Uncertainty in the Stratospheric Mean State In Reanalyses

Climate Change

Bill Bell, Patrick Laloyaux,

Hans Hersbach, Paul Berrisford, András Horányi, Joaquin Muñoz Sabater, Julien Nicolas, Paul Poli, Raluca Radu, Dinand Schepers, Adrian Simmons and Cornel Soci

and many others !

European Commission

ECMWF

Climate Change

Overview

Introduction: The ERA5 reanalysis

Challenges:

- the impact of model biases on stratospheric temperatures
- lack of uncertainty estimate on the mean state

Approaches:

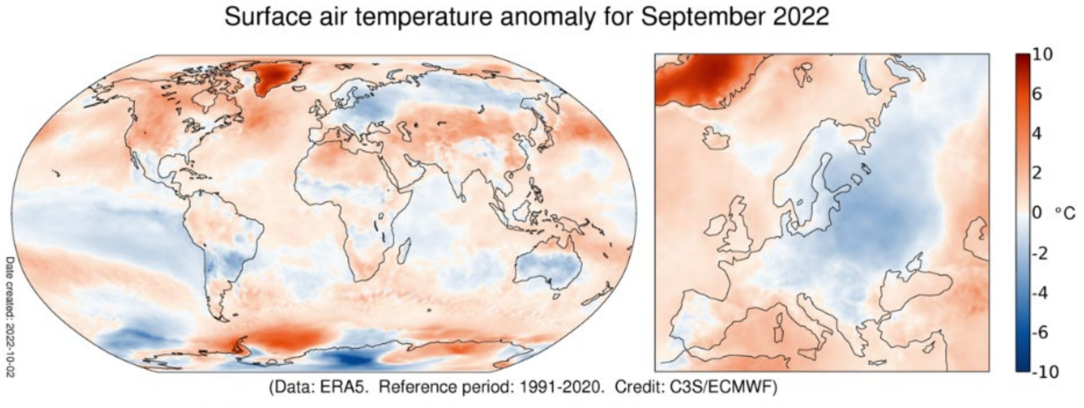
- diagnostics (model and observation space)
- improved modelling (see Inna's presentation)
- weak constraint 4D-Var & estimation of a model error climatology
- determination, & validation, of uncertainties in the mean state

The ERA5 global reanalysis

Climate Change

Full-observing-system global reanalysis for the atmosphere, land surface and ocean waves

- Produced at ECMWF, by the **Copernicus Climate Change Service**
- >92,000 users, >500 Tbyte of downloads per week
- Total dataset ~ 12 petabyte
- Over 100 billion observations assimilated so far



- Now extended back to **1940**
- **Continues** into the present, daily updates **5 days behind real time**
- **Hourly state estimates** at **31 km resolution** up to ~80 km
- **Uncertainty estimate*** from a 10-member ensemble of DAs at half resolution (* 'synoptic uncertainties' – uncertainty of each analysis)
- Based on CY41R2 (2016 version of ECMWF operational system)
- Will be superseded by ERA6, based on CY49R1, due to start in 2024

Multiple classes of applications, including :

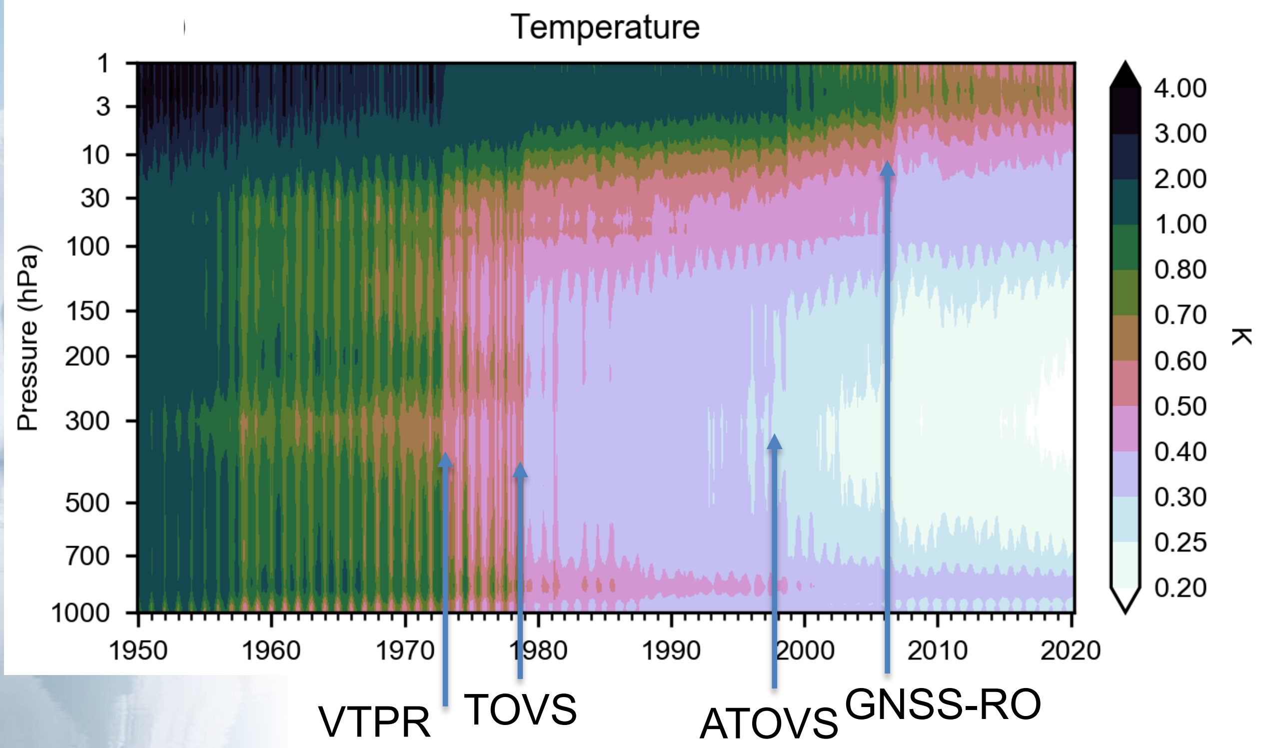
✓ Study of **specific events** or phenomena:
  - requires accurate **the weather of the day**

✓ **Climate** applications:
  - low-frequency variability of **the mean state**
  - Statistics of, e.g., extremes

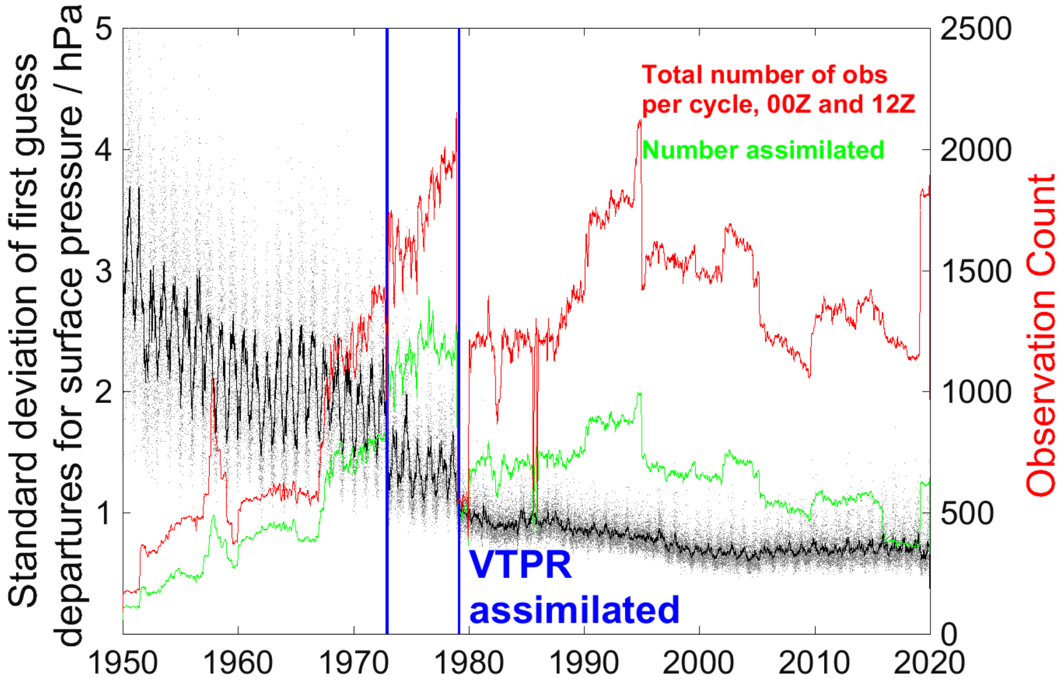
Ensemble of Data Assimilations (EDA) in ERA5 & provision of ‘synoptic uncertainties’

Climate Change

Ensemble of Data Assimilations (EDA)
analysis spread (a proxy for ‘*synoptic*’ analysis error)



Impact of VTPR
Background fits to surface pressure observations 1950-2020
Southern Hemisphere



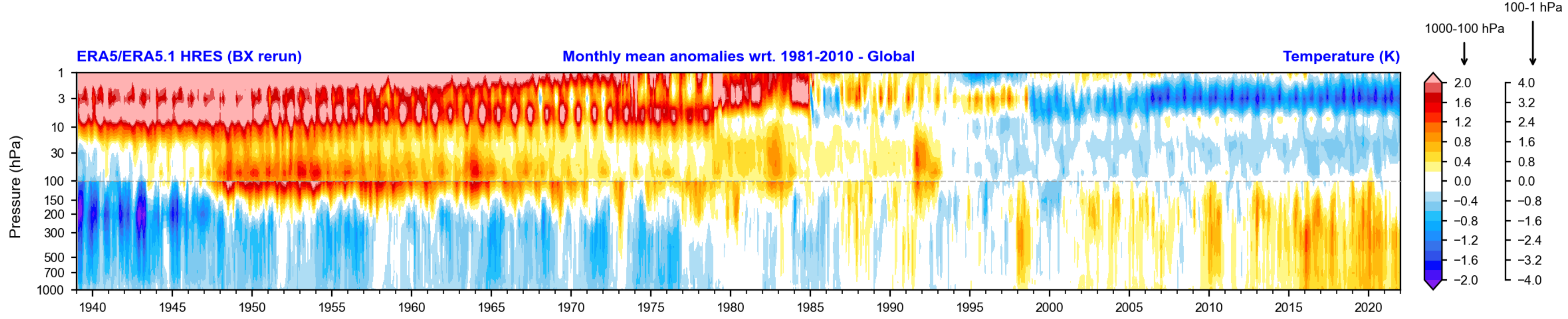
Vertical Temperature Profiling Radiometer (VTPR)

- 8-channel IR sounder. ‘HIRS predecessor’
- Flown on NOAA2 - 5 (Nov 1972 - Feb 1979)
- Same L1 data assimilated in ERA-40 & JRA-55

- The EDA is useful for characterizing the uncertainty in each analysis, but …
- The EDA doesn’t represent the uncertainty in the **mean state**

Climate trends in ERA5

Climate Change



25ºN – 25ºS, Temperature trends 1980-2018

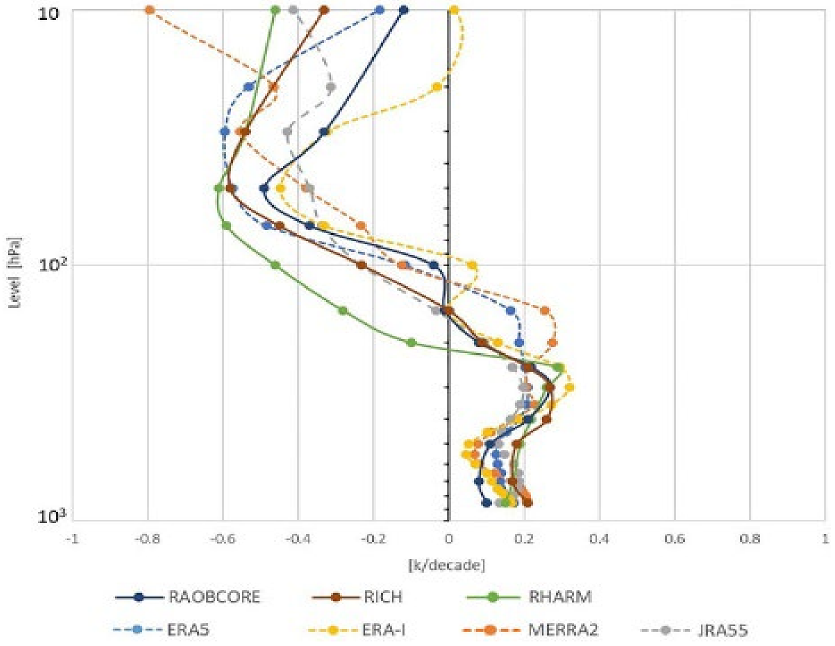


Fig. 9 from Essa et al., 2022, Front. Earth Sci. doi:10.3389/feart.2022.935139

- Reanalyses increasingly credible for climate trend analysis

  (*e.g.* for surface parameters, see Simmons, Weather Clim. Dynam, 2022)

- More challenging in stratosphere, particularly upper stratosphere

- Trend analyses usually don’t take into account (time varying) systematic biases in the mean state
  (as the relevant uncertainty components are generally not estimated)

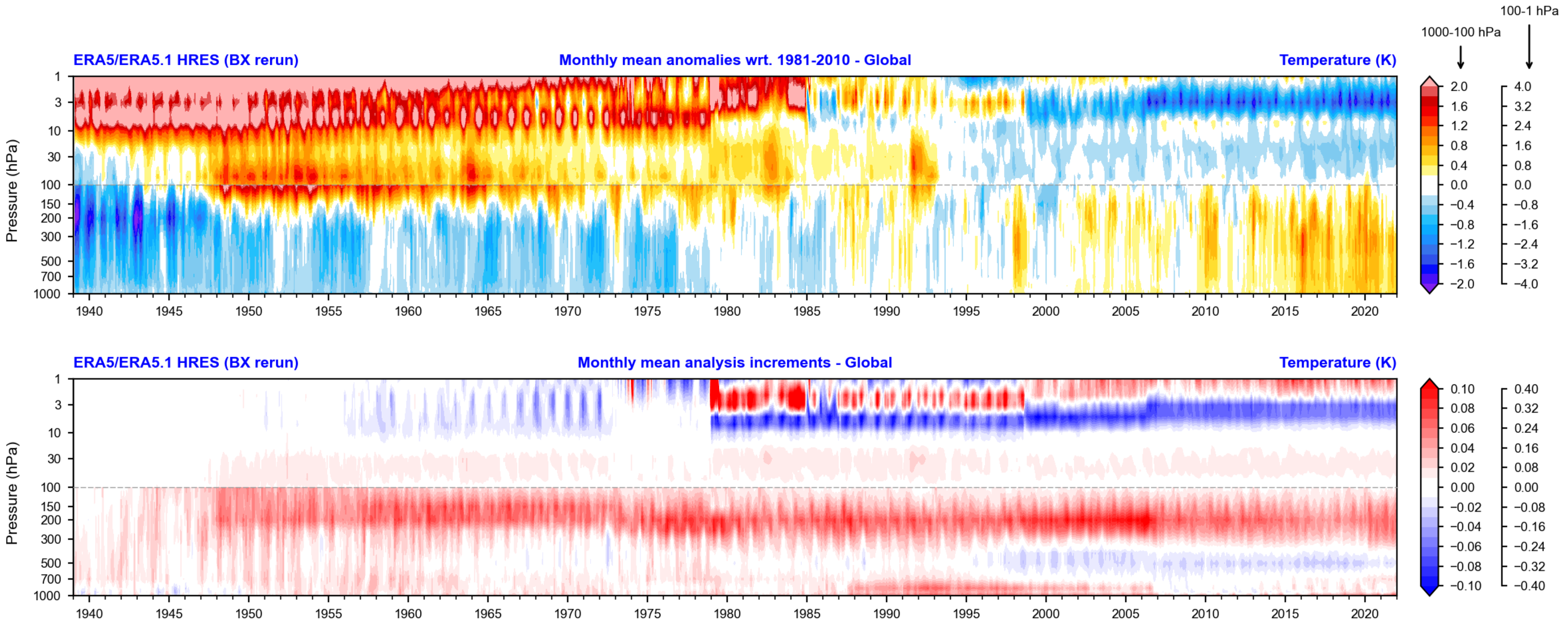
Copernicus Europe's eyes on Earth

European Commission

ECMWF

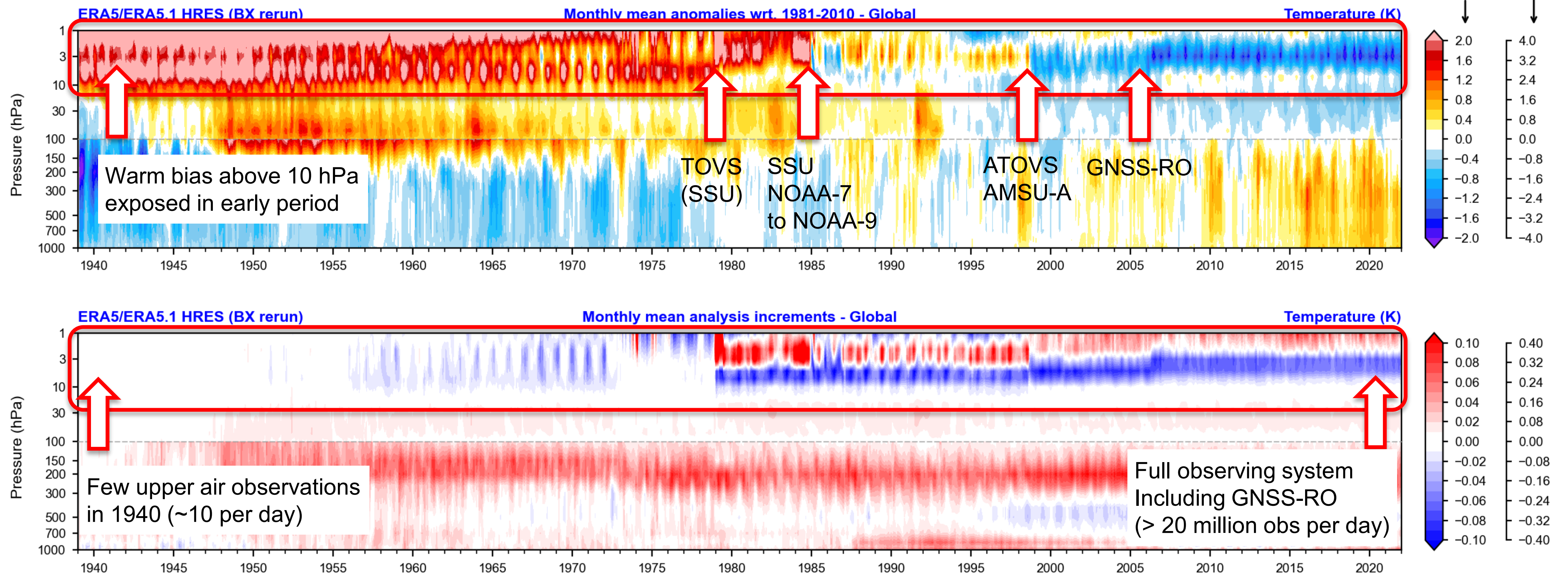
Climate trends in ERA5

Climate Change



Impacts of model and observation biases in ERA5

(1) Discontinuities above 10 hPa

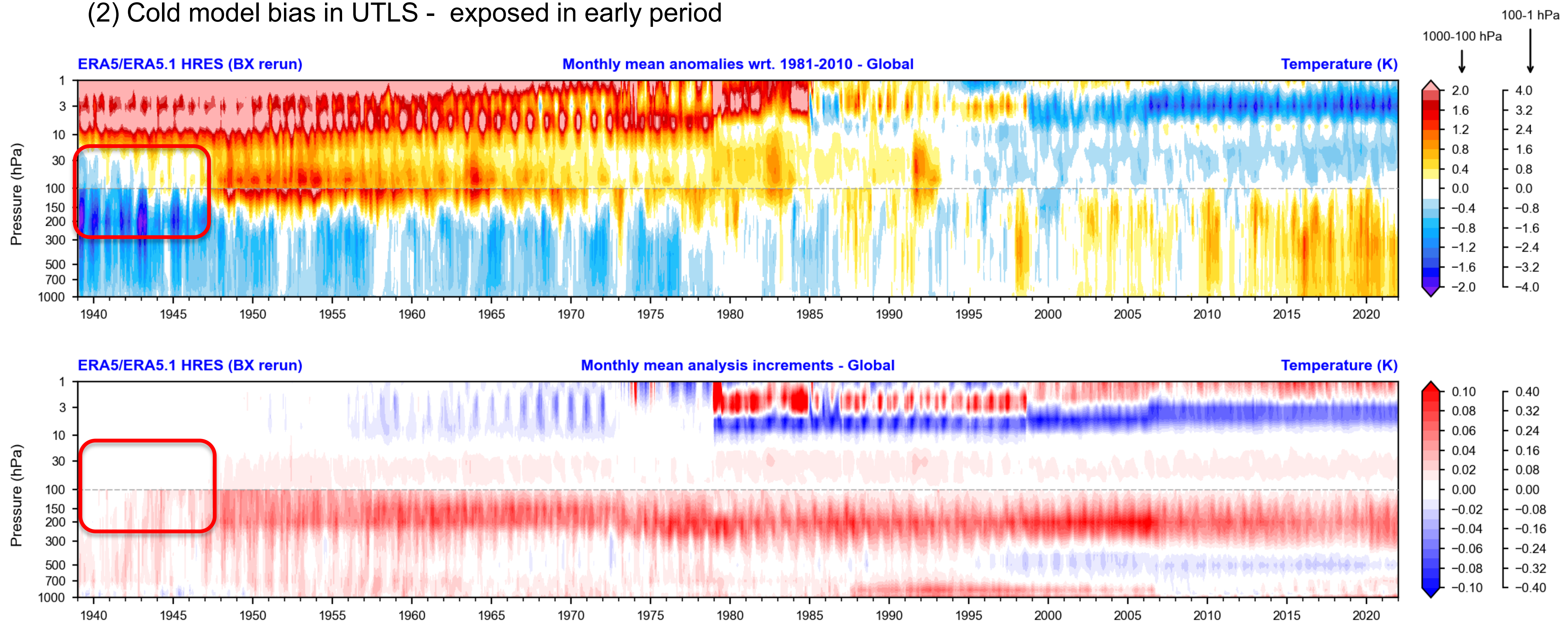


- General problems in reanalysis temperatures above 10 hPa well documented (see SPARC-RIP report 2021).

Impacts of model and observation biases in ERA5

Climate Change

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

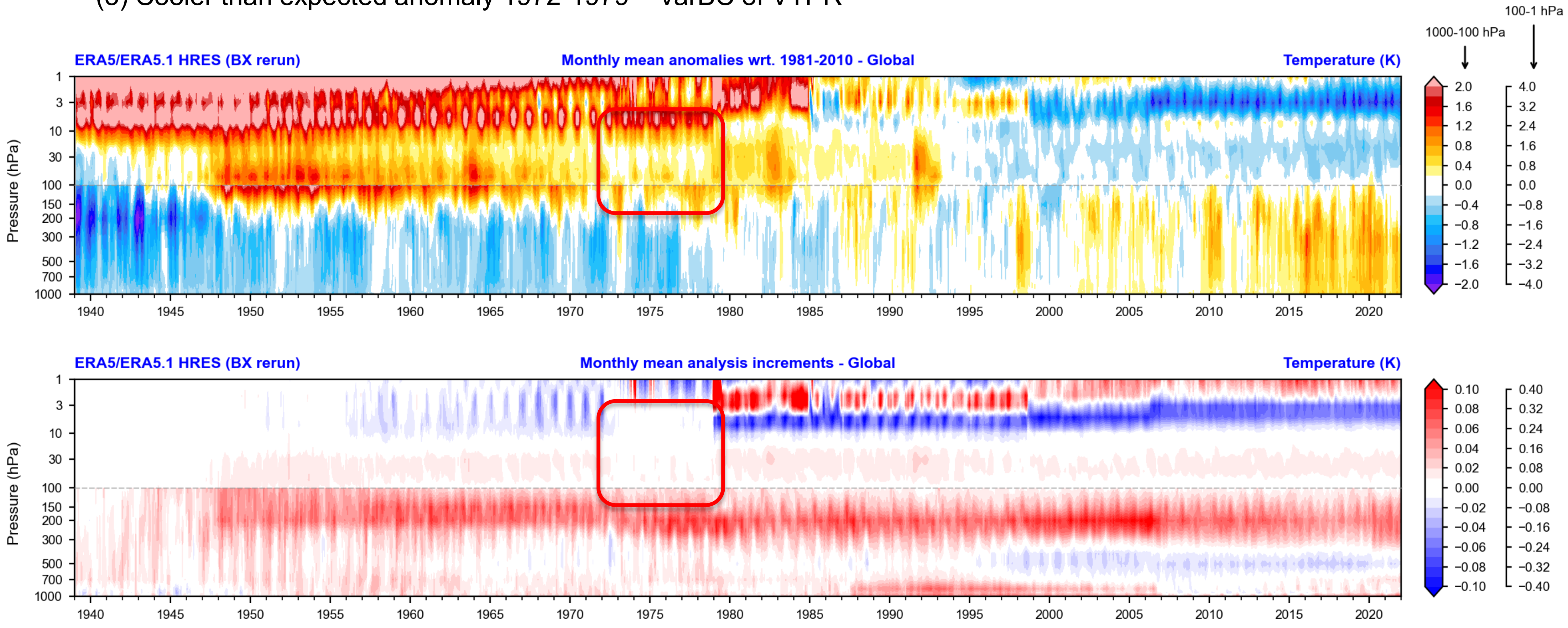


- Very few observational constraints on stratospheric temperature analysis in the early 1940s – so UTLS cold bias is exposed.
- Analysis increments in 10-200 hPa layer very small 1940 (< 20mK above 100 hPa as a global mean)

Impacts of model and observation biases in ERA5

Climate Change

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

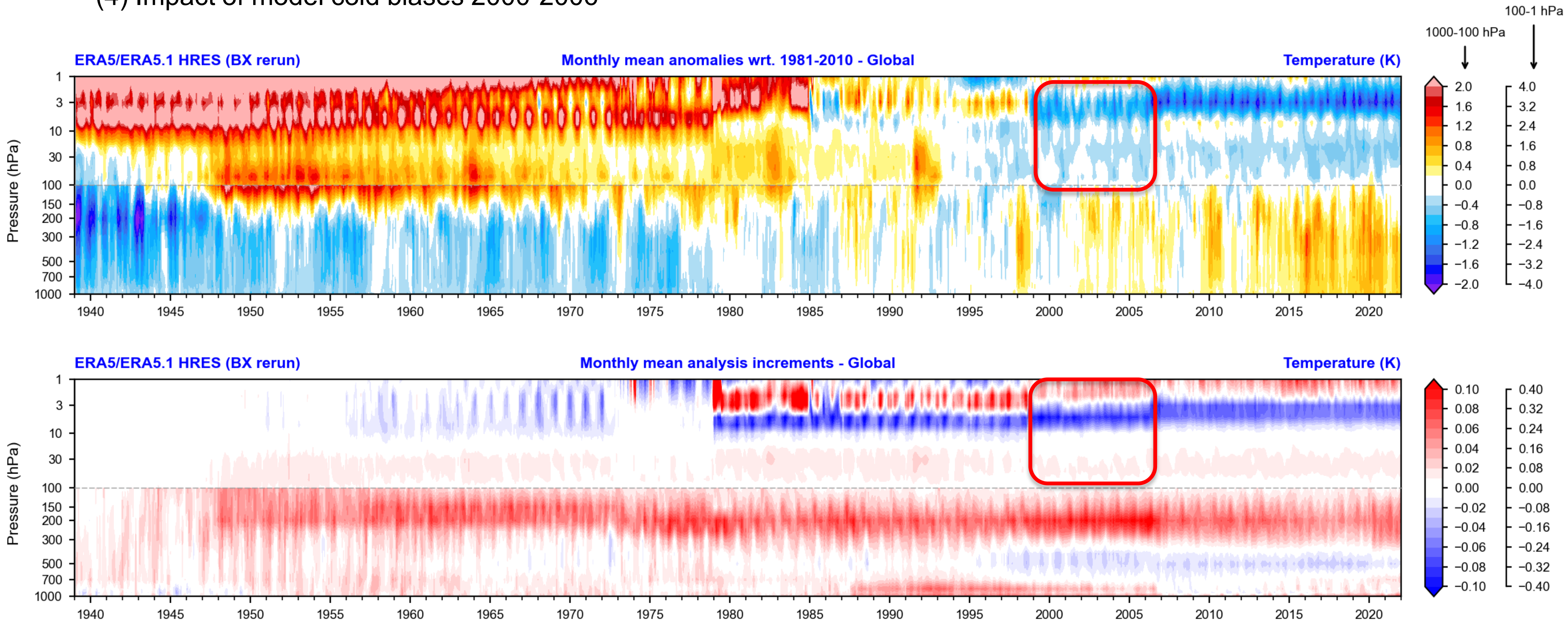


- General problem foreseen & analysed in Eyre (QJ, 2017): with VarBC, if radiances are dominant (cf anchors) model bias is reinforced
- VTPR channels 1 & 2 bias corrected using VarBC – reinforcing model cold bias
- Despite clear benefits (from assimilating VTPR) in improving synoptic analysis (earlier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

Impacts of model and observation biases in ERA5

Climate Change

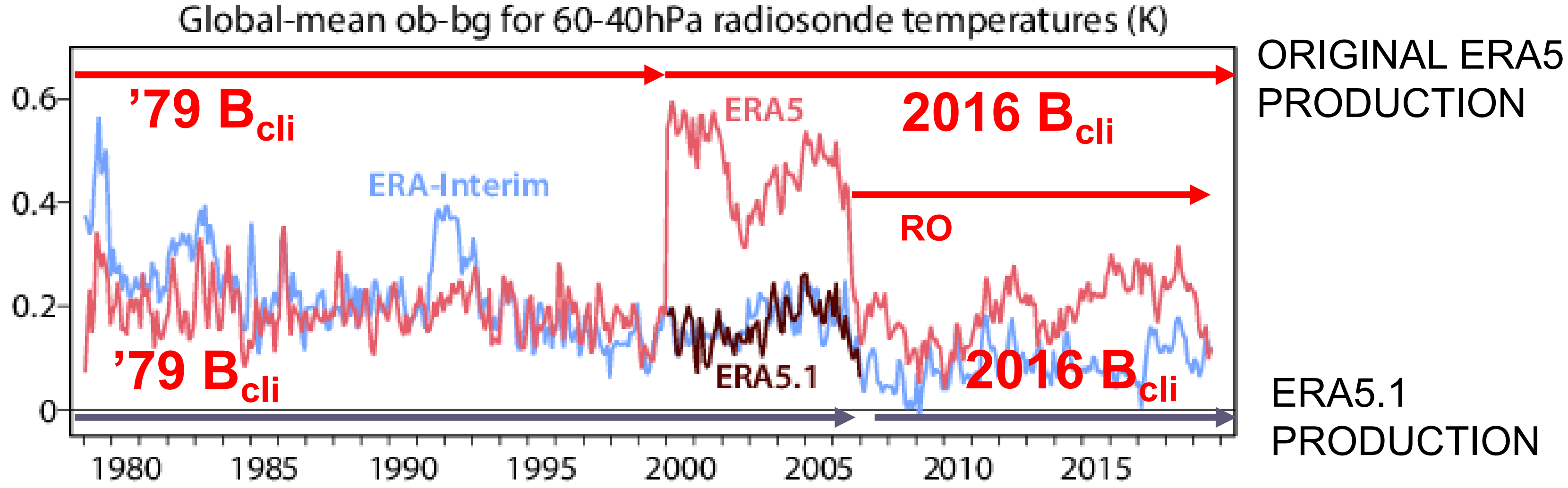
(4) Impact of model cold biases 2000-2006



- ERA5 and ERA5.1: See next slide

Climate Change

The improved mean state for stratospheric temperature in ERA5.1



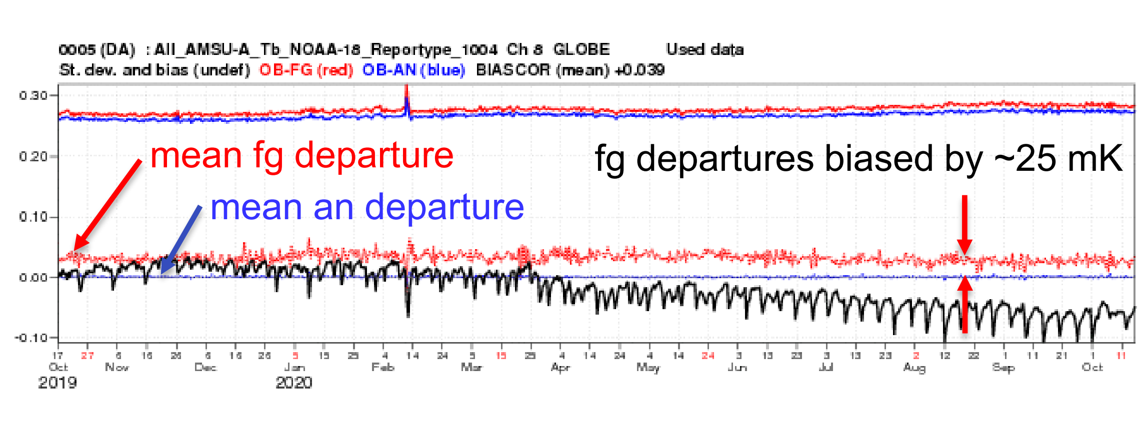
Monthly average observation-background differences from 1979 onwards for all assimilated bias-adjusted radiosonde temperature data (K) between 40 and 60 hPa, for ERA-Interim, ERA5 (based on 1979-B_{cli} before 2000 and 41r2-B $_{cli}$ afterwards) and ERA5.1 (using 1979-B_{cli} from 2000-2006).

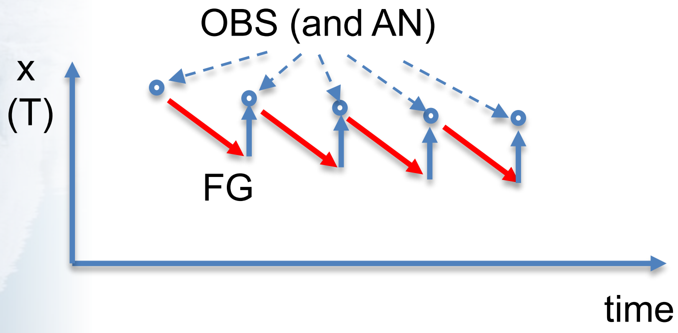
Hersbach, H. et al., 2020 , doi:10.1002/qj.3803

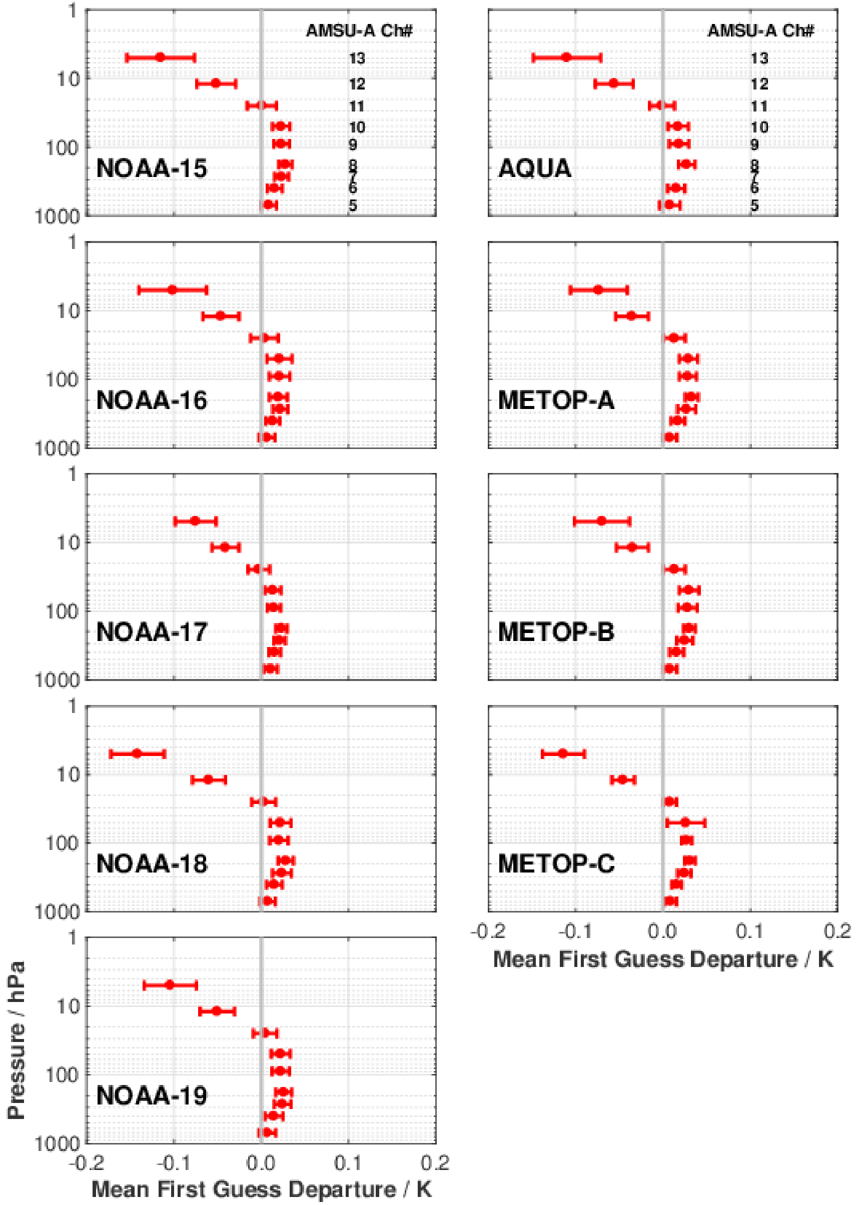
Climate Change

DA system diagnostics exposing bias

NOAA-18 AMSU-A8







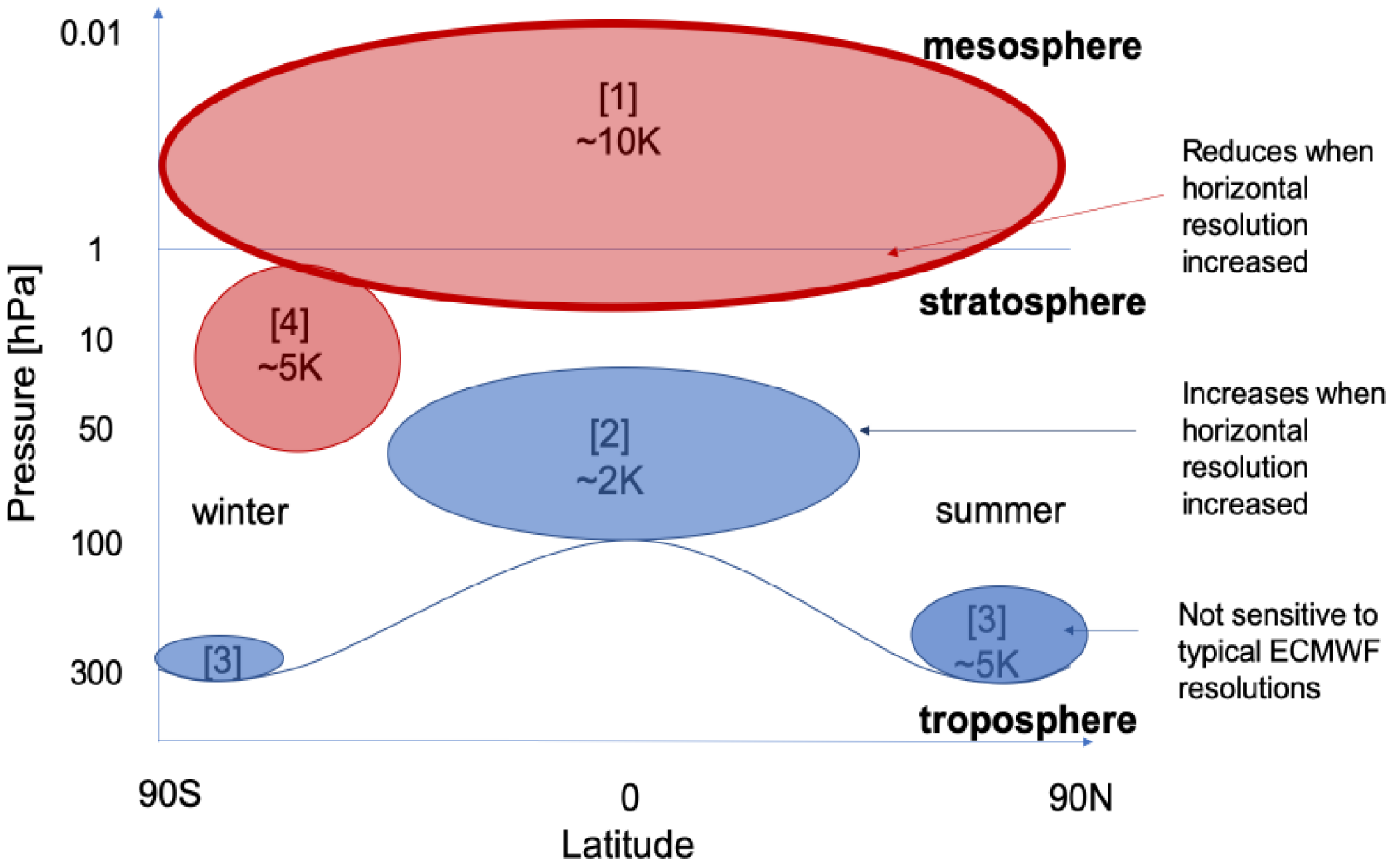
Error bars represent the sample stdev (1σ) in daily mean fg departures over the lifetime of the instruments typically years - decades

ECMWF

Climate Change

Model biases in the stratosphere: physical corrections in the forecast model

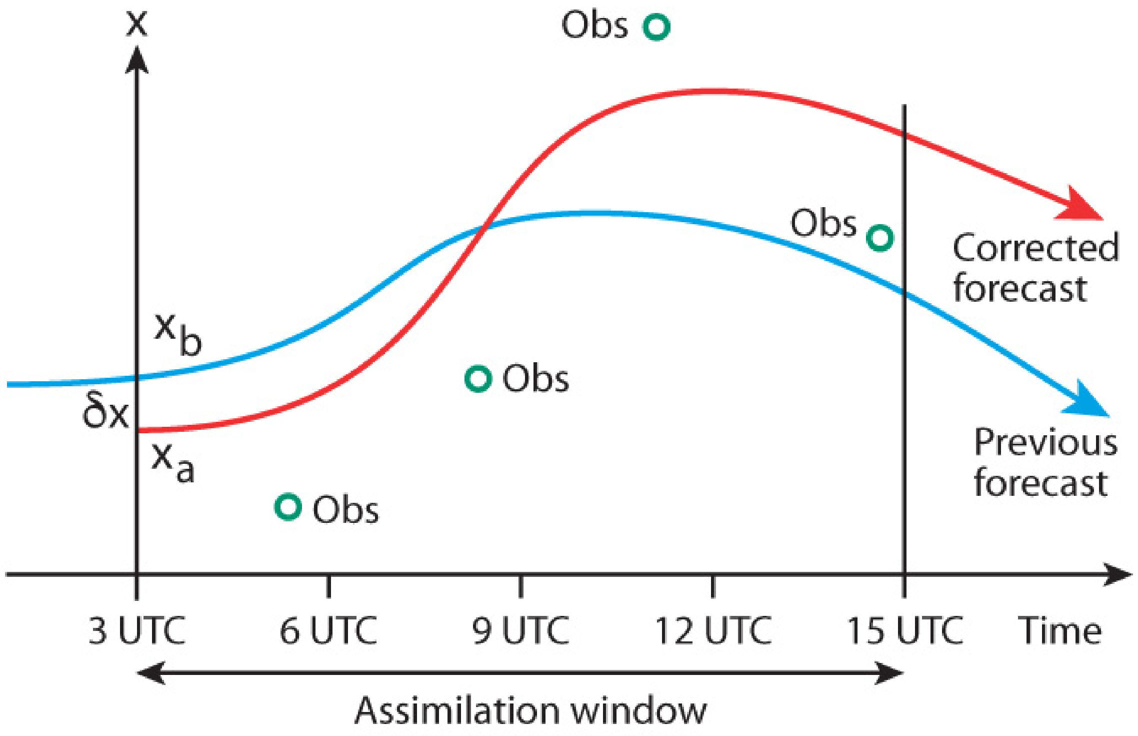
See Inna's talk earlier for details



Climate Change

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

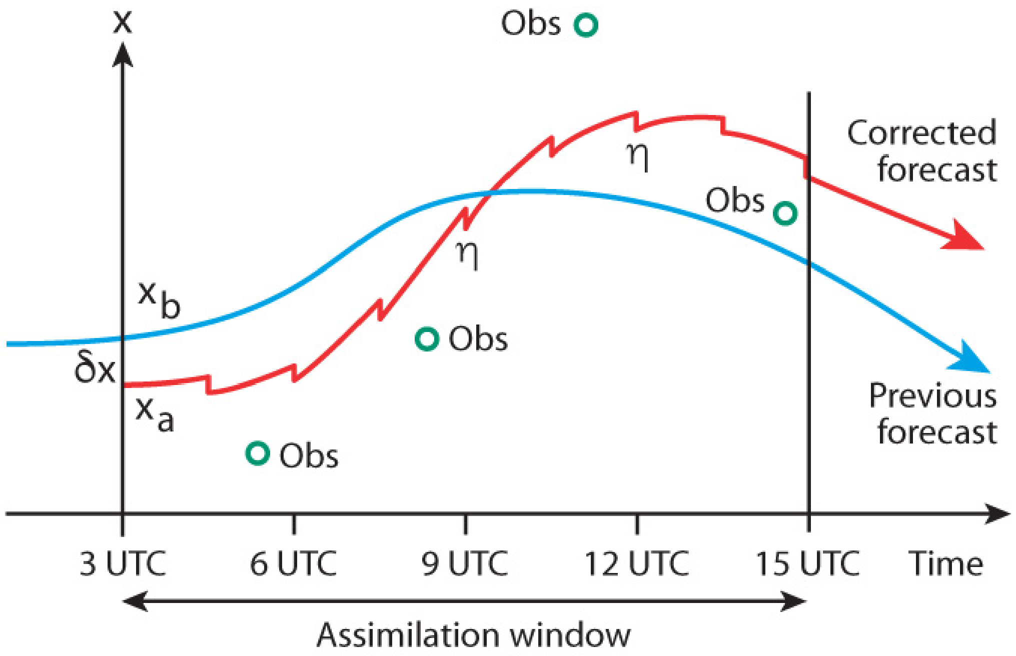
Weak-constraint 4D-Var formulation

Climate Change

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

Climate Change

Weak-constraint 4D-Var formulation

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

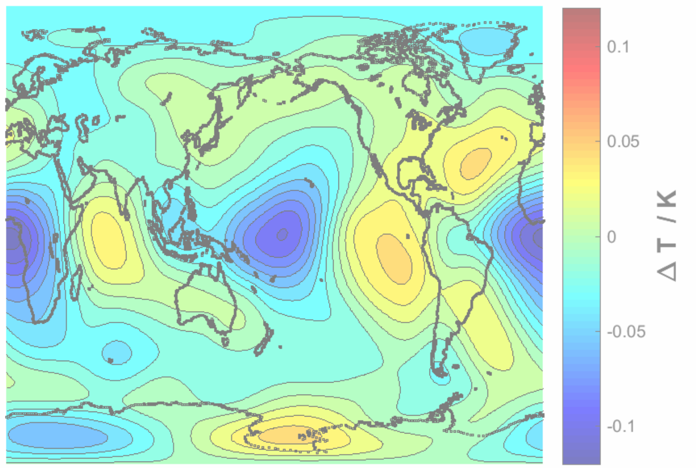
$$x_k = \mathcal{M}_k(x_{k-1}) + \eta \quad \text{for } k = 1, 2, \cdots, K$$

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

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

Model initial condition

Model bias correction



➔ 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

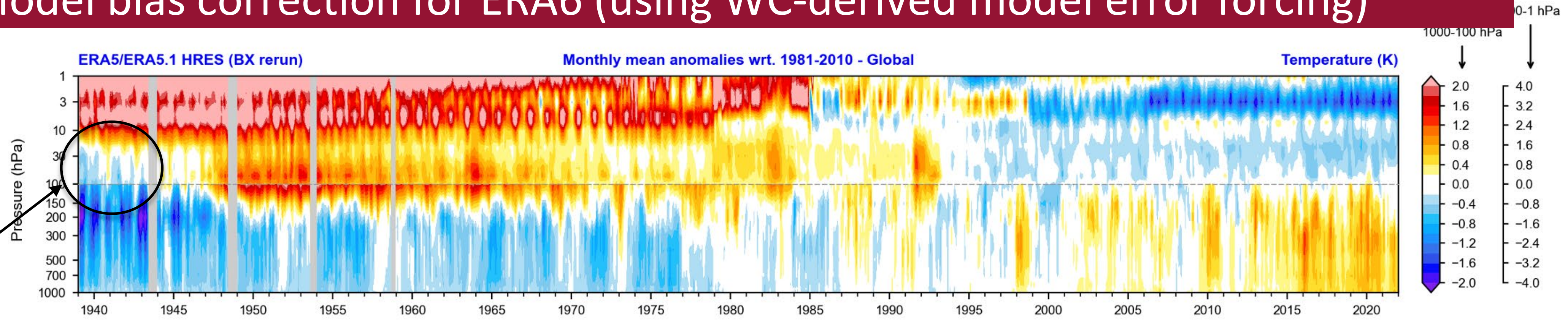
➔ Concept of scale separation introduced between background and model errors

➔ Constant model error forcing over the assimilation window

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

Climate Change

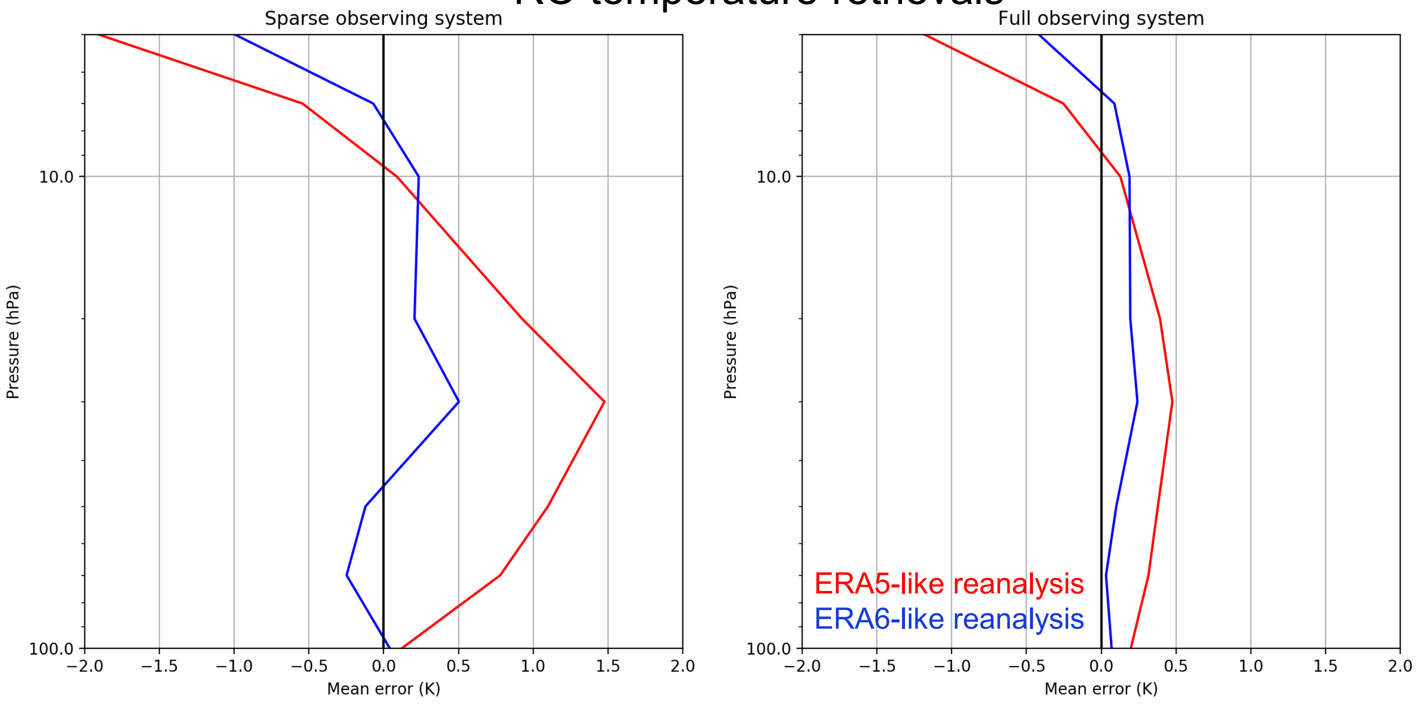
Model bias correction for ERA6 (using WC-derived model error forcing)



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

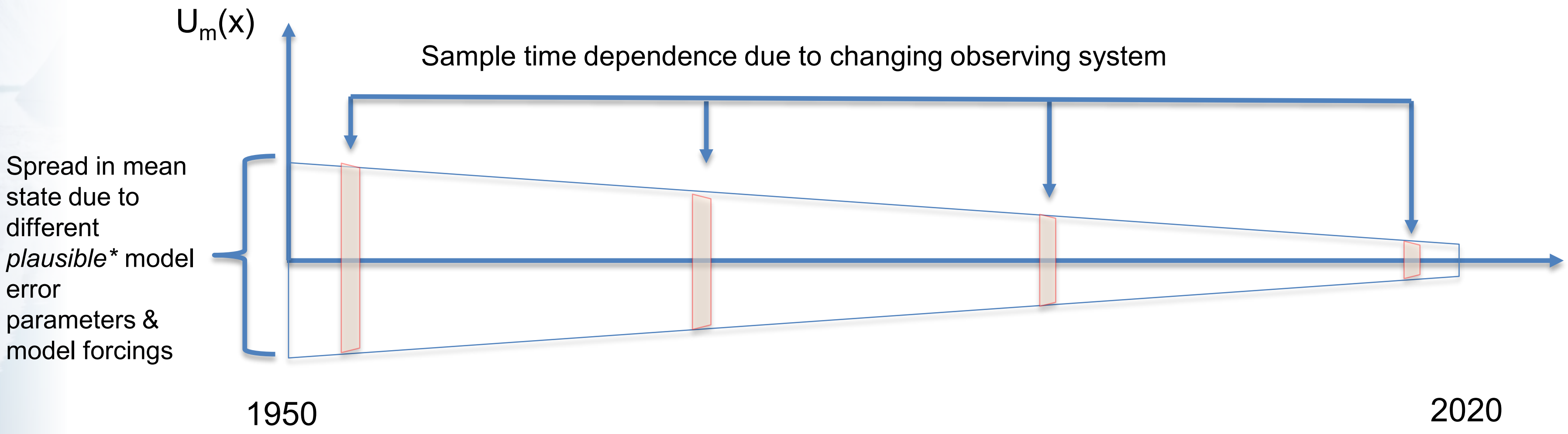
Possible approaches to determining mean-state uncertainty

Climate Change

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

Copernicus Europe's eyes on Earth | European Commission | ECMWF

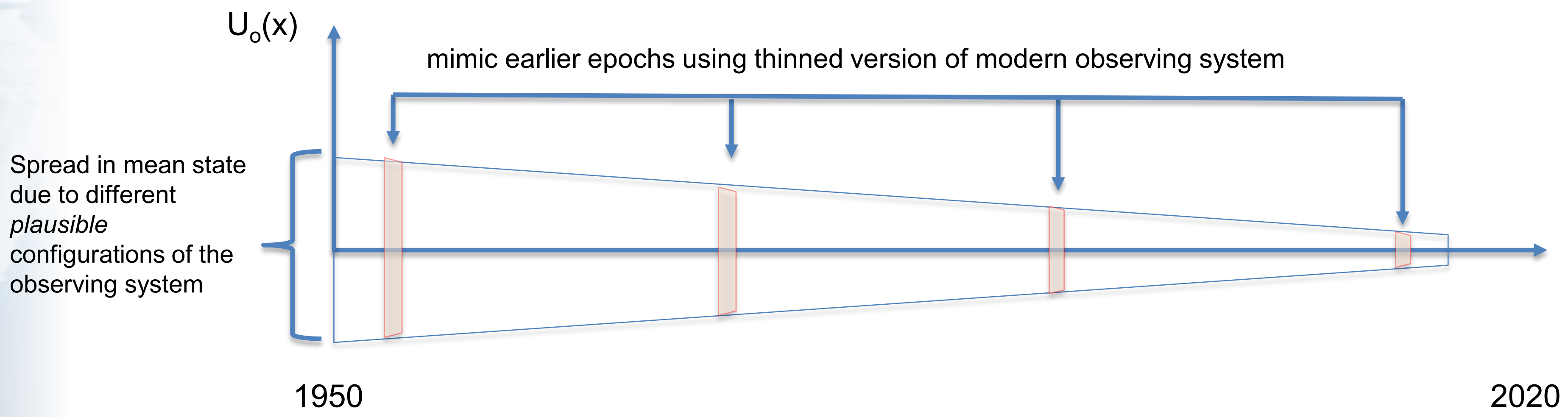
Climate Change

Possible approaches to determining mean-state uncertainty

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, …



Validating the mean state uncertainties

Climate Change

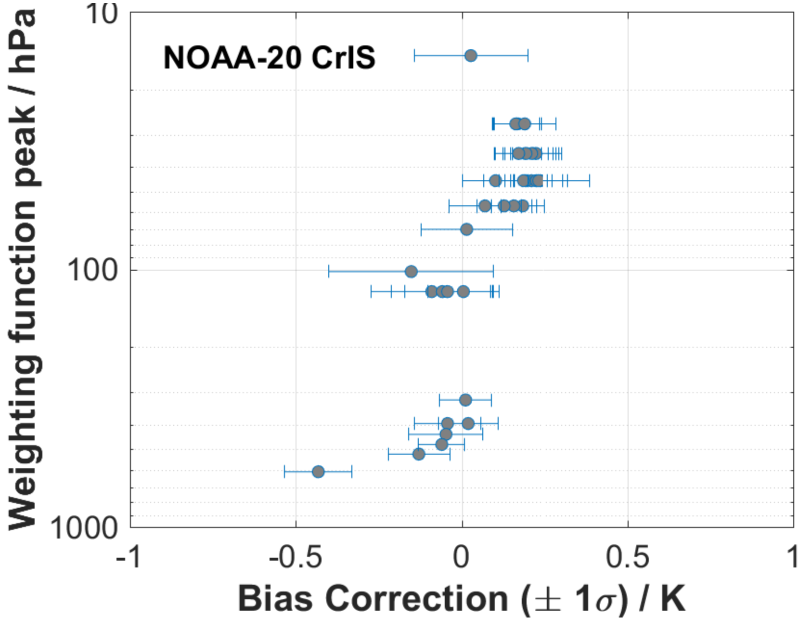
Several components of the observing system could be considered 'reference' quality:

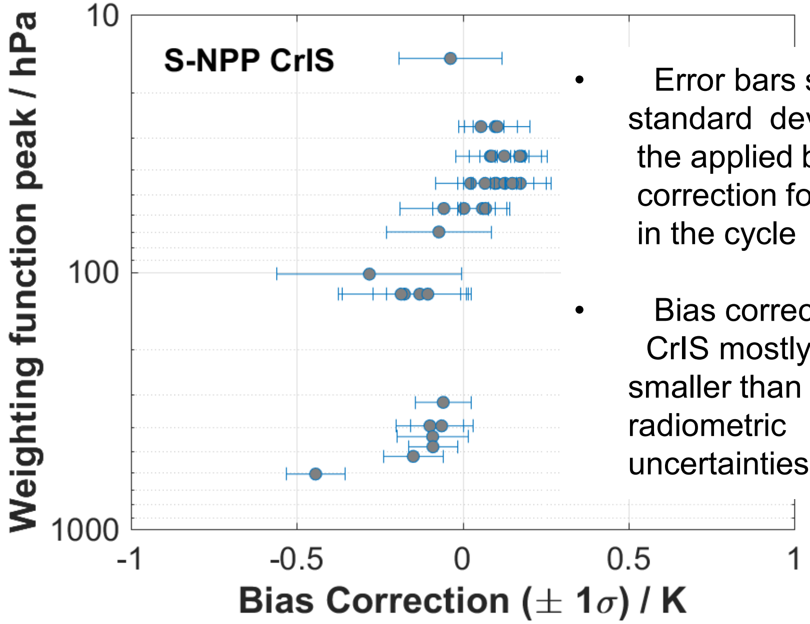
- **GNSS-RO** - direct traceability chain to time standards
- **GRUAN radiosondes** – available post-2010 in numbers
- **CrIS** - well characterised uncertainties
- **GMI** – reference MW imager mission

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)

Climate Change

Summary

"The workshop will encourage an active discussion on relative merits of active development of physical models and parametrisations to address systematic errors versus bias correction methods."

- Biases in stratospheric temperature have created several challenges during the production of ERA5 & compromise both the accuracy and continuity of the ERA5 analyses
- Solutions to these challenges will include both *ideal* (improvements to physical models) and *pragmatic* (WC 4DVar & model error forcing) approaches. These approaches are **complementary** and, combined, are expected to result in improvements in ERA6
- Determination of mean state uncertainties remains a challenge, but 'ensemble' of reanalyses approaches (with obs and model perturbations) should yield first estimates of these uncertainties. Choice of parameters will be crucial (?)
- Validation of these uncertainties will use the highest quality 'redundant' components of the observing system

Climate Change

Thanks !