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The importance of anchor observations in data assimilation

Graphic: WMO

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Introduction

- The assimilation of satellite radiances has the largest impact on NWP skill of any observation type (e.g. Cardinali, 2009, *QJRMS*).
- But first, they need to be bias-corrected typically using Variational bias correction (VarBC).
- To ensure VarBC identifies observation bias and not model bias, unbiased (anchor) observations are necessary (Eyre, 2016, *QJRMS*).

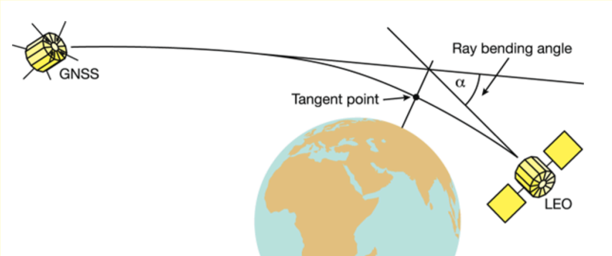
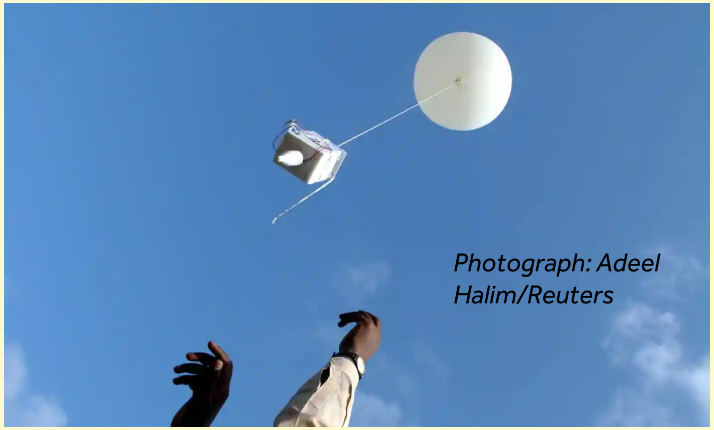


Figure from Gleisner et al. (2022)



Photograph: Adeel Halim/Reuters

FIGURE: The most important anchor observations are RO and radiosonde data

- As the proportion of satellite radiances assimilated increases it is essential to understand how the requirements of the network of anchor observations will also evolve.

Variational Bias correction

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VarBC (Auligné et al., 2007, *QJRMS*) allows for an online estimate of the observation bias by augmenting the control vector in 4DVar with the bias parameters, $\boldsymbol{\beta}$, which are then used to correct the observation operator:

$$h_v(\mathbf{x}, \boldsymbol{\beta}) = h(\mathbf{x}) + c(\mathbf{x}^b, \boldsymbol{\beta}) \qquad (1)$$

Observation bias correction

Original uncorrected observation operator

VarBC in the presence of model bias

In the presence of model bias, the success of VarBC depends on having a network of anchor observations so that the estimate $\boldsymbol{\beta}$ is not contaminated by the model bias. The expected error in the estimate of $\boldsymbol{\beta}$, $\langle \boldsymbol{\varepsilon}_{\beta}^{a} \rangle$, can be expressed as:

$\widehat{\mathbf{H}}_{anchor}$ and $\widehat{\mathbf{H}}_{BC}$ are the 4D ob operators for the anchor and bias-corrected observations respectively

sensitivity of the estimate of $\boldsymbol{\beta}$ to the bias-corrected (BC) observations

$$\langle \boldsymbol{\varepsilon}_{\beta}^{a} \rangle = -\mathbf{S}\left(\widehat{\mathbf{H}}_{BC}\left(\mathbf{I} - \mathbf{D}\widehat{\mathbf{H}}_{anchor}\right)\langle \boldsymbol{\varepsilon}_{x}^{b} \rangle + \langle \boldsymbol{\eta}_{BC} \rangle - \widehat{\mathbf{H}}_{BC}\mathbf{D}\langle \boldsymbol{\eta}_{anchor} \rangle\right), \qquad (2)$$

bias in the background state

$\langle \boldsymbol{\eta}_{anchor} \rangle$ and $\langle \boldsymbol{\eta}_{BC} \rangle$ are the model bias as 'observed' by the anchor and BC obs respectively

$$\mathbf{D} = \mathbf{B}_x \widehat{\mathbf{H}}_{anchor}^{T}\left(\widehat{\mathbf{H}}_{anchor}\mathbf{B}_x\widehat{\mathbf{H}}_{anchor}^{T} + \widehat{\mathbf{R}}_{anchor}\right)^{-1} \qquad (3)$$

See Francis 2023, chapter 7, for full derivation.

The importance of the position of anchor observations

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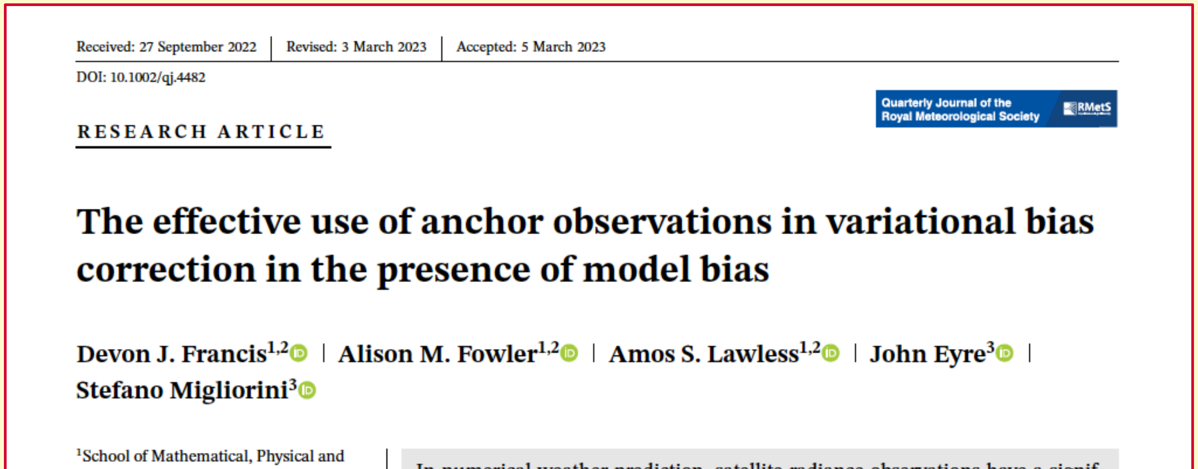
The importance of the position of the anchor observations relative to the BC observations and background bias was studied by Francis et al. 2023. It was shown that:

- Anchor observations can only effectively reduce the contamination of model bias if they observe states with a similar model bias to those observed by bias-corrected observations.
- Background error correlations are important in transferring information about model biases between states that are observed by bias-corrected and anchor observations.



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RESEARCH ARTICLE

The effective use of anchor observations in variational bias correction in the presence of model bias

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The importance of the timing of anchor observations

CASE 1: **Anchor and bias-corrected observations observe the same variables, locations and times:**

- In this case $\widehat{\mathbf{H}}_{anchor} = \widehat{\mathbf{H}}_{BC} = \widehat{\mathbf{H}}$ and $\langle \boldsymbol{\eta}_{BC} \rangle = \langle \boldsymbol{\eta}_{anchor} \rangle = \langle \boldsymbol{\eta} \rangle$ and (2) reduces to

$$\langle \boldsymbol{\varepsilon}_{\beta}^{a} \rangle = -\mathbf{S}\left((\mathbf{I} - \widehat{\mathbf{H}}\mathbf{D})\widehat{\mathbf{H}}\langle \boldsymbol{\varepsilon}_{x}^{b} \rangle + (\mathbf{I} - \widehat{\mathbf{H}}\mathbf{D})\langle \boldsymbol{\eta} \rangle \right). \qquad (4)$$

- From (3) the more precise the anchor observations ($\widehat{\mathbf{R}}_{anchor} \rightarrow \mathbf{0}$), the closer $\widehat{\mathbf{H}}\mathbf{D}$ will be to $\mathbf{I}$ and the smaller the contamination of both the background bias and the model bias.

The importance of the timing of anchor observations

CASE 2: **Anchor observations observe later than the bias-corrected observations but the same variables and locations:**

- To simplify this problem let us assume that BC observations are available at time 1 and anchor observations are at time 2, such that in this case $\hat{\mathbf{H}}_{BC} = \mathbf{HM_0}$, $\hat{\mathbf{H}}_{anchor} = \mathbf{HM_1M_0}$ and $\langle \boldsymbol{\eta}_{BC} \rangle = \mathbf{H}\boldsymbol{\eta}_{\mathbf{1}}$, $\langle \boldsymbol{\eta}_{anchor} \rangle = \mathbf{HM_1}\boldsymbol{\eta}_{\mathbf{1}} + \mathbf{H}\boldsymbol{\eta}_{\mathbf{2}}$ and (2) reduces to

$$\langle \boldsymbol{\varepsilon}_\beta^a \rangle = -\mathbf{SH}\left(\mathbf{M_0}(\mathbf{I} - \mathbf{DHM_1M_0})\langle \boldsymbol{\varepsilon}_x^b \rangle + (\mathbf{I} - \mathbf{M_0DHM_1})\boldsymbol{\eta}_{\mathbf{1}} - \mathbf{M_0DH}\boldsymbol{\eta}_{\mathbf{2}}\right). \quad (5)$$

- In this case, from the definition of $\mathbf{D}$ the more precise the anchor observations the smaller the contamination of both the background bias and the model bias up to the time of the BC observation ($\boldsymbol{\eta}_{\mathbf{1}}$).
- However, more precise observations will have less of an ability to reduce the contamination of the extra model bias observed by the anchor observation ($\boldsymbol{\eta}_{\mathbf{2}}$).

The importance of the timing of anchor observations

CASE 3: **Anchor observations earlier than the bias-corrected observations but the same variables and locations:**

- To simplify this problem let us assume that anchor observations are available at time 1 and BC observations are at time 2, such that in this case $\widehat{\mathbf{H}}_{anchor} = \mathbf{HM_0}$, $\widehat{\mathbf{H}}_{BC} = \mathbf{HM_0M_1}$ and $\langle \boldsymbol{\eta}_{anchor} \rangle = \mathbf{H}\boldsymbol{\eta}_1$, $\langle \boldsymbol{\eta}_{BC} \rangle = \mathbf{HM_1}\boldsymbol{\eta}_1 + \mathbf{H}\boldsymbol{\eta}_2$ and (2) reduces to

$$\langle \boldsymbol{\varepsilon}^a_\beta \rangle = -\mathbf{SH}\big(\mathbf{M_1M_0}(\mathbf{I} - \mathbf{DHM_0})\langle \boldsymbol{\varepsilon}^b_x \rangle + \mathbf{M_1}(\mathbf{I} - \mathbf{M_0DH})\boldsymbol{\eta}_1 + \boldsymbol{\eta}_2\big). \qquad (6)$$

- In this case, from (3) the more precise the anchor observations, the smaller the contamination of both the background bias and the model bias up to the time of the anchor observations ($\boldsymbol{\eta}_1$).
- However, more precise observations will *not* reduce the contamination of the extra model bias observed by the BC observation ($\boldsymbol{\eta}_2$).

Illustration using the Lorenz 96

To illustrate the theoretical results presented we use the 40-variable Lorenz 96 model with

- anchor and BC observations of every variable are assimilated every 10 timesteps using 4DVar, with an assimilation window of 10 timesteps.
- Model bias is generated by using a forcing of 12 in the assimilation whereas 8 is used when simulating the observations.

Results are averaged over 1000 experiments for three different observation configurations:

CASE 1: both the anchor and BC observations at the end of the assimilation window,

CASE 2: BC observations half-way through the window but anchor observations at the end;

CASE 3: anchor observations half-way through the window but BC observations at the end.

Illustration using the Lorenz 96, $\sigma_o^2 = 1$ for anchor observations

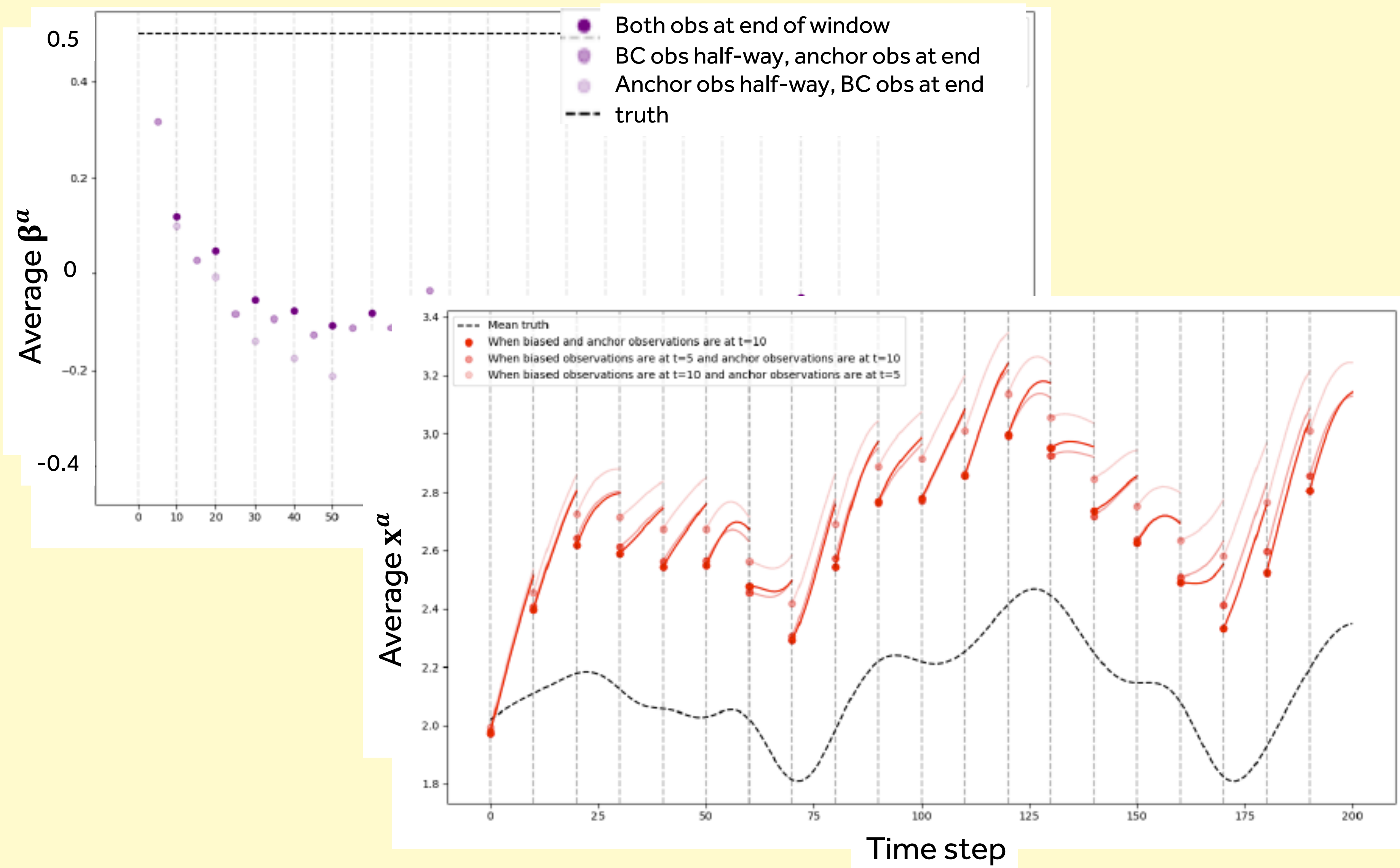

Illustration using the Lorenz 96, $\sigma_o^2 = 0.1$ for anchor observations

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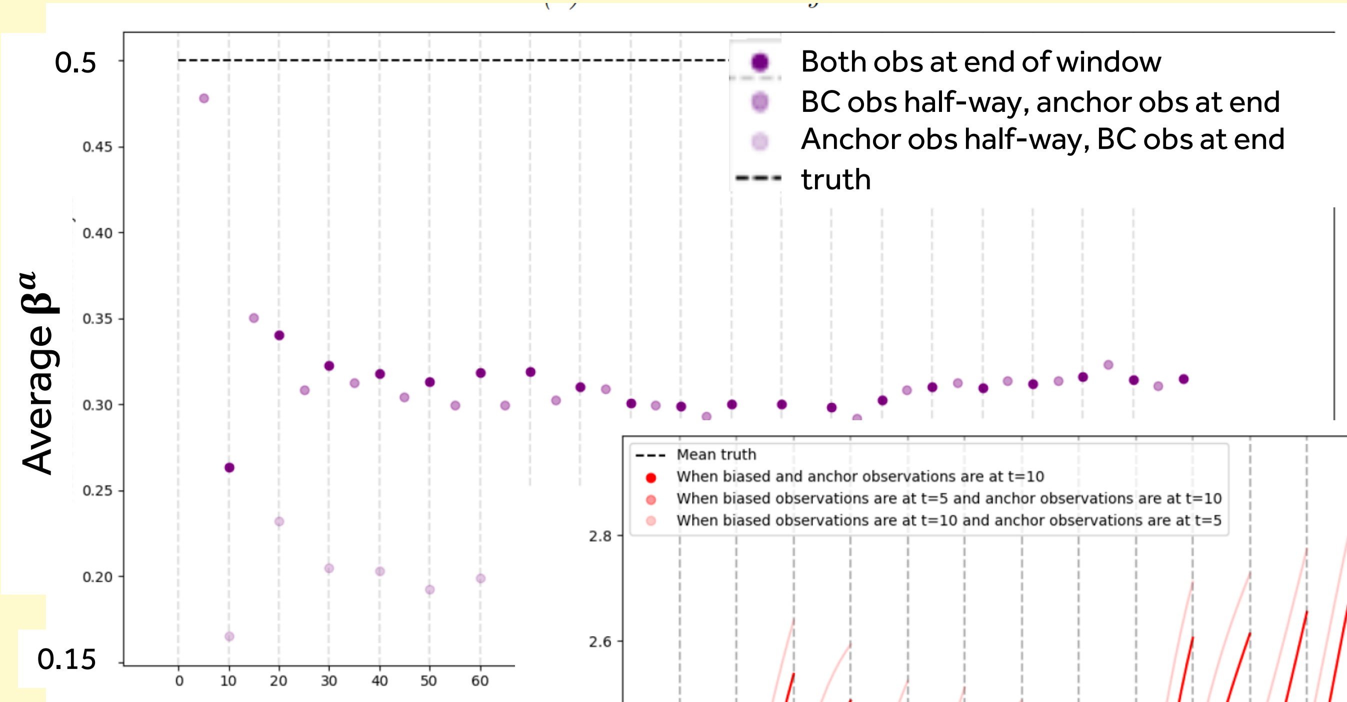

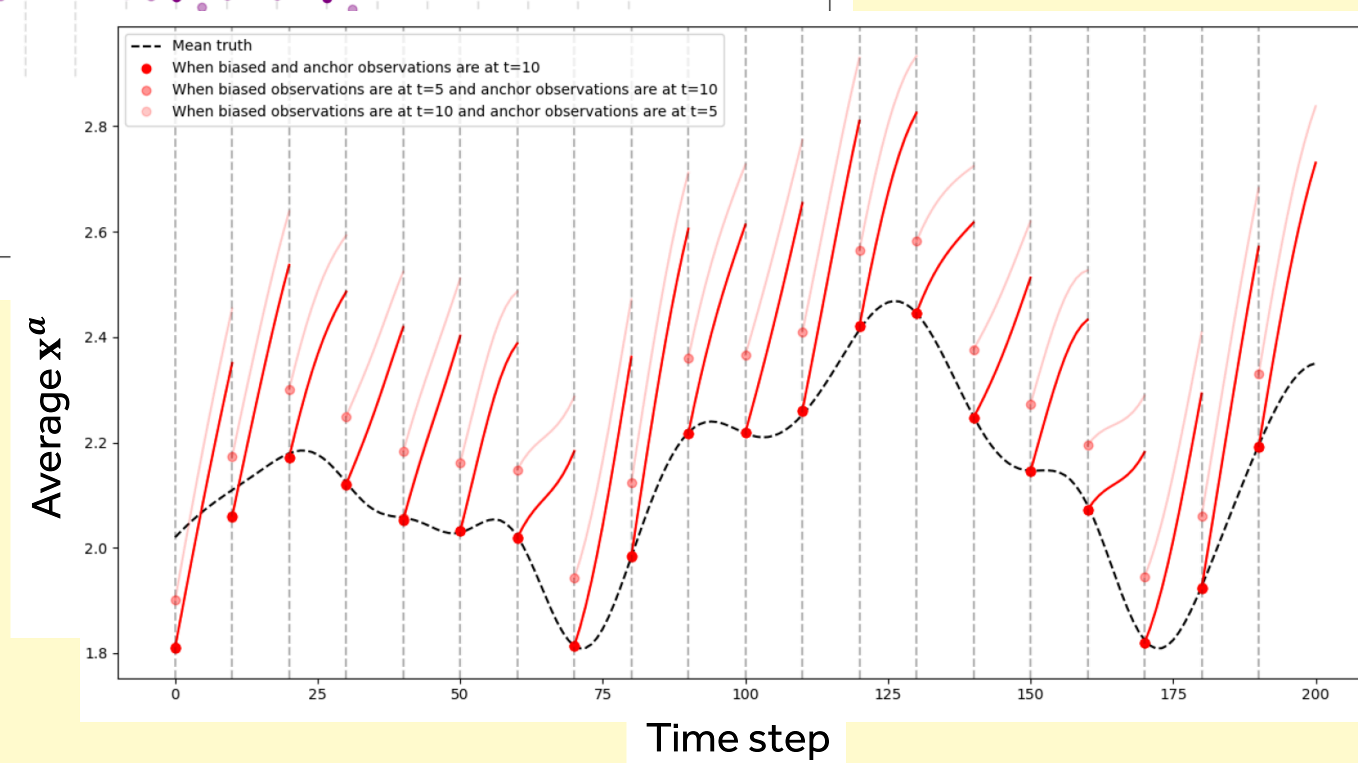

Quantifying the importance of anchor observations using the FSOI

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The forecast Sensitivity to Observation Impact (FSOI) is a convenient metric for quantifying the relative value of observations in an assimilation system and can be used to guide changes to the observing network (Langland and Baker, 2004, *Tellus A*).

For the three observation configurations we have computed the value of the BC and anchor observations using two metrics:

- FSOI % : the percentage of reduction in forecast error attributed to the observations of interest as measured by FSOI .

$$FSOI_i \,\% = 100 \frac{\delta e_i^f}{\sum_{j \in allobs} \delta e_j^f}$$

- DDE % : the increase in forecast error when the spatial resolution of the observations of interest is halved as a percentage of the forecast error when assimilating all observations.

$$DDE_i \,\% = 100 \, \frac{\varepsilon^f_{\text{obs halved } i} - e^f}{e^f}$$

Quantifying the importance of anchor observations using the FSOI

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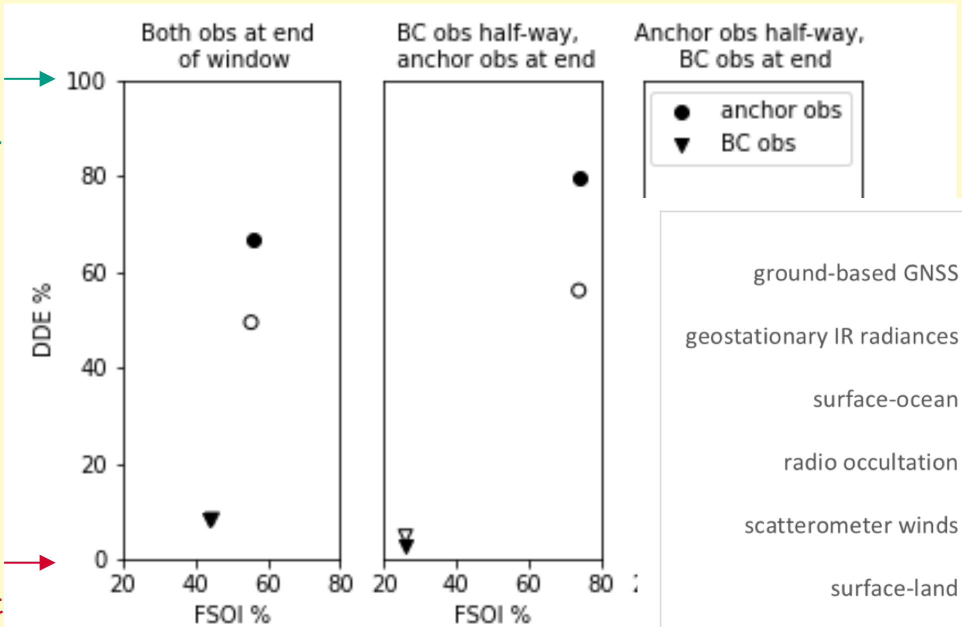
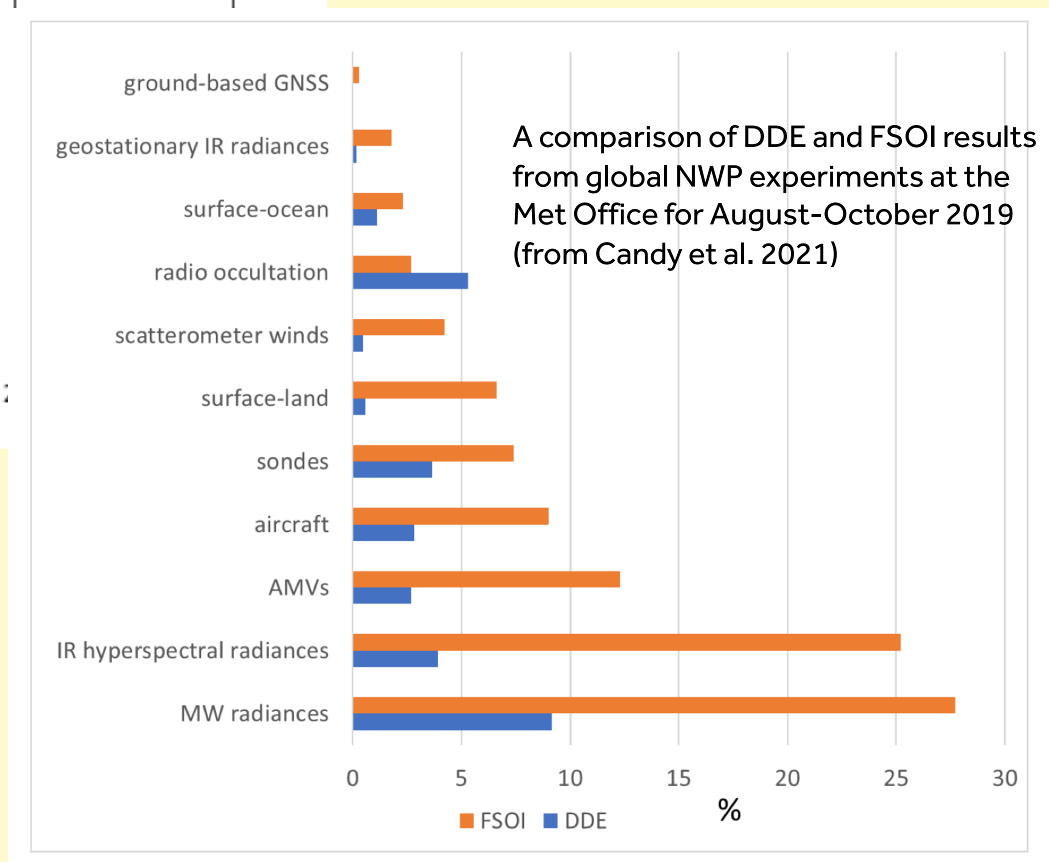
Halving the number of observations doubles the forecast error

Halving the number of observations has no impact on forecast error





A comparison of DDE and FSOI results from global NWP experiments at the Met Office for August-October 2019 (from Candy et al. 2021)

Summary

- As the proportion of satellite radiance data assimilated increases it is important to know how the network of anchor observations should also evolve to minimise the contamination of model bias in VarBC.
- We have shown theoretically that this depends on the overlap between the model bias ‘observed’ by the bias-corrected and anchor observations, with anchor observations later in the window generally being more beneficial.
- It is demonstrated that the FSOI is not reliable in guiding the network of anchor observations.

Thank you for listening