The Treatment of Biases in ERA5

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Overview

- Background: **pragmatists** and **idealists**

  (**VarBC, B,** WC 4D-Var, ML, …) (root cause analyses & traceable uncertainties)

- The treatment of biases in ERA5 (and ERA-Interim) – some examples:
  - Instrumental biases in MSU, AMSU and ATMS
  - Model biases in the stratosphere
  - RT model biases (HIRS & the advanced IR sounders, SSU)
  - $\mathbf{B}_{\mathbf{cli}}$ in a hybrid 4D-Var DA system

- Summary and prospects

Background (1): EDA Ensemble spread as a measure for the *synoptic* ERA5 uncertainty

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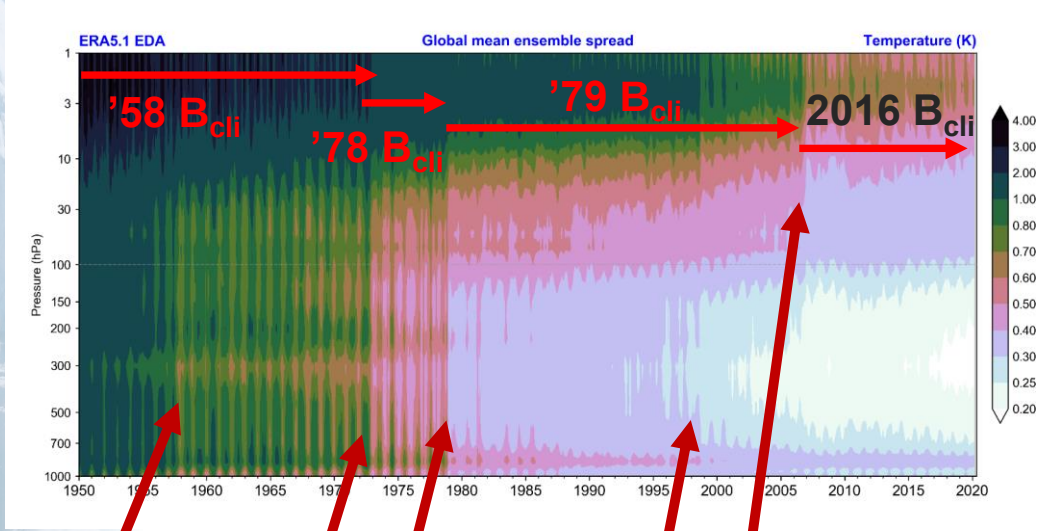
Spread decreases over time when more and more observations become available

Major changes in the observing system are clearly visible

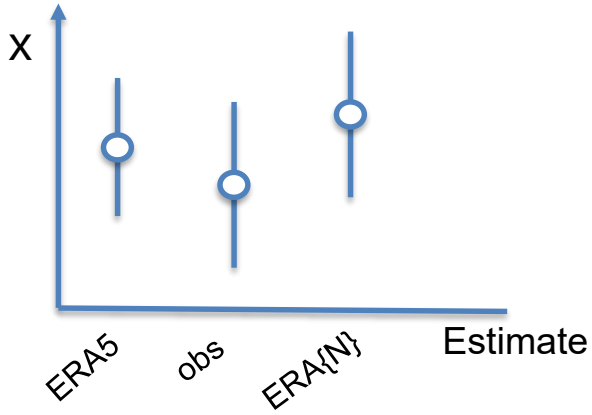


International Geophysical Year (1957/58)

VTPR **TOVS** (HIRS, MSU, SSU)

ATOVS (AMSU-A)

GNSS-RO (COSMIC,..)



Assumes :

- EDA represents day-to-day 'random' errors in the analysis &;
- 'systematic' components can be neglected

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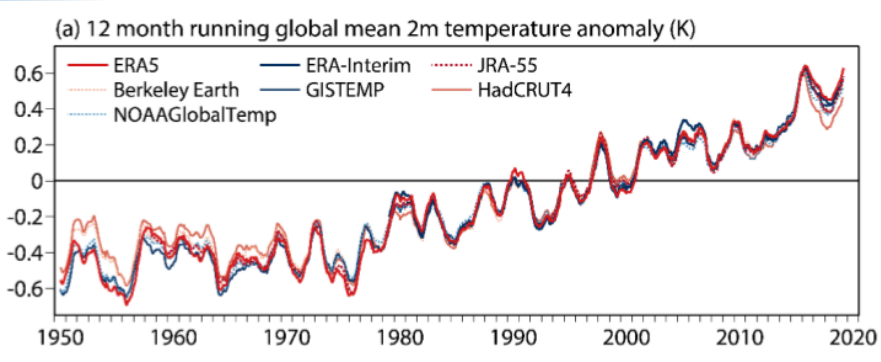
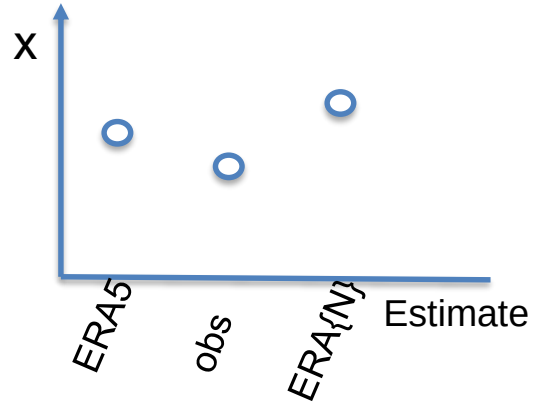
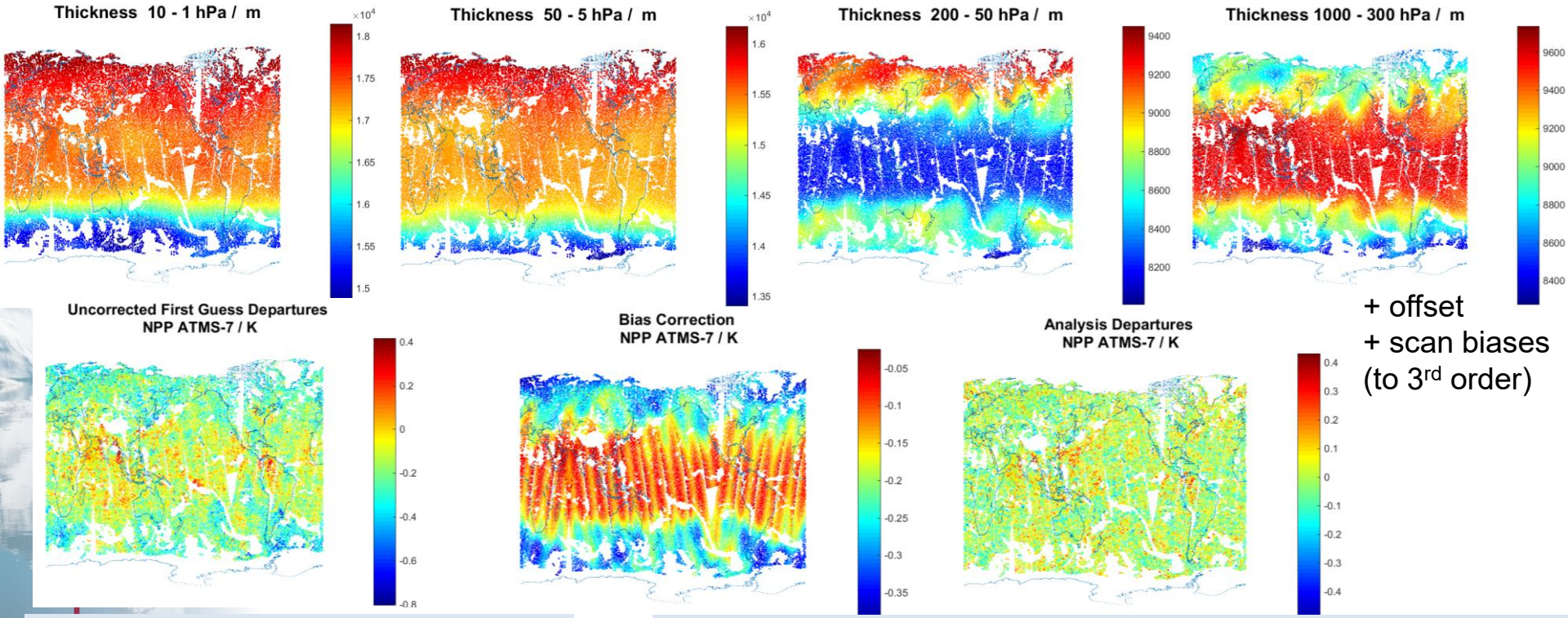
Background (2): Mean state uncertainties ? Comparison of global 2m temperature anomalies





- Spread in EDA collapses when averaging over large / long scales & systematic components of the uncertainty budget are not currently estimated.
- Likely to be a priority for reanalysis in the coming decade (? for Panel / WG), less so for NWP.
- An uncertainty estimate that works across scales (space and time) requires, longer term, progress on partitioning and reducing the sources of bias.
- Should we develop a '*benchmark*' period (2010 – 2020 ?) within the next reanalysis for which an uncertainty estimate is developed, based on:
  - Targeted data denials, and perturbed forecast model experiments (to derive the uncertainties)
  - Validation of the uncertainties (using GRUAN, some RO, CrIS, …) ?

Background (3):
Variational Bias Correction in ERA5 – bias model & typical corrections (example : ATMS-7)



+ offset
+ scan biases
(to 3rd order)

Accounts for:
- Instrument errors (spectral, radiometric, …)
- Forecast model errors
- RT model errors

Expect (hope!) that in time, as instruments & models improve:
- The (mean) amplitude of bias corrections reduce; and
- The variance of the bias corrections reduce
- Eventually – the corrections are (i) small & (ii) bounded by the uncertainties

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Instrument biases in the temperature sounding channels of MSU, AMSU-A and ATMS

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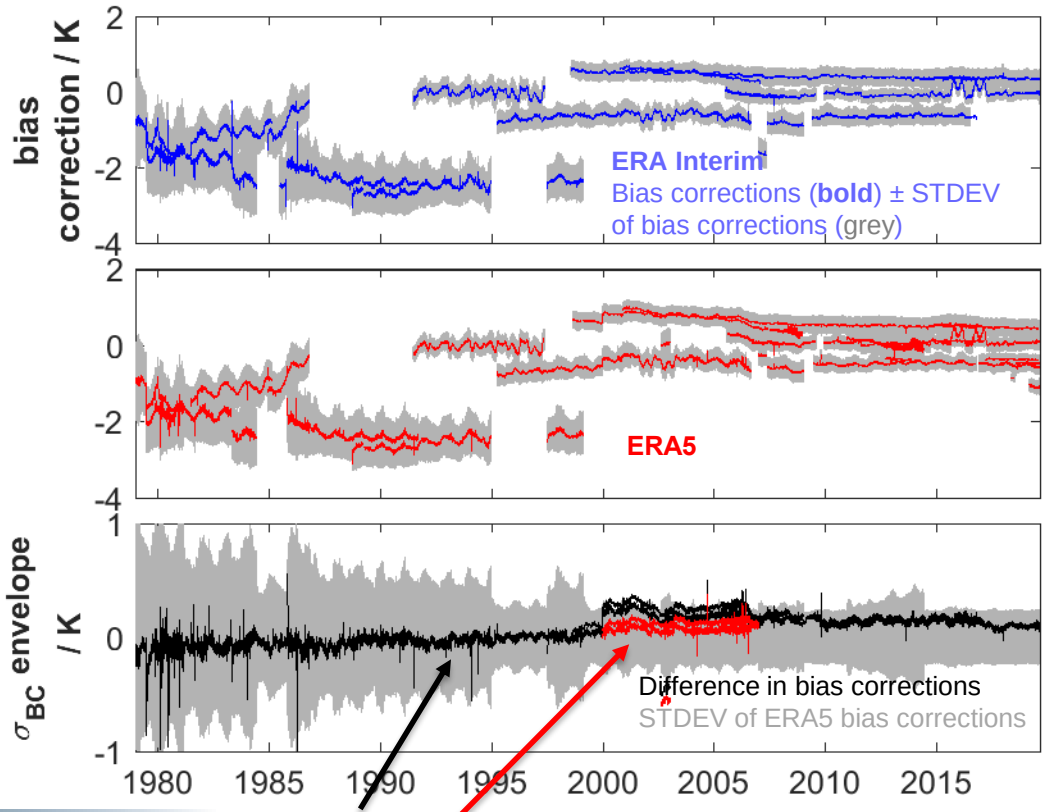
MSU-3 / AMSU-A7 / ATMS-8 Bias Corrections



ERA5 – ERA Interim

ERA5.1 – ERA Interim

MSU-3 / AMSU-A7 / ATMS-8
(54.96 / 54.94 / 54.94 GHz)
T –sounding, w.fn. peak at 270 hPa

- Improvements MSU - > AMSU-A - > ATMS
  (FY-3 MWTS / MWTS-2, Metop-SG MWS ?)
- Little change from ERA-Interim to ERA5
- Suggests model bias and RT related biases are less significant than instrument biases
- MSU & AMSU-A possible mechanisms identified:

  - Radiometer non-linearities. Zou *et al* (JTECH, 2010)
  - Spectral shifts. Zou *et al* (JGR, 2011), Lu and Bell (JTECH, 2013)

- But disappointing results in NWP testing so far (for AMSU-A, Lupu *et al*, ECMWF TM 770, 2016)

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MSU-2 / -3 / -4 Bias Corrections

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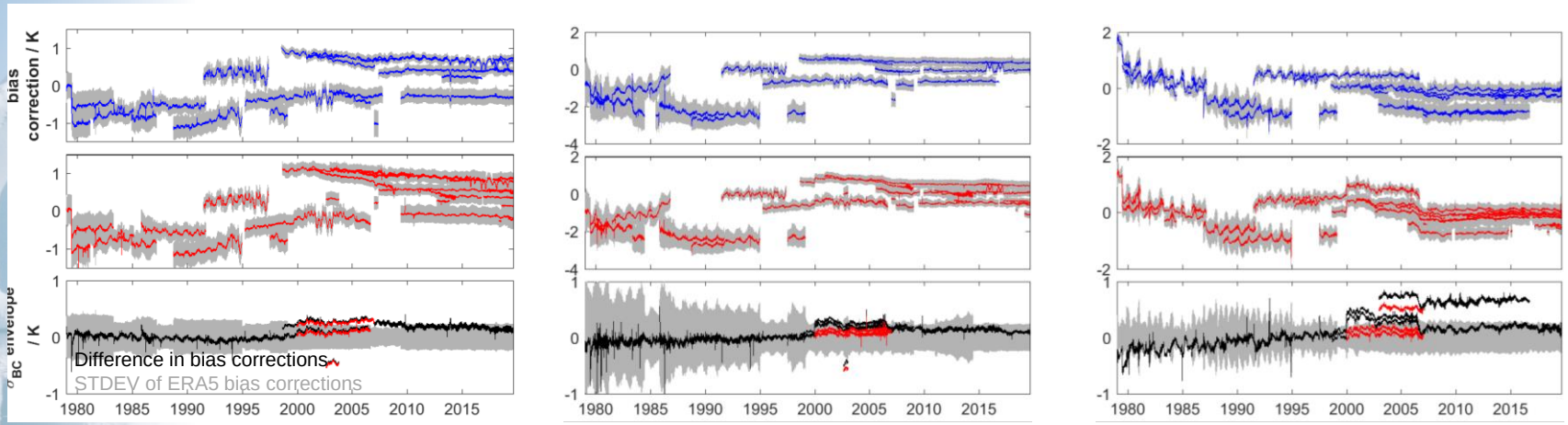
MSU-2 / AMSU-A5 / ATMS-6
Peak 700 hPa

MSU-3 / AMSU-A7 / ATMS-8
Peak 270 hPa

MSU-4 / AMSU-A9 / ATMS-10
Peak 90 hPa



- Similar picture (to MSU-3) for MSU-2 and MSU-4.
- Changes in bias correction *wrt* ERA-Interim are generally small, with the exception of:
  - Aqua AMSU-A 2003-2016
  - The period from 2000 - 2006 (fixed in ERA5.1) - see next few slides
- Largest discrepancies AMSU-9 (0.5K), but still detectable in AMSU-7 and AMSU-5

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Model biases in the upper troposphere and stratosphere

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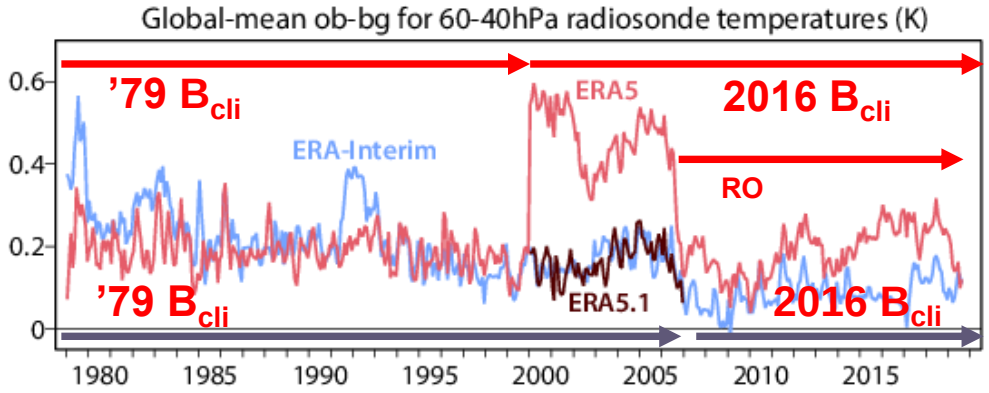
The improved mean state for stratospheric temperature in ERA5.1



ORIGINAL ERA5 PRODUCTION

ERA5.1 PRODUCTION

Monthly average observation-background differences from 1979 onwards for all assimilated bias-adjusted radiosonde temperature data (K) between 40 and 60 hPa, for ERA-Interim, ERA5 (based on 1979-B_{cli} before 2000 and 41r2-B_{cli} afterwards) and ERA5.1 (using 1979-B_{cli} from 2000-2006).

Hersbach, H. et al., 2020 , doi:10.1002/qj.3803

- ERA5.1 provides an improved mean state for stratospheric temperature.
- In the troposphere the difference between ERA5 and ERA5.1 is very small.

(see A. Simmons *et al*, ECMWF Tech Memo 859, Jan 2020)

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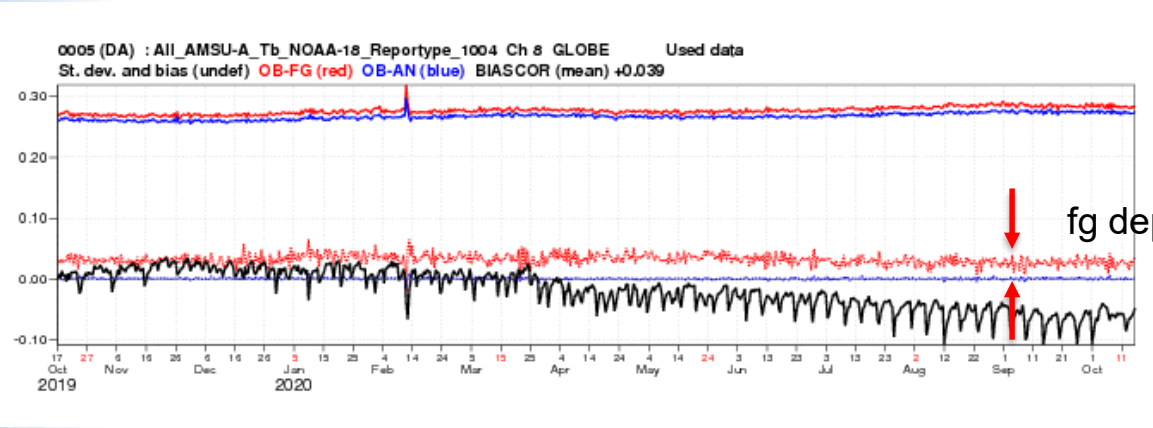
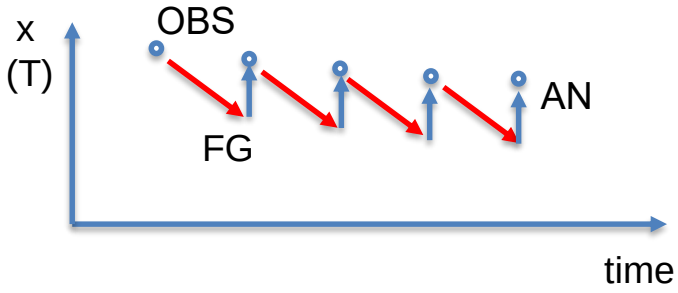
Model error manifested in biased fg_departures

NOAA-18 AMSU-A8



fg departures biased by ~25 mK



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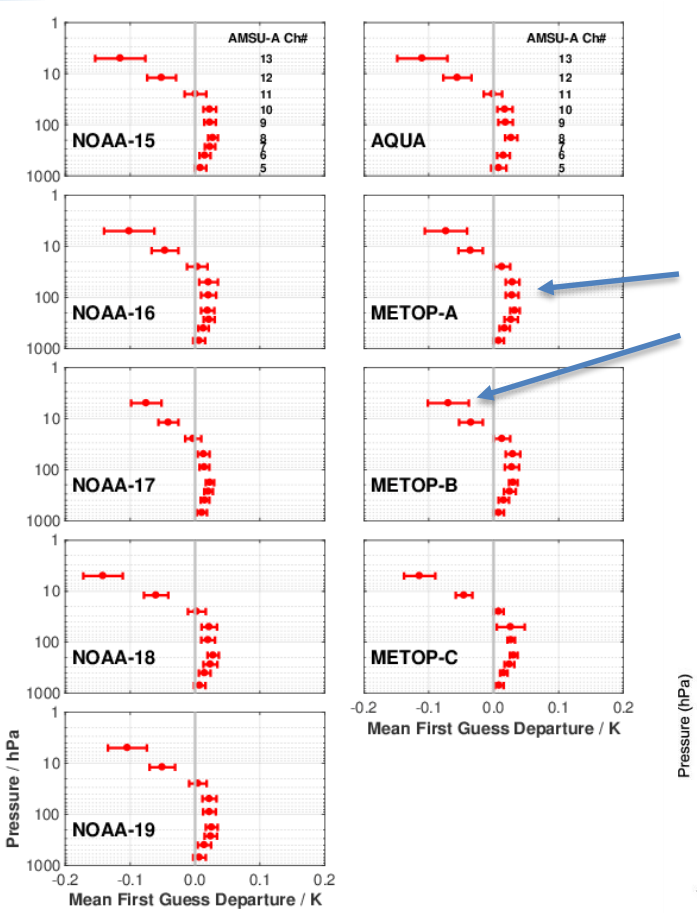
Model Error / AMSU-A Mean FG_DEPS in ERA5



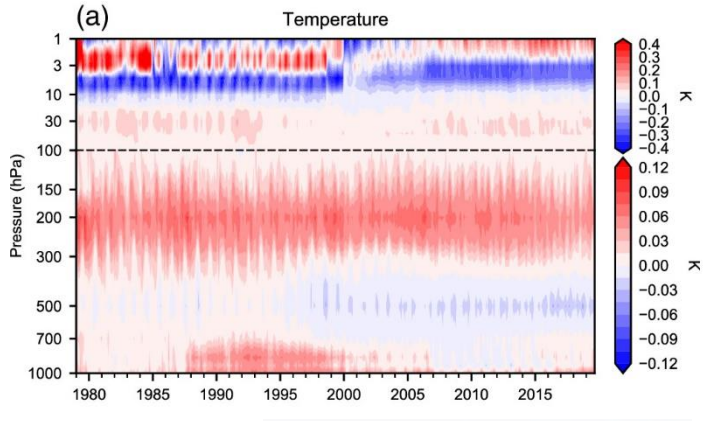
ERA5 mean first guess departures shown for AMSU-A

Error bars represent (±1σ) spread over the lifetime of each sensor

Consistent picture of :

- a cold model bias mid-trop to mid-strat
- a (larger) warm model bias above 10 hPa

Broadly consistent with analysis increments in ERA5 (*below, from Fig 16, Hersbach et al, 2020*)



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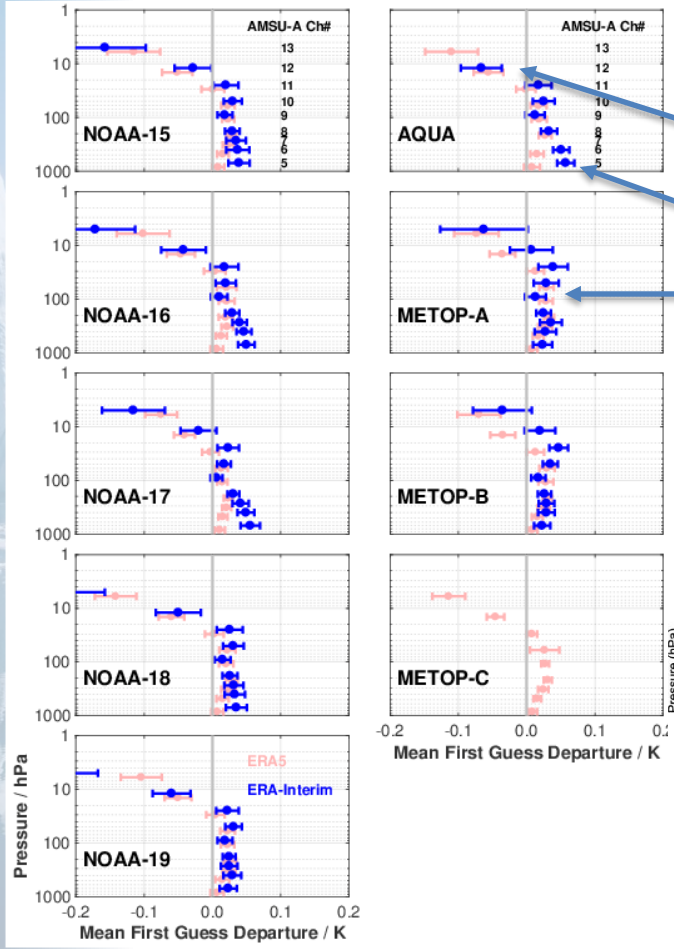
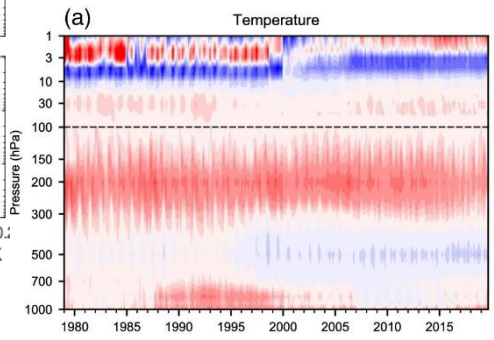
Model Error / AMSU-A Mean FG_DEPS in ERA-Interim



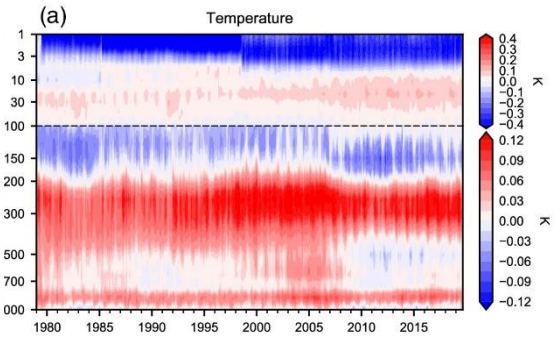
Indications that ERA-Interim:

- Exhibits similar biases (to ERA5) above 10 hPa
- Exhibits larger biases below 200 hPa
- Exhibits smaller biases around 100 hPa.

ERA5 analysis increments



ERA-Interim analysis increments



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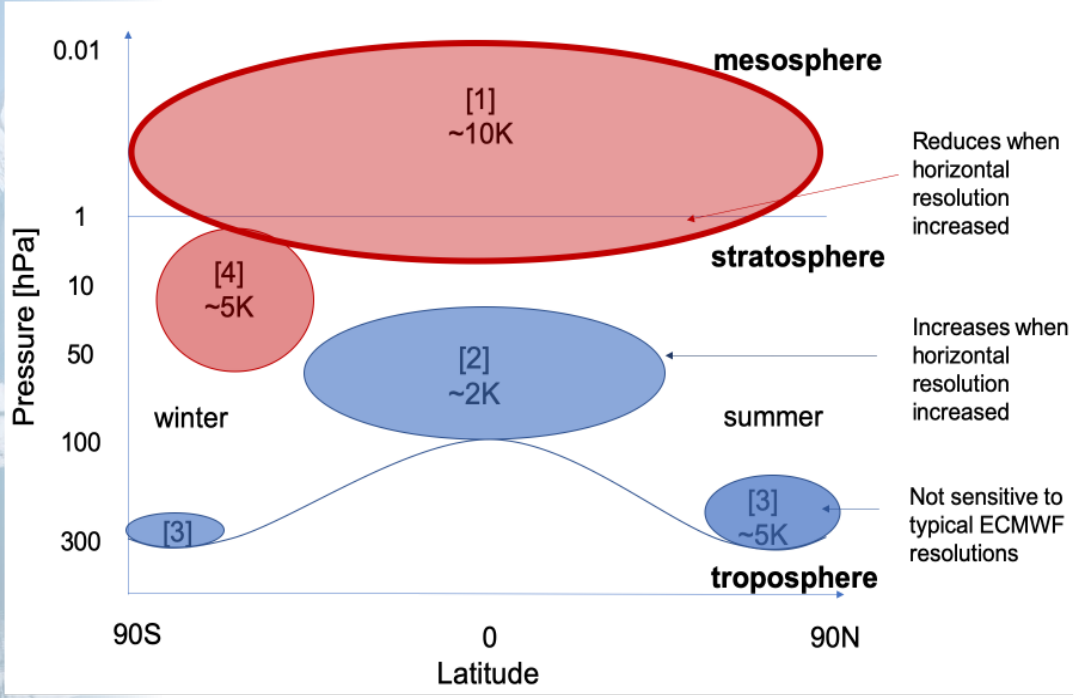
Model biases in the stratosphere



WC 4D-Var (Patrick's talk) offers a solution for ERA6.

In addition, improvements are expected from :

[1] – revised radiation scheme, improved SW solar spectrum, improved (and interactive) ozone,

[2] improved dynamical core

[3] reduction of H_2O in lower stratosphere, improved methane oxidation scheme

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Radiative Transfer Model biases in the IR sounders (HIRS, AIRS, IASI, CrIS and SSU)

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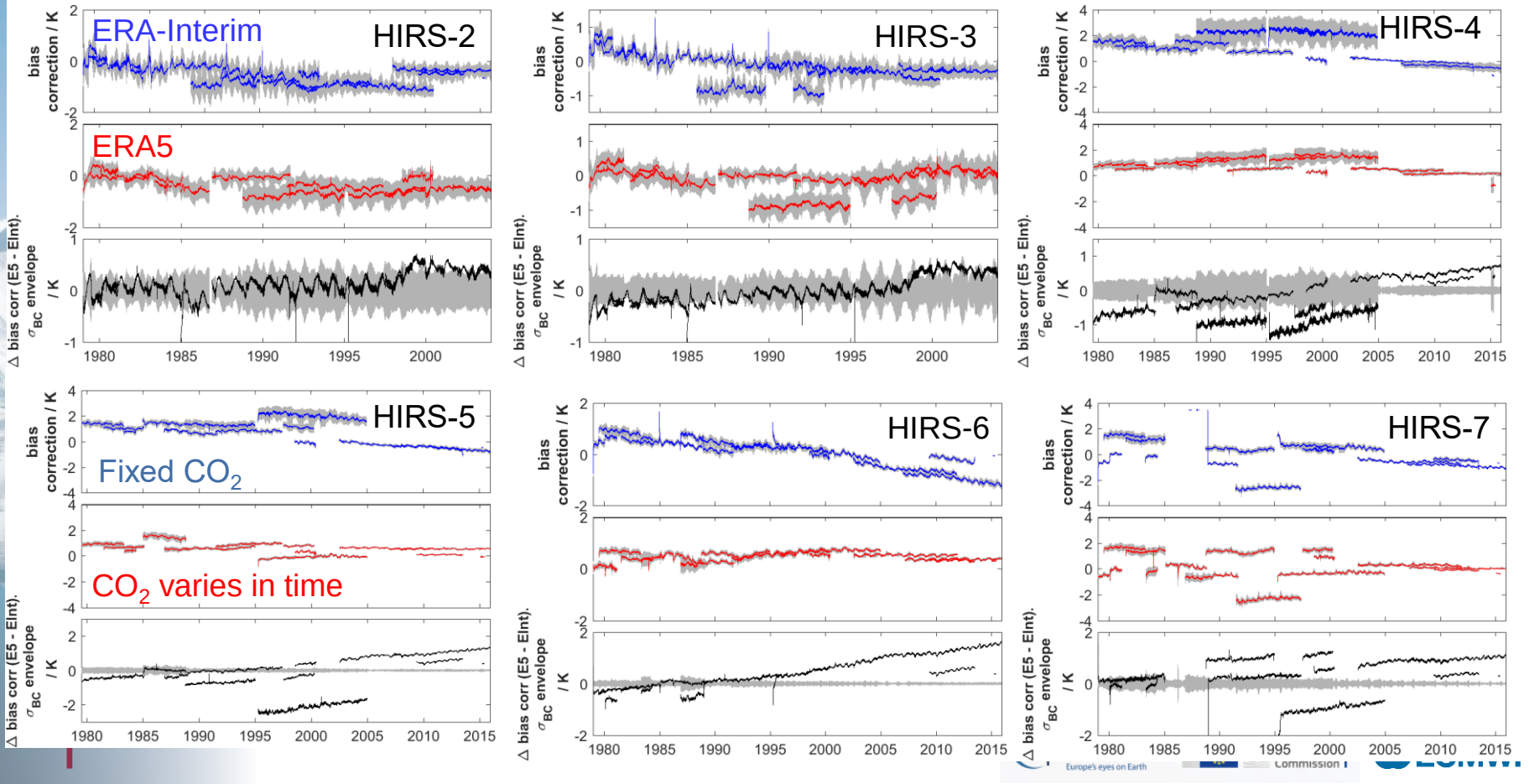
Improvements in RT modelling: HIRS Temperature Sounding Channels 2 - 7



Improvements in RT modelling: bias corrections for Adv. IR Sounders in ERA5

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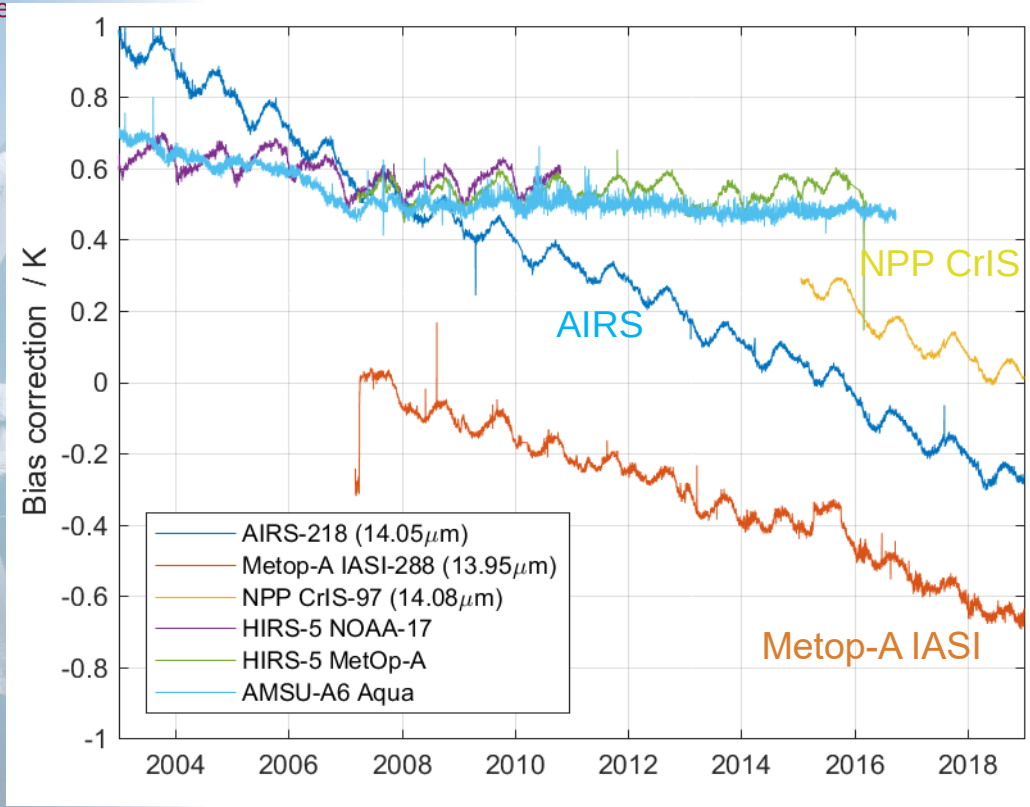
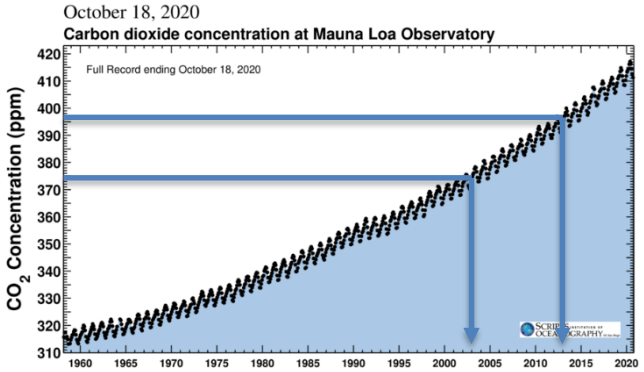


- AIRS, IASI and CrIS channels shown at ~14μm (710 - 717 cm^{-1}) & peak in the range 430 - 480 hPa
- AIRS & IASI: assume [CO_2] = 376 ppm CrIS assumes [CO_2] = 396 ppm
- HIRS (& SSU & VTPR): assume time varying [CO_2]



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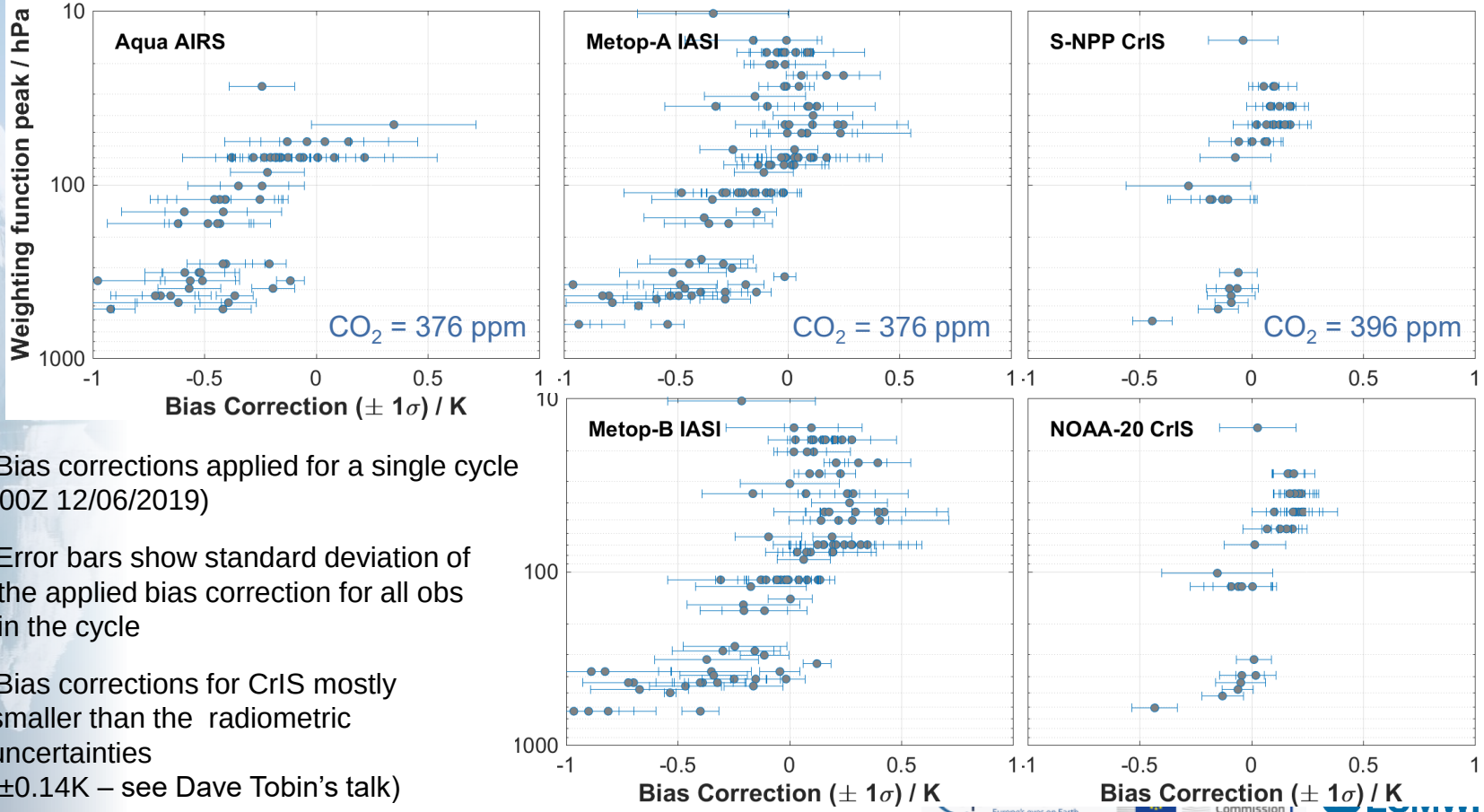
Improvements in RT modelling: bias corrections with height for the Adv. IR sounders



- Bias corrections applied for a single cycle (00Z 12/06/2019)
- Error bars show standard deviation of the applied bias correction for all obs in the cycle
- Bias corrections for CrIS mostly smaller than the radiometric uncertainties (±0.14K – see Dave Tobin's talk)

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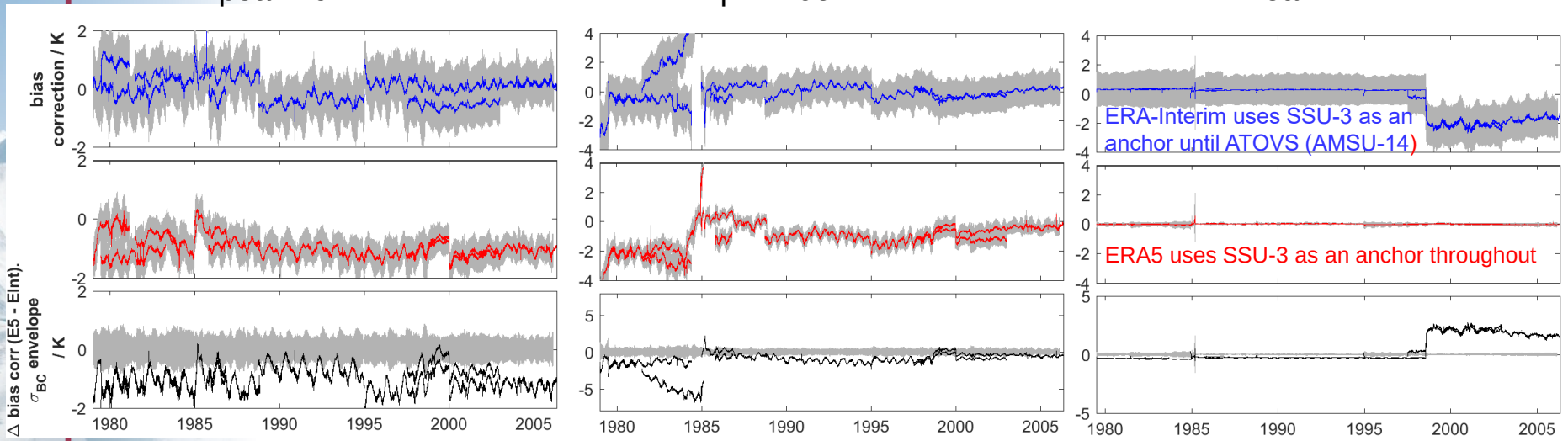
Improved RT modelling : SSU Bias Corrections



Improved treatment of RT (cell pressure leaks) in ERA5:

- Reduced inter-satellite biases
- Reduced variance in bias corrections
- Reduced drift in biases (NOAA-7 during 1982-1985)

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Evolving B_{cli} in a Hybrid 4D-Var Assimilation System

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The current hybrid DA scheme
scheme & a way of generating a time varying B_{cli}

Current scheme
(α=0.15)

$B_{cli} = B_{cli}^{1958}, B_{cli}^{1978}, B_{cli}^{1979}, B_{cli}^{41r2}$

$$B(t) = (1-\alpha)B_{cli} + \alpha B_{EDA}(t)$$

New scheme
(α=0.15)

$$B(t) = (1-\alpha)B_{cli}(t) + \alpha B_{EDA}(t)$$

Implementation
(α'=0.03, *currently*)

$$B_{cli}^{i} = (1-\alpha')B_{cli}^{i-1} + \alpha' B_{EDA}^{i}$$

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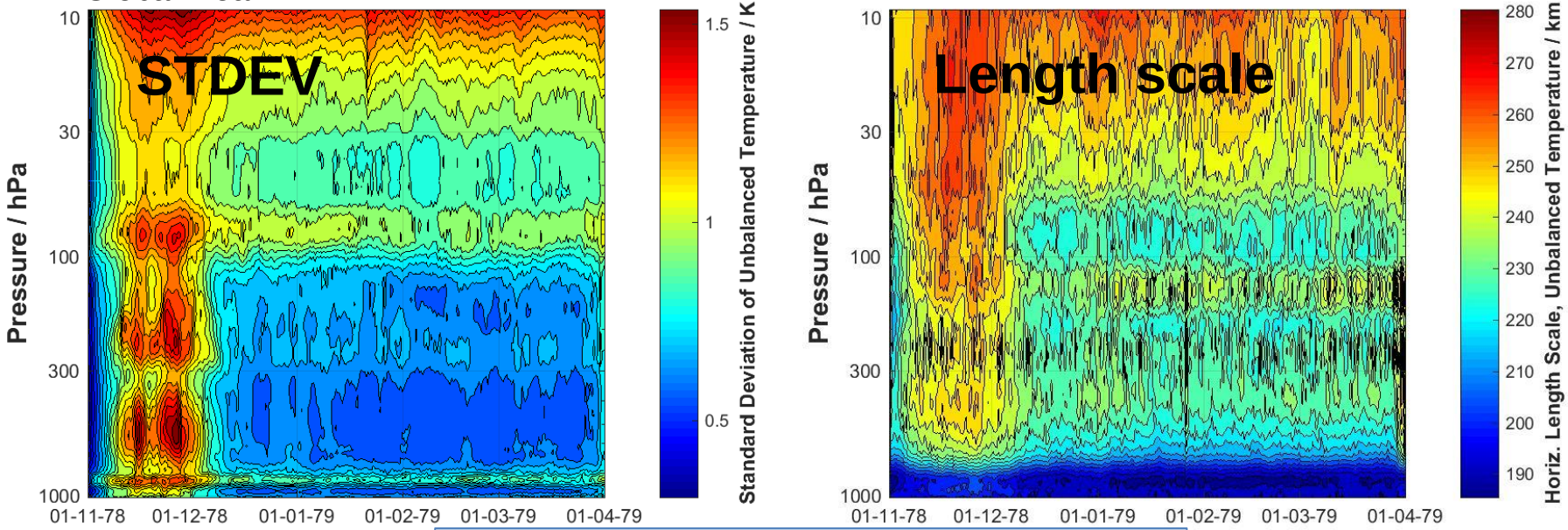
The TOVS transition: November 1978 - April 1979

Background error variances (STDEVS) and length scales for $\mathbf{B_{EDA}}$

Unbalanced temperature

Global mean



TOVS

Following the introduction of TOVS in Dec 78

- Mid trop standard deviations reduced by ×2
- Length scales 255km -> 230km

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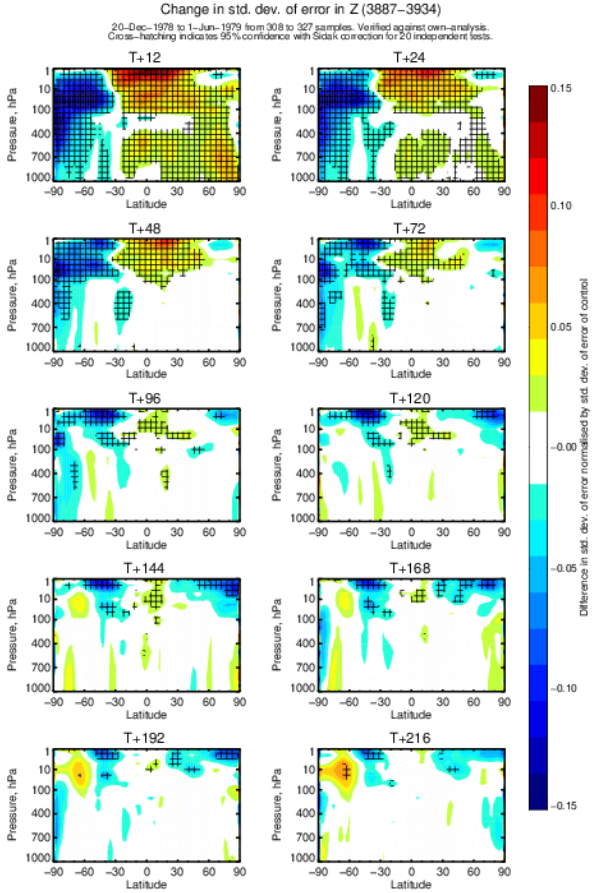
Verification of B_{cli} (t) vs B_{cli}^{1979} for TOVS transition Dec 1978-June 1979

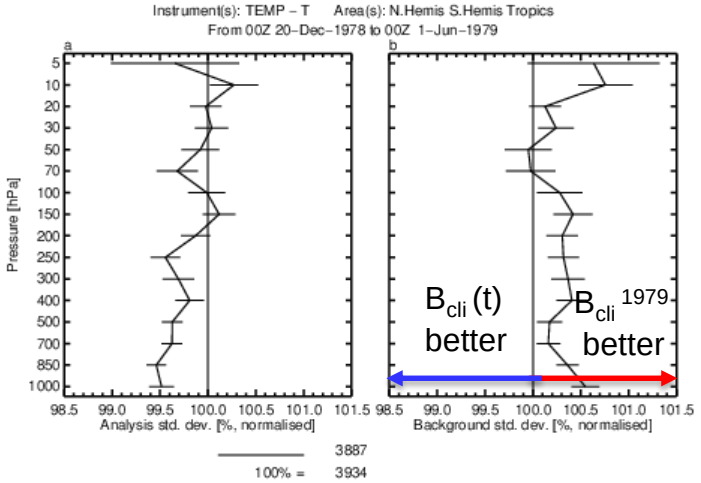


Change in STDEV in error in Z shown

Blue - B_{cli} (t) better

Red - B_{cli}^{1979} better

Change in STDEV of analysis & background fits for radiosonde temperatures



Scope for tuning α' (currently 0.03)

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Summary & Prospects

- In the treatment of biases - some steps forward at ERA5 (RT model biases), some sideways steps (MSU/AMSUA) and some backward steps (at least initially, stratospheric biases).

- In the short term the prospects are good for improved pragmatic correction (WC 4D-Var [Patrick's talk] & $\mathbf{B}_{cli}(t)$) as well as corrections at source (reprocessed data [Paul's talk], stratospheric biases, improved RT modelling)

- Both pragmatic and ideal approaches are bearing fruit, is the balance right for all issues (*e.g.* stratosphere – yes ? early sounding data – no ?) – can more be done to accelerate progress & improve the links ?

- Priorities for NWP and reanalysis are mainly well aligned, but not always: *e.g.* how do we make progress on estimating mean state uncertainties ?

- Should we use the 'redundancy' of the very recent satellite era (~2010-2020) to withhold some (subset of) very high quality observations (GRUAN, RO, CrIS, …) and use these to independently validate ERA6 during a **benchmark** period in the reanalysis (at the cost of a small degradation in analysis quality)?

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Thanks for your time !

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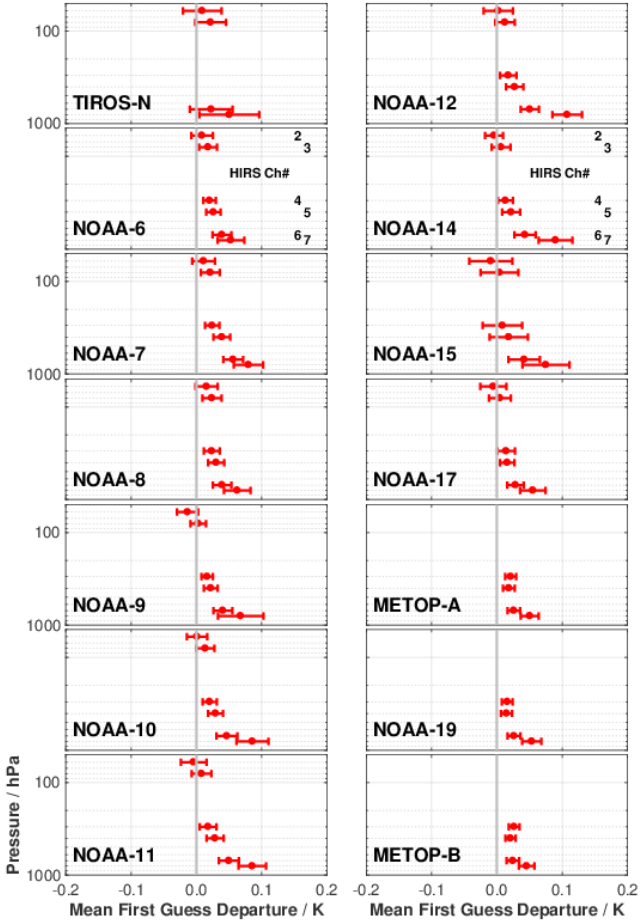
HIRS Mean FG departures



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What is new in ERA5?

	ERA-Interim	ERA5
Period	1979 – present	***1950 – present***, produced in 2 phases
Availability behind real time	2-3 months	2-3 months (final product) ***5 days*** (ERA5T)
Assimilation system	2006 (31r2), 4D-Var soil moisture: 1D-OI	***2016*** (41r2), ***4D-Var, hybrid EDA*** ***soil moisture: SEKF***
Model input (radiation and surface)	As in operations, *(inconsistent SST and sea ice)*	***Appropriate for climate***, e.g., evolution of greenhouse gases, volcanic eruptions, sea surface temperature and sea ice
Land-surface model	TESSEL	***HTESSEL***
Spatial resolution	79 km globally 60 levels to 10 Pa	***31 km globally*** 137 levels to 1 Pa
Uncertainty estimate		***from*** 10-member ***EDA at 63 km***
Output frequency	6-hourly Analysis fields	***Hourly*** (three-hourly for the ensemble), Extended list of parameters ~ 9 Peta Byte (1950 - timely updates)
Extra Observations	Mostly ERA-40, GTS	Various ***reprocessed CDRs***, ***latest instruments***
Variational Bias control Radiosondes	Satellite radiances, RAOBCORE	Also ozone, aircraft, surface pressure, RISE
Land downscaling product	ERA-Interim land, 79km	ERA5L, ***9km*** (forced by ERA5)