Diagnostics (developed for operational forecast system) applied to ERA5

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Workshop on Future US Earth System Reanalysis

Boulder, CO (virtual)

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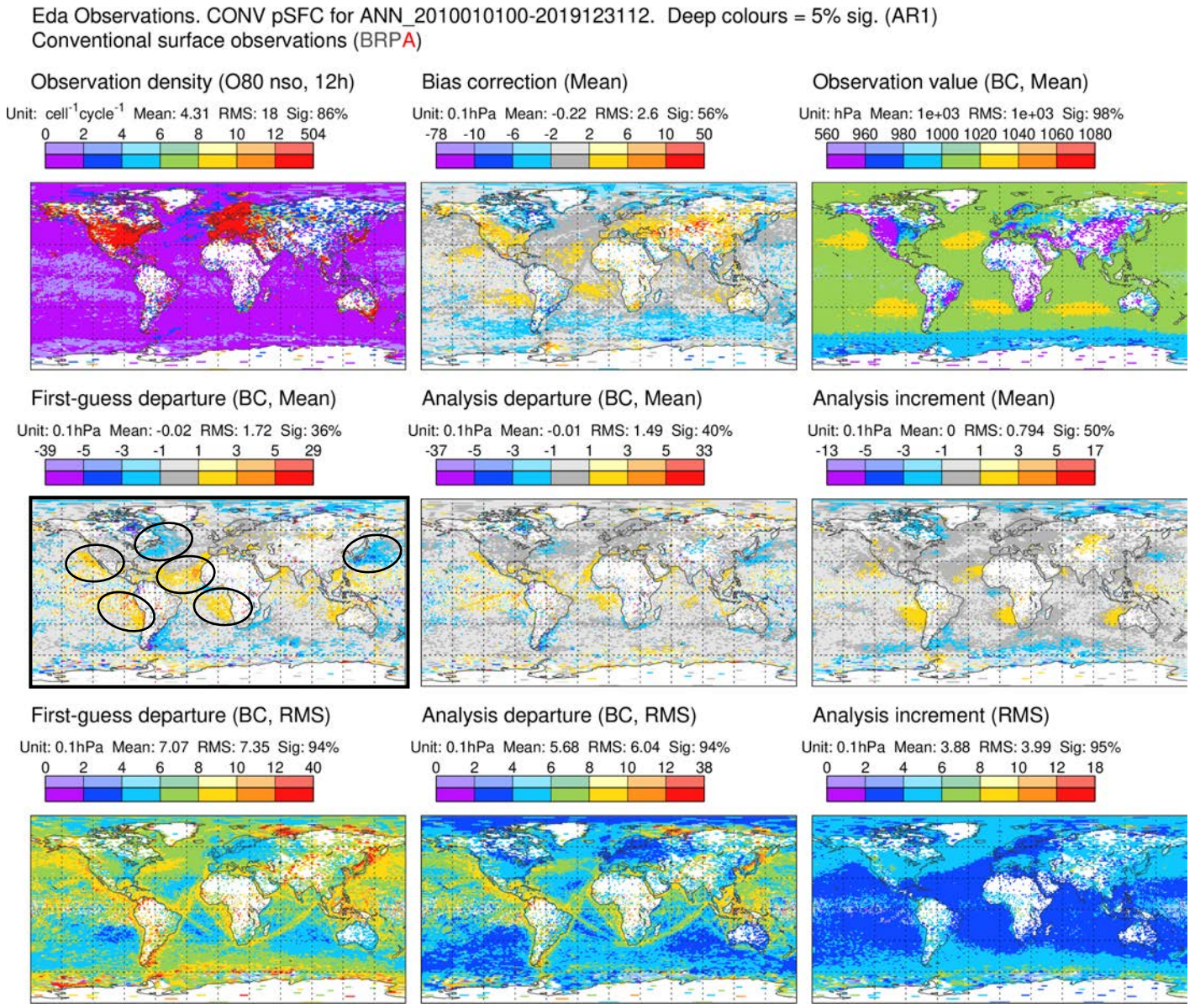
Thanks to: The creators and archivers of ERA5

Diagnostics of ERA5 EDA control for surface pressure observations – 2010-2019

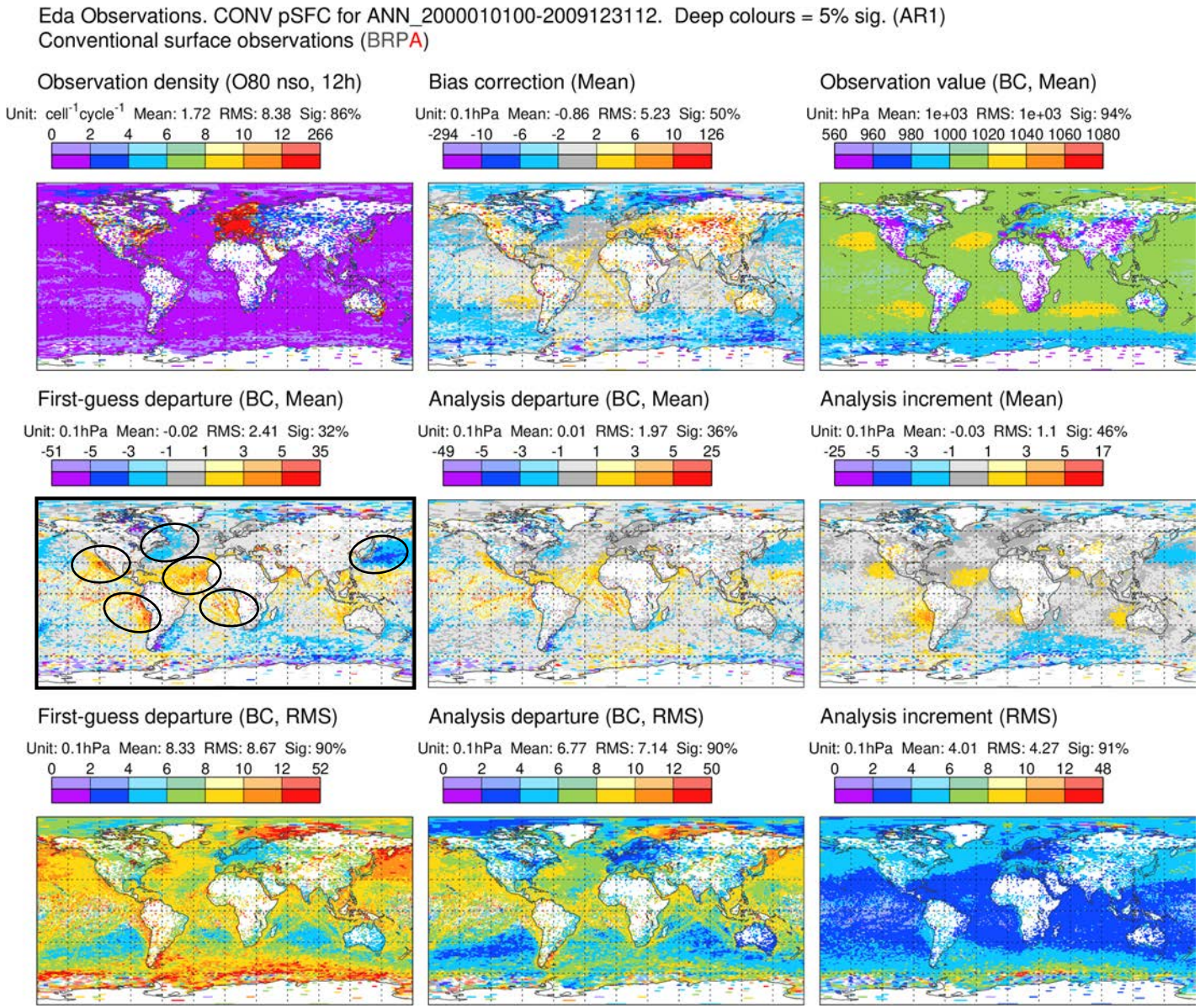
Observation:	o
Background:	b
Analysis:	a
Variational bias correction:	$o-o_{BC}$
First-guess departure:	$o_{BC}-b$
Analysis departure:	$o_{BC}-a$
Analysis increment:	a-b

Decadal-means give coverage over most ocean regions



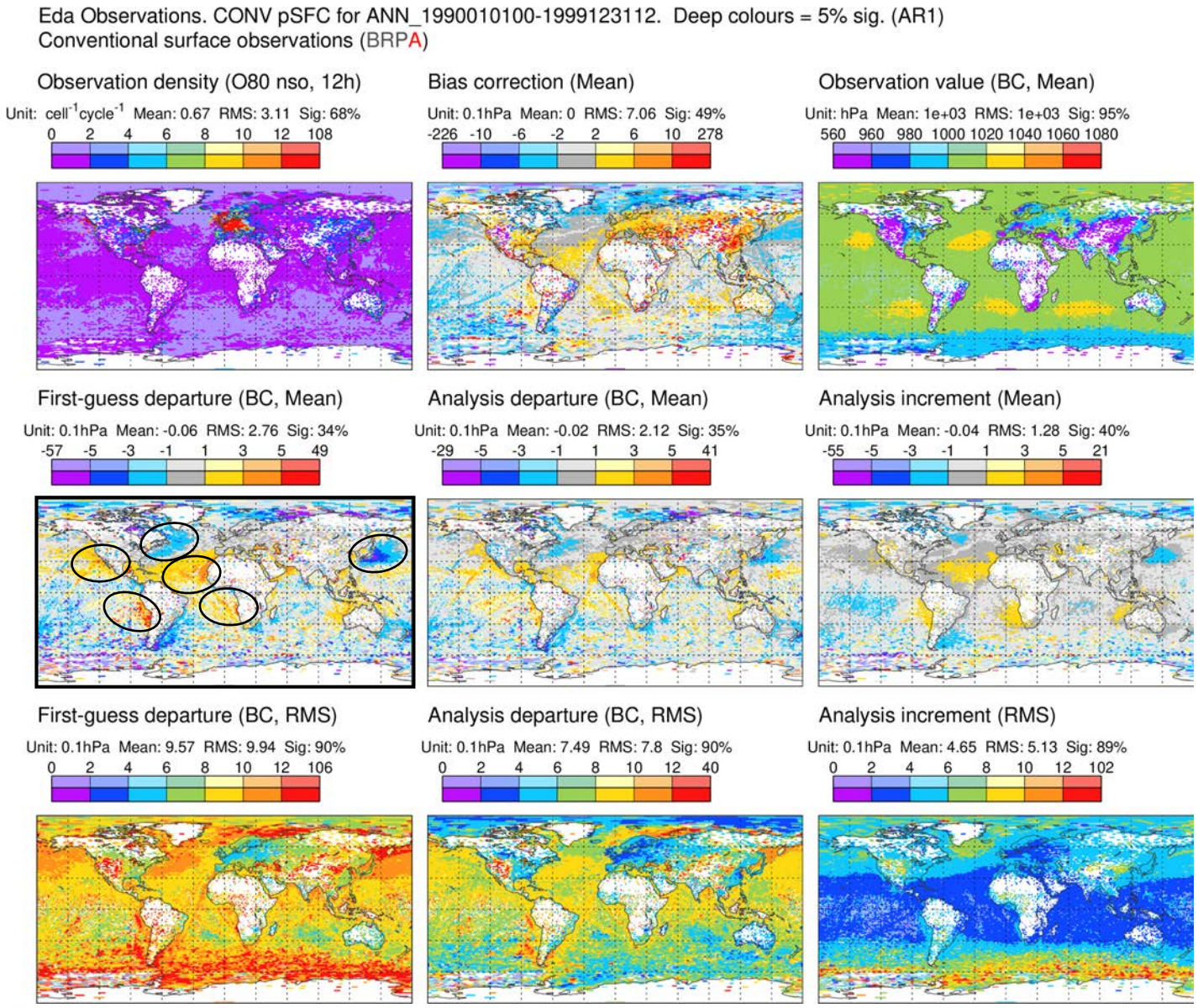
Mean first-guess departures show re-distribution of mass by the model – Subtropical anticyclones and stormtracks are key climate uncertainties

Diagnostics of ERA5 EDA control – 2000-2009



Departures and increments grow

Diagnostics of ERA5 EDA control – 1990-1999



Departures and increments continue to grow

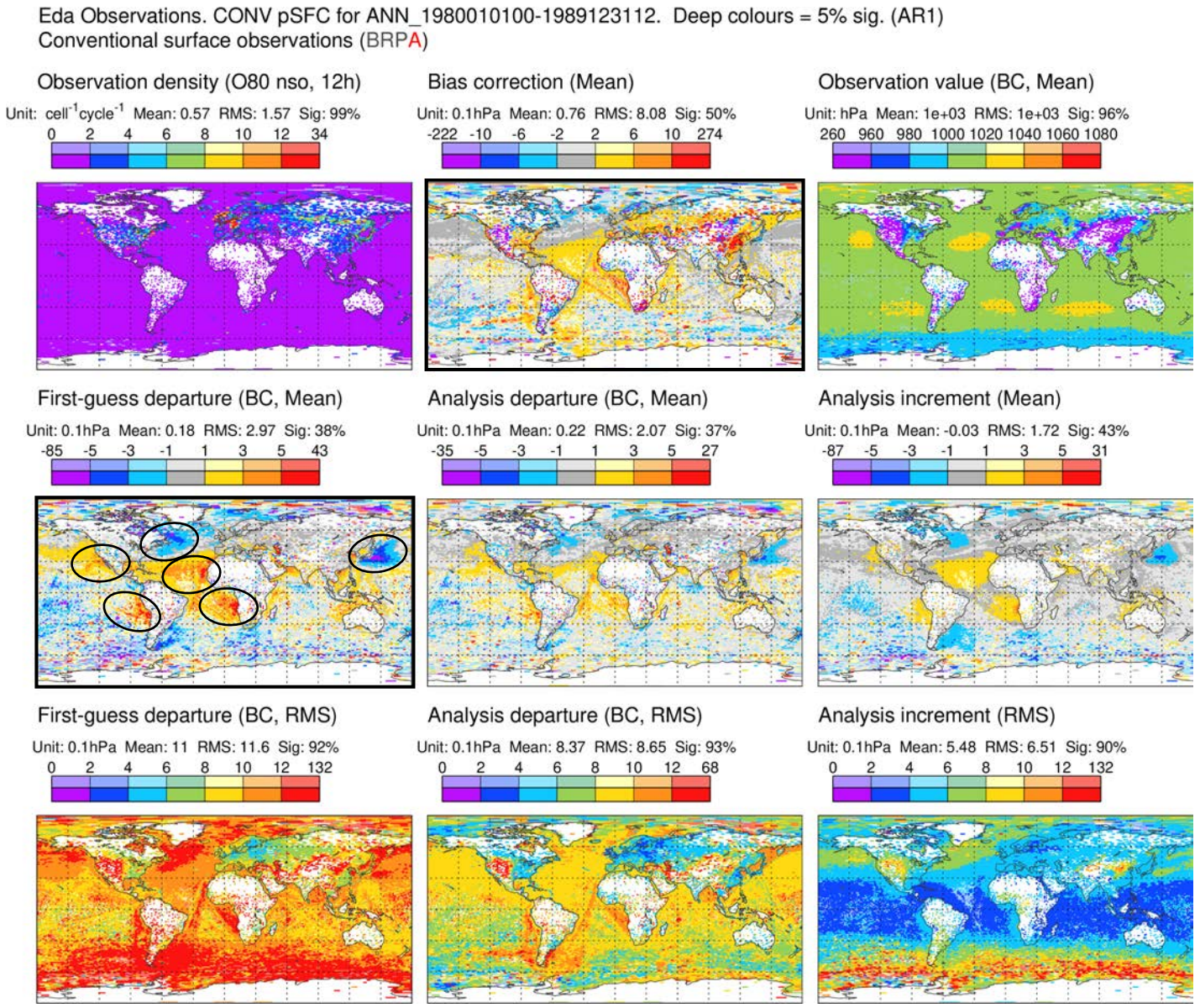
Diagnostics of ERA5 EDA control – 1980-1989

Trend of increasing mean first-guess departures ⇒ trend in analysis bias ⇒ erroneous component to re-analysis trend

Sparser observations, more impact of model bias, need for model error representation

Bias correction strengthens (particularly over Atlantic) – it incorrectly absorbs some of the departures: o-b = (o-o_{BC}) + (o_{BC}-b)

Problem can be underestimated



Trend in first-guess departures and bias corrections ⇒ Erroneous analysis trends – Require model error representation and tuning of VarBC?

Reliability budget for Ensemble Data Assimilation

Rodwell et al (2016), doi: 10.1002/qj.2663

The error-spread equation*:

$$\overrightarrow{(\overline{f}-T)^2} = \overrightarrow{\overline{(f-\overline{f})^2}} + \vec{R}$$

EM Error^2 | EnsVar | Residual

Reliability $\Rightarrow$ Truth indistinguishable from forecast members $\Rightarrow$ Residual $\rightarrow 0$

f = ensemble member $\quad \overline{\cdot}$ = ensemble mean (EM)

T = truth $\quad \vec{\cdot}$ = mean over forecasts

* Adjustment factor $\frac{m+1}{m-1}$ to EnsVar, which accounts for variance in $\overline{f}$ (in Error^2 and EnsVar) due to finite ensemble size m, is not shown.

When observations of the truth have non-negligible errors, and we explicitly account for mean bias**:

$$\overrightarrow{\left\{(\overline{b}-o)-\overrightarrow{(\overline{b}-o)}\right\}^2} = \overrightarrow{\overline{\{(b+\delta o)-\overline{b}\}^2}} + \vec{R}$$

EM departure^2 (mean bias removed) | ENS variance (with observation error perturbations) | Residual (uncertainty deficit, variance in bias)

b = background member

o = observation $\quad \delta o$ = obs perturbation to b

** Adjustment factors (which $\rightarrow 1$ for large m and large forecast sample size n) are not shown. In EDA $\overline{\delta o} \equiv 0$.

Rearranging gives us the EDA reliability budget***:

$$\overrightarrow{(\overline{b}-o)^2} = \overrightarrow{\overline{(b-\overline{b})^2}} + \overrightarrow{\overline{\delta o^2}} + \overrightarrow{(\overline{b}-o)}^2 + \vec{R}$$

EM Depar^2 | EnsVar | ObsUnc^2 | Bias^2 | Residual

Reliability $\Rightarrow$ Bias $\rightarrow 0$ and Residual $\rightarrow 0$

*** Adjustment factors not shown. Note that $\overrightarrow{\overline{2\delta o(b-\overline{b})}}$ subsumed into Residual, but $\rightarrow 0$ in any case.

This reliability budget is sensitive to the non-linear model's error growth-rate and the statistical reliability of the analysis

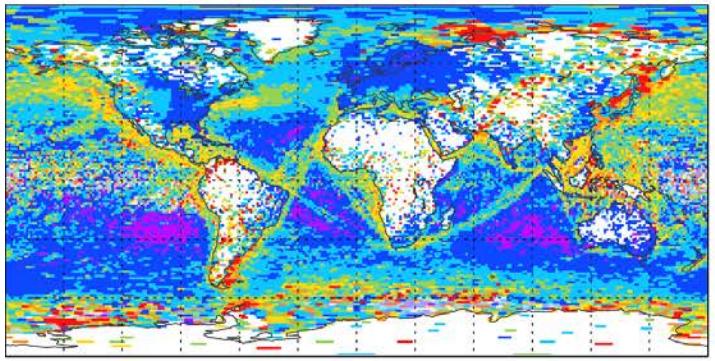
Reliability budget of ERA5 EDA for surface pressure observations – 2010-2019

Eda Observations. CONV pSFC for ANN_2010010100-2019123112. Deep colours = 5% sig. (AR1)
Conventional surface observations (BRPA)

Depar^2

Unit: 0.1(hPa)^2 Mean: 5.48 RMS: 7.08 Sig: 94%

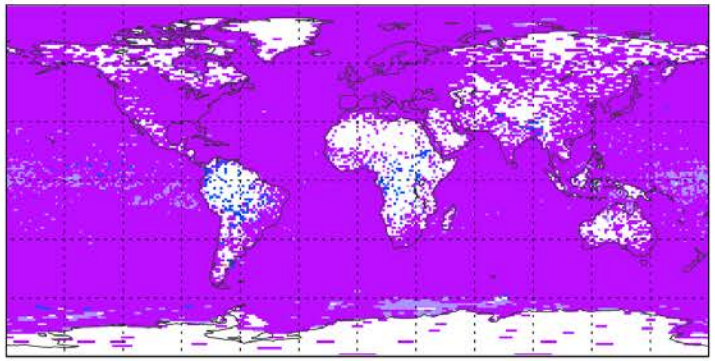
0 2 4 6 8 10 12 172



EnsVar

Unit: 0.1(hPa)^2 Mean: 1.03 RMS: 1.08 Sig: 96%

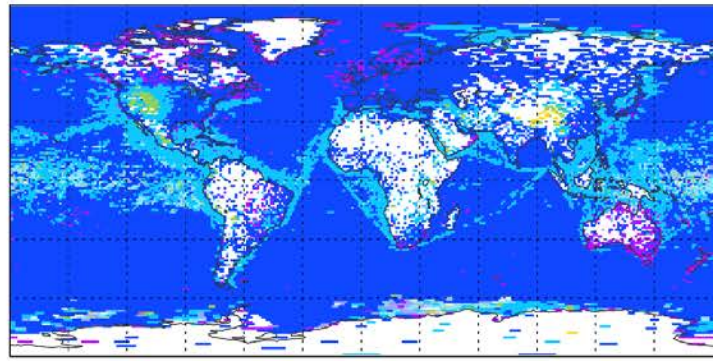
0 2 4 6 8 10 12 16



ObsUnc^2

Unit: 0.1(hPa)^2 Mean: 3.2 RMS: 3.37 Sig: 96%

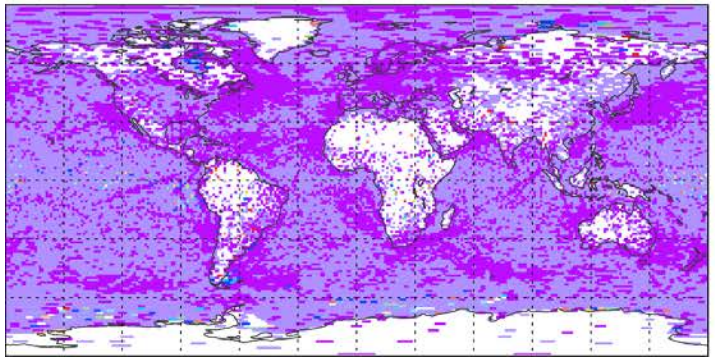
0 2 4 6 8 10 12 14



Bias^2

Unit: 0.1(hPa)^2 Mean: 0.28 RMS: 2.44 Sig: 37%

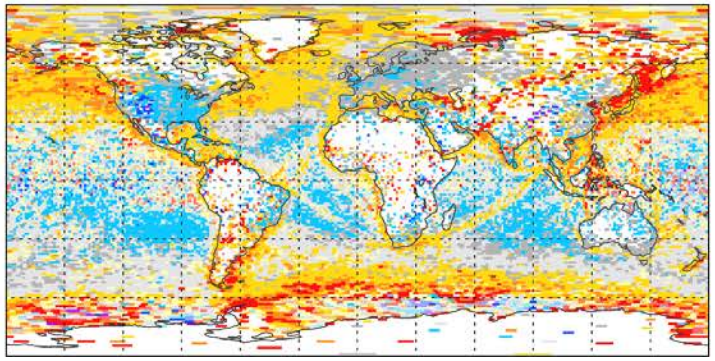
0 2 4 6 8 10 12 166



Residual

Unit: 0.1(hPa)^2 Mean: 0.95 RMS: 3.29 Sig: 56%

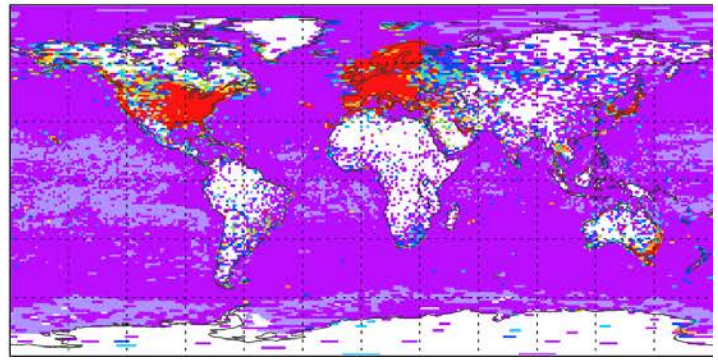
-17 -5 -3 -1 1 3 5 111



Observation density (O80 nso, 12h)

Unit: cell^{-1}cycle^{-1} Mean: 4.31 RMS: 18 Sig: 86%

0 4 8 12 16 20 24 504



Residual term ⇒ stormtracks under-spread – Lack of SVs in EDA or SPPT tapering? Tropical ship (buoy) obs errors worse (better) than estimated?

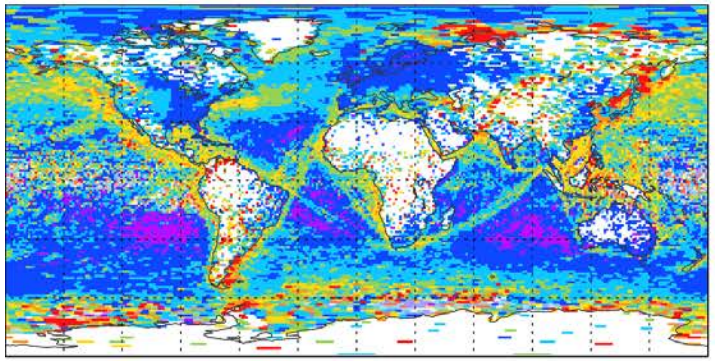
Reliability budget of ERA5 EDA – 2010-2019 (residual re-scaled for decadal comparison)

Eda Observations. CONV pSFC for ANN_2010010100-2019123112. Deep colours = 5% sig. (AR1)
Conventional surface observations (BRPA)

Depar^2

Unit: 0.1(hPa)^2 Mean: 5.48 RMS: 7.08 Sig: 94%

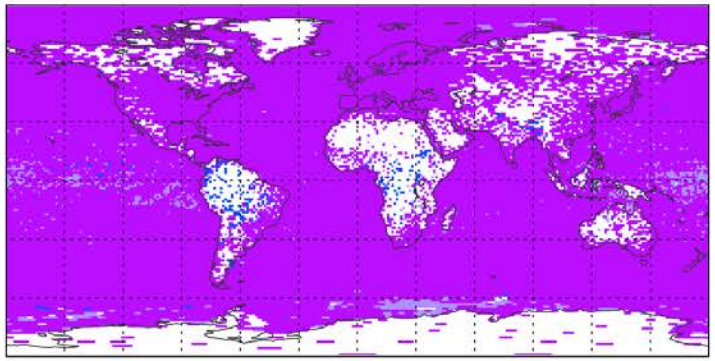
0 2 4 6 8 10 12 172



EnsVar

Unit: 0.1(hPa)^2 Mean: 1.03 RMS: 1.08 Sig: 96%

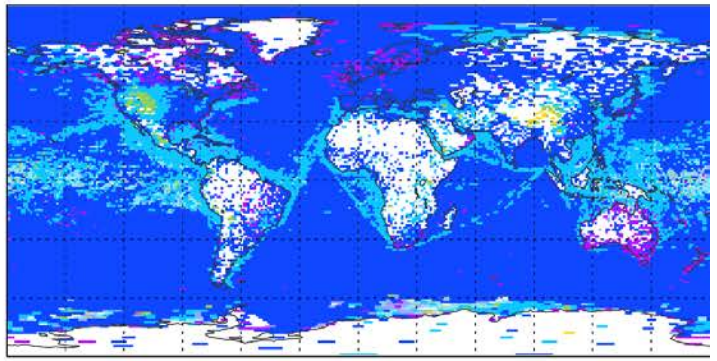
0 2 4 6 8 10 12 16



ObsUnc^2

Unit: 0.1(hPa)^2 Mean: 3.2 RMS: 3.37 Sig: 96%

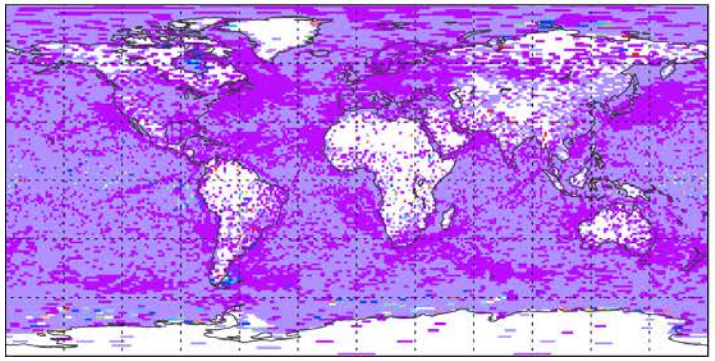
0 2 4 6 8 10 12 14



Bias^2

Unit: 0.1(hPa)^2 Mean: 0.28 RMS: 2.44 Sig: 37%

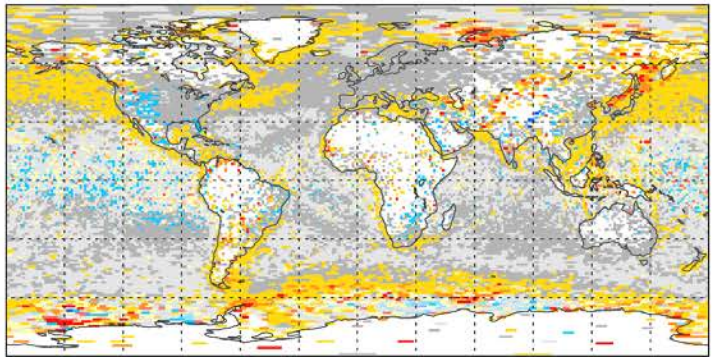
0 2 4 6 8 10 12 166



Residual

Unit: 0.1(hPa)^2 Mean: 0.95 RMS: 3.29 Sig: 56%

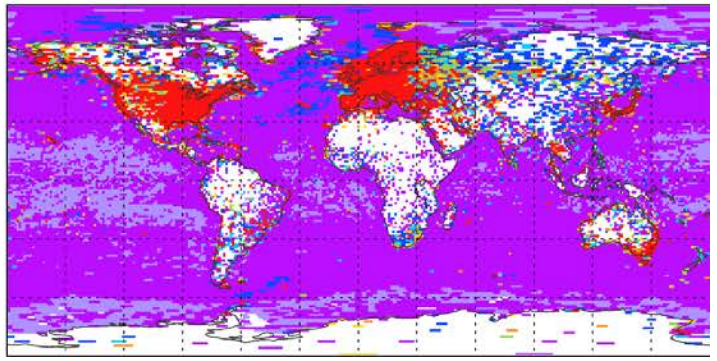
-18 -10 -6 -2 2 6 10 110



Observation density (O80 nso, 12h)

Unit: cell^{-1}cycle^{-1} Mean: 4.31 RMS: 18 Sig: 86%

0 2 4 6 8 10 12 504



Residual looks better when scaled to compare with previous decades!

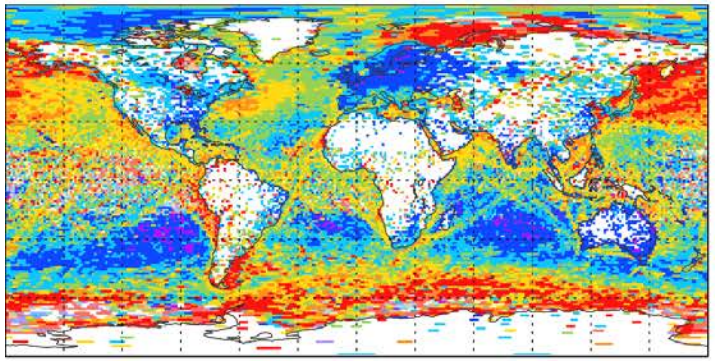
Reliability budget of ERA5 EDA – 2000-2009

Eda Observations. CONV pSFC for ANN_2000010100-2009123112. Deep colours = 5% sig. (AR1)
Conventional surface observations (BRPA)

Depar^2

Unit: 0.1(hPa)^2 Mean: 7.76 RMS: 10.4 Sig: 90%

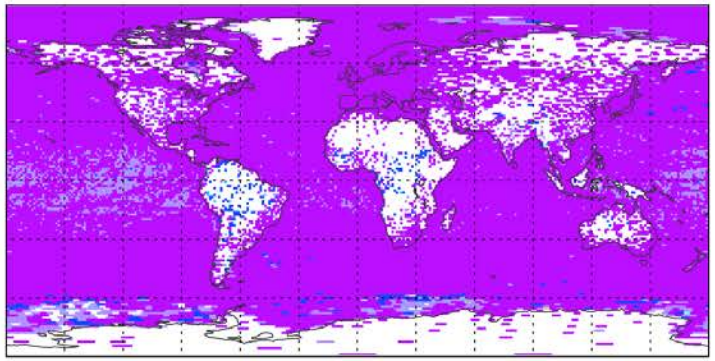
0 2 4 6 8 10 12 276



EnsVar

Unit: 0.1(hPa)^2 Mean: 1.12 RMS: 1.17 Sig: 92%

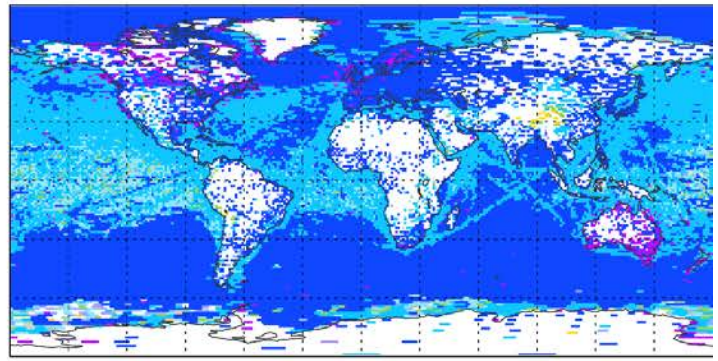
0 2 4 6 8 10 12 14



ObsUnc^2

Unit: 0.1(hPa)^2 Mean: 3.68 RMS: 3.88 Sig: 91%

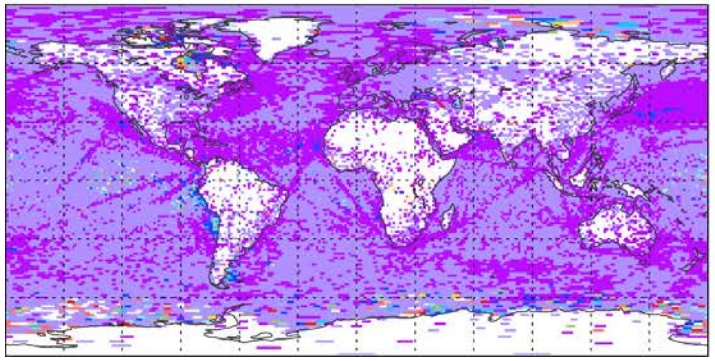
0 2 4 6 8 10 12 14



Bias^2

Unit: 0.1(hPa)^2 Mean: 0.52 RMS: 2.91 Sig: 36%

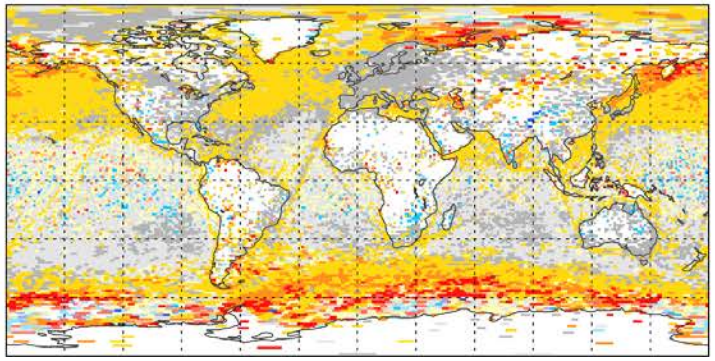
0 2 4 6 8 10 12 178



Residual

Unit: 0.1(hPa)^2 Mean: 2.42 RMS: 6.21 Sig: 56%

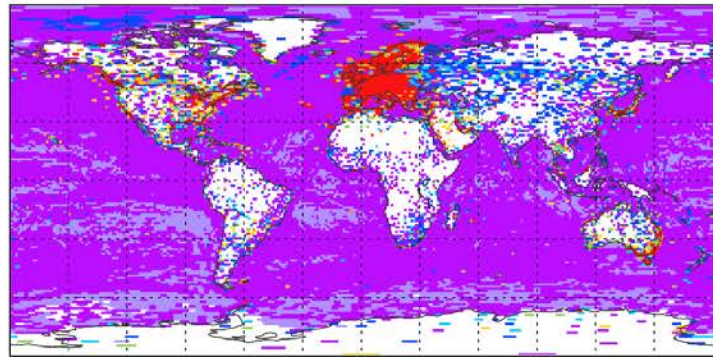
-14 -10 -6 -2 2 6 10 274



Observation density (O80 nso, 12h)

Unit: cell^{-1}cycle^{-1} Mean: 1.72 RMS: 8.38 Sig: 86%

0 2 4 6 8 10 12 266



Increasing assigned observation errors and background variance – but these do this not keep pace with departure growth (Residual increasing)

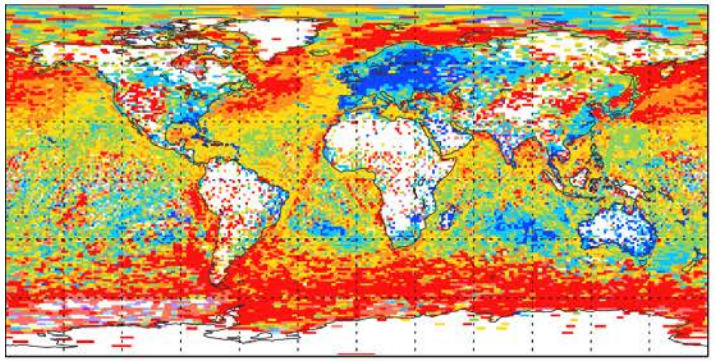
Reliability budget of ERA5 EDA – 1990-1999

Eda Observations. CONV pSFC for ANN_1990010100-1999123112. Deep colours = 5% sig. (AR1)
Conventional surface observations (BRPA)

Depar^2

Unit: 0.1(hPa)^2 Mean: 10.4 RMS: 15.6 Sig: 90%

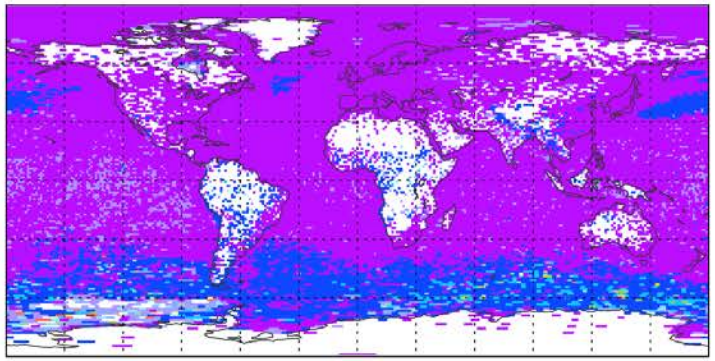
0 2 4 6 8 10 12 1074



EnsVar

Unit: 0.1(hPa)^2 Mean: 1.57 RMS: 1.79 Sig: 91%

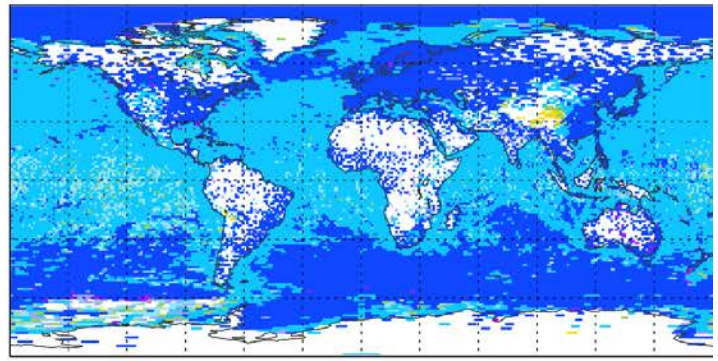
0 2 4 6 8 10 12 32



ObsUnc^2

Unit: 0.1(hPa)^2 Mean: 4.15 RMS: 4.33 Sig: 92%

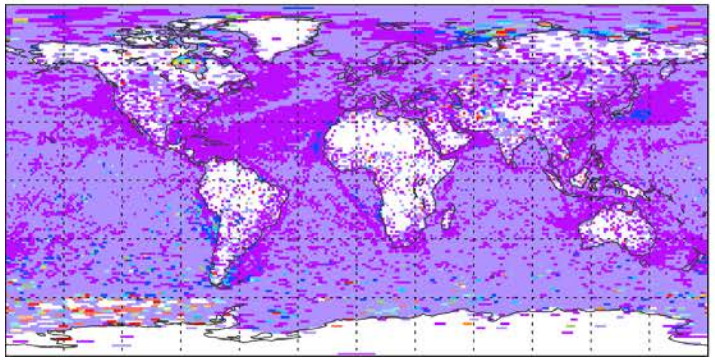
0 2 4 6 8 10 12 16



Bias^2

Unit: 0.1(hPa)^2 Mean: 0.69 RMS: 4.7 Sig: 35%

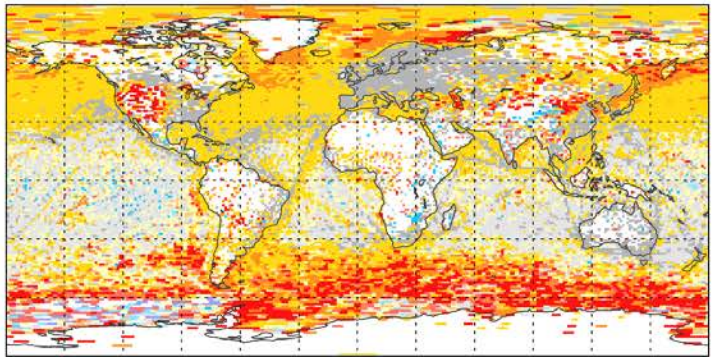
0 2 4 6 8 10 12 280



Residual

Unit: 0.1(hPa)^2 Mean: 4.02 RMS: 9.72 Sig: 58%

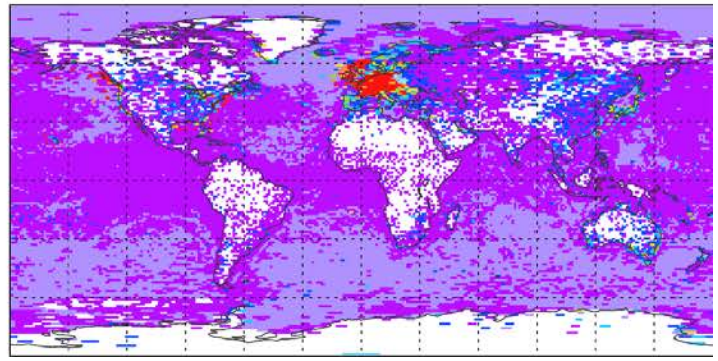
-26 -10 -6 -2 2 6 10 786



Observation density (O80 nso, 12h)

Unit: cell^{-1}cycle^{-1} Mean: 0.67 RMS: 3.11 Sig: 68%

0 2 4 6 8 10 12 108



Under-spread increasingly apparent in the stormtracks (particularly over the Southern Ocean)

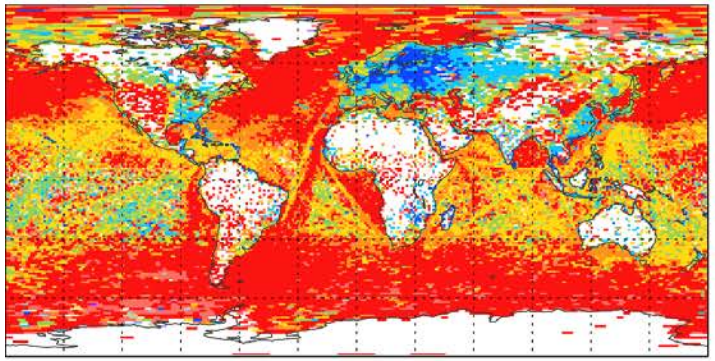
Reliability budget of ERA5 EDA – 1980-1989

Eda Observations. CONV pSFC for ANN_1980010100-1989123112. Deep colours = 5% sig. (AR1)
Conventional surface observations (BRPA)

Depar^2

Unit: 0.1(hPa)^2 Mean: 14.3 RMS: 28.9 Sig: 92%

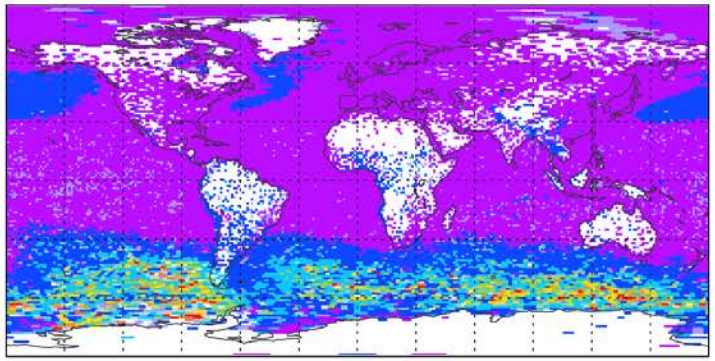
0 2 4 6 8 10 12 1794



EnsVar

Unit: 0.1(hPa)^2 Mean: 2.21 RMS: 3.02 Sig: 91%

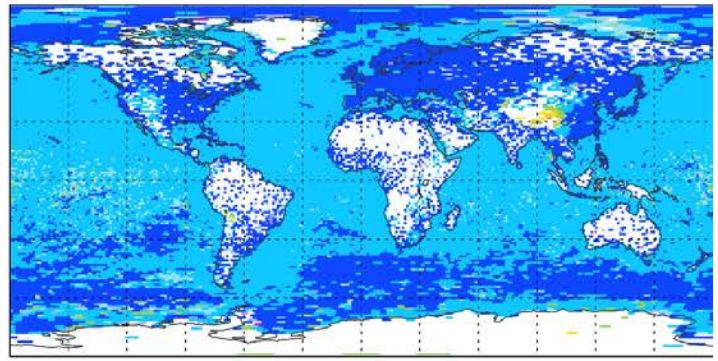
0 2 4 6 8 10 12 68



ObsUnc^2

Unit: 0.1(hPa)^2 Mean: 4.5 RMS: 4.66 Sig: 94%

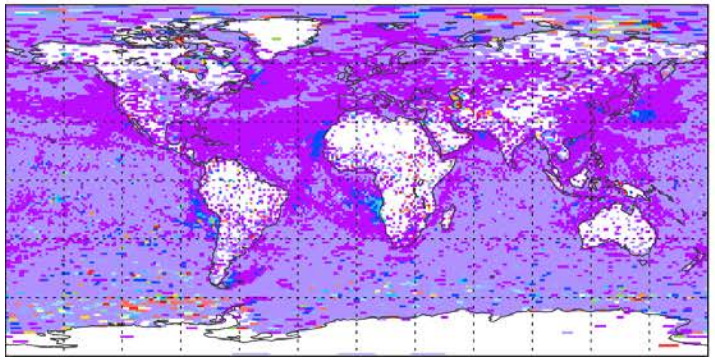
0 2 4 6 8 10 12 56



Bias^2

Unit: 0.1(hPa)^2 Mean: 0.89 RMS: 7.16 Sig: 40%

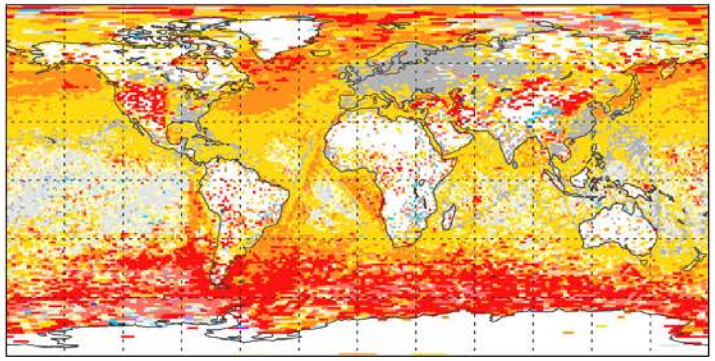
0 2 4 6 8 10 12 712



Residual

Unit: 0.1(hPa)^2 Mean: 6.68 RMS: 21.5 Sig: 70%

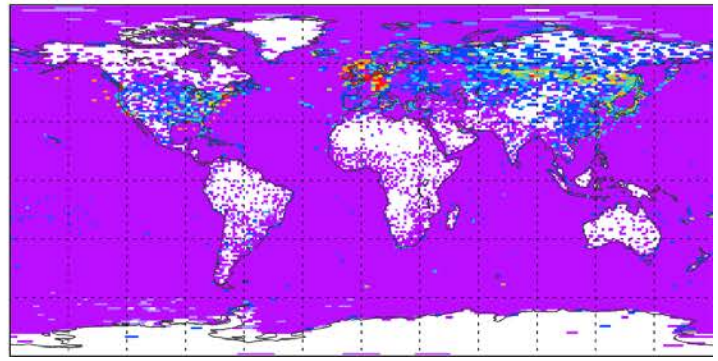
-70 -10 -6 -2 2 6 10 1682



Observation density (O80 nso, 12h)

Unit: cell^{-1}cycle^{-1} Mean: 0.57 RMS: 1.57 Sig: 99%

0 2 4 6 8 10 12 34



Trend of increasing under-spread – Due to increased influence of prescribed SST or under-estimation of early satellite errors?

Summary – Diagnostics can help inform design of future re-analyses

Going back in time:

Sparser observations leave re-analysis at the mercy of model bias
- Tackle with “Weak Constraint” (model error term) in assimilation
- To prevent climate projection biases, improve underlying model
- Attention to variational observation bias correction too

Larger uncertainty (but not large enough)
- False impression of accuracy of product
- Unreliable initialisation of re-forecasts
- Due to under-estimation of uncertainties in SST or early satellite observations?

Operational diagnostics applied to ERA5 are available at:

https://apps.ecmwf.int/webapps/intraplots/packages/diagnostics/
(Move of computing facilities to Bologna so can be a little intermittent)