Stratospheric Temperature Biases in the ERA5 reanalysis & plans for ERA6

Bill Bell[1], Hans Hersbach[1], Paul Berrisford[1], András Horányi[1], Joaquin Muñoz Sabater[1], Julien Nicolas[1], Paul Poli[1], Raluca Radu[1], Dinand Schepers[1], Adrian Simmons[1], Cornel Soci[1], Alison Cobb[1] Mikael Kaandorp[1]

Patrick Laloyaux[1] , Massimo Bonavita[1] ,

Andrzej Klonecki[2]

[1] ECMWF, Reading, UK

[2] Spascia, Toulouse, France

Climate Change

European Commission

ECMWF

Overview

Biases in stratospheric temperatures in ERA5

- In '*model space*' - anomalies & analysis increments
- ERA 5.1 & the role of RO observations
- In '*observation space*' - mean first guess departures in ERA5, ERA-Interim & *proto-ERA6*

Southern winter polar bias in ERA5

- Exposed by anomalies & IRIS data

Exploiting information from RO observations back in time

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

Summary

Overview

Climate Change

Biases in stratospheric temperatures in ERA5

- In '*model space*': anomalies & analysis increments
- ERA 5.1 & the role of RO observations
- In '*observation space*': mean first guess departures in ERA5, ERA-Interim & *proto-ERA6*

Southern winter polar bias in ERA5

- Exposed by anomalies & IRIS data

Exploiting information from RO observations back in time

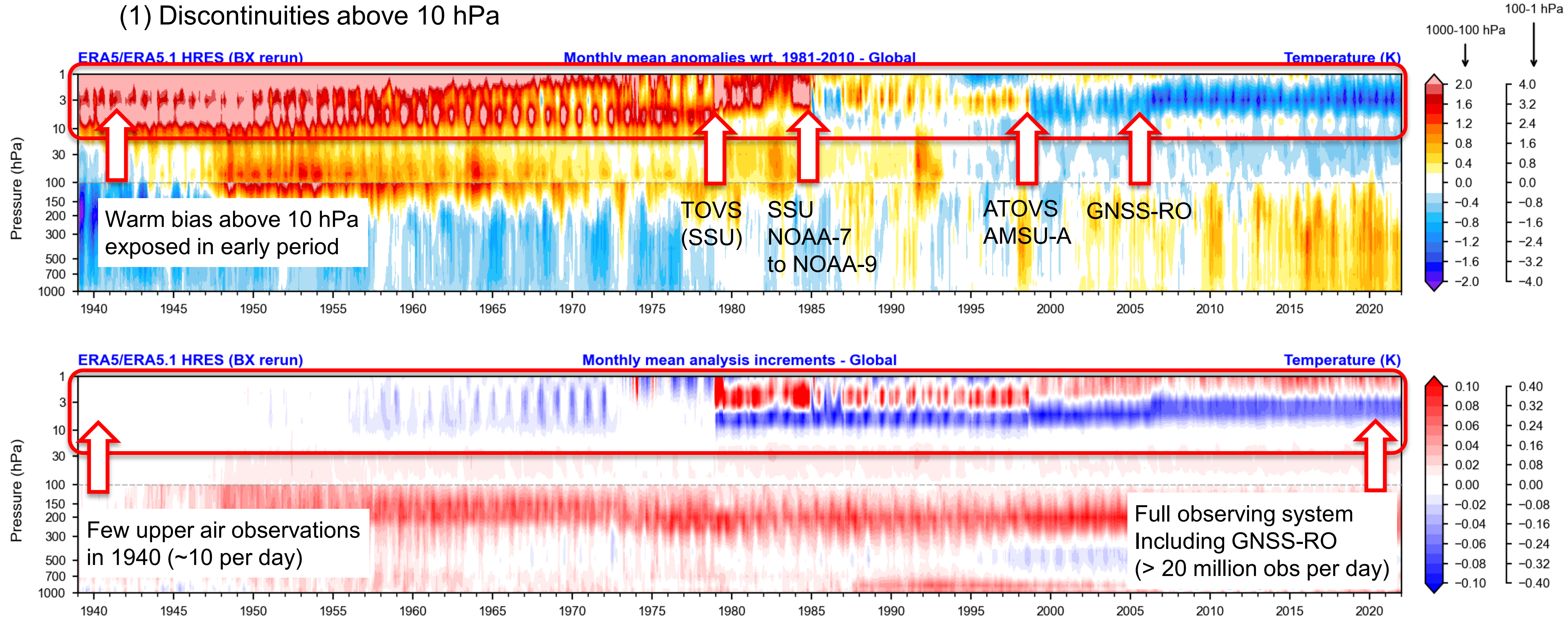
- Weak constraint 4D-Var & model error forcing
- Using early sounding data (IRIS in 1970) to evaluate model error correction strategies

Summary

Impacts of model and observation biases in ERA5

Climate Change

(1) Discontinuities above 10 hPa

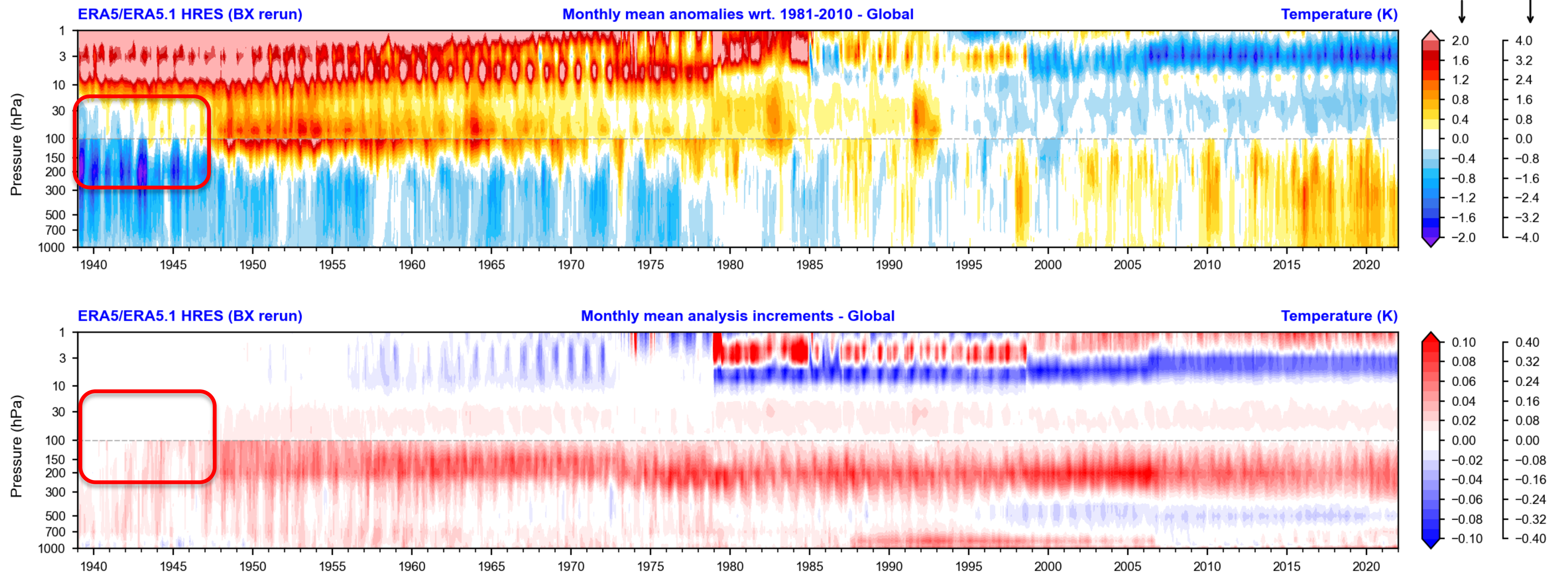


- General problems in reanalysis temperatures above 10 hPa well documented (see SPARC-RIP report 2021).

Climate Change

Impacts of model and observation biases in ERA5

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



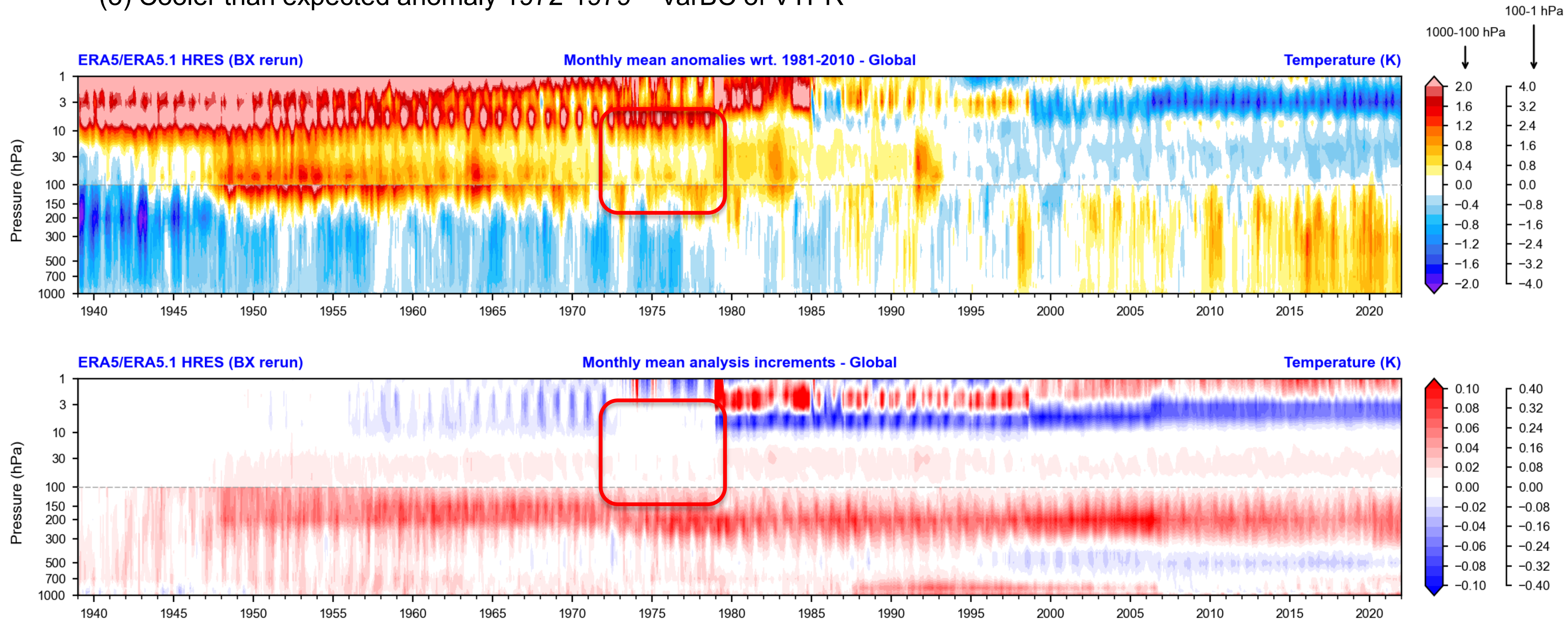
- Very few observational constraints on stratospheric temperature analysis in the early 1940s – so UTLS cold bias is exposed.
- Analysis increments in 10-200 hPa layer very small 1940 (< 20mK above 100 hPa as a global mean)

Copernicus Europe's eyes on Earth
European Commission
ECMWF

Impacts of model and observation biases in ERA5

Climate Change

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



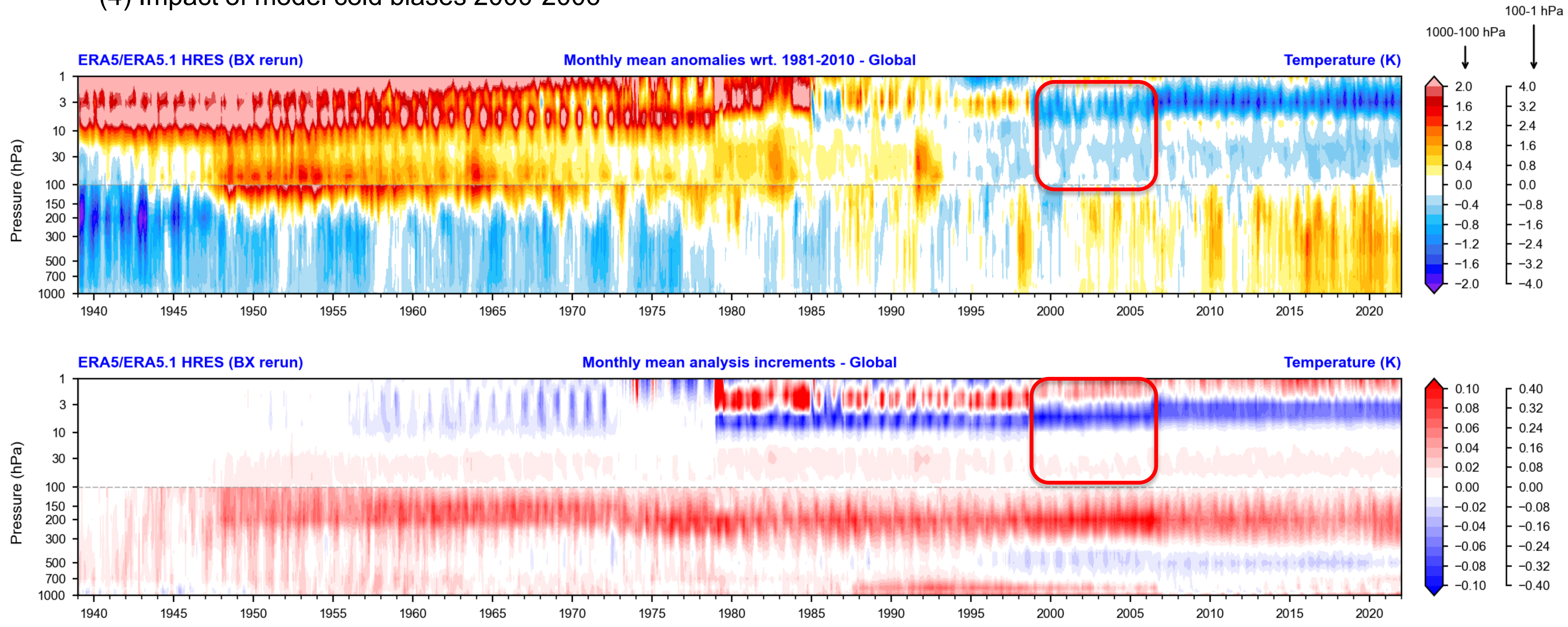
- General problem foreseen & analysed in Eyre (QJ, 2017): with VarBC, if radiances are dominant (cf anchors) model bias is reinforced
- VTPR channels 1 & 2 bias corrected using VarBC – reinforcing model cold bias
- Despite clear benefits (from assimilating VTPR) in improving synoptic analysis (earlier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

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

Impacts of model and observation biases in ERA5

Climate Change

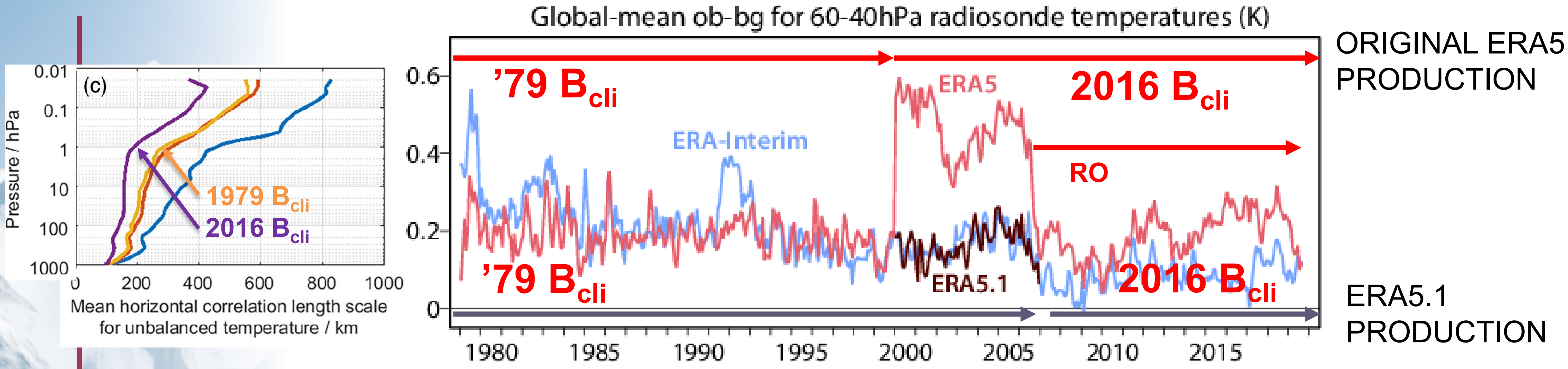
(4) Impact of model cold biases 2000-2006



- ERA5 and ERA5.1: See next slide

The improved mean state for stratospheric temperature in ERA5.1

Climate Change



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).

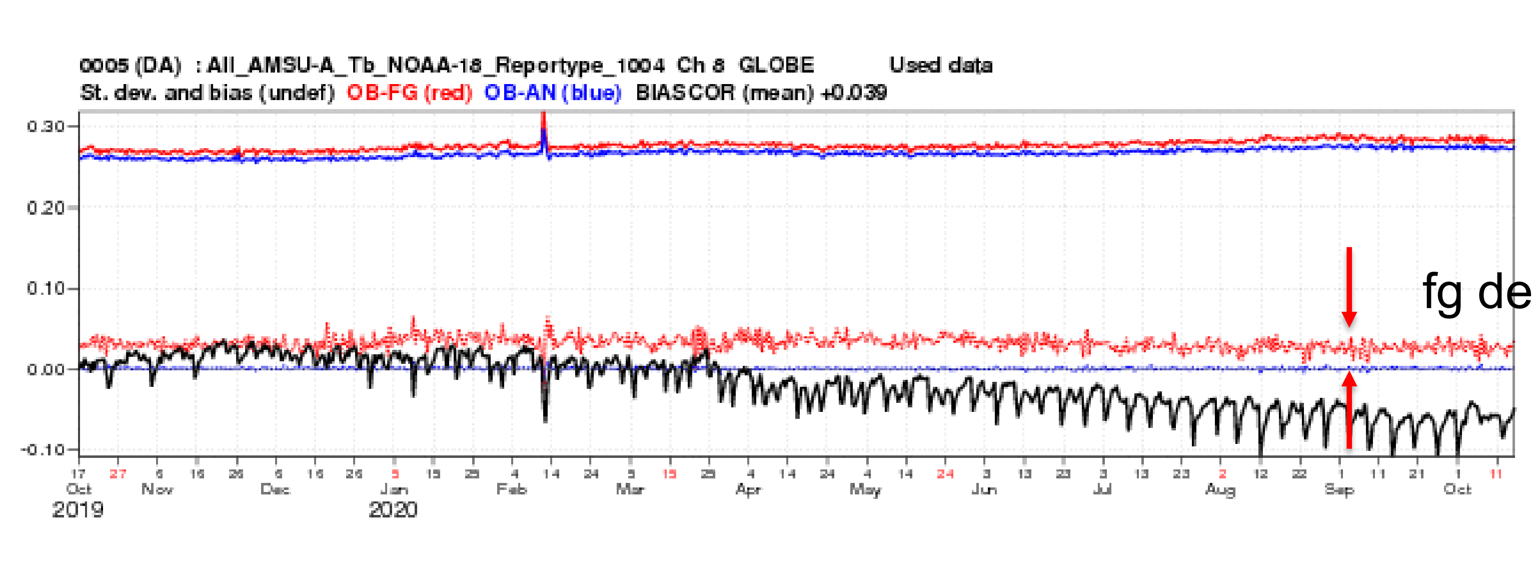
Hersbach, H. et al., 2020 , doi:10.1002/qj.3803

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

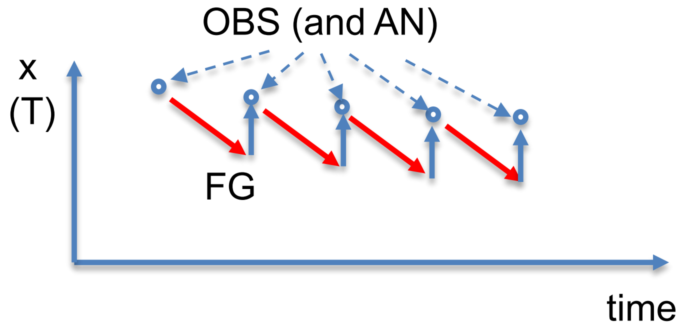
(see A. Simmons *et al*, ECMWF Tech Memo 859, Jan 2020)

Model error manifested in biased first guess departures

NOAA-18 AMSU-A8

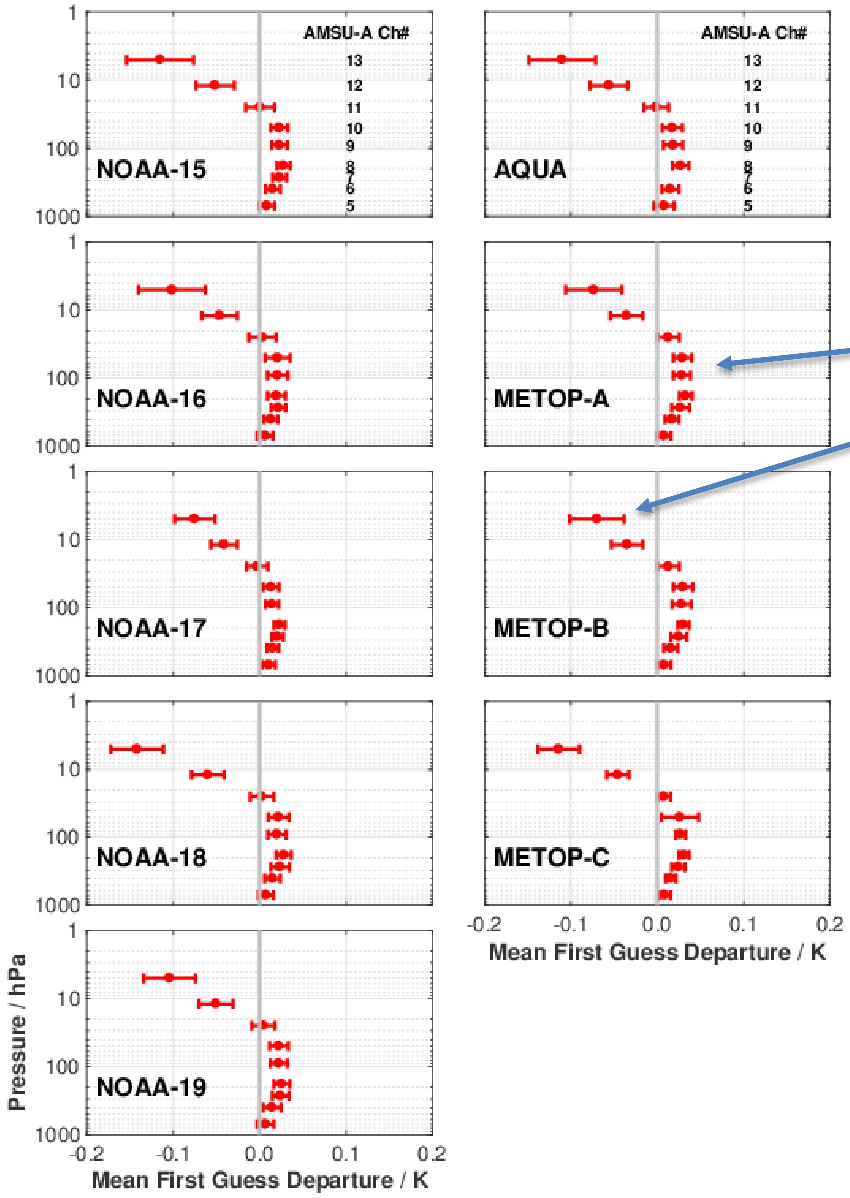


fg departures biased by ~25 mK



Climate Change

Model Error / AMSU-A Mean first guess departures in ERA5



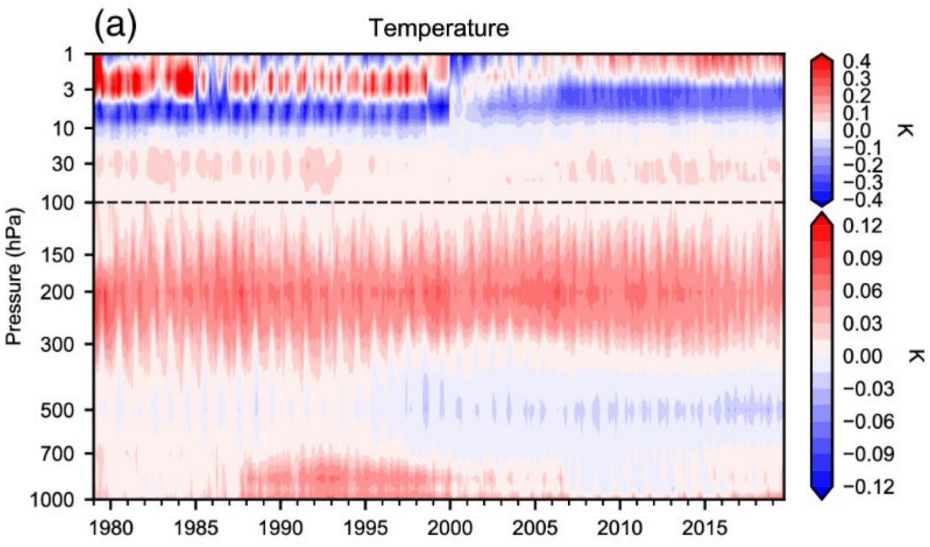
ERA5 mean first guess departures shown for AMSU-A

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

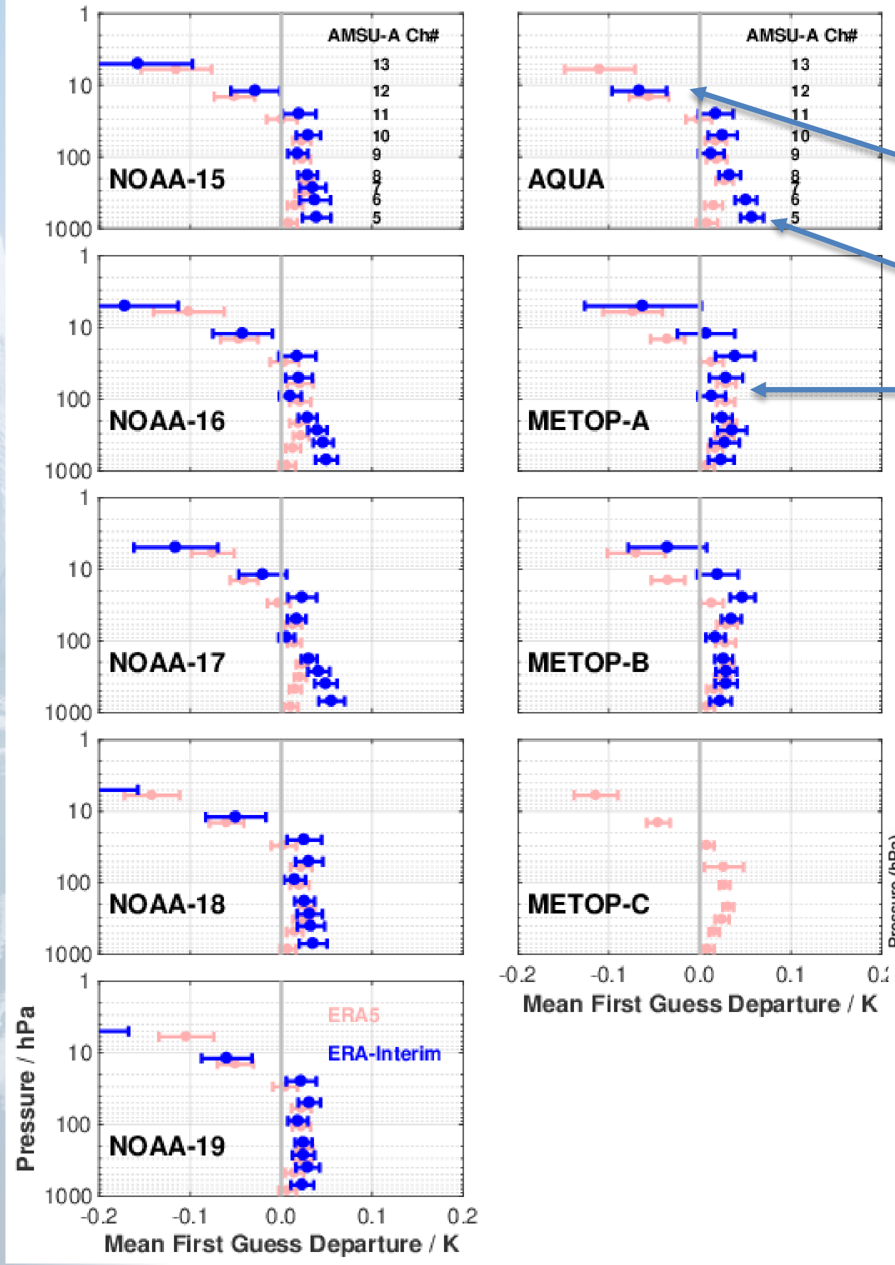
Broadly consistent with analysis increments in ERA5 (*below, from Fig 16, Hersbach et al, 2020*)



ECMWF

Climate Change

Model Error / AMSU-A Mean first guess departures in ERA-Interim



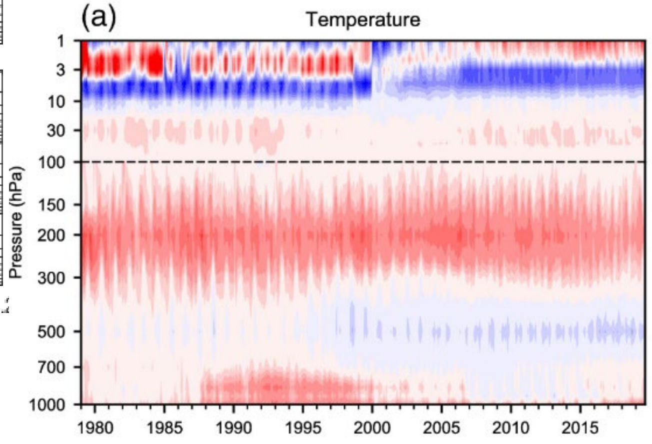
Indications that ERA-Interim:

Exhibits similar biases (to ERA5) above 10 hPa

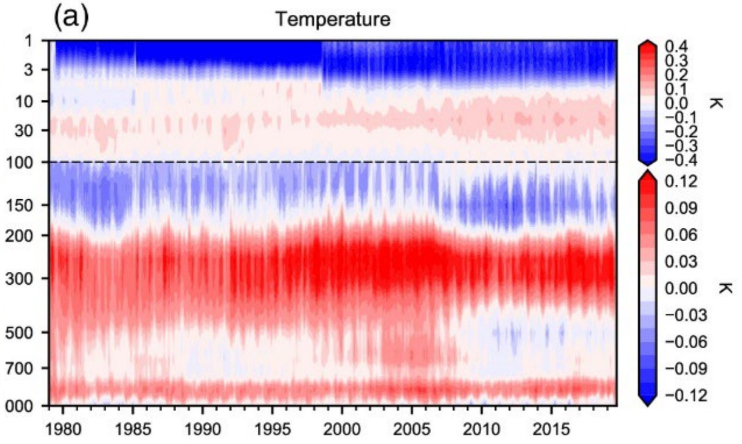
Exhibits larger biases below 200 hPa

Exhibits smaller biases around 100 hPa.

ERA5
analysis increments



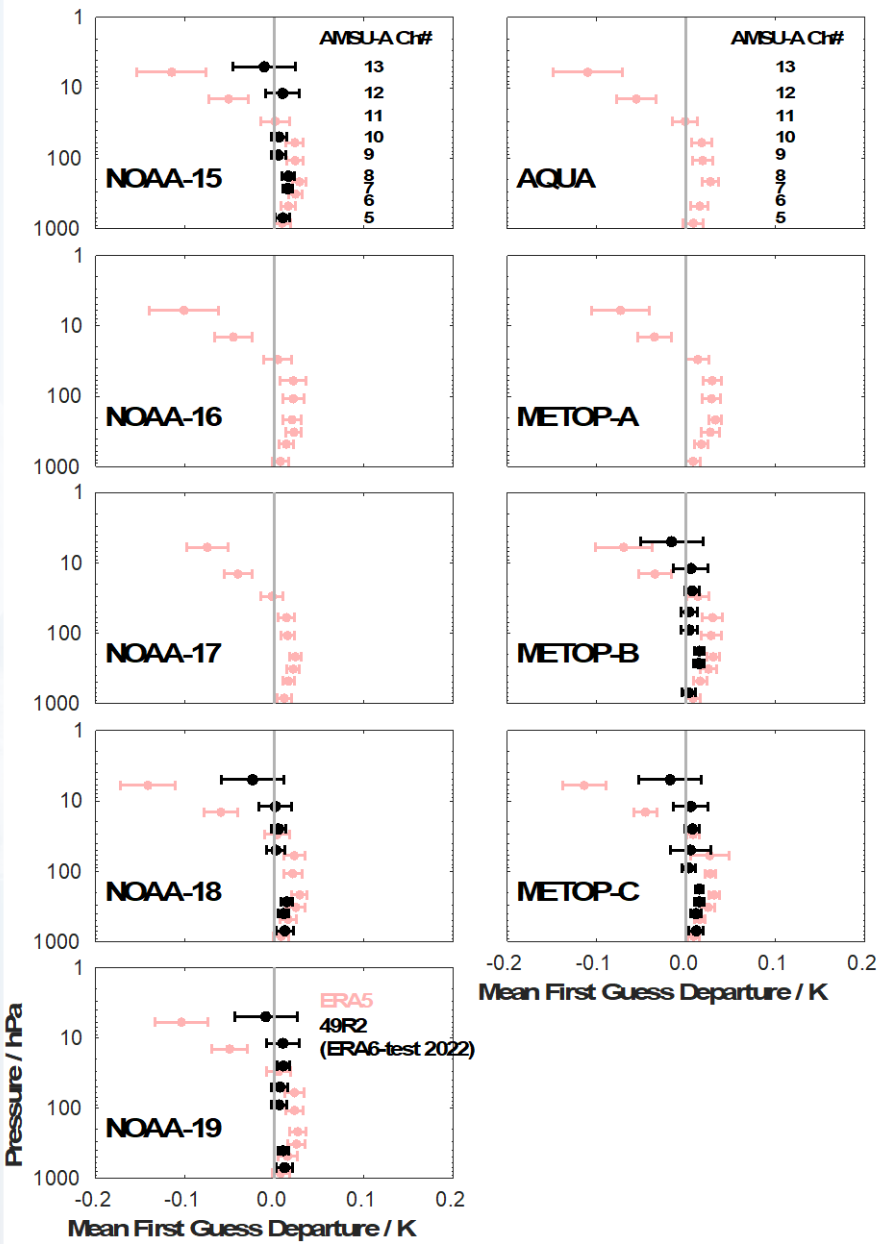
ERA-Interim
analysis increments



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

Model Error / AMSU-A Mean first guess departures in proto-ERA6 testing (CY49R2)

Climate Change



- Several improvements in analysis of the stratosphere since 2016:
  - Weak constraint 4D-Var
  - Improvement in dynamics
- Statistics shown based on JJA 2022 49R2 experiment
- Tco639 (18 km resolution) - ERA6 production will be 14 km
- Overall – forecast model in better agreement with observations

Climate Change

Overview

Biases in stratospheric temperatures in ERA5

- In '*model space*': anomalies & analysis increments
- ERA 5.1 & the role of RO observations
- In '*observation space*': mean first guess departures in ERA5, ERA-Interim & *proto-ERA6*

Southern winter polar bias in ERA5

- Exposed by anomalies & IRIS data

Exploiting information from RO observations back in time

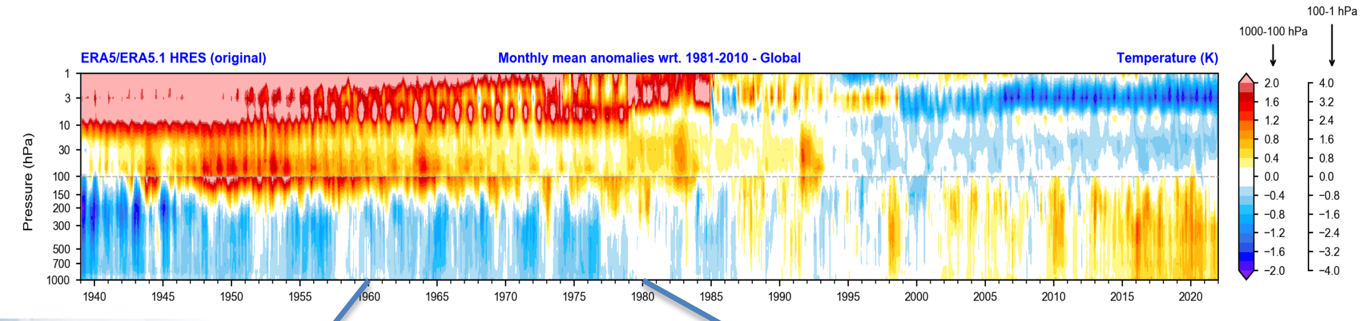
- Weak constraint 4D-Var & model error forcing
- Using early sounding data (IRIS in 1970) to evaluate model error correction strategies

Summary / Future Perspectives

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

Climate Change

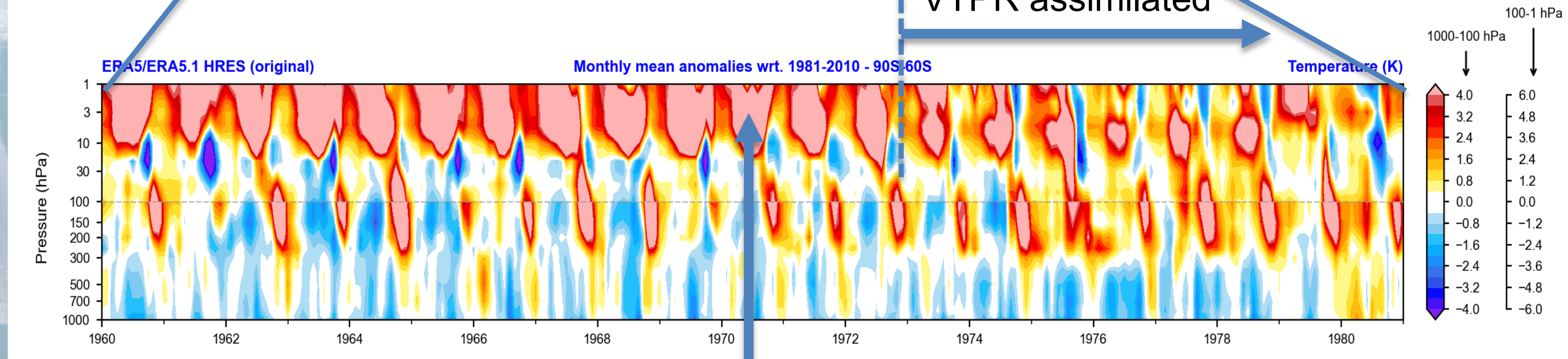
Global statistics 1940 - 2022



- Generally, ERA5 temperature analyses above 10 hPa exhibit biases and discontinuities

Southern polar statistics 1960 - 1980

VTPR assimilated



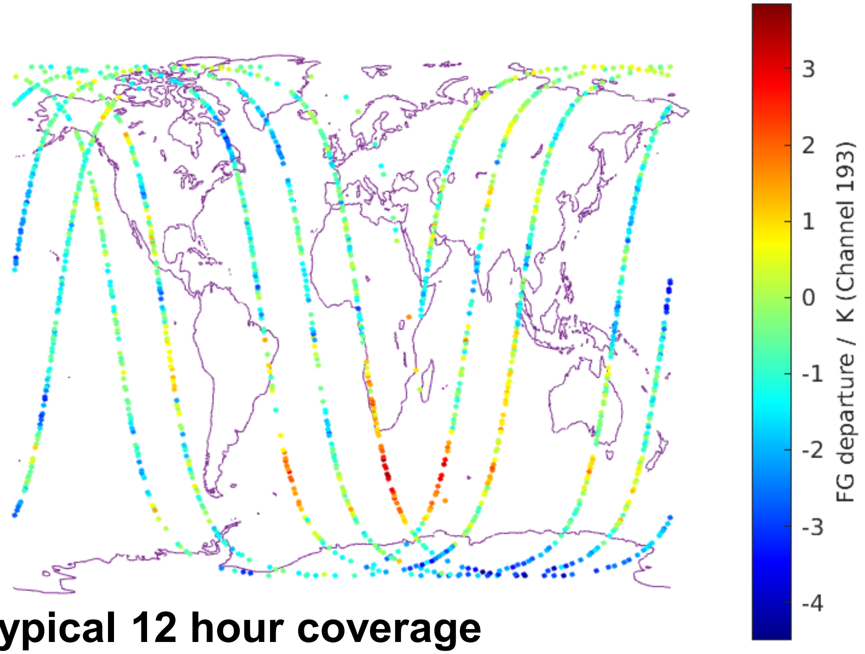
IRIS experiments

- 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)

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

Climate Change

Initial experiments assimilating IRIS in the IFS



Typical 12 hour coverage

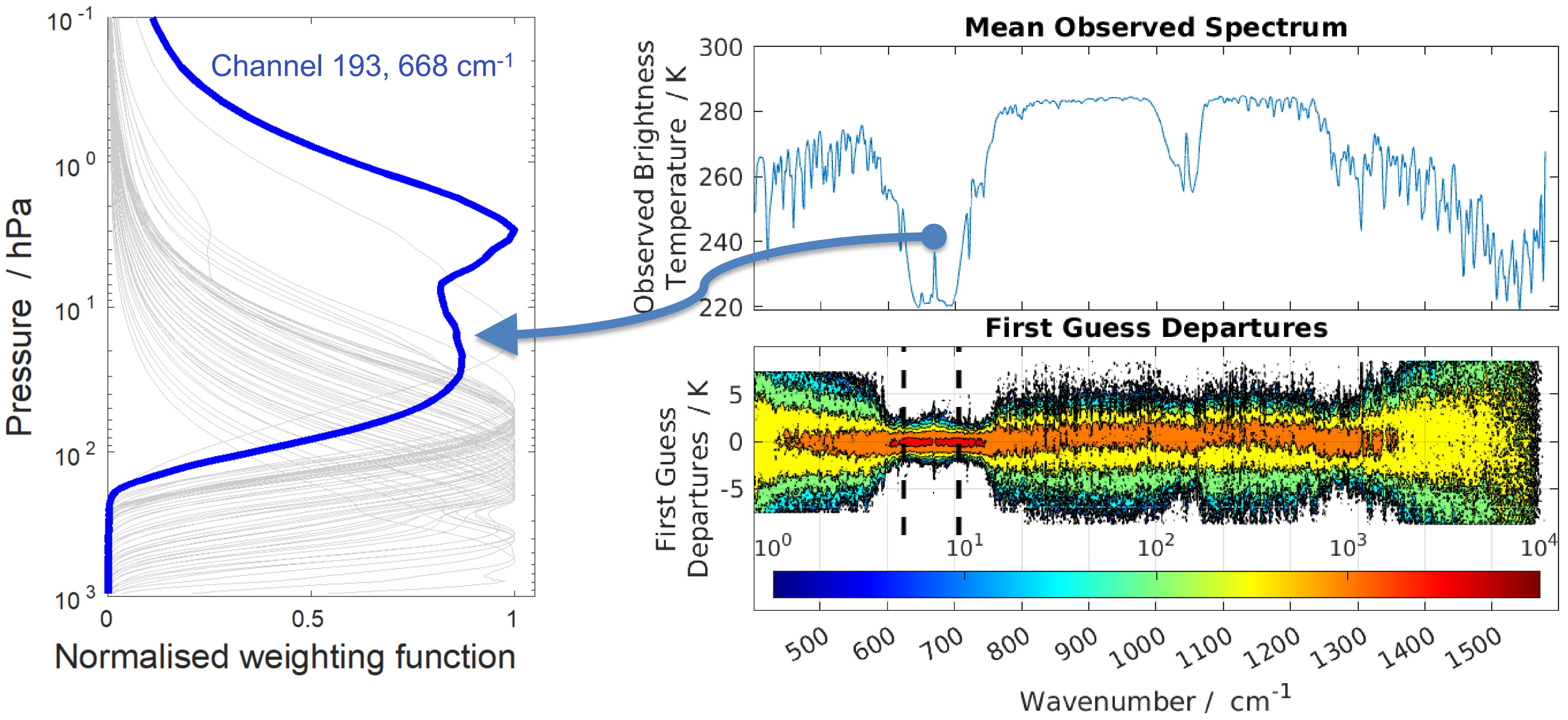
- Operated on Nimbus-4, from April 1970 – January 1971
- Nadir only observations. Spectral range 400 - 1600 cm^{-1}
- Resolution: 2.53 cm^{-1} to 2.69 cm^{-1}
- 94 km footprint
- 13 s measurement time
- Coverage to 80°N to 80°S (rely on **B** to propagate information to poles)

Daily time coverage / %

Year	Month	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
1970	04									18	63	0	0	2	95	88	77	86	2	79	93	88	85	85	5	83	0	1	86	79	76	
	05	82	3	85	5	92	79	85	85	93	93	93	93	79	52	84	93	93	5	93	86	81	0	92	86	93	90	90	82	79	5	88
	06	90	0	90	77	59	59	71	70	86	63	77	79	93	93	91	93	6	90	0	3	93	93	93	93	5	93	91	0	91	93	
	07	93	1	90	93	93	85	85	5	0	89	89	68	92	73	4	76	94	3	0	0	4	86	5	94	94	79	79	1	0	0	89
	08	85	79	88	1	0	76	9	91	85	86	82	90	86	94	80	0	55	5	94	2	59	2	79	80	86	5	0	0	2	82	47
	09	86	88	2	88	95	80	95	86	95	2	0	91	89	80	94	5	75	0	47	36	3	0	0	0	96	94	88	89	93	94	
	10	2	85	61	63	58	85	95	86	6	0	0	0	4	21	93	80	5	89	1	90	63	3	88	94	88	4	4	85	78	0	0
	11	93	91	91	85	0	0	60	86	83	0	93	81	93	97	1	91	92	94	89	93	98	93	82	54	2	96	93	69	82	81	
	12	71	70	68	1	69	77	76	0	77	0	1	63	66	61	0	61	70	69	0	76	72	72	73	68	74	3	71	72	69	69	75
1971	01	0	70	64	73	63	69	0	0	53	0	0	0	0	0	0	0	46	52	0	36	42	46	0	35	44	46	0	40	40	48	

Copernicus Europe's eyes on Earth
European Commission
ECMWF

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

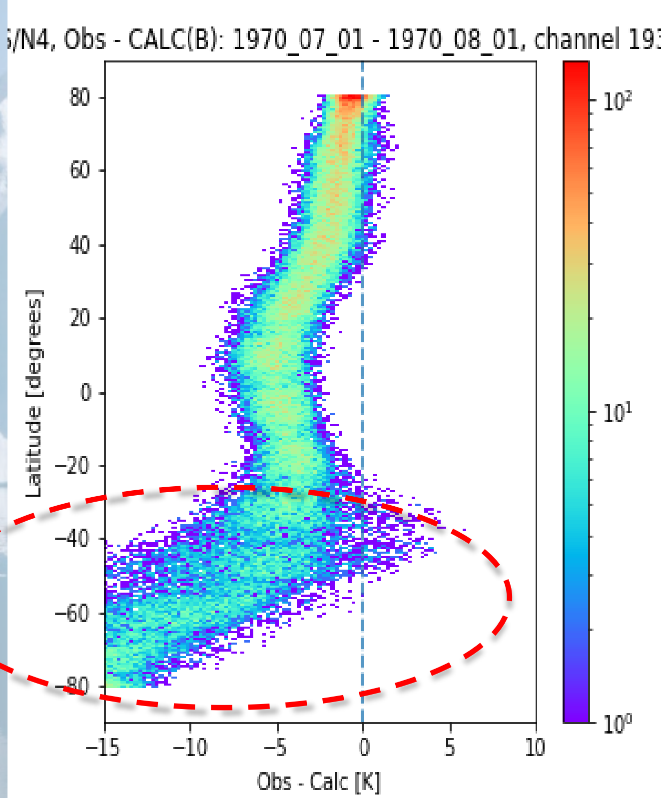


- IRIS data has been shown to be valuable in improving SH analysis quality (April 1970 – January 1971)
- Valuable for assessing biases in ERA5 in previously unobserved regions (eg S. Polar upper stratophere)
- Highest peaking channel is particulalry valuable

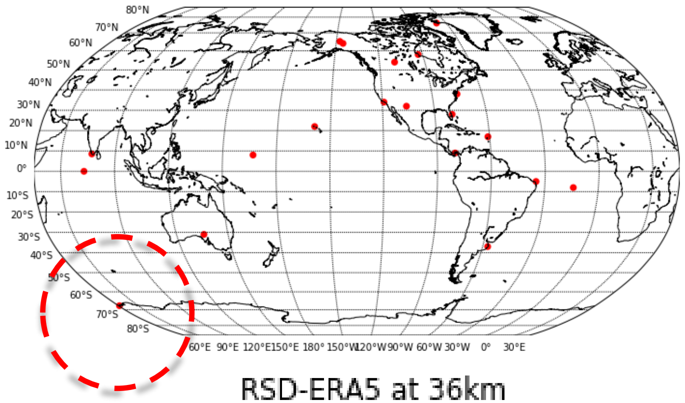
Evaluation of IRIS radiances relative to ERA5, rocketsondes & SIRS radiances (Andrzej Klonecki *et al* , Spascia)

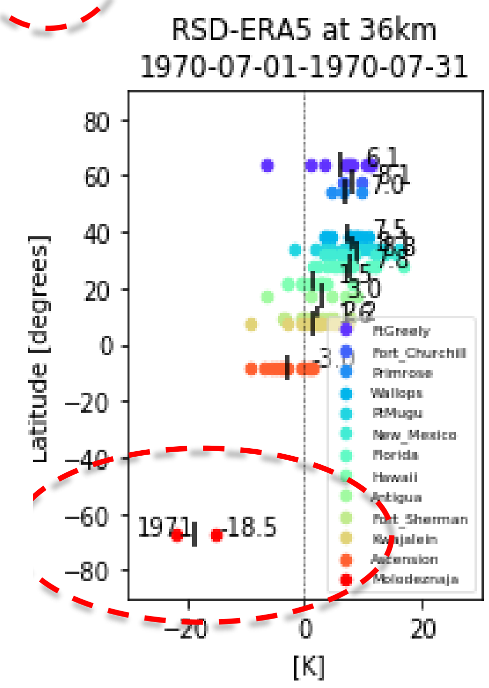
Climate Change

IRIS Obs vs ERA5 channel 193 peaking at 3 - 40hPa

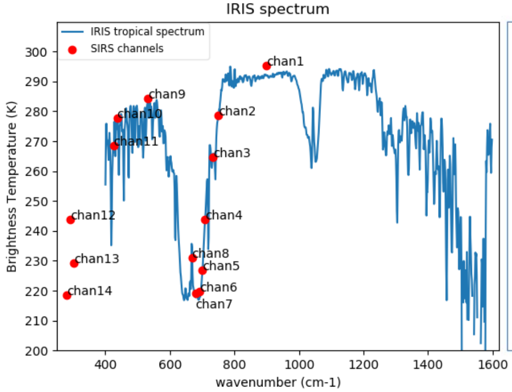


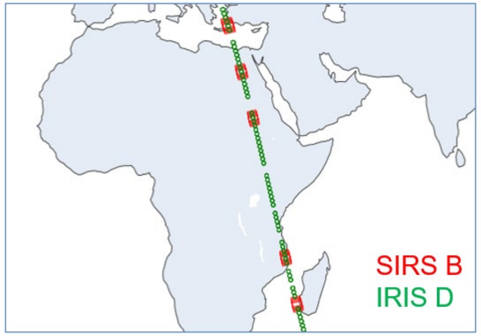
rocket sondes vs ERA5

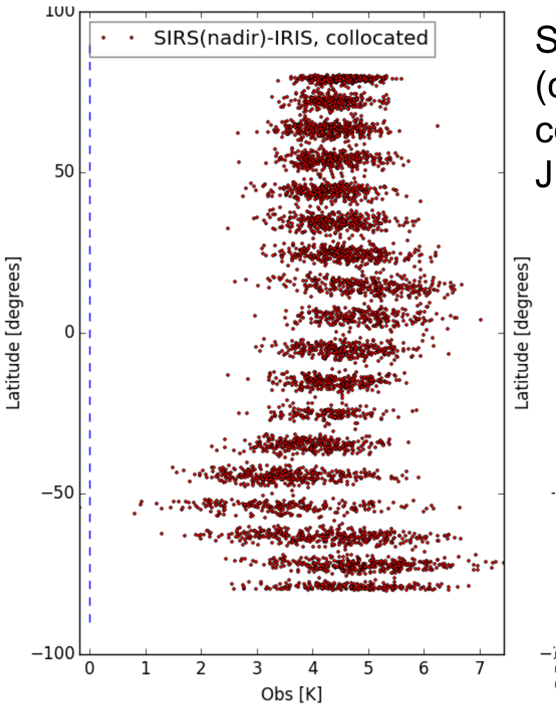




Nimbus-4 IRIS vs SIRS







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

In summary, relative to :

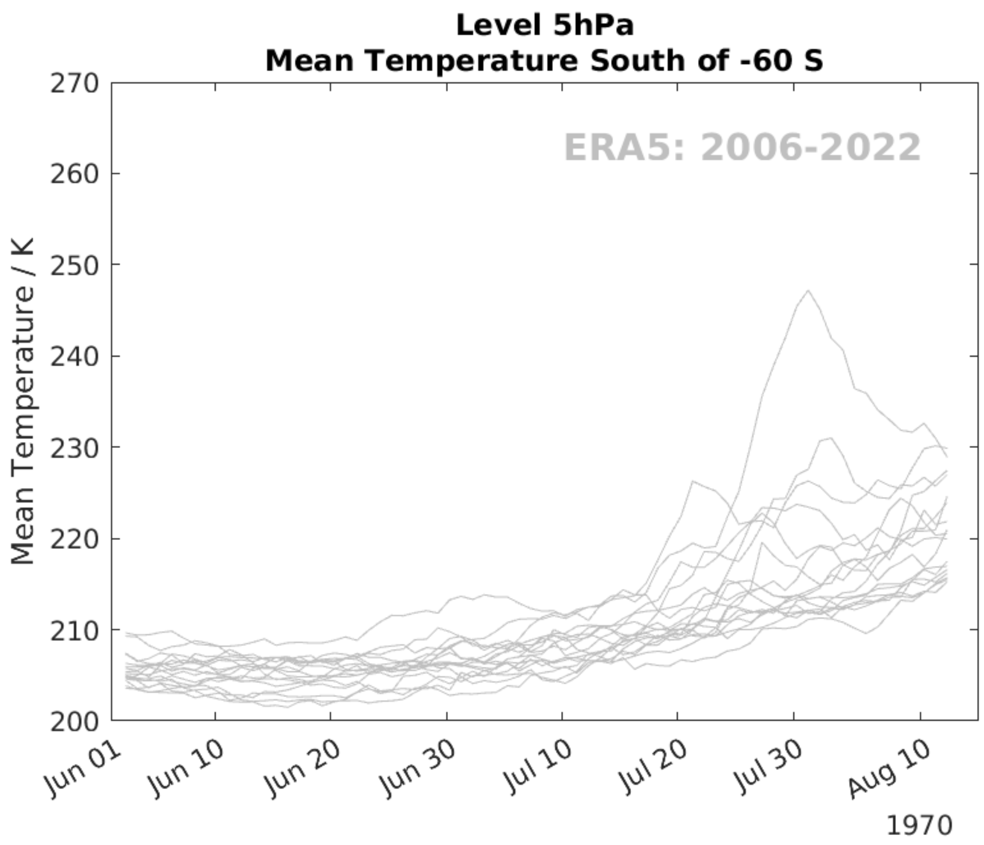
- Its own climate (1981-2010);
- IRIS observations;
- SIRS observations; and
- Rocket-sonde data

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

ECMWF

Impact of assimilating IRIS on southern polar stratospheric biases

Climate Change

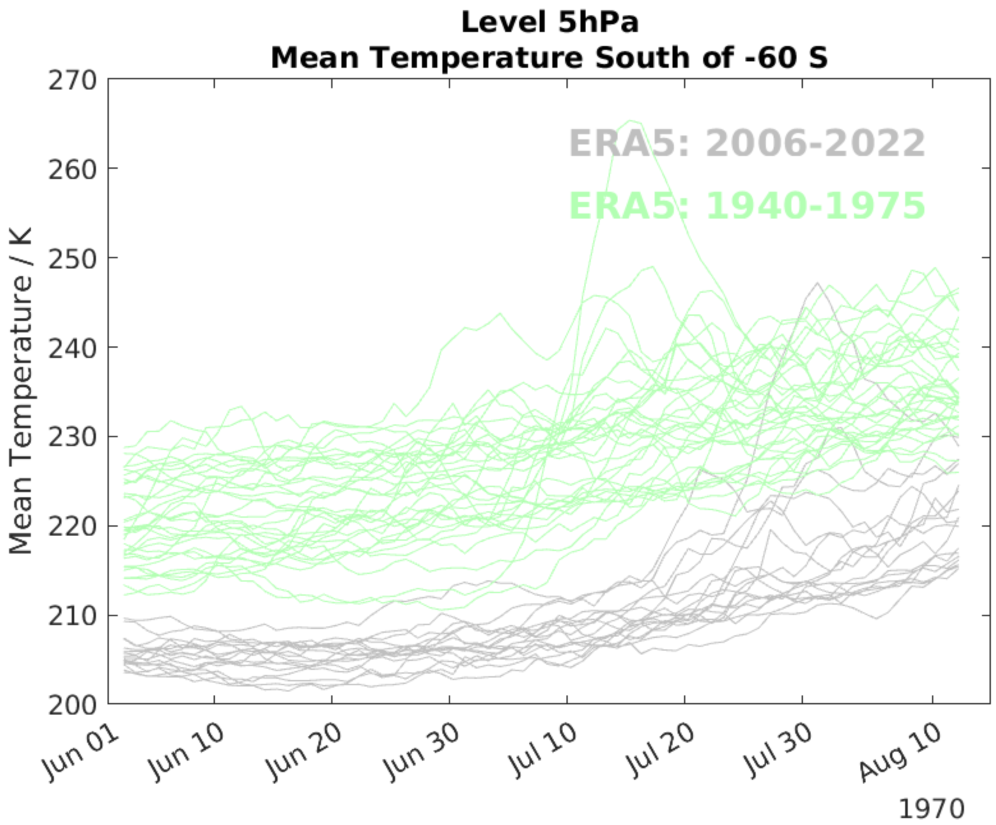


- During the GNSS-RO era (2006 -) the stratospheric temperature analysis is realistic

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

Climate Change

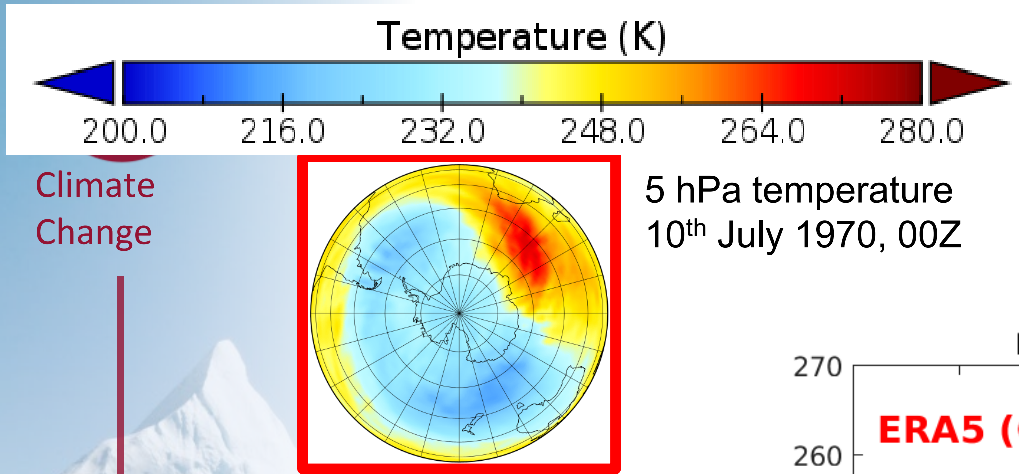
Impact of assimilating IRIS on southern polar stratospheric biases



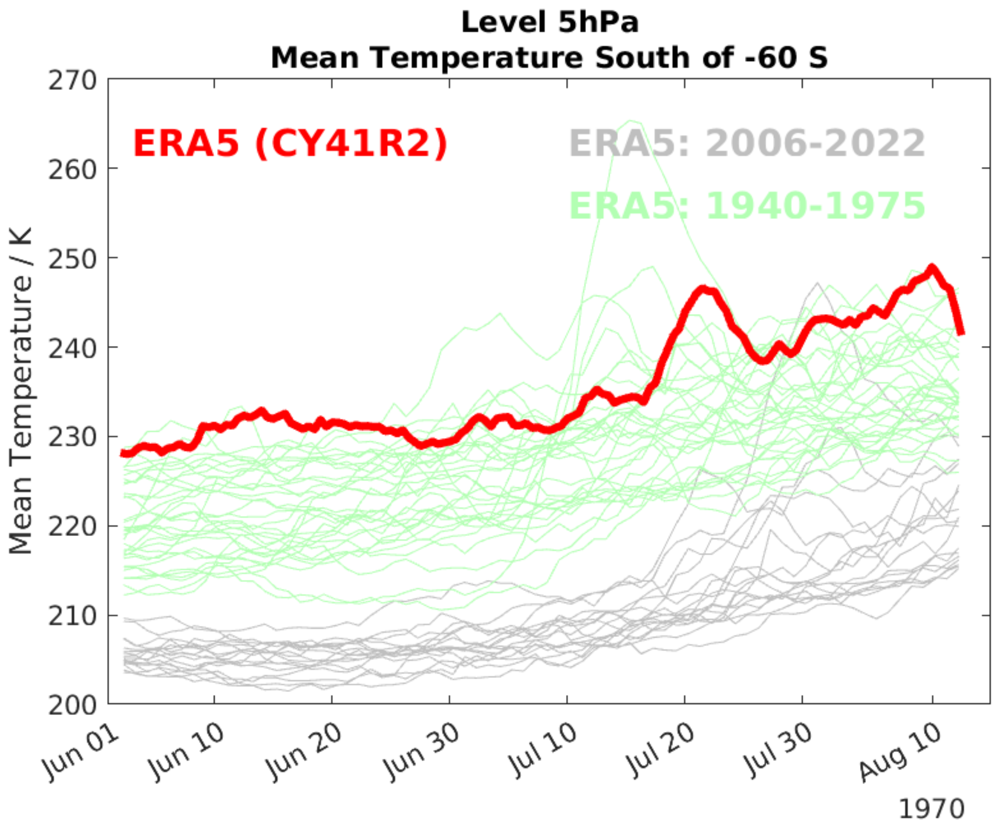
- During the GNSS-RO era (2006 -) the stratospheric temperature analysis is realistic
- In the early period (1940-75) of the reanalysis, few observations constrain the analysis ⇒ model biases are exposed. At 5hPa, temperatures are **10 – 25 K warmer** in mid-winter, relative to 2006-2022

Impact of assimilating IRIS on S. polar stratospheric biases

Climate Change



5 hPa temperature
10th July 1970, 00Z

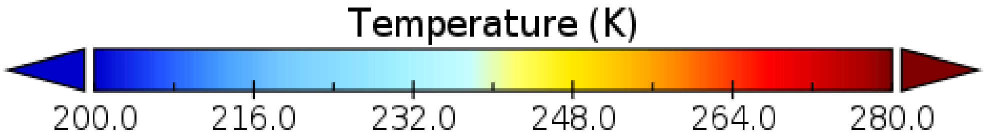


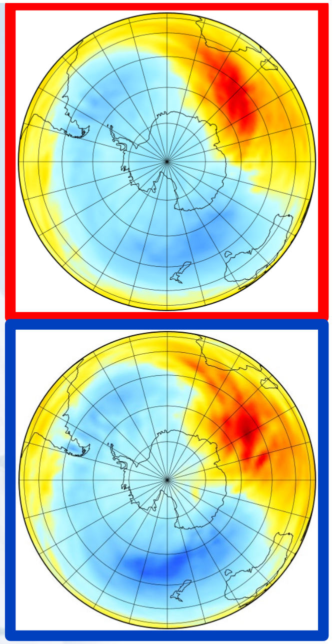
- During the GNSS-RO era (2006 -) the stratospheric temperature analysis is realistic
- In the early period (1940-75) of the reanalysis, few observations constrain the analysis ⇒ model biases are exposed. At 5hPa, temperatures are **10 – 25 K warmer** in mid-winter, relative to 2006-2022
- **ERA5** (41R2, 2016) in 1970 is at the top end of this range, with temperatures of 230K in mid-winter

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

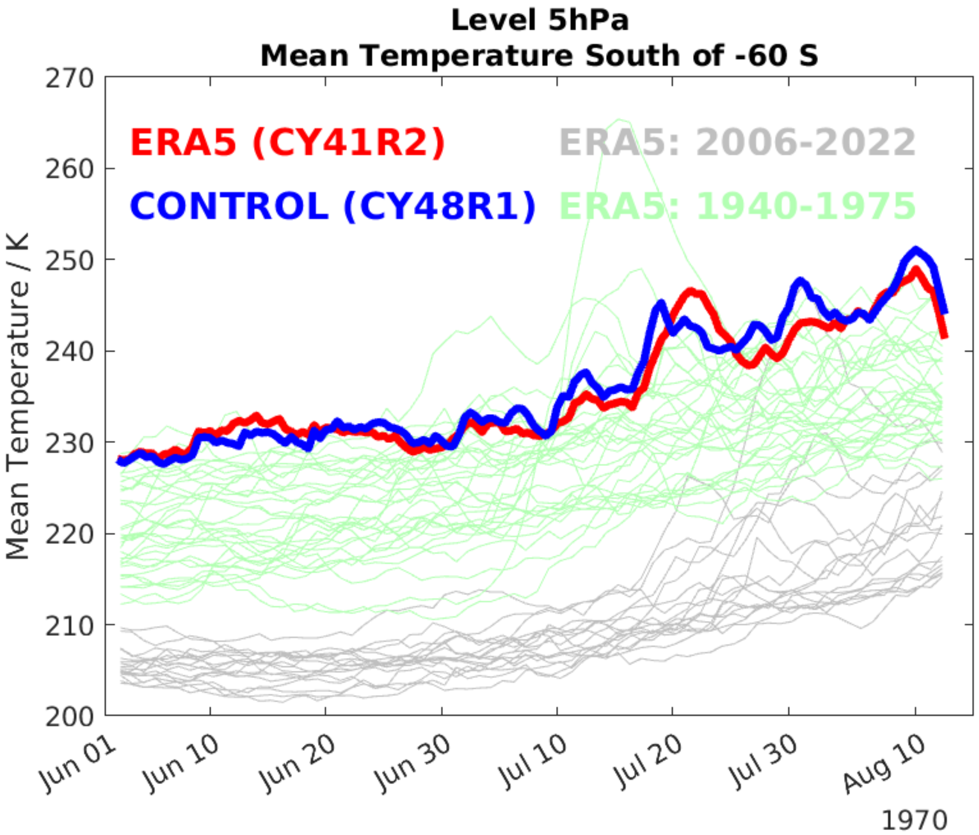
Impact of assimilating IRIS on S. polar stratospheric biases

Climate Change





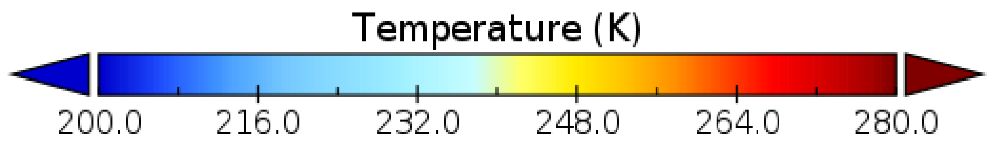
5 hPa temperature
10th July 1970, 00Z

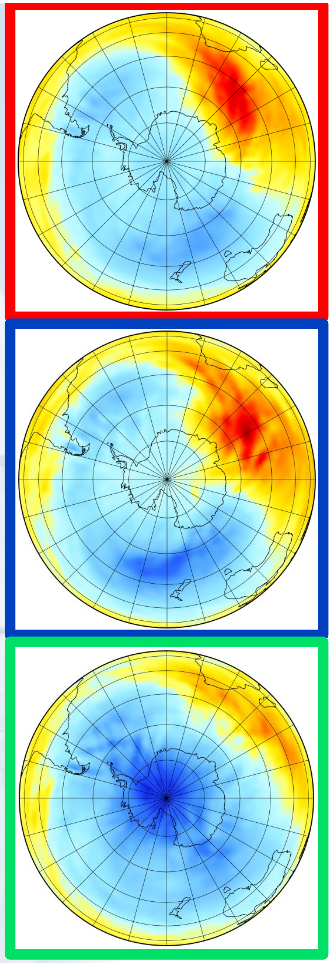


- During the GNSS-RO era (2006 -) the stratospheric temperature analysis is realistic
- In the early period (1940-75) of the reanalysis, few observations constrain the analysis ⇒ model biases are exposed. At 5hPa, temperatures are **10 – 25 K warmer** in mid-winter, relative to 2006-2022
- **ERA5** (41R2, 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

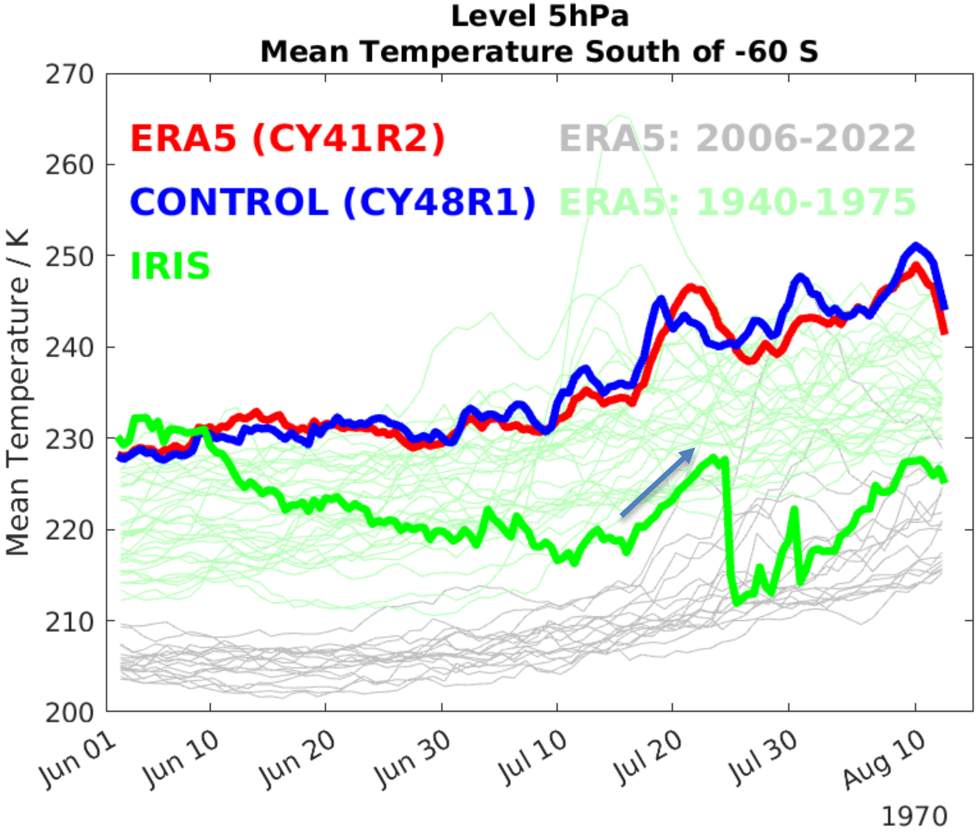
Impact of assimilating IRIS on S. polar stratospheric biases

Climate Change





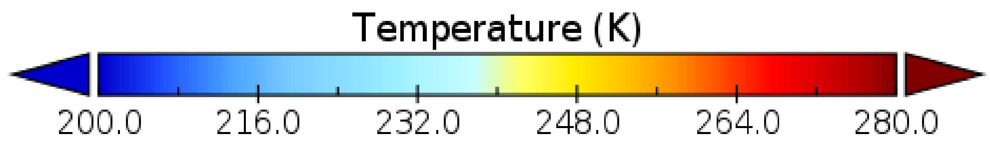
5 hPa temperature
10th July 1970, 00Z

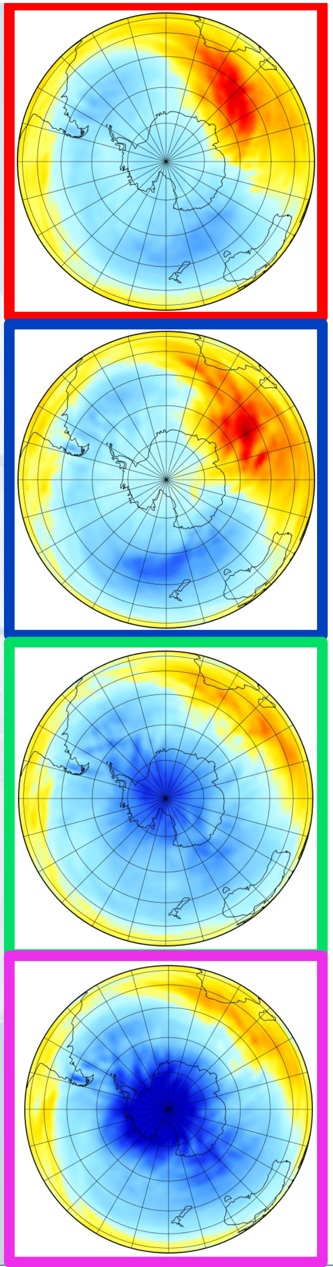


- During the GNSS-RO era (2006 -) the stratospheric temperature analysis is realistic
- In the early period (1940-75) of the reanalysis, few observations constrain the analysis ⇒ model biases are exposed. At 5hPa, temperatures are **10 – 25 K warmer** in mid-winter, relative to 2006-2022
- **ERA5** (41R2, 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

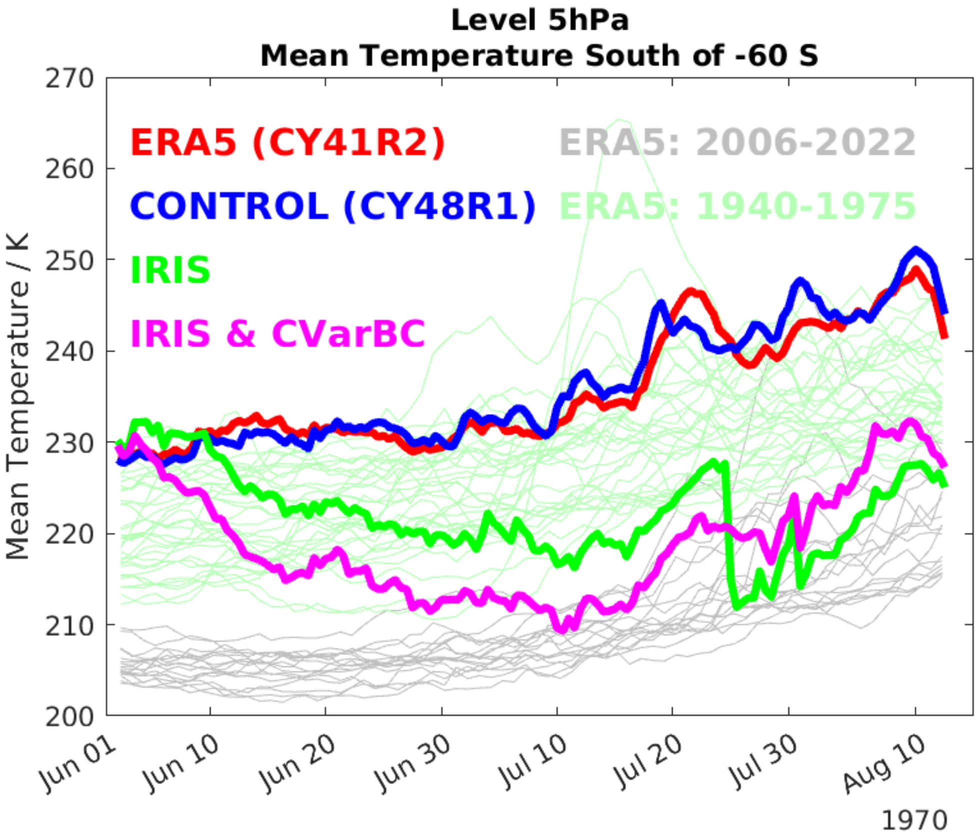
Impact of assimilating IRIS on S. polar stratospheric biases

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.

Climate Change

Overview

Biases in stratospheric temperatures in ERA5

- In '*model space*': anomalies & analysis increments
- ERA 5.1 & the role of RO observations
- In '*observation space*': mean first guess departures in ERA5, ERA-Interim & *proto-ERA6*

Southern winter polar bias in ERA5

- Exposed by anomalies & IRIS data

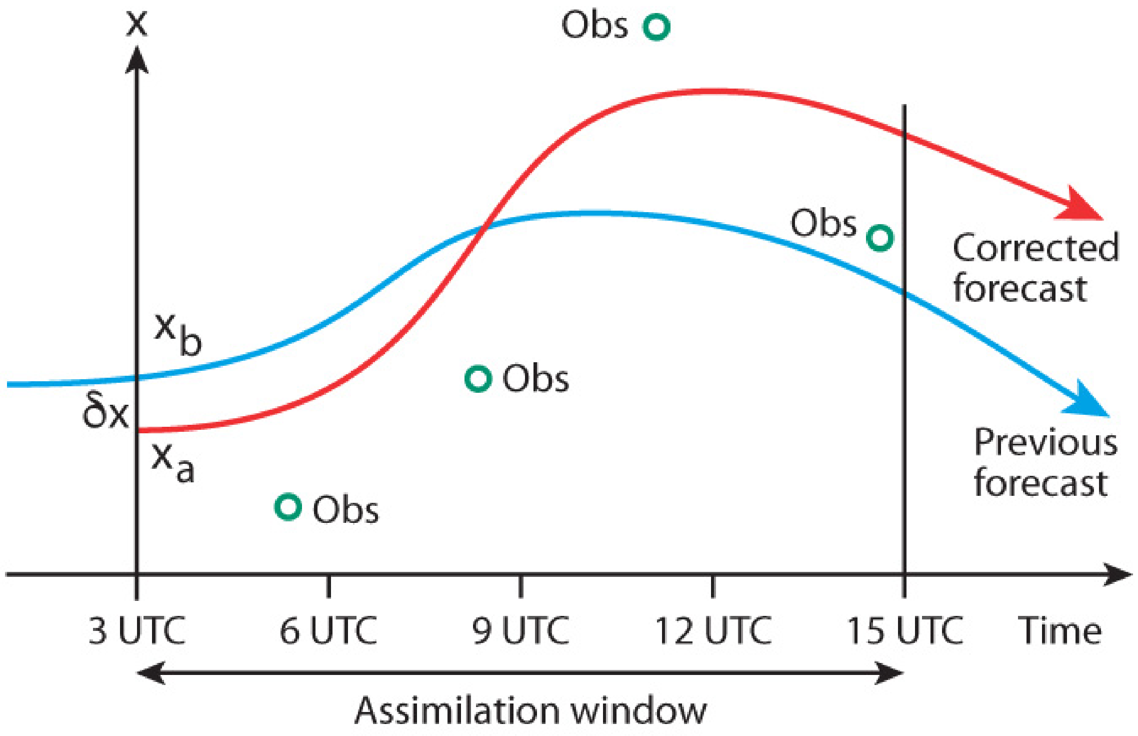
Exploiting information from RO observations back in time

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

Summary / Future Perspectives

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

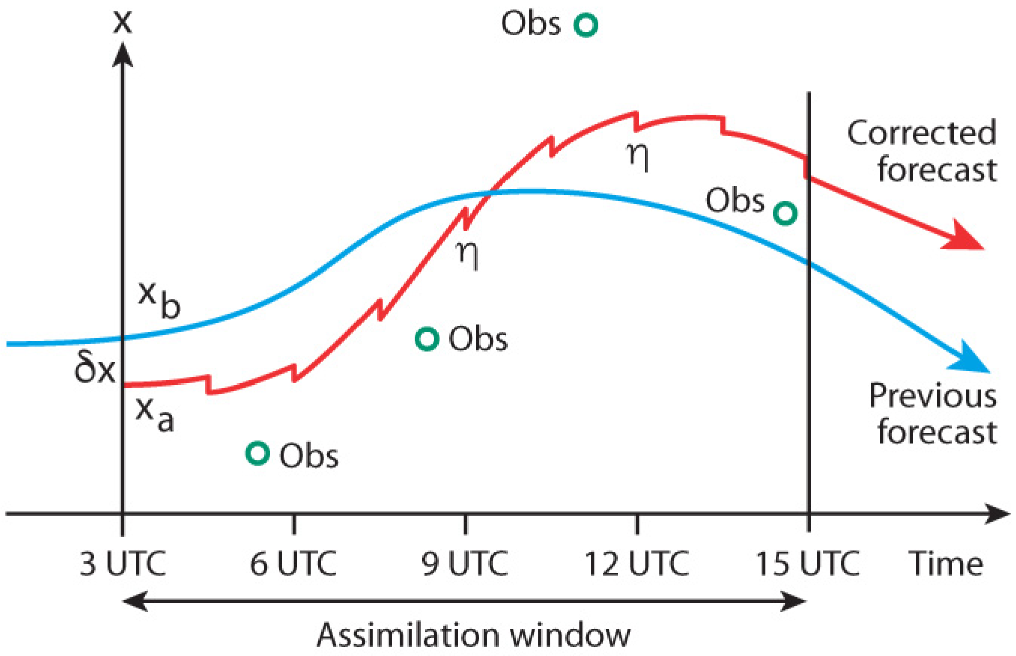
Climate Change

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

Weak-constraint 4D-Var formulation

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

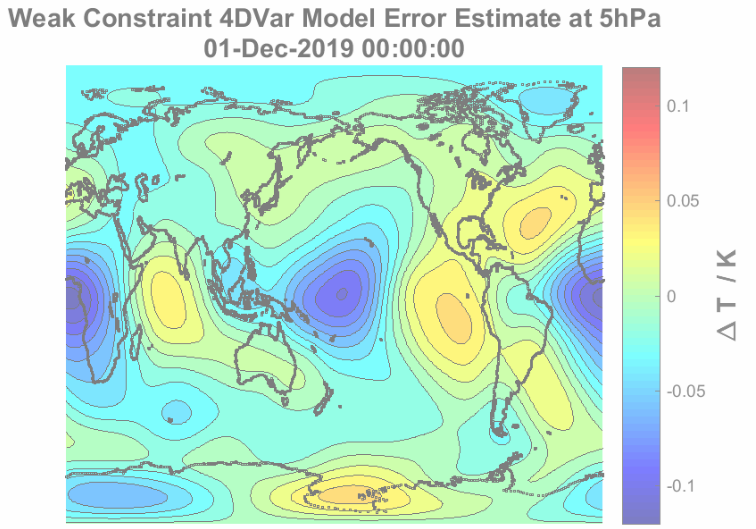
$$x_k = \mathcal{M}_k(x_{k-1}) + \eta \quad \text{for } k = 1, 2, \cdots, K$$

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 → x_0

Model bias correction → η



➔ 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

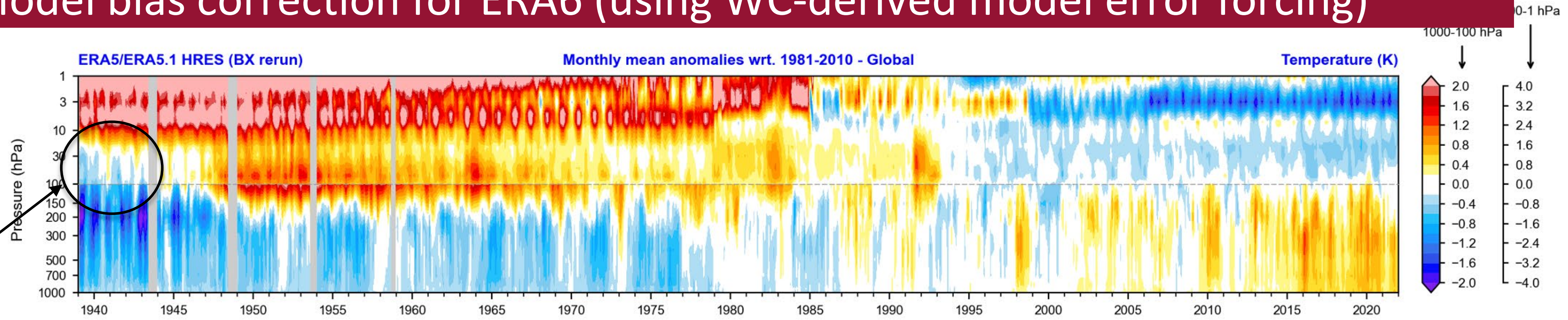
➔ Concept of scale separation introduced between background and model errors

➔ Constant model error forcing over the assimilation window

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

Climate Change

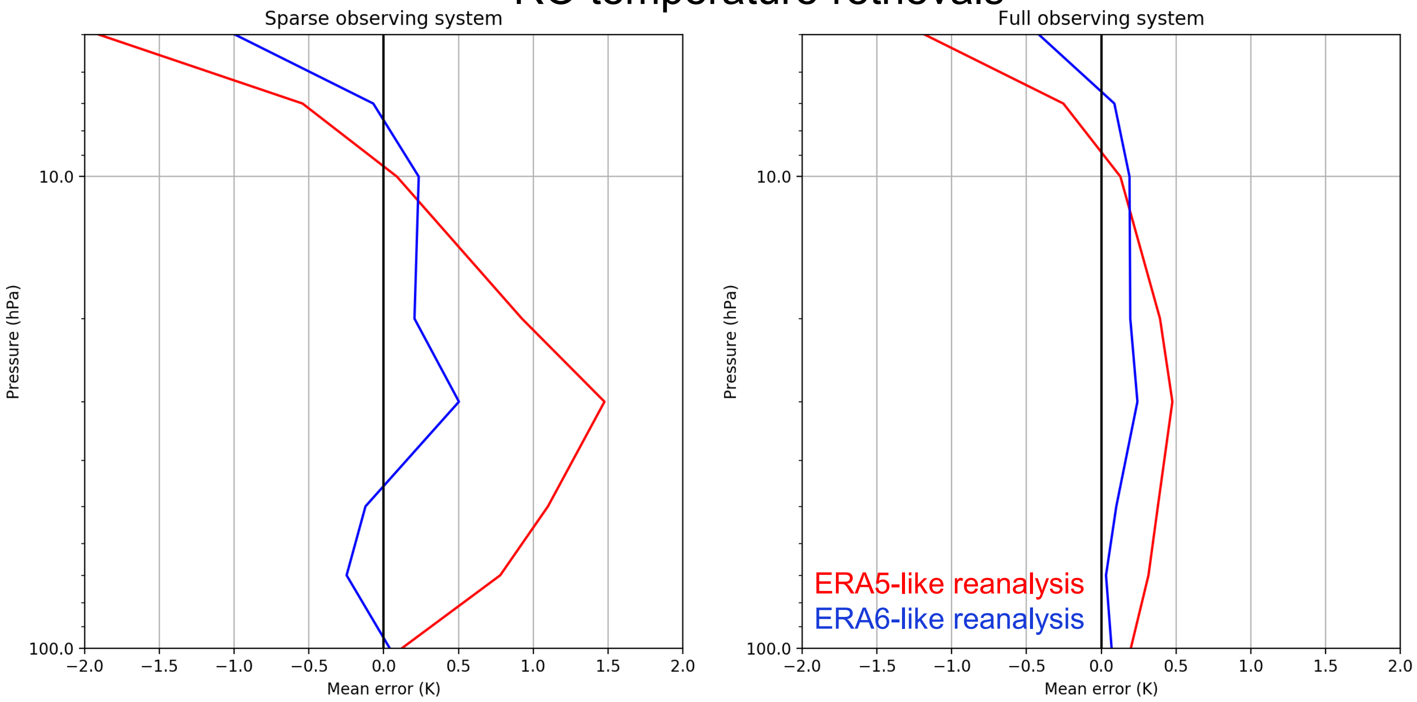
Model bias correction for ERA6 (using WC-derived model error forcing)



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)



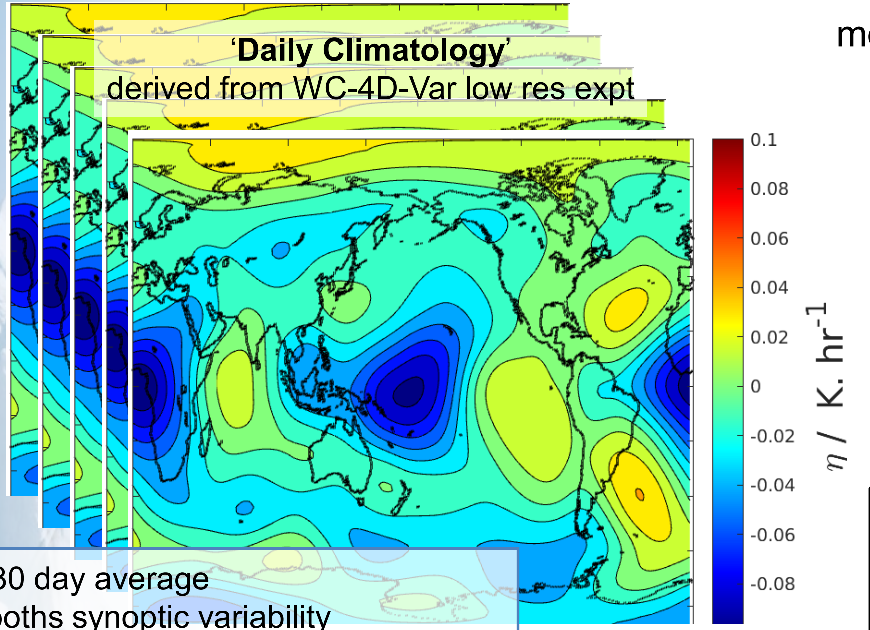
Recent observing system

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

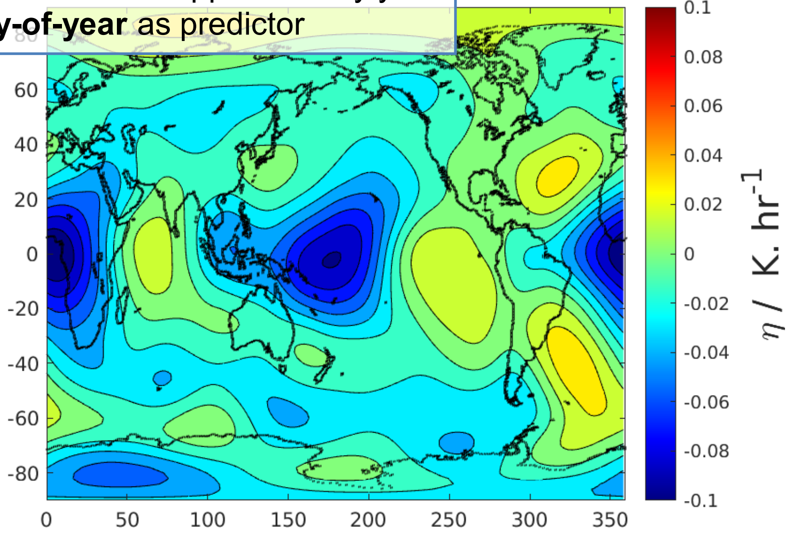
Climate Change

model error estimates at 5hPa

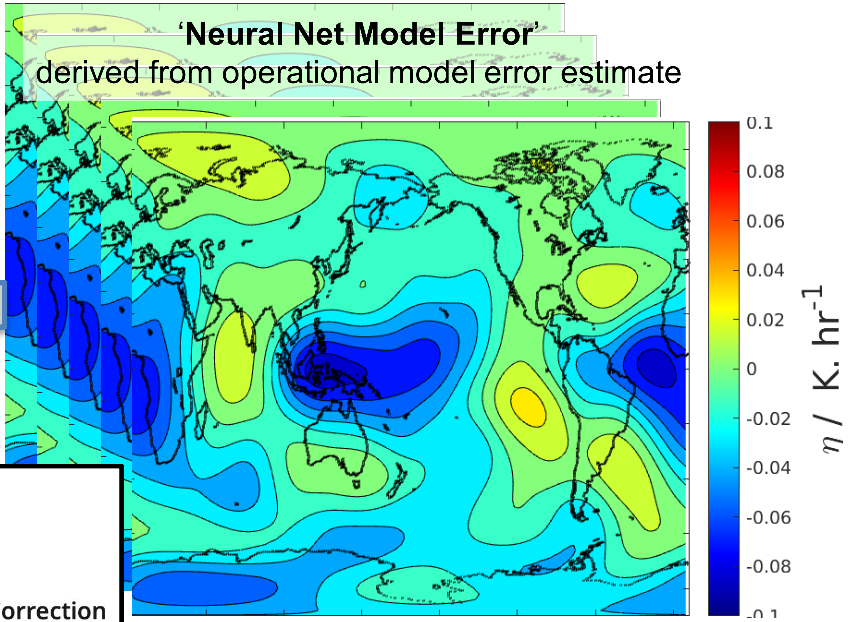
'Daily Climatology'
derived from WC-4D-Var low res expt



- +/- 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

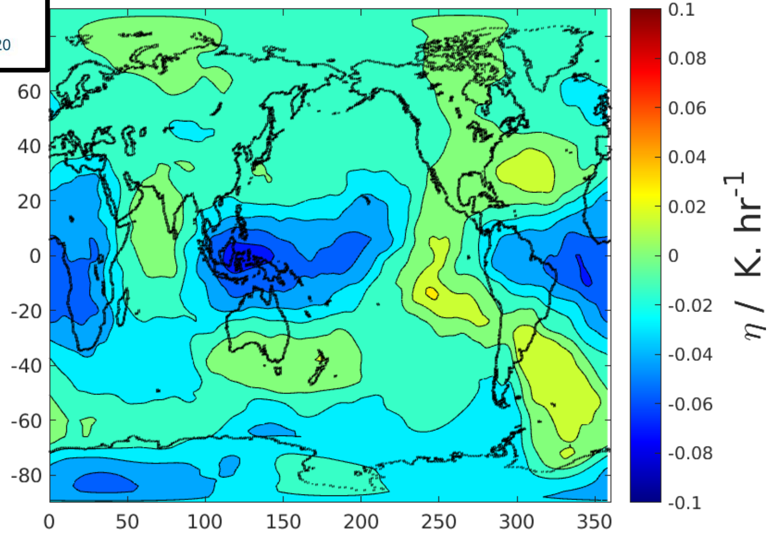
Research Article | Open Access

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

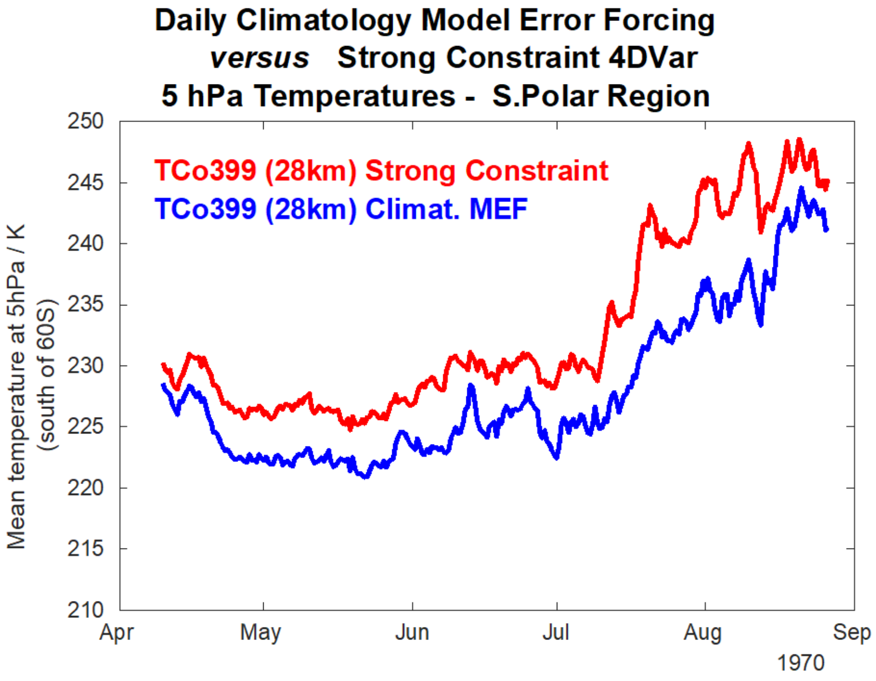
- derived from June 2020 - Feb2022
- predictors:
  - lat & lon
  - time of day & month of year
  - background state (T)

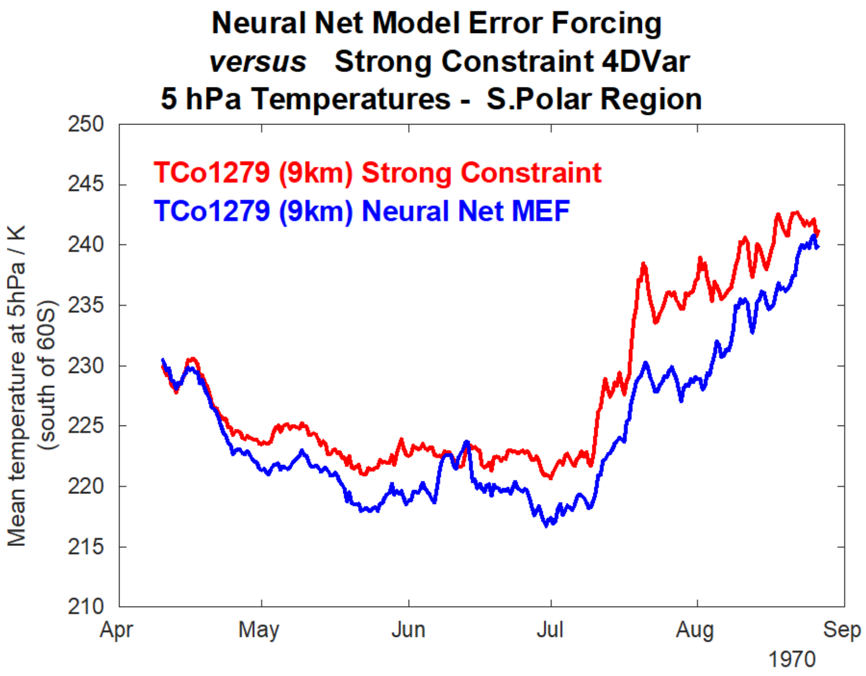


estimates shown for 1/7/1970

Climate Change

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





- 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

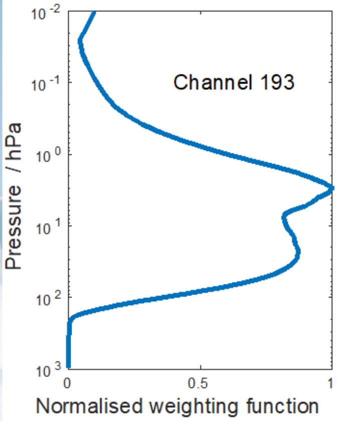
… but doesn't bring temperatures to the minimum temperatures expected (from IRIS assimilation experiments) of ~210K

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

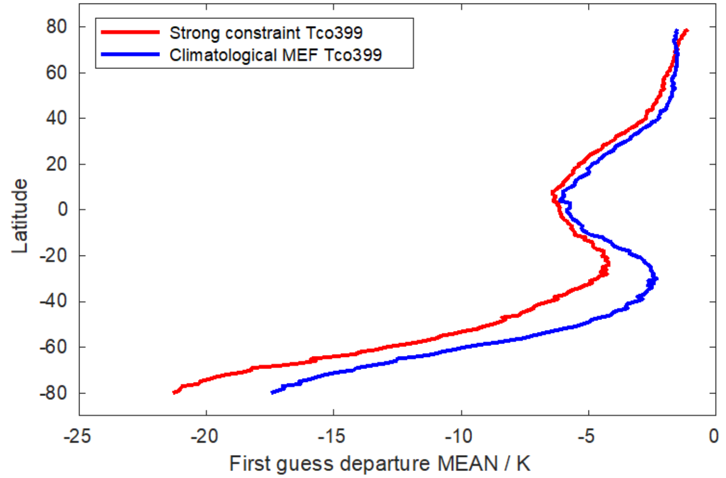
opernicus Europe's eyes on Earth | European Commission | ECMWF

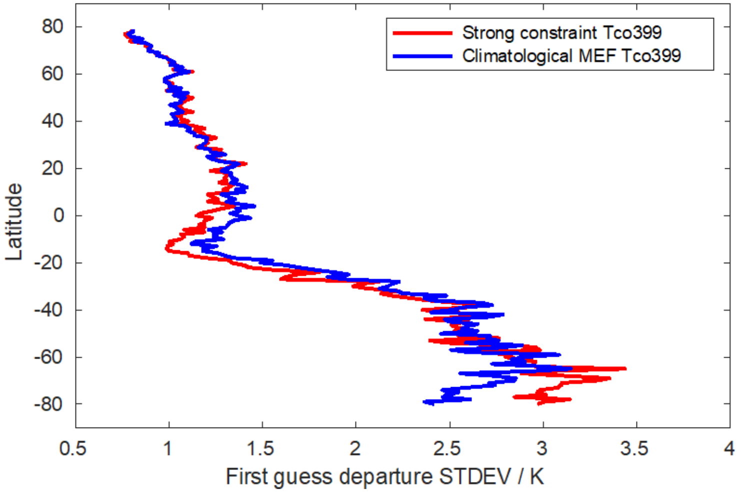
Climate Change

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

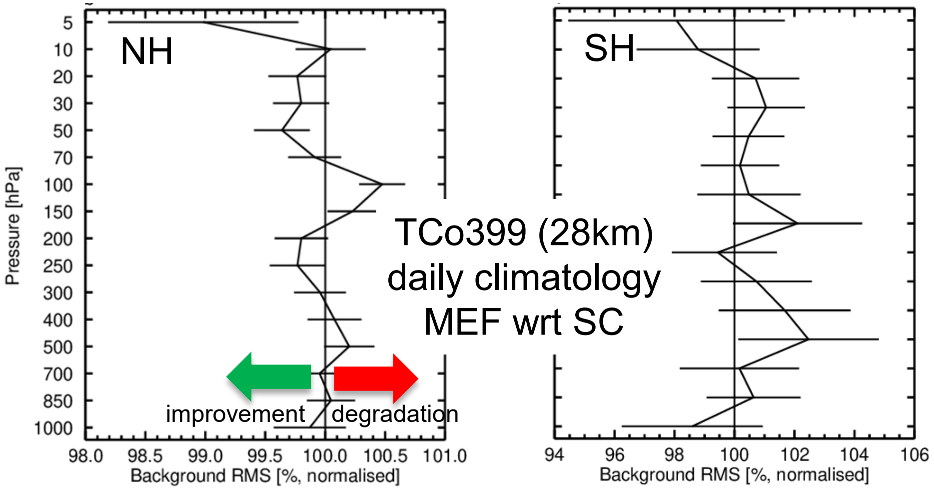


Impact of model error forcing
***versus* strong constraint 4DVar**
on (passive) IRIS channel 193 fg departures
July 1970



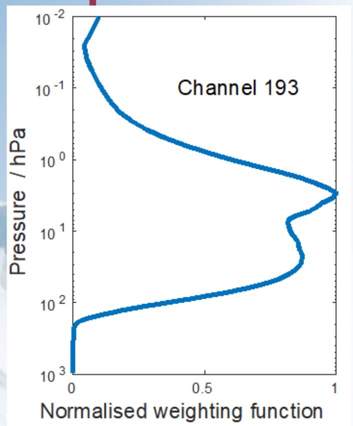


Background fits to radiosnde temperatures
20th April – 26th August 1970

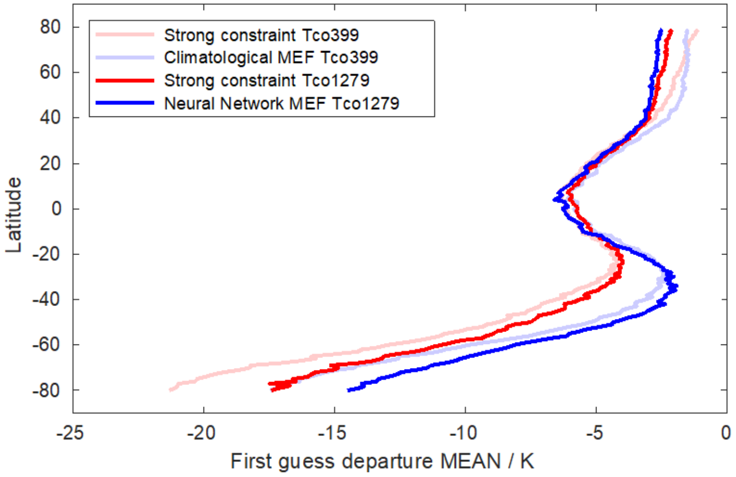


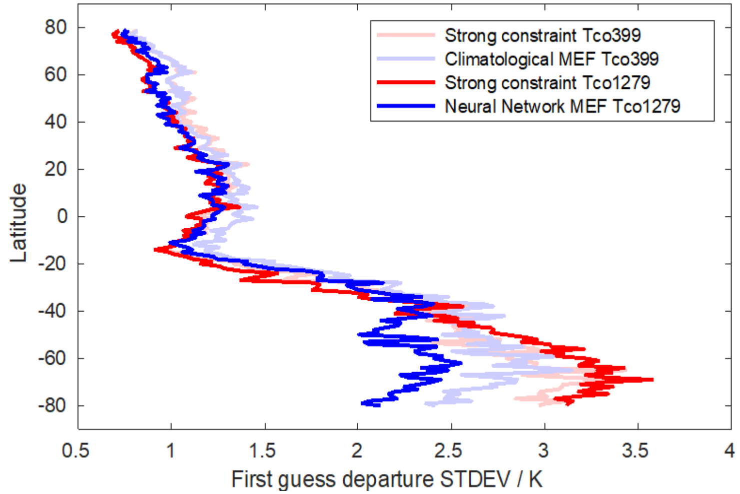
Verification of impacts of MEF: background fits to IRIS and radiosondes

Climate Change

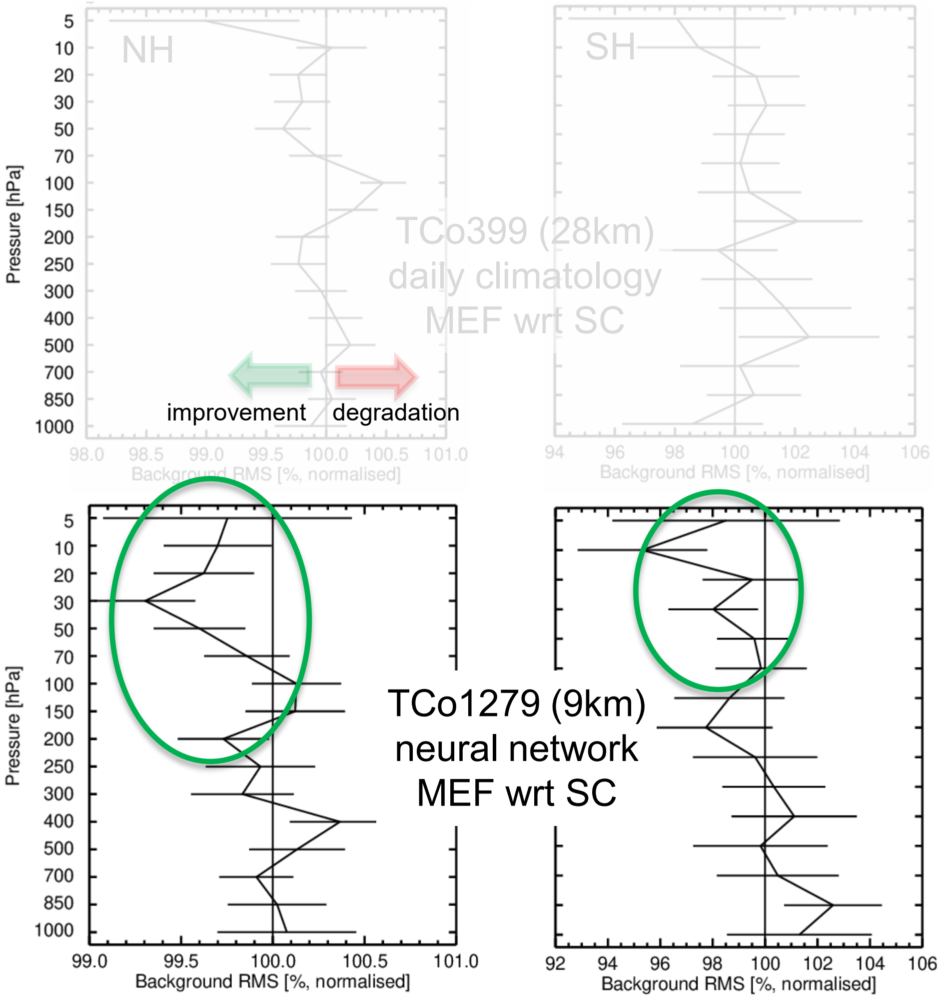


Impact of model error forcing *versus* strong constraint 4DVar on (passive) IRIS channel 193 fg departures July 1970





Background fits to radiosnde temperatures
20^{th} April – 26^{th} August 1970



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

opernicus Europe's eyes on Earth
European Commission
ECMWF

Overview

Biases in stratospheric temperatures in ERA5

- In '*model space*': anomalies & analysis increments
- ERA 5.1 & the role of RO observations
- In '*observation space*': mean first guess departures in ERA5, ERA-Interim & *proto-ERA6*

Southern winter polar bias in ERA5

- Exposed by anomalies & IRIS data

Exploiting information from RO observations back in time

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

Summary / Future Perspectives

Summary & conclusions

Climate Change

- Biases in stratospheric temperatures are particularly evident in ERA5. GNSSRO data:
  - **Has played a key role in mitigating the effects of these biases** in the recent (2006 →) era, and ;
  - **Will play a role in mitigating their effects in earlier epochs of ERA6** (1950 → 2006) through WC-4DVar & model error forcing

- The magnitude of the biases is large (typically ~1K, but up to 20K!). In successive generations of reanalyses, attention will turn to much smaller biases in other regions (& variables). We hope that the diagnostics and methods used to mitigate in ERA5 & ERA6 will be useful in those cases

- Short lived early satellite missions (*e.g.* IRIS, in 1970) have proved valuable in assessing the performance of model error forcing, by providing observations in otherwise unobserved regions/domains

- ERA6 will make use of reprocessed RO datasets for COSMIC, CHAMP, GRACE and GRAS – provided by EUMETSAT. Impacts (not shown here) are generally positive

- RO data , and other reference datasets (e.g. GRUAN radiosondes & CrIS radiances), perhaps have a role to play in evaluating uncertainties in ERA6 (withhold a subset of RO observations, and use to validate the reanalysis ?)

Climate Change

Extra slides

Copernicus Europe's eyes on Earth
European Commission
ECMWF

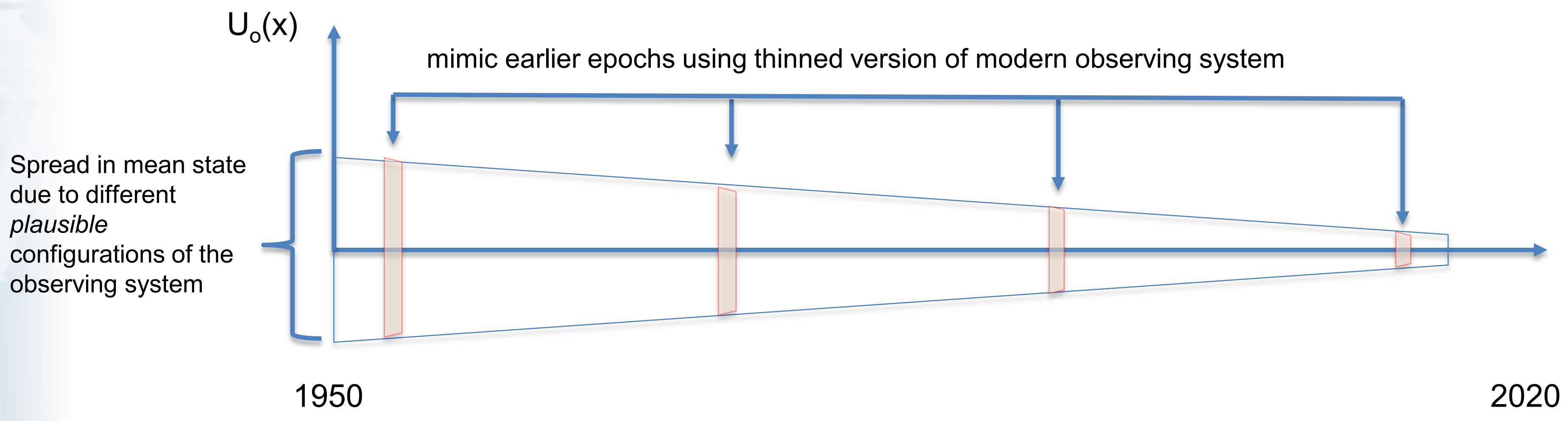
Possible approaches to determining mean-state uncertainty

Climate Change

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, …



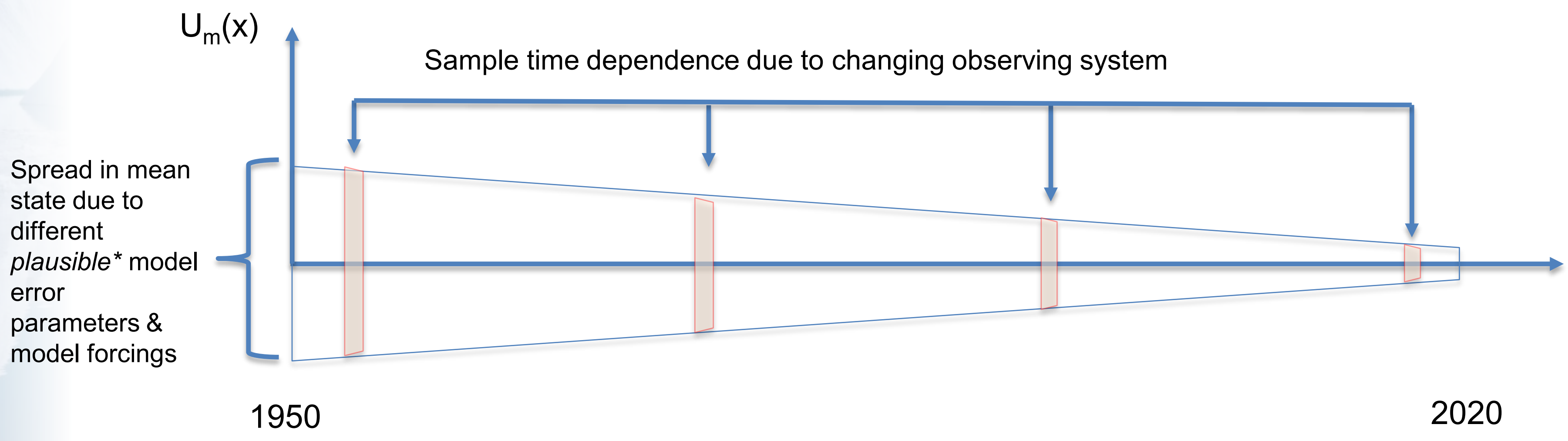
Climate Change

Possible approaches to determining mean-state uncertainty

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

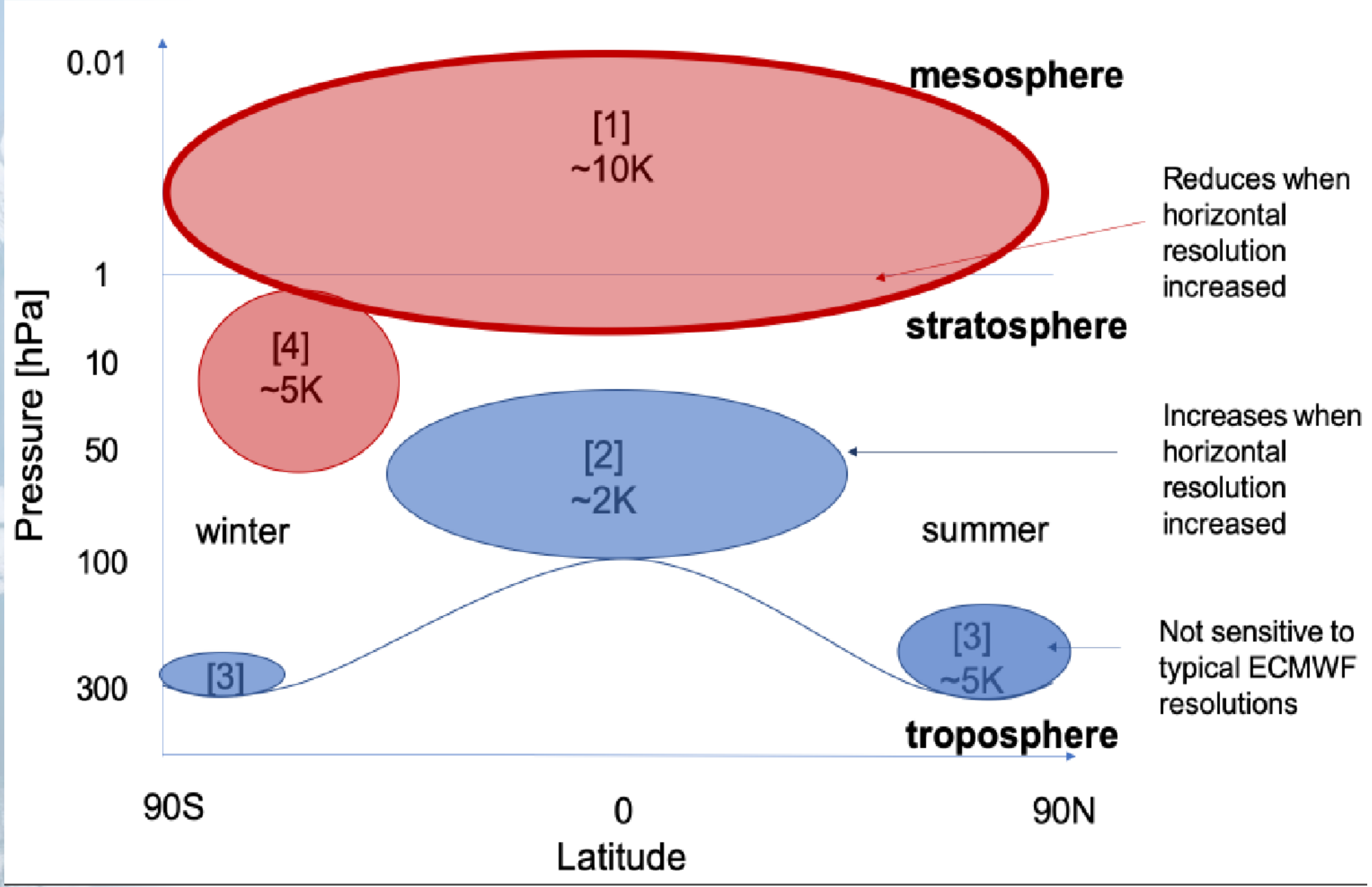
- OSEs with perturbed model parameters & alternative choices of forcings
- Key model parameters? - draw upon experience of EPS and climate modelling communities
- Sample time dependence using paired down modern observing system, or run in past epochs



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

Model biases in the stratosphere

Climate Change



Weak constraint 4D-Var offers a solution for ERA6.

In addition, future 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