Bias in Reanalysis

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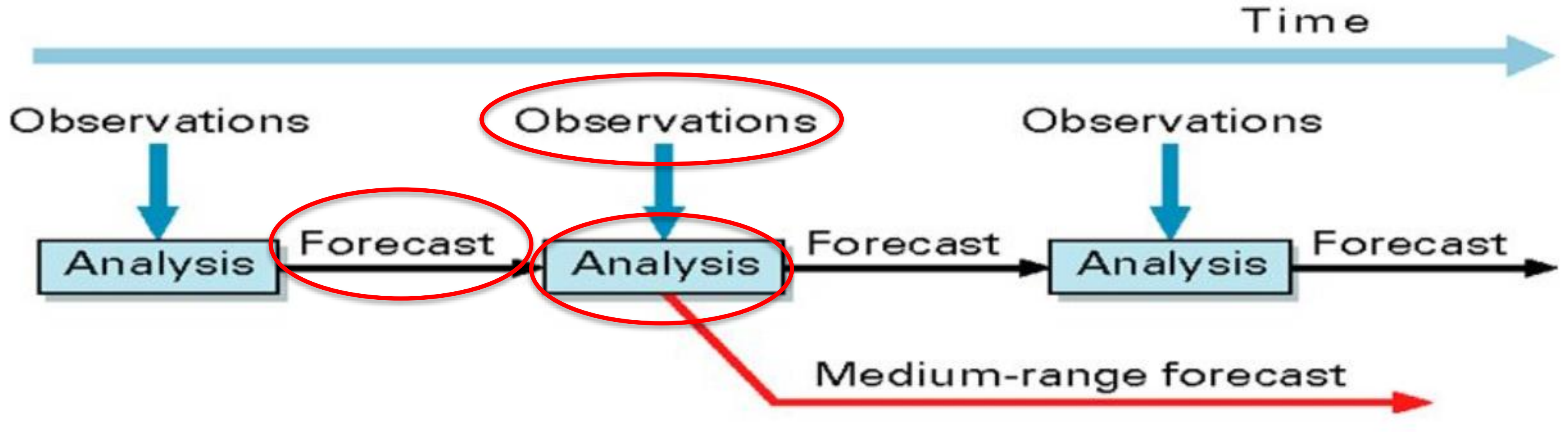
Introduction: The challenge presented by biases



In reanalyses, we aim for :

- **continuity**
- **accuracy** - in synoptics and climate
- well characterised **uncertainties**

Biases present challenges for all three aspects

We mitigate biases through:

'**Pragmatic**' approaches

- **observation domain** – *e.g.* VarBC
- **model domain** – *e.g.* weak constraint 4D-Var

'**Ideal**' approaches

- **improved physical modelling** of root causes

Overview

Biases: How are they manifested in reanalyses ? What do we do about them ? … and what next ?

Observational biases

- Radiances in ERA-Interim / ERA5 & future prospects
- Other innovations

Model biases

- ERA5 stratospheric temperatures
- Weak constraint 4D-Var & model error forcing
- Using early sounding data (IRIS in 1970) to evaluate model error correction strategies

Mean state uncertainties - The systematic component

Summary / Future Perspectives

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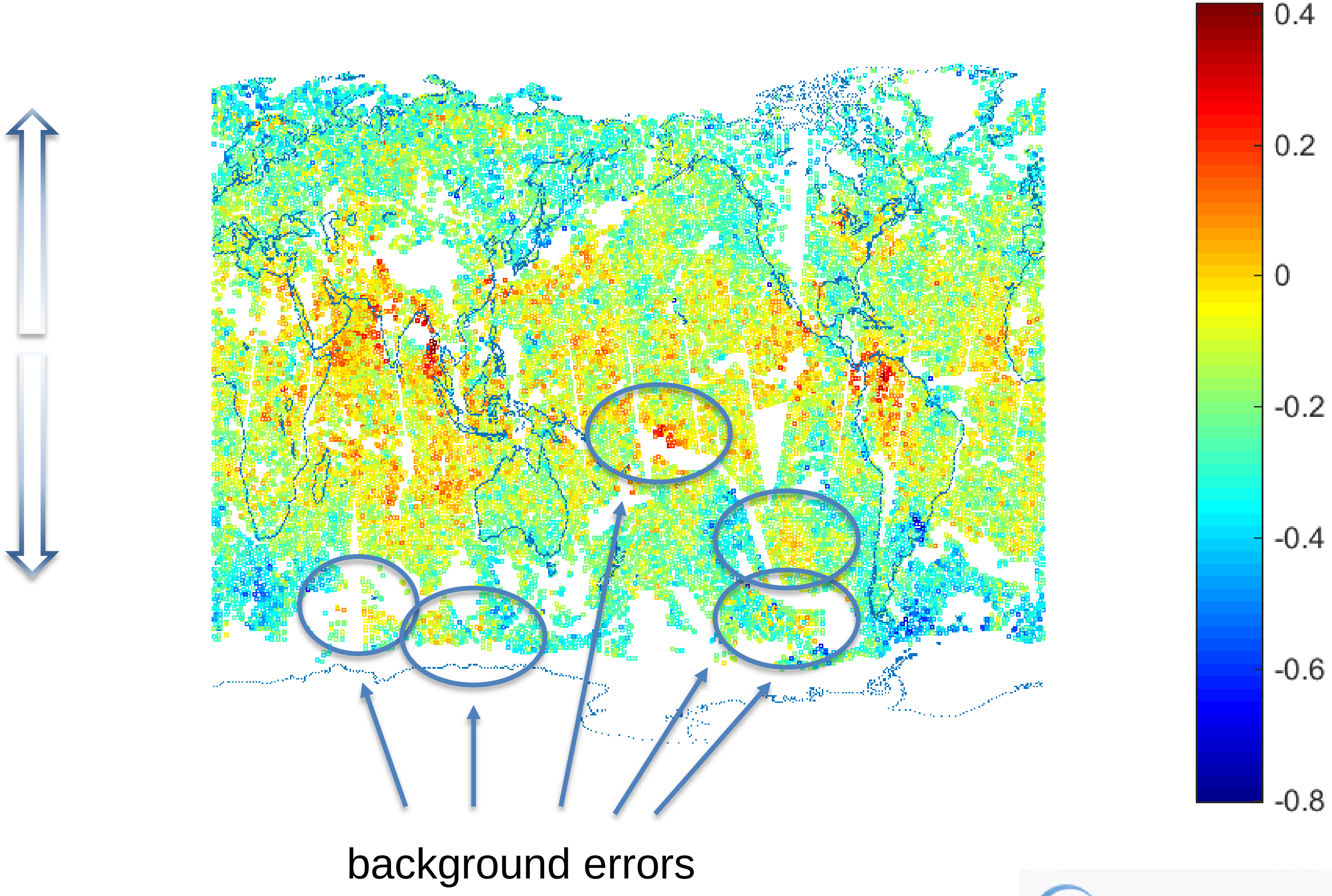
Uncorrected First Guess Departures
NPP ATMS-7 / K

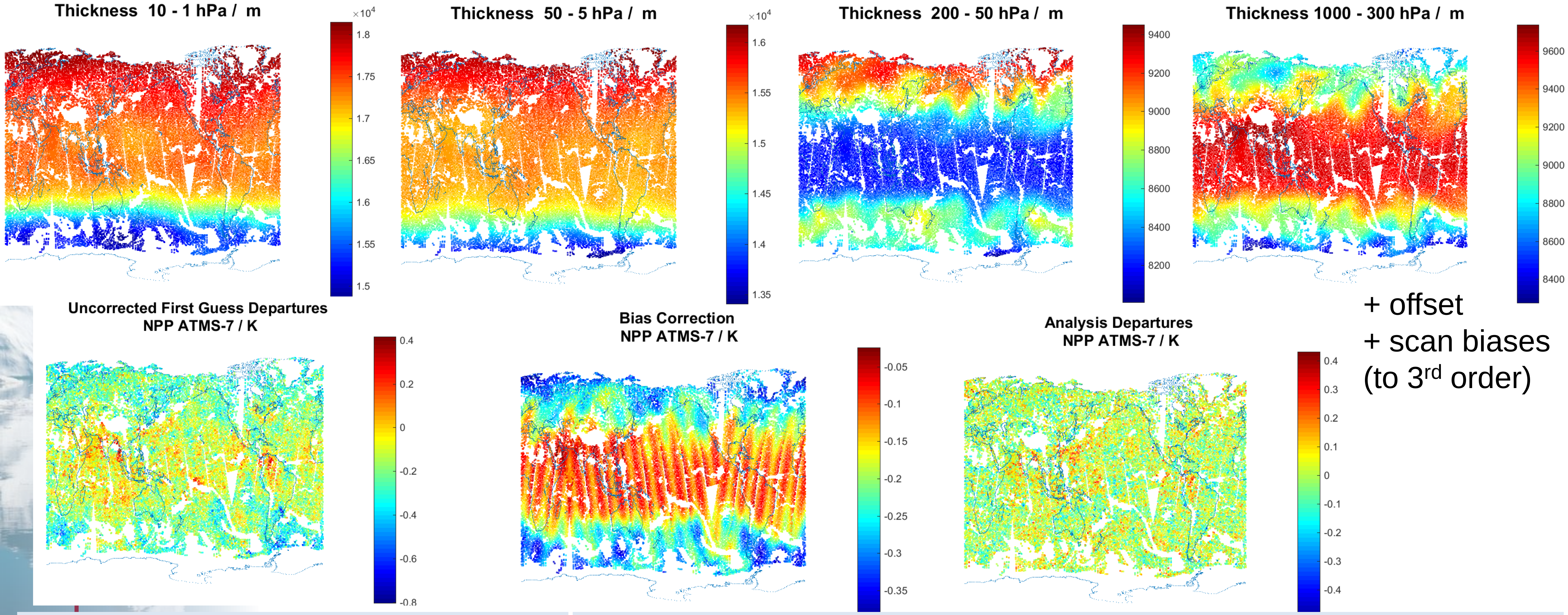
latitudinal bias
(instrumental & forecast model contributions)



- bias ~ background error ~ noise: **O**(0.1K)
- For early sounding obs, biases are larger
- DA methods assume observations unbiased wrt background/analysis
- Biases corrected using variational bias correction (VarBC)

Dee, QJRMS, 2005
Auligne et al, QJRMS, 2007

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 that in time, as instruments & models improve & datasets are reprocessed:
- The (mean) amplitude of bias corrections reduce; and
- The variance of the bias corrections reduce
- <u>Eventually</u> – 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 in ERA5 and ERA-Interim

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

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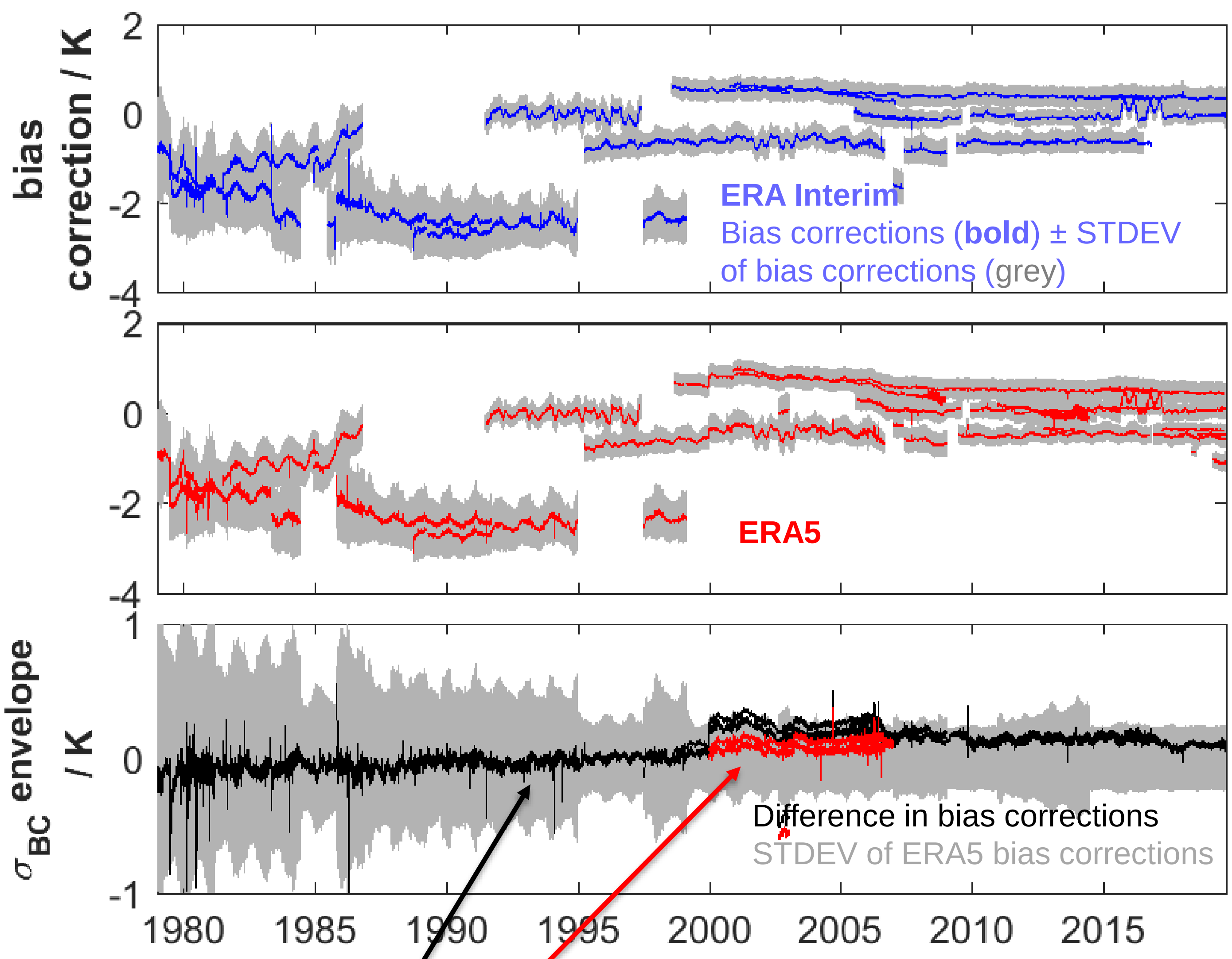

ERA5 – ERA Interim
ERA5.1 – ERA Interim

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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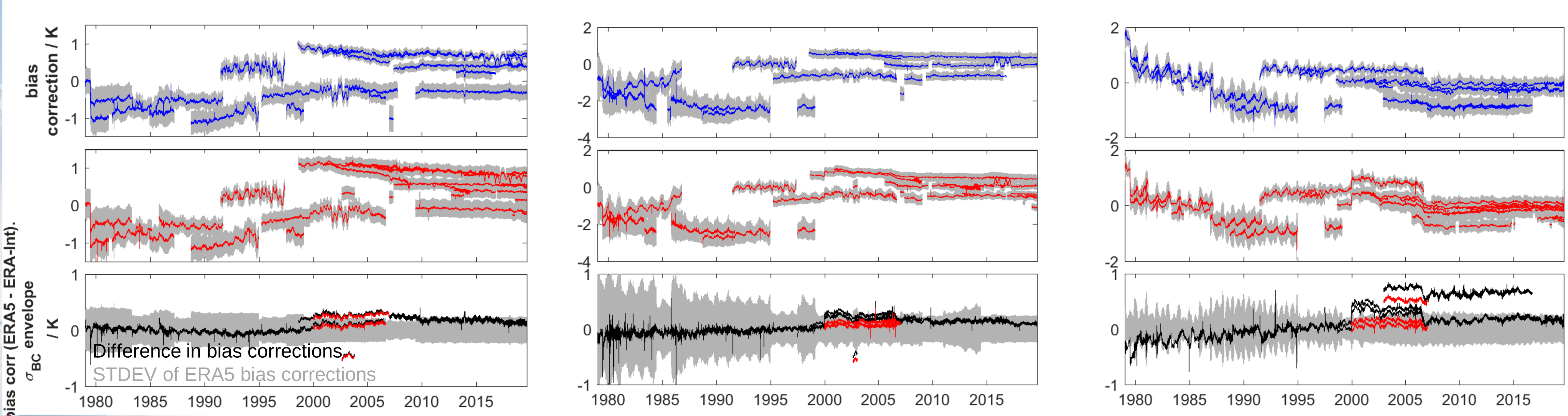
MSU-2 / -3 / -4 Bias Corrections

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

Forward look: Re-characterisation of the MSU instruments NOAA-6 to NOAA-14

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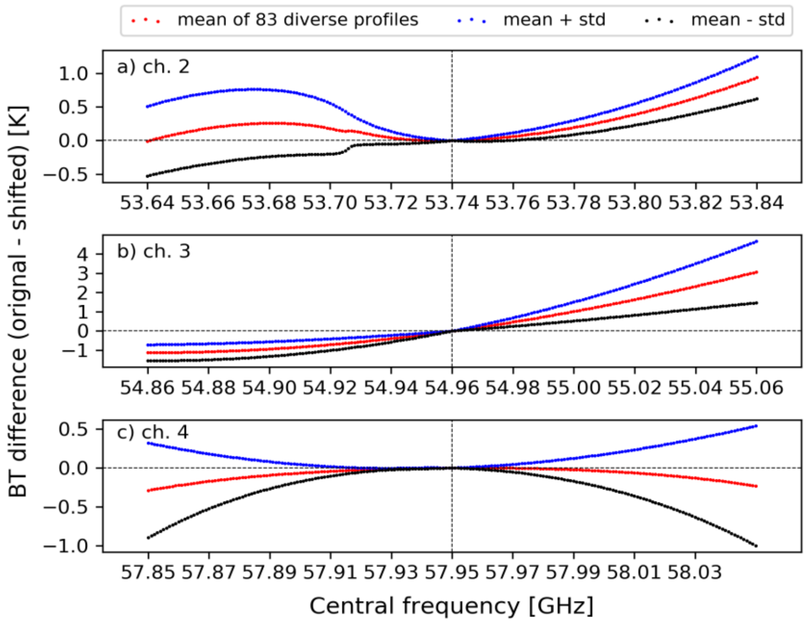
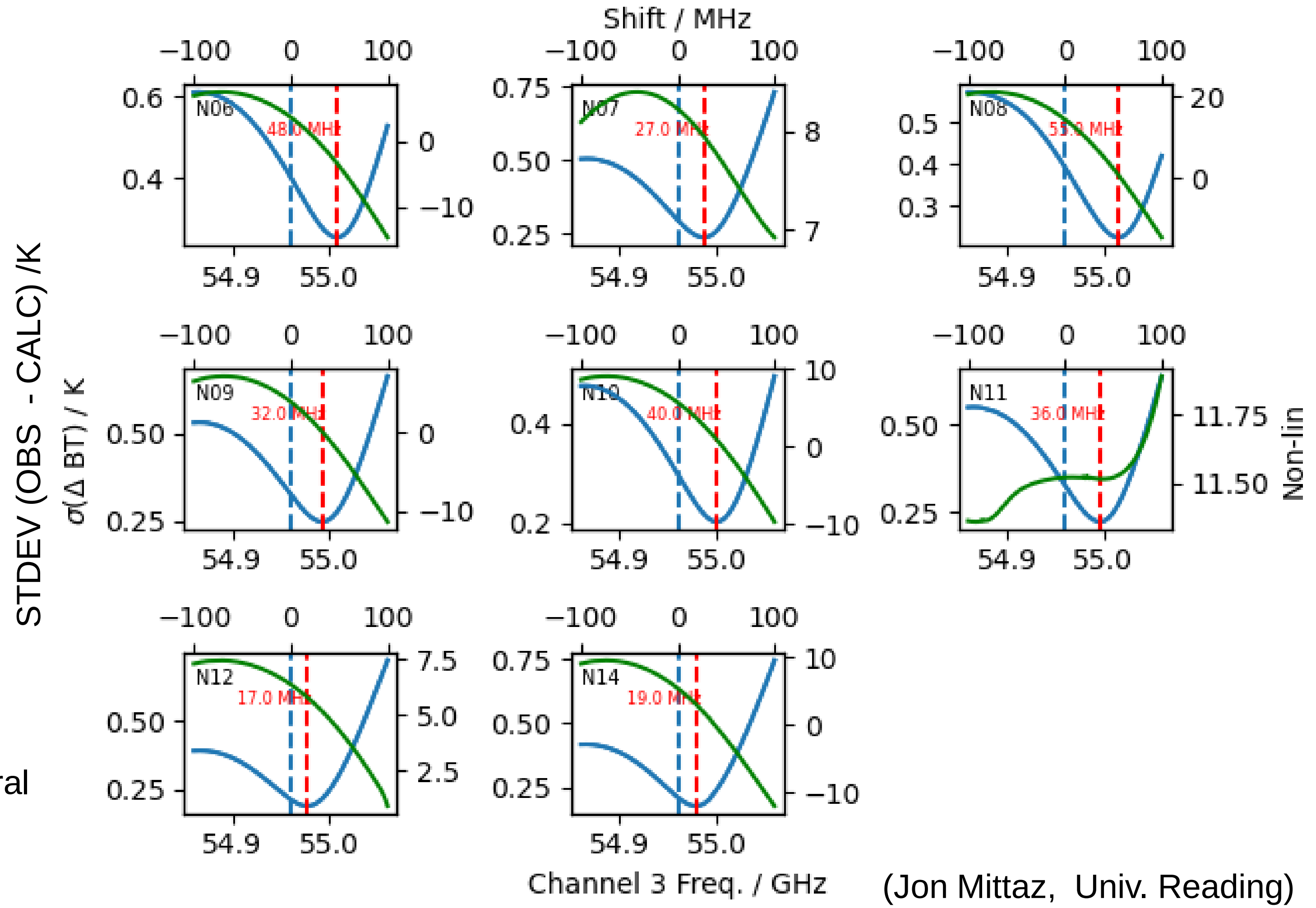
(Emma Turner, Met Office)



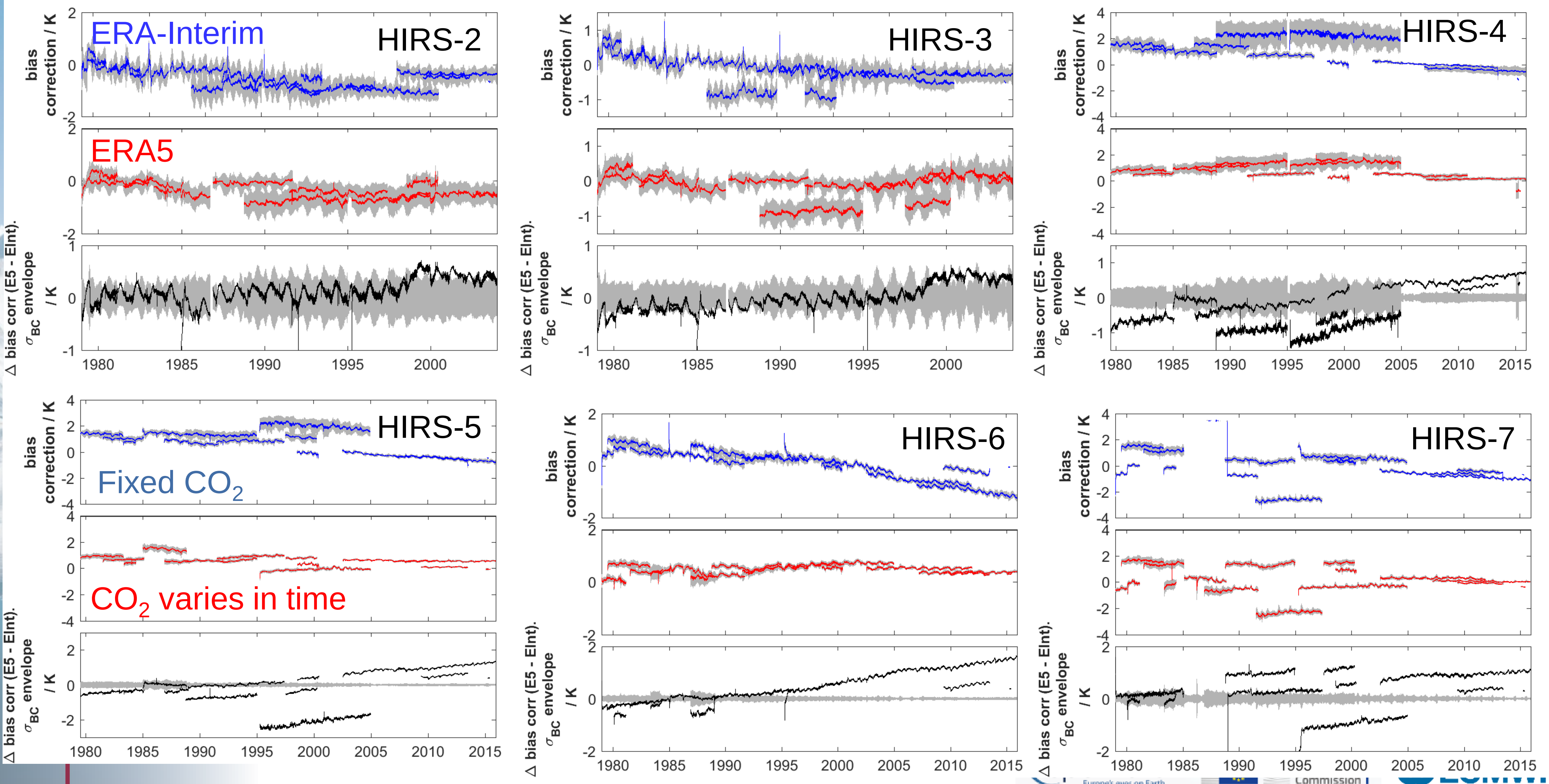


(Jon Mittaz, Univ. Reading)

- Largest sensitivity of bias to spectral shifts expected in MSU channel 3
- Simultaneous estimation of non-linearity and spectral shifts carried out – with several calibration models
- Plan to evaluate the impact of the new data / new RT modelling in advance of ERA6 back extension.

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

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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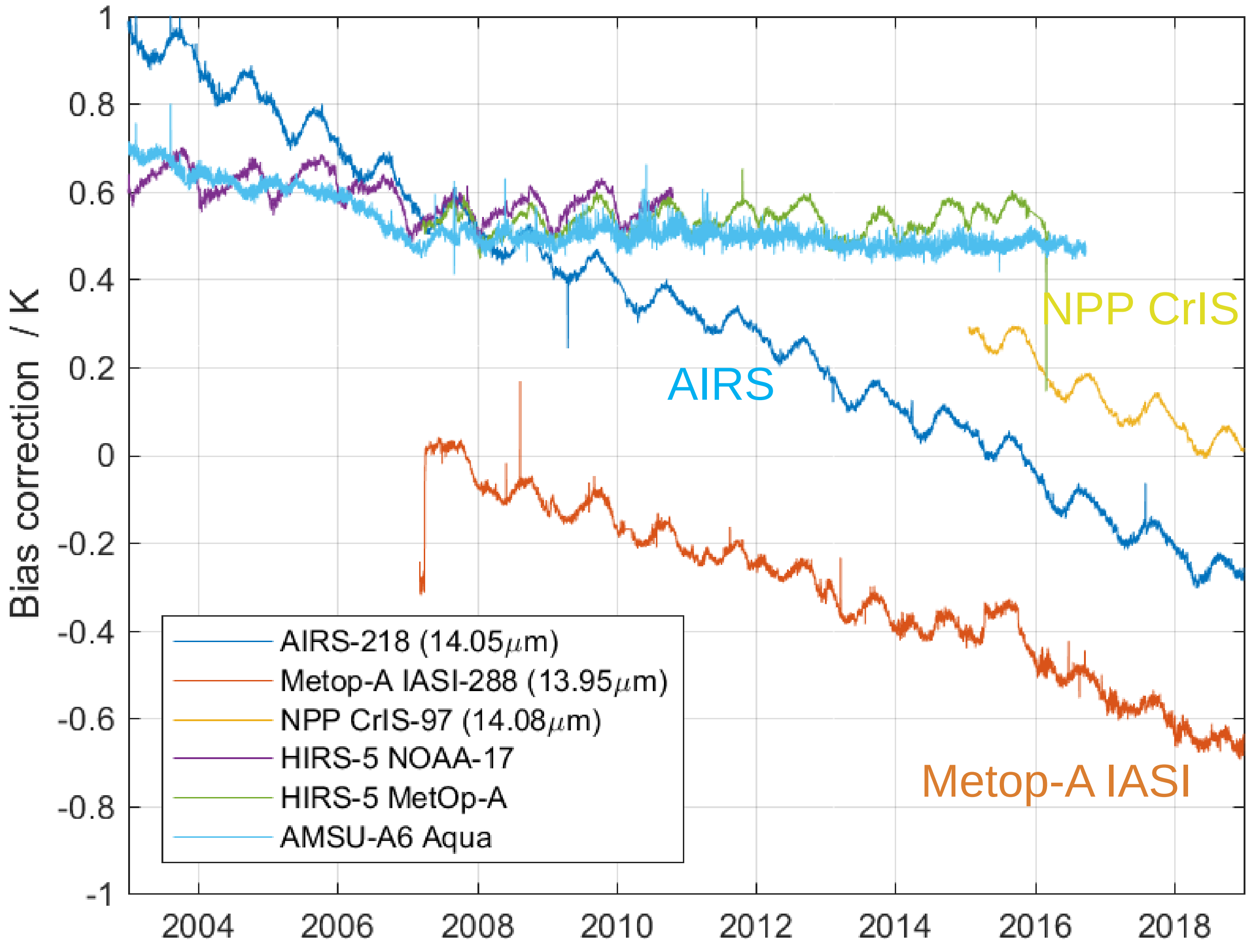
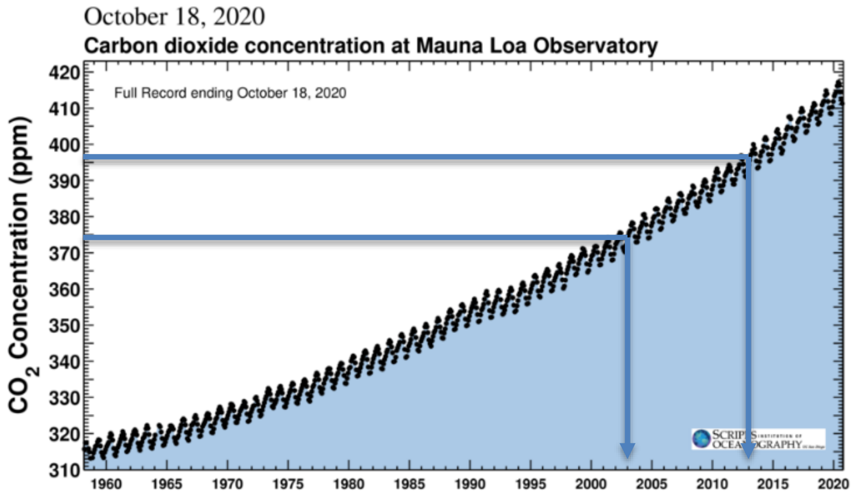


- AIRS, IASI and CrIS channels shown at ~14µm (710 - 717 cm^{-1}) & peak in the range 430 - 480 hPa
- AIRS & IASI: assume $[CO_2]$ = 376 ppm CrIS assumes $[CO_2]$ = 396 ppm
- HIRS (& SSU & VTPR): assume time varying $[CO_2]$



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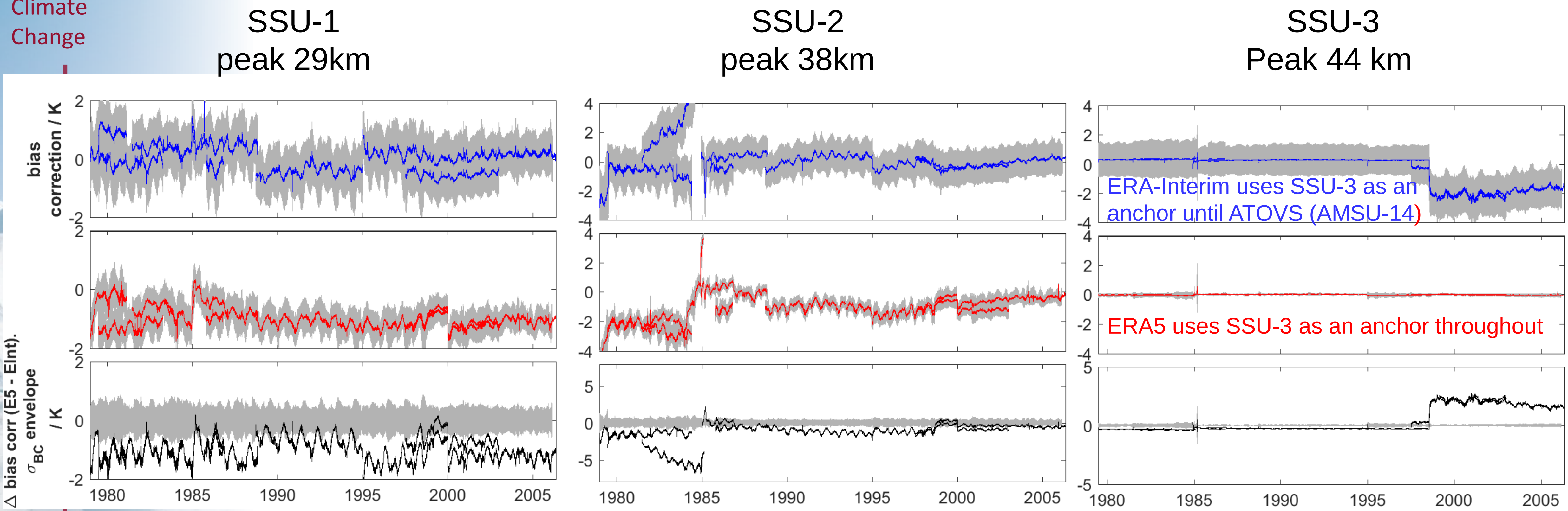
Improved RT modelling : SSU Bias Corrections



Improved treatment of RT (cell pressure leaks) in ERA5 (Kobayashi, QJRMS, 2009):

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

Other innovations

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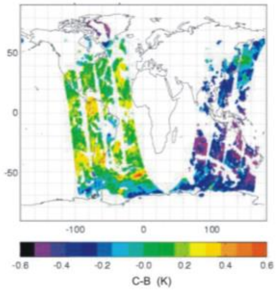
- Reprocessing and data resue efforts for ERA6 (see Paul's presentation on Wednesday)
    - Conventional and satellite data
    - Copernicus Climate Change Service work & other work by agencies (EUMETSAT, ESA, NOAA/NASA, CMA)

- Improved bias models for ascending-descending / orbital / harmonic biases
    - for sounding radiances (Booton et al [2013], Bormann et al [2023])
    - also applied to microwave imager radiances



- Correction of biases related to thermal gradients in main mirror for Aeolus winds (Rennie at al, 2021)

- Constrained variational bias correction (Han and Bormann, ECMWF Tech Memo 782, 2016)

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Model biases in the upper troposphere and stratosphere

The improved mean state for stratospheric temperature in ERA5.1

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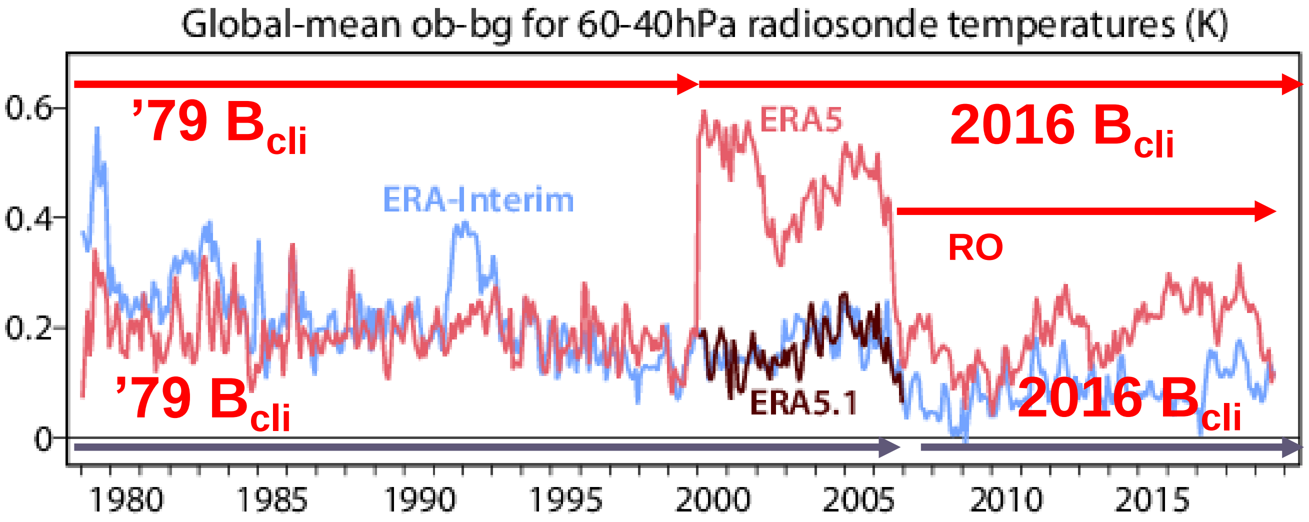

Monthly average observation-background differences from 1979 onwards for all assimilated bias-adjusted radiosonde temperature data (K) between 40 and 60 hPa, for ERA-Interim, ERA5 (based on 1979-B_{cli} before 2000 and 41r2-B $_{cli}$ afterwards) and ERA5.1 (using 1979-B_{cli} from 2000-2006).

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 first guess departures

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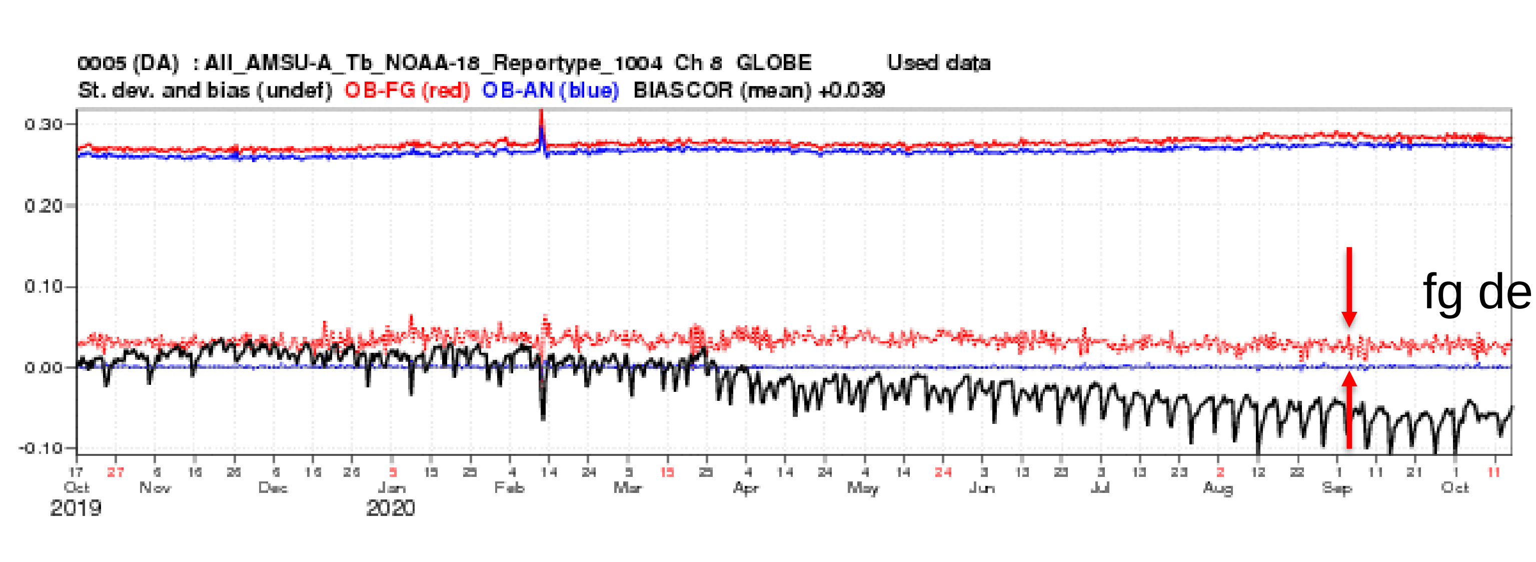
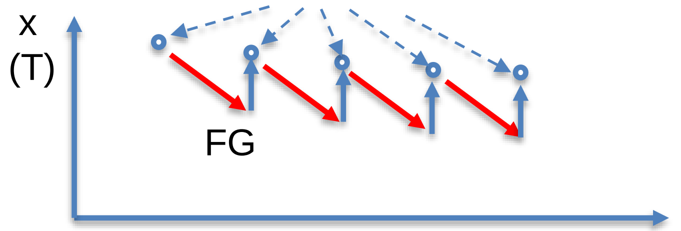
NOAA-18 AMSU-A8



fg departures biased by ~25 mK



Model Error / AMSU-A Mean First Guess Departures in ERA5

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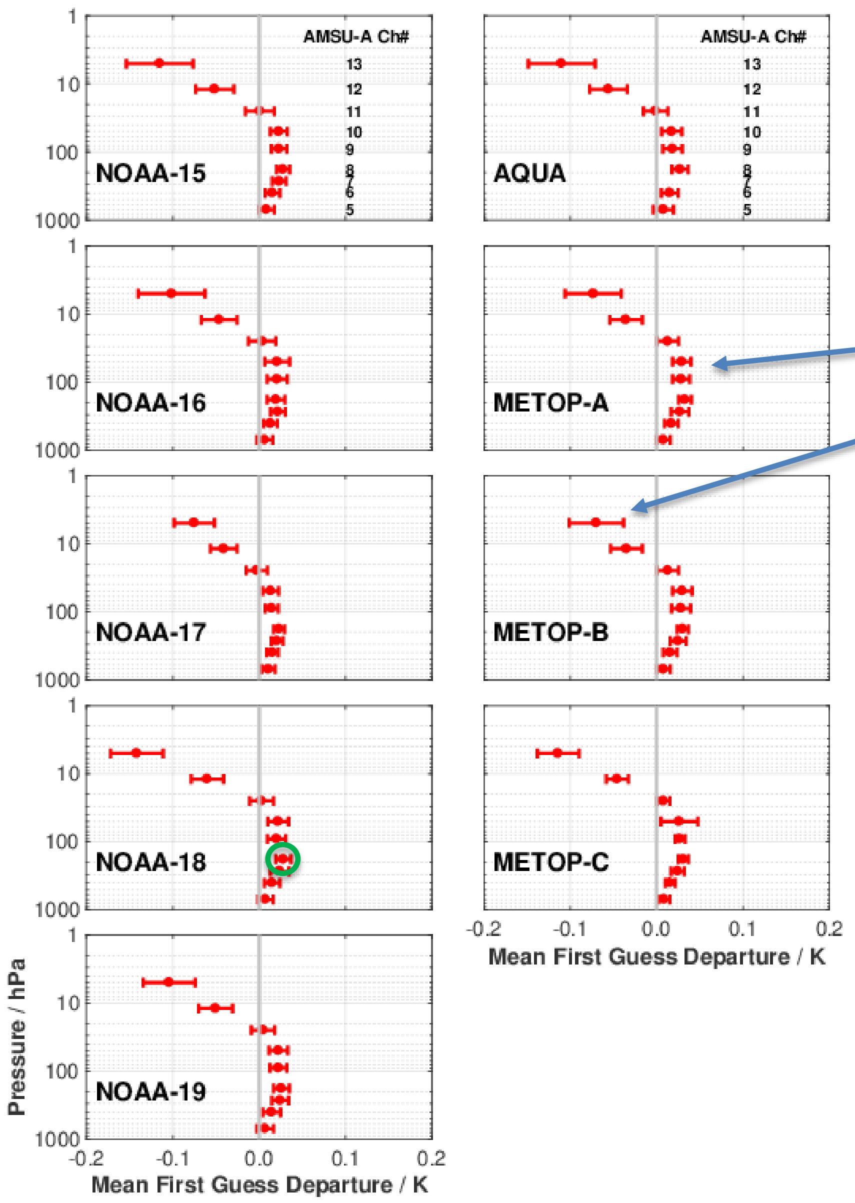


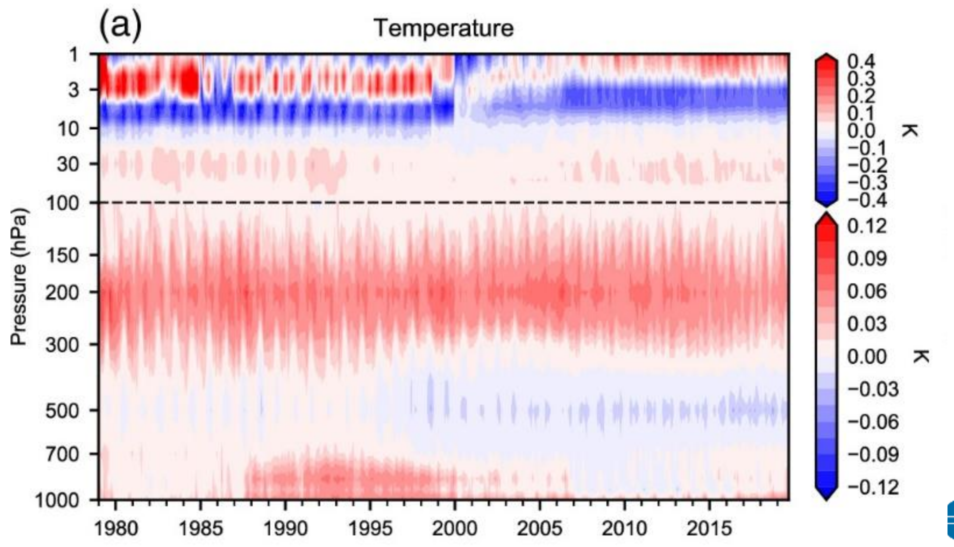
ERA5 mean first guess departures shown for AMSU-A

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 First Guess Departures in ERA-Interim

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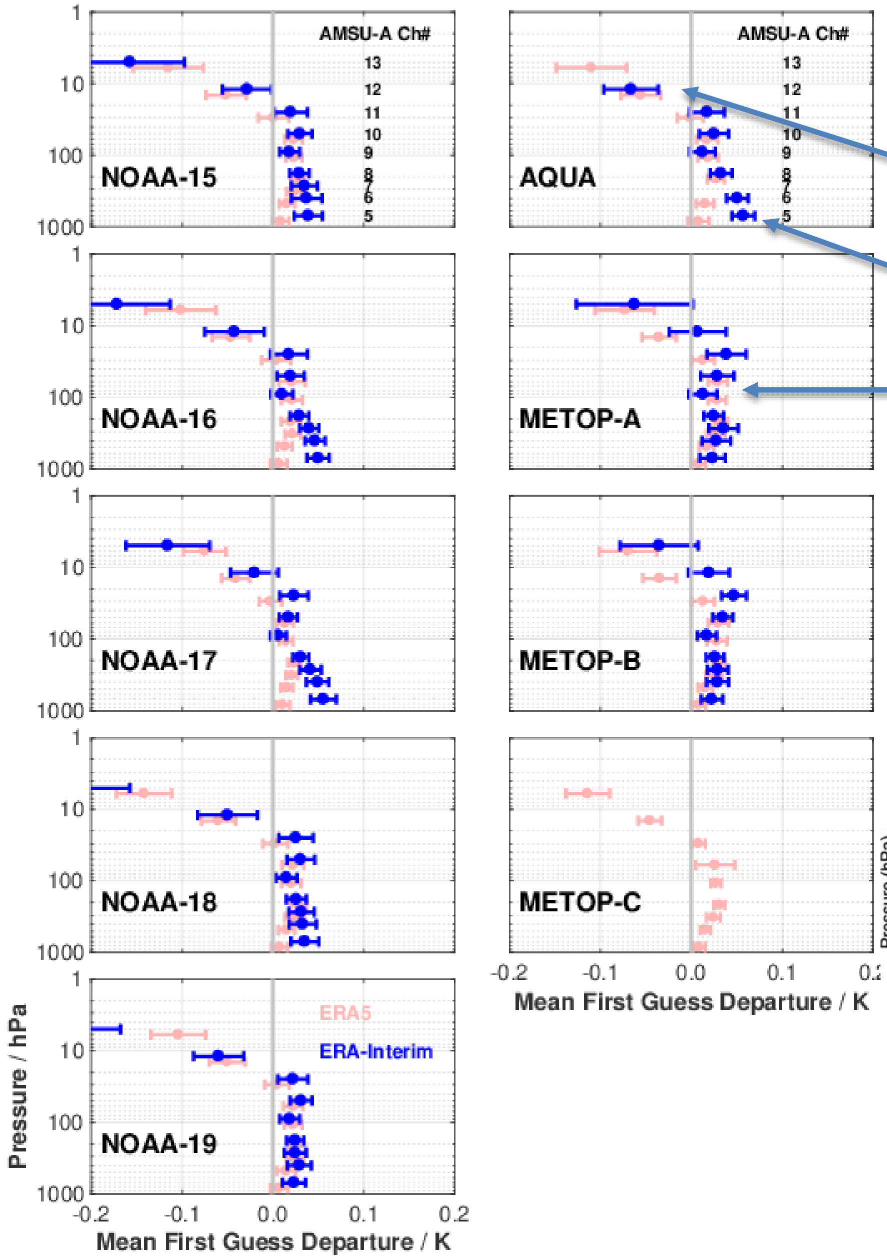


Indications that ERA-Interim:

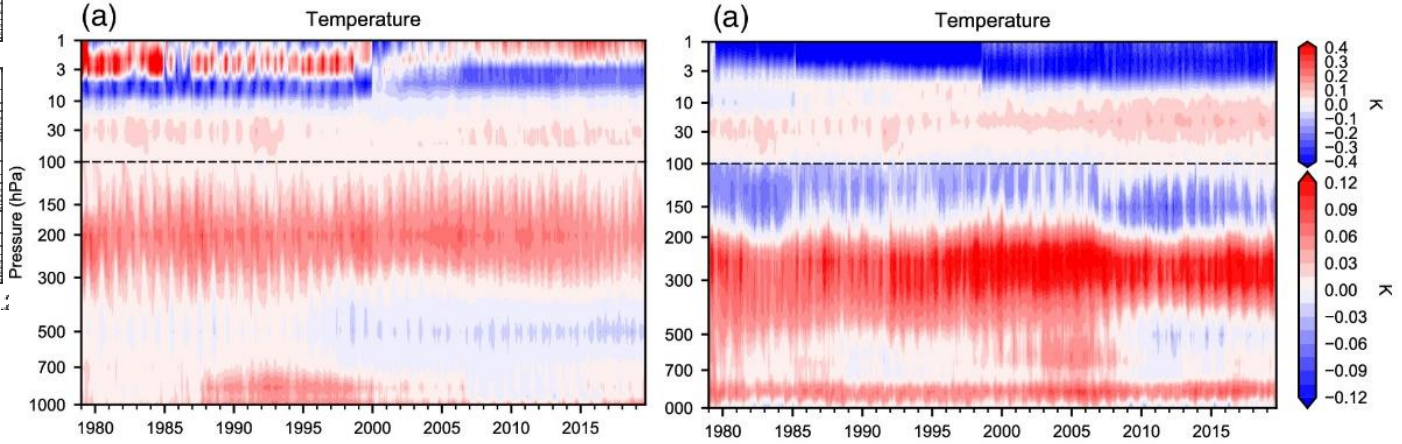
Exhibits similar biases (to ERA5) above 10 hPa

Exhibits larger biases below 200 hPa

Exhibits smaller biases around 100 hPa.

ERA5 analysis increments

ERA-Interim analysis increments



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Model Error / AMSU-A Mean First Guess Departures in proto-ERA6 testing (CY48R1)

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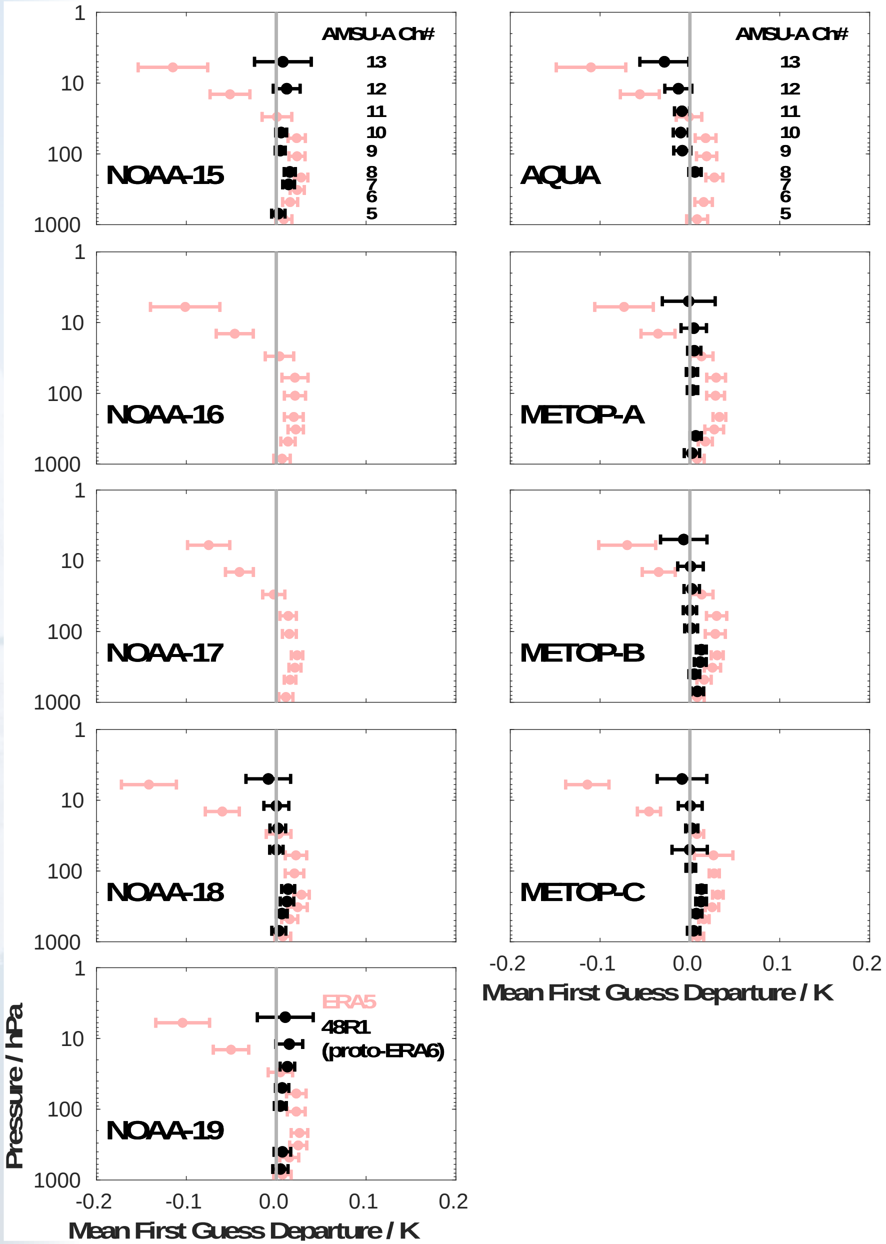

- Based on JJA 2020 CY48R1 experiment
- Significant changes since ERA5 cycle (CY41R2, 2016):
  - Weak Constraint 4D-Var above 100 hPa
  - Improved dynamics: quintic interpolation
  - Clear sky -> all sky scheme for tropospheric channels
- Overall – model in better agreement with observations

Impacts of model and observation biases in ERA5

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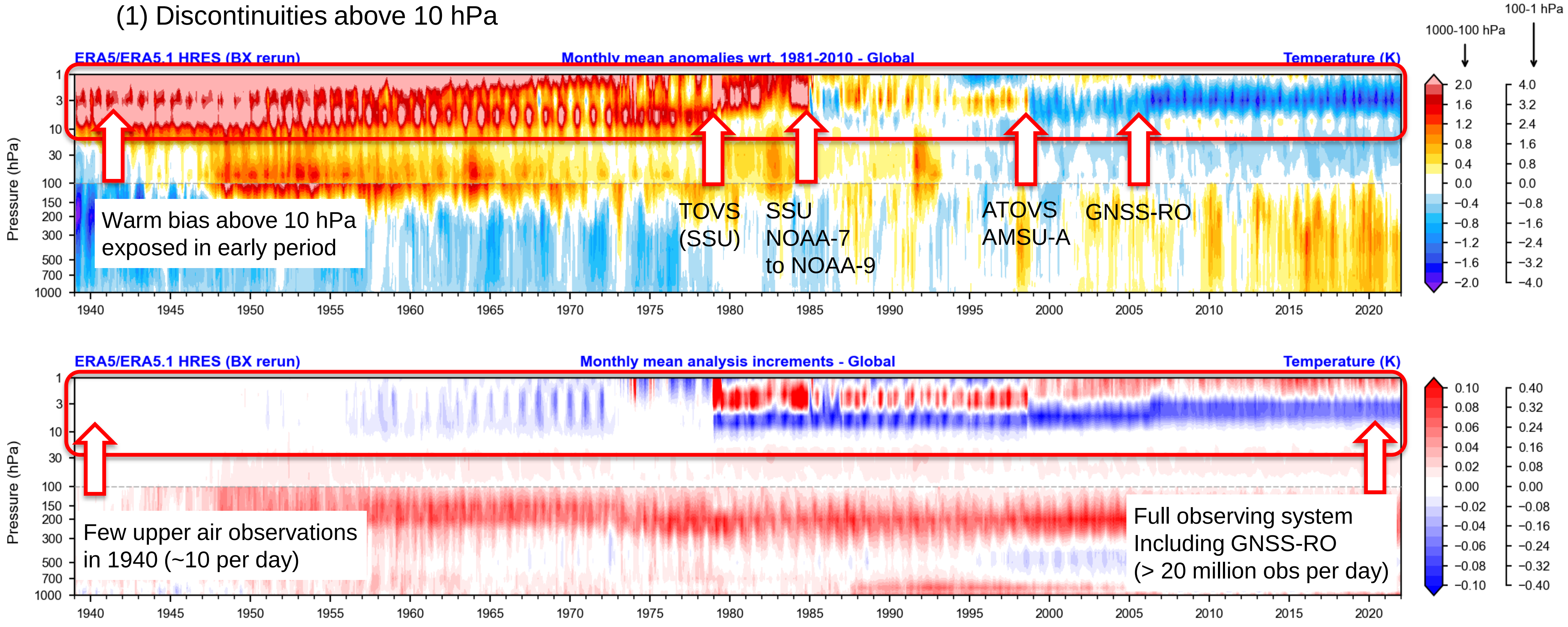
(1) Discontinuities above 10 hPa



- General problems in reanalysis temperatures above 10 hPa well documented (see SPARC-RIP report 2021).

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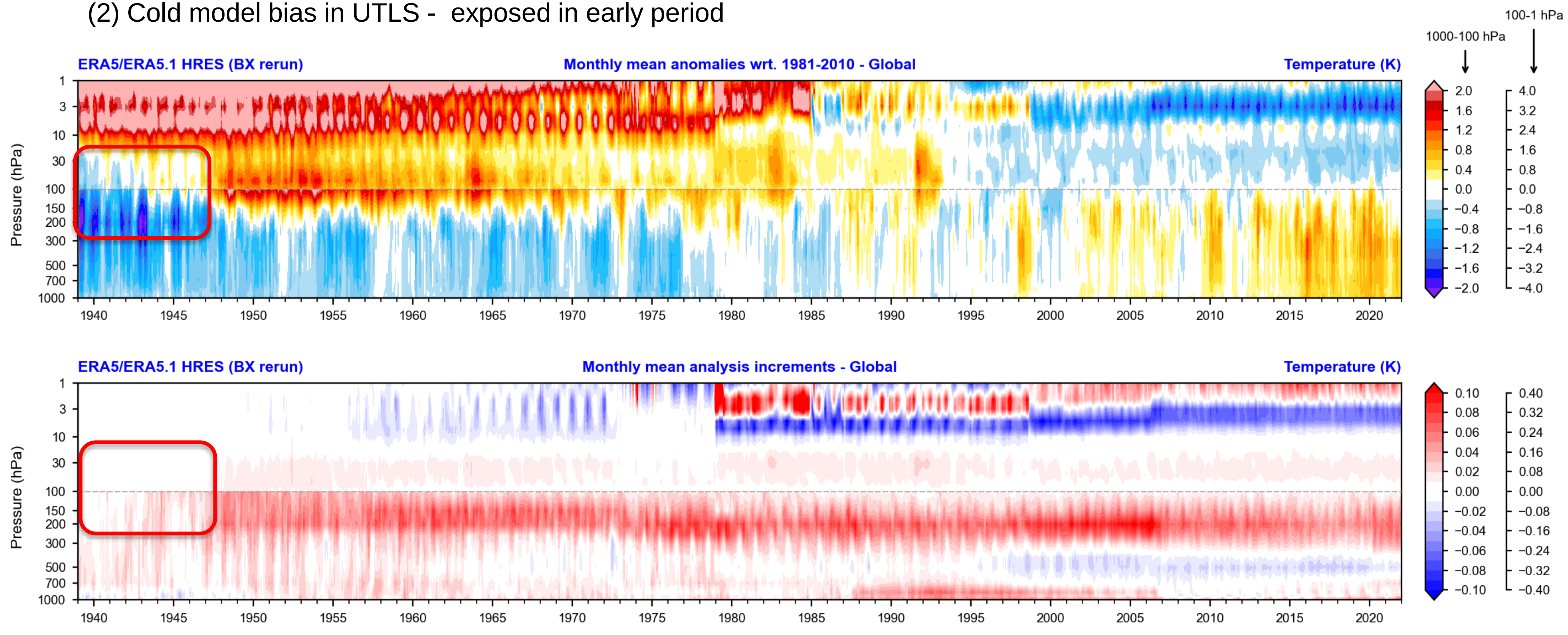
(2) Cold model bias in UTLS - exposed in early period



- Very few observational constraints on stratospheric temperature analysis in the early 1940s – so UTLS cold bias is exposed.
- Analysis increments in 10-200 hPa layer very small 1940 (< 20mK above 100 hPa as a global mean)

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Impacts of model and observation biases in ERA5

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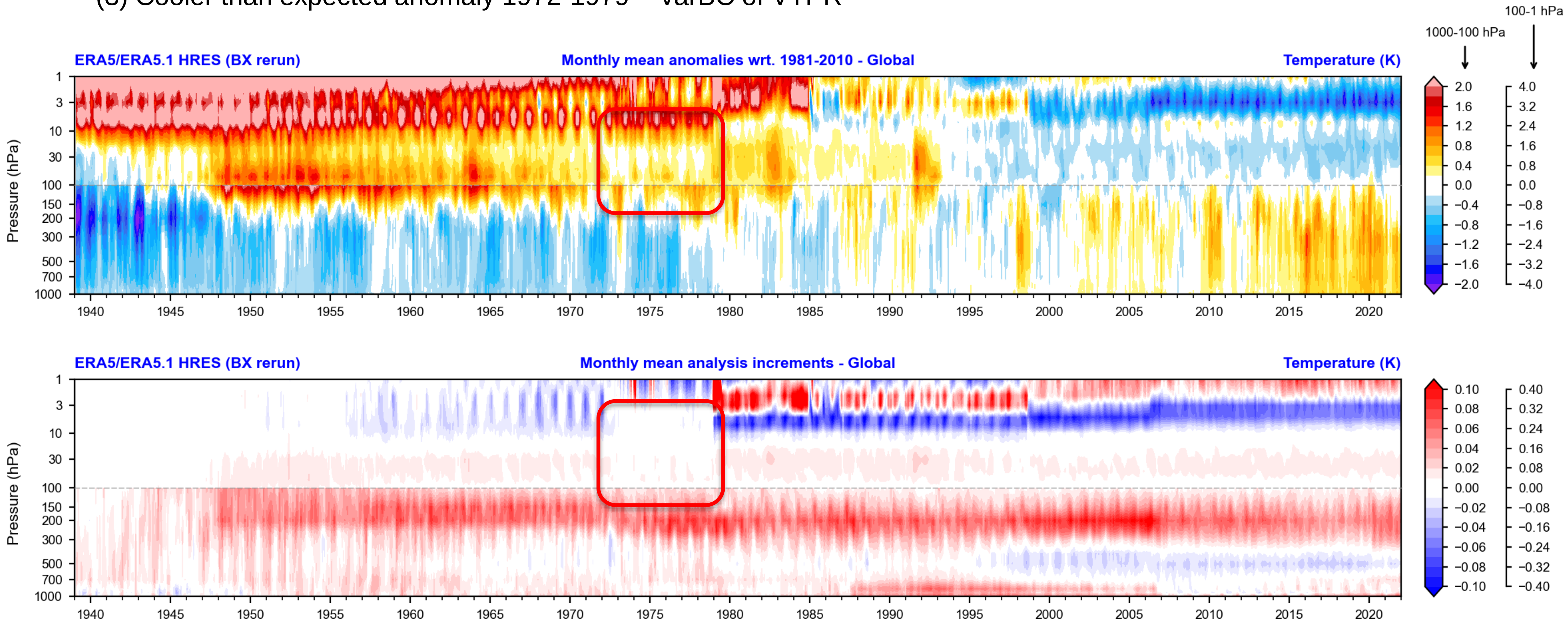
(3) Cooler than expected anomaly 1972-1979 – VarBC of VTPR



- General problem foreseen & analysed in Eyre (QJ, 2017): with VarBC, if radiances are dominant (cf anchors) model bias is reinforced
- VTPR channels 1 & 2 bias corrected using VarBC – reinforcing model cold bias
- Despite clear benefits (from assimilating VTPR) in improving synoptic analysis – mean state exhibits a discontinuity.
- VTPR exhibits significant radiometric and spectral errors ⇒ we need VarBC

Impacts of model and observation biases in ERA5

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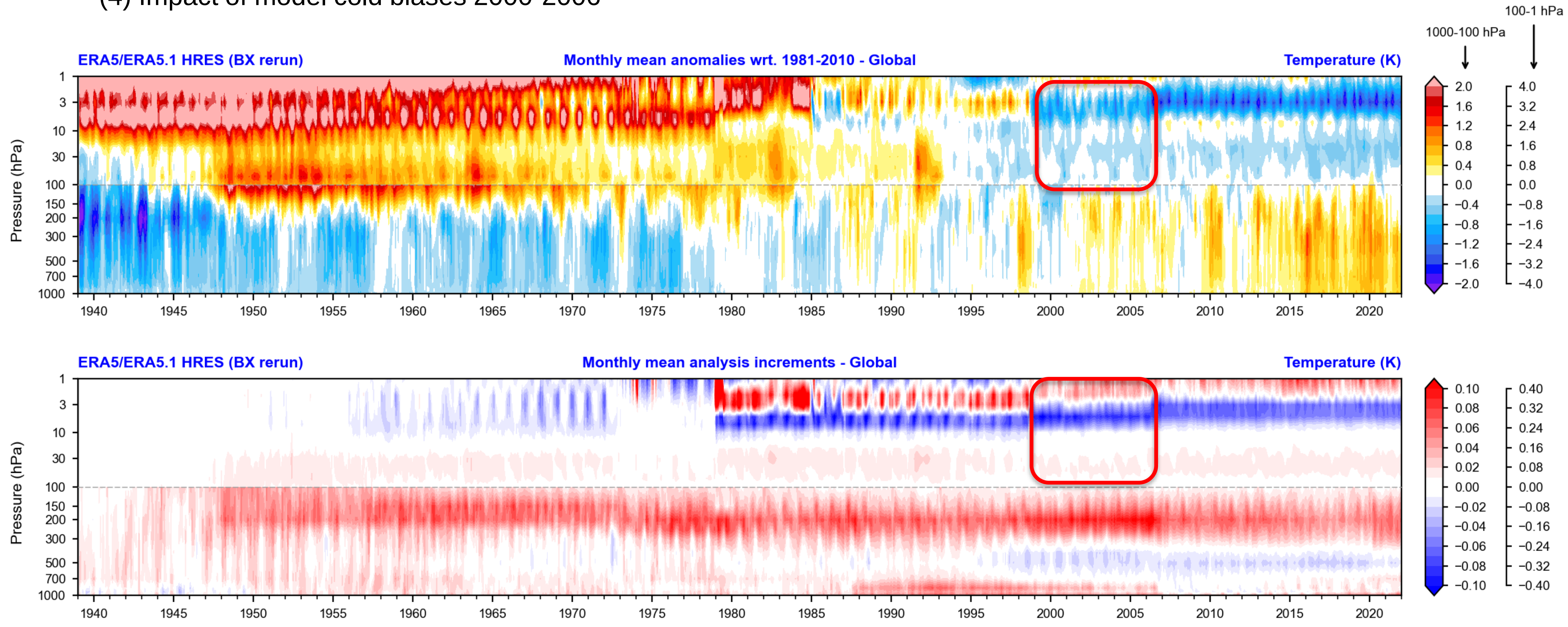
(4) Impact of model cold biases 2000-2006



- ERA5 and ERA5.1: See previous slides

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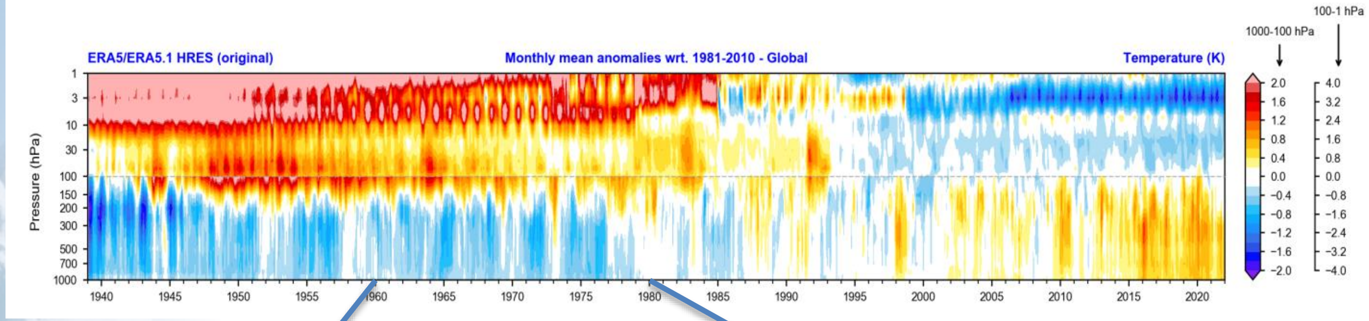
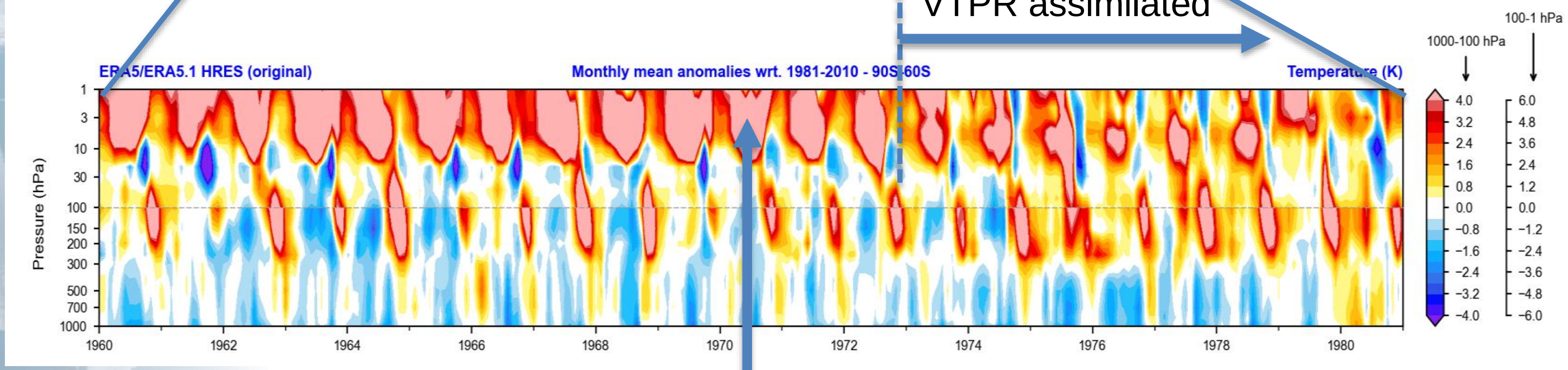
Upper stratospheric biases in ERA5: Temperature anomalies relative to ERA5 climate

Global statistics 1940 - 2022



Southern polar statistics 1960 - 1980

VTPR assimilated



IRIS experiments

- Generally, ERA5 temperature analyses above 10 hPa exhibit biases and discontinuities
- Particularly large biases evident in southern polar winter (>> 6K in the plot shown)
- Repeatable from year-to-year (before 1972)
- Reduced following the assimilation of VTPR data (Nov 1972 - Jan 1979)

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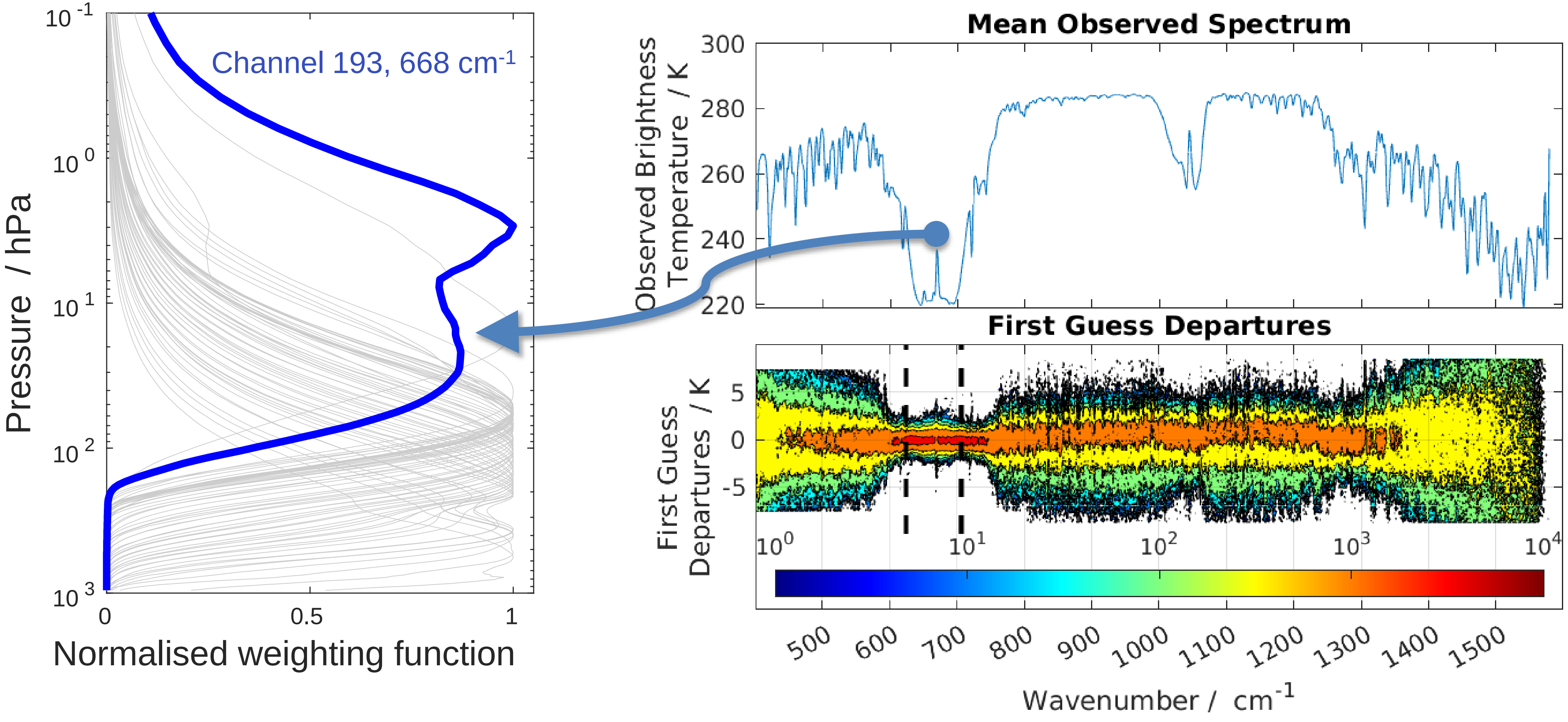
Investigating biases using ealry hyperspectral sounding data (Nimbus-4 IRIS, 1970)



- IRIS data has been shown to be valuable in improving SH analysis quality (April 1970 – January 1971)
- Valuable for assessing biases in ERA5 in previously unobserved regions (eg S. Polar upper stratophere)
- Highest peaking channel is particularly valuable

Evaluation of IRIS radiances relative to ERA5, rocketsondes & SIRS radiances (Andrzej Klonecki *et al* , Spascia)

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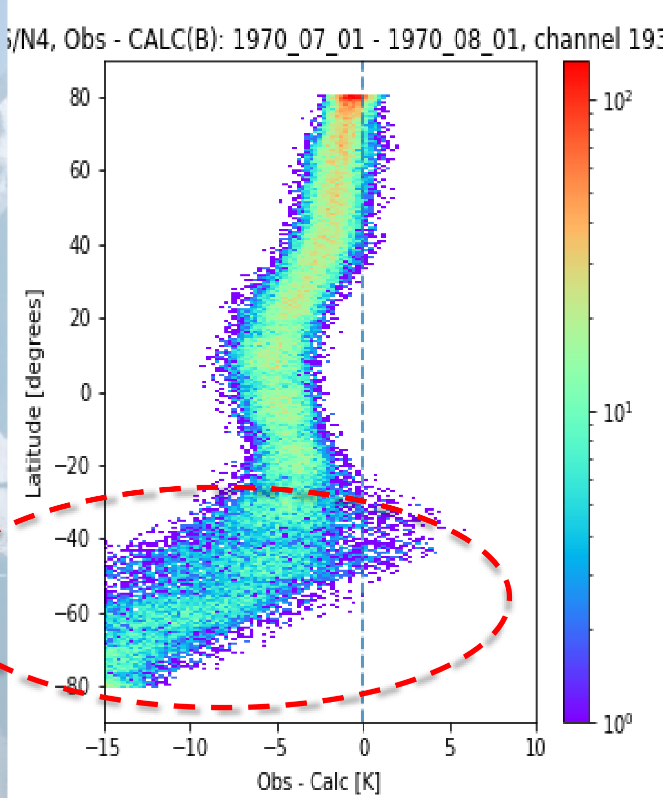
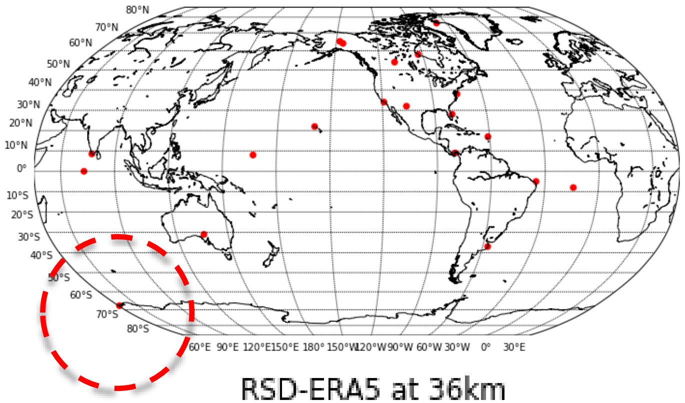
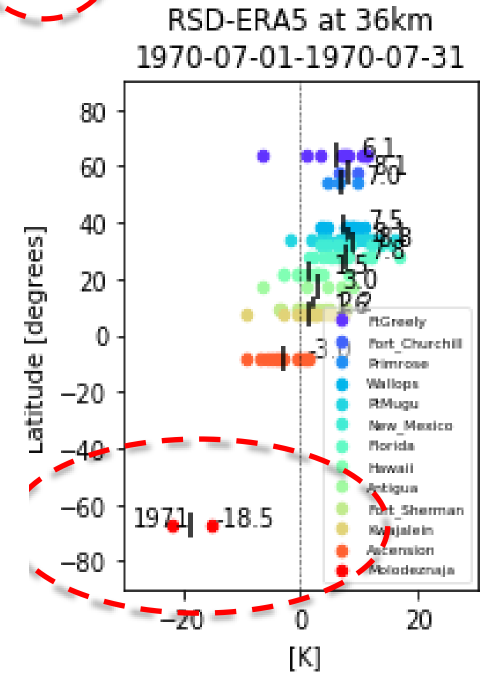
IRIS Obs vs ERA5 channel 193 peaking at 3 - 30hPa

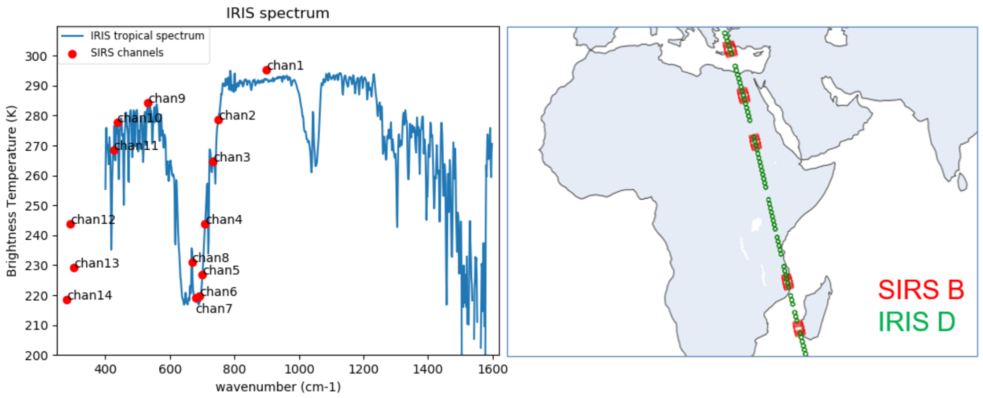


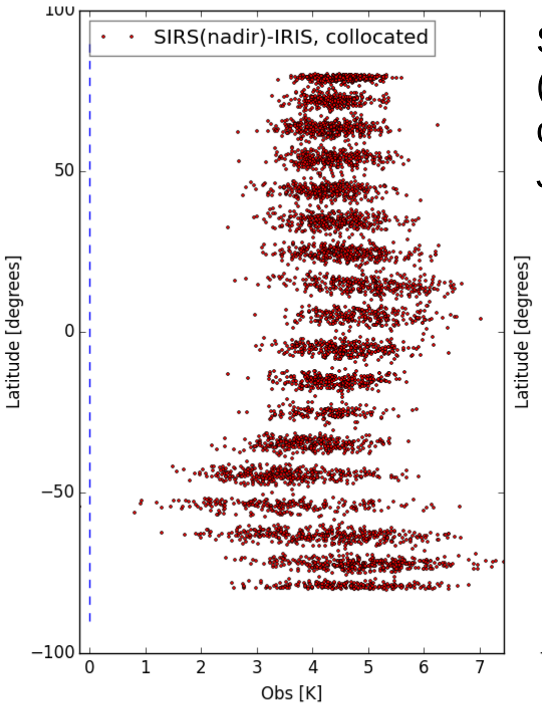
rocket sondes vs ERA5





Nimbus-4 IRIS vs SIRS





SIRS / IRIS (ch 8 / ch 193) colocations for July 1970

In summary, relative to :

- Its own climate (1981-2010);
- IRIS observations;
- SIRS observations; and
- Rocket-sonde data

ERA5 exhibits a warm bias, at 36km / 5hPa, of ~15K

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Impact of assimilating IRIS on southern polar stratospheric biases

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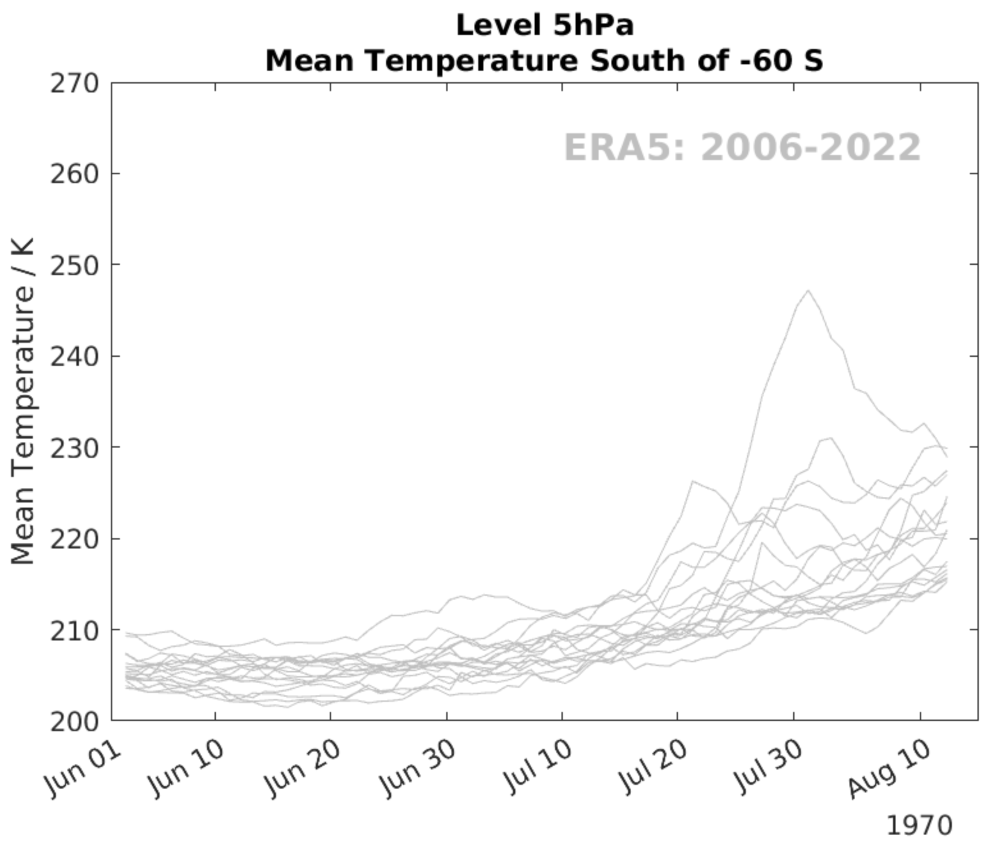

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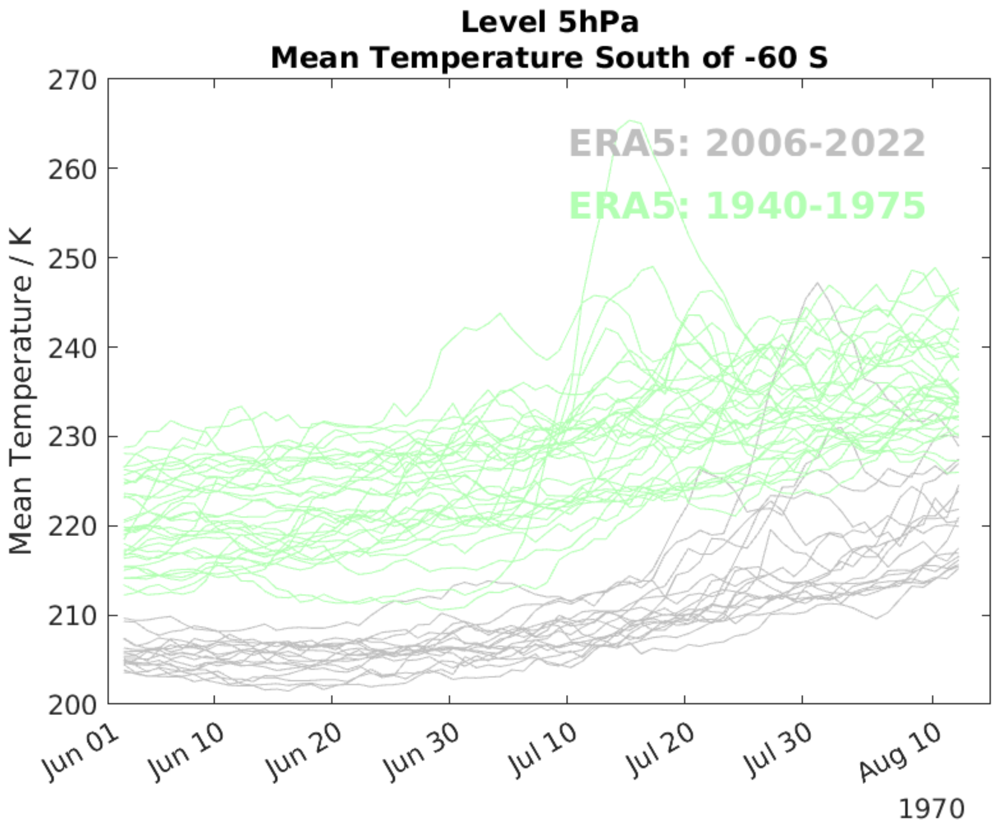
Impact of assimilating IRIS on southern polar stratospheric biases



- During the GNSS-RO era (2006 -) the stratospheric temperature analysis is realistic
- In the early period (1940-75) of the reanalysis, few observations constrain the analysis ⇒ model biases are exposed. At 5hPa, temperatures are **10 – 25 K warmer** in mid-winter, relative to 2006-2022

Impact of assimilating IRIS on S. polar stratospheric biases

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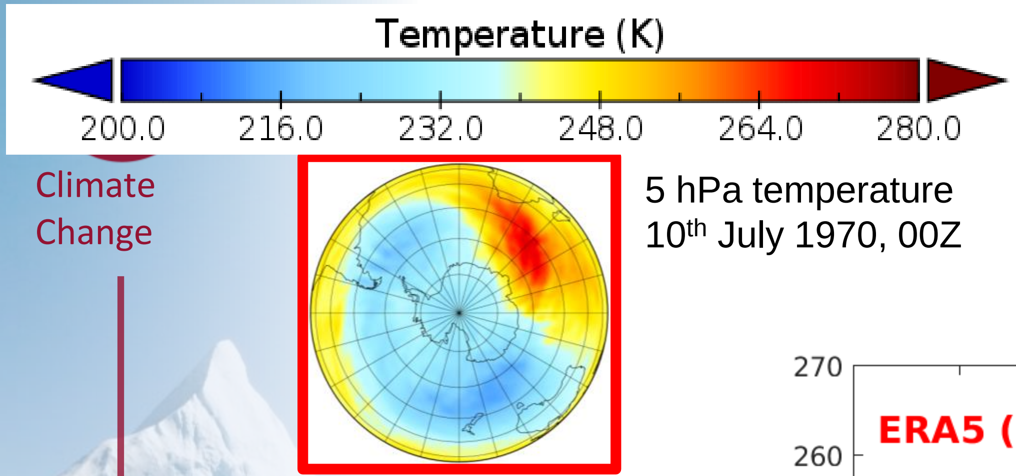
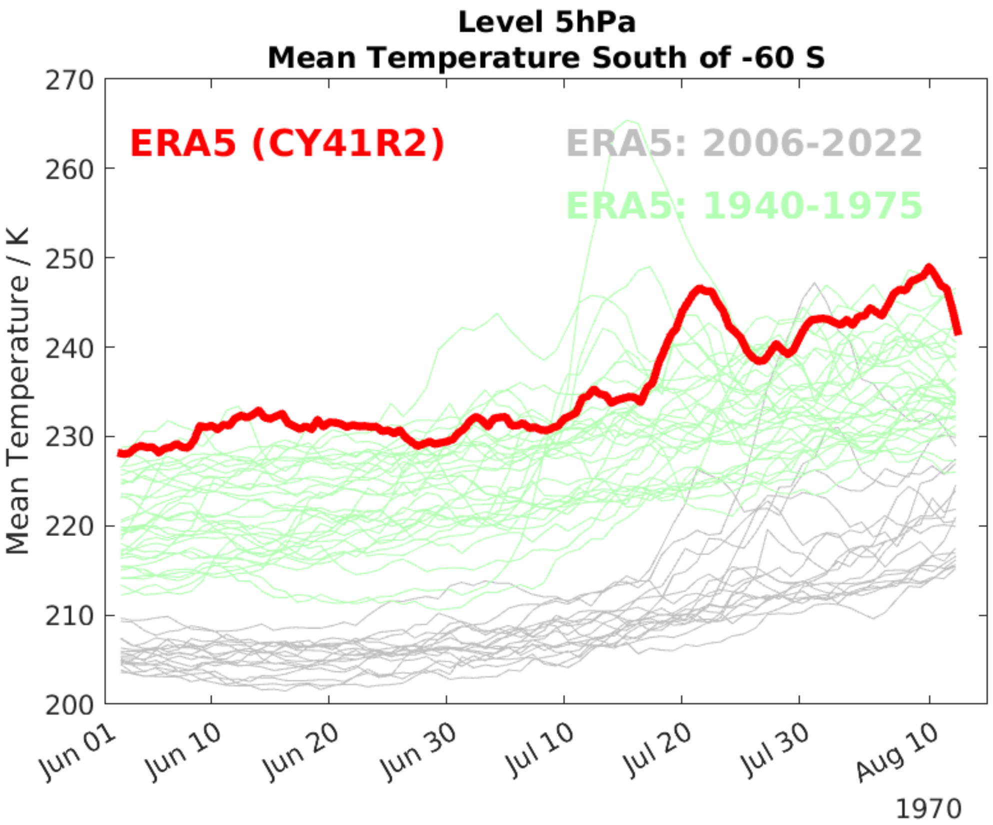


5 hPa temperature
10th July 1970, 00Z



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Impact of assimilating IRIS on S. polar stratospheric biases

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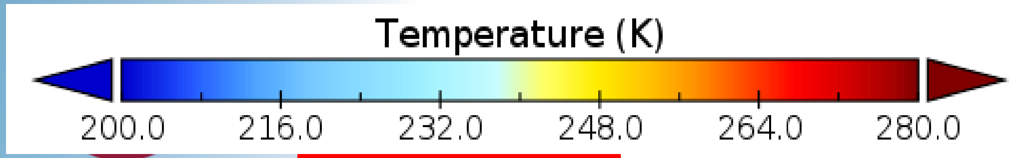

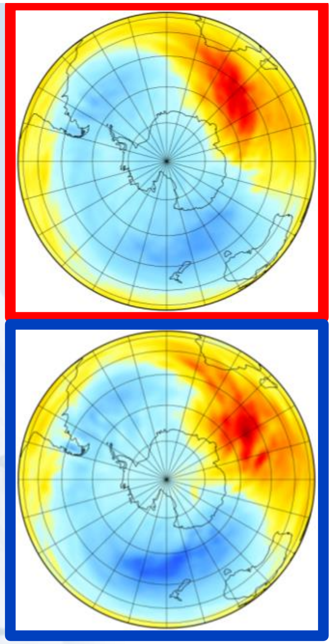

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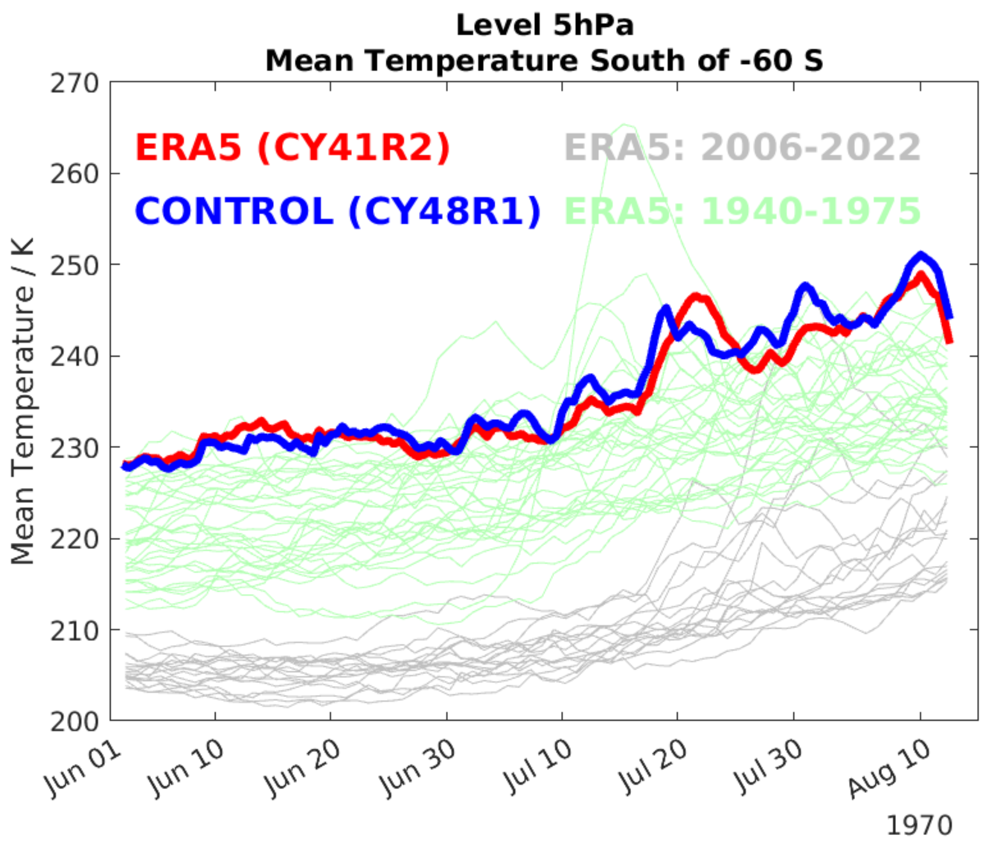

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Impact of assimilating IRIS on S. polar stratospheric biases

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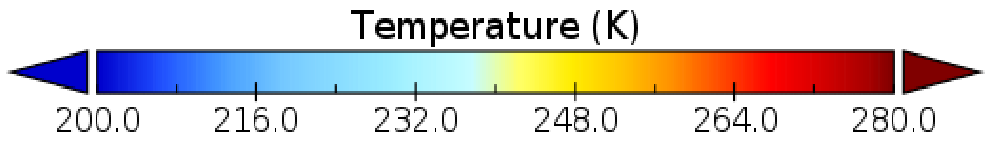

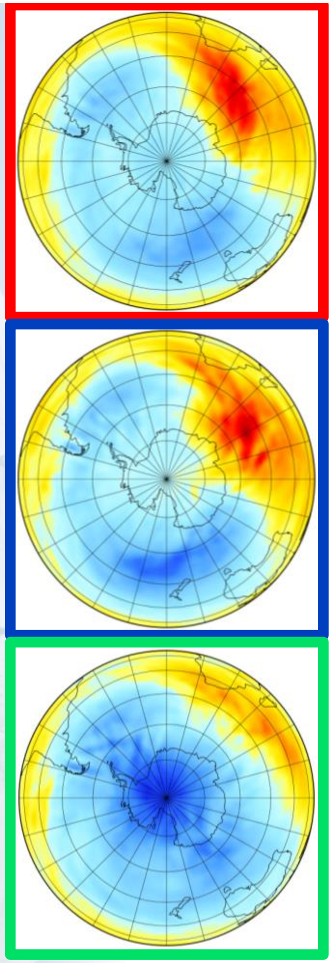

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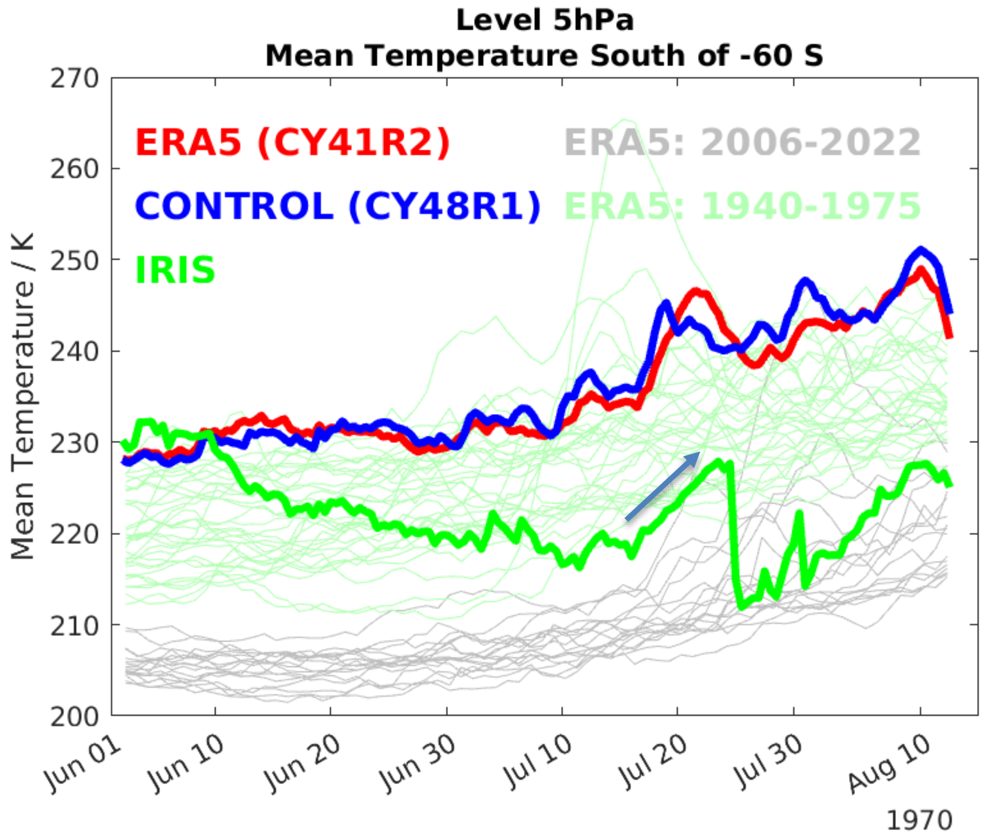

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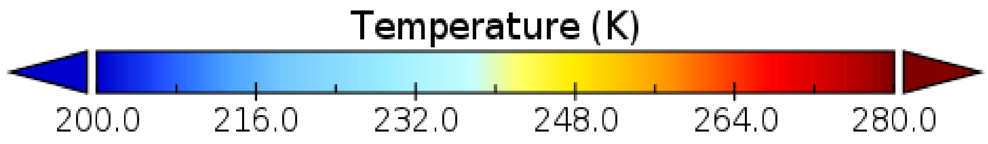
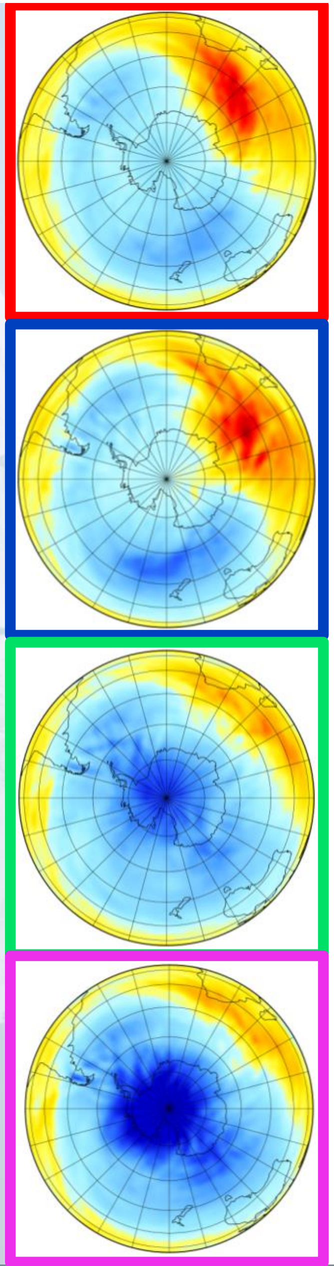
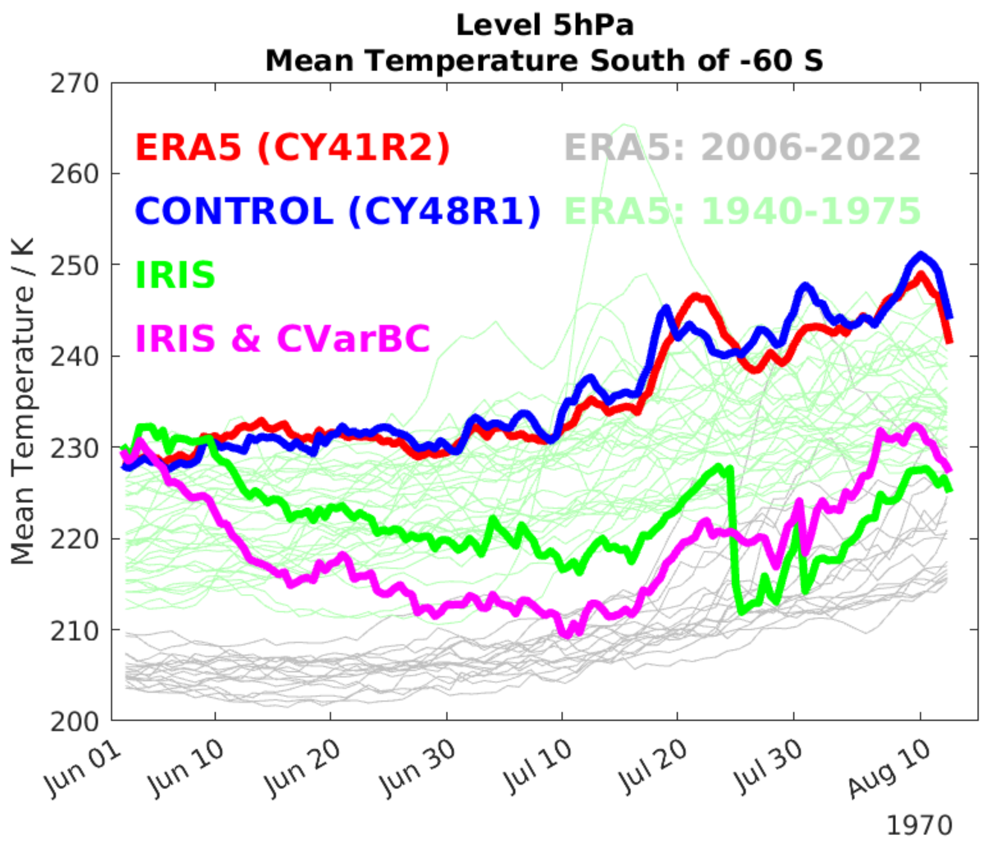


Impact of assimilating IRIS on S. polar stratospheric biases

Climate
Change



5 hPa temperature
10th July 1970, 00Z



- During the GNSS-RO era (2006 -) the stratospheric temperature analysis is realistic
- In the early period (1940-75) of the reanalysis, few observations constrain the analysis ⇒ model biases are exposed. At 5hPa, temperatures are **10 – 25 K warmer** in mid-winter, relative to 2006-2022
- **ERA5** (41R2, 2016) in 1970 is at the top end of this range, with temperatures of 230K in mid-winter
- The **CONTROL** (48R1, 2022) exhibits the same warm bias
- **Assimilating IRIS** *gradually* brings temperatures to more realistic values. Note: increase (↗) from 16th-24th July is associated with an **outage** of IRIS observations
- Using **Constrained VarBC** (Han & Bormann) reduces the bias absorbed by VarBC, and accelerates cooling of the analysis towards more realistic values.

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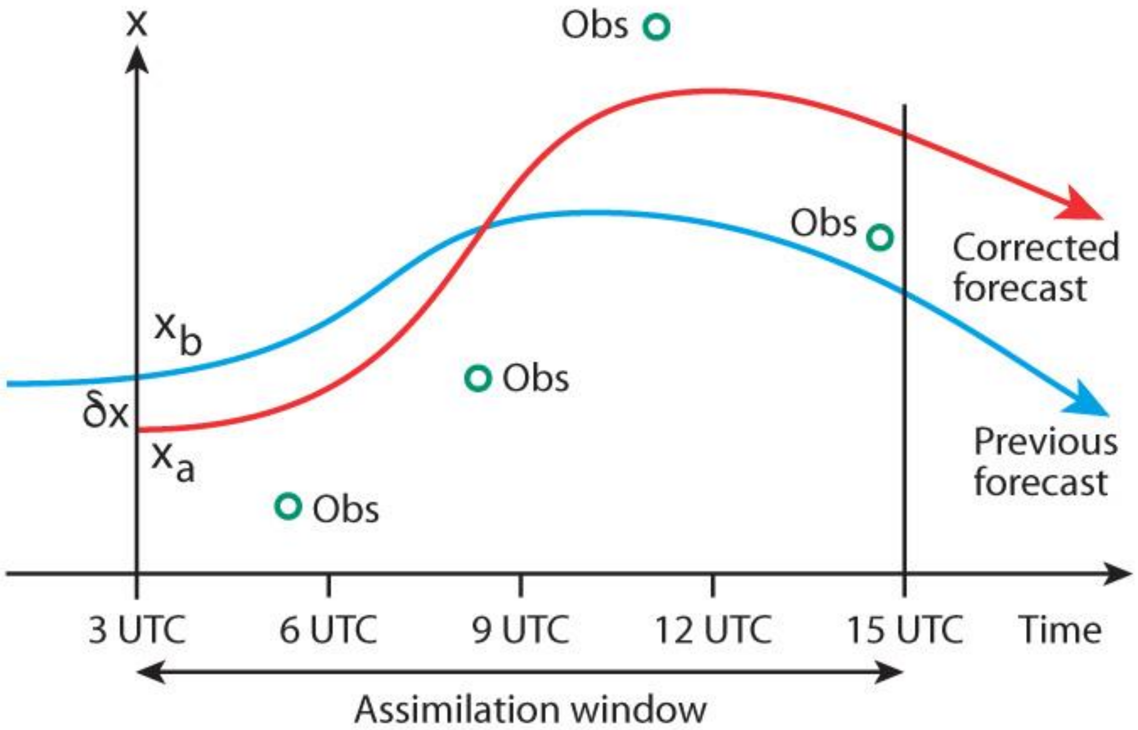
Standard 4D-Var formulation

4D-Var is a common algorithm to find the optimal initial state by minimising the discrepancies with the prior estimate and the observations



Model's equation

$$x_k = \mathcal{M}_k(x_{k-1})$$

4D-Var cost function

$$\begin{aligned} J(x_0) &= \frac{1}{2}(x_0 - x_b)^T \mathbf{B}^{-1}(x_0 - x_b) \\ &+ \frac{1}{2}\sum_{k=0}^{K}[y_k - \mathcal{H}(x_k)]^T \mathbf{R}_k^{-1}[y_k - \mathcal{H}(x_k)] \end{aligned}$$

➔ Standard formulation assumes that the model is perfect

➔ A model trajectory is entirely determined by its initial condition

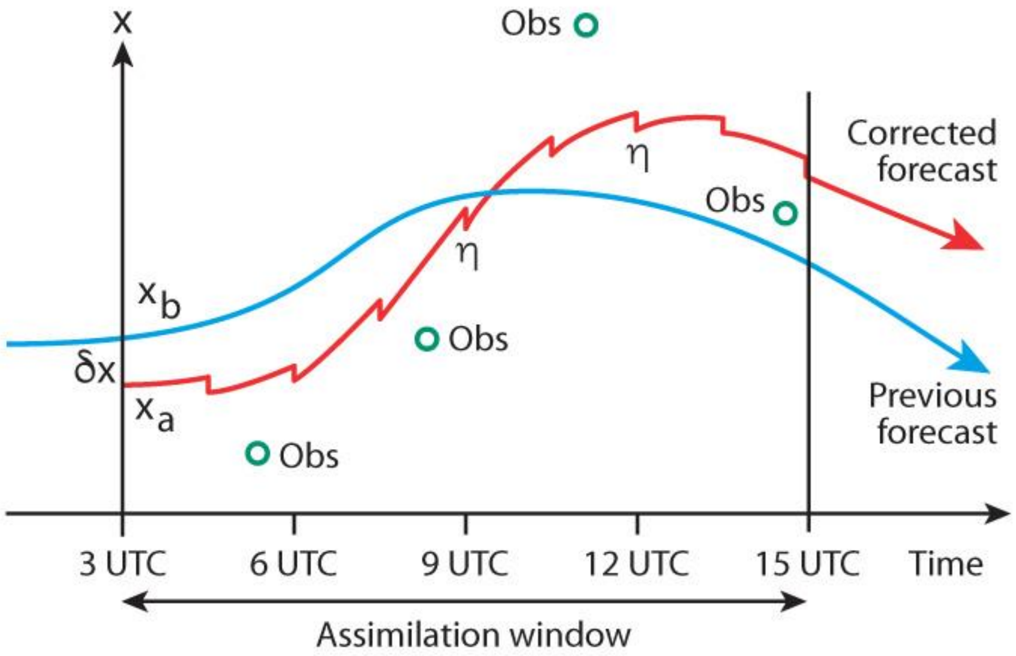
Climate Change

Weak-constraint 4D-Var formulation

We assume that the model is not perfect, adding an error term η in the model equation

$$x_k = \mathcal{M}_k(x_{k-1}) + \eta \quad \text{for } k = 1, 2, \cdots, K$$

The model error estimate η contains 3 physical fields (temperature, vorticity and divergence)



➔ Introduce additional degrees of freedom to fit background and observations

➔ A model trajectory is entirely determined by its initial condition and the model error forcing

➔ Concept of scale separation introduced between background and model errors

➔ Constant model error forcing over the assimilation window

Laloyaux et al., Exploring the potential and limitations of weak-constraint 4D-Var, 2020

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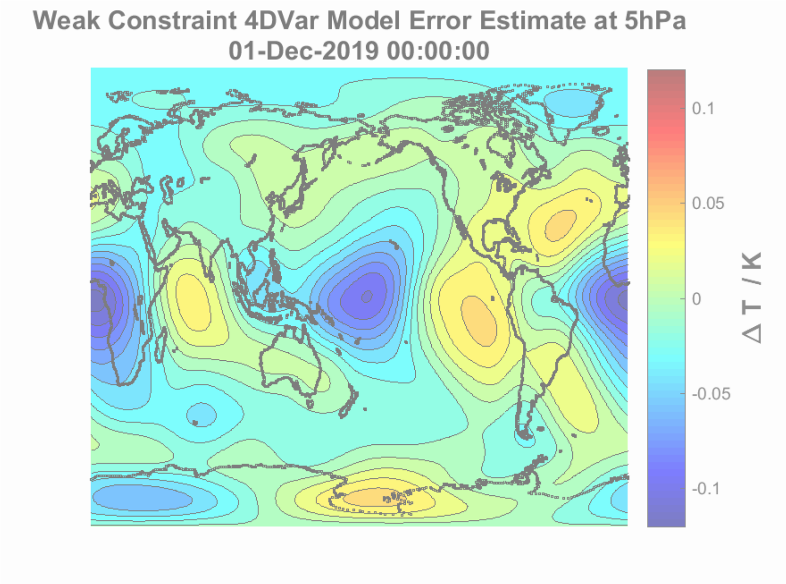
Model initial condition

Model bias correction



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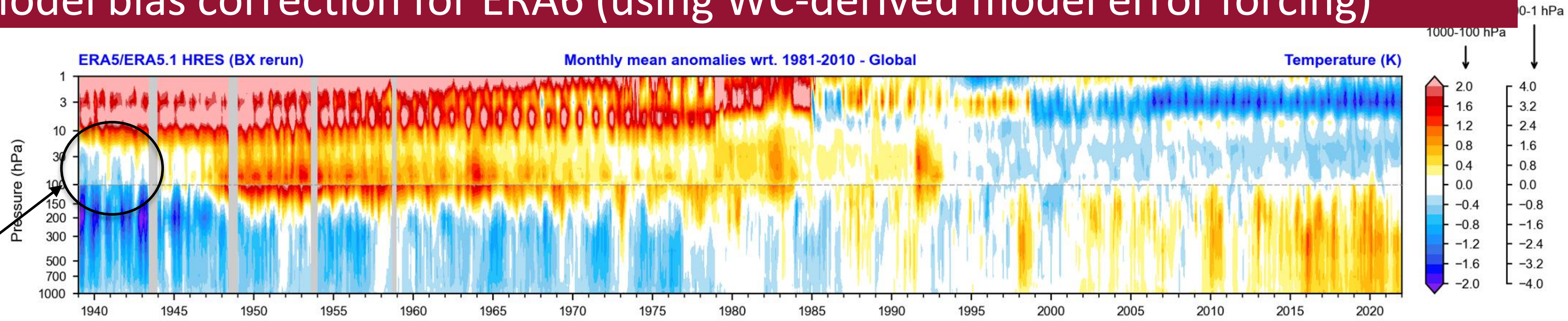
Laloyaux et al., Exploring the potential and limitations of weak-constraint 4D-Var, 2020

Model bias correction for ERA6 (using WC-derived model error forcing)

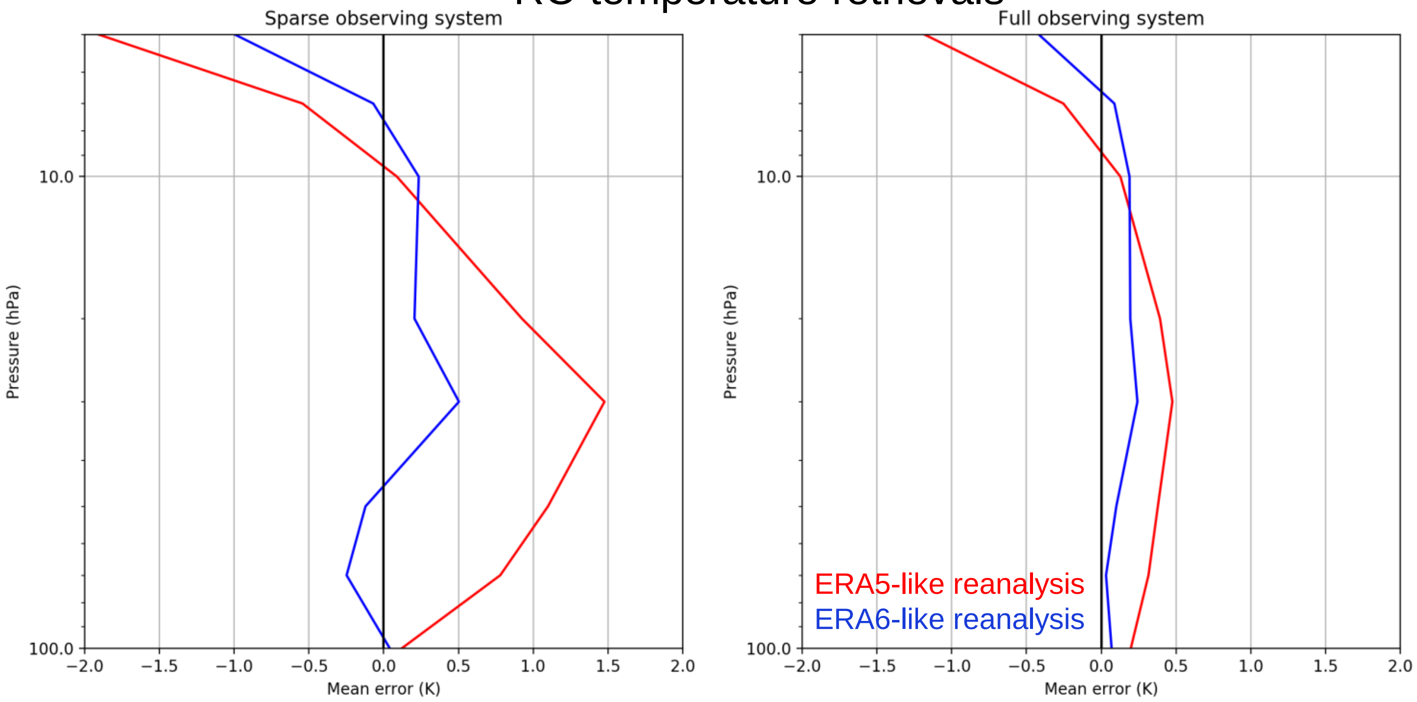
Climate Change



Extension of ERA5 to 1940
Few upper air observations exposed the model bias

First guess mean error with respect to RO temperature retrievals

Sparse observing system (modern system with all stratospheric observations blocklisted)



Recent observing system

ECMWF

Model error climatology derived from weak constraint 4D-Var estimates of model error

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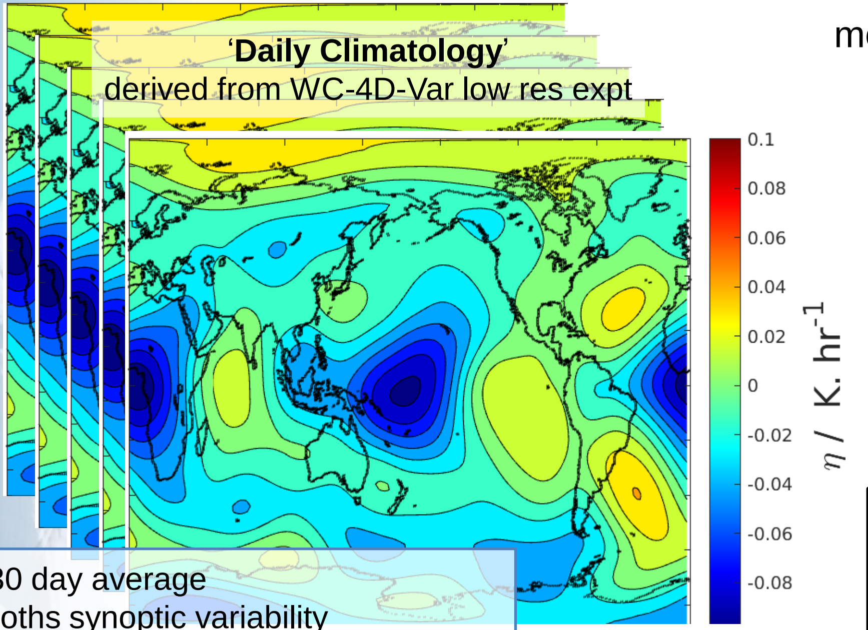
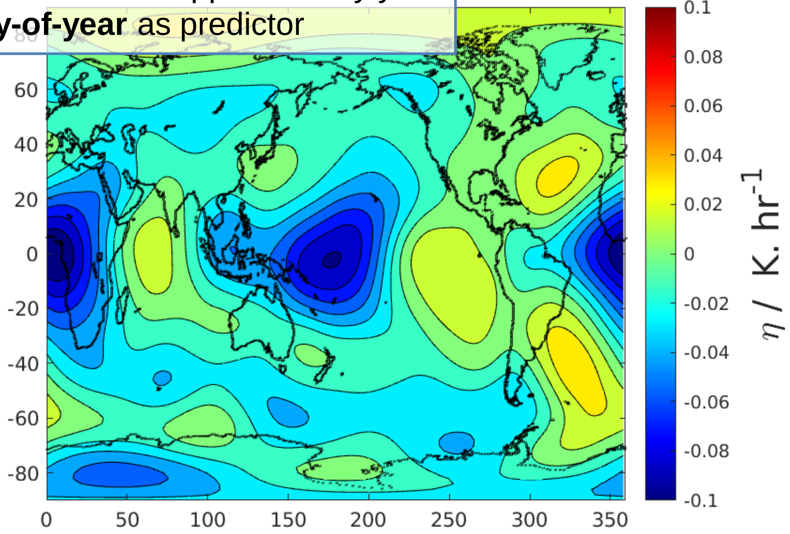
model error estimates at 5hPa

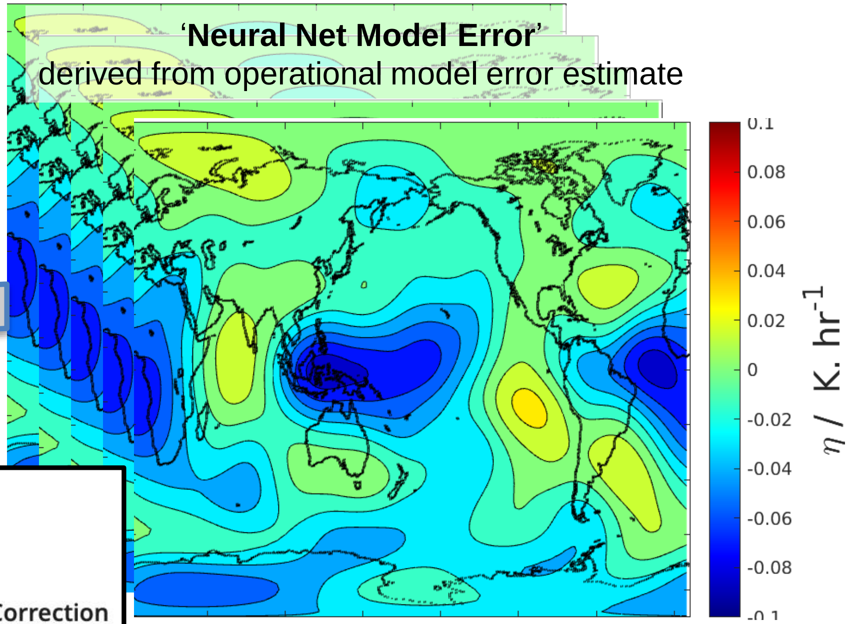
'Daily Climatology'
derived from WC-4D-Var low res expt



- +/- 30 day average
- smooths synoptic variability
- TCo399 resolution (28km)
- derived from 2019 – applied in any year
- uses **day-of-year** as predictor



'Neural Net Model Error'
derived from operational model error estimate



JAMES Journal of Advances in Modeling Earth Systems

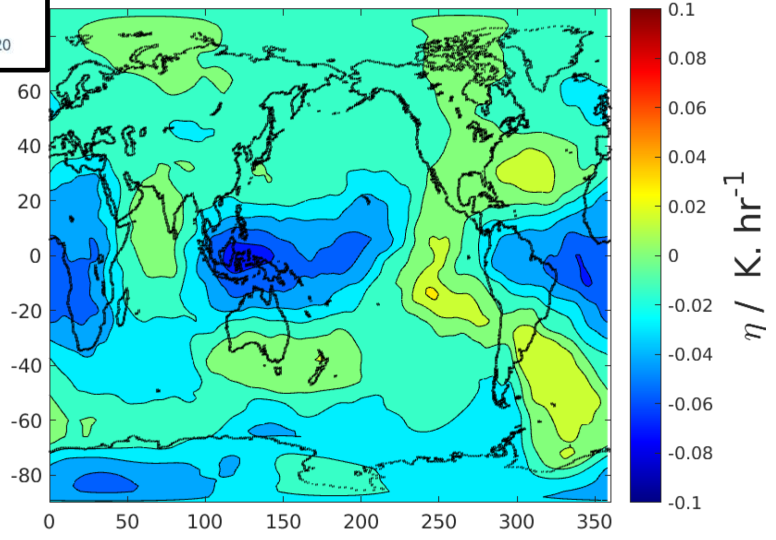
Research Article | Open Access

Machine Learning for Model Error Inference and Correction

Massimo Bonavita, Patrick Laloyaux

First published: 13 November 2020 | https://doi.org/10.1029/2020MS002232 | Citations: 20

- derived from June 2020 - Feb2022
- predictors:
  - lat & lon
  - time of day & month of year
  - background state (T)



estimates shown for 1/7/1970

Model error forcing experiments in 1970 – impact on upper stratospheric temperatures

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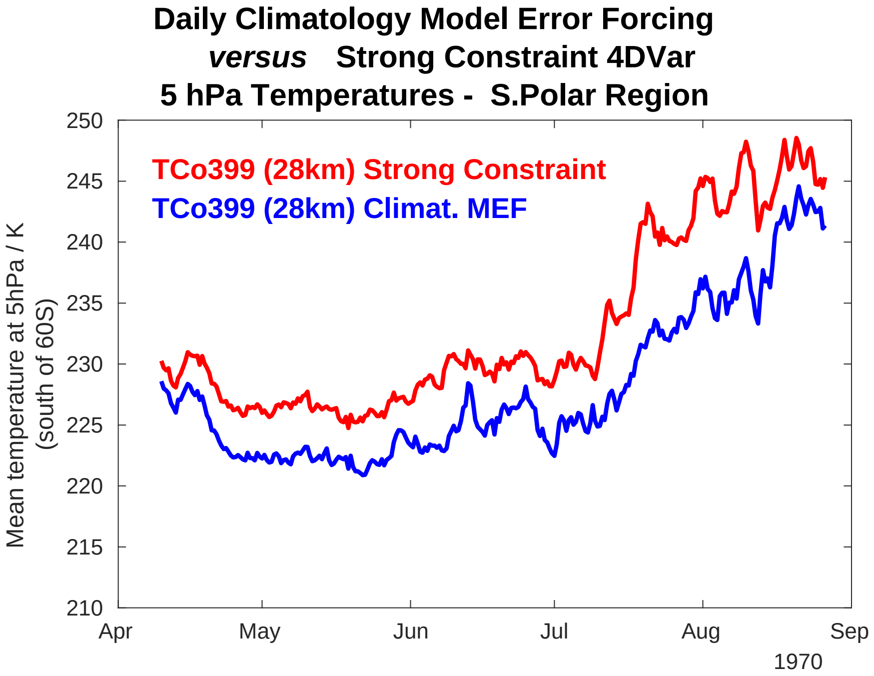

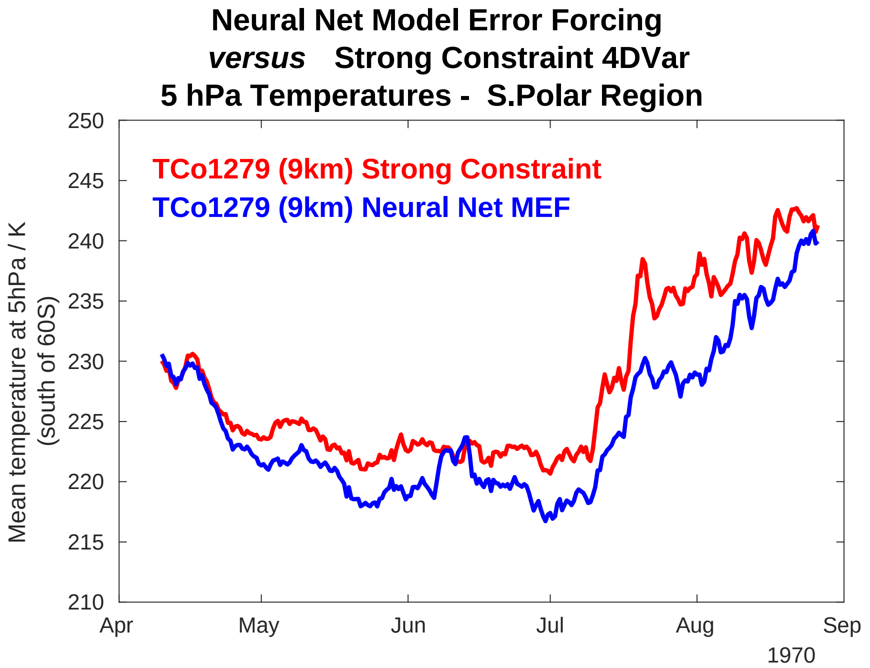

- For strong constraint & model error forcing experiments: increase in resolution (28km to 9km) helps lower minimum temperatures (230K->223K in June 1970)

- Model error forcing (both types) results in additional cooling of ~5K, with minimum temperatures of 217K

… but doesn't bring temperatures to the minimum temperatures expected (from IRIS assimilation experiments) of ~210K

- expect ERA6 (TCo799) will be closer to behavior of TCo1279 experiment shown here.

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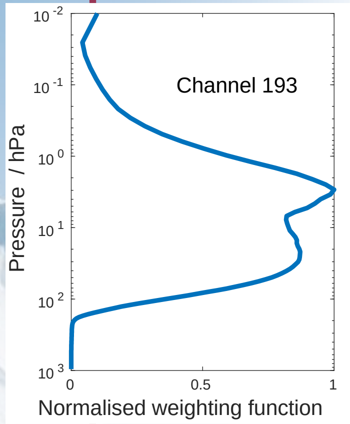
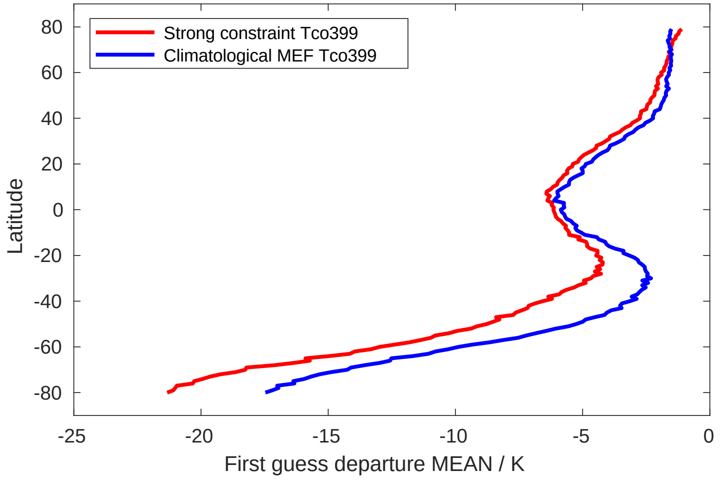
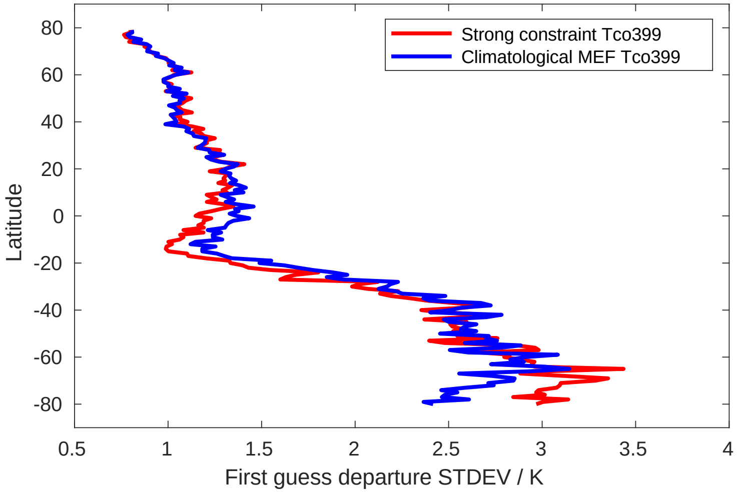
Verification of impacts of MEF: background fits to IRIS and radiosondes

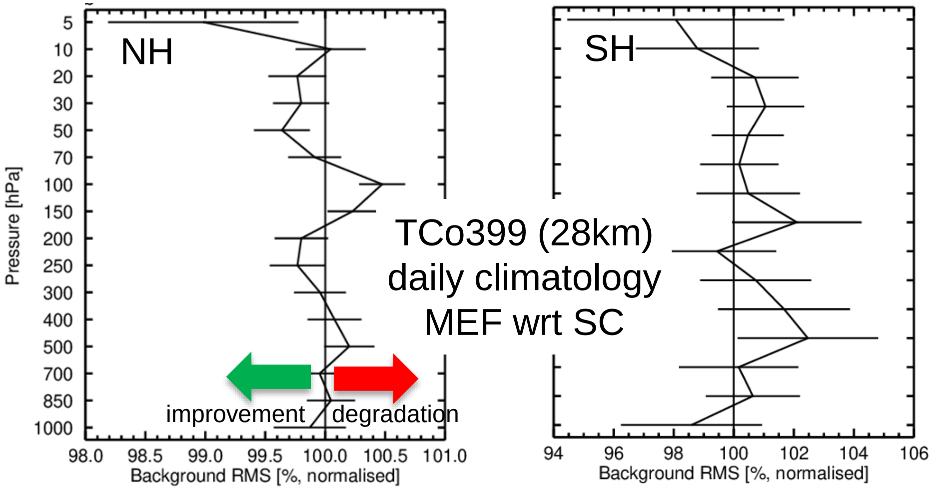


Impact of model error forcing
versus **strong constraint 4DVar**
on (passive) IRIS channel 193 fg departures
July 1970





Background fits to radiosonde temperatures
20th April – 26th August 1970



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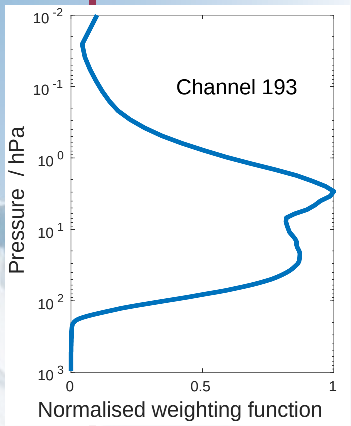
Climate Change



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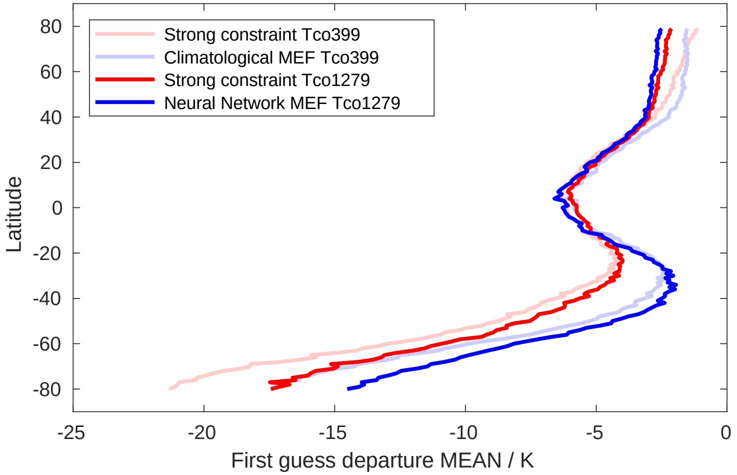

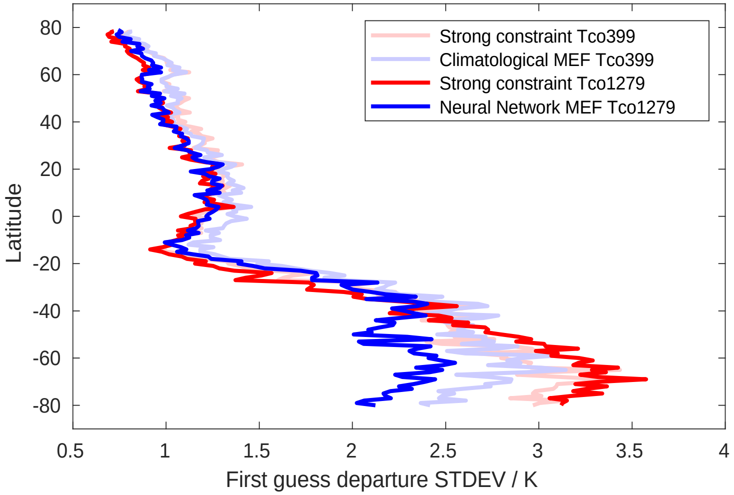

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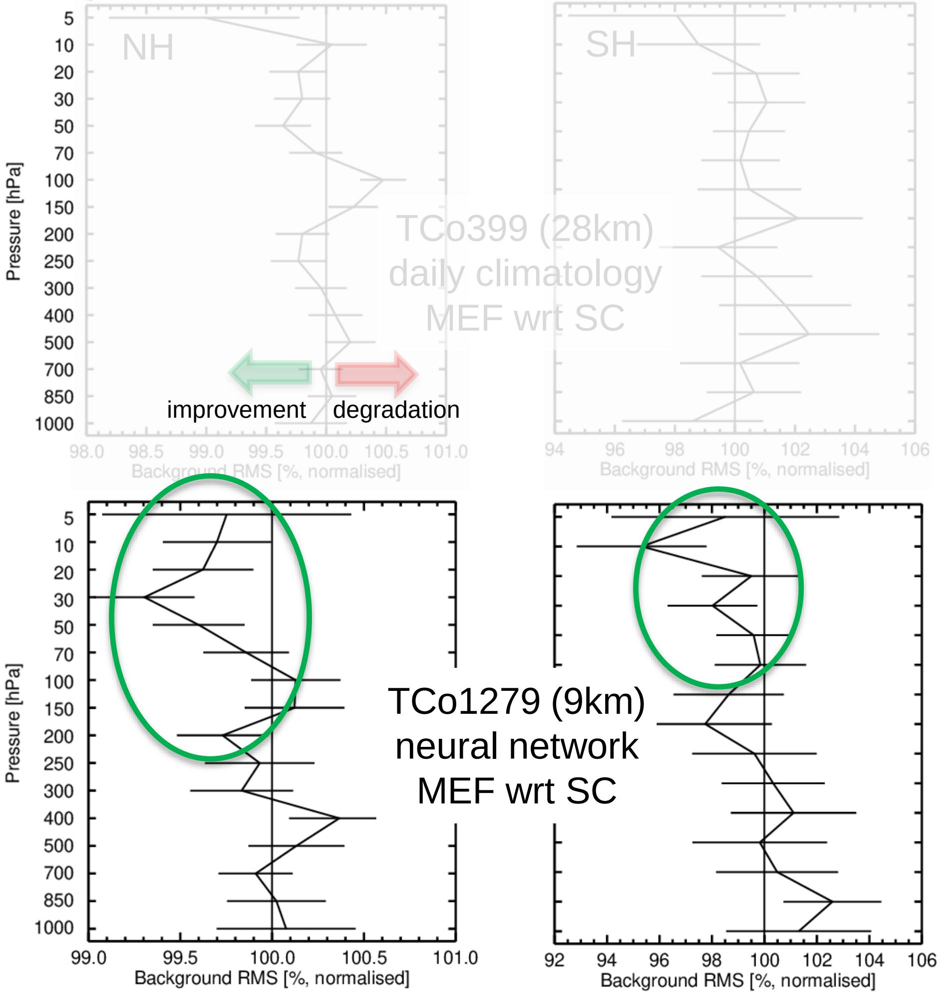

- NN MEF improves bias and synoptic performance
- IRIS provides unique insight into biases in otherwise observation sparse domains
- But significant biases remain (work in progress)

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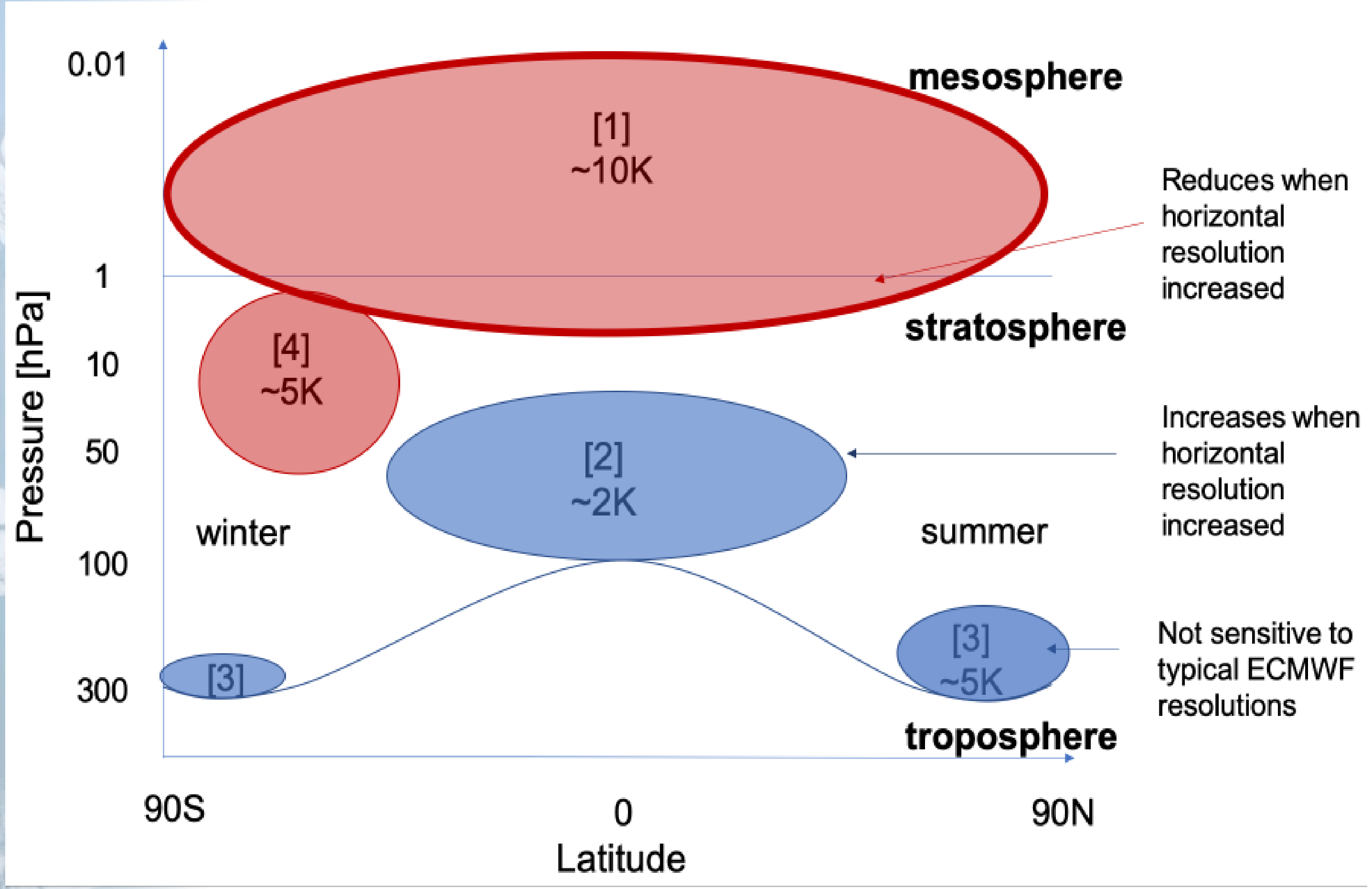
Prospects for reducing model biases in the stratosphere



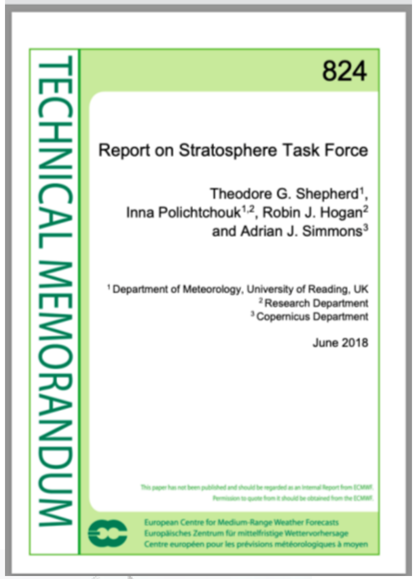
Improvements are anticipated from more accurate physical modelling, including:

[1] revised radiation scheme

[2] improved dynamical core

[3] reduction of H_2O in lower stratosphere

[4] Improved representation of GWD


TECHNICAL MEMORANDUM

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Report on Stratosphere Task Force

Theodore G. Shepherd[1], Inna Polichtchouk[1,2], Robin J. Hogan[2] and Adrian J. Simmons[3]

[1] Department of Meteorology, University of Reading, UK
[2] Research Department
[3] Copernicus Department

June 2018

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen

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Determining the systematic component of uncertainty in reanalysis estimates

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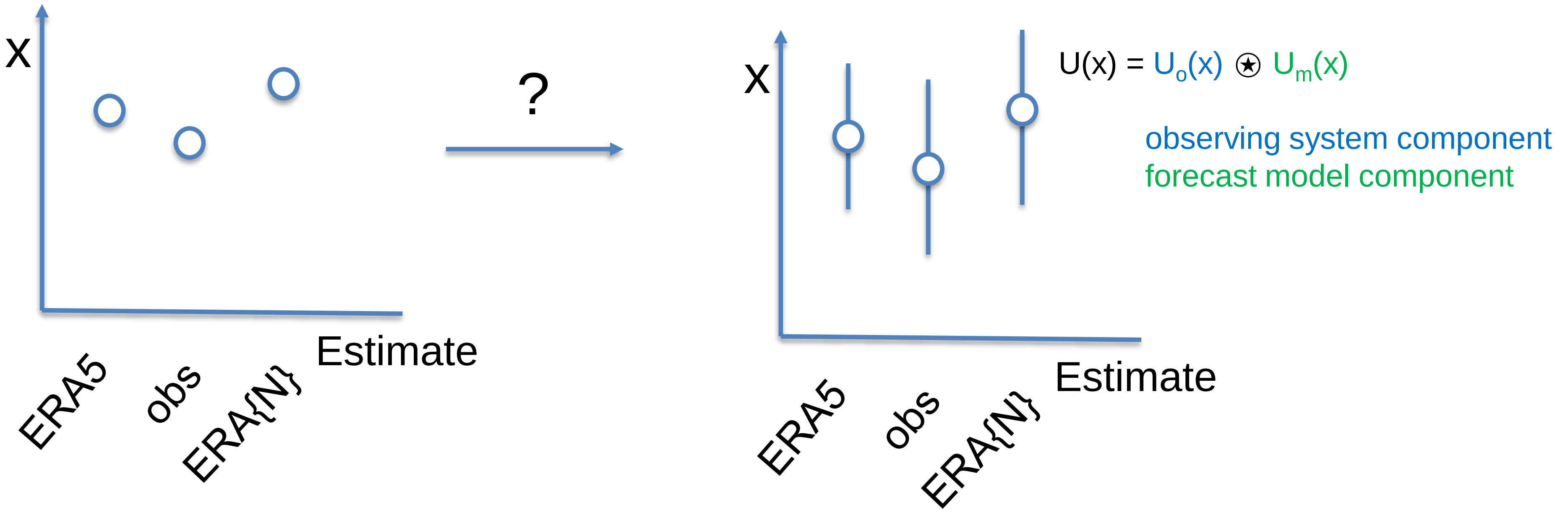

- **Uncertainties are derived from an inspection / understanding of the system** – rather than ascribed after comparison with independent observations
- **Validation** should, ideally, involve a comparison of independent estimates, each associated with it's own independent uncertainty estimate

Possible approaches to determining mean-state uncertainty

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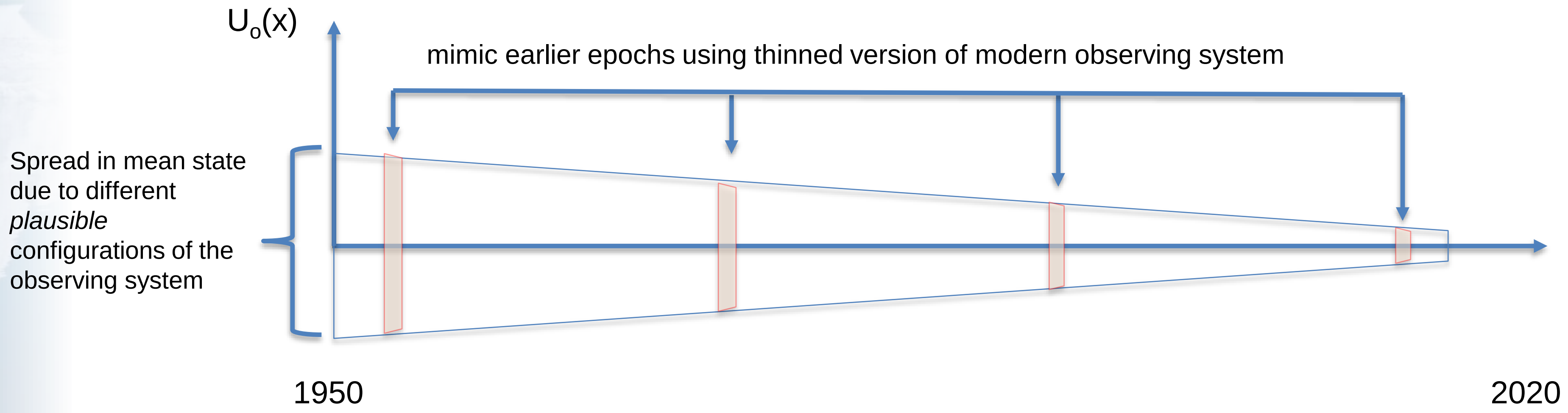
The observing system component

- Defined here as - “*uncertainty in mean state arising from uncorrected biases in the observing system & choice of observing system configuration*”

- OSEs with different plausible configurations of observing system, for each epoch
- Simplest approach: withdraw ‘redundant’ components of observing system and evaluate change in the mean state (next slide)
- Other factors: choice of observational data, bias model, QC/thinning, observation errors, …



Possible approaches to determining mean-state uncertainty

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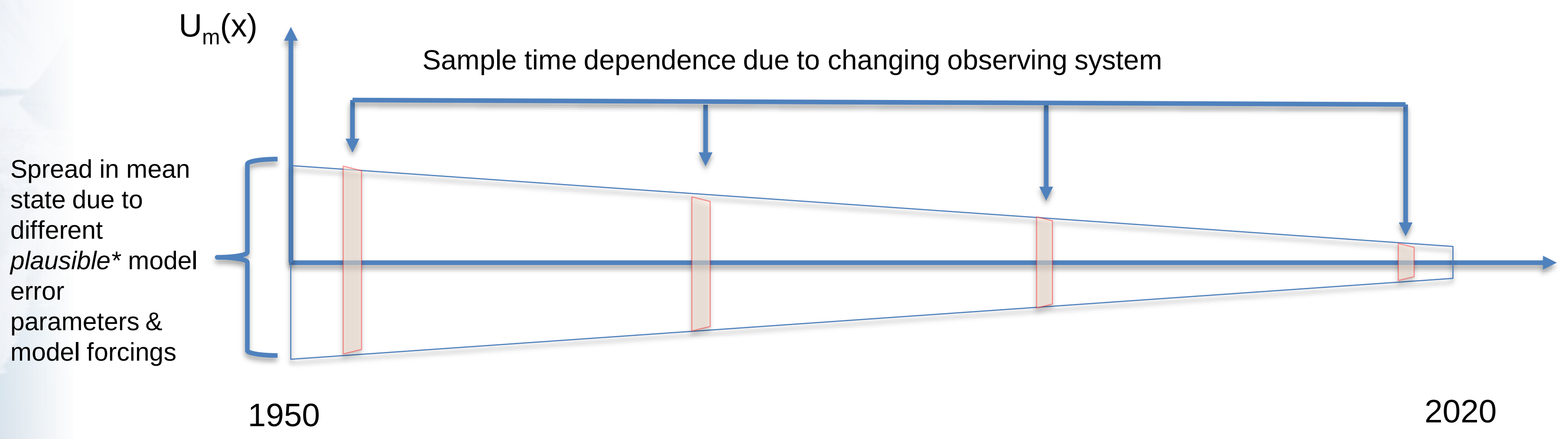
The model component

- Defined here as - “*uncertainty in mean state arising from uncertain model parameters and forcings*”
- Changes in time, due to the changing observing system

- OSEs with perturbed model parameters & alternative choices of forcings
- Key model parameters? - draw upon experience of EPS and climate modelling communities
- Sample time dependence using paired down modern observing system, or run in past epochs



- Perturbed by magnitudes consistent with documented uncertainties and/or giving rise to no significant degradation in forecast skill in OSEs

Validating the mean state uncertainties

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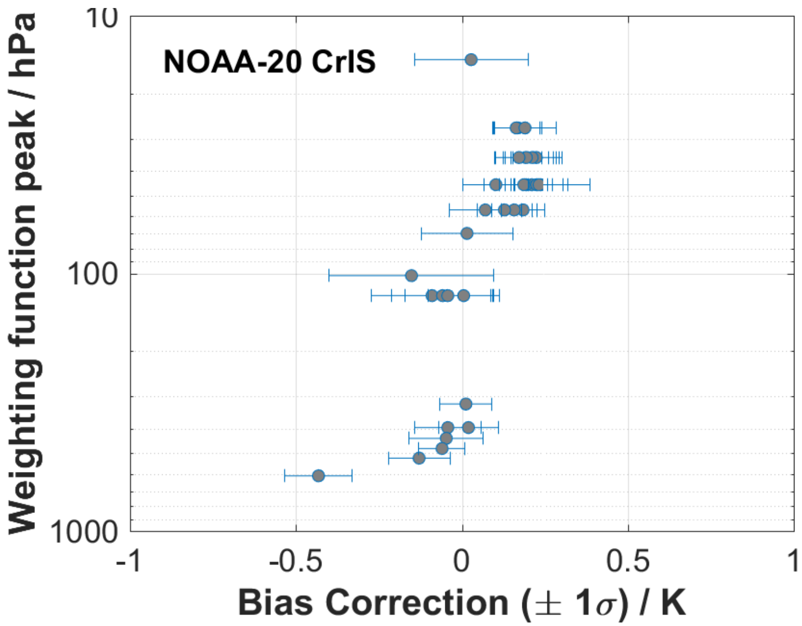
Several components of the observing system could be considered ‘reference’ quality:

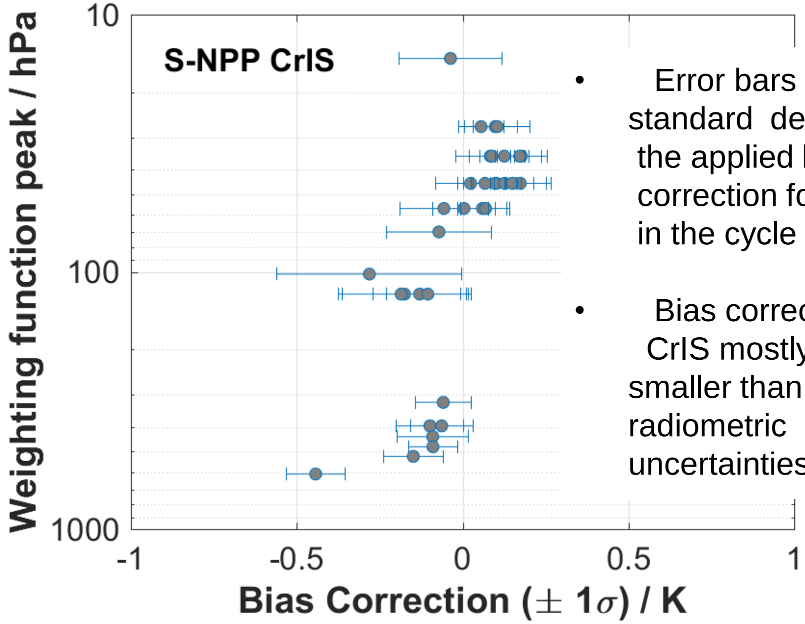
- **GNSS-RO** - direct traceability chain to time standards
- **GRUAN radiosondes** – available post-2010 in numbers
- **CrIS** - well characterised uncertainties
- **GMI** – reference MW imager mission

Use (a subset of) these observations passively (*i.e.* withhold from the analysis) to assess the uncertainty estimates from a **benchmark** period in the ERA6 reanalysis (~ 2010-2020, or 2015-2025)

*Benchmark** - defined in this context as “ associated with robustly defined uncertainties ideally validated through comparison with traceable independent measurements ”

(borrowed from CLARREO, TRUTHS mission concepts)





- 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)

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Summary

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

- In the short/medium term the prospects are good for improved pragmatic correction (WC 4D-Var / WC 4D-Var MEF) as well as corrections at source (reprocessed data [Paul's talk], stratospheric model biases, improved RT modelling)

- 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) – as a first step towards methods for establishing the full uncertainty budget for reanalyses products ?

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Thanks for listening !