To what extent are reanalyses actually constrained by observations ?

Tony McNally ECMWF

(contributions stolen from many)

Rationale for the question…

- Reanalyses are an optimal fusion of observations, numerical models and physical / statistical knowledge. They currently provide **the** best possible comprehensive historical description of the atmospheric state

- But it is important to understand when, where and how our reanalyses are observation deficient and how well these deficiencies are mitigated by the skill of the data assimilation process

- This understanding allows the science community to make better use of reanalyses and adds to their credibility as a resource to understand climate change

- Reanalyses are increasingly becoming the backbone of ML training where the trade off between quantity vs quality may be important

Outline

How do observations constrain an analysis system ?

- a quick look at the 4D-Var algorithm
- the power of indirect and non-local mechanisms

Some limitations of the observation constraint

- vertical scales
- horizontal scales

Observation constraint upon the mean state

- VARBC and WC-4D-Var
- The need for anchor observations

Coupling across Earth systems for reanalysis

- using observations of one component to anchor another
- Enhance wind tracing from chemical species

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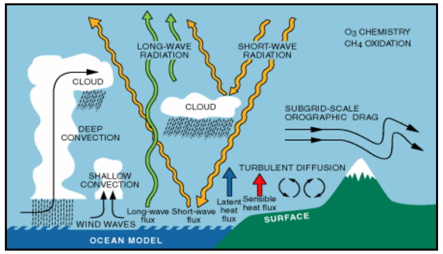
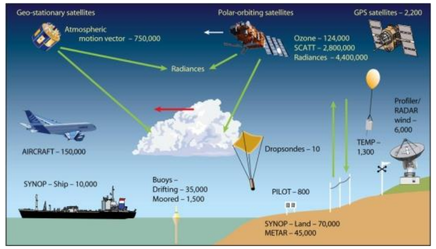
A brief introduction to Data Assimilation

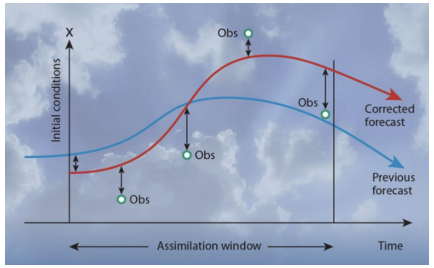
- **Models** give a **<u>complete</u>** description of the atmospheric state, but errors can grow rapidly in time



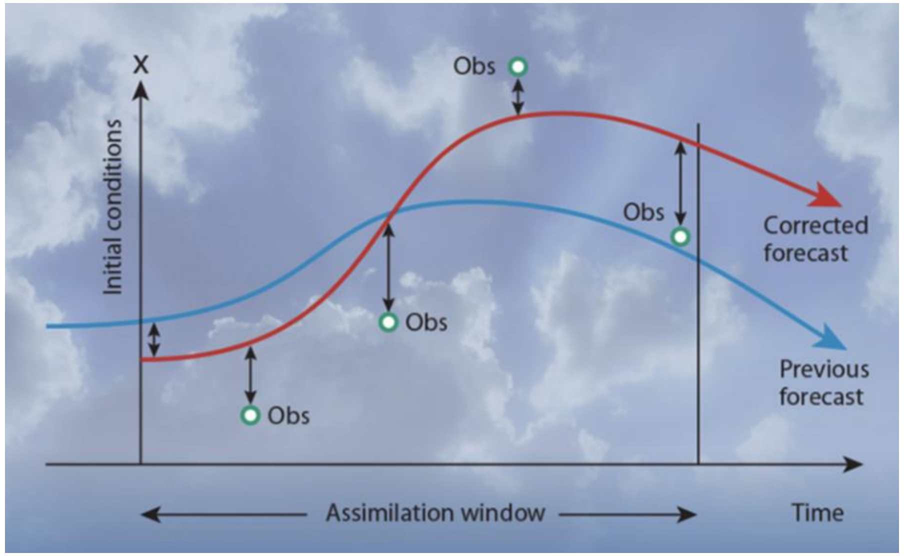
- **Observations** provide an incomplete description of the atmospheric state, but do bring **<u>accurate</u>** up to date information



- The **Data Assimilation algorithm** combines these two sources of information to produce an **<u>optimal</u>** (best) estimate of the atmospheric state



The 4D-Var Data Assimilation algorithm



State vector

background error covariance

$$J(x) = (x - x_b)^T \mathbf{B}^{-1} (x - x_b) + (y - \mathrm{H}[x])^T \mathbf{R}^{-1} (y - \mathrm{H}[x])$$

observations

observation* error covariance

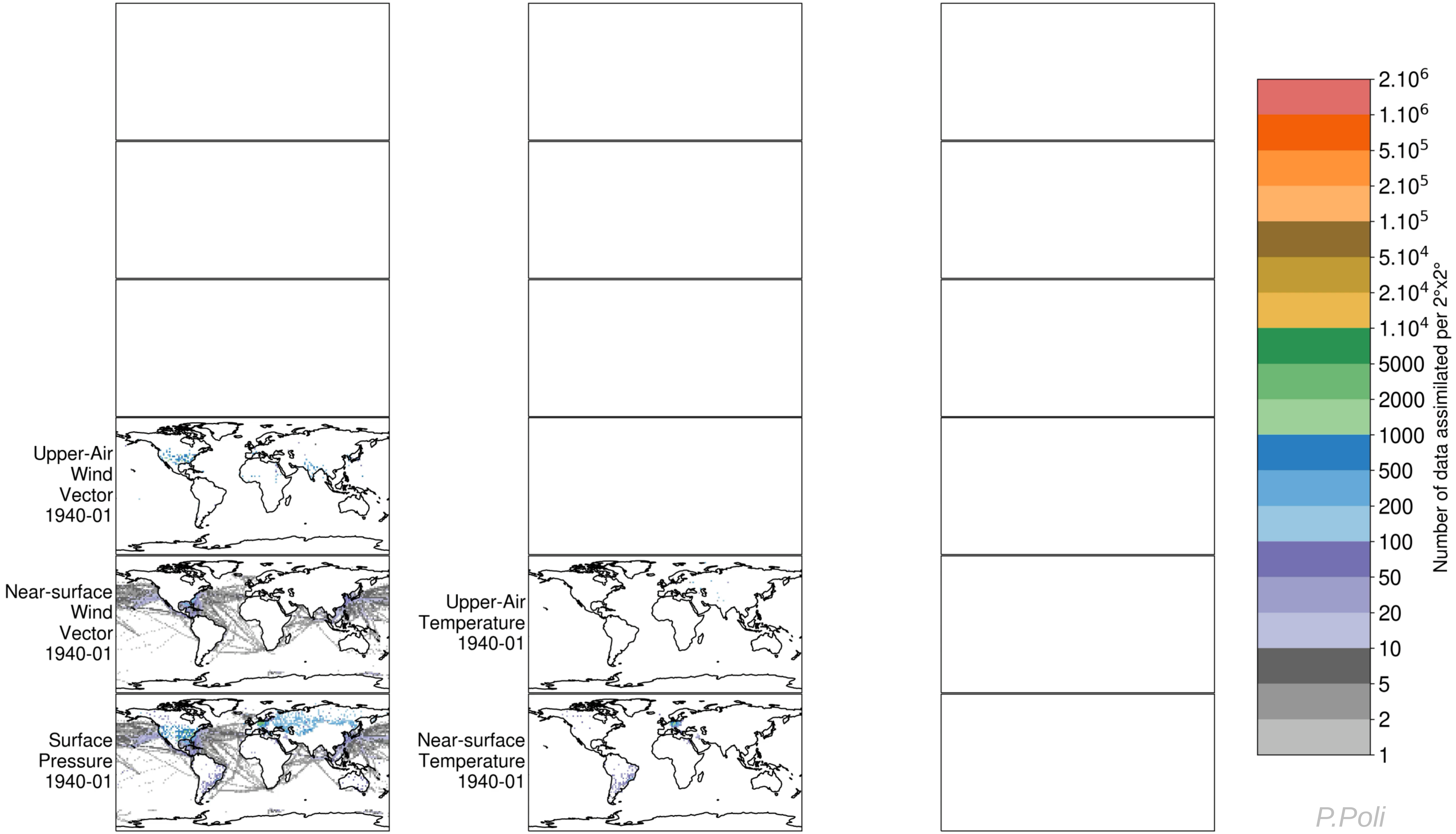
observation operator (maps the model state to the observation space)

Quarterly Journal of the Royal Meteorological Society
RMetS
Article | Free to Read

The ECMWF operational implementation of four-dimensional variational assimilation. I: Experimental results with simplified physics

F. Rabier, H. Järvinen, E. Klinker, J.-F. Mahfouf, A. Simmons

First published: April 2000 Part A | https://doi.org/10.1002/qj.49712656415 | Citations: 534


Upper-Air
Wind
Vector
1940-01
Near-surface
Wind
Vector
1940-01
Surface
Pressure
1940-01
Upper-Air
Temperature
1940-01
Near-surface
Temperature
1940-01
2.10^6
1.10^6
5.10^5
2.10^5
1.10^5
5.10^4
2.10^4
1.10^4
5000
2000
1000
500
200
100
50
20
10
5
2
1
Number of data assimilated per 2°x2°
P.Poli

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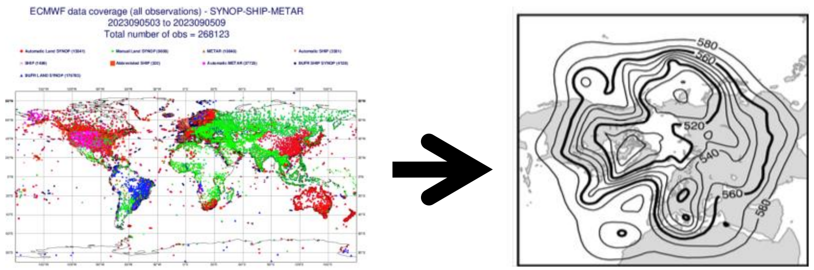
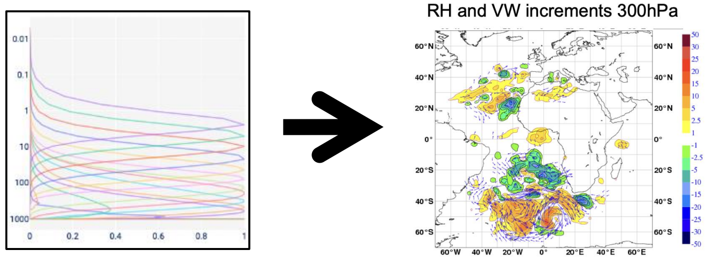
Different mechanisms of observation constraint

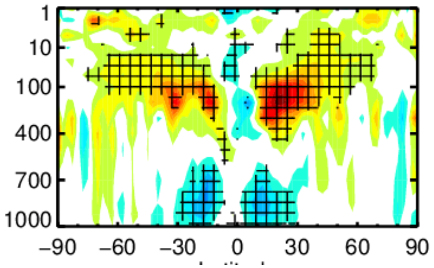
- **Directly** observed (e.g. surface pressure)



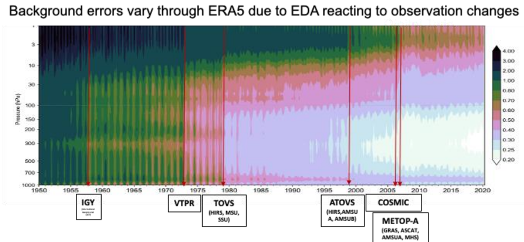
- Indirectly observed **within the assimilation window** (e.g. temperature or wind from satellite radiances)



- Indirectly observed **outside the assimilation** window
(e.g. large-scale circulation changes satellite radiances)

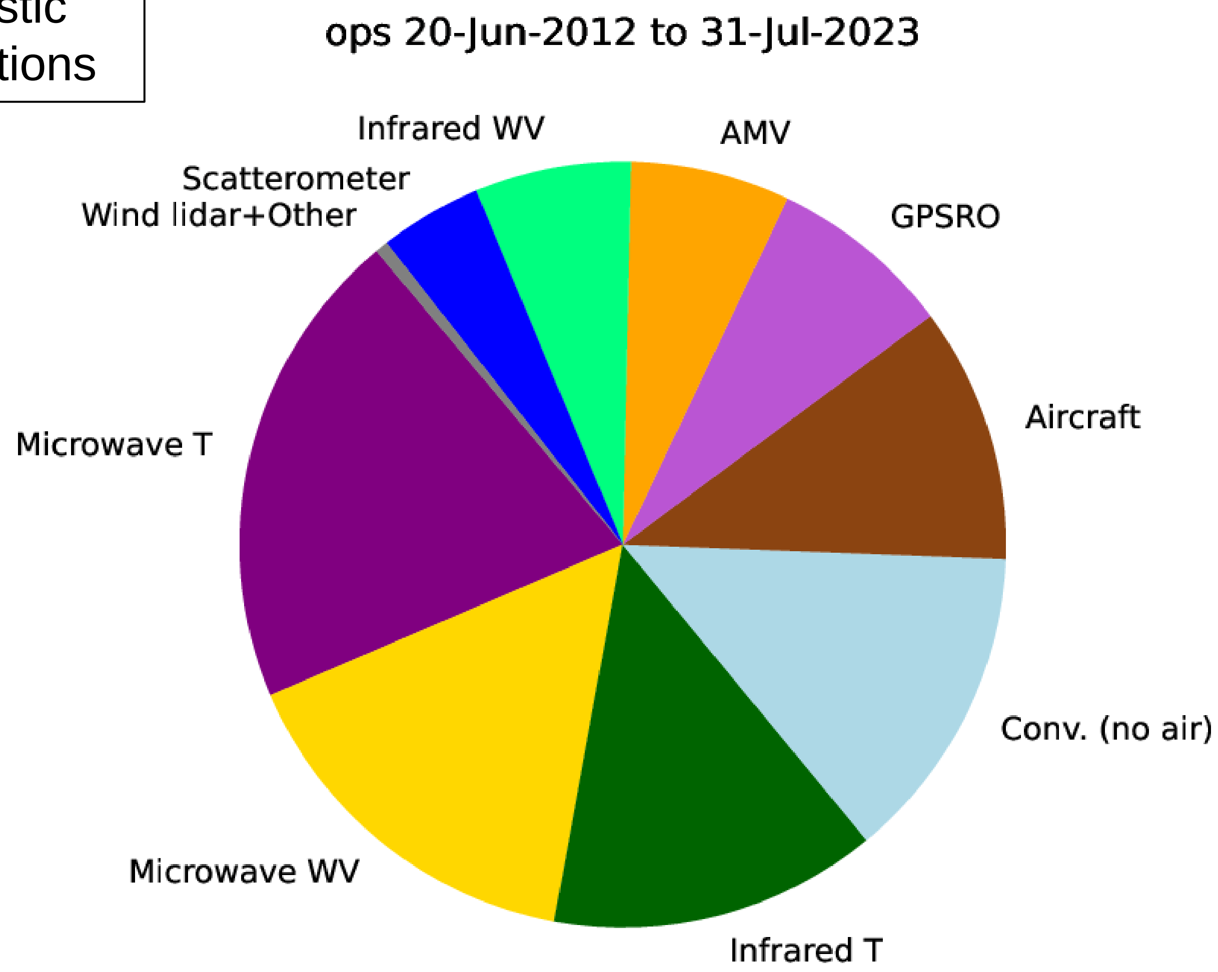


- Indirect by improving the **tuning of the DA**



The majority of observation constraint is indirect – can we trust this ?

FSOI Impact diagnostic from ECMWF operations

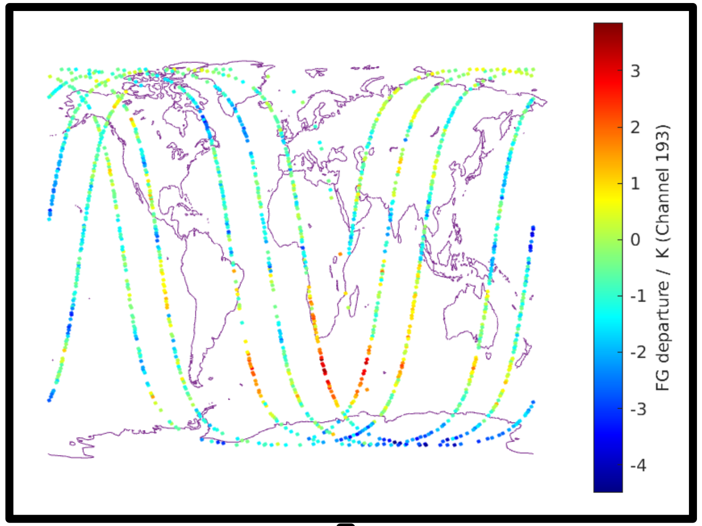


A. Geer / B.Ingleby

Example: satellite radiances indirectly constraining wind…

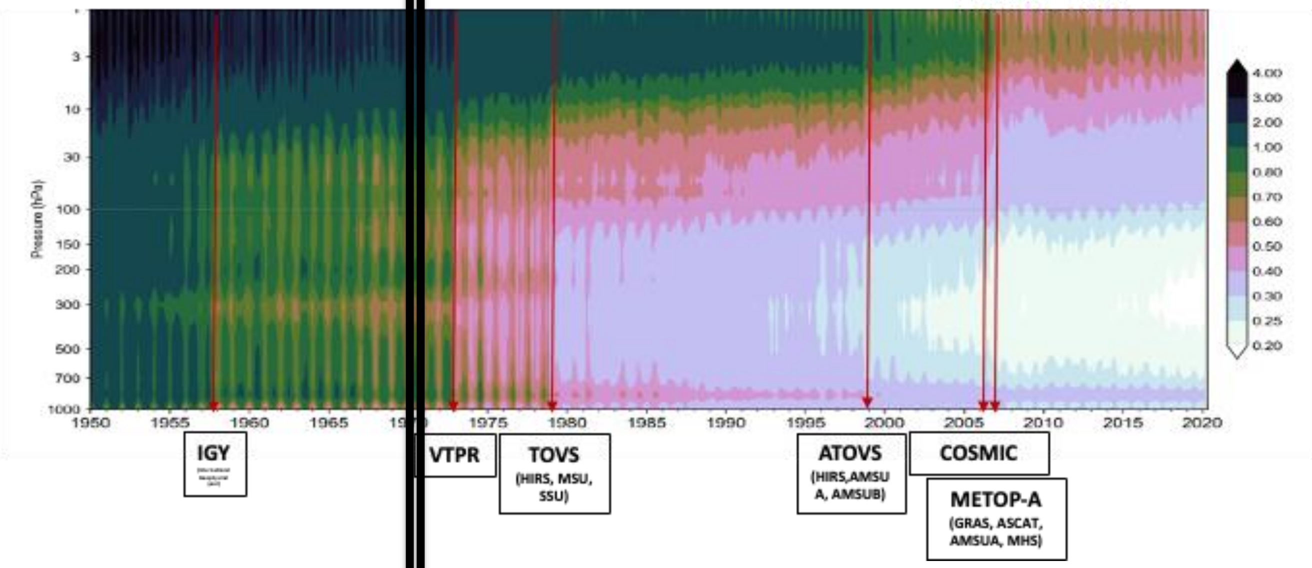
Radiance information accurately constraining wind …via geostrophic balance

The brief flight of NIMBUS-4



- 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

Background errors vary through ERA5 due to EDA reacting to observation changes



B. Bell / H.Hersbach

Radiance information accurately constraining wind …via geostrophic balance

Impact of assimilating NIMBUS-4 IRIS infrared radiances

- Operated on Nimbus-4, from April 1970 – January 1971
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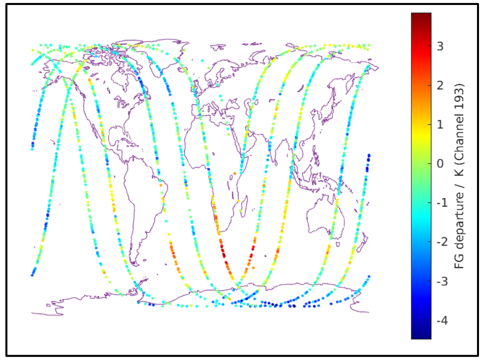
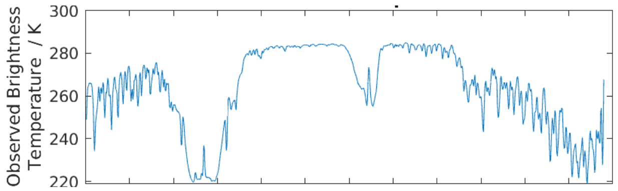
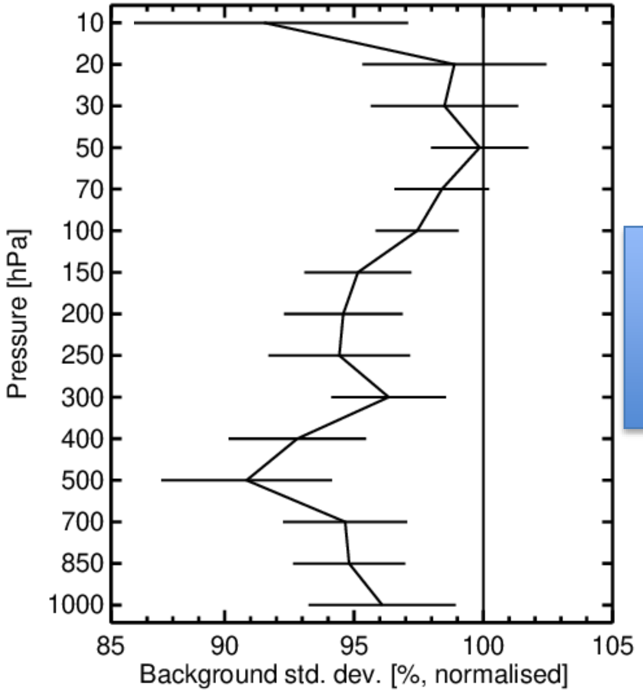




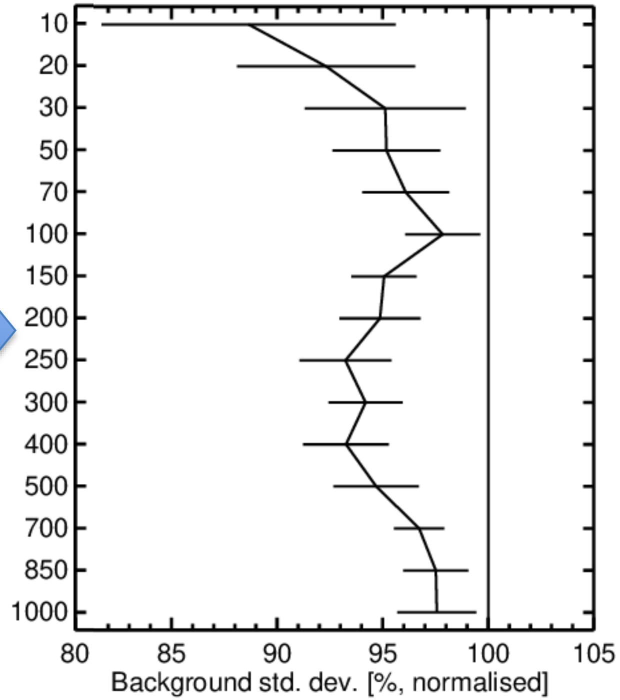
Improve thermal field

radiosonde temperature fit



indirect wind impact <u>verified</u> v radiosondes

radiosonde wind fit



Radiance information accurately constraining wind …via humidity feature tracing (GEO)

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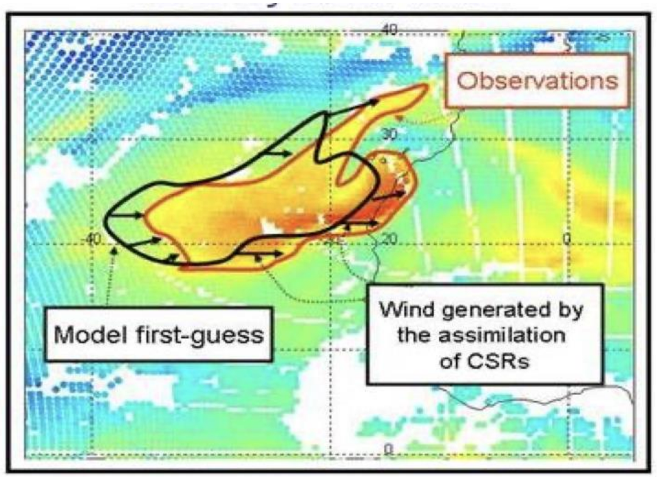
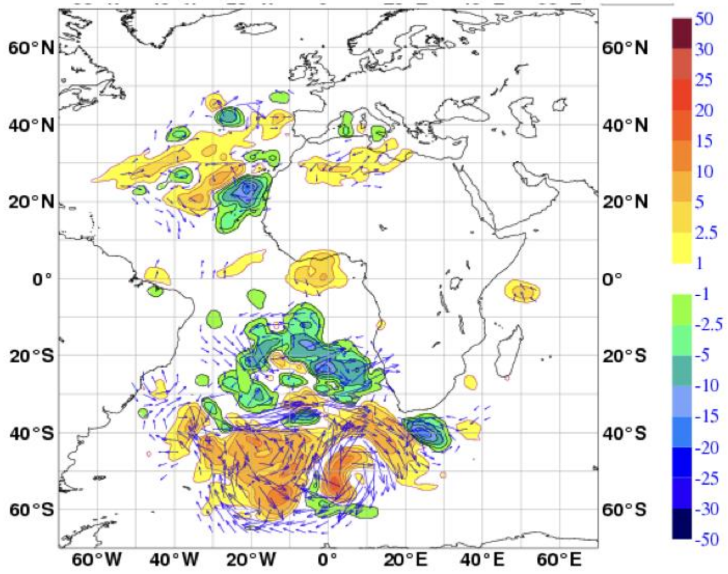
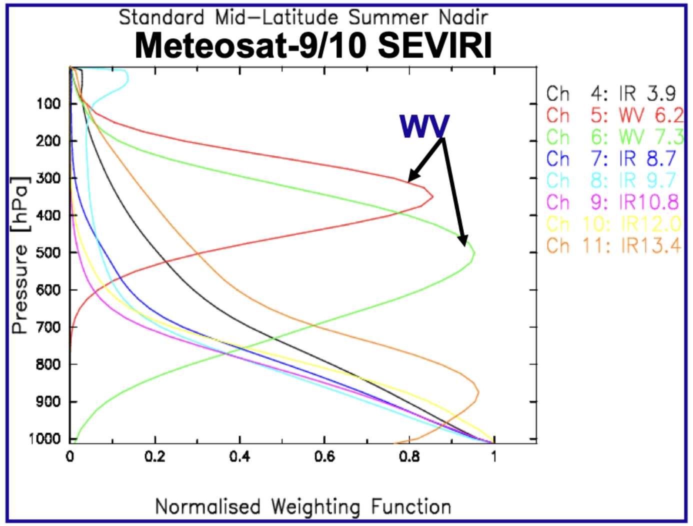


RH and VW increments 300hPa





Effective without geostrophic balance (Tropics) and constraint improves with more frequent observations (i.e. with GEO satellites or multiple LEO satellites)

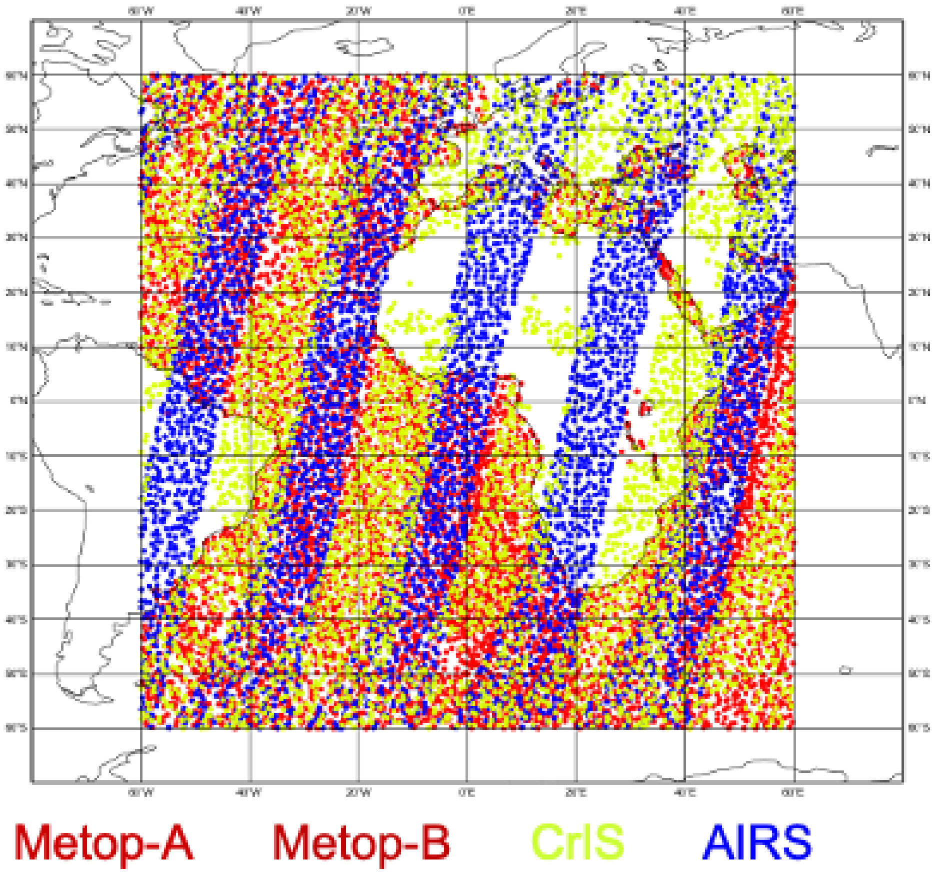
Quarterly Journal of the Royal Meteorological Society
RMetS
Research Article

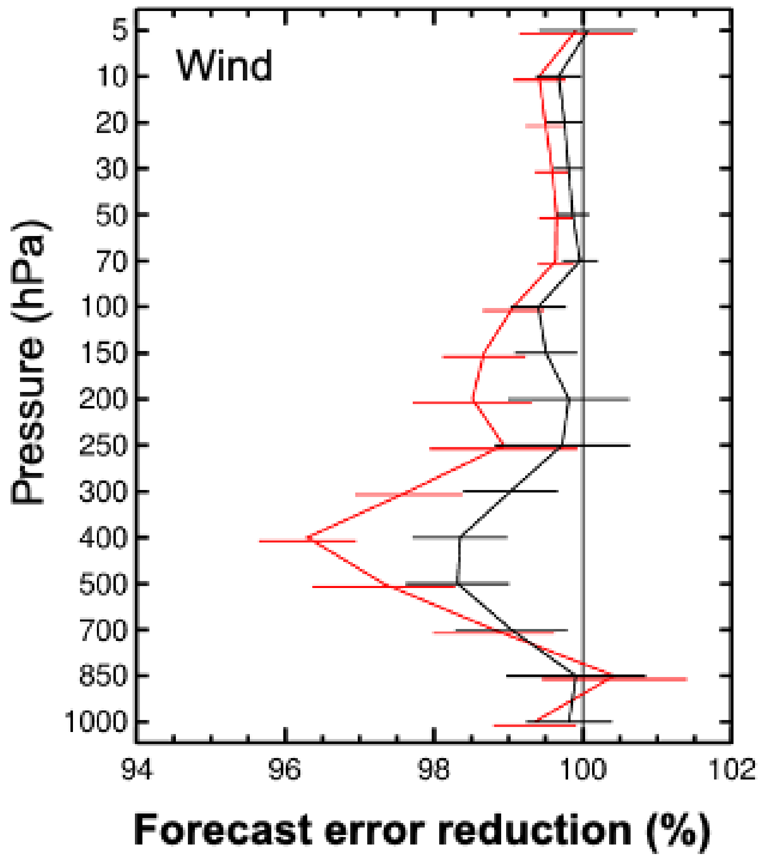
Characterization of the impact of geostationary clear-sky radiances on wind analyses in a 4D-Var context

C. Peubey, A.P. McNally

First published: 06 October 2009 | https://doi.org/10.1002/qj.500 | Citations: 34

Multiple LEO satellite can also provide wind information via humidity feature tracing





Kirsti Salonen

Radiance information accurately constraining wind …via large-scale model adjustment

Radiance information accurately constraining wind …via large-scale model adjustment

Quarterly Journal of the Royal Meteorological Society

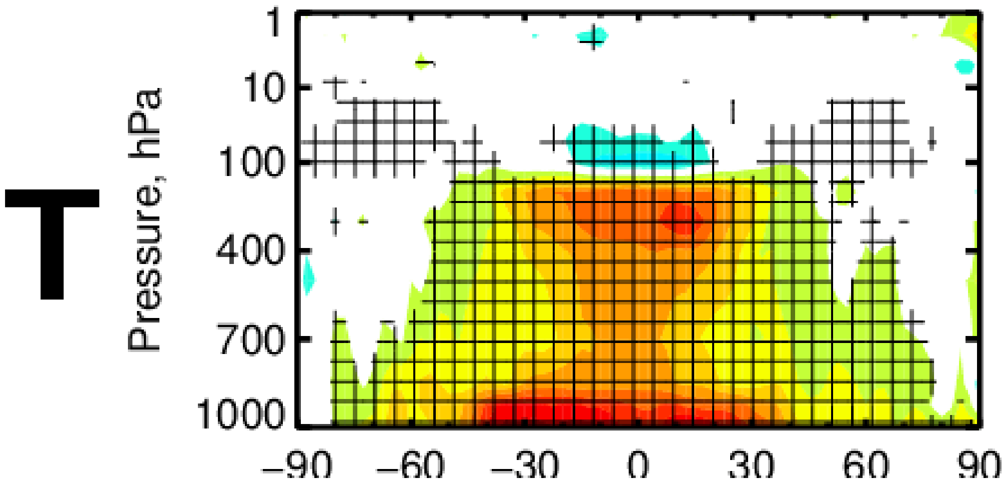
Article

Variational analysis of humidity information from TOVS radiances

A. P. McNally, M. Vesperini

First published: October 1996 Part A | https://doi.org/10.1002/qj.49712253504 | Citations: 48

Assimilating IR window channels warmed the ocean surface…



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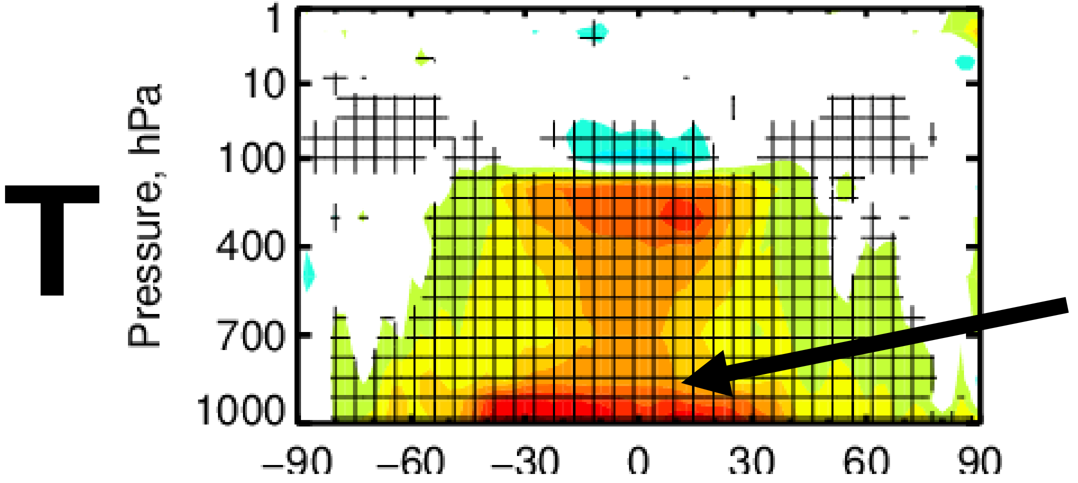
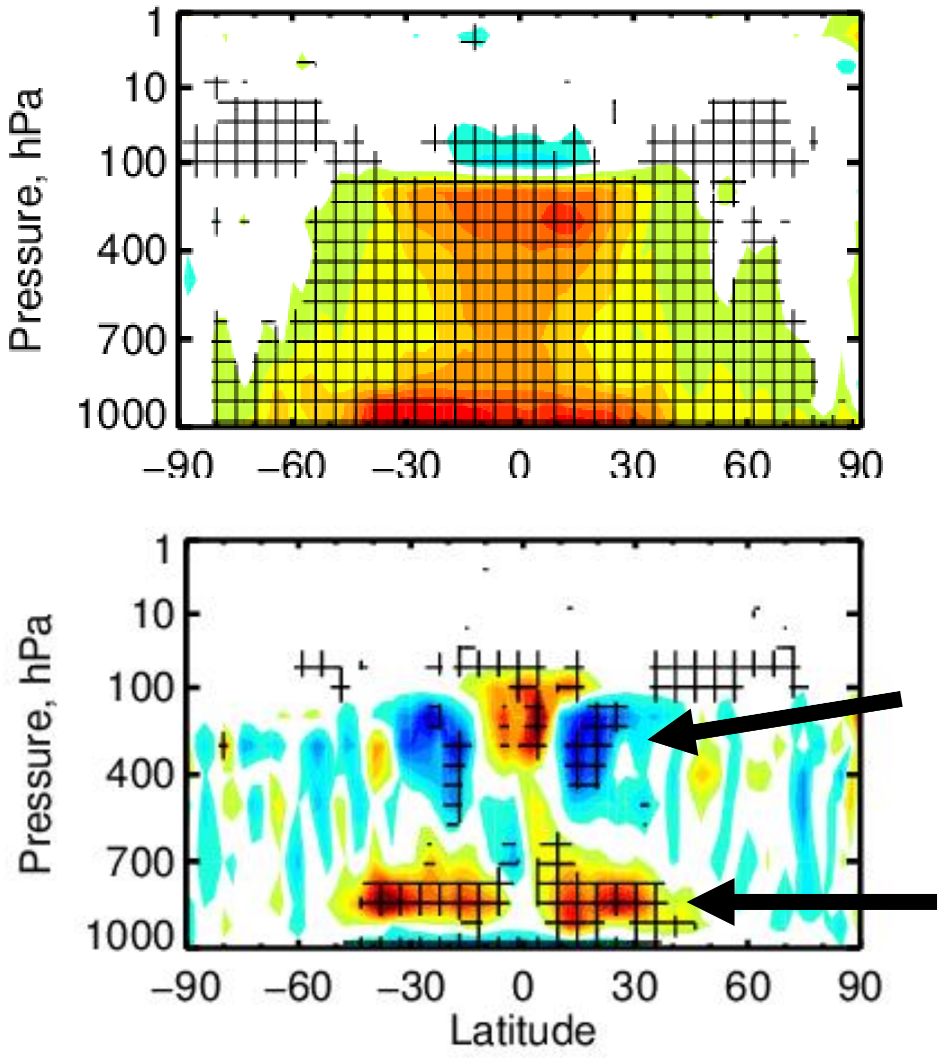


Heating of the surface enhances evaporation and convection and ascent in ITCZ

Enhancing ascent in the ITCZ…

T

Q

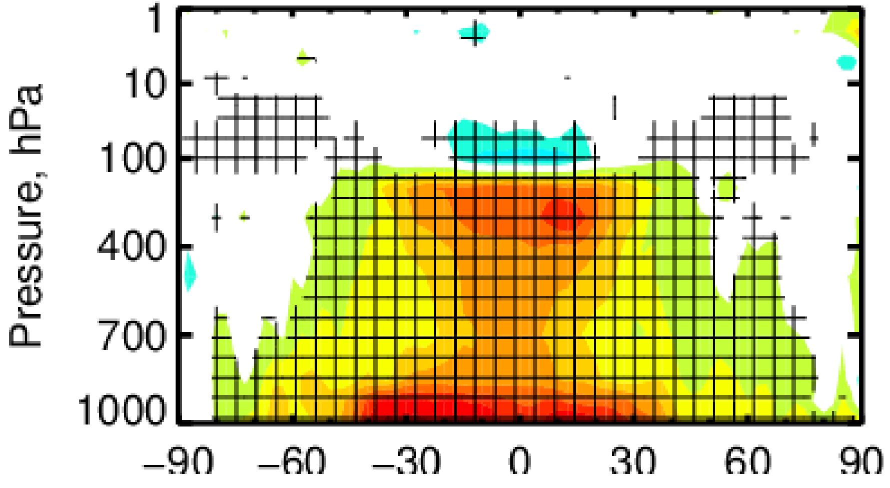


enhanced longwave cooling and drying in UTH

enhanced low level moisture convergence return to ITCZ

Enhancing equatorward flow in the ITCZ…

T



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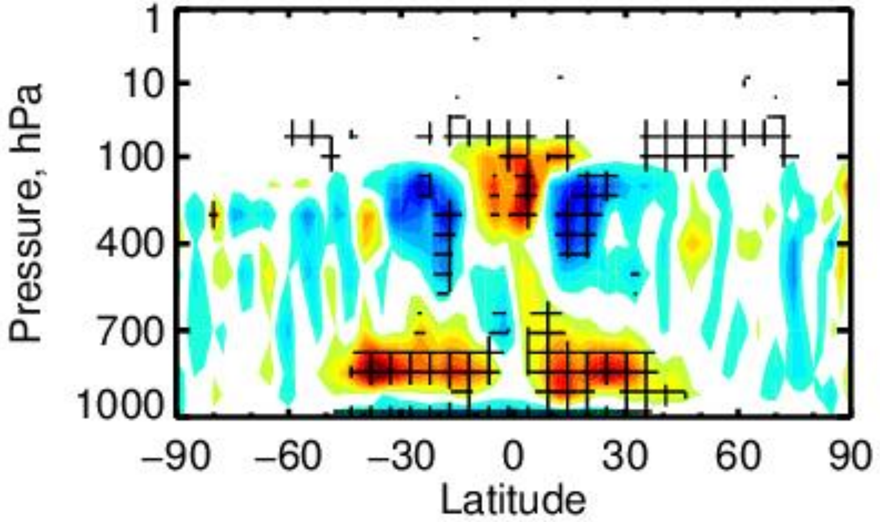
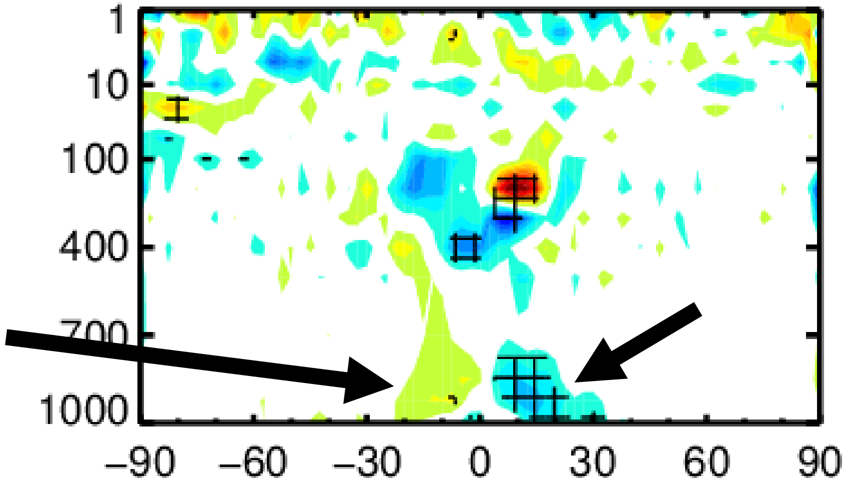
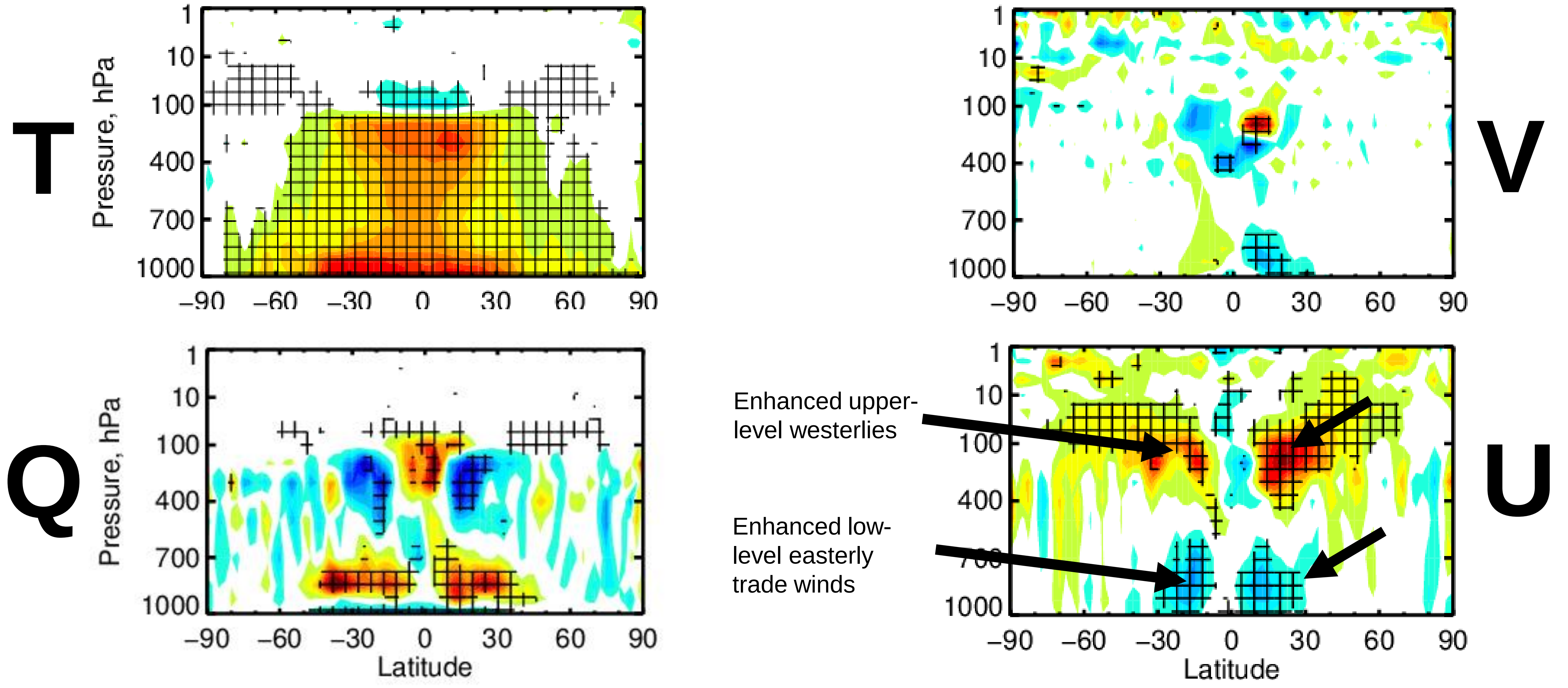


Enhanced low-level equatorward trade winds

V



Stronger mean Hadley Circulation…just from IR window channels!



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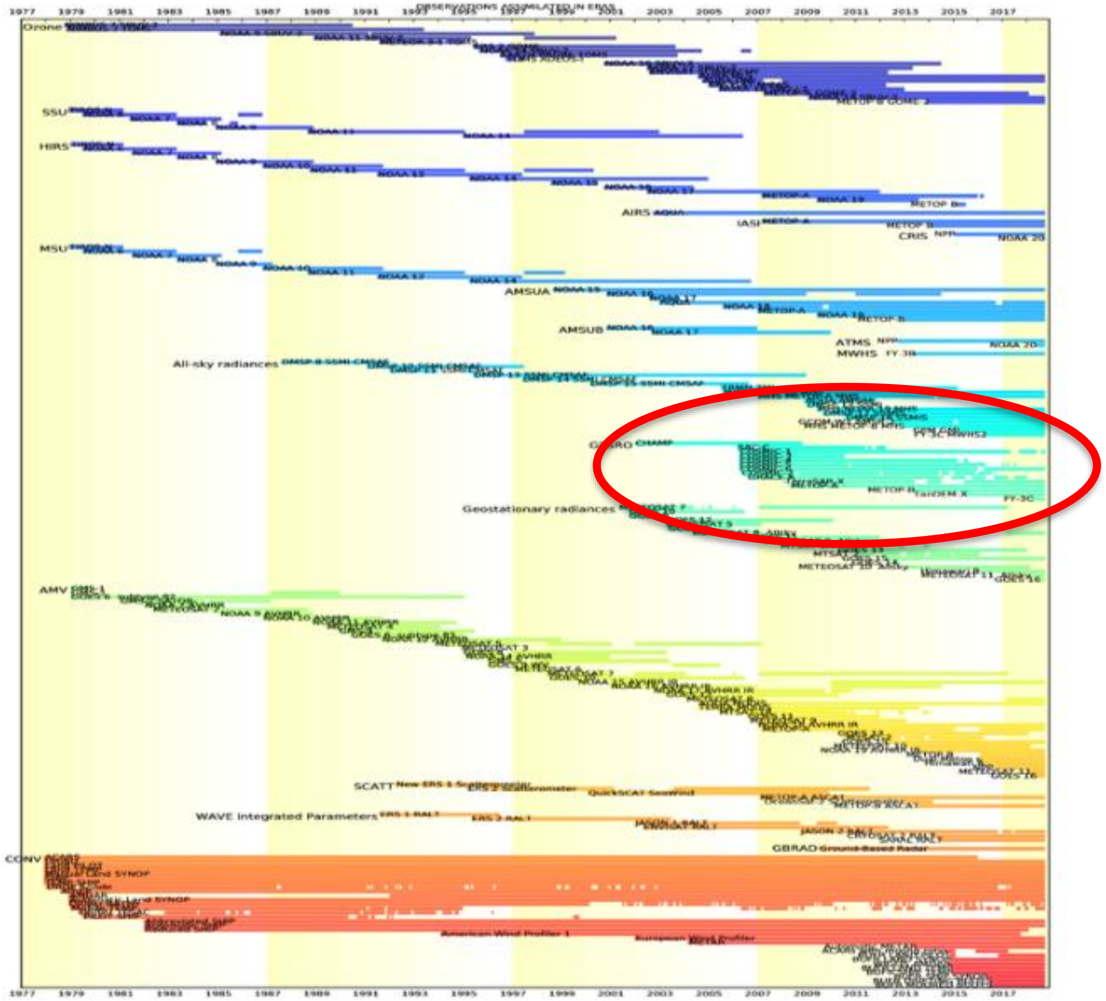
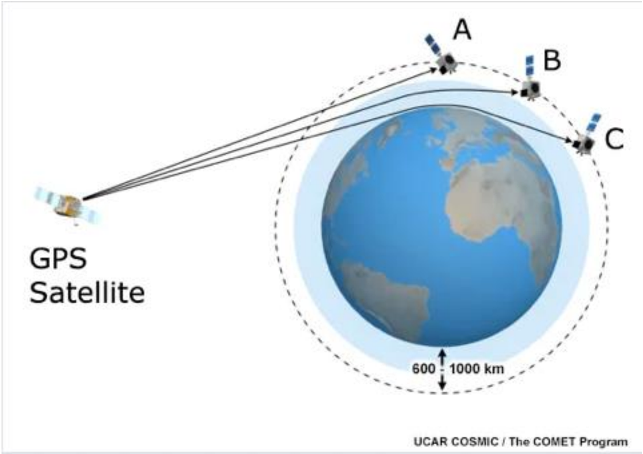
To what extent do observations constrain fine vertical scales ?

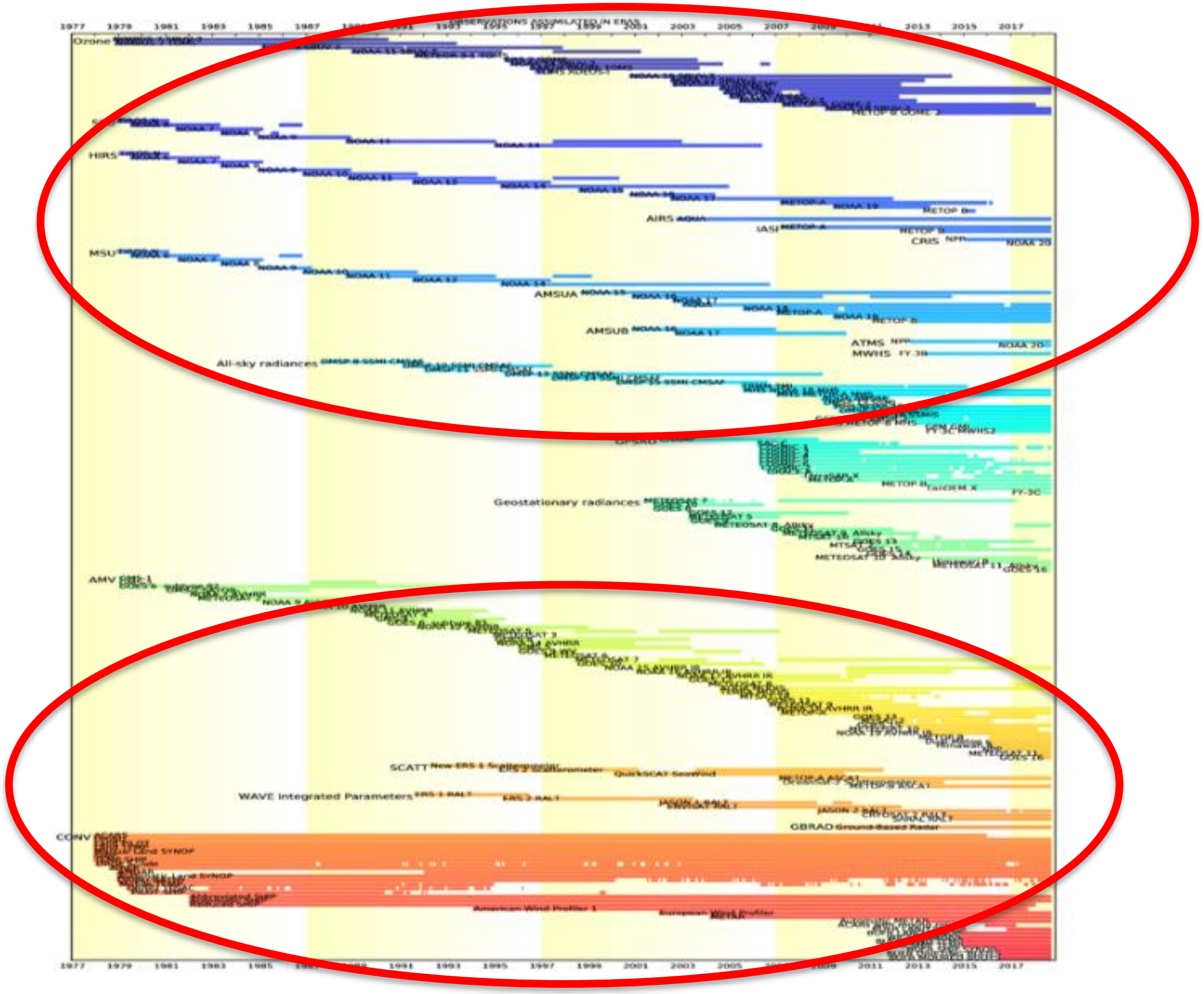
GNSS-RO has excellent vertical resolution…



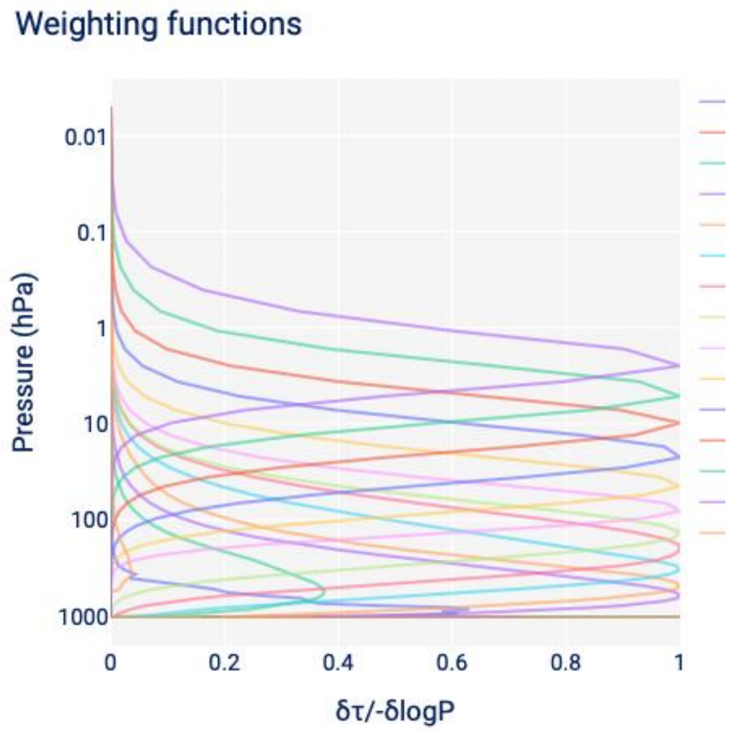


But only becomes effective from 2007 onwards

But most of reanalysis is dominated by downward viewing radiances…



The vertical resolution of these systems is determined by their channel weighting functions and the number of channels



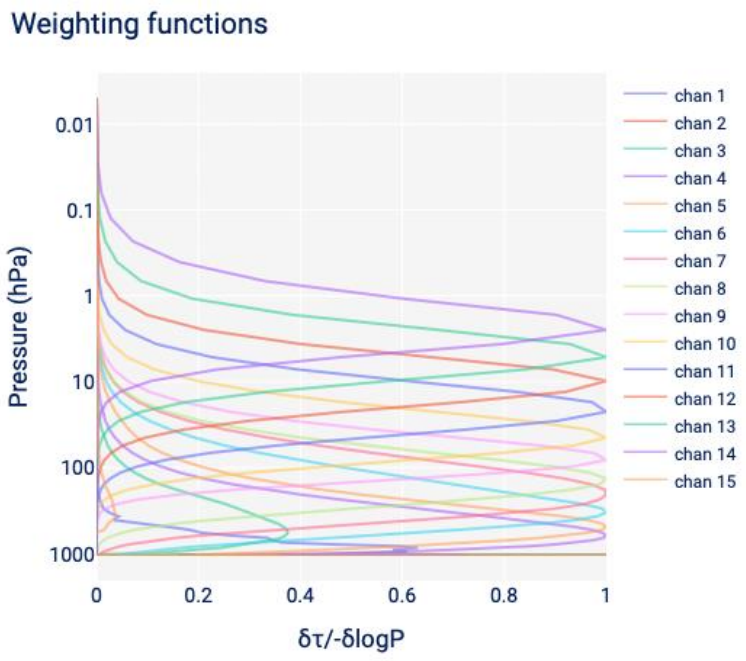
To what extent do radiances constrain fine vertical scales ?

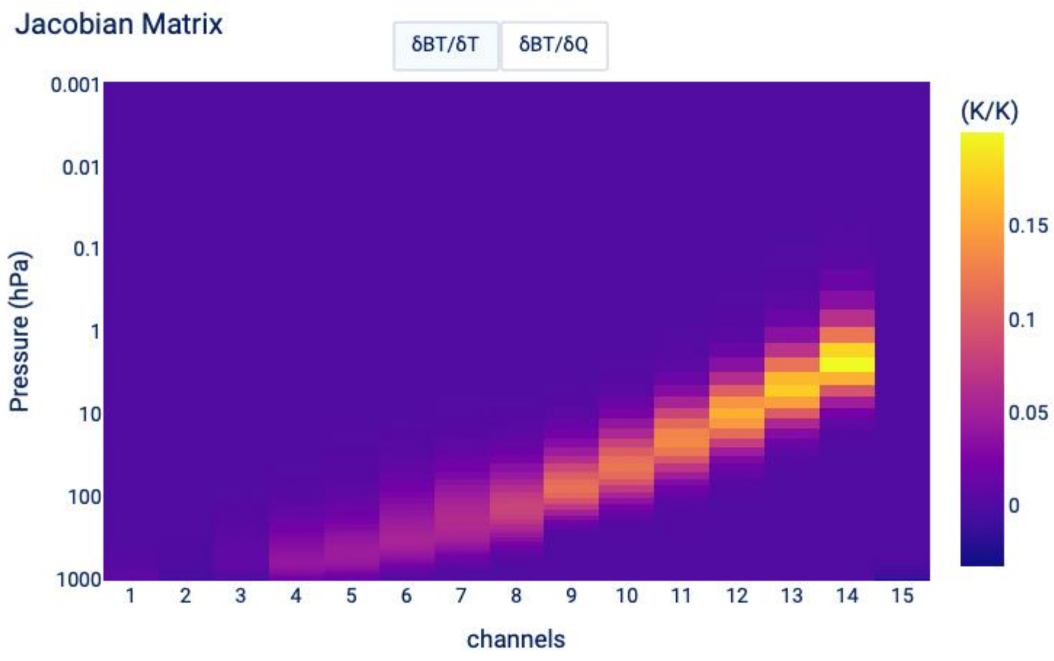
Reviews of Geophysics

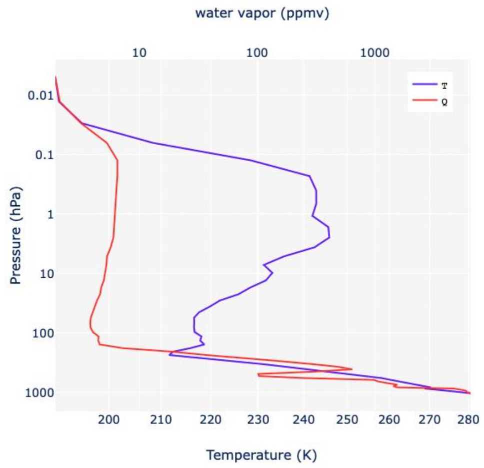
Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation

C. D. Rodgers

First published: November 1976 | https://doi.org/10.1029/RG014i004p00609 |
Citations: 1,136







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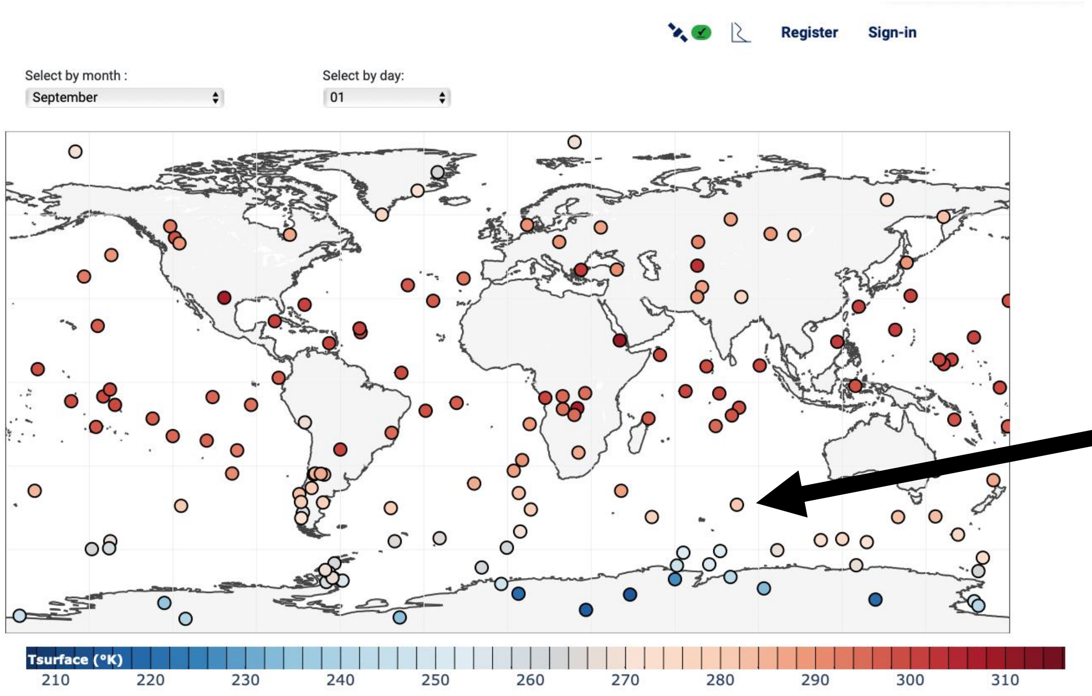
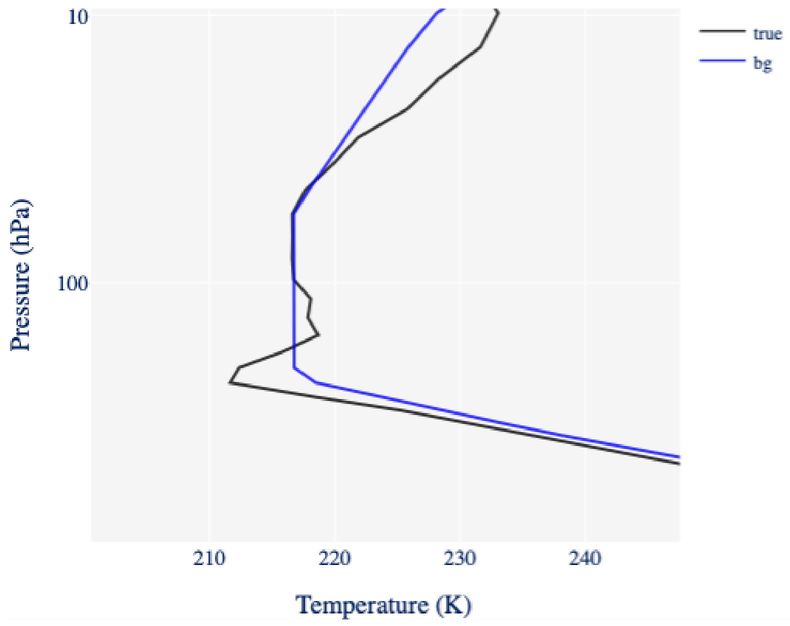


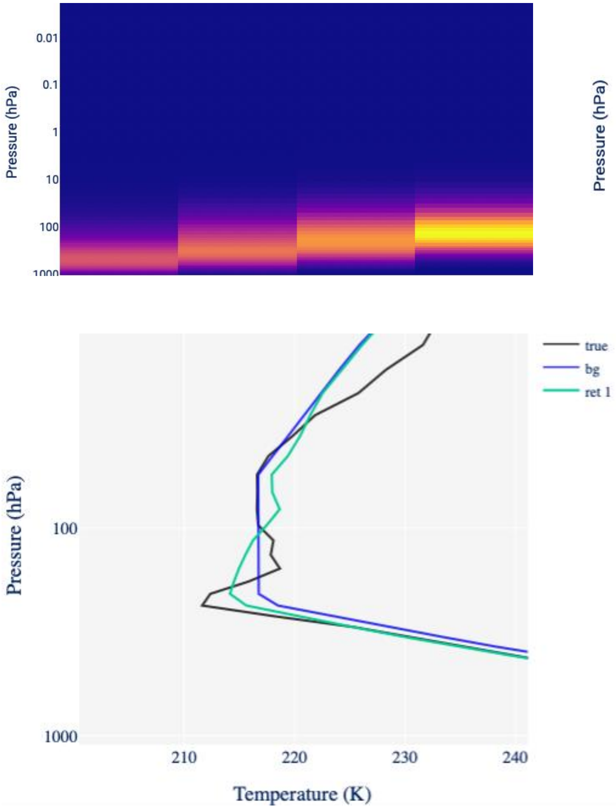


$$x_a = x_b + [\mathbf{HB}]^T [\mathbf{HBH}^T + \mathbf{R}]^{-1} (y - \mathbf{H} x_b)$$

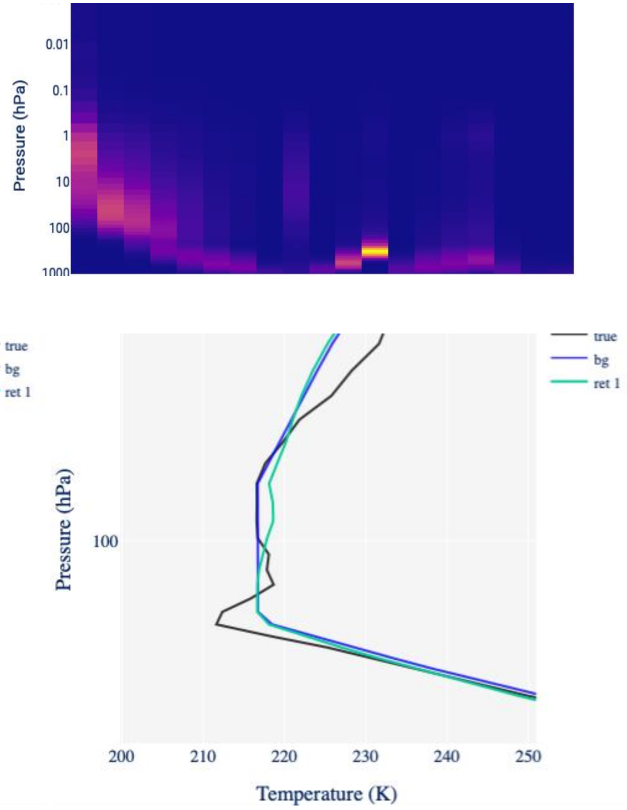
correction term

Very much depends on which satellite sensors are in use

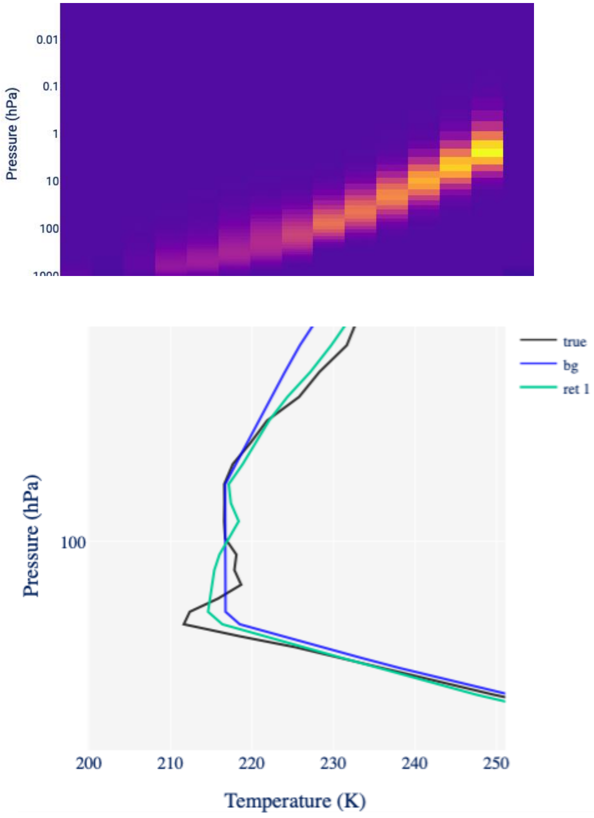
MSU (4 channels)



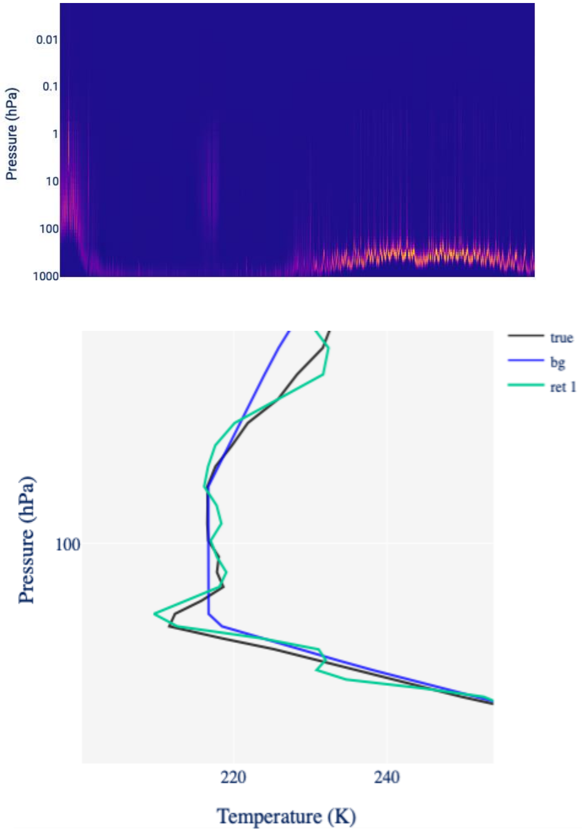
HIRS (19 channels)



AMSU (15 channels)

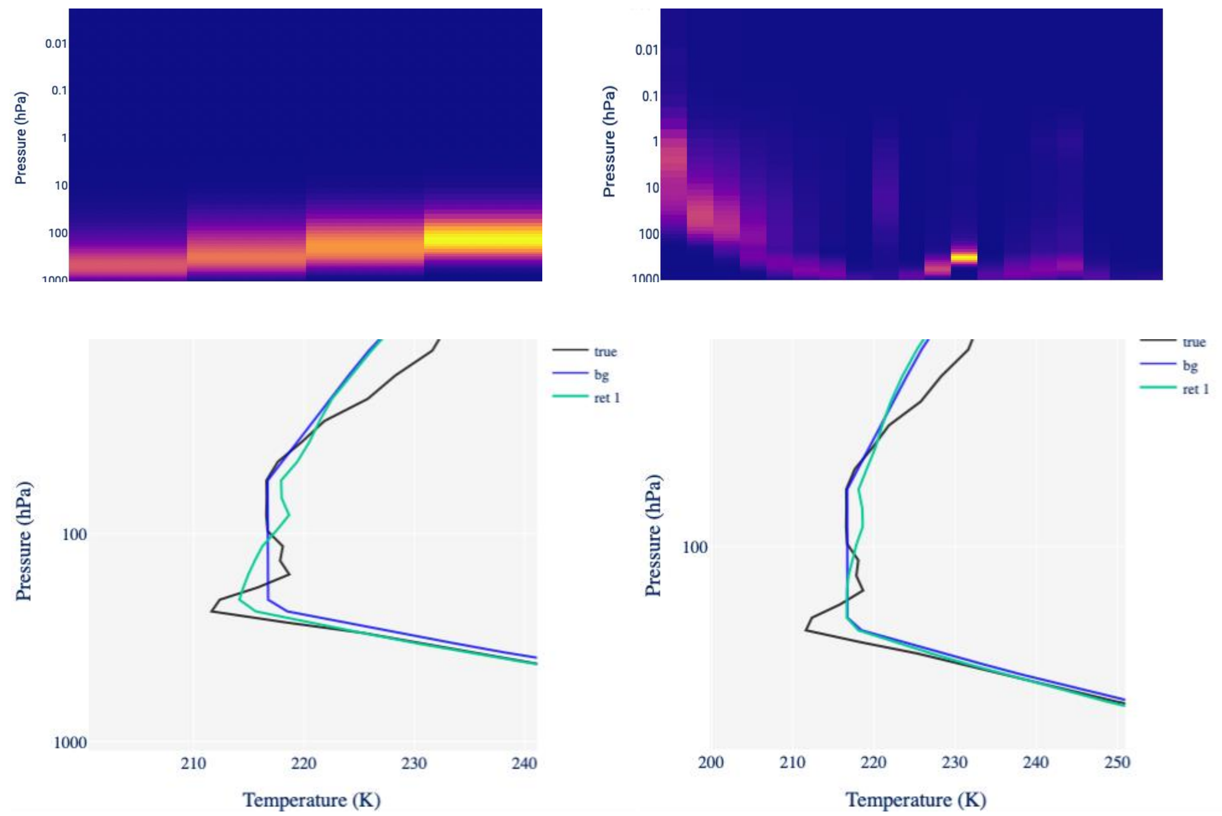


IASI (5000 channels)



Early satellite periods have little or no constraint on fine vertical scales

MSU (4 channels) HIRS (19 channels)



Implications is that during these early periods sharp vertical features do not come from the observations…they come from the **model**

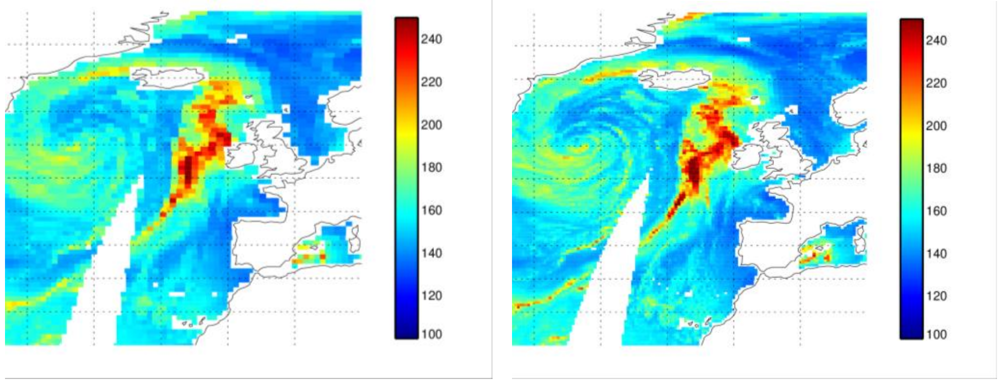
In later years GPS-RO and hyperspectral IR will provide more direct information on fine vertical scales.

To what extent do observations constrain fine horizontal scales ?

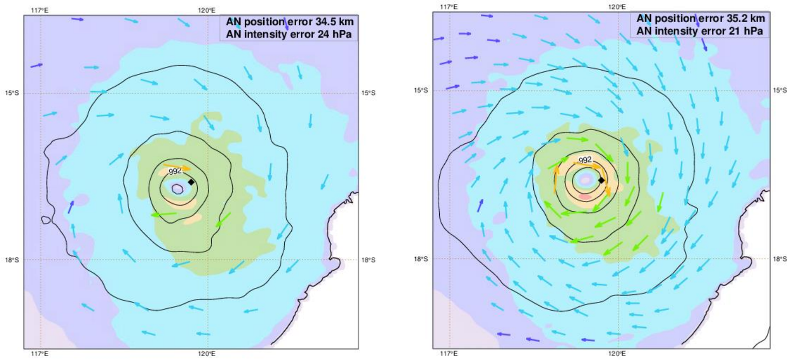
Observation density is key …

Microwave imager radiances

CY48R1 **CY49R1**

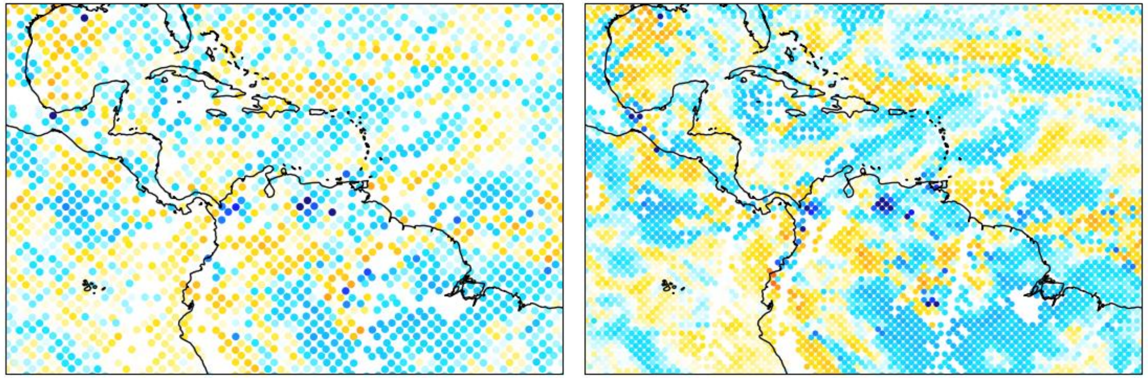


CY47r3 **ASCAT** **CY48R1**



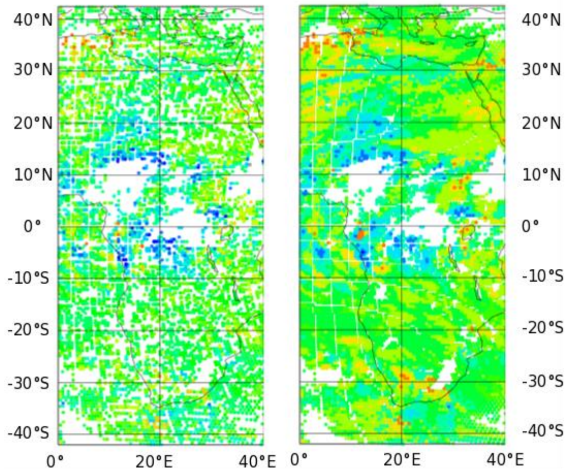
MHS 183GHz radiances

CY48R1 **CY49R1**



Met-11 radiances

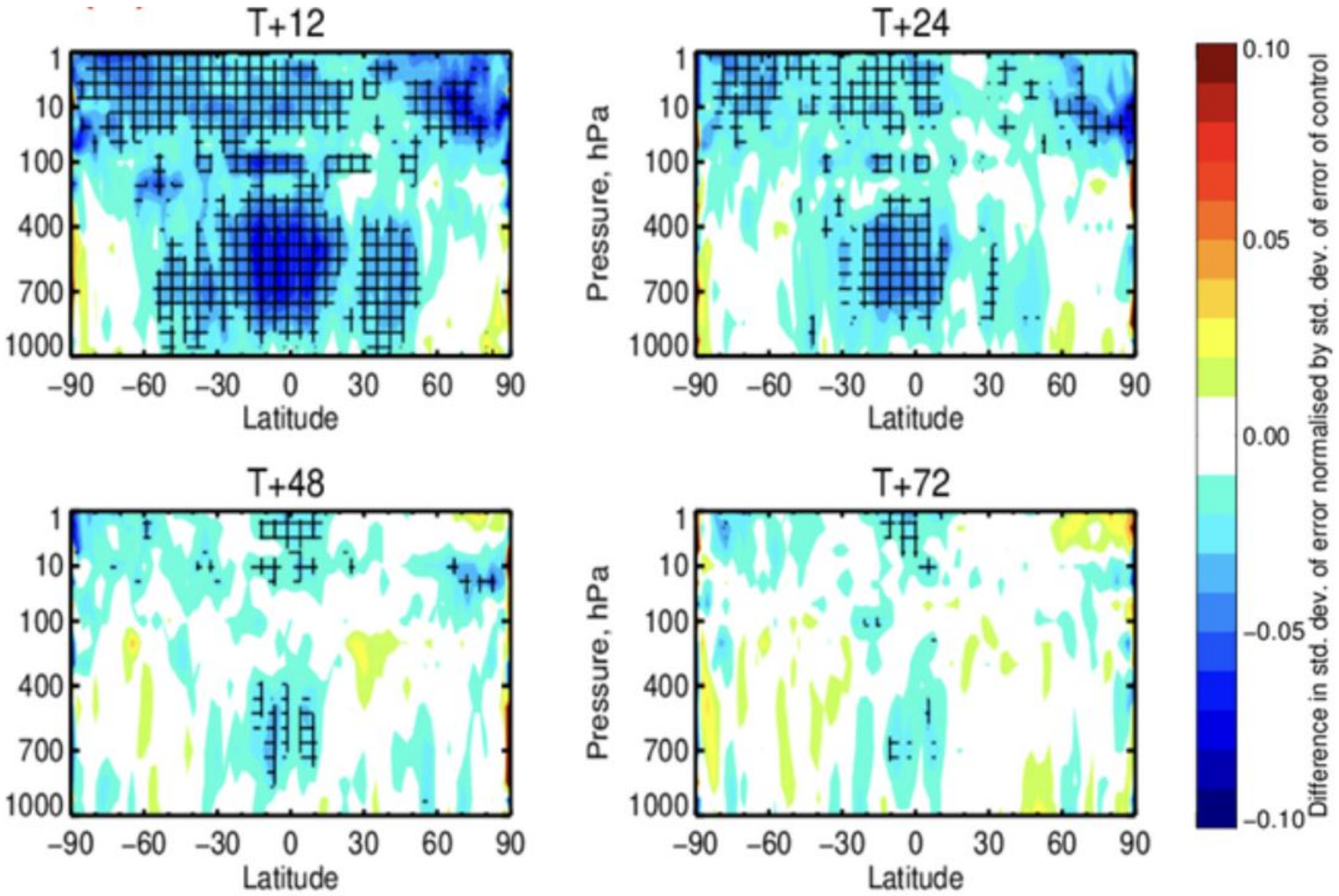
CY48R1 **CY49R1**



A. Geer
D. Duncan (EF)
G. Di Chiara (C)
J. Schroettle

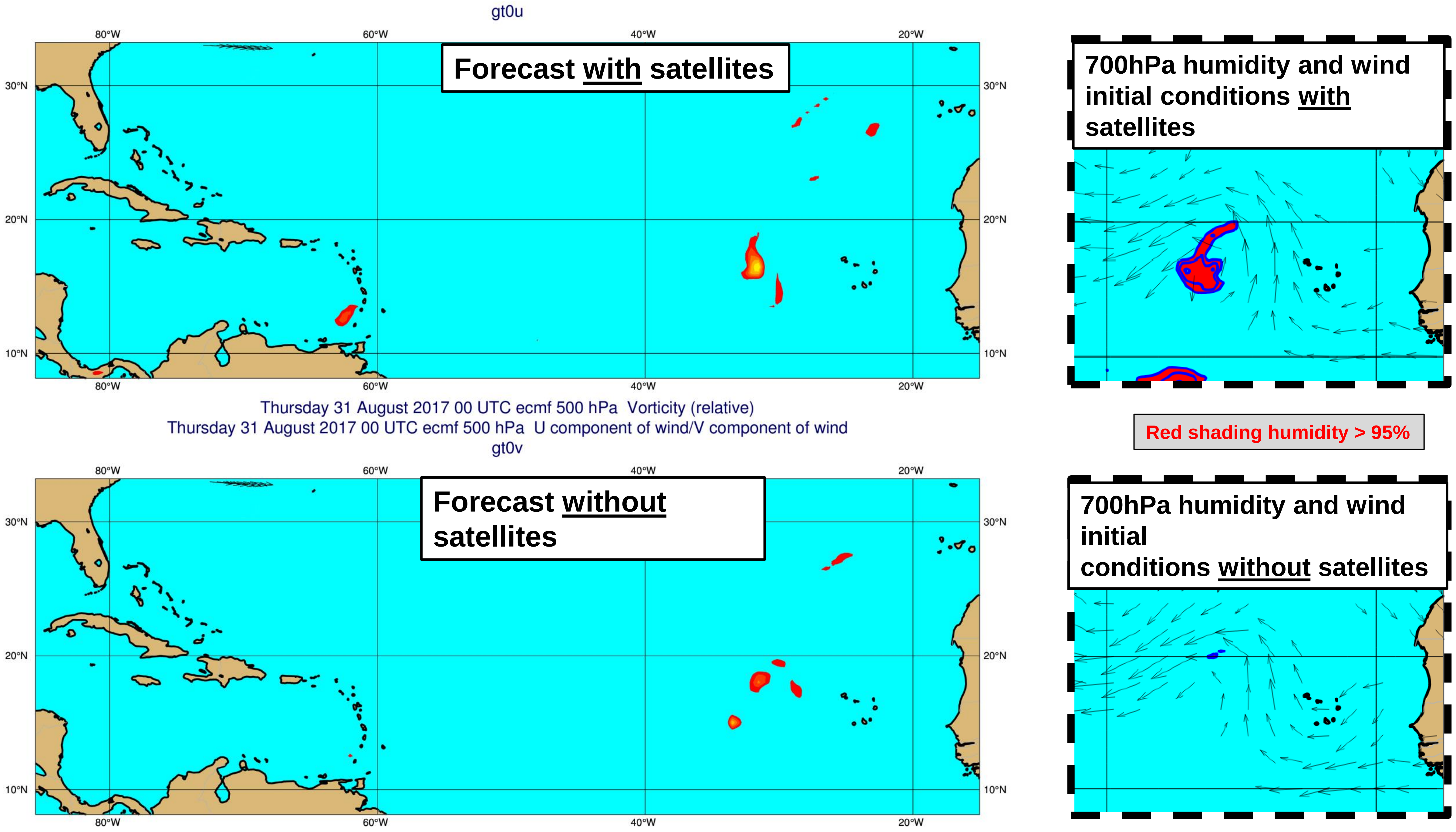
But so is inner-loop resolution …

Reduction of vector wind forecast errors moving from 50km to 40km inner-loop resolution in CY48R1…



M. Bonavita, Elias Holm

Very fine scale features can be created from low-resolution DA …Tropical cyclones


gt0u
Forecast with satellites
80°W
60°W
40°W
20°W
30°N
20°N
10°N
Thursday 31 August 2017 00 UTC ecmf 500 hPa Vorticity (relative)
Thursday 31 August 2017 00 UTC ecmf 500 hPa U component of wind/V component of wind
gt0v
Forecast without satellites
700hPa humidity and wind initial conditions with satellites
Red shading humidity > 95%
700hPa humidity and wind initial conditions without satellites

Tropical Cyclones are captured very successfully in reanalysis (from radiances)

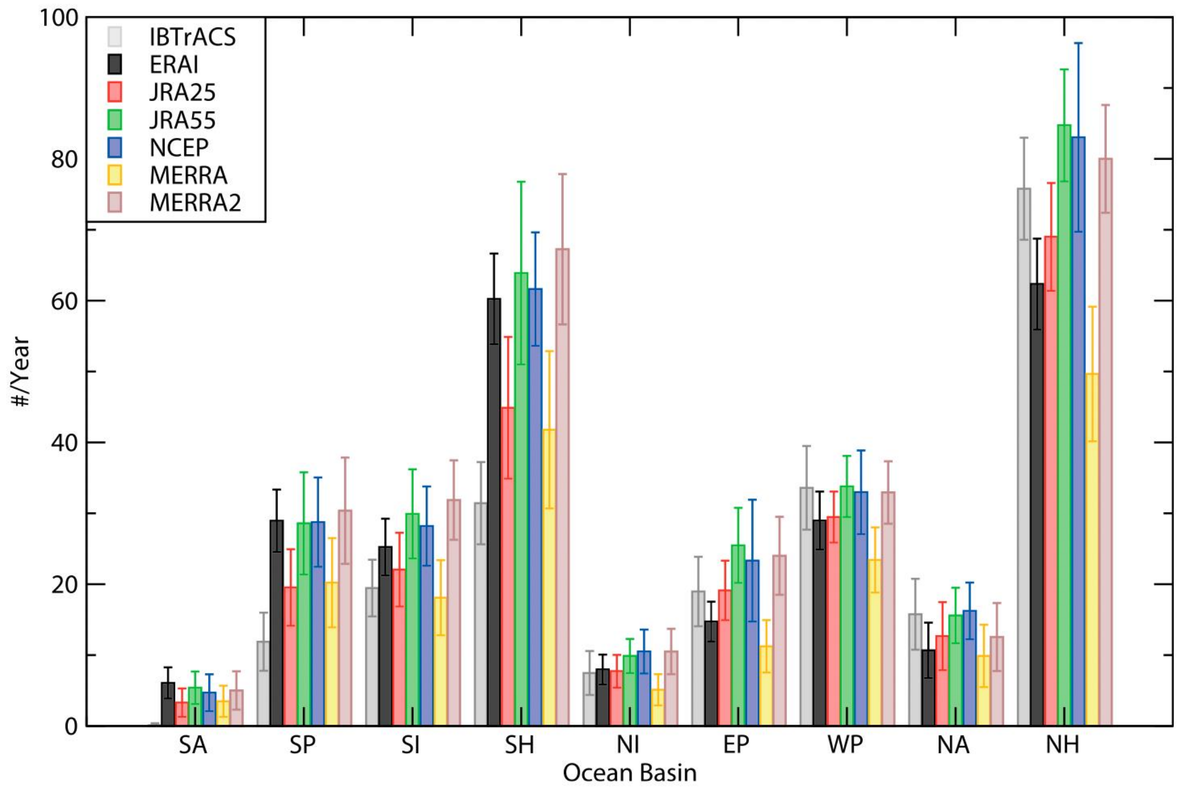


FIG. 5. The average number of TCs per year for each of the seven basins (defined in Fig. 4) for IBTrACS and identified in the reanalyses based on the objective detection method (cf. section 3b). Vertical lines at the tops of the bars indicate the standard deviation.

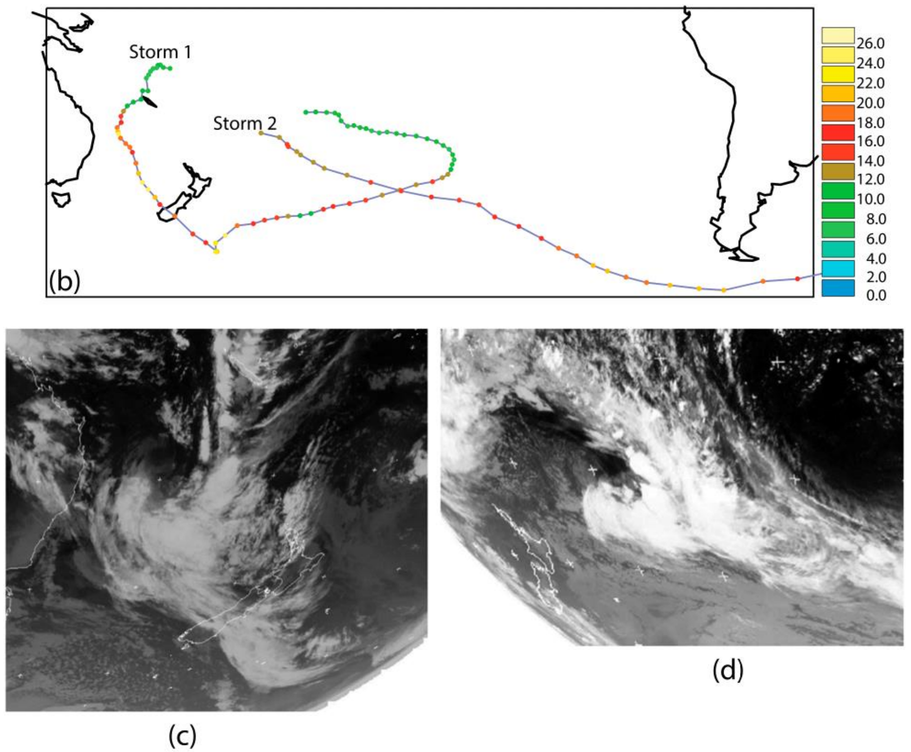
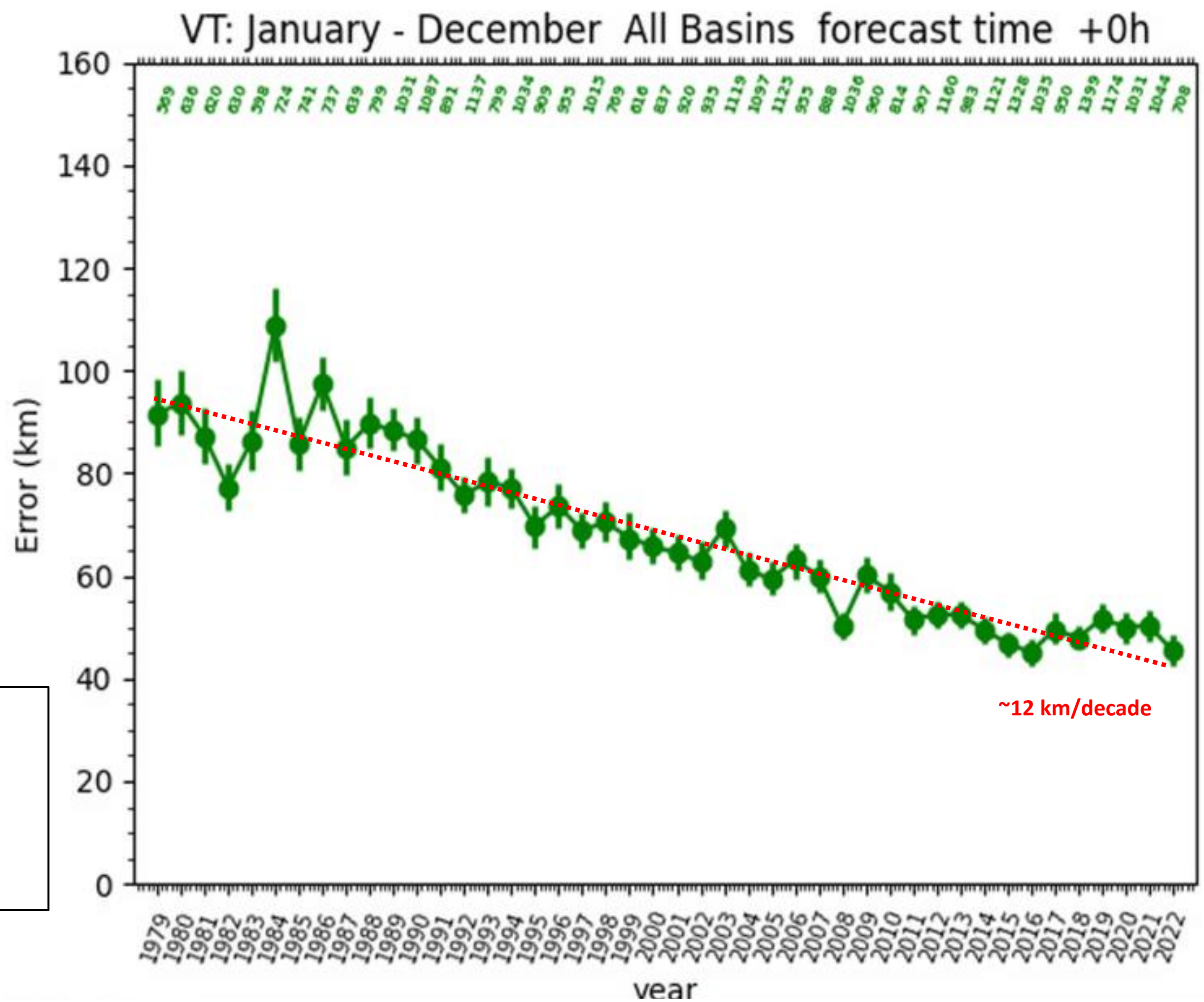


FIG. 6. (a) Latitude at which genesis occurs in the SH for the objectively identified TCs in the reanalyses that do not match with IBTrACS (number per year). (b) Examples of two tracks identified in the ERAI with no matching track in IBTrACS [colored dots indicate 10-m wind speeds (m s^{-1})]. (c) MTSAT infrared satellite image of Storm 1 in (b) on 1800 UTC 1 Jan 2011. (d) GOES West infrared satellite image of Storm 2 in (b) on 1200 UTC 24 Dec 2011.

https://centaur.reading.ac.uk/70250/8/jcli-d-16-0557.1.pdf

Tropical Cyclones are captured very successfully in reanalysis (from radiances)



Mean Position Error (ERA5)

VT: 1979-2022 Jan-Dec

F. Prates

Outline

How do observations constrain an analysis system ?

- a quick look at the 4D-Var algorithm
- the power of indirect and non-local mechanisms

Some limitations of the observation constraint

- vertical scales
- horizontal scales

Observation constraint upon the mean state

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Quarterly Journal of the Royal Meteorological Society — RMetS

Research Article

Adaptive bias correction for satellite data in a numerical weather prediction system

T. Auligné, A. P. McNally, D. P. Dee

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Monthly Weather Review

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Sections

Editorial Type: Article

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John C. Derber and Wan-Shu Wu

Print Publication: 01 Aug 1998

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How do VARBC and WC-4D-Var work ?

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How do VARBC and WC-4D-Var work together ?

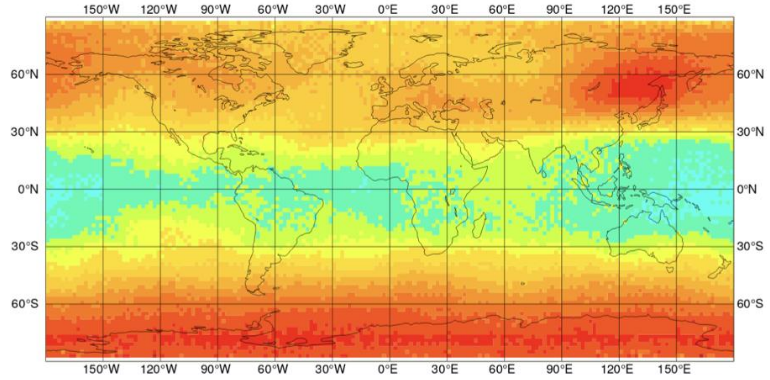
systematic departure (O-B)

Adjust estimate of **observation bias** (VARBC)

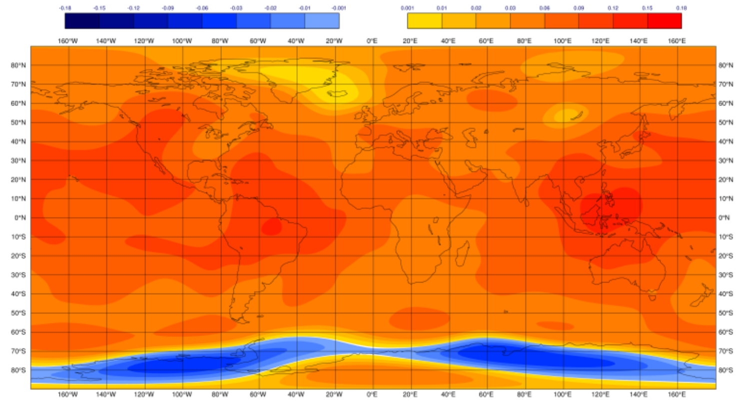
Correct the atmospheric state (locally / remotely) with **mean increments**

Adjust estimate of **model bias** (WC-4D-Var)

Correcting observation bias with VARBC



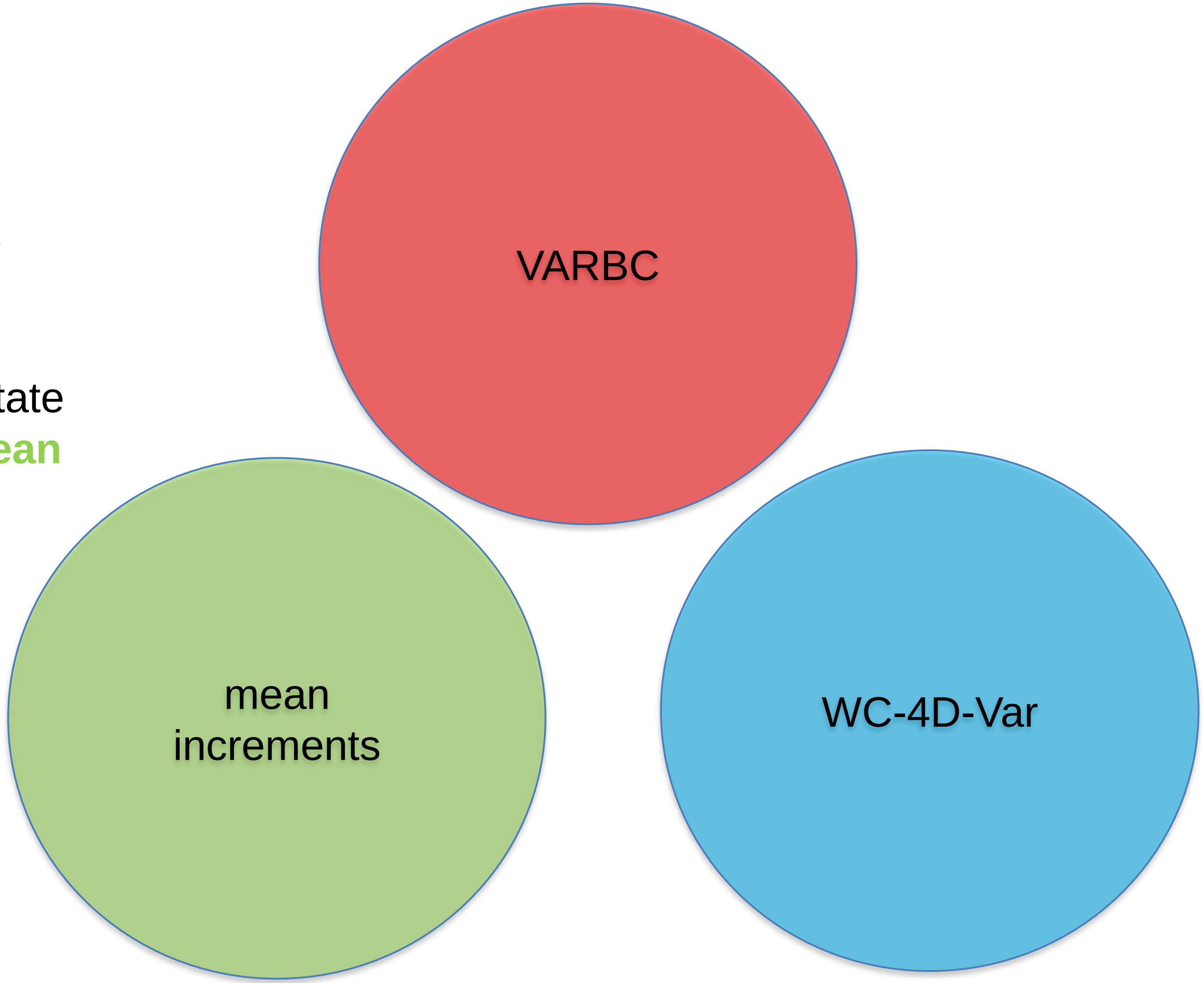
Correcting model bias via weak-constraint 4D-Var



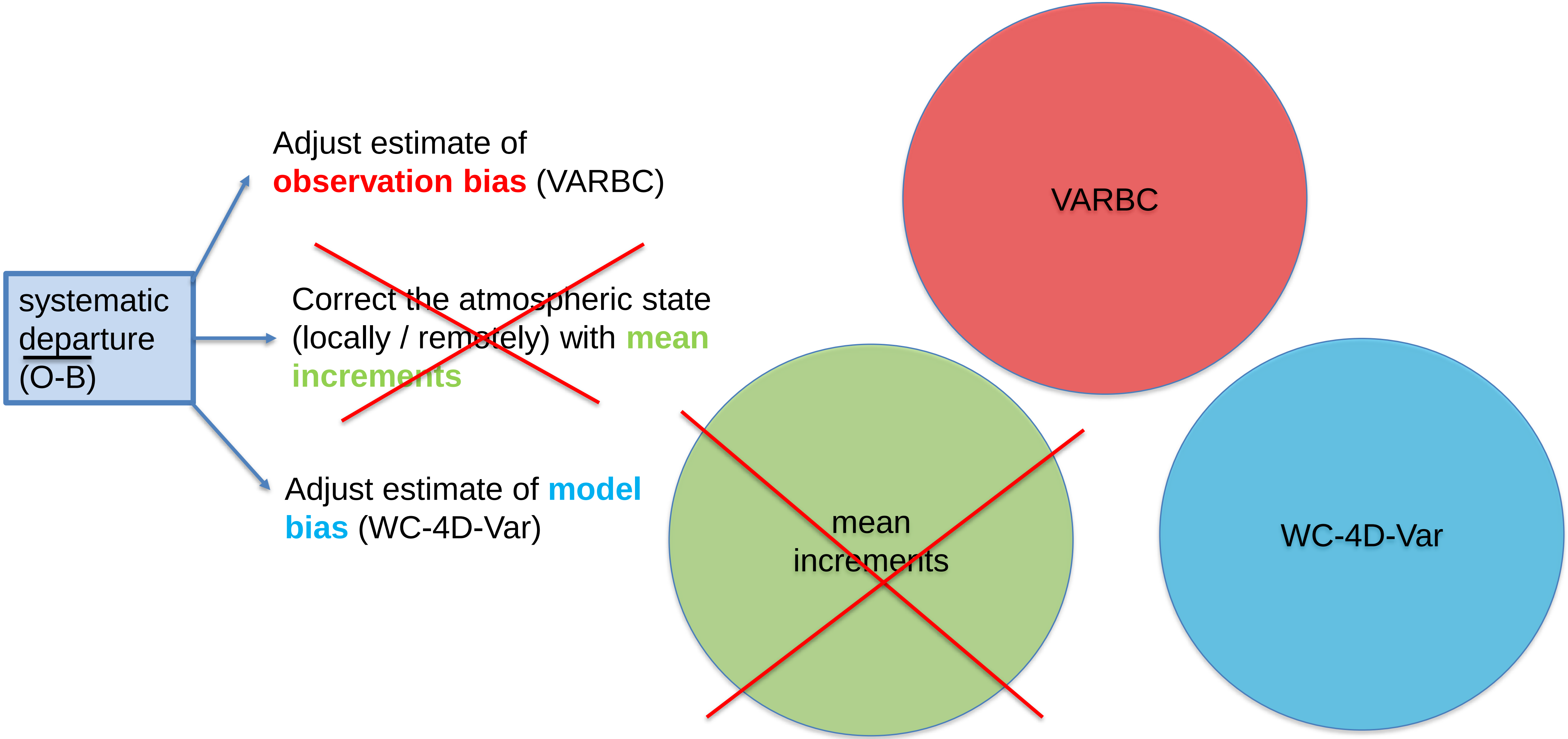
We want VARBC and WC-4D-Var to work independently…

systematic departure (O-B)

- Adjust estimate of **observation bias** (VARBC)
- Correct the atmospheric state (locally / remotely) with **mean increments**
- Adjust estimate of **model bias** (WC-4D-Var)



…to remove mean increments from the system and produce an unbiased analysis…



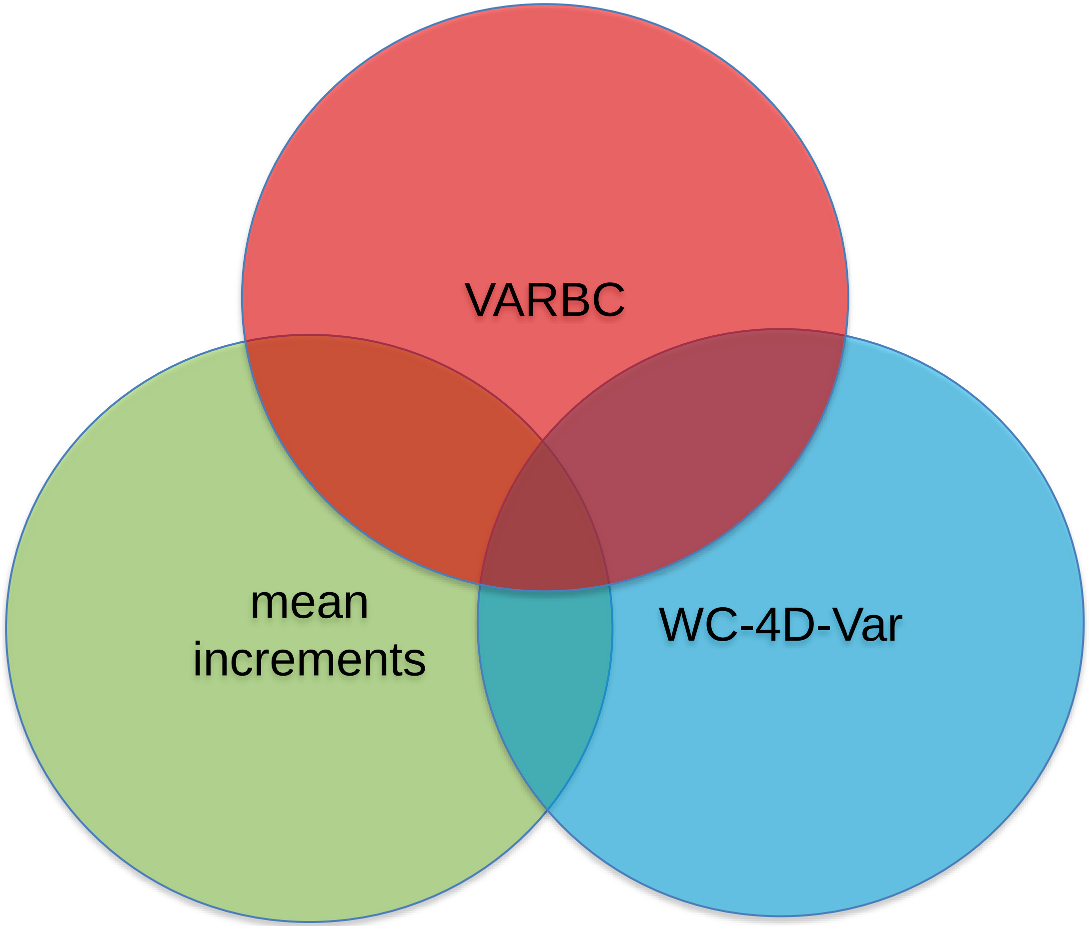
But in practice it is a challenge to avoid overlap…and mean increments still persist

systematic departure (O-B)

→ Adjust estimate of **observation bias** (VARBC)

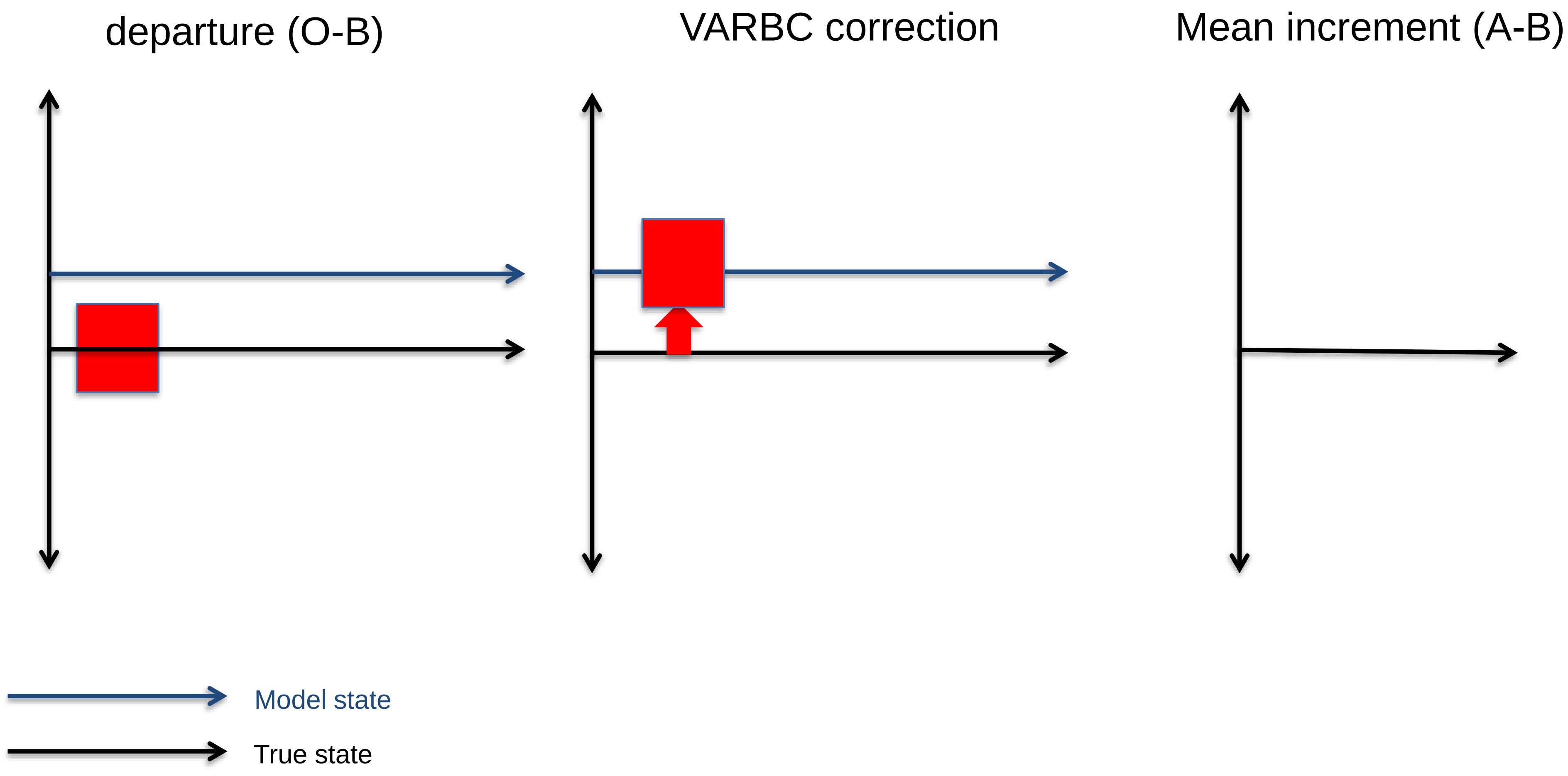
→ Correct the atmospheric state (locally / remotely) with **mean increments**

→ Adjust estimate of **model bias** (WC-4D-Var)



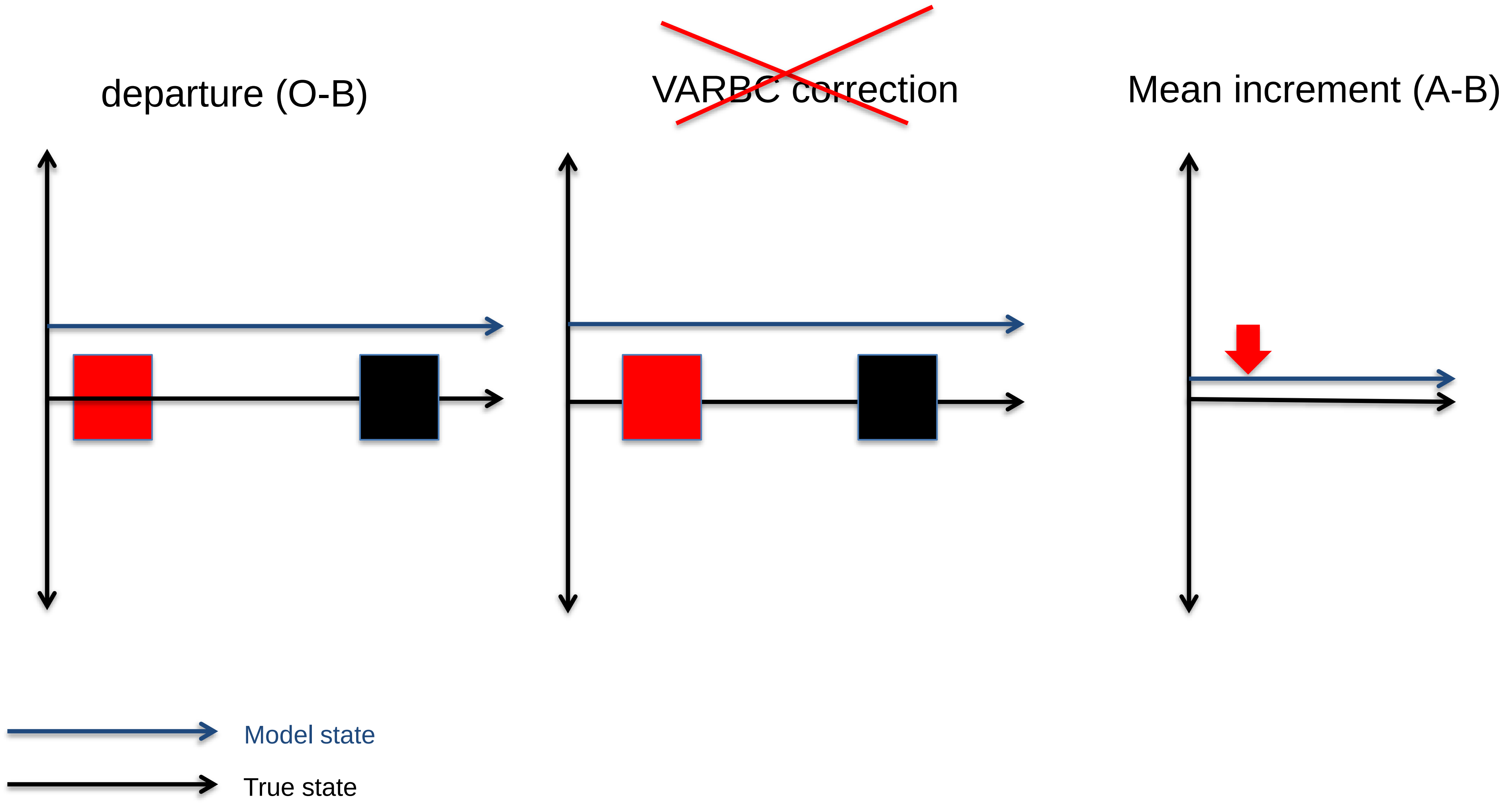
No anchoring observations (with a model bias)

$$J(x) = (x - x_b)^T \mathbf{B}^{-1}(x - x_b) + (y - \mathrm{H}[x])^T \mathbf{R}^{-1}(y - \mathrm{H}[x]) + (\beta - \beta_b)^T \mathbf{B}_\beta^{-1}(\beta - \beta_b) + (\eta - \eta_b)^T \mathbf{Q}^{-1}(\eta - \eta_b)$$



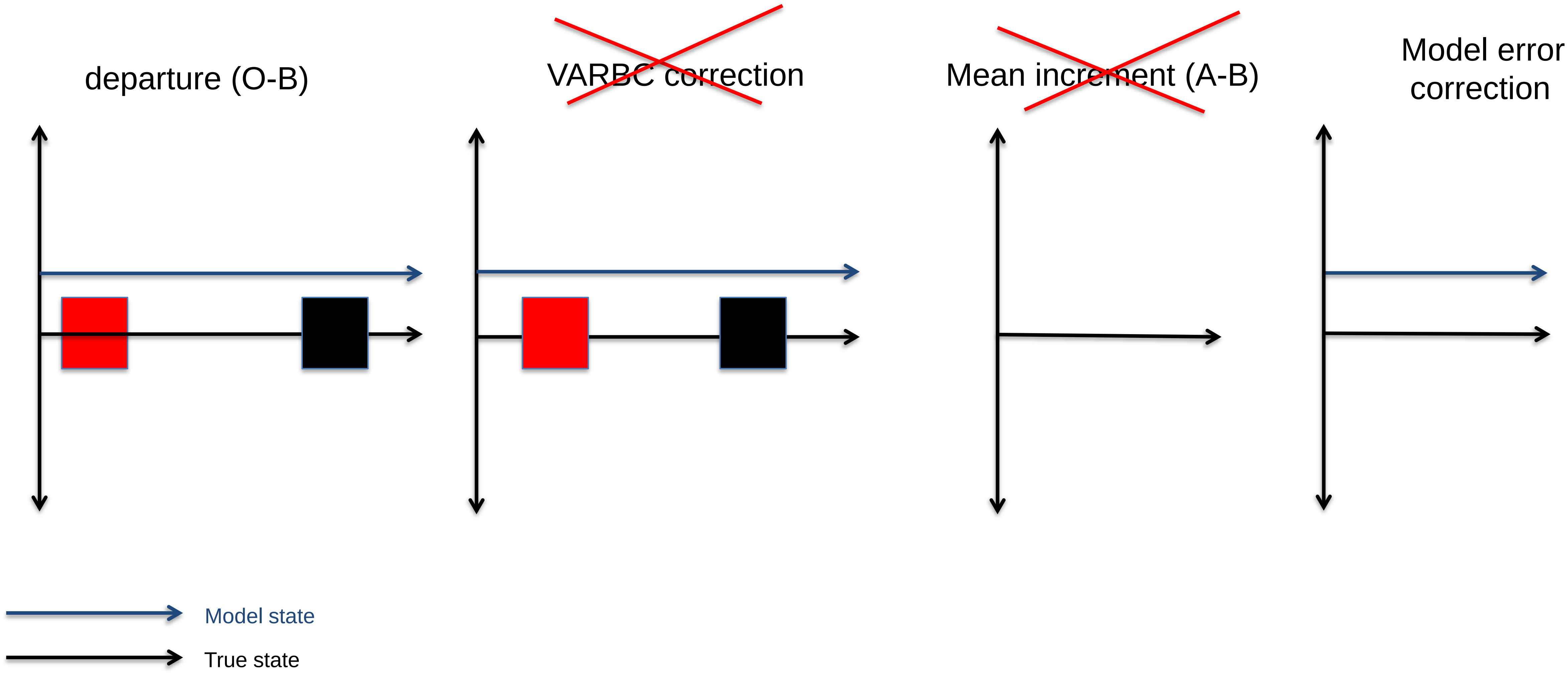
With anchoring observations (good VARBC correction)

$$J(x) = (x - x_b)^T \mathbf{B}^{-1}(x - x_b) + (y - \underline{H[x]})^T \mathbf{R}^{-1}(y - \underline{H[x]}) + \underline{(\beta - \beta_b)^T \mathbf{B}_\beta^{-1}(\beta - \beta_b)} + \underline{(\eta - \eta_b)^T \mathbf{Q}^{-1}(\eta - \eta_b)}$$

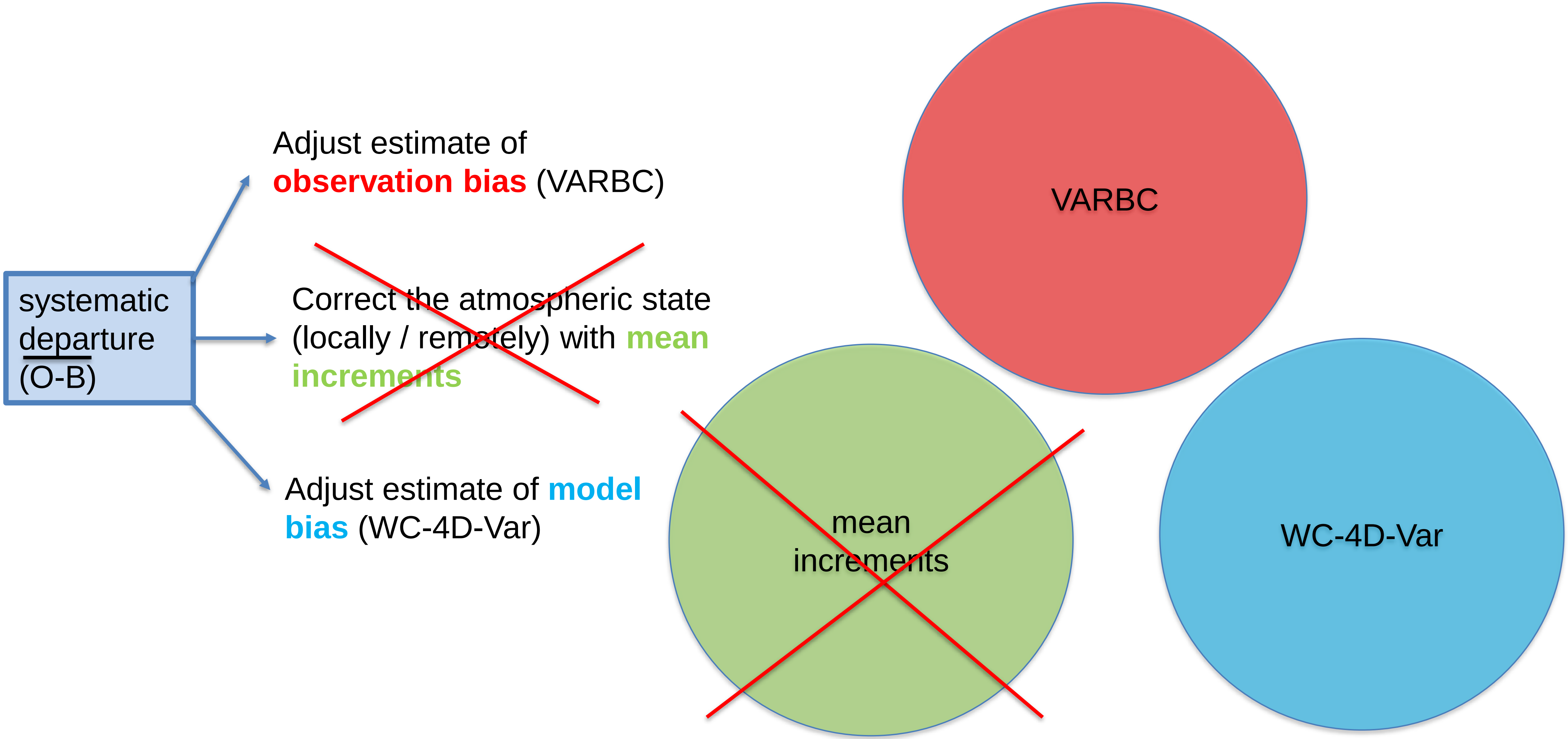


With anchoring observations… and WC-4D-Var

$$J(x) = (x - x_b)^T \mathbf{B}^{-1}(x - x_b) + (y - \mathrm{H}[x])^T \mathbf{R}^{-1}(y - \mathrm{H}[x]) + (\beta - \beta_b)^T \mathbf{B}_\beta^{-1}(\beta - \beta_b) + (\eta - \eta_b)^T \mathbf{Q}^{-1}(\eta - \eta_b)$$



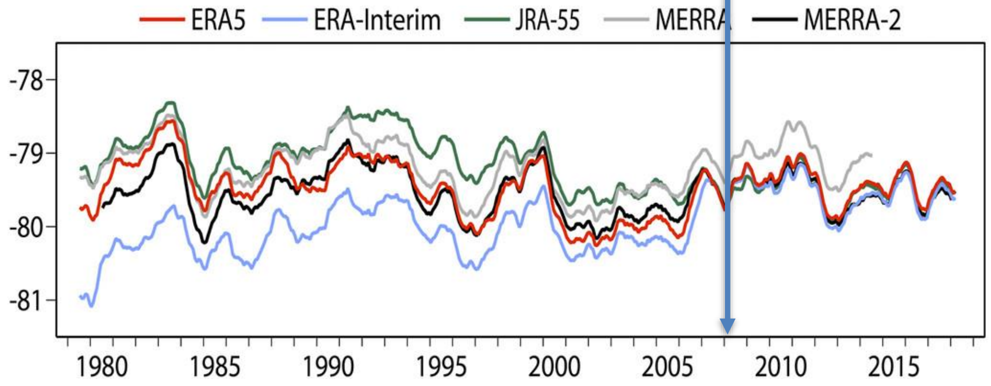
Anchor observations are key to the operation of VARBC and WC-4D-Var



Anchor observations are critical to reanalysis!

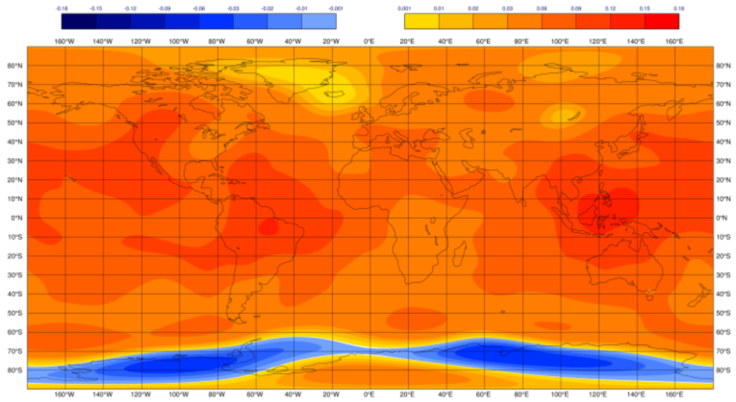
S. Healy

VARBC Bias anchoring with GPS-RO



Anchor observations produce better estimates of satellite bias corrections and better estimates of the model error component

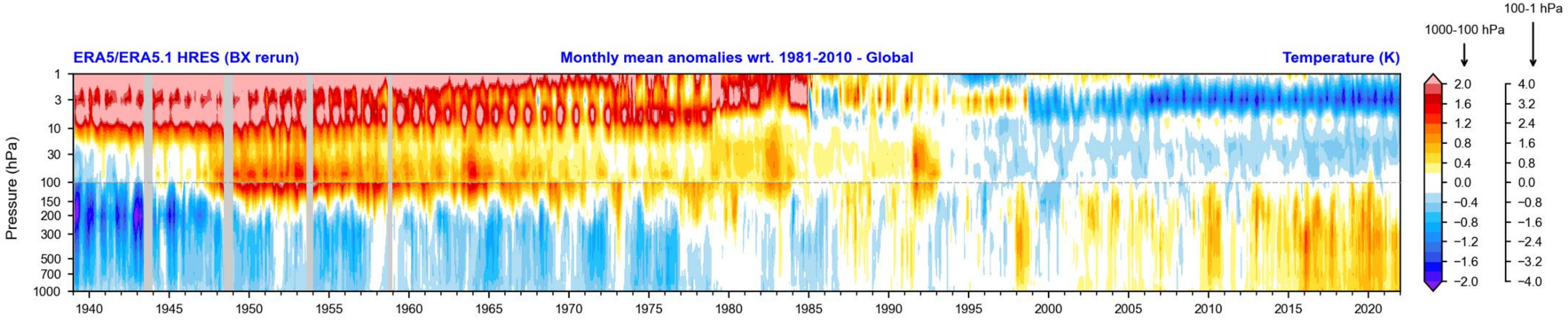
Correcting model bias via weak-constraint 4D-Var



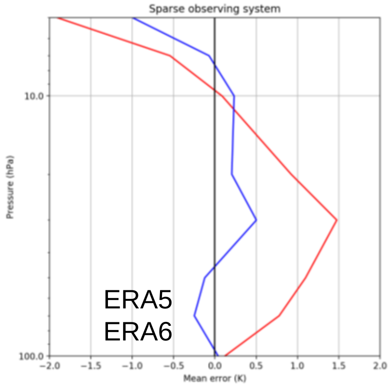
P. Laloyaux

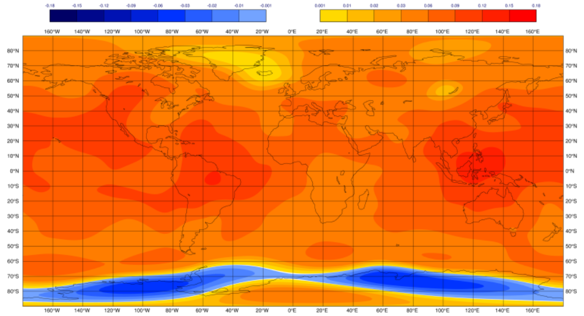
…and can be used to constrain historical periods

Reanalysis during periods poorly constrained by observations (e.g. pre-satellite) *inherit* systematic model error, causing shocks when major observing systems come and go which can compromise climate trends



Mean fit to radiosonde data in pre-satellite era





Which can be applied back during <u>poorly</u> observed periods to improve the reanalysis

Running weak constraint 4D-Var during current <u>well observed</u> periods provides an accurate estimate of systematic model error

Outline

How do observations constrain an analysis system ?
- a quick look at the 4D-Var algorithm
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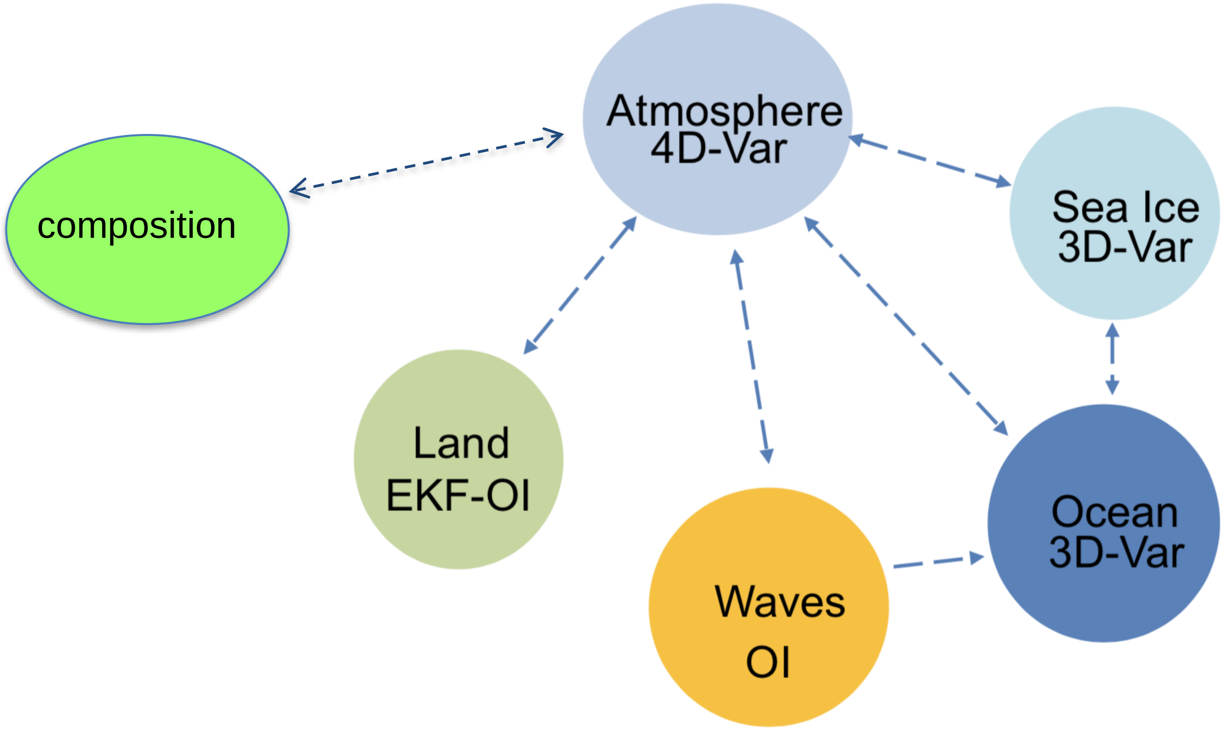
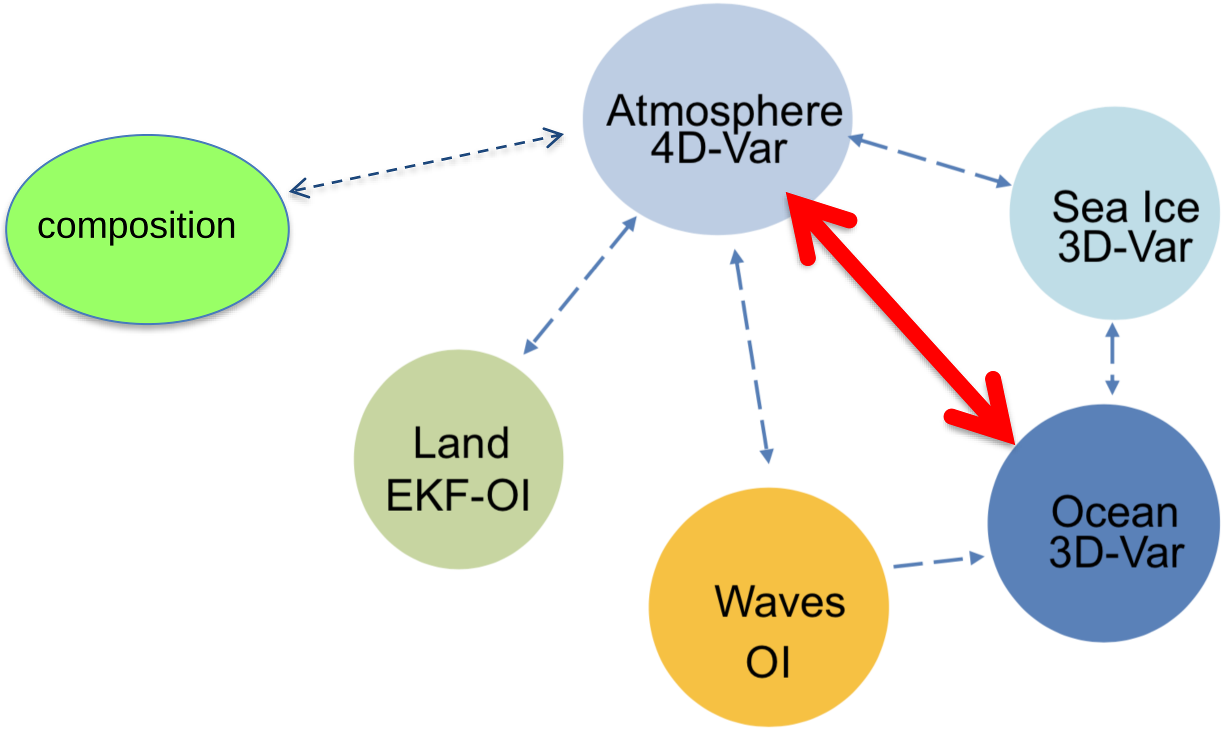
- Enhance wind tracing from chemical species

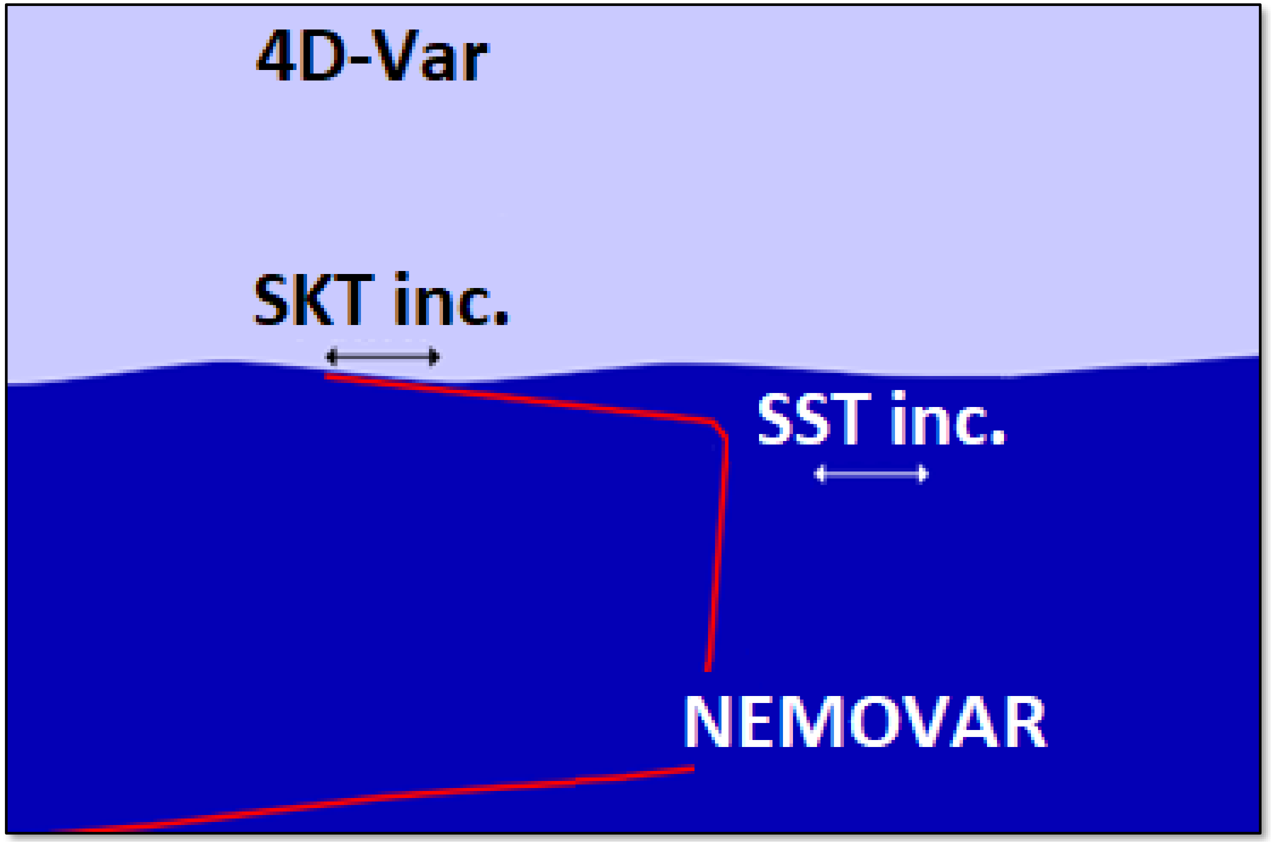
How coupled DA can help anchor reanalyses across different Earth system components



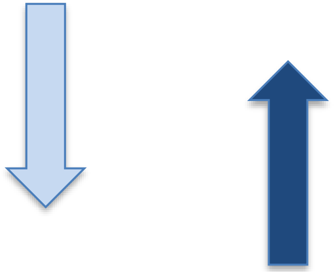
How coupled DA can help anchor reanalyses across different Earth system components



How coupled DA can help anchor the mean state across Earth system components



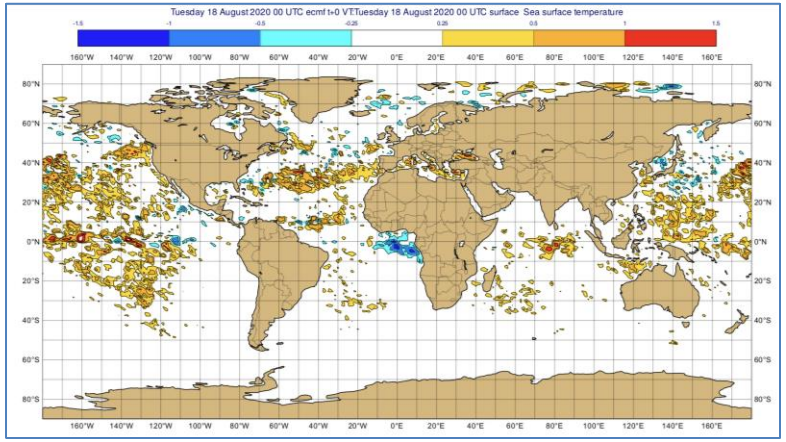
A bad atmosphere propagates in the ocean and is confronted with ocean OBS



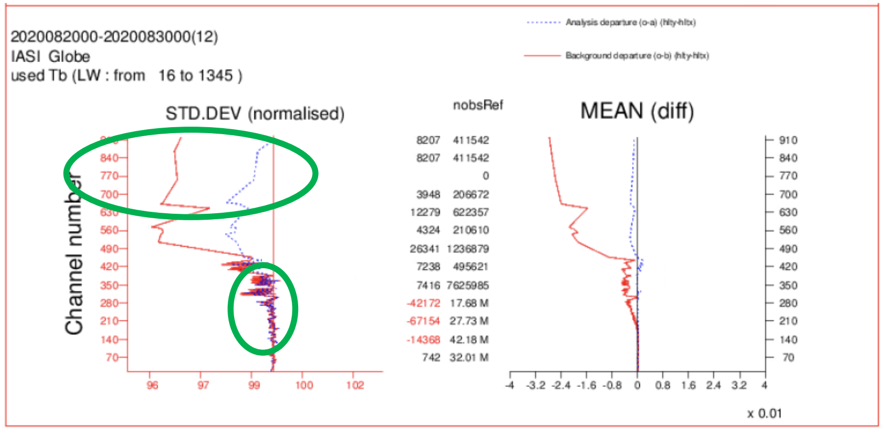
A bad ocean propagates int the atmosphere and is confronted with atmospheric OBS

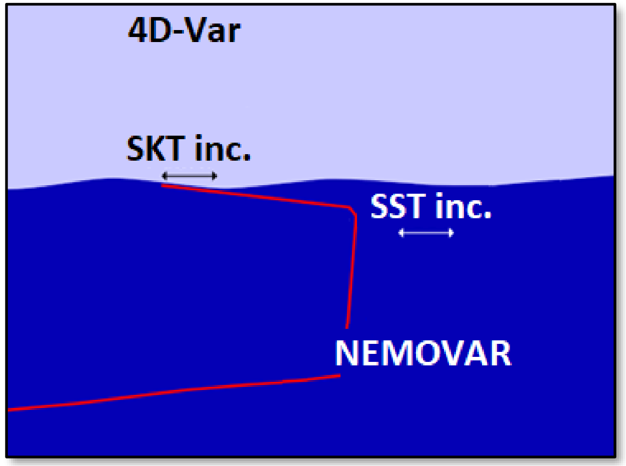
Coupled radiance based SST analysis (RADSST)

NEMOVAR SST changes forced by IASI

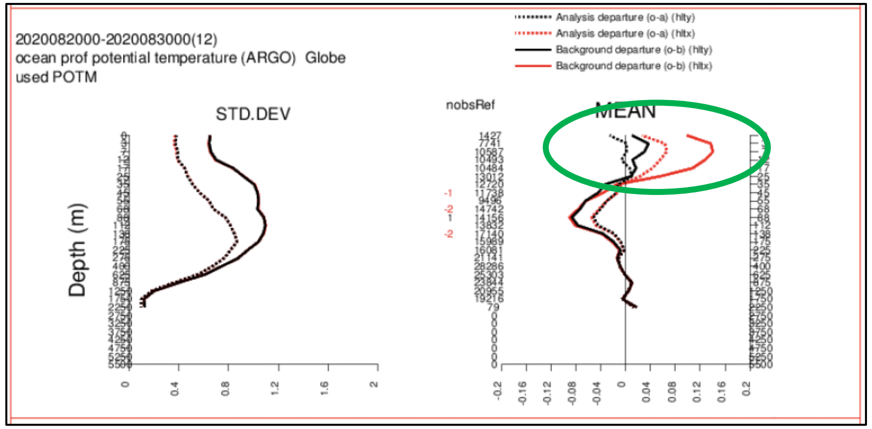


Changes have ***memory*** in the ocean and feed back to improve IASI use in the atmosphere

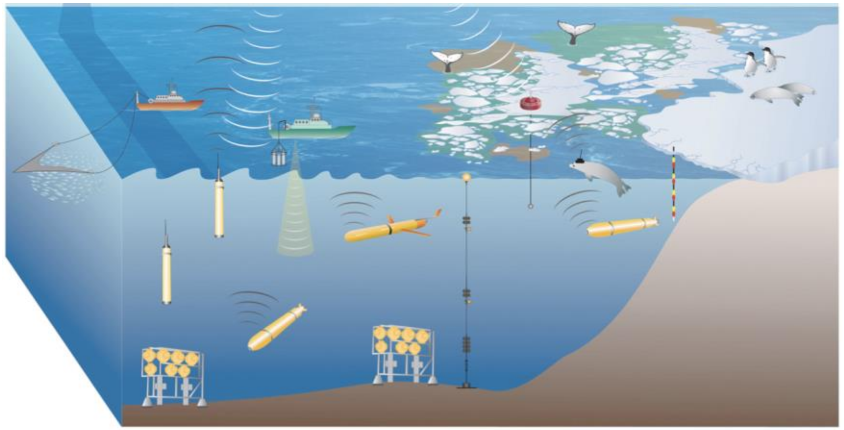




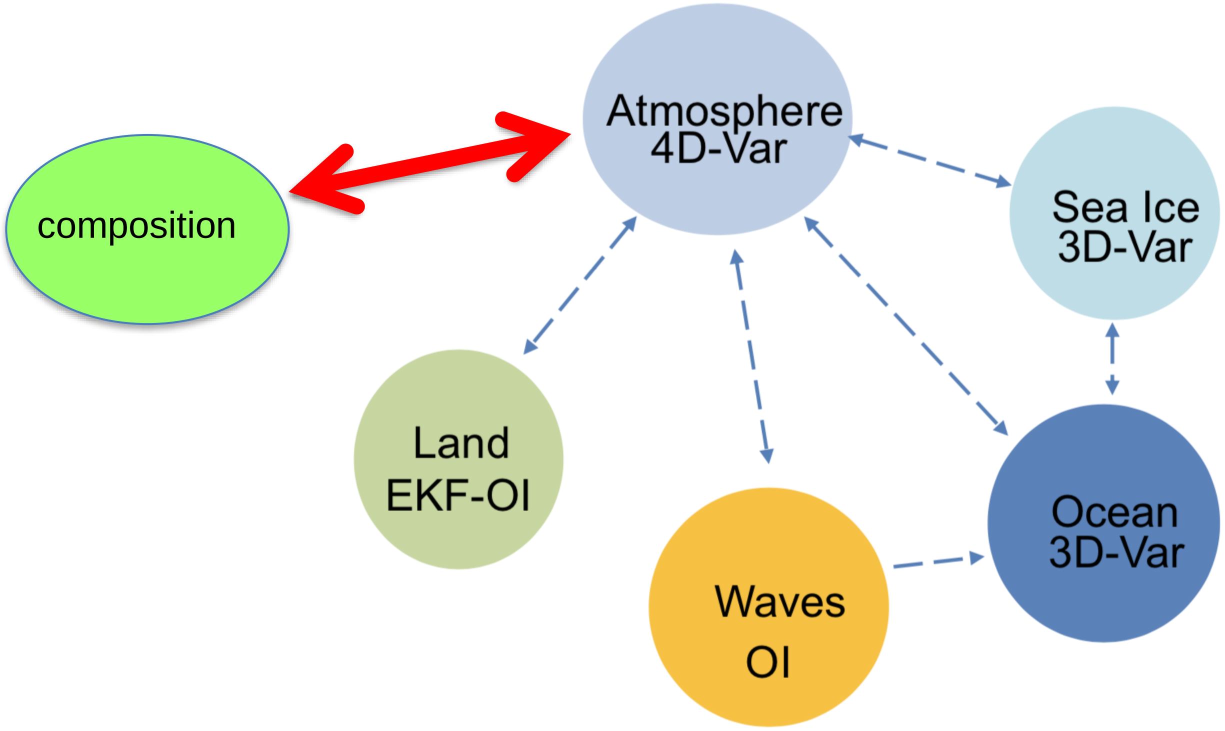
ARGO floats



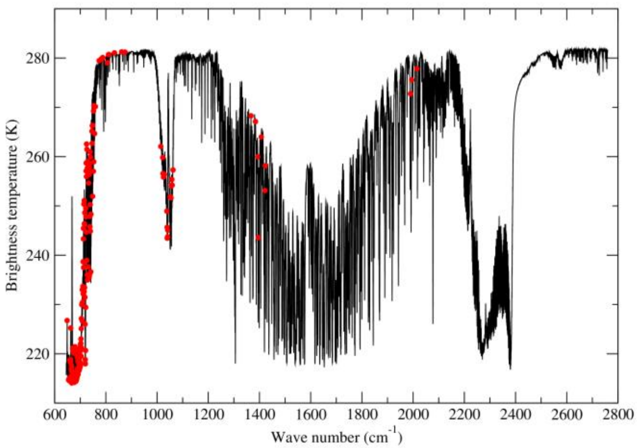
Assimilating IASI in RADSST produces a better fit to surface **and** sub-surface **in situ ocean observations** which simultaneously **anchor the IASI assimilation**

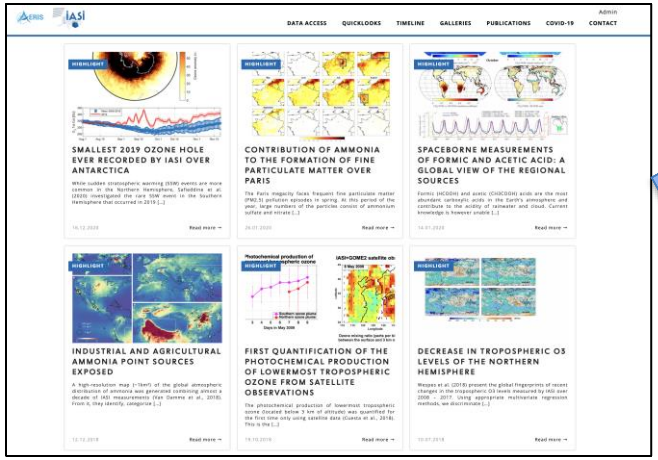


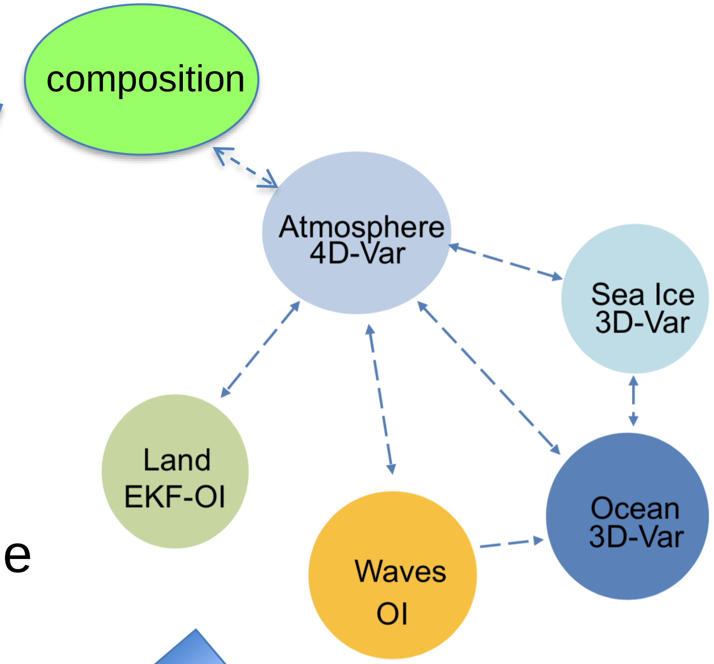
How coupled DA can help anchor reanalyses across different Earth system components



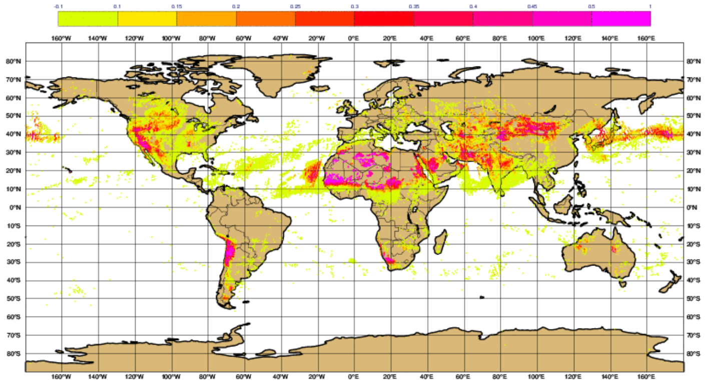
Chemical species providing wind information



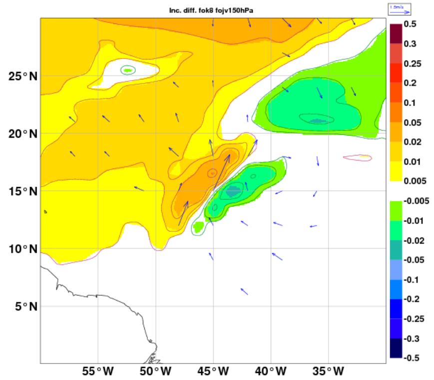




Advection wind tracing from dust aerosol ?

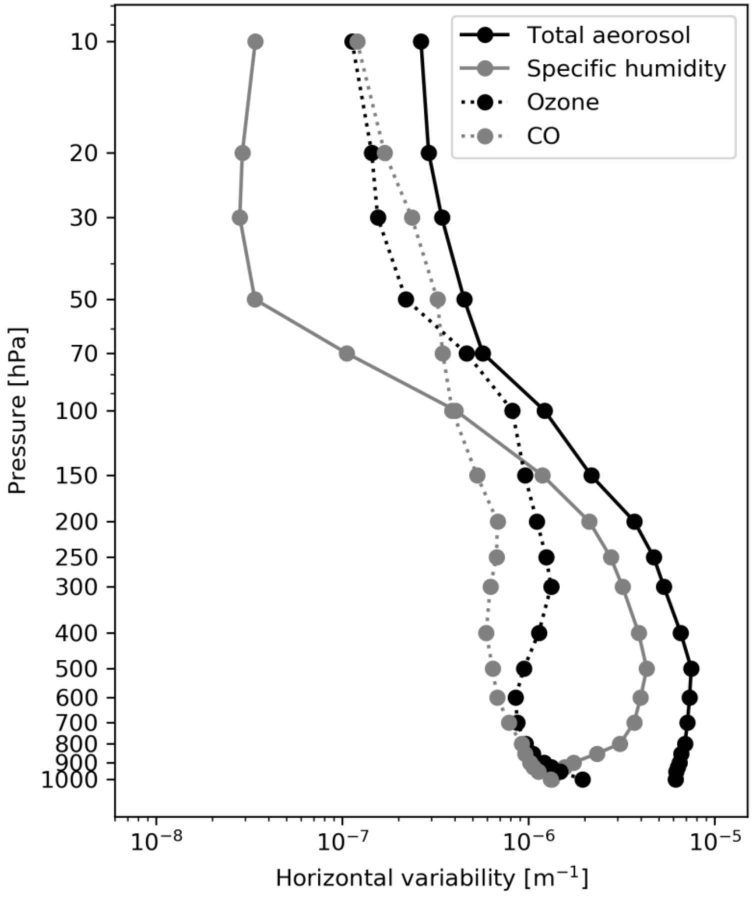


Advection wind tracing from ozone in the stratosphere. *(C Lupu)*



Chemical species providing wind information

Analysis of <u>relative tracer gradient</u> for other constituents suggests aerosol also has a large potential to provide wind information for the troposphere and CO / ozone in the stratosphere



4D-Var has the option to modify composition locally <u>or</u> advect the tracer species from one location to another with wind increments to better fit the observations

The effective tracing potential depends on the relative tracer spatial gradient:

$$|\delta \mathbf{v}| \propto |\nabla c / c|$$

Ziga Zaplotnik

Summary

1) Reanalysis is highly constrained by observations…but mainly via **indirect mechanisms** exploiting the skill of the DA / model.

2) The DA / model systems are able to **spread observation information** accurately to areas, times and parameters that cannot be directly observed, thus adding huge value (over observation only datasets)

3) Great care must be taken in interpreting **fine scale information** (vertical and horizontal), but intelligent DA systems can provide a good representation of small scale features such as **Tropical cyclones** from low-resolution satellite observations

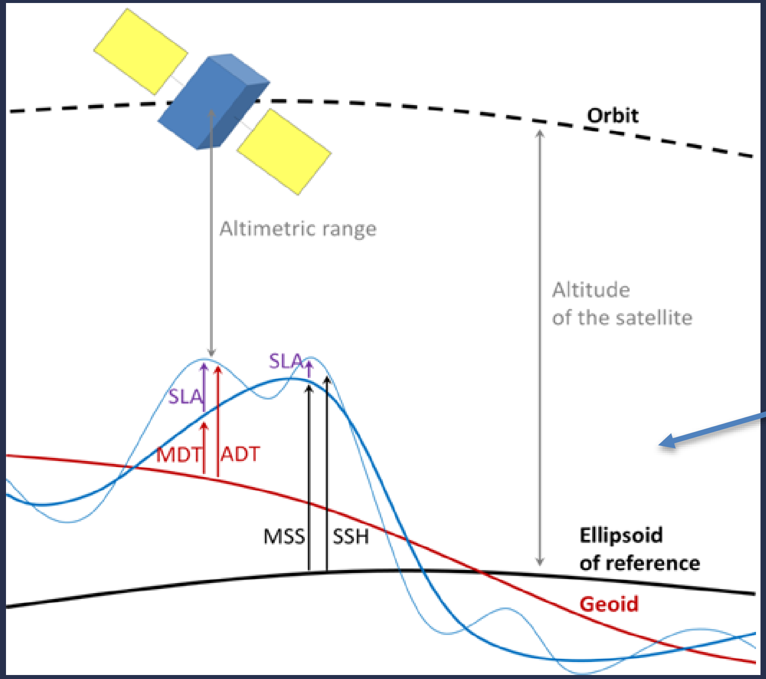
4) Bias correction systems like VARBC and WC-4D-Var can accurately constrain the mean state in reanalysis (even historically), but **only if anchor observations are available**

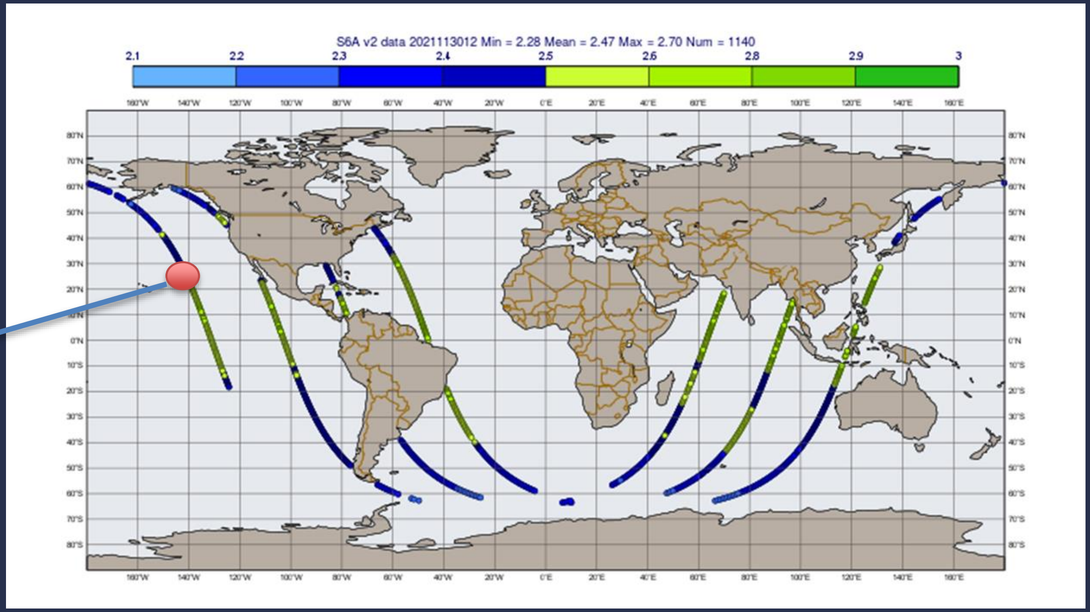
5) **Coupling** across different Earth systems can greatly increase the constraint provided by observations for reanalysis, different components being more consistent, but also helping anchor mean states

Coupled assimilation of altimeter range measurement (future collaboration RSP)

- Better partition of sea level height and atmospheric humidity effects
- Altimeters will provide all sky humidity information to NWP
- Altimeters will no longer need to fly microwave radiometers

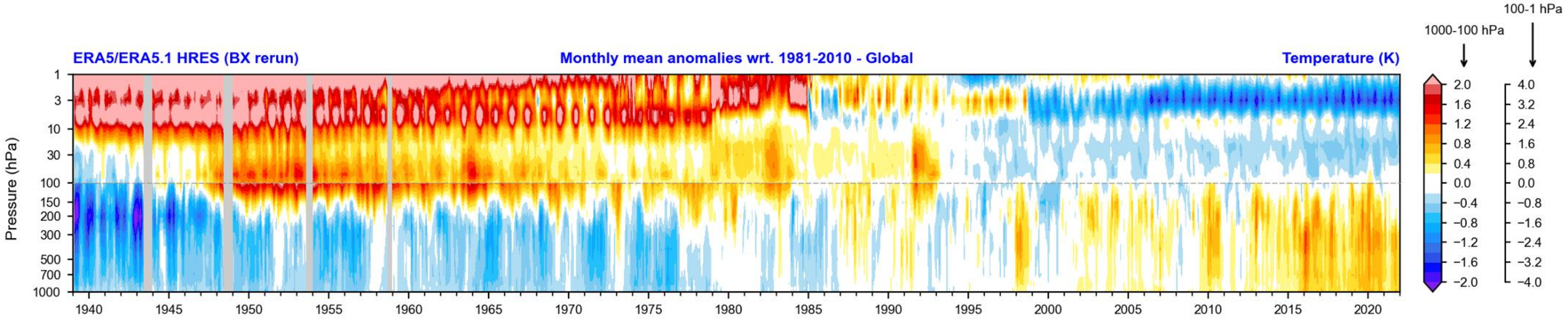
SSH: Sea Surface Height
MSS: Mean Sea Surface
SLA: Sea Level Anomaly (Assimilated in NEMOVAR)
ADT: NEMO Absolute Dynamic Topography
MDT: NEMO Mean Dynamic Topography





S. Healy
N. Semanne

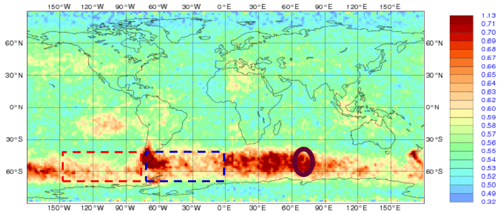
Which observations can constrain the mean state ?

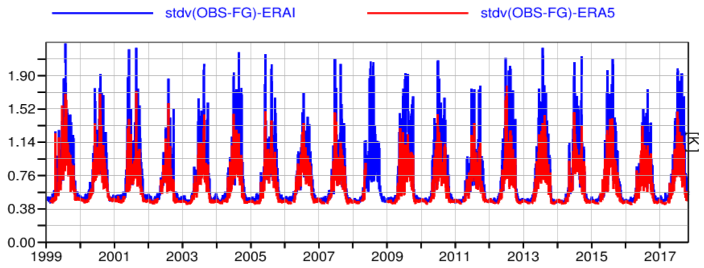


Hierarchy

- Reference data (truly unbiased…very rare…perhaps we need more…should they be assimilated?)
- Anchor data (data which we do not bias correct, e.g. RO))
- Data bias corrected against independent reference (R/S)
- Data VARBC bias corrected against the well anchored analysis in the DA (satellite radiances over land)
- Data VARBC bias corrected against a poorly anchored analysis in the DA (satellite radiances over ocean)

Using observations to improve the forecast model > improves reanalyses





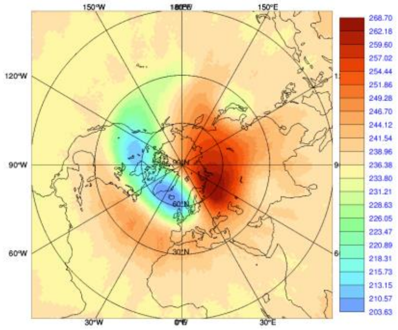
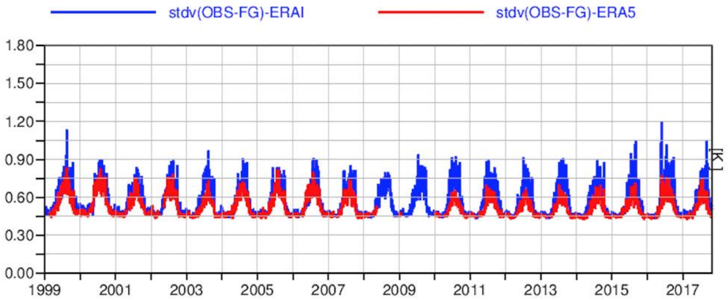
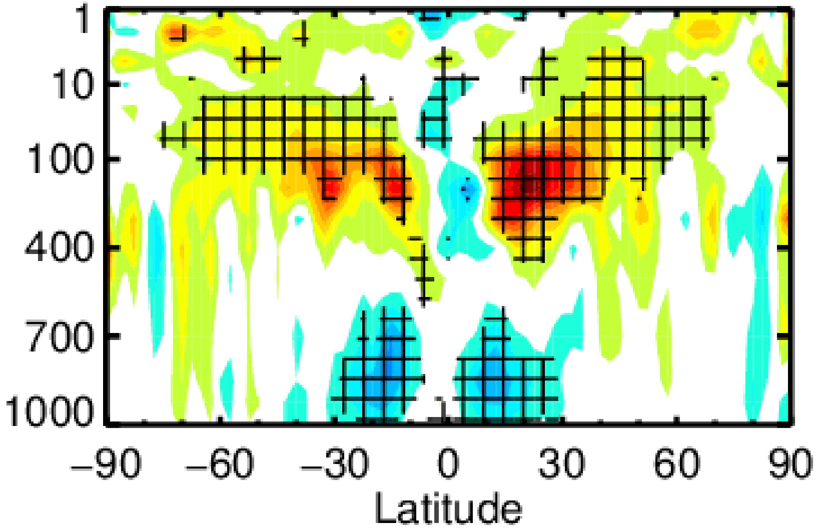


Figure 10: Observed brightness temperatures (in K) from all available AMSUA Valid from 06/01/2013 09UTC to 07/01/2013 UTC



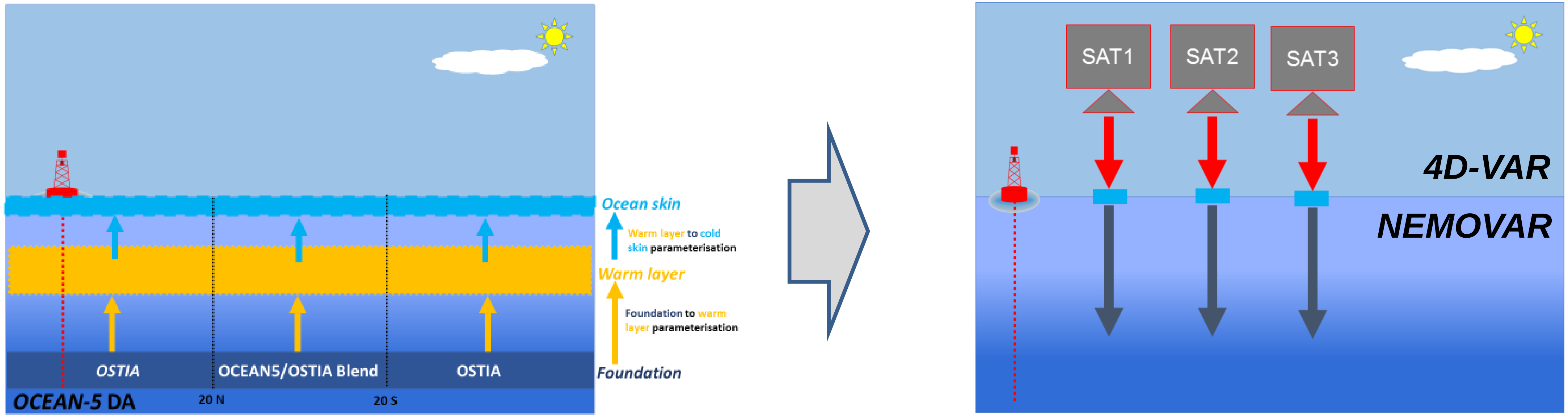


Coupled ocean SST assimilation

Tony McNally, Phil Browne, David Fairburn, Hao Zou, Seb Massart, Marcin Chrust, + …

The ocean surface can no longer be treated as a lower boundary condition of the atmosphere or an upper boundary condition of our ocean, it is at the **centre** of our coupled DA / FC system and must be treated as such.

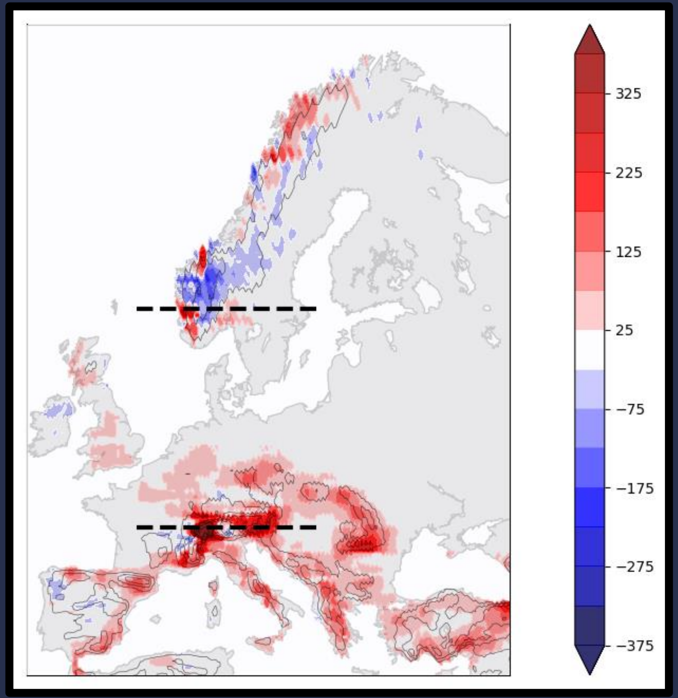
SST constrained by OSTIA **SST constrained by 4D-Var SKT**



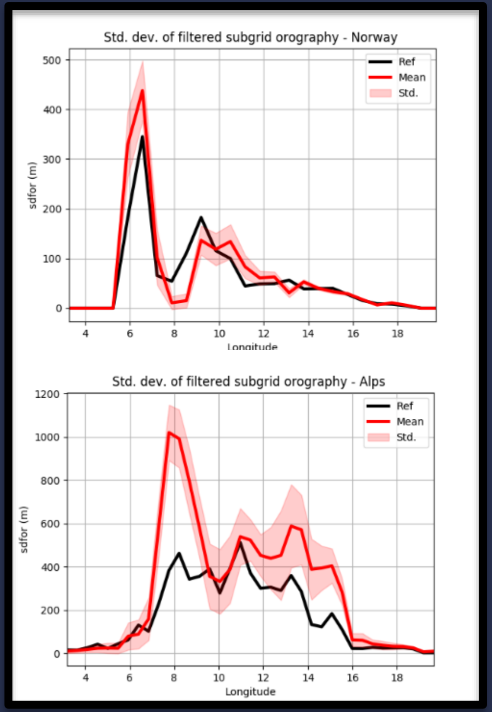
The new system will avoid unnecessary external / internal mapping and conversion of satellite information …and improve operational scheduling

Model parameter estimation with 4D-Var to improve forecasts

Application of parameter estimation to improving the standard deviation of model sub-grid orography



Mean analysis increments applied to SGO

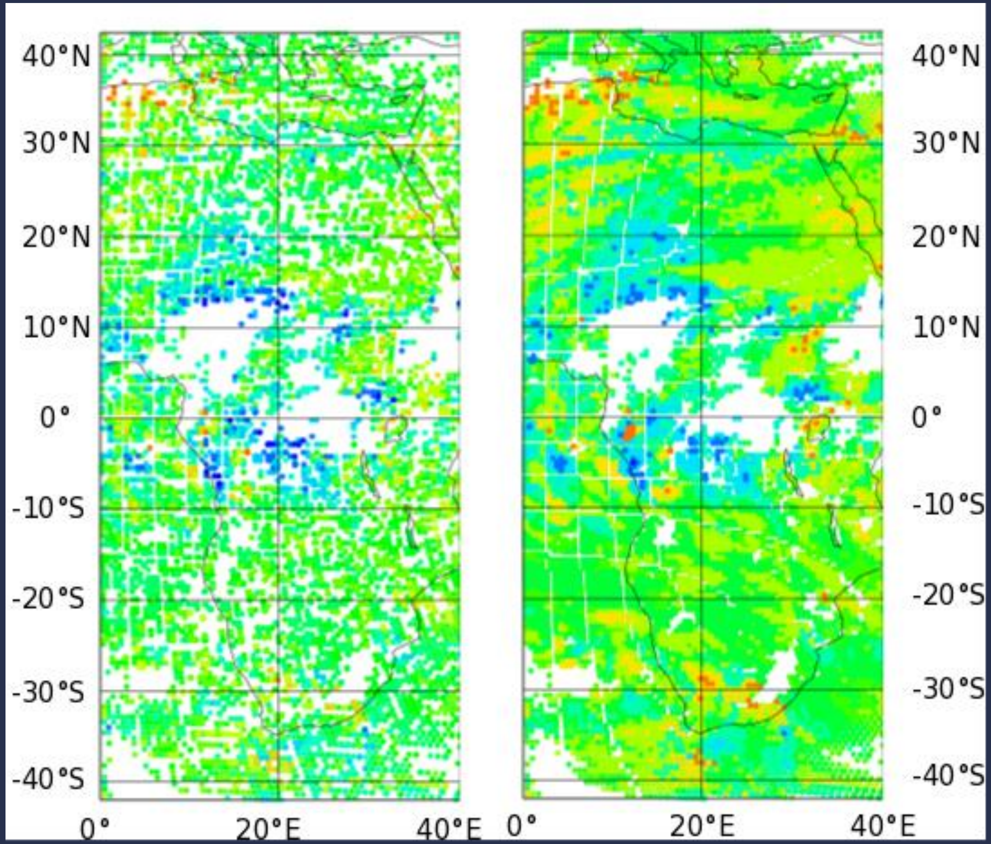


Original (black) and optimized (red) model parameter values for Norway (top) and Alps (lower)

- Surface pressure observations are very sensitive to changes in the assumed model sub-grid orography (SGO) which is <u>part of the observation operator</u>
- Adding SGO as an <u>augmentation</u> of the 4D-Var control vector (XCV formulation) allows the observations to improve this parameter of the model
- Use of the 4D-Var <u>optimized</u> SGO parameter in medium-range forecasts improves skill

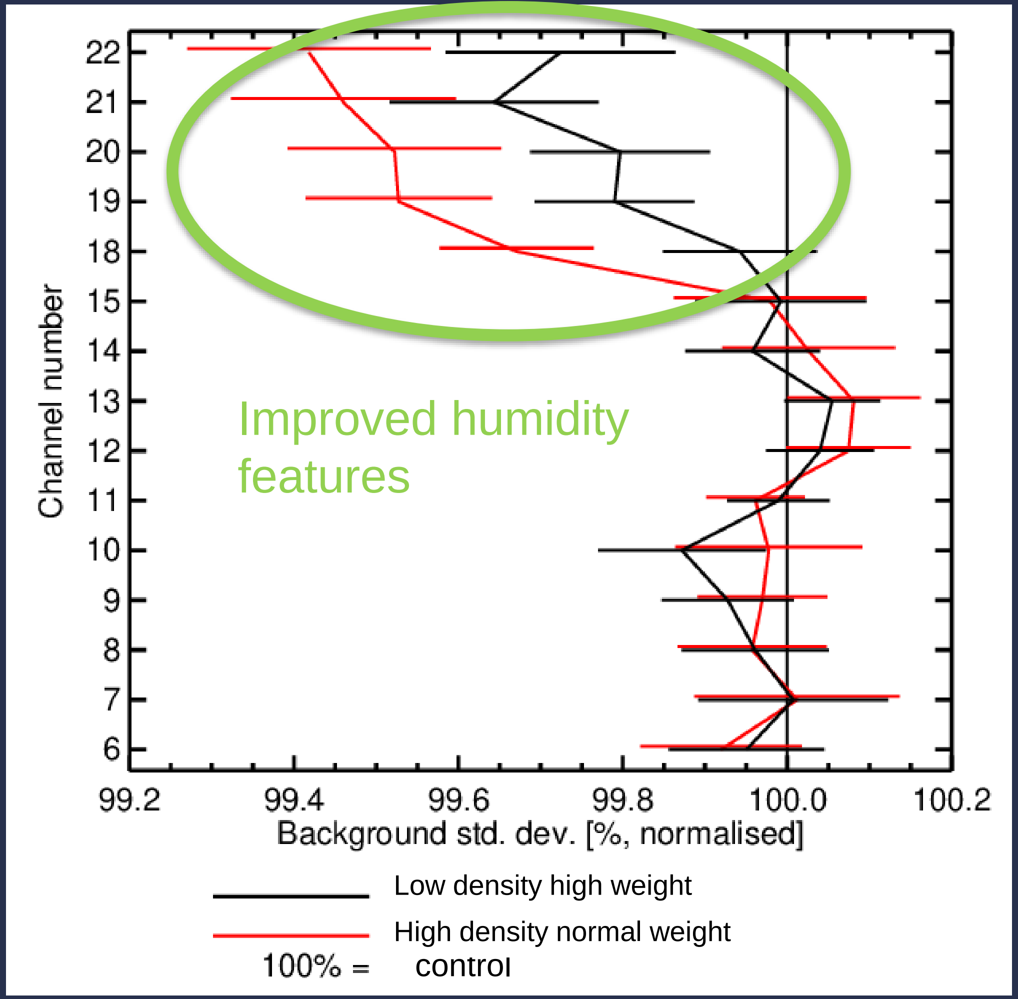
Higher spatial density - resolving horizontal gradients

Experiments increasing the **weight** of the low-density data confirm that the higher density observations are adding more skill to capturing of small-scale gradients



DestinE will investigate space / time resolution links

Reduction in 12hr forecast error from ATMS



Background errors vary throughout ERA5

Large background errors give high weight to sparse observations

Large background errors in highly observation constrained system

Background errors vary through ERA5 due to EDA reacting to observation changes