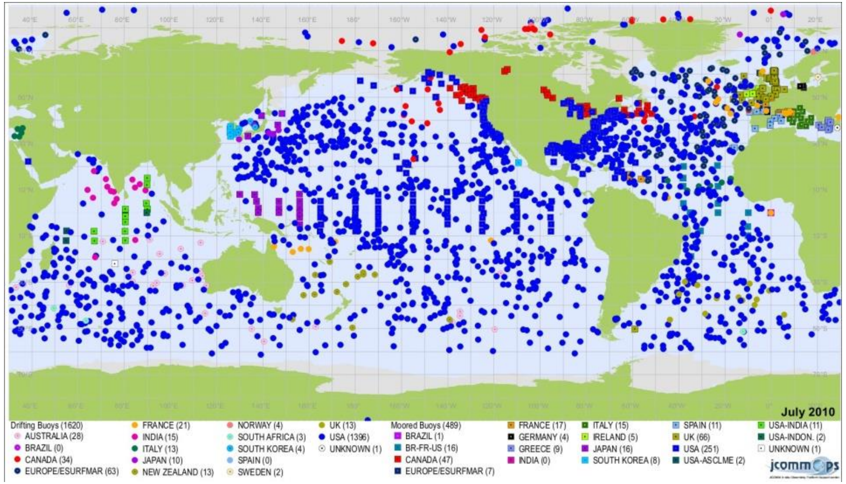


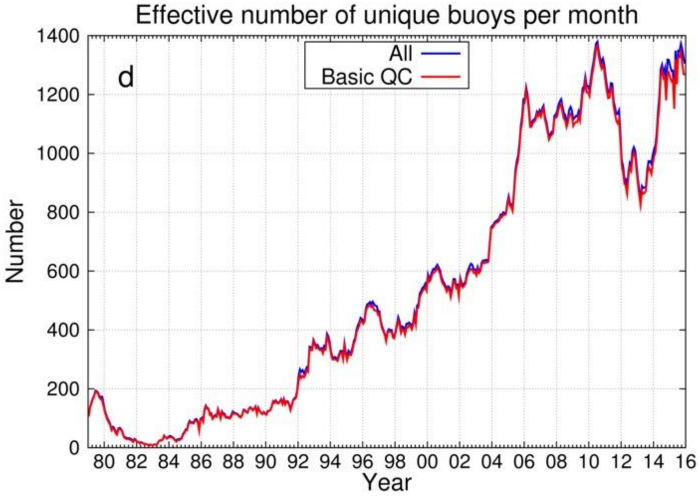




- Basic QC removes ~ 3%, although more in early years.
- Number of observations gradually increases to 6 millions.

Unique drifting buoys

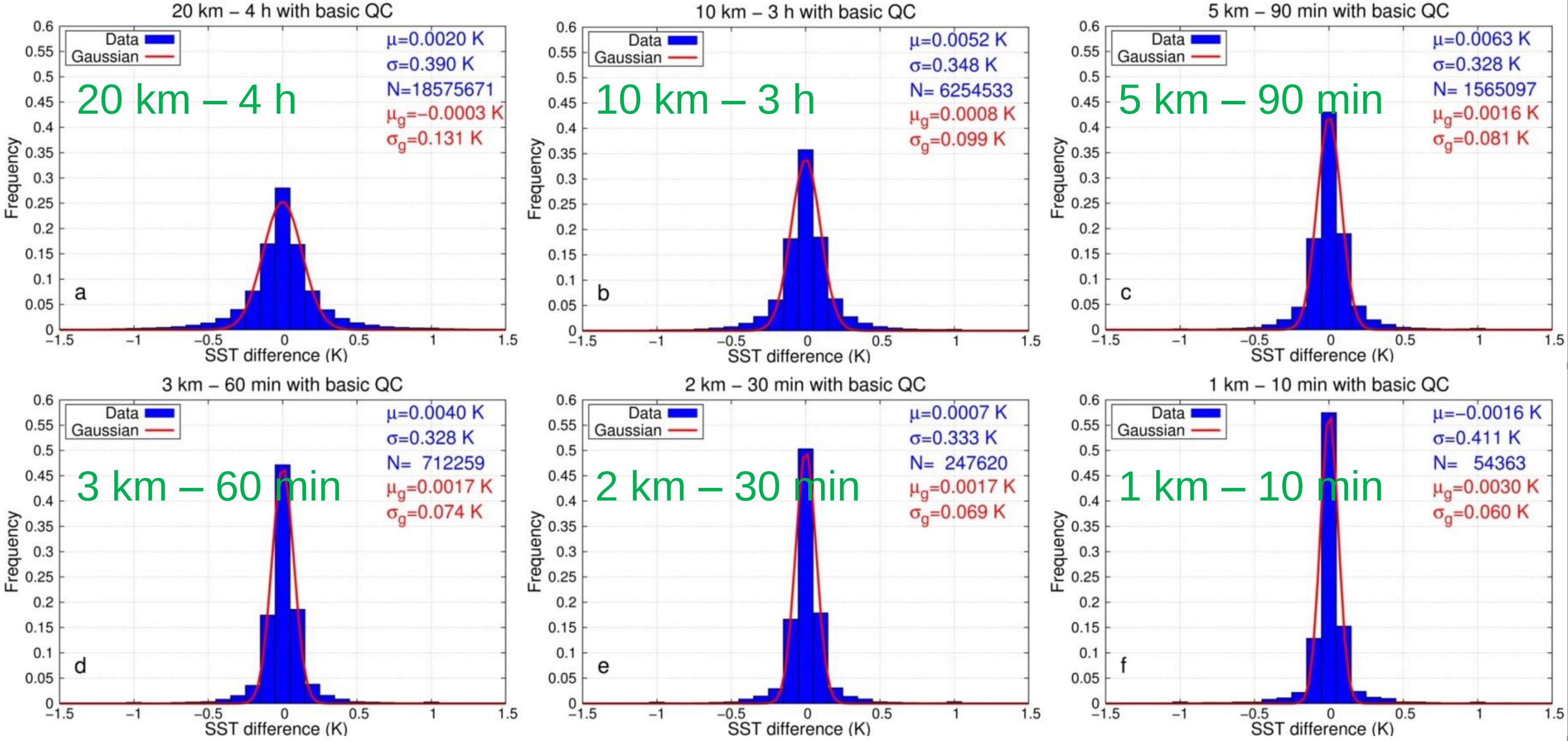




According to JCOMMOPS there 1620 buoys in July 2016, but in HadIOD we never overpass 1400.

➢ Not all drifting buoys report every day.

Histograms – Basic QC



6 ad hoc collocation windows

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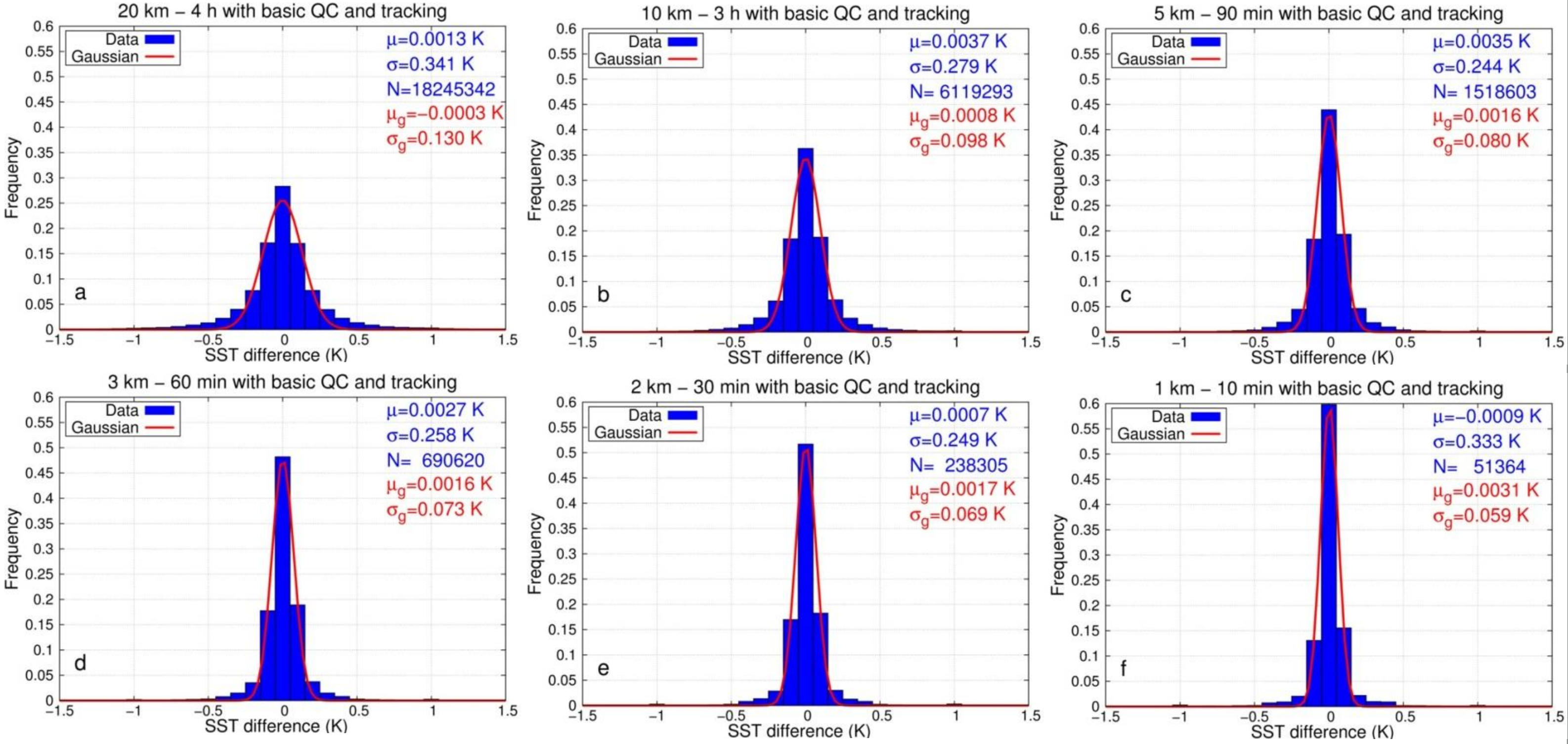
Histograms – QC + Tracking



Narrower distributions. Only after 1985!

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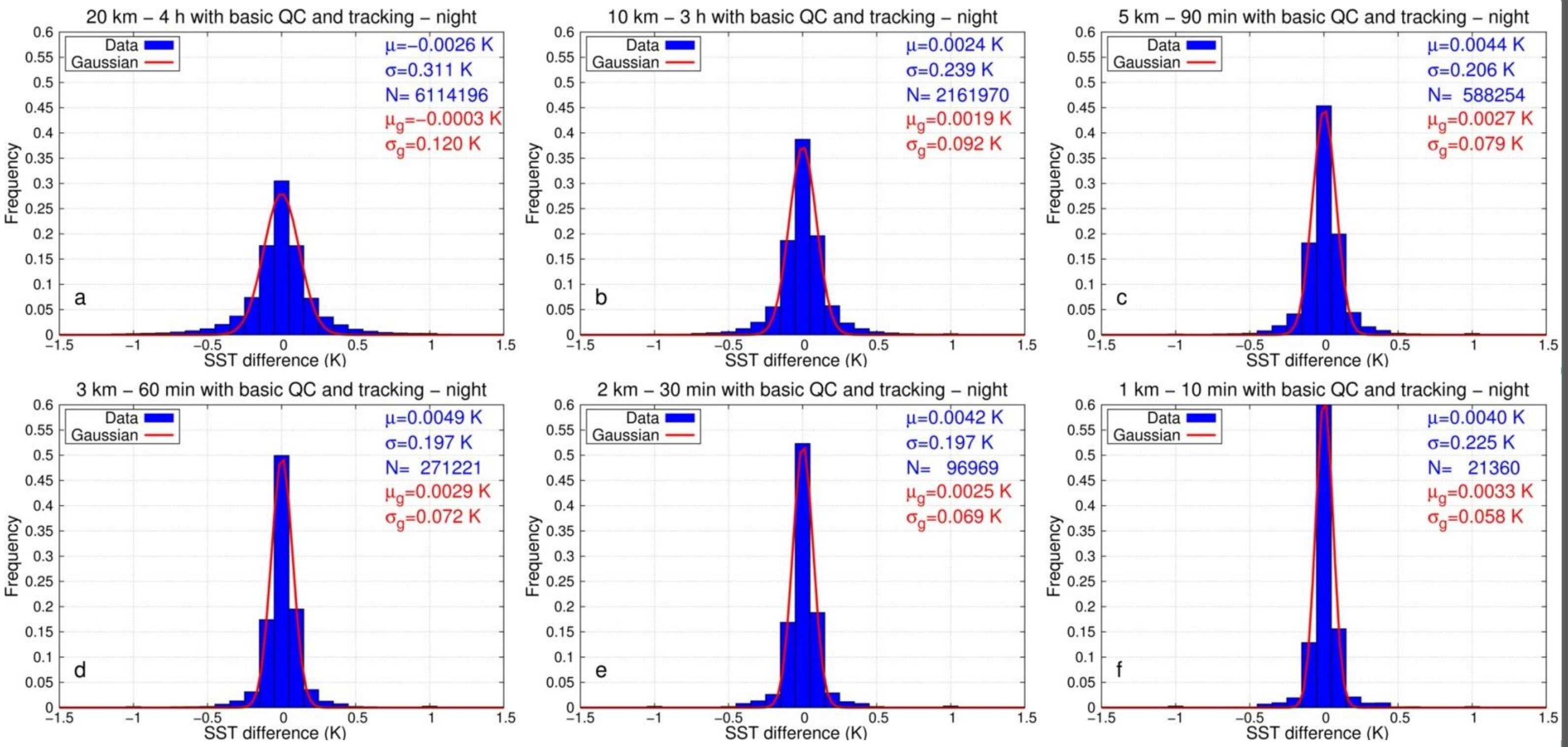
Histograms – QC + T + Night



Even narrower distributions. After 1985.

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Focus on quantitative results

Window	Basic QC			Basic QC and tracking			Night basic QC and tracking		
	μ	σ	N	μ	σ	N	μ	σ	N
20 km – 4 h	0.0020	0.390	18575671	0.0013	0.341	18245342	-0.0026	0.311	6114196
10 km – 3 h	0.0052	0.348	6254533	0.0037	0.279	6119293	0.0024	0.239	2161970
5 km – 90 min	0.0063	0.328	1565097	0.0035	0.244	1518603	0.0044	0.206	588254
3 km – 60 min	0.0040	0.328	712259	0.0027	0.258	690620	0.0049	0.197	271221
2 km – 30 min	0.0007	0.333	247620	0.0007	0.249	238305	0.0042	0.197	96969
1 km – 10 min	-0.0016	0.411	54363	-0.0009	0.333	51364	0.0040	0.225	21360

- Global mean value is always smaller than ±0.01 K.
  - not identical systematic uncertainty
- Standard deviation does not decrease with window size!!! Impact of QC, note behaviour for 1 km – 10 min.

Random uncertainty and SST natural variability

$$\sigma_{DB} \approx \frac{\sigma}{\sqrt{2}} = \frac{0.2}{\sqrt{2}} = 0.14K$$

Night basic QC and tracking

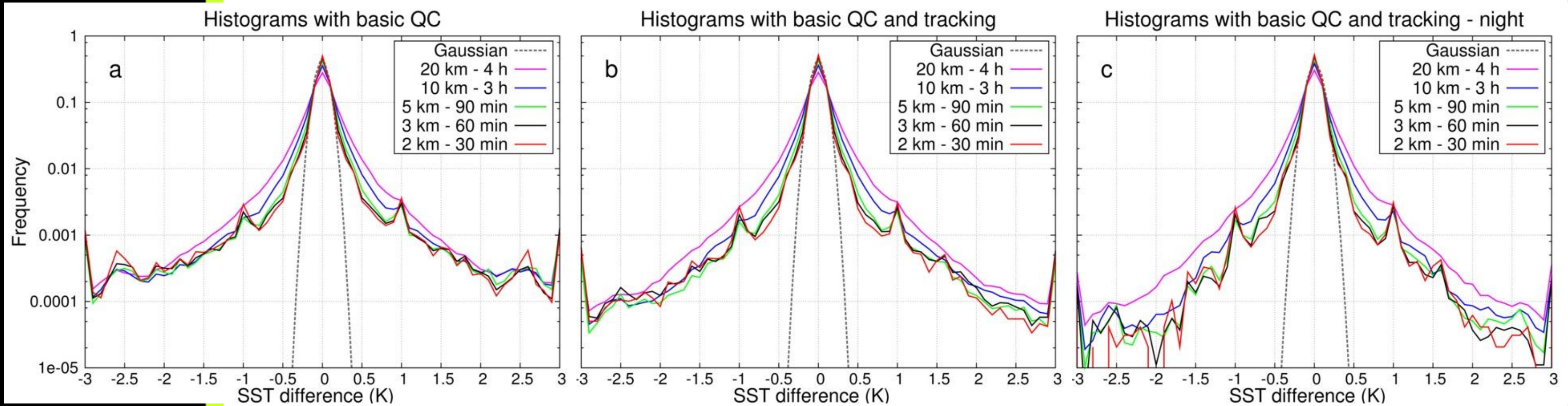
μ	σ	N
-0.0026	0.311	6114196
0.0024	0.239	2161970
0.0044	0.206	588254
0.0049	0.197	271221
0.0042	0.197	96969
0.0040	0.225	21360

$$\sigma^2 = \sigma_{\Delta T}^2 + \sigma_{\Delta\beta}^2 + 2*\sigma_{DB}^2 \Rightarrow$$

$$\sigma_{\Delta T}^2 = \sigma^2 - \sigma_{\Delta\beta}^2 - 2*\sigma_{DB}^2$$

- 10 km – 3 h: $\sigma_{\Delta T}$=0.13 K similar to σ_{DB} (0.14 K)!
- 20 km – 4 h: $\sigma_{\Delta T}$=0.24 K almost double of σ_{DB}.

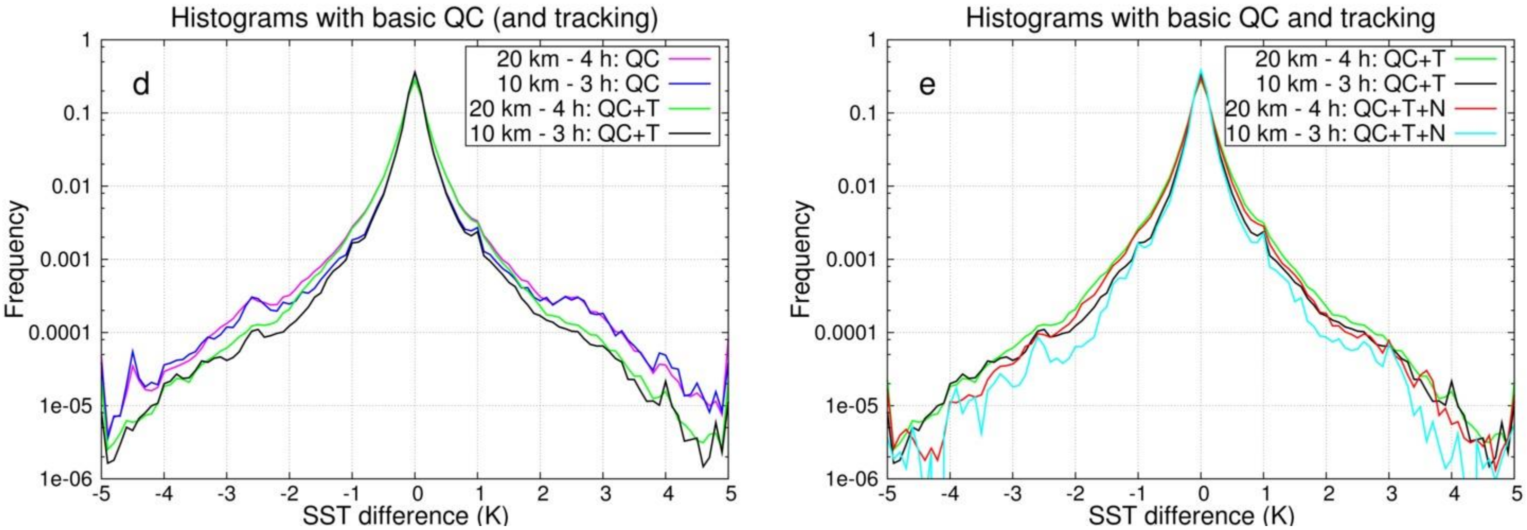
Another view of histograms



Distinct stratification below ±1 K, especially with tracking during night.

Peaks at ± 1 K due to bad transmission (?), not observed at 20 km – 4 h.

Histograms for the 2 big windows



- Tracking with OSTIA clearly removes bad observations above ±2 K.
- There still room for improvement.

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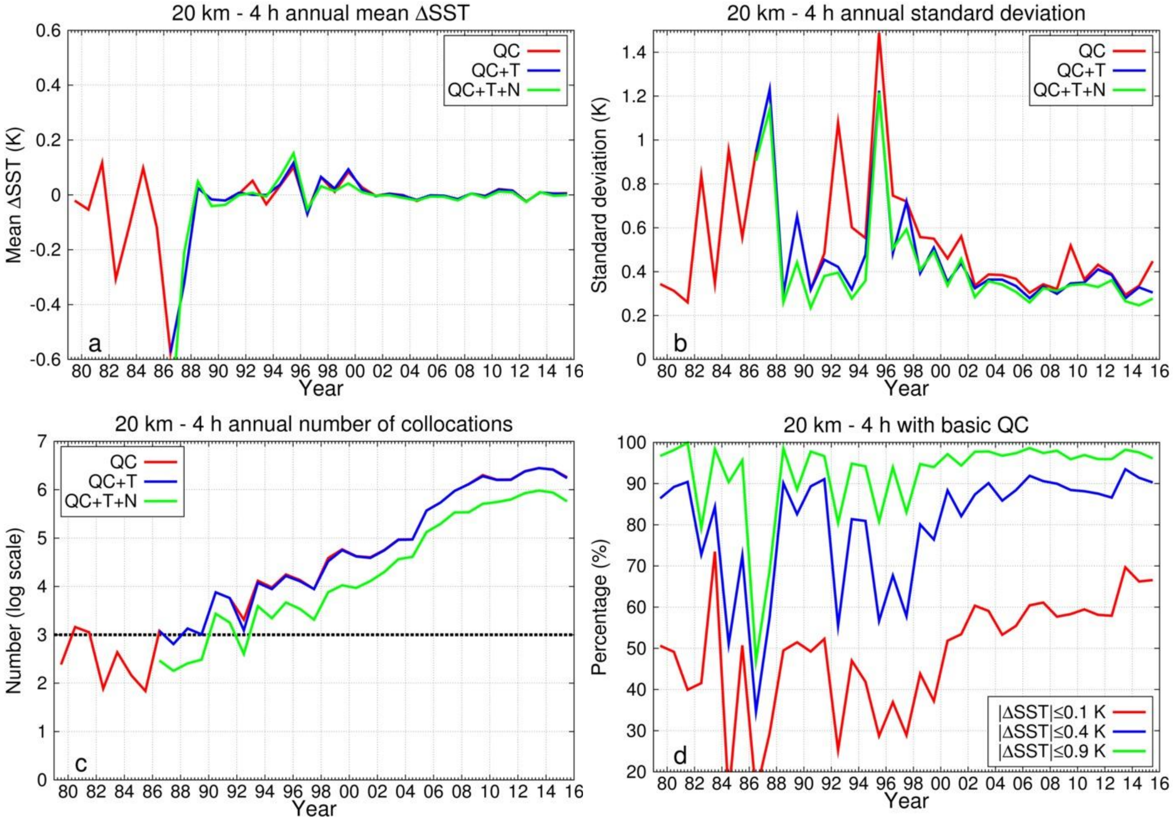
What the percentages tell us?

Window	*Basic QC*			*Basic QC and tracking*			*Night basic QC and tracking*		
	P[0.1]	**P[0.4]**	**P[0.9]**	**P[0.1]**	**P[0.4]**	**P[0.9]**	**P[0.1]**	**P[0.4]**	**P[0.9]**
20 km – 4 h	61.9	89.6	96.9	62.5	90.4	97.5	65.8	91.8	97.9
10 km – 3 h	72.5	93.4	97.7	73.5	94.4	98.4	77.1	95.6	98.8
5 km – 90 min	80.0	95.1	97.8	81.7	96.5	98.7	83.6	97.2	99.0
3 km – 60 min	83.2	95.4	97.7	84.9	96.7	98.5	86.9	97.6	99.0
2 km – 30 min	84.9	95.4	97.5	86.9	97.0	98.4	88.0	97.6	98.9
1 km – 10 min	85.6	94.3	96.5	88.4	96.2	97.7	90.1	97.5	98.7

- While P[0.1] always increases with decreasing window it is not the case for the other two.
- 99% of DB difference is below or equal to ±0.9 K.

Time-series: 20 km – 4 h



Before 1990 less than ~1000 collocations.

86-90 all collocations passed tracking QC.

1995 peak!!!

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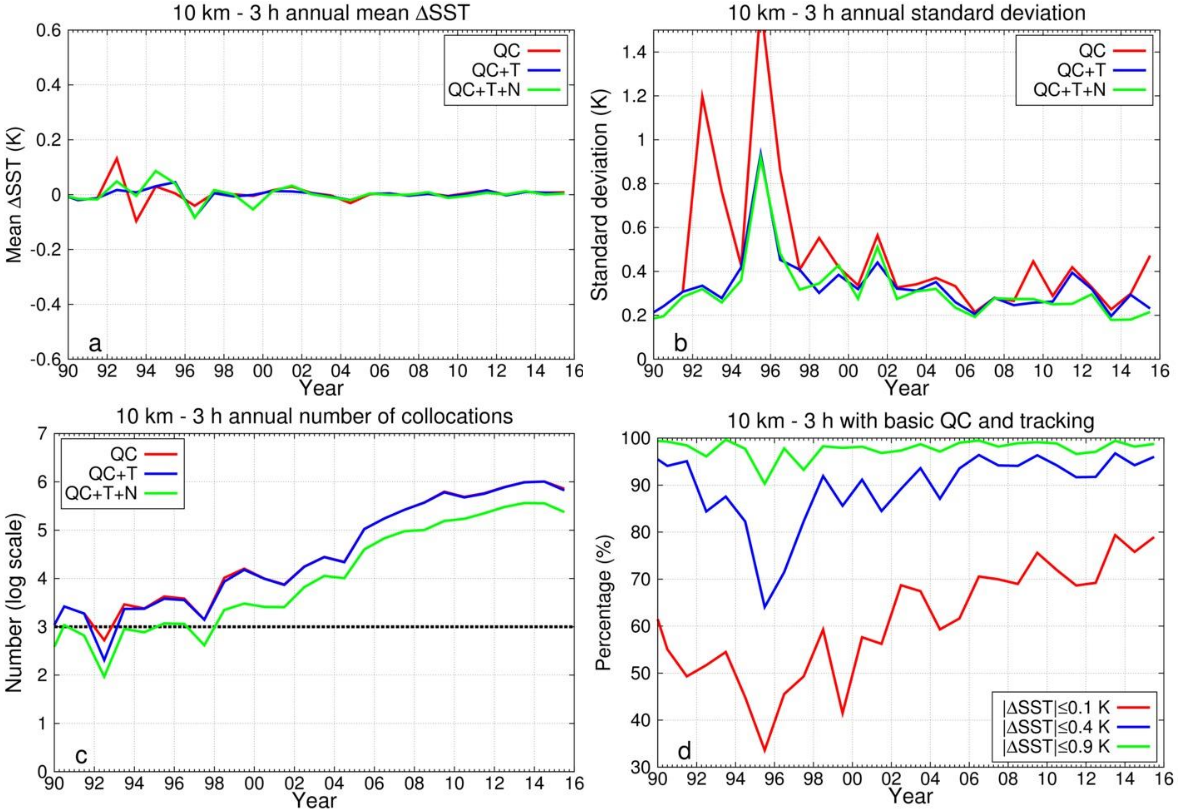
Time-series: 10 km – 3 h

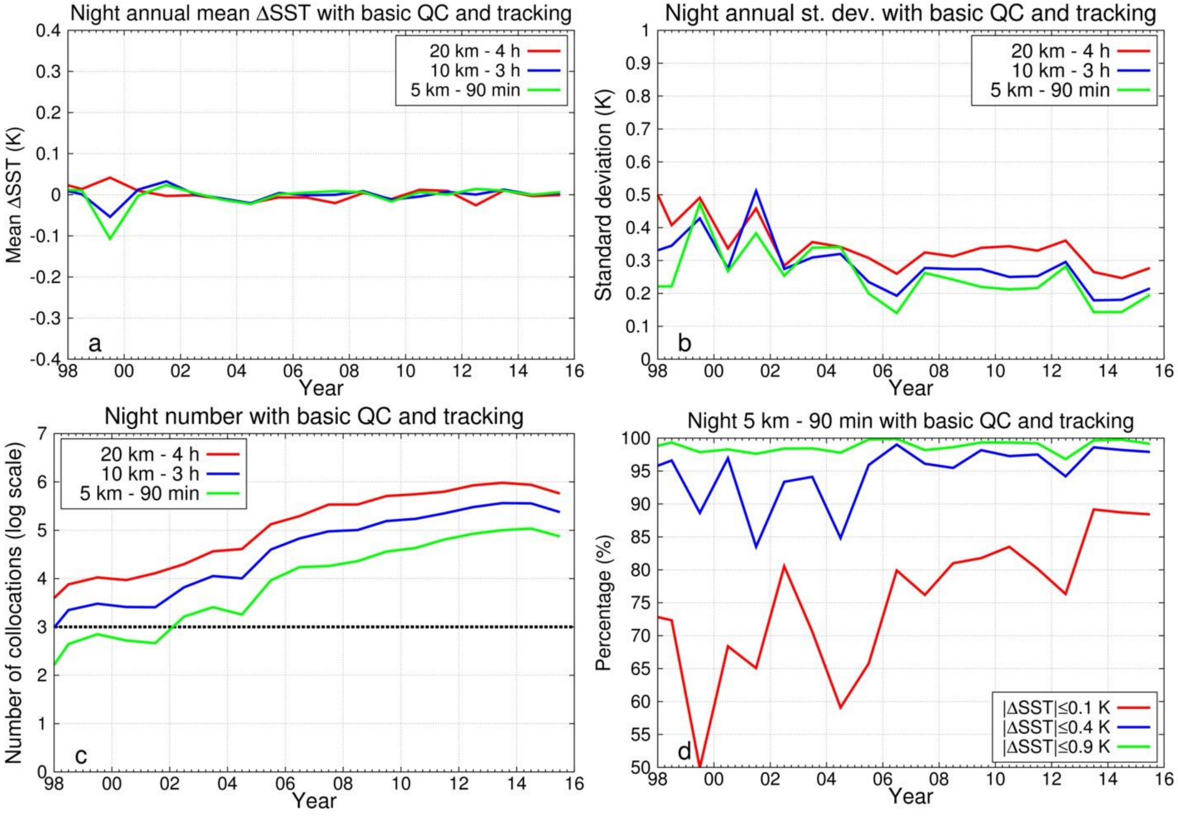


Limit to 1990 onwards.

Tracking reduces 1995 peak, but it does not remove the peaks after 2010.

P[0.9] stable, but P[0.1] improves!

Time-series: 5 km – 90 min



1998 onwards.

St. deviation is stratified with window after 2005, but not always before.

Peculiar 2005 for 5 km – 90 min.

σ is stable-ish since 2002.

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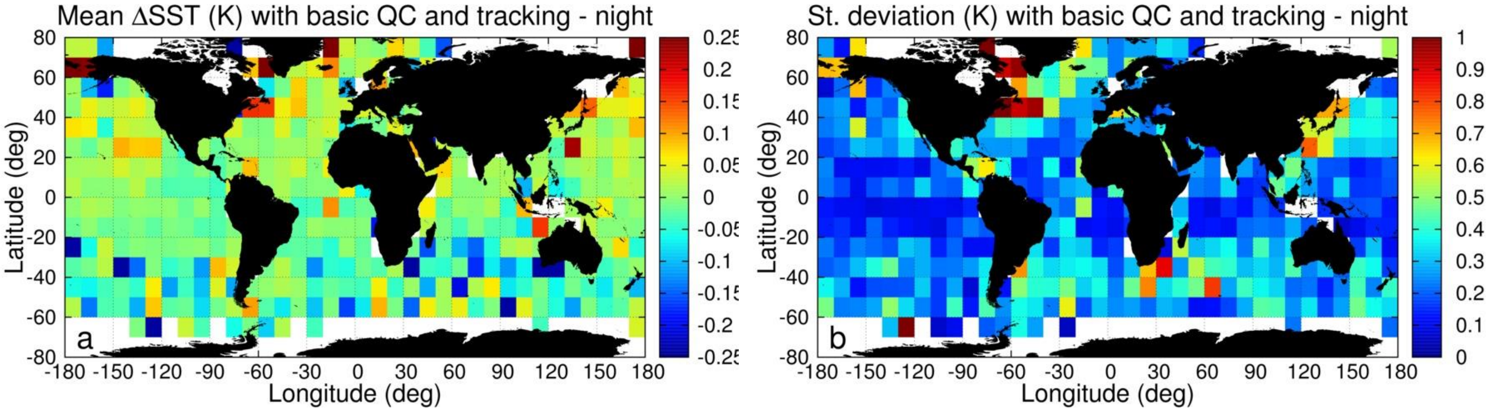
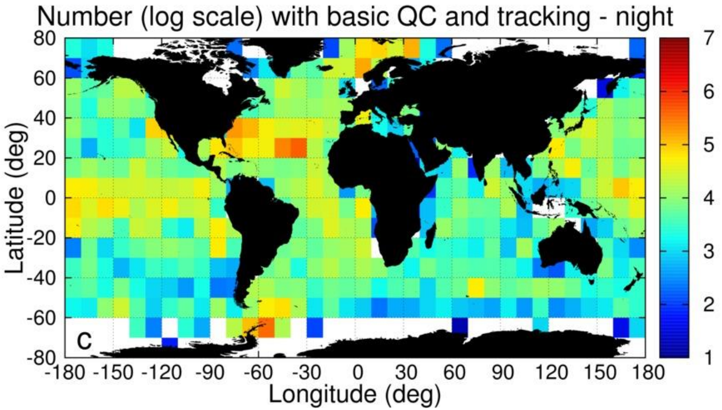
Geographical distribution





20 km - 4 h with at least 100 collocations per grid box.

Mean is very different from 0 K for some grid boxes.

σ is generally higher over ocean currents, although some points looks strange.

Conclusions

- Drifting buoys SST random uncertainty is at most 0.14 K using night collocations and tracking. → SST natural variability should be taken into account above scales of 5 km - 90 min (*currently*).
- Performance is variable with time, being of lower quality in early 80s and 1995 compared to 1988-1994 and 2002-2015.
- OSTIA tracking is doing a reasonable job, but there is still need/room for improvement.
    - *need for higher resolution? diurnal cycle?*

Thank you!

Questions?