# Toward analysis of trend sensitivity to RAP cadence

M. Hakuba & Libera team

Libera & RBSP Operations Meeting, Nov 9, 2023,

# Content

- Introduction
  - Libera goals & objectives
  - Specific EVC-1 Objectives
  - Recommendations of the  EVC RBSWG Report
  - Thoughts & questions
  - Trend sensitivity to RAP cadence (“every $X^{th}$ day”)

# *Libera*, NASA's first *Earth Venture* ***Continuity*** Mission

## Overarching Science Goals

**OG1:** Provide broadband radiances in support of seamless **continuity** of the CERES ERB Climate data record.

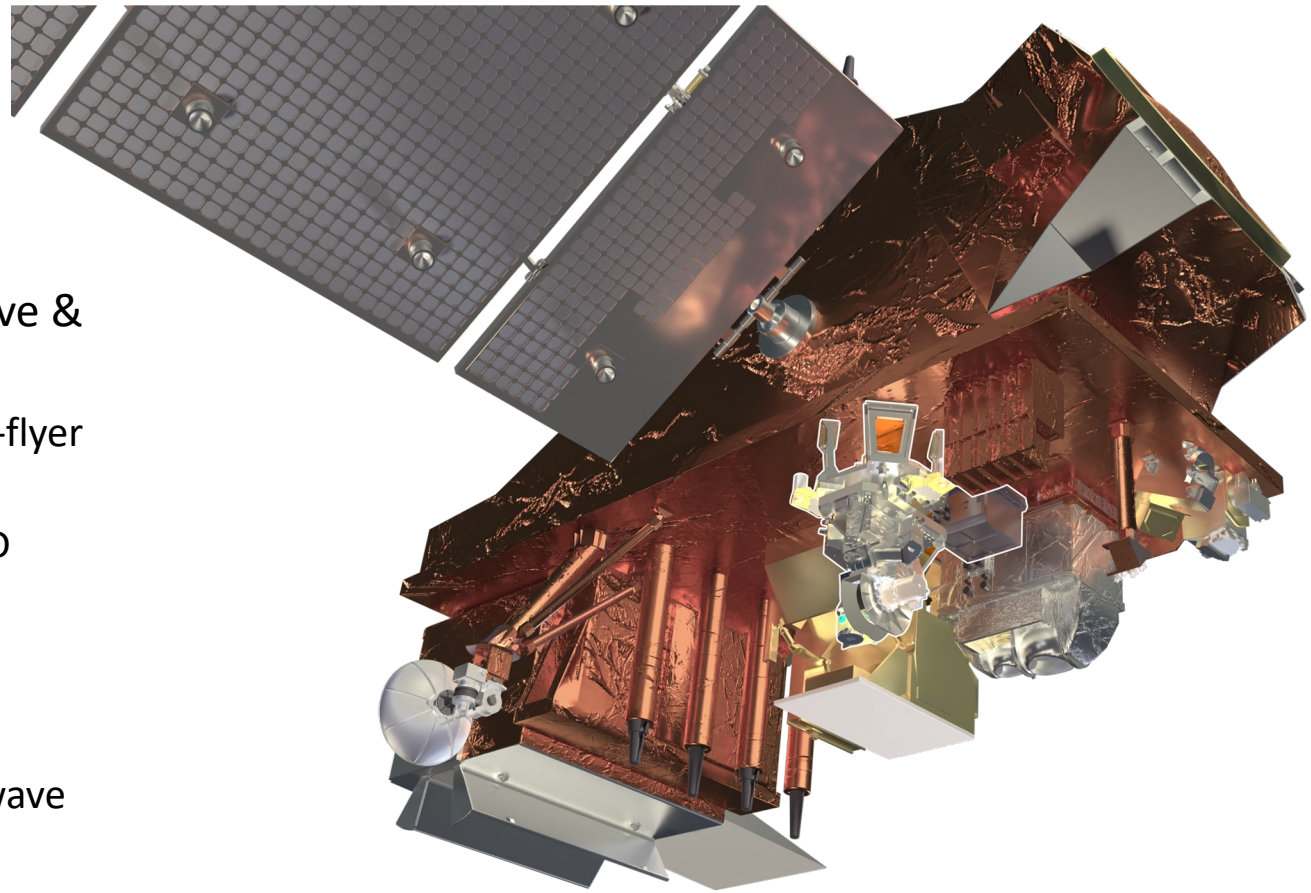
- TOTAL (0.3->100 $\mu$m), SW (0.3-5 $\mu$m) and LW (0.5-50 $\mu$m), 24km nadir footprint, **uncertainty ~ 0.2%**
- On JPSS-4 with VIIRS imager, launch 2027, 5-year mission
- **Electrical Substitution Radiometers using VACNT detectors**

**OG2:** Advance the development of a self-contained, innovative & affordable observing system – "TechDemo" experiment

- **WFOV monochromatic camera** to help pave way for **future** free-flyer ERB observing system (international small-sat constellation?)
  - Derive sub-footprint cloud properties in support of Scene ID
  - (Accelerated) ADM development for novel split-SW channel

**OG3:** Provide new and enhanced capabilities that support extending ERB science goals.

- Additional **split-SW channel** (near-IR: 0.7-5 $\mu$m) to derive shortwave visible and near-IR irradiances.
- Improved understanding of solar energy deposition in climate system.



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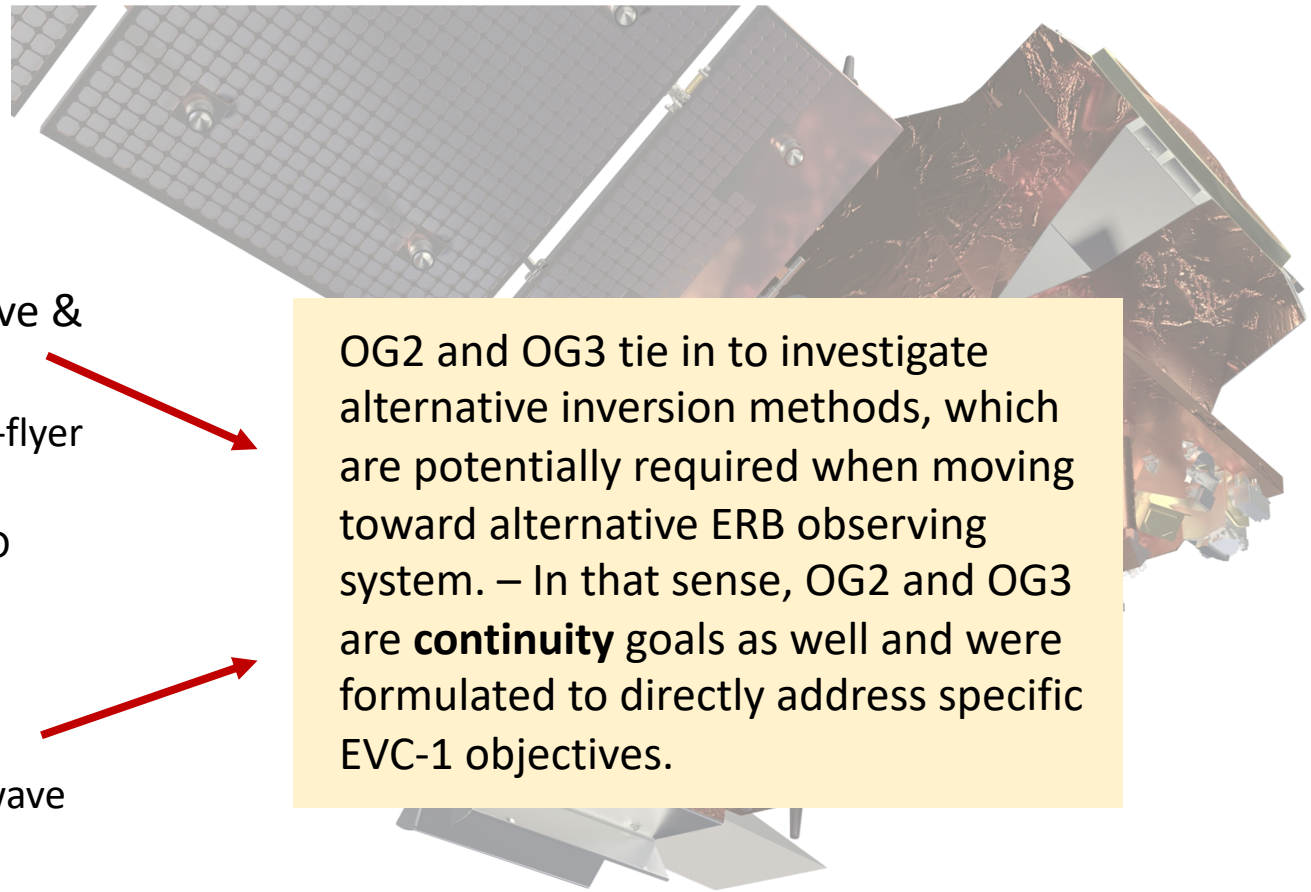

OG2 and OG3 tie in to investigate alternative inversion methods, which are potentially required when moving toward alternative ERB observing system. – In that sense, OG2 and OG3 are **continuity** goals as well and were formulated to directly address specific EVC-1 objectives.

## 2.2 Specific Earth Venture Continuity-1 Objectives

The objectives of the EVC-1 solicitation are to identify an approach to extend and continue the ERB CDR, and – using measurements from the proposed observing system – to conduct research and analyses that advance understanding of radiances, radiative fluxes, and the ERB.

**Specific objectives include**:

- **Develop and demonstrate an innovative, cost-effective, and capable spaceborne observing system that supports continuation of the NASA ERB CDR.**
- **Measure radiances** which allow the RBSP to **seamlessly extend** the ERB CDR, with appropriate **wavelength ranges, accuracy, precision, stability, geographic and temporal sampling to** advance the science goals and objectives listed in Section 2.1
- Demonstrate pre-flight and in-flight **calibration** procedures appropriate for the maintenance of long-term, multi-instrument continuity data products.
- Produce a full set of global **Level 1 radiances at TOA** using the proposed observing system.
- Provide to the RBSP **unique algorithms and documentation**, as needed, to accurately calculate radiative fluxes.
- Deliver the observing system by a date that allows overlap with currently operational instruments sufficient to conduct the inter-calibration necessary to preserve continuity.
- **Demonstrate a sustainable, innovative, and low-cost approach to acquiring the needed observations that could be used for future ERB continuity measurements.**
- **Enable the cost of future copies to remain low** (i.e., producibility).
- **Enable future technology infusion**, allowing for upgrades in subsequent versions of the instrument/observing system to take advantage of advanced component designs that could improve performance or reduce costs.
- Conduct research and analysis activities, using the measurements from the proposed observing system, to advance the science goals listed above in Section 2.1.

# Recommended Measurement and Instrument Characteristics for an Earth Venture Continuity Earth Radiation Budget Instrument

Report of the Earth Venture Continuity
Radiation Budget Science Working Group

Libera team took recommendations very seriously; the mission meets and exceeds (almost) all of the baseline characteristics.

Table 5-1 EVC ERB instrument and mission characteristics. Threshold characteristics are consistent with CERES. Objective characteristics are consistent with Bates and Zhao (2011).

| Category | Threshold | Objective | Note |
|---|---|---|---|
| Spectral Range | 0.3 to 5 μm (SW) | 0.3 to 5 μm (SW) | Three channels to buy down risk for redundancy and validation. |
| | 5 to >35 μm (LW) | 5 to >50 μm (LW) | |
| | 0.3 to >100 μm (TOT) | 0.2 to >100 μm (TOT) | |
| Field-of-View (IFOV) | ~25km equivalent diameter @ nadir | ~25km equivalent diameter @ nadir | FOVs for different channels must be co-registered. |
| Geographic Coverage | Near-Global | Near-Global | |
| Angular Sampling | Fixed Azimuth* | Rotating Azimuth; Programmable | *Requires reuse of existing CERES ADMs |
| Radiometric Accuracy | 1.0% (SW), k=1 | 1.0% (SW), k=2 | 5-year requirement |
| | 0.5% (LW), k=1 | 0.5% (LW), k=2 | |
| | 0.5% (TOT), k=1 | 0.5% (TOT), k=2 | |
| Radiometric Stability | 0.3%/decade, k=1 | 0.3%/decade, k=2 | Allocated from accuracy requirement; All wavelength ranges |
| Radiometric Precision | <0.2 $Wm^{-2}$ $sr^{-1}$ + 0.1% of measured (SW) | <0.2 $Wm^{-2}$ $sr^{-1}$ + 0.1% of measured (SW) | |
| | <0.45 $Wm^{-2}$ $sr^{-1}$ + 0.1% of measured (LW) | <0.45 $Wm^{-2}$ $sr^{-1}$ + 0.1% of measured (LW) | |
| | <0.3 $Wm^{-2}$ $sr^{-1}$ + 0.1% of measured (TOT) | <0.3 $Wm^{-2}$ $sr^{-1}$ + 0.1% of measured (TOT) | |
| Linearity | 0.3% from linear over dynamic range, k=2 | 0.3% from linear over dynamic range, k=2 | |
| Onboard Calibration | SW Internal Cal Source LW Blackbody Source | SW Internal Cal Source LW Blackbody Source | Across all wavelength ranges |
| Vicarious Calibration | Enable periodic solar & lunar calibration | Enable periodic solar & lunar calibration | |
| Mission Class | C | C | |
| Lifetime | 5 yrs | 5 yrs | |
| Orbit | Sunsync. 1:30 pm ascending orbit | Sunsync. 1:30 pm ascending orbit | Consistent with CERES FM3-FM6 |
| Overlap | 6 months | 1 yr | |
| Scene Identification | VIIRS-Class Imager | VIIRS-Class Imager | On same platform or within 3 min of and in the same viewing geometry |

# Recommended Measurement and Instrument Characteristics for an Earth Venture Continuity Earth Radiation Budget Instrument

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- RAP capability and angular sampling appear to be a baseline characteristic for the continuity instrument and mission.
- Implies the potential need for RAP throughout mission to build EVC-specific ADMs or at least enhance/validate?

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# Thoughts on collecting angular radiances throughout Libera mission lifetime.

**Thought 1:** RAP in some capacity throughout the Libera mission is desired to ensure **ALL** ADMs and inverted fluxes are of top-quality throughout the record.

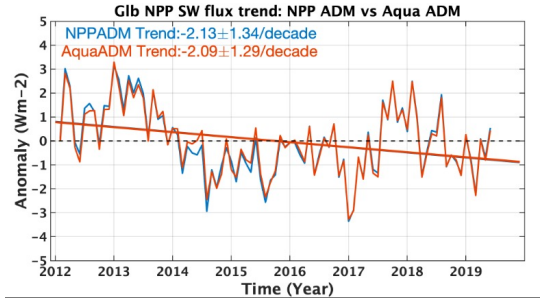
- Flux inversion plays important role for the quality of CERES data products including EBAF.
- EBAF is extremely important for science based on which top-level communication (e.g., IPCC reports) and decisions are made.
- EBAF is widely used by the modeling community, who seem generally unaware of how the data are produced and what the quality caveats are. **We have the responsibility to maintain** (or even enhance) **current level of quality.**

Question:

Even if use of RAP data is limited due to sparsity – how can RAP data be utilized for ADM validation/enhancement to maintain CDR quality? (for well-sampled scene types)

**Thoughts 2:** NPP fluxes and trends differ depending on whether Aqua or NPP ADMs & Scene ID are used (Wenying, CERES STM 2023, NASA GISS).

- Do we have to expect the same for Libera? – probably not since Libera/VIIRS and FM6/VIIRS characteristics are closer?
- How significant is the impact really?
  - Trend impact is of similar magnitude (trend bias: 1.4%, trend uncertainty difference: 4%) to the impact of missing days due to RAP.
  - *"Global monthly mean instantaneous NPP SW fluxes inverted from NPP ADMs can differ from those inverted from Aqua ADMs by more than 1.5 $Wm^{-2}$, with the regional fluxes differing by up to 10 $Wm^{-2}$ ."*




- Could this imply Libera needs its own ADM generation? Or at least validation/enhancement (over time)? How?

**Thoughts on collecting angular radiances throughout Libera mission lifetime.**

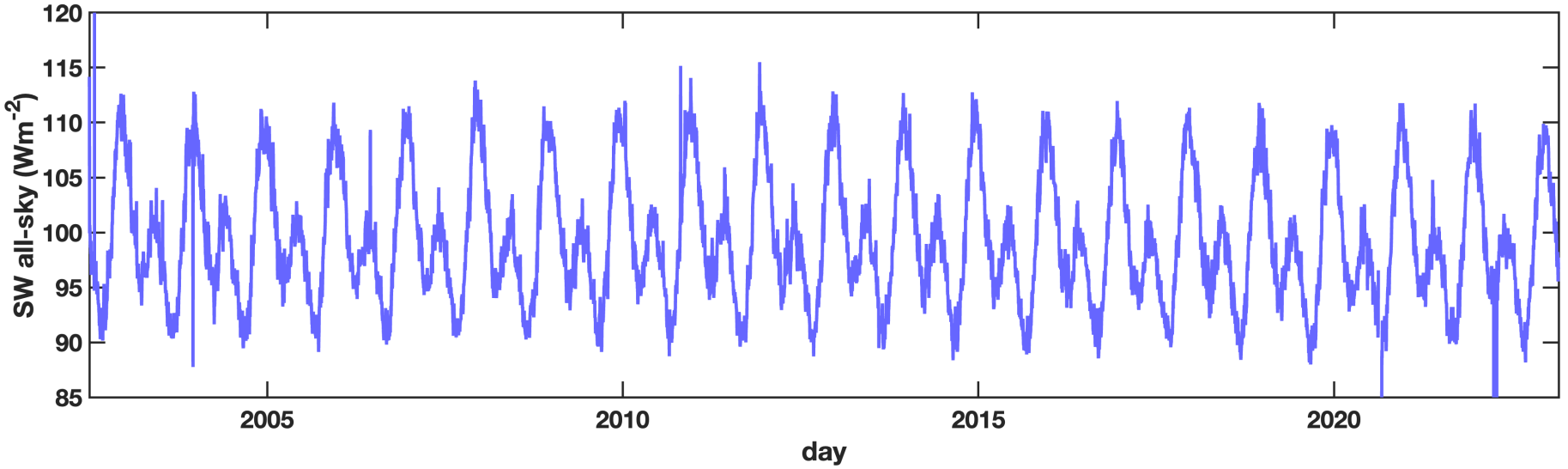
Are we really sure we only want the minimum amount of non-cross-track operations in years beyond year 1 ?

Intention is to do the best we can for the heritage ERB record and to address Libera novelties.

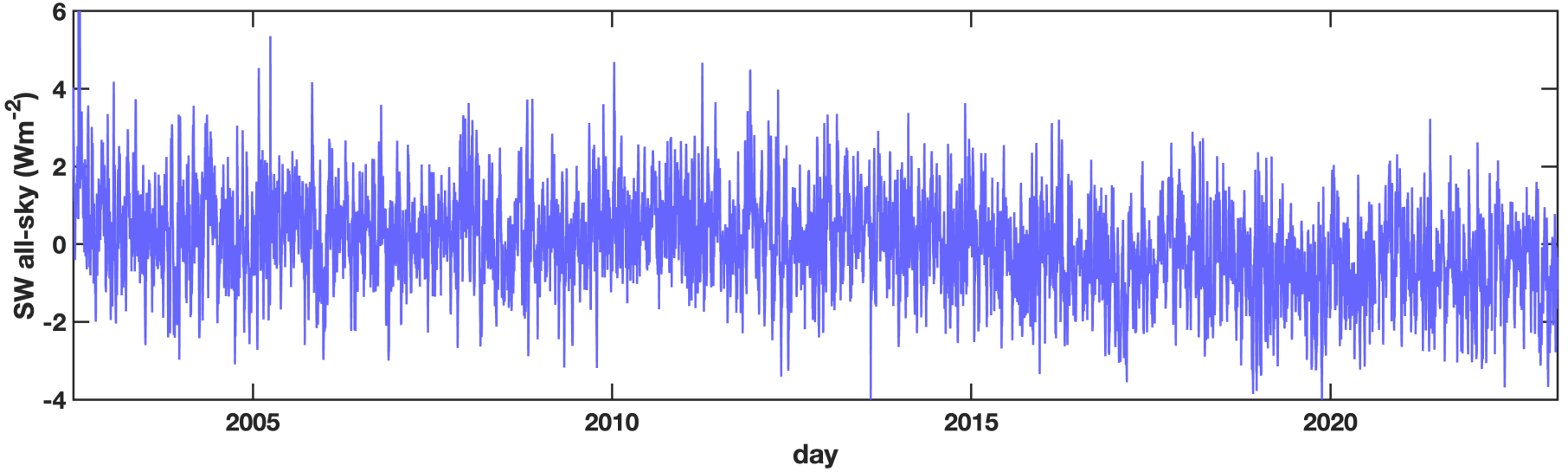
# Toward analysis of trend sensitivity to RAP cadence

# Methods and data

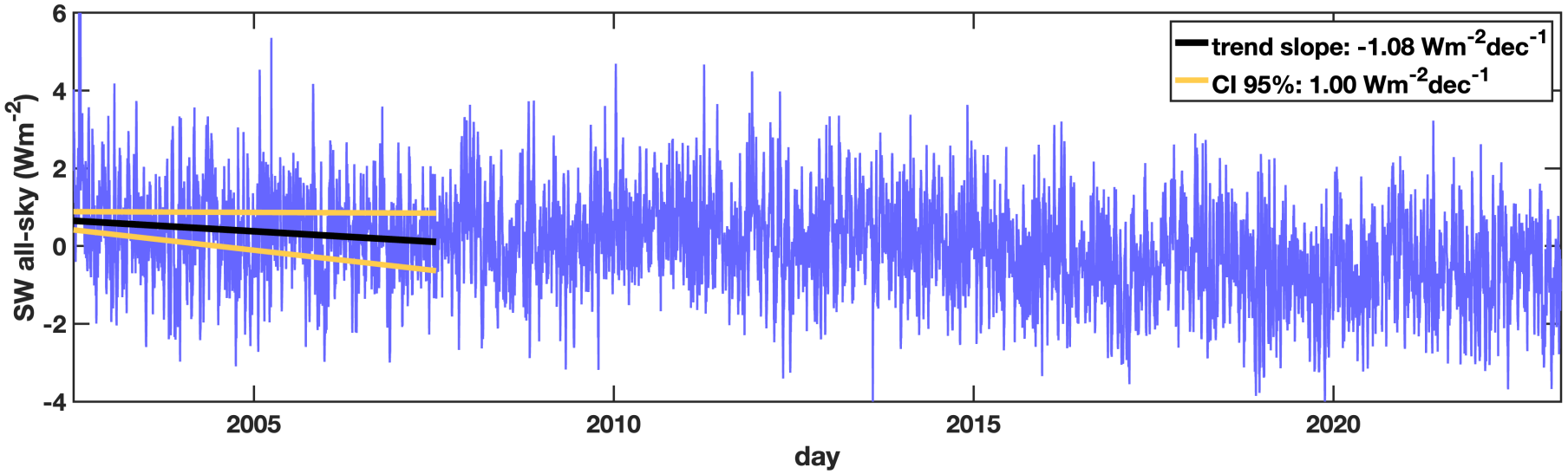
**SSF1deg-Aqua** (afternoon orbit like Libera), **daily mean SW all-sky** irradiances at TOA:




**SSF1deg-Aqua** (afternoon orbit like Libera), **daily deseasonalized SW all-sky** irradiances at TOA:

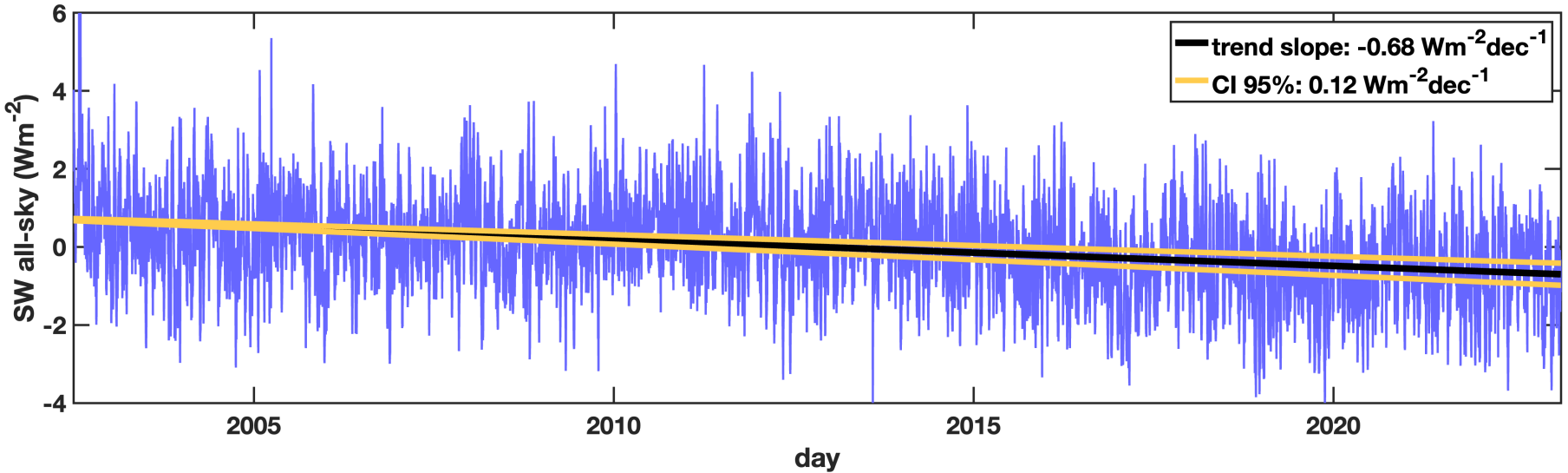


**SSF1deg-Aqua + 5-year trend line.** Different 5-year periods have different trends and uncertainties




**Note:** outliers have impact on result: slope according to robust regression is -0.58 $Wm^{-2}$ $dec^{-1}$

**SSF1deg-Aqua + full-record trend line**; significant ERB change over full record is **"climate signal"?**




**Note:** outliers still have impact on result: slope according to robust regression = -0.62

**Metrics** for comparing trends in original timeseries with timeseries where RAP days are set to NaN:

- Trend slopes from ordinary least square regression
- Trend bias in %: (Trend2-Trend1)/Trend1

- 95% confidence interval (trend uncertainty due to “natural variability”):
  - Standard error of residuals accounting for lag-1 autocorrelation
  - Multiply with 1.96
- CI95 bias in %: (CI95_2-CI95_1)/CI95_1

- Trend error 1: sqrt((Trend2-Trend1)^2+ (CI95_2-CI95_1)^2) / CI95_1
- Trend error 2: sqrt(TB%^2 + CI95B%^2)

# Impact of 10-day RAP

**5-year record**

| | SSF Aqua Jul 2002-Jul 2007 | | SSF Aqua 10-day RAP – orig. | | | |
|---|---|---|---|---|---|---|
| | Trend ($Wm^{-2}$ $dec^{-1}$) | 95% CI ($Wm^{-2}$ $dec^{-1}$) | Trend bias (%) | 95% CI bias (%) | TE2 Error combi. (%) | TE1/CI (%) |
| **SW** | -1.08 | 1.00 | -1.06 | -5.75 | 5.85 | 5.87 |

| | XTK | | RAPFILL–XTK | | | |
|---|---|---|---|---|---|---|
| | Trend ($Wm^{-2}$ $dec^{-1}$) | 95% CI ($Wm^{-2}$ $dec^{-1}$) | Trend ($Wm^{-2}$ $dec^{-1}$) | 95% CI ($Wm^{-2}$ $dec^{-1}$) | Error ($Wm^{-2}$ $dec^{-1}$) | Error/CI (%) |
| **SW** | -1.4 | 1.0 | 0.032 (2.2%) | 0.024 (2.4%) | 0.040 | 3.9 |

Trend error 1

$$E(\hat{\omega}) = \sqrt{(\hat{\omega} - \omega)^2 + (\delta\hat{\omega} - \delta\omega)^2},$$

Indicates if impact on trend is significant: if error is >=100% then trend is significantly different from original?

Norman's analysis

**Full record with last 5 years in RAP** – more realistic scenario for assessing impact on climate signal?

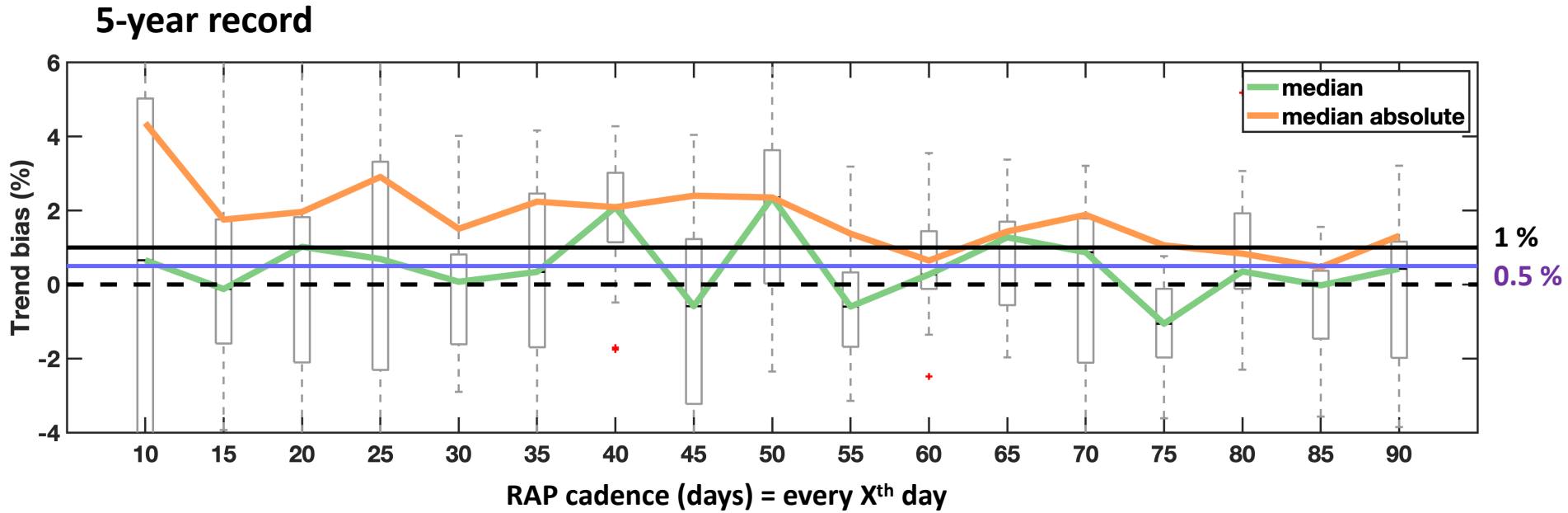
| | SSF Aqua Jul 2002-Feb 2023 | | SSF Aqua 10-day RAP – orig. | | | |
|---|---|---|---|---|---|---|
| | Trend ($Wm^{-2}$ $dec^{-1}$) | 95% CI ($Wm^{-2}$ $dec^{-1}$) | Trend bias (%) | 95% CI bias (%) | Error combi. (%) | Error/CI (%) |
| **SW** | -0.68 | 0.12 | 1.20 | -0.21 | 1.21 | 6.58 |

Trend error 1 can be much larger than individual % biases in trend magnitude and trend uncertainty.

Perturbation analyses to systematically study

1. Impact of different RAP cadences
2. Role of non-random natural variability in data record (RAP day placement)

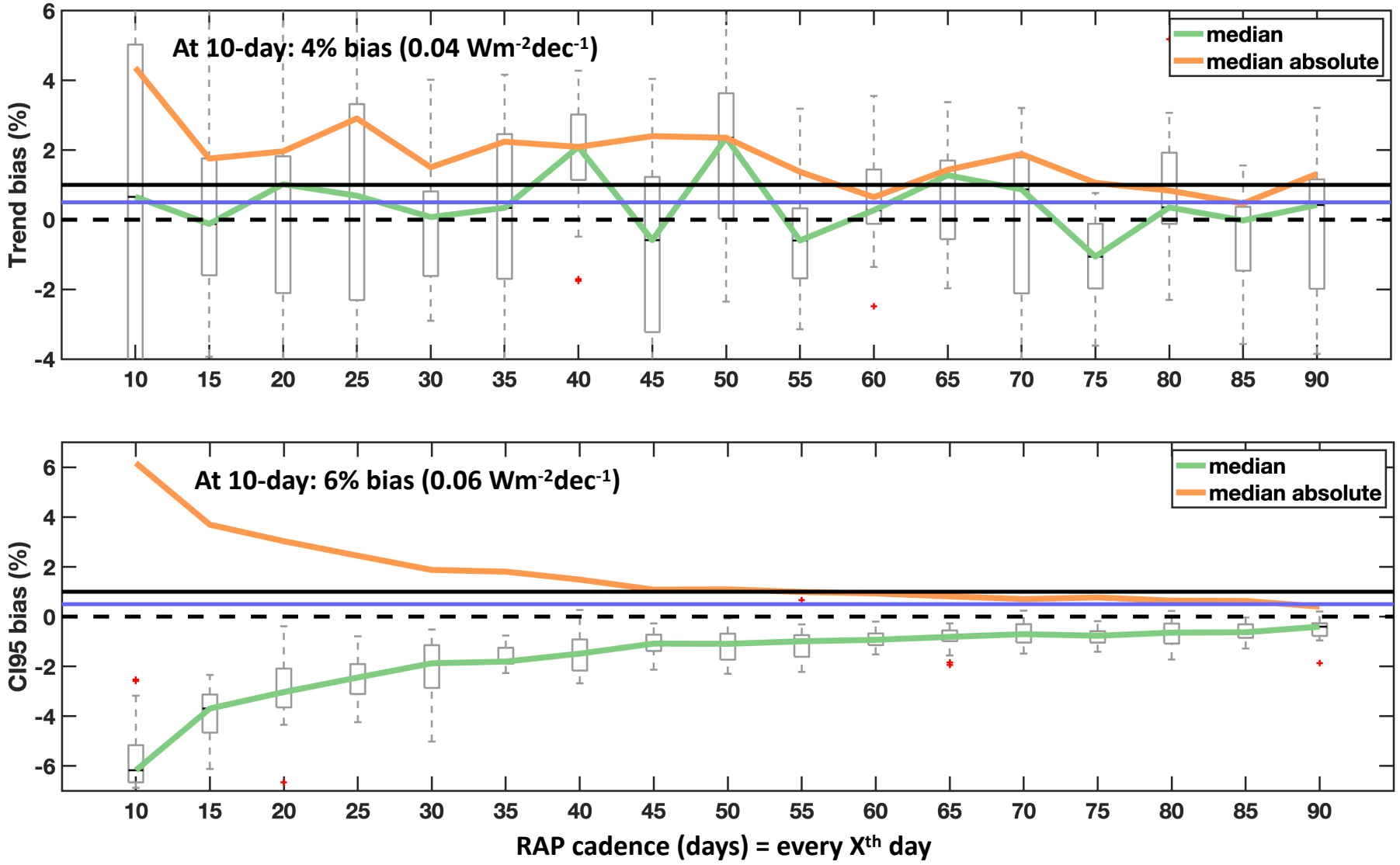
# RAP cadence and placement – perturbation analysis




- Cadence = **RAP every X$^{th}$ day** – replace RAP days with NaN
- 20-member **ensemble** (box-plot): vary RAP starting date by up to ±10 days – **considers impact of natural variability**
- Ensemble (absolute) median is estimate of average trend bias per RAP cadence
- For 5-year trends, there is large variability (box plot) in trend bias depending on RAP start date.
- Median bias fluctuates around zero, median absolute bias indicates 4% (0.04 $Wm^{-2}dec^{-1}$) average bias at 10-day RAP cadence. This is 4 times larger than result on previous slide.

# RAP cadence and placement – perturbation analysis

**5-year record**

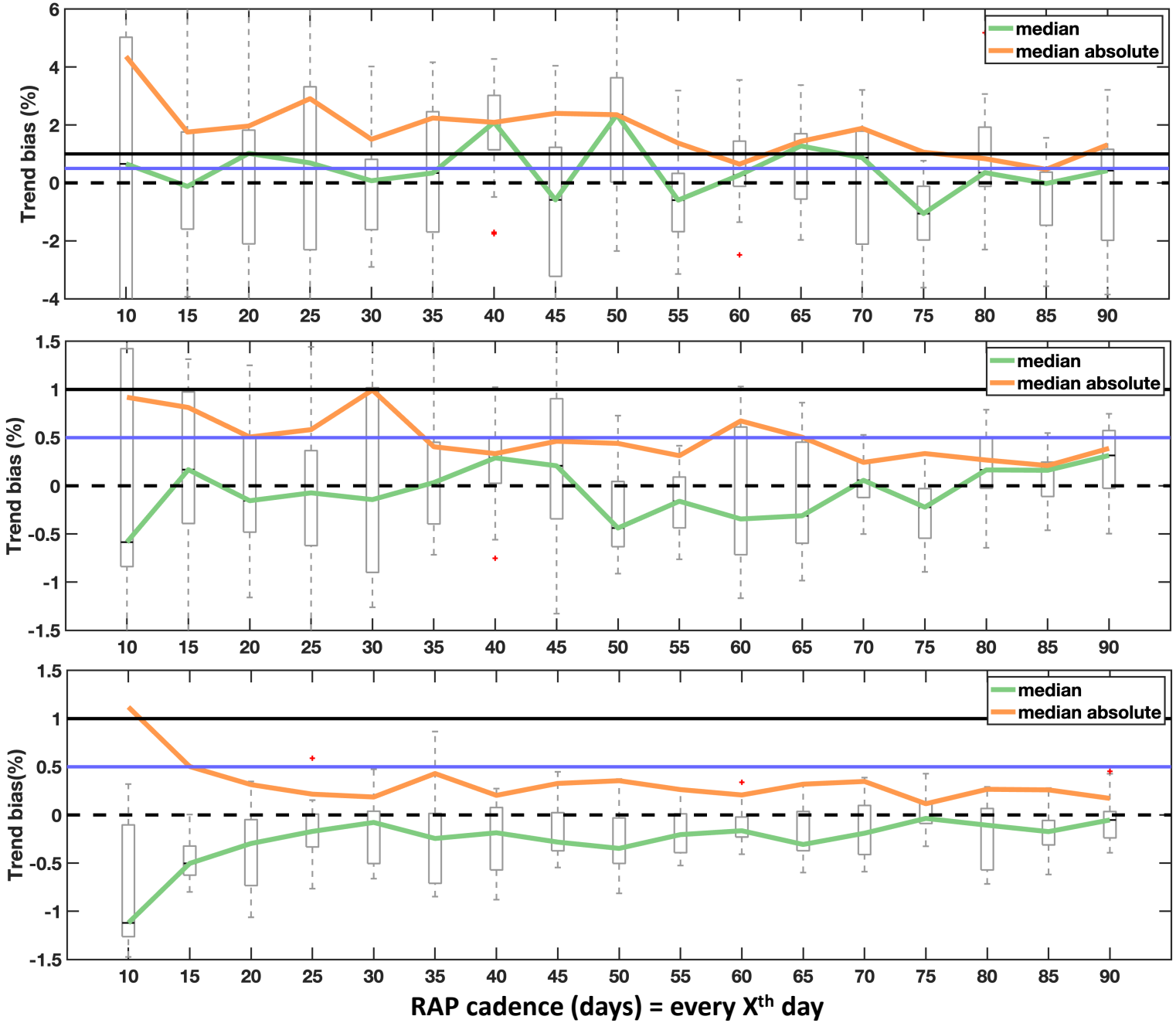



No-RAP time series:

| Trend: -1.08 | CI95: 1.00 |
|---|---|

- Steady decline of absolute CI95 bias.
- Below 1% at 45-day RAP and higher cadences.
- Note: CI95 bias is negative throughout – odd?

# RAP cadence impact on trend bias




**5-year record**

No-RAP time series:

| Trend: -1.08 | CI95: 1.00 |
|---|---|

**Full record in RAP**

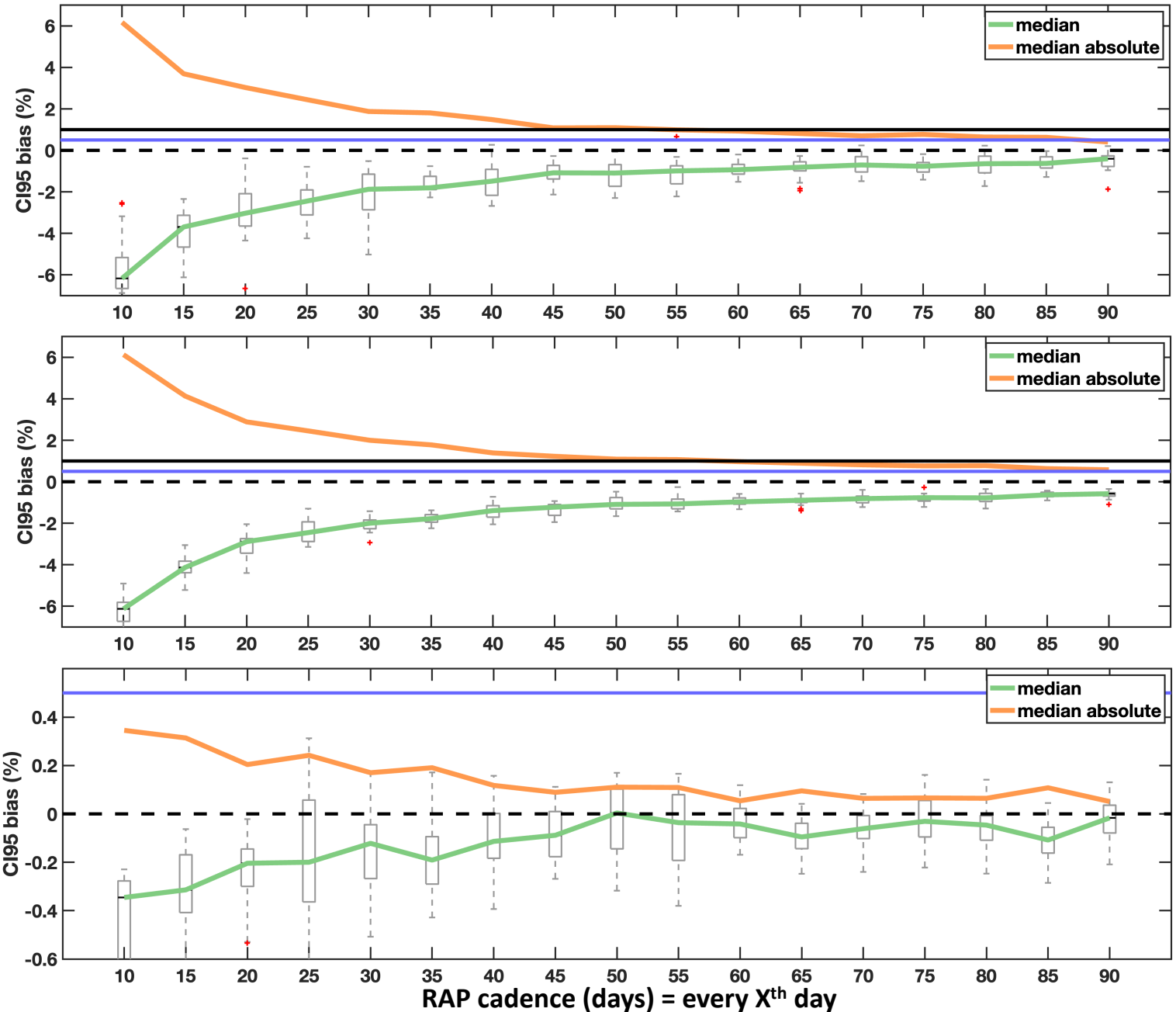
No-RAP time series:

| Trend: -0.68 | CI95: 0.12 |
|---|---|

**Full record last 5 years in RAP**

- Over the full record, RAP impact on trend is 4X smaller and near or below 1% for all RAP cadences.
- Full record only last 5 years in RAP:
  - Below 0.5 % for all cadences > 15.

# RAP cadence impact on CI95% bias




**5-year record**

No-RAP time series:

| Trend: -1.08 | CI95: 1.00 |
|---|---|

- Very similar CI95% biases in 5-year and full record due to RAP.
- 5-year: 6% is 0.06 $Wm^{-2}dec^{-1}$
- Full record: 6% is 0.007 $Wm^{-2}dec^{-1}$

**Full record**

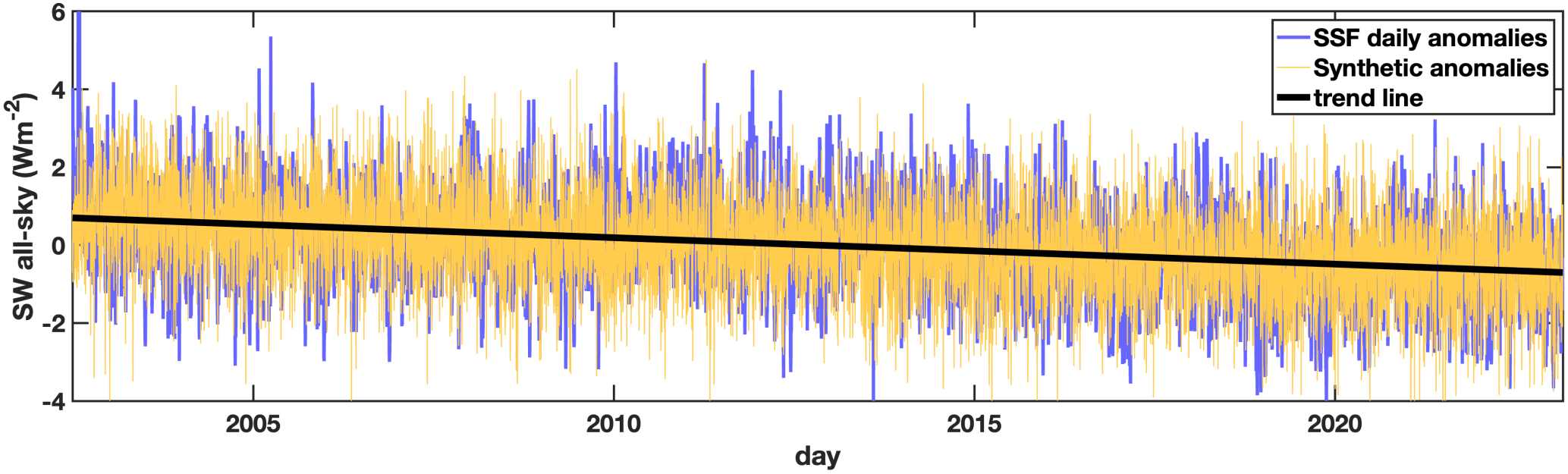
No-RAP time series:

| Trend: -0.68 | CI95: 0.12 |
|---|---|

**Full record last 5 years in RAP**

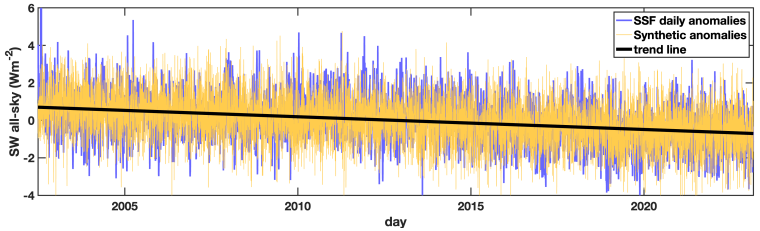
- Over the full record with last 5 years in RAP, CI95 bias much smaller and below <0.5% for all frequencies

# Role of natural variability – vs. synthetic

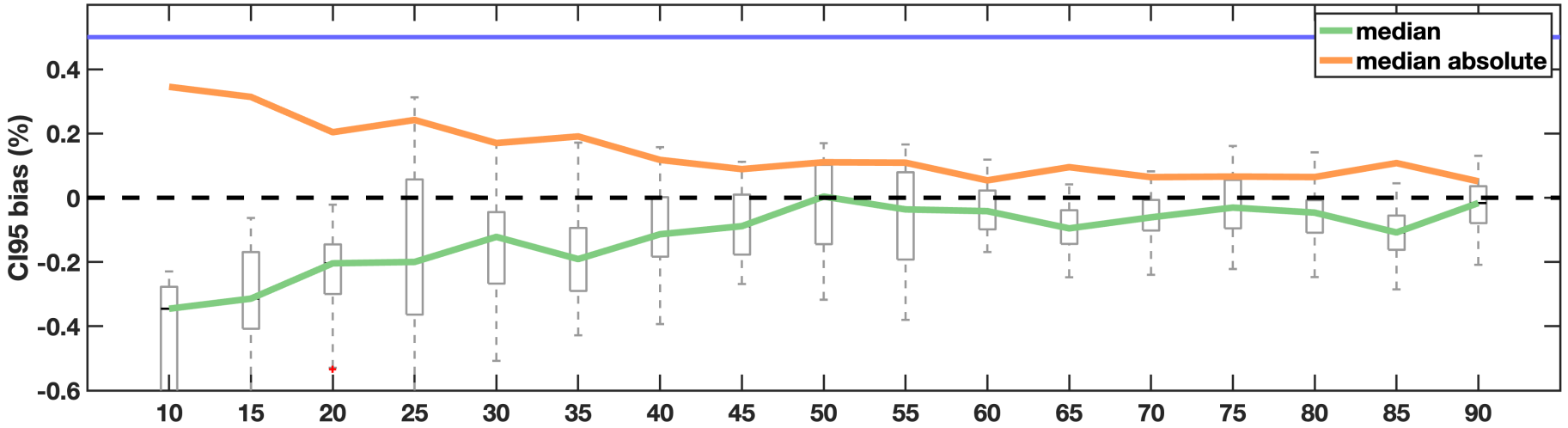



Synthetic time series has same trend, but variability is random noise (Gaussian) with same mean and standard deviation as original time series.

# Role of natural variability – vs. synthetic



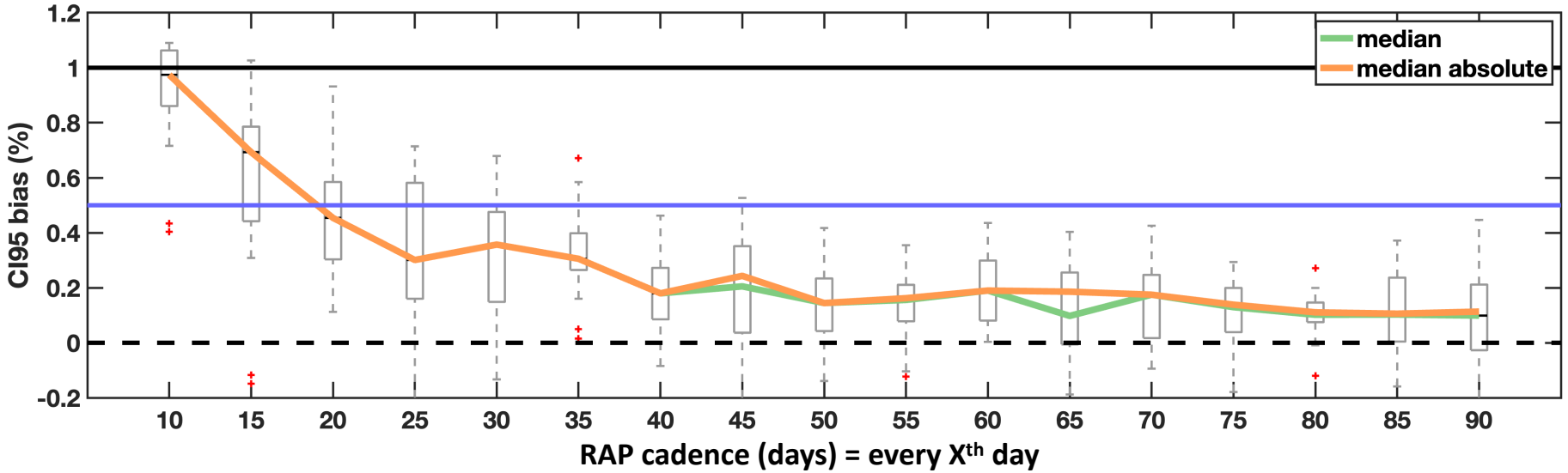

## Full record last 5 years in RAP




No-RAP time series:

| Trend: -0.68 | CI95: 0.12 |
|---|---|

## Full record synth. last 5 years in RAP

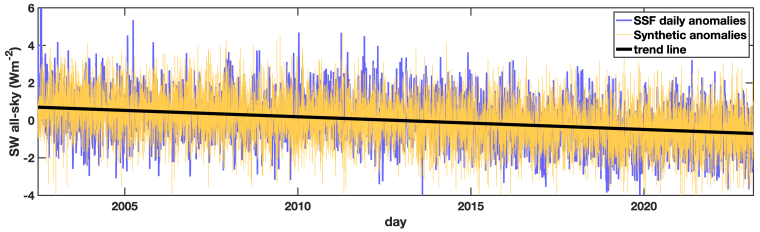



No-RAP time series:

| Trend: -0.68 | CI95: 0.05 |
|---|---|

- CI95 is half of original CI95.
- CI95 bias is positive (as expected?) and larger, but always below 1%.

# Role of natural variability – vs. synthetic

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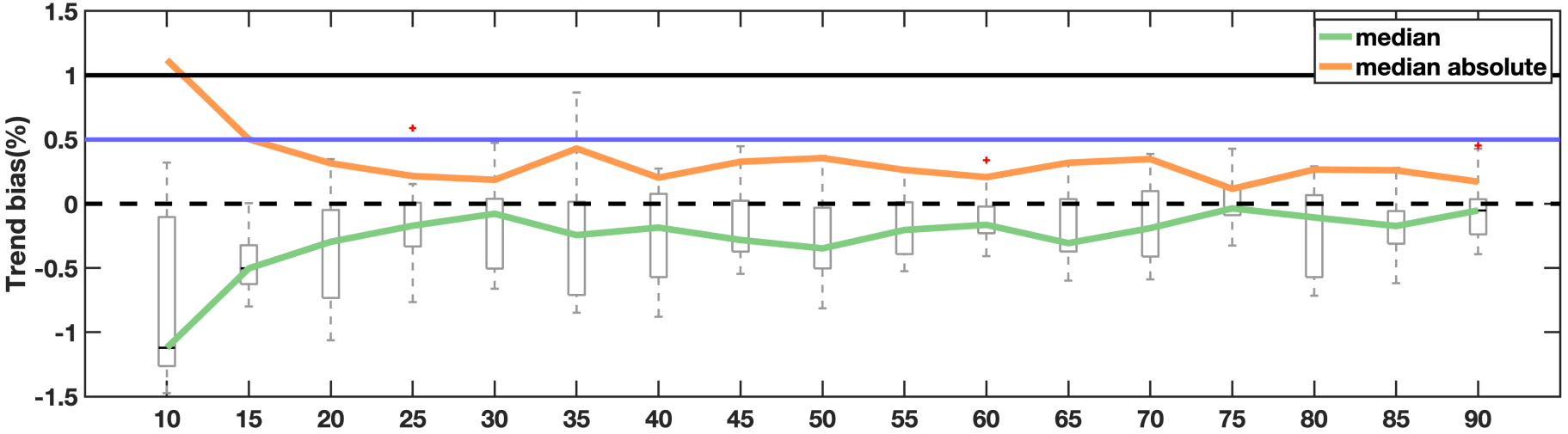


| Trend: -0.68 | CI95: 0.12 |
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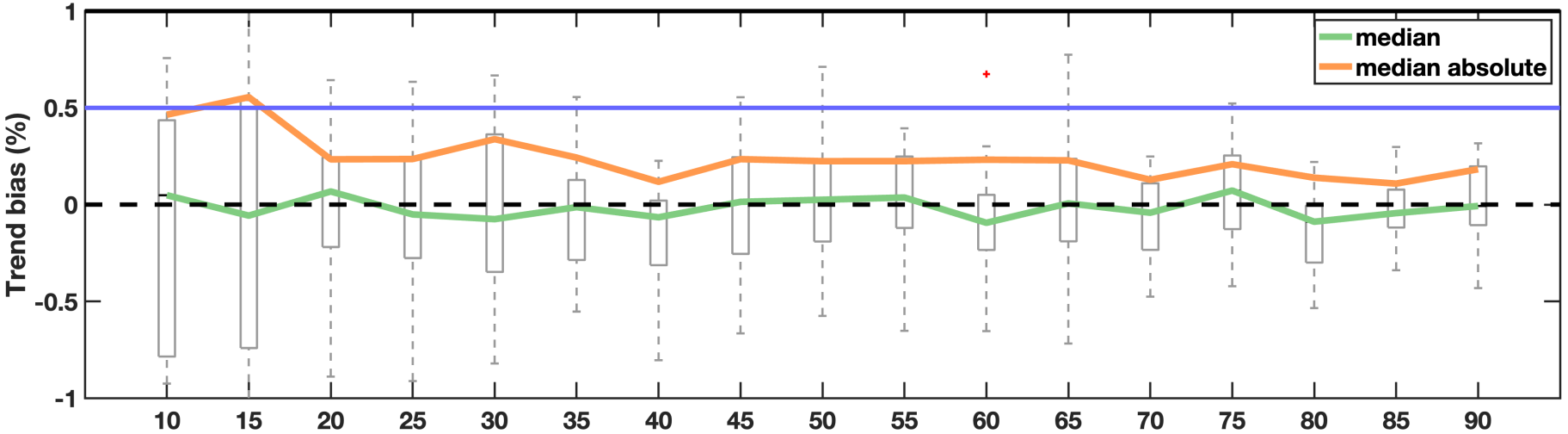
## Full record synth. last 5 years in RAP



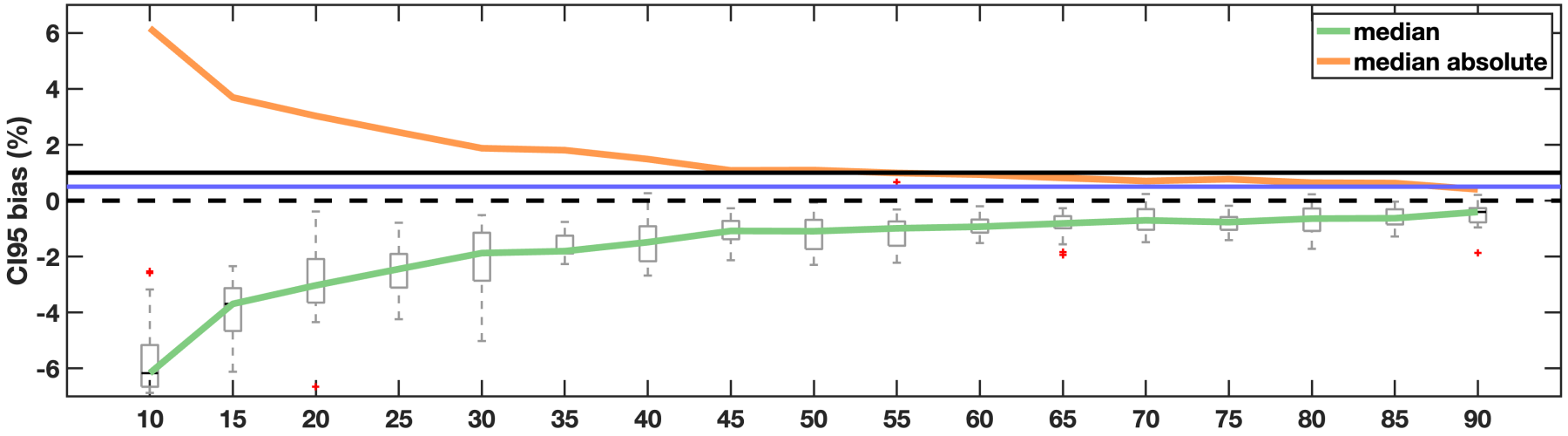

No RAP time series:

| Trend: -0.68 | CI95: 0.05 |
|---|---|

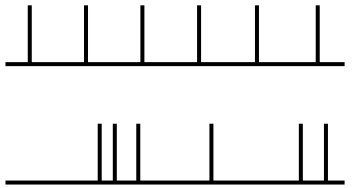
- Trend bias reduced
- A series with random variability reflects barley any impact of RAP.

# Role of fixed cadence – CI95% bias

## 5-year record

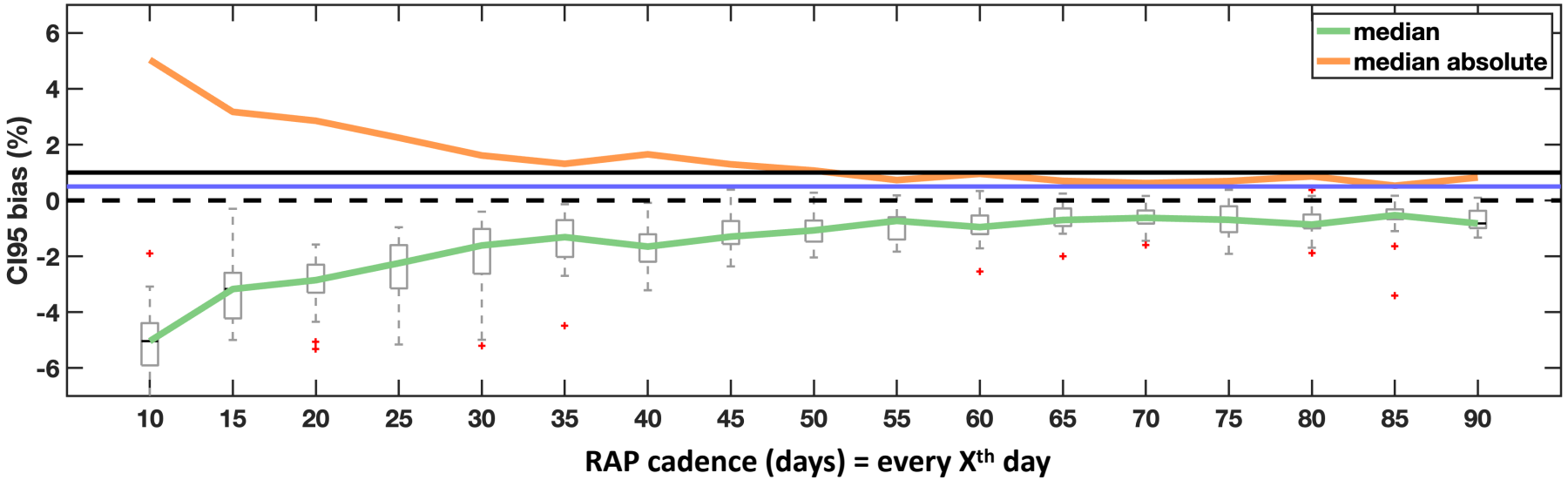



Fixed cadence, e.g., every 10 days



Random cadence, e.g., every 10 days plus/minus X days

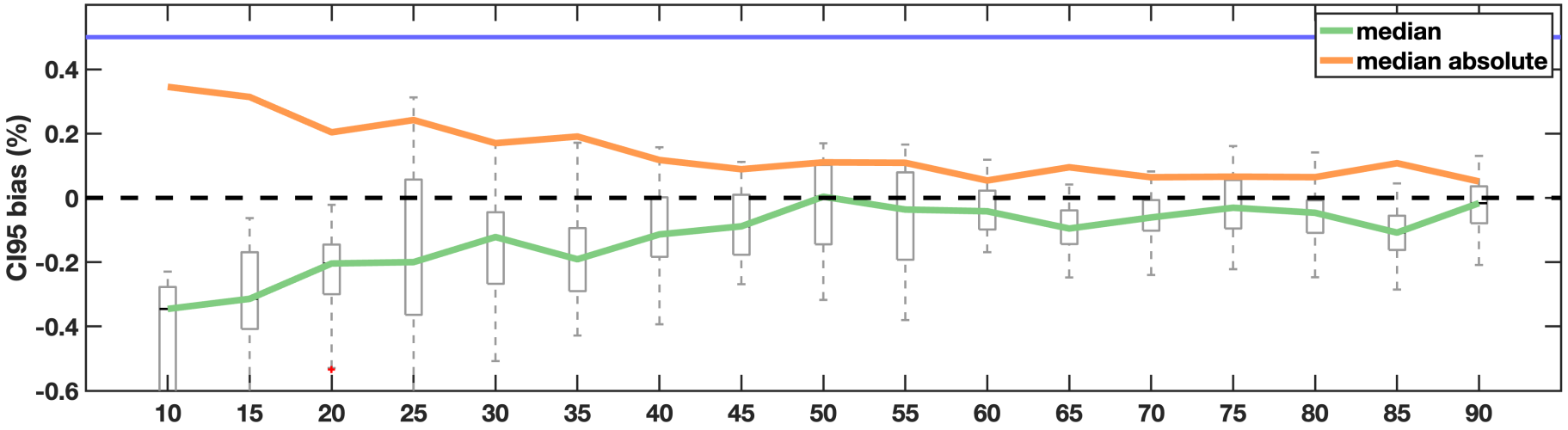
## 5-year record with random RAP day placement



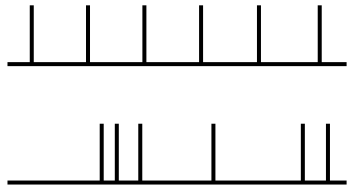

- Slight reduction in CI95 bias (by ~1%)
- Aliasing of cadence and potentially cyclic behavior is small.

# Role of fixed cadence – CI95% bias

## Full record - last 5 years in RAP

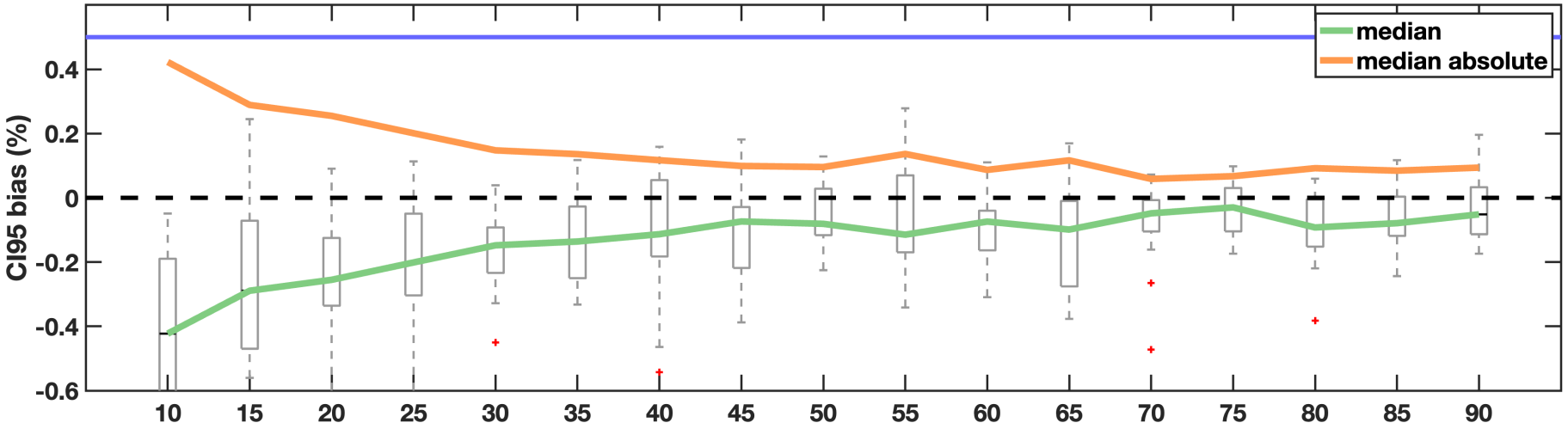



Fixed cadence, e.g., every 10 days



Random cadence, e.g., every 10 days plus/minus X days

## Full record with random placement




- Biases in CI95 remain similar.
- No aliasing of cadence and potentially cyclic behavior.

# Conclusions and next steps

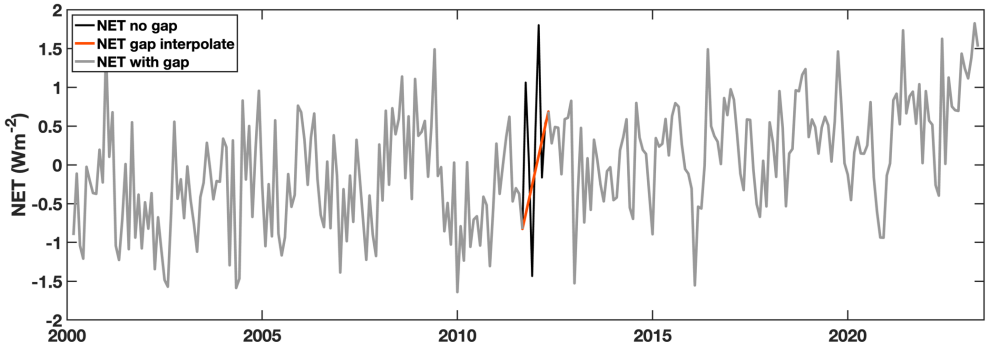
RAP impact on trend …

- Is sensitive to cadence and RAP day placement.
- Is potentially negligible (≤1%), assuming the full record with only last 5 years in RAP (realistic scenario for assessing impact on climate signal) – even for 10-day RAP
- Biases are a function of natural variability (placement); synthetic record illustrates idealized RAP impact on trend magnitude is even smaller.
- Fixed RAP cadence appears not to alias cyclic variability in record (if there is any).
- Are RAP impacts > or < than other sources of uncertainty? E.g., due to ADM/Scene ID or radiometric characteristics (CERES vs. Libera)?
- What is the impact on regional long-term trends?

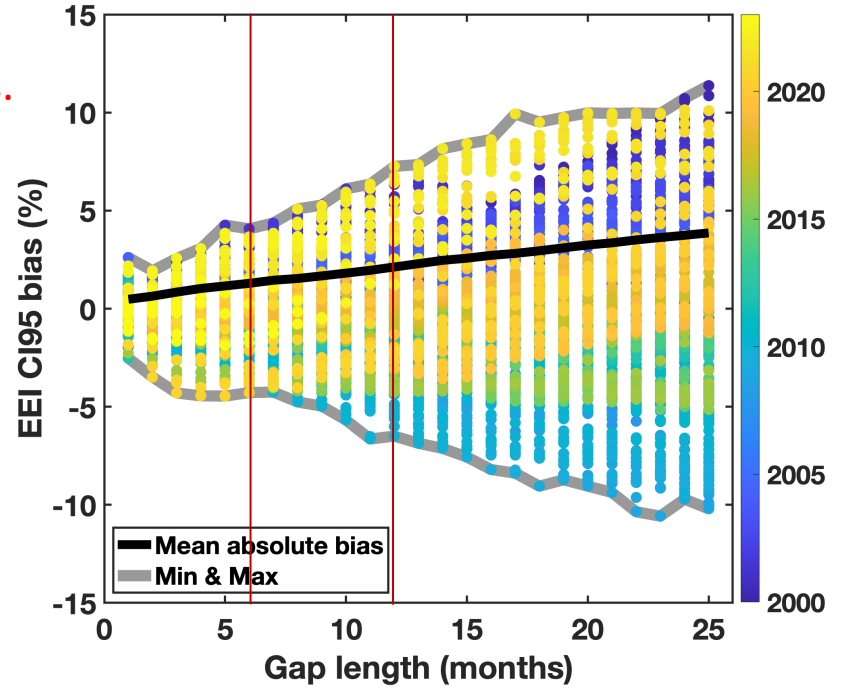
# Extras

# Impact of 1-to-24-month gaps on trend

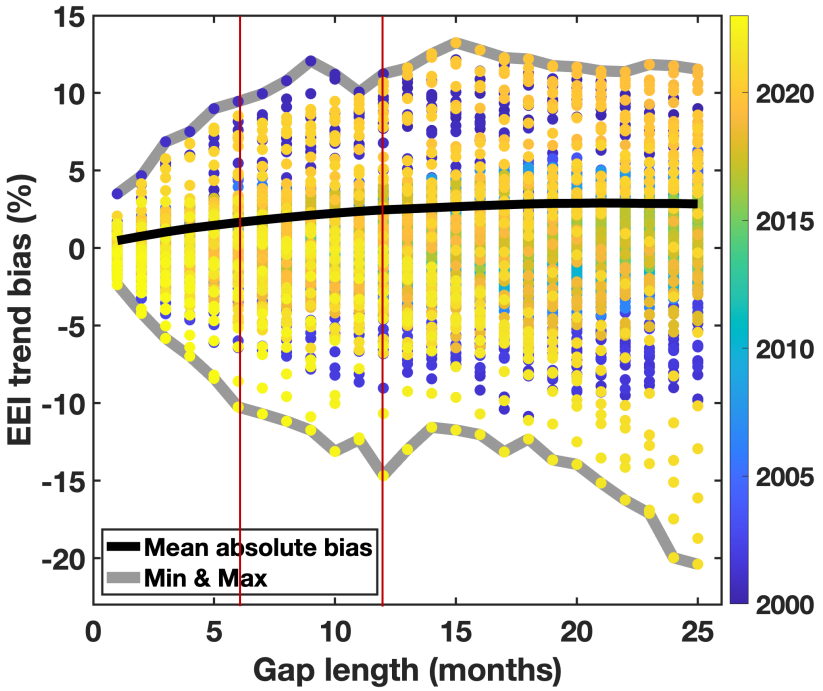
Does not consider measurement accuracy nor shifts in timeseries.



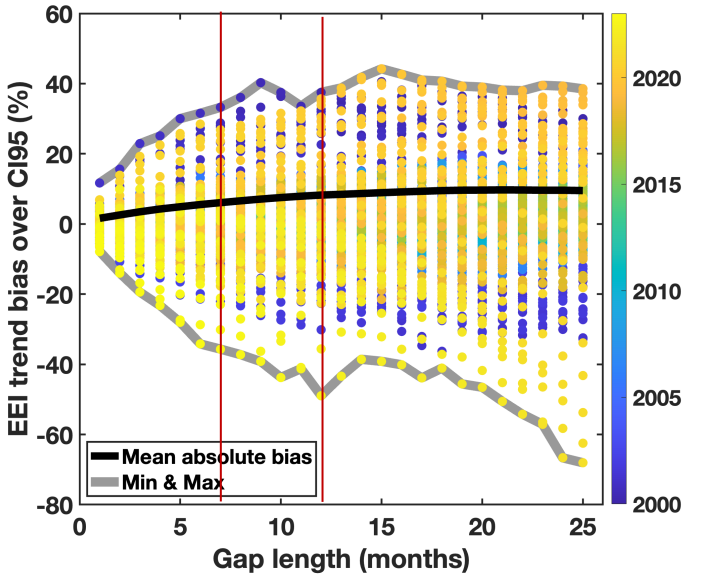

**Net radiative flux using monthly anomalies (EBAF): 0.50 +- 0.15 $Wm^{-2}dec^{-1}$**




**Depending on where gap is, CI95 bias is ± 5% for a 6-month gap and ± 7% for a 12-month gap.**



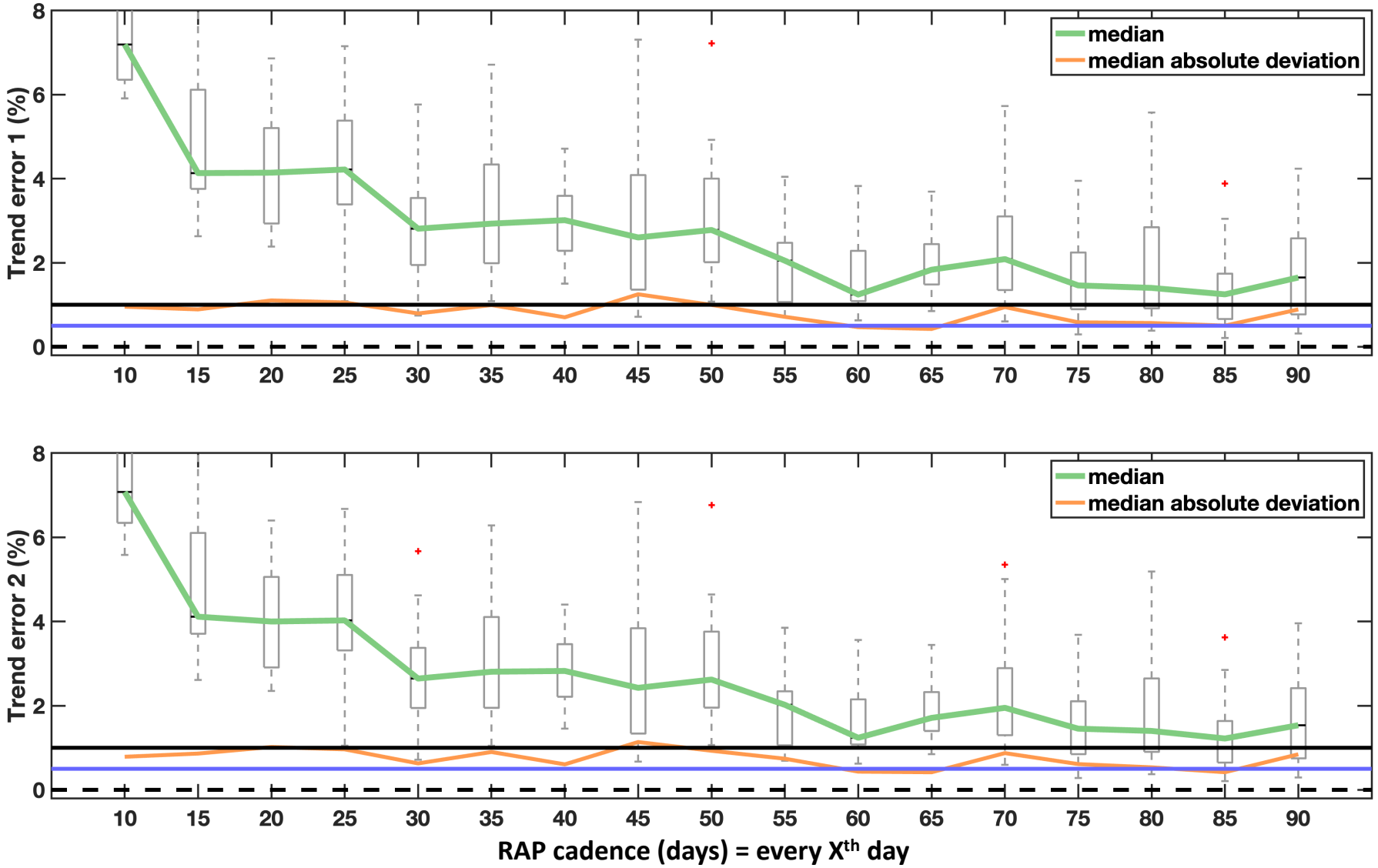

**Depending on where gap is, trend bias is ± 10% for a 6-month gap and ± 15% for a 12-month gap.**




**Depending on where gap is, trend bias with respect to CI95 is ± 35% for a 6-month gap and ± 45% for a 12-month gap.**

# RAP cadence and placement – perturbation analysis

**5-year record**

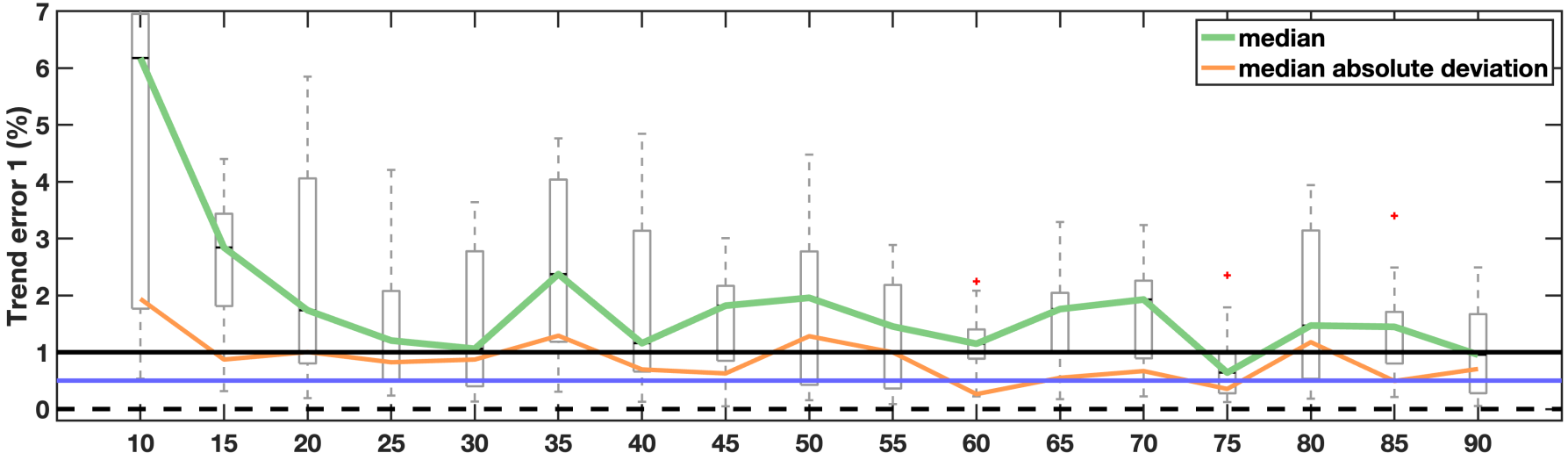



| TE2 Error combi. (%) | TE1/CI (%) |
|---|---|
| 5.85 | 5.87 |

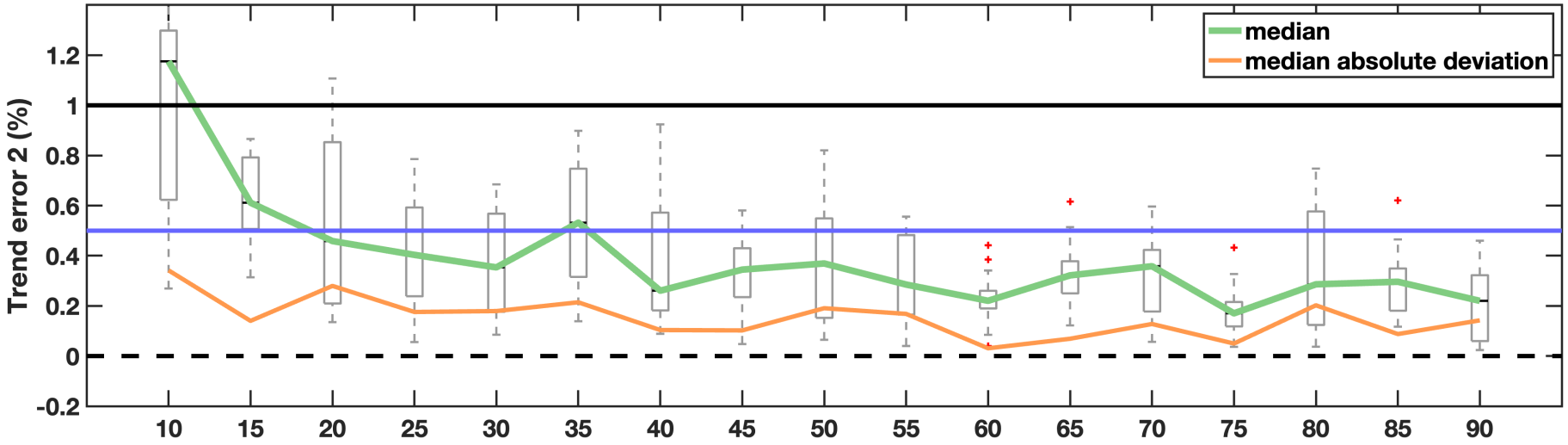
- For the 5-year period both trend errors are ~7% for 10-day RAP.
- 3% at 30-day
- 1% at 60-day

# RAP frequency – Trend error

**Full record with last 5-year in RAP**




$$E(\hat{\omega}) = \sqrt{(\hat{\omega} - \omega)^2 + (\delta\hat{\omega} - \delta\omega)^2},$$




- % trend error retains trend and CI95 bias magnitudes.
- Below 1% for 15-day RAP and larger.