Applications of data assimilation and current challenges

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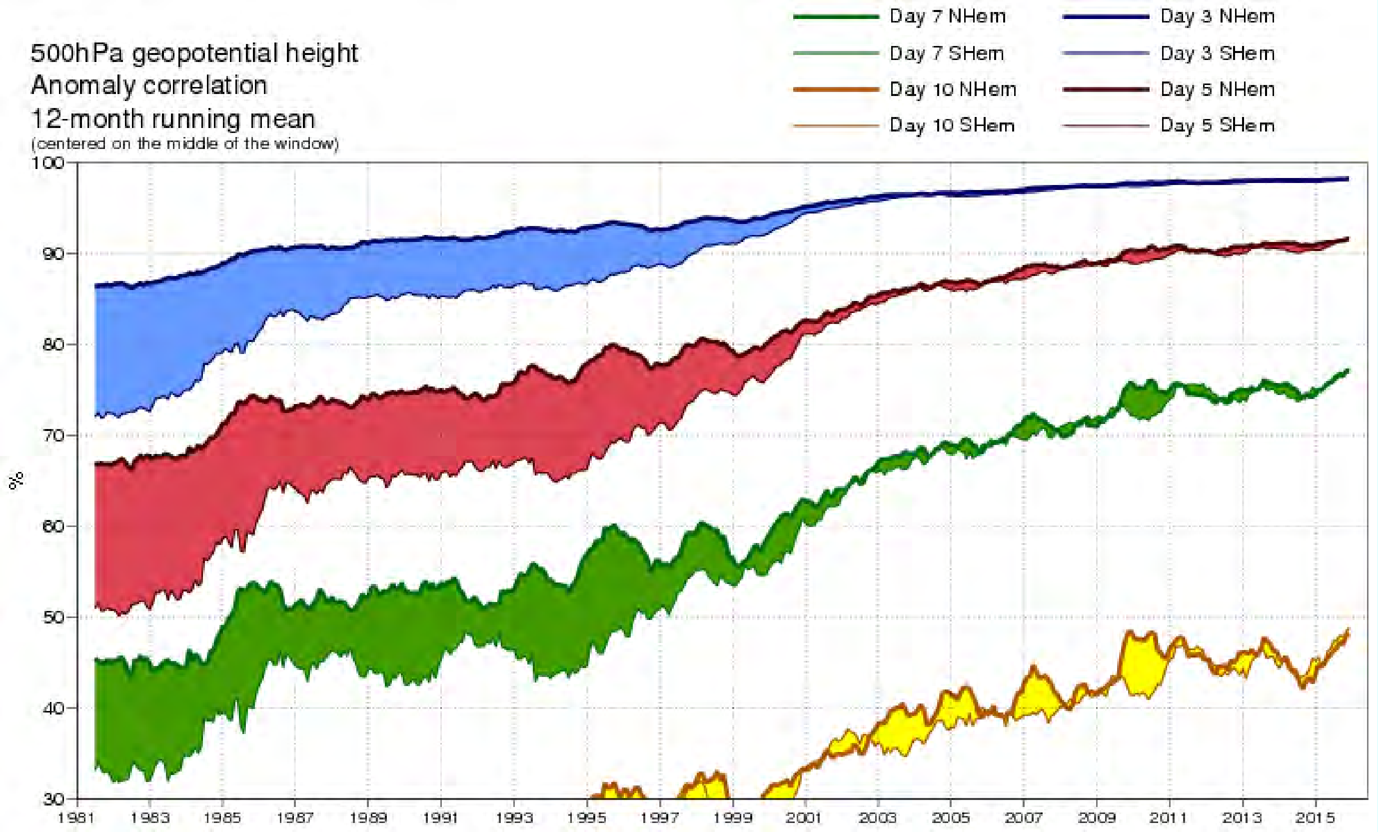
Numerical weather prediction



4D-Var introduced

Assimilation update

From www.ecmwf.int

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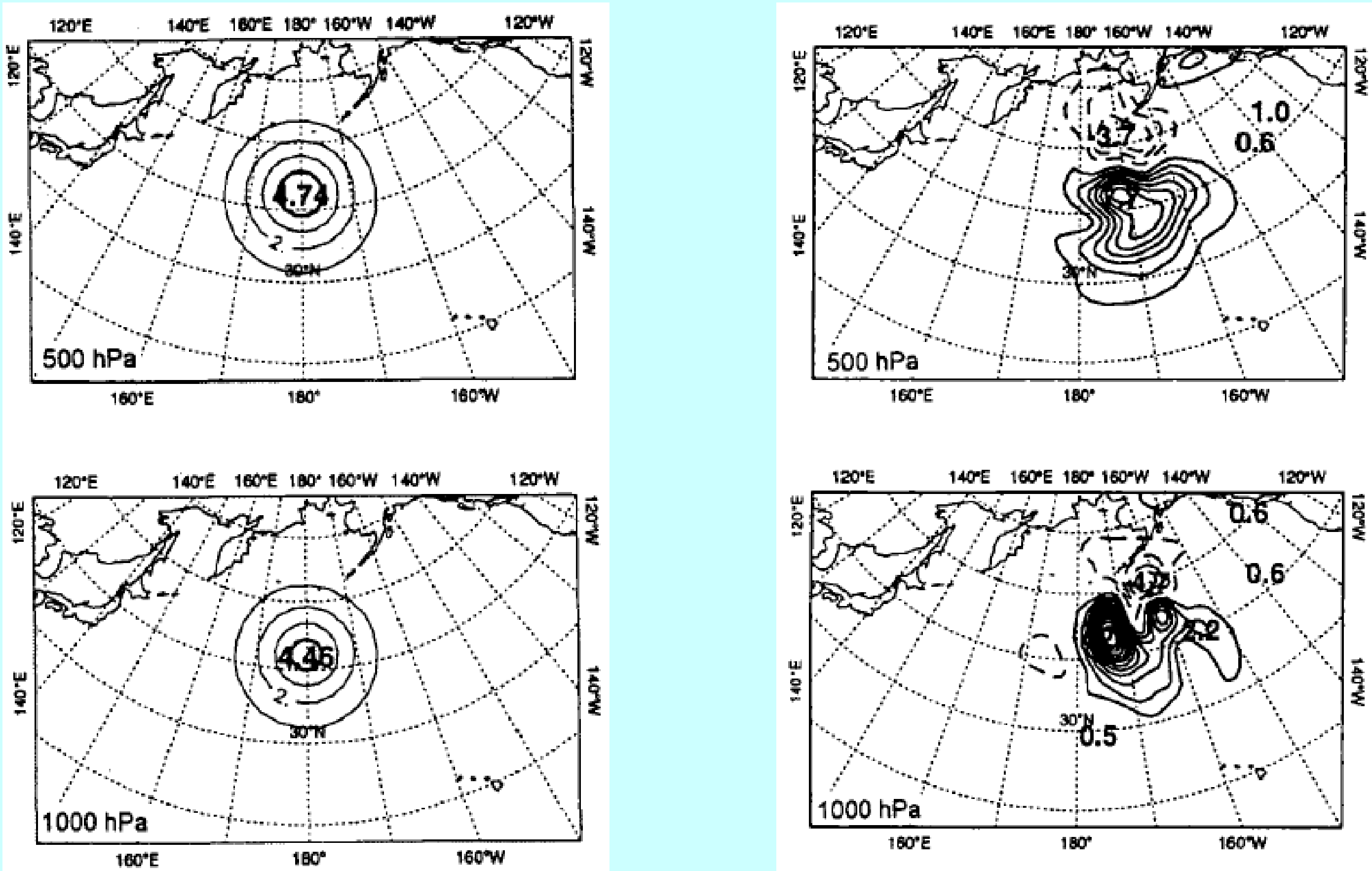
Flow-dependent covariances



3D-Var 4D-Var

Increments from single observation of height at 500 hPa.

Thepaut et al. (1996)

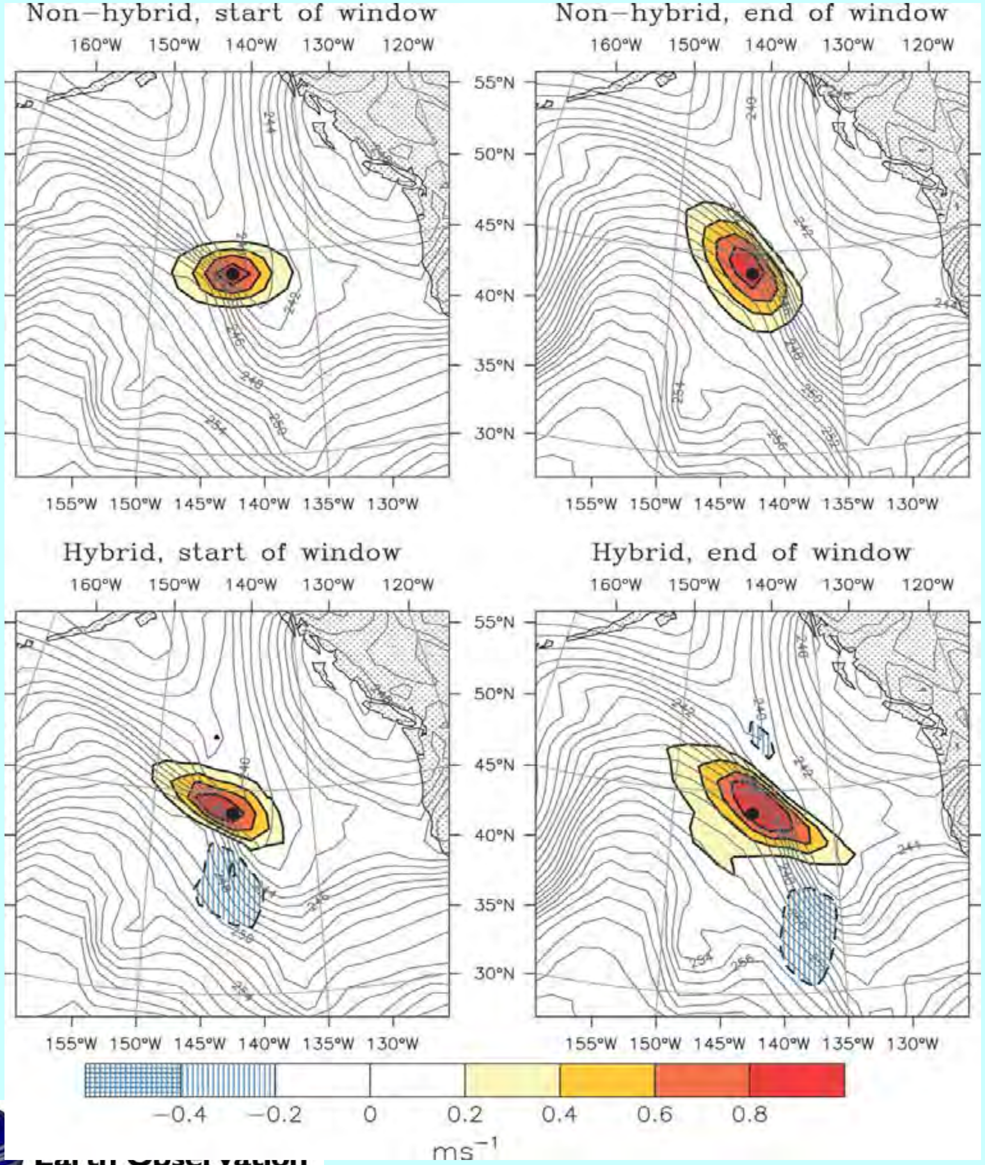
Next generation NWP assimilation

Can we get more flow dependence by combining variational and ensemble methods?

Various proposals:

- En4DVar
- 4DEnVar
- Ensembles of 4DEnVar
- …

Met office implementation

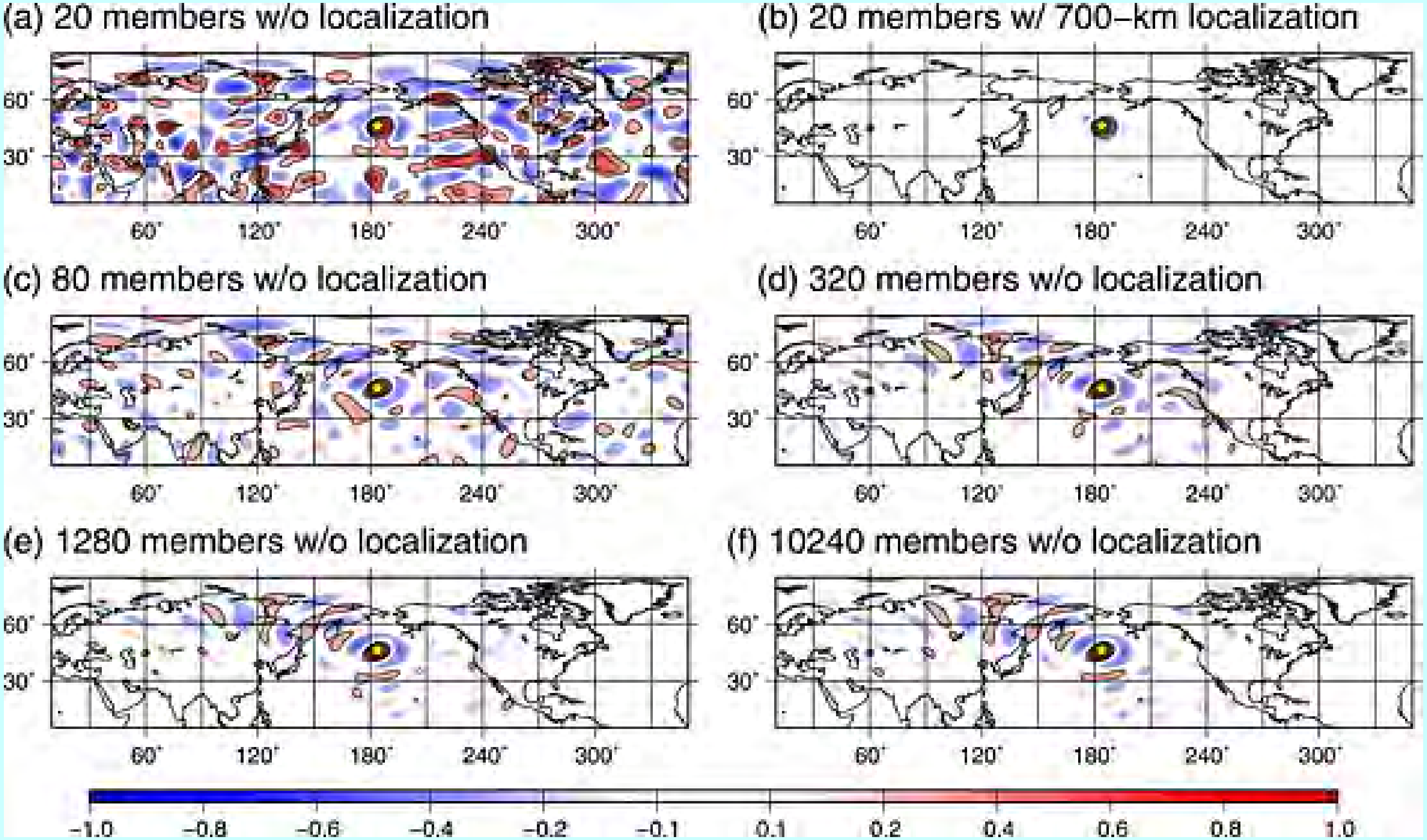


Zonal wind responses (filled thick contours, with negative contours dashed) to a single zonal wind observation.

The unfilled contours show the background temperature field.

Clayton et al. (2012)

Localisation



Experiments on 10 Petaflop ‘K’ supercomputer! *Miyoshi et al. (2014)*

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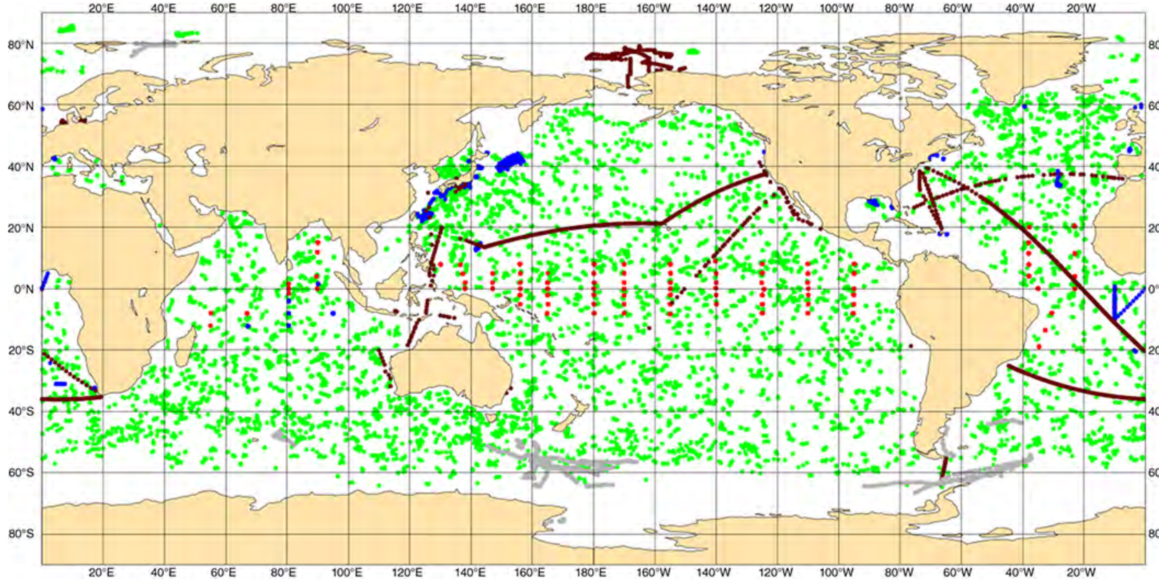
Ocean DA

A coupled data assimilation system for climate reanalysis



Quarterly Journal of the Royal Meteorological Society
Volume 142, Issue 694, pages 65-78, 24 SEP 2015 DOI: 10.1002/qj.2629
http://onlinelibrary.wiley.com/doi/10.1002/qj.2629/full#qj2629-fig-0013

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Figure from *Lalayoux et al (2016)*

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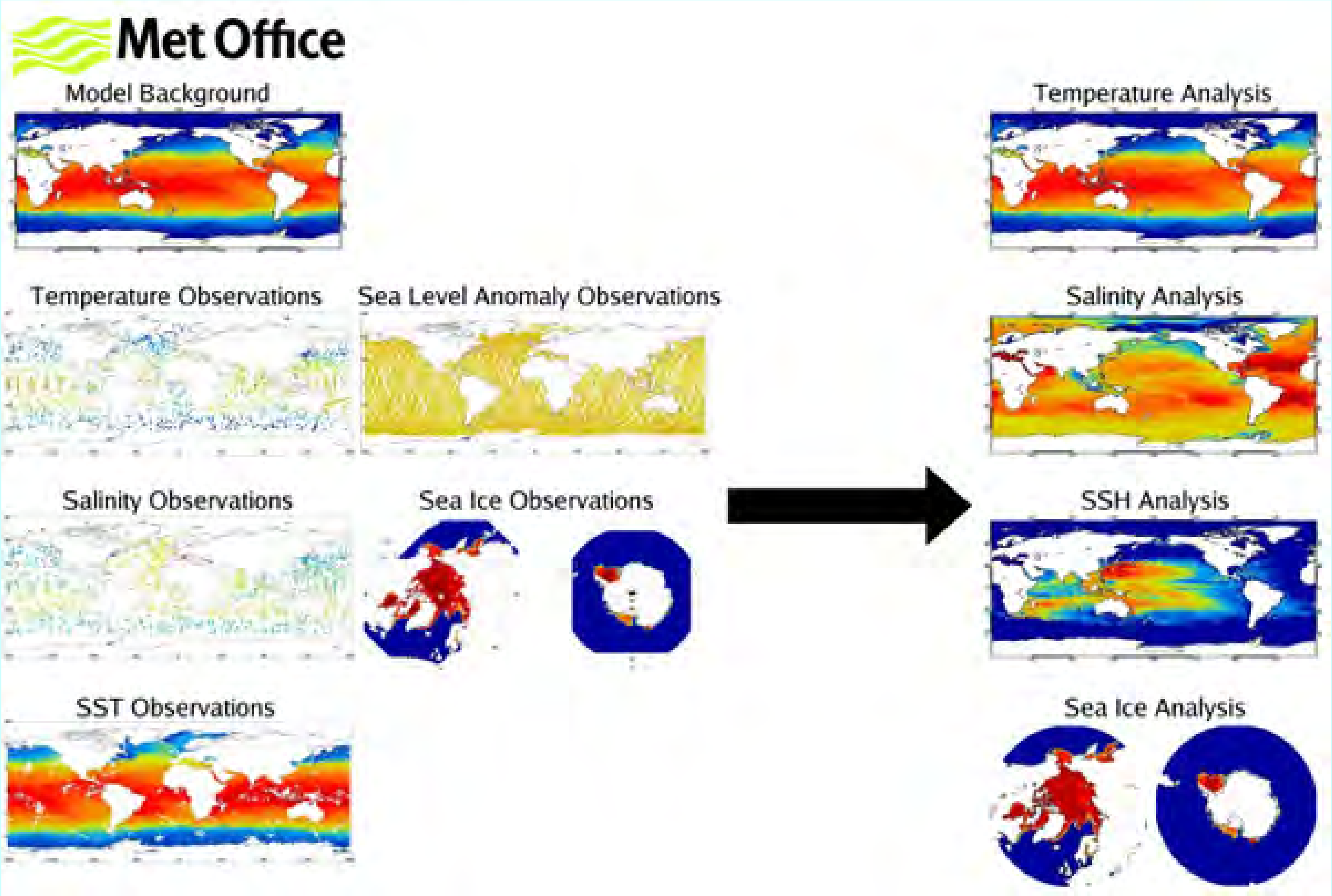
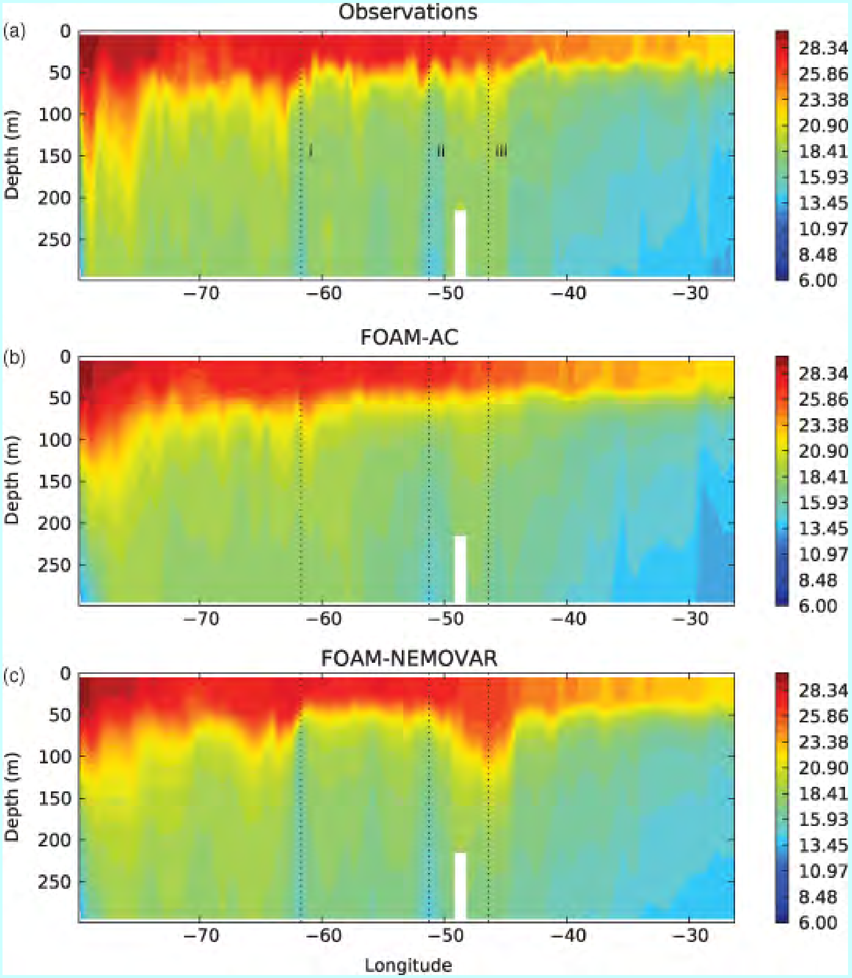


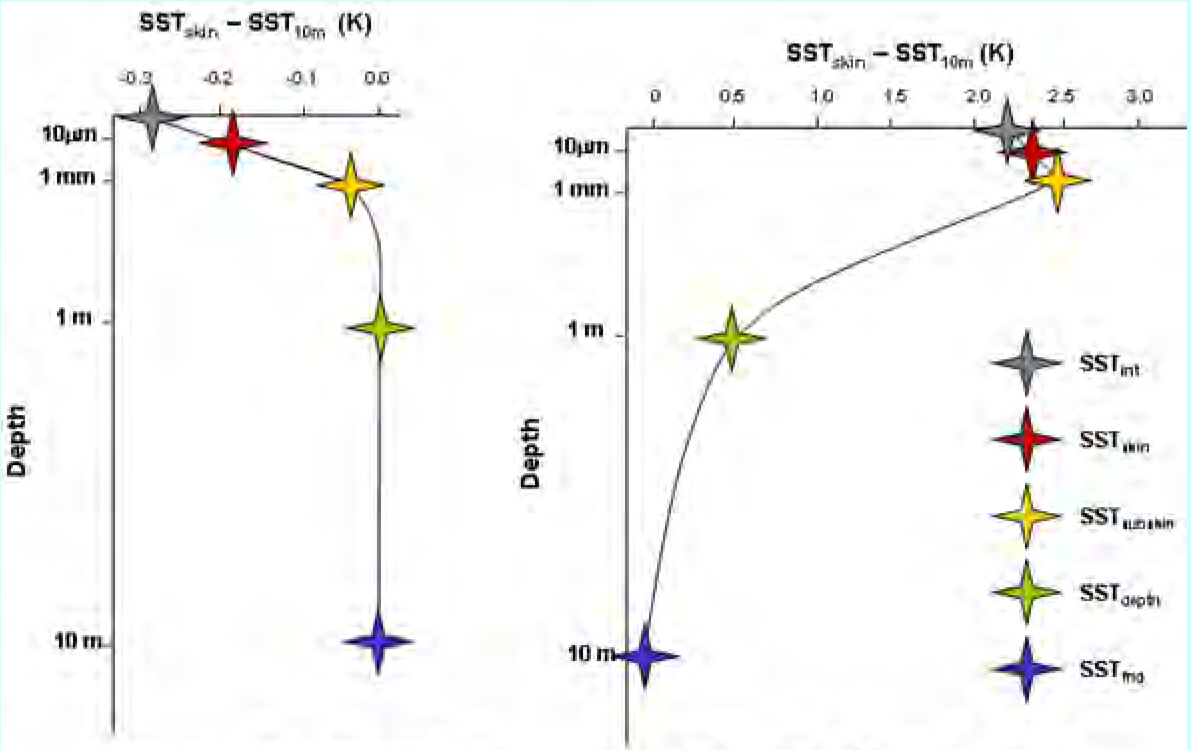
Figure from www.metoffice.gov.uk

Implementing a variational data assimilation system in an operational 1/4 degree global ocean model



Waters et al (2015)

Sea surface temperature



(a) Night time situation, light wind

(b) Day time time situation, strong solar radiation and light winds

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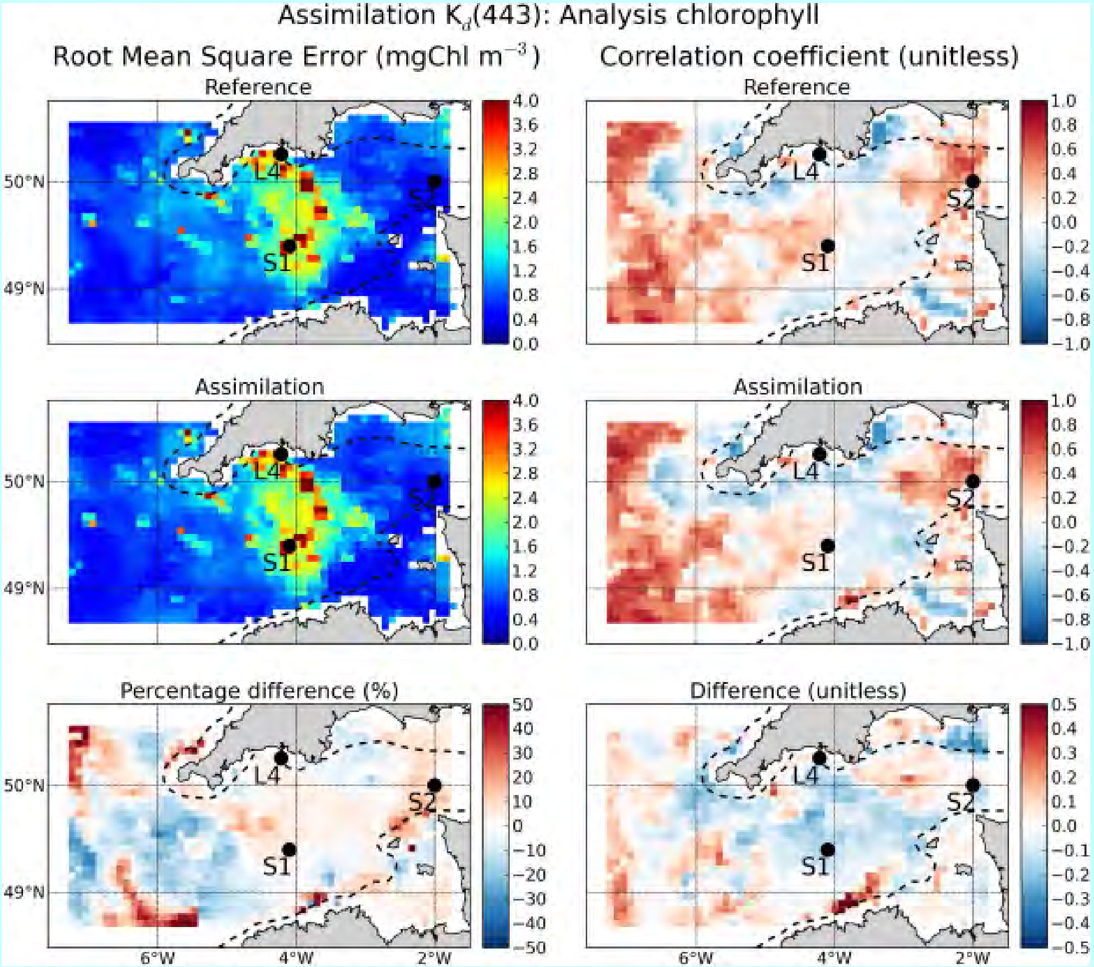
Ocean colour - Chlorophyll



Ciavatta et al (2014)

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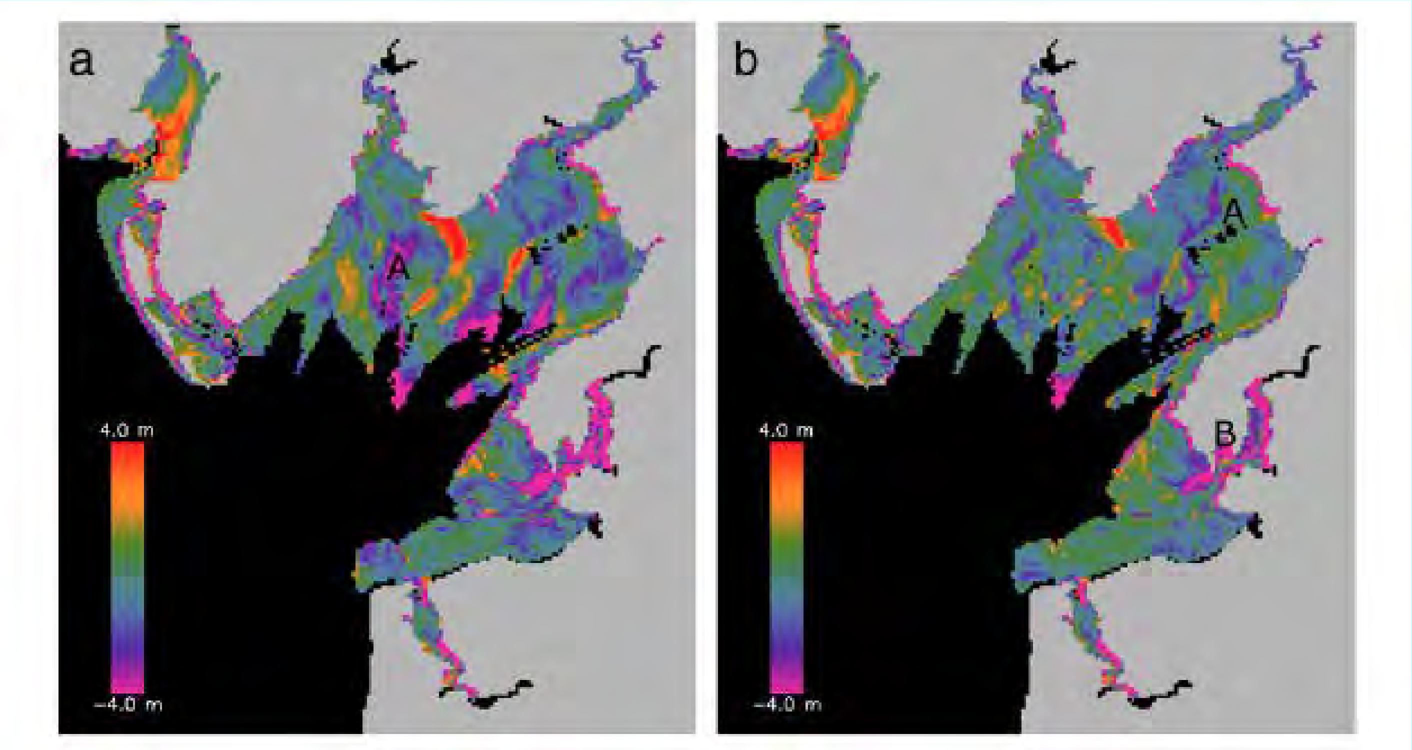
Coastal bathymetry



Errors in predicted bathymetry (a) without assimilation and (b) with assimilation, from *Thornhill et al (2012)*

Carbon cycle

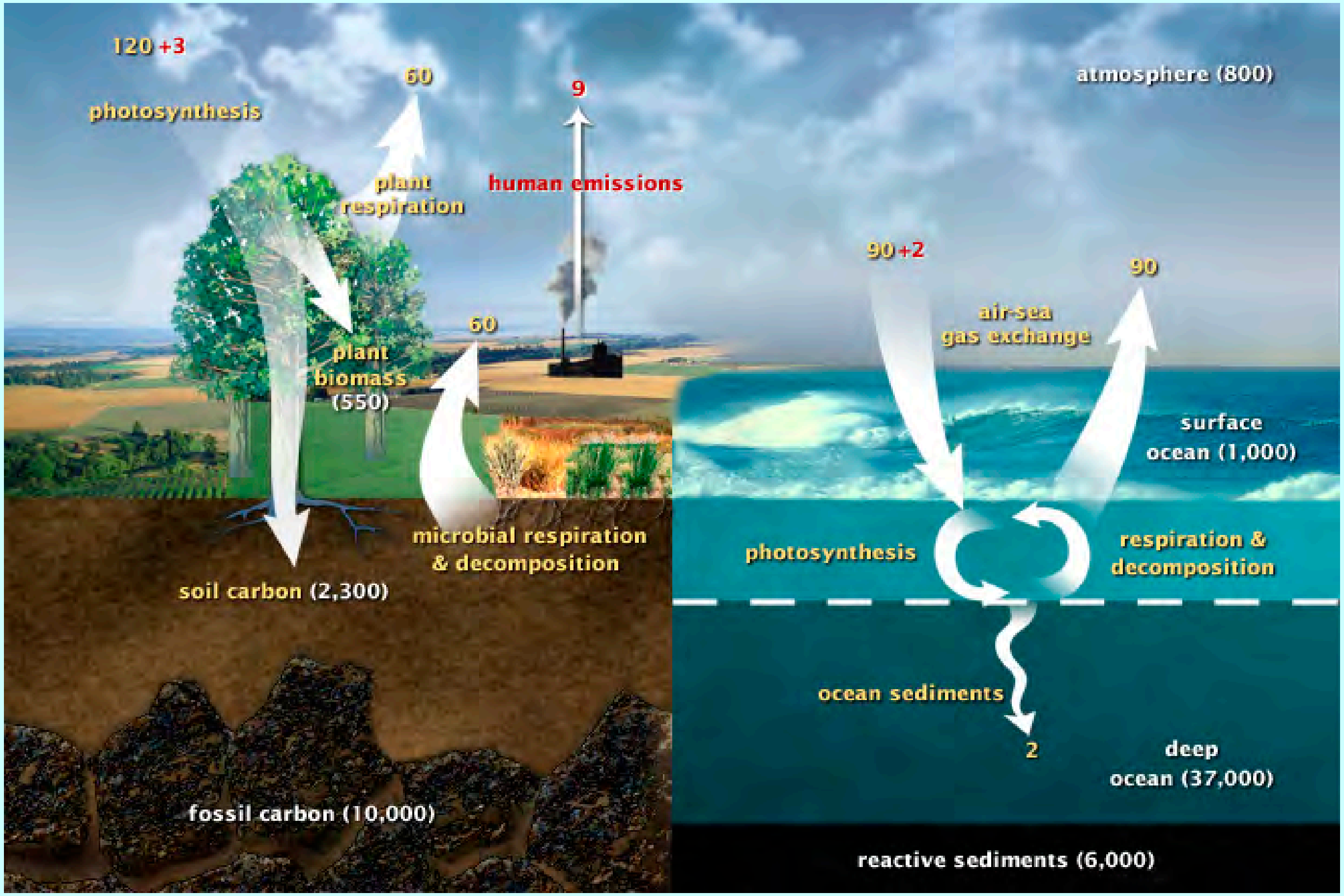


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Figure from http://earthobservatory.nasa.gov

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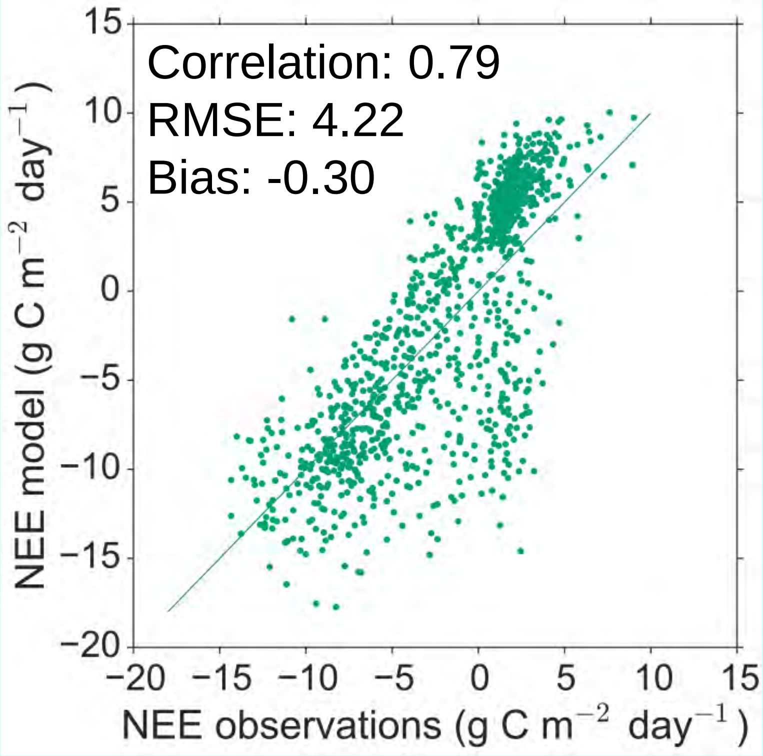
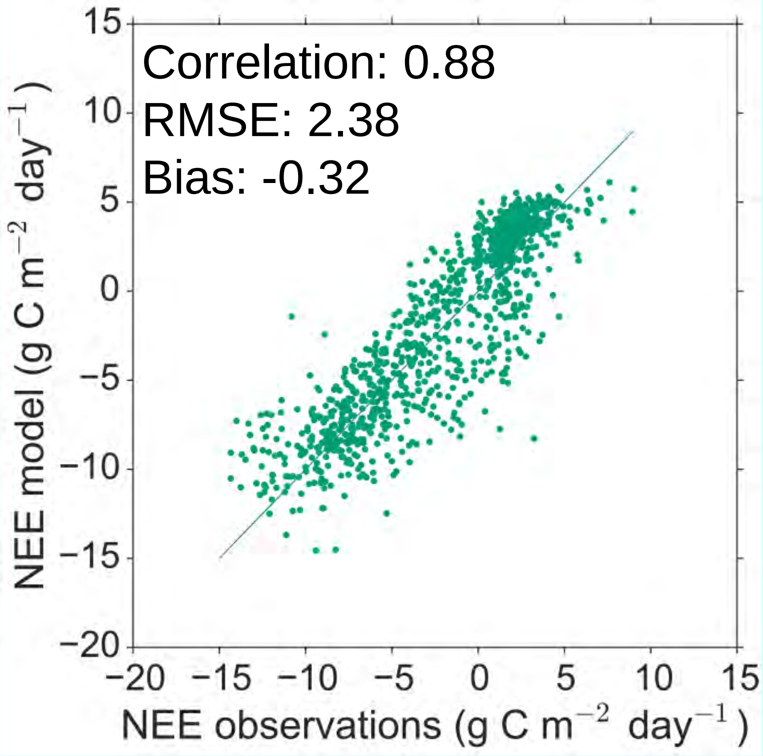
Assimilation of Net Ecosystem Exchange observations into a carbon cycle model – Forecast 2000-2013



No correlations



With correlations

From *Pinnington et al (2016)*

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Coupled atmosphere-ocean DA

- Seasonal to decadal forecasting requires initialisation of coupled atmosphere-ocean models
- Currently atmosphere and ocean systems are initialised separately using data assimilation.
- Forecasting centres want to move towards more coupled data assimilation
- Variational or ensemble methods?

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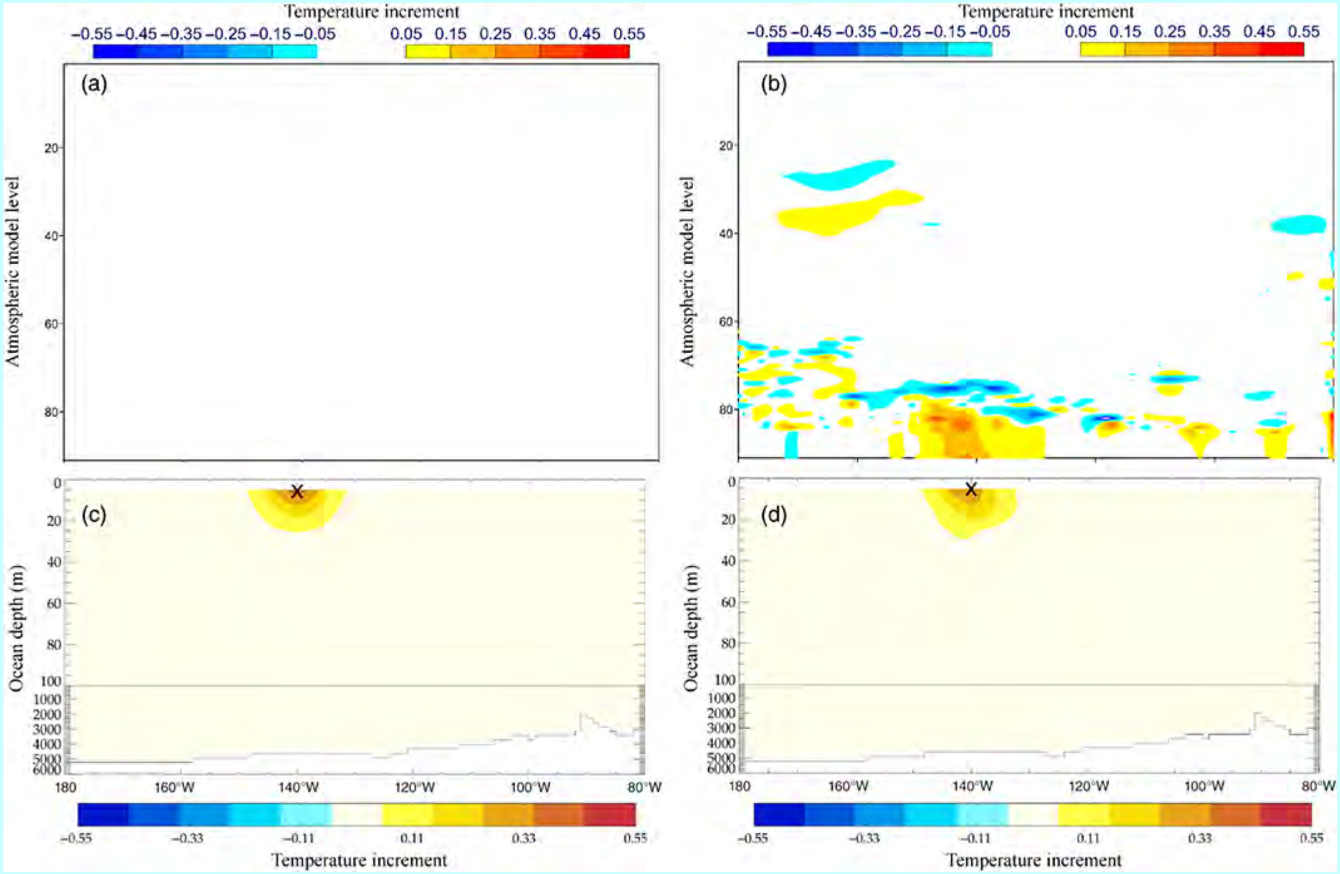
Coupled atmosphere-ocean DA

Atmos

Ocean



Start of assimilation window

End of assimilation window

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ECMWF system - *Lalayoux et al (2016)*

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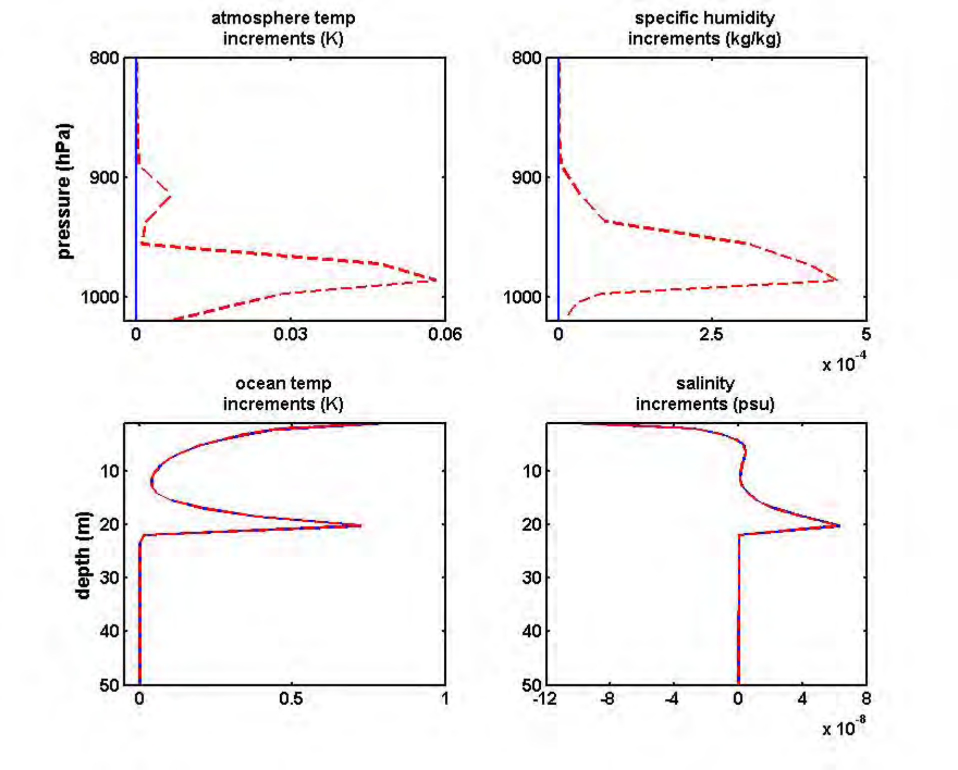
Transfer of information

How well can the schemes transfer information across the coupling interface?



--- Strongly coupled

--- Weakly coupled

Increments at initial time from single observation of SST at end of window

From *Smith et al (2015)*

Reanalysis

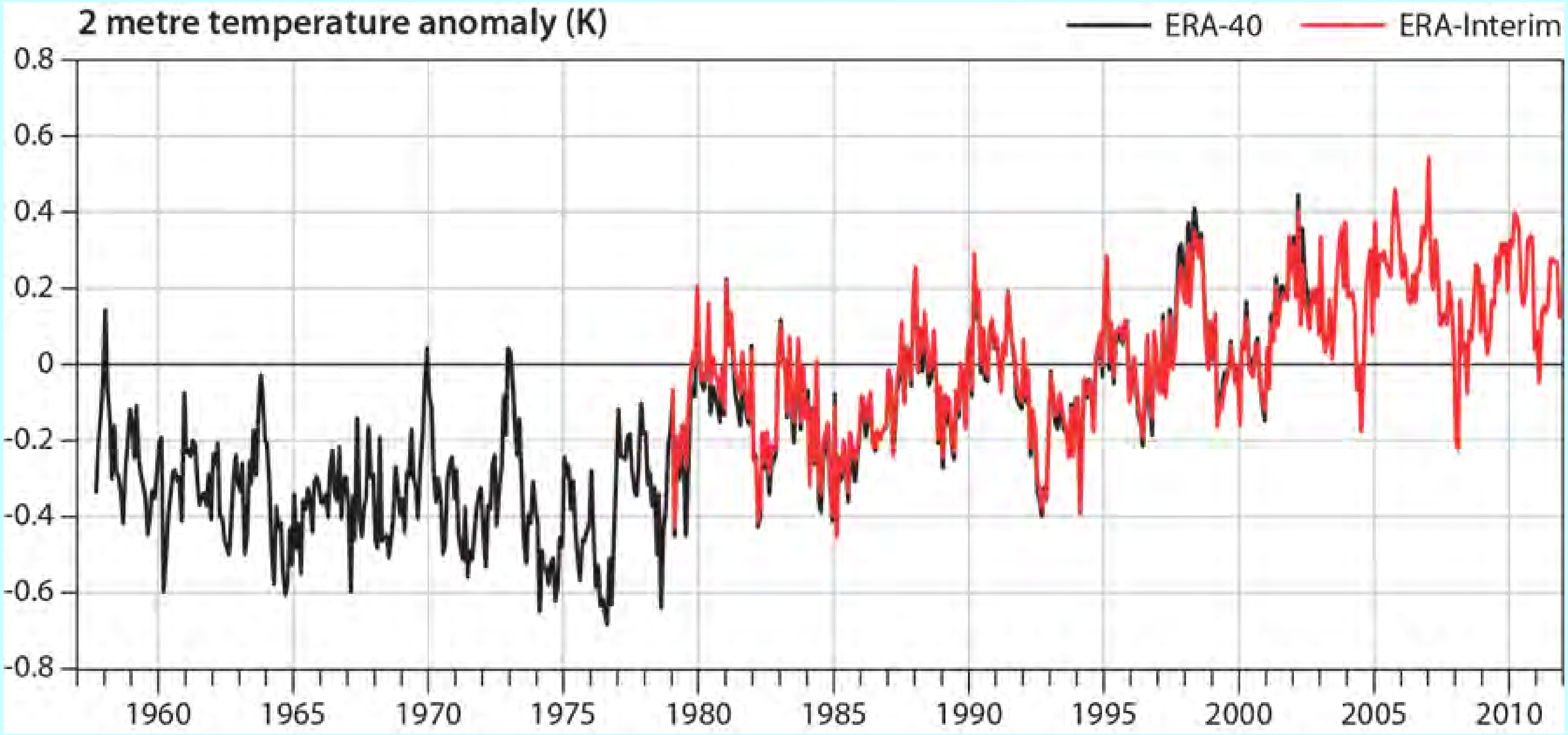


Figure from www.ecmwf.int

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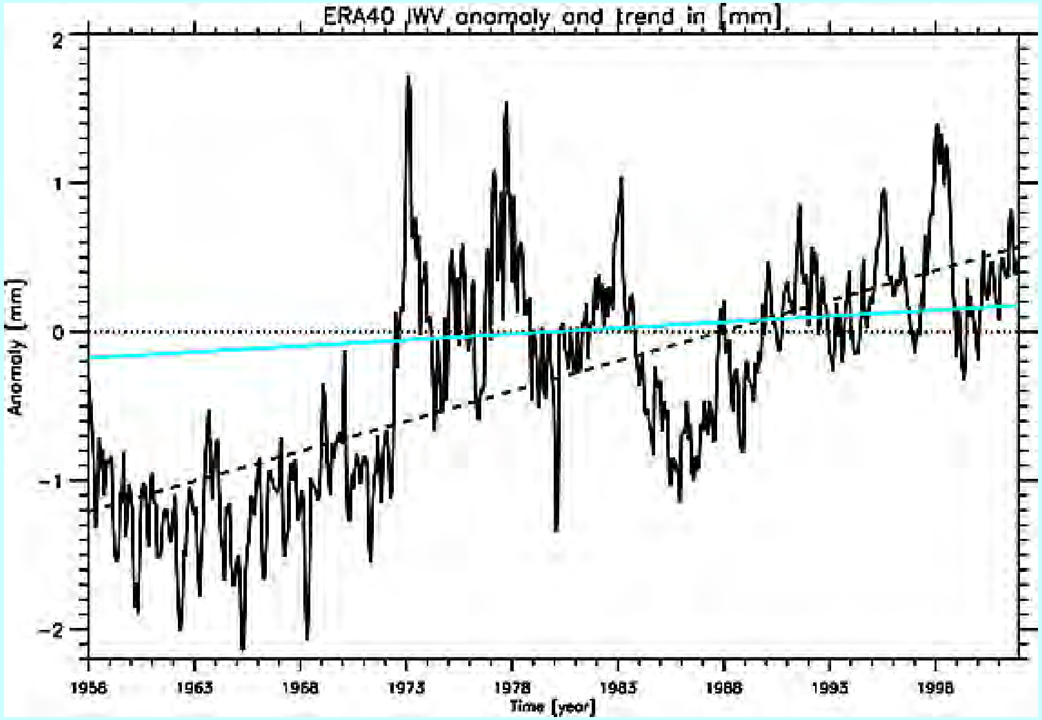
Can climate trends be calculated from reanalysis data?



Vertically integrated water vapour, IWV, of ERA40 for the period 1958–2001.
From *Bengtsson et al (2004)*

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Observation System Simulation Experiments (OSSEs)

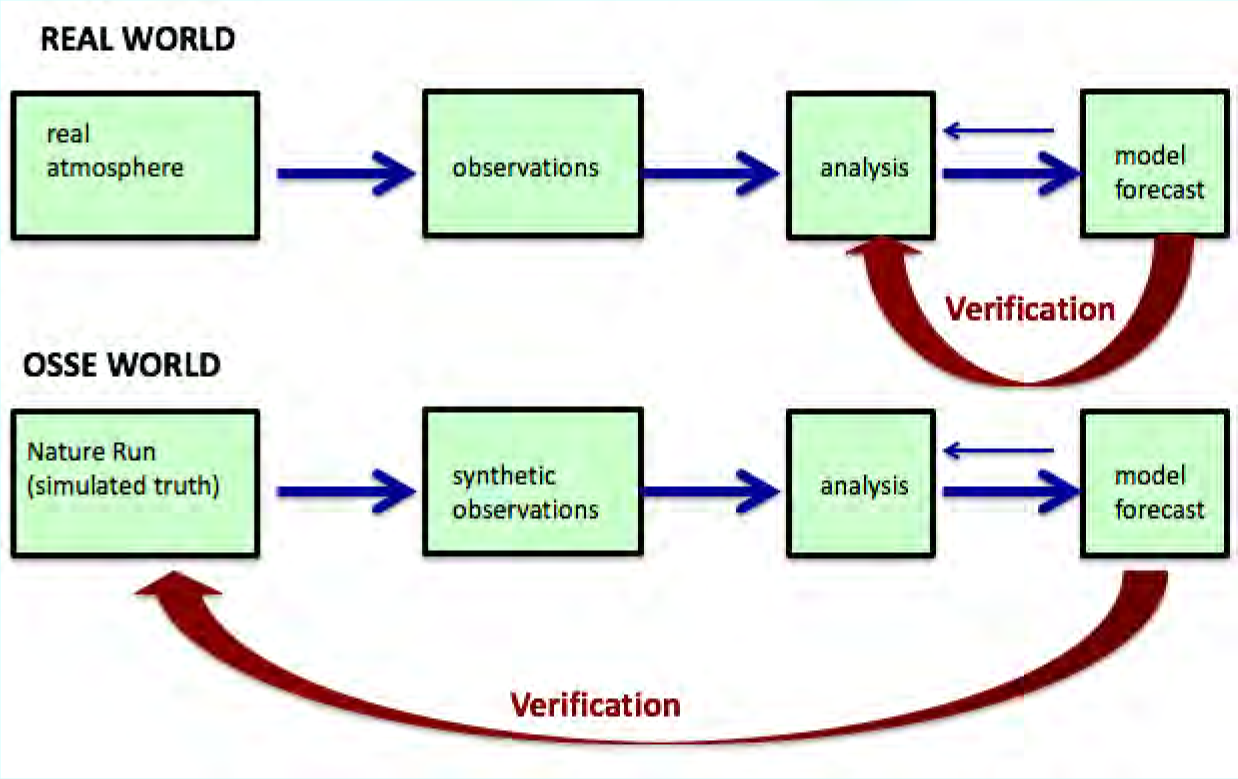

Figure from http://www.esrl.noaa.gov/gsd/gosa/ose-osse.html

Observation System Simulation Experiments (OSSEs)

- Useful for estimating the potential impact of new instruments.
- Must be carried out with great care, e.g. calibration of nature run.
- Results must be interpreted with care, especially for potential new satellite instruments – the observing system and assimilation method may be very different by the time the satellite flies.

Some current challenges

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Challenges: Data amount

- Satellites produce a lot of data!
- Modern satellite instruments may have thousands of channels.
- Currently operational weather forecasting centres use less than 5% of the satellite data they receive.
- Lots of challenges in big data, data manipulation, etc.

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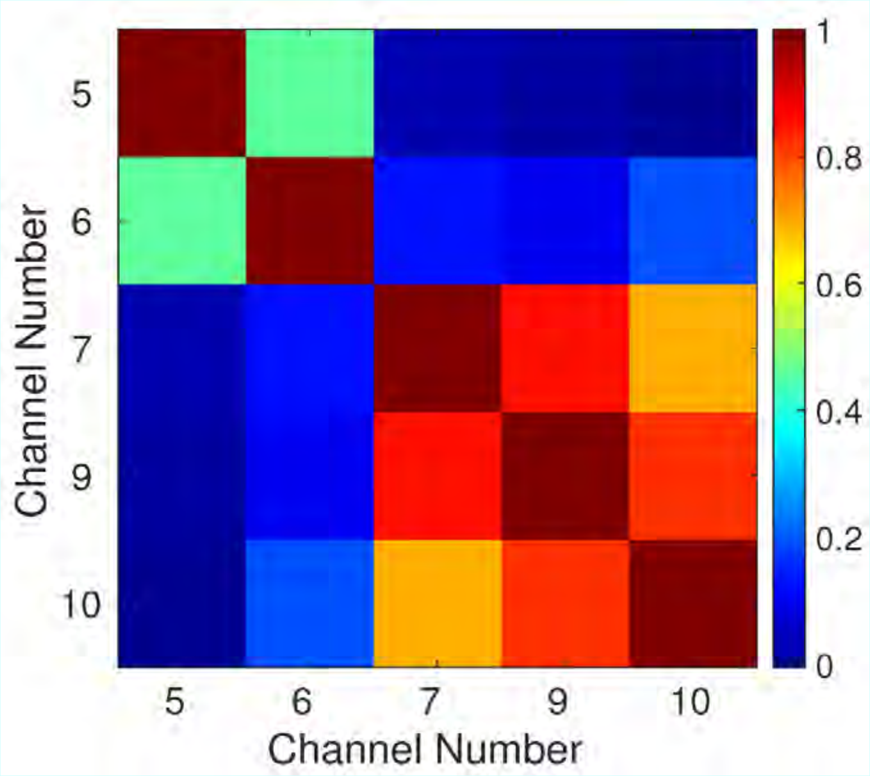
Challenges: Observation error correlations

- Part of the reason so much data is thrown away is that we don't know how to deal with correlations in the observation errors
  - Understanding what the correlations are.
  - Representing them in the matrix **R**.
- Much current work in this area.

Observation error correlations



Estimated observation error correlation matrix for assimilated SEVIRI channels.
From *Waller et al (2016)*

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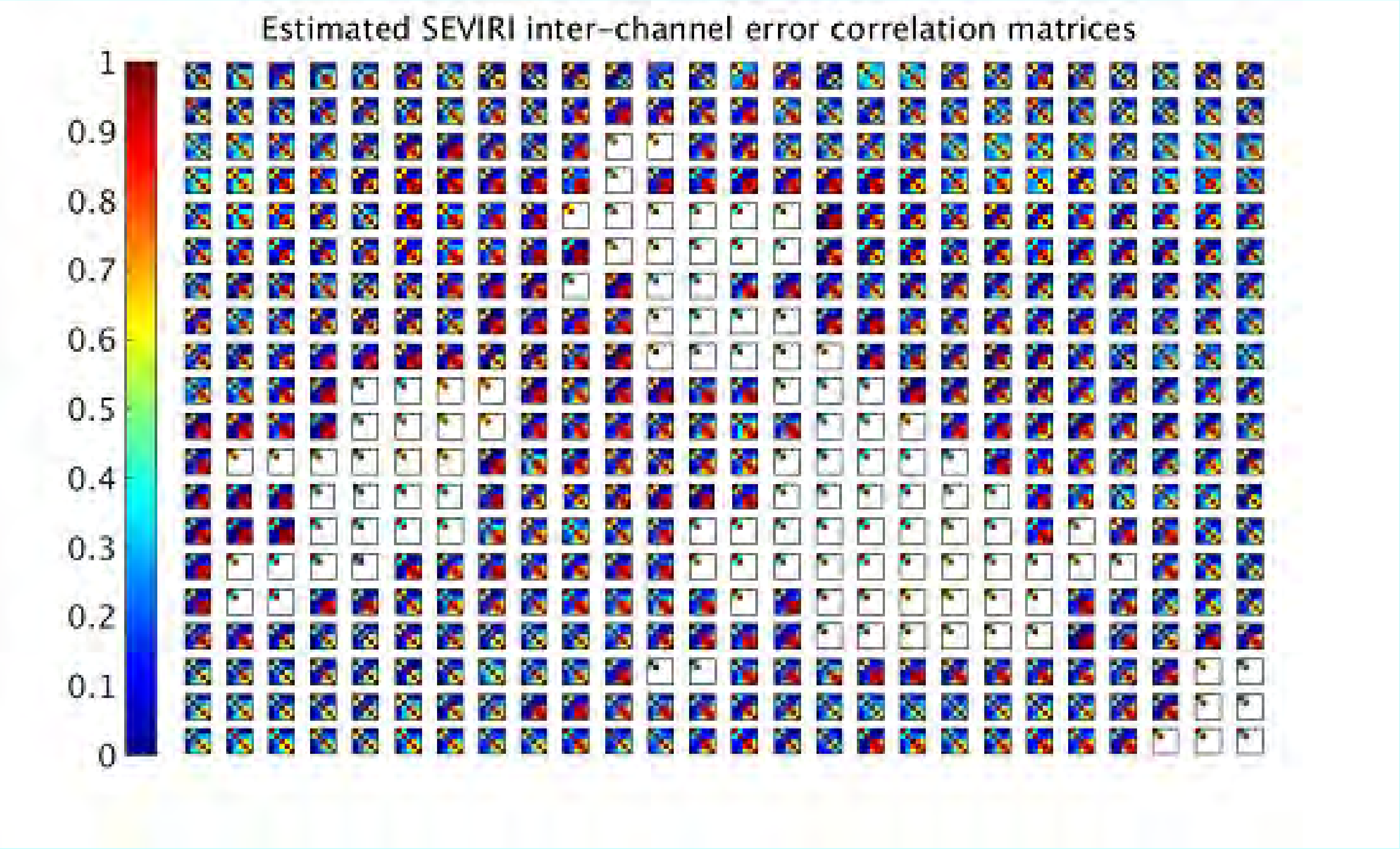

Spatial variation of estimated observation error correlation matrix for assimilated SEVIRI channels.
From *Waller et al (2016)*

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Challenges: Bias correction

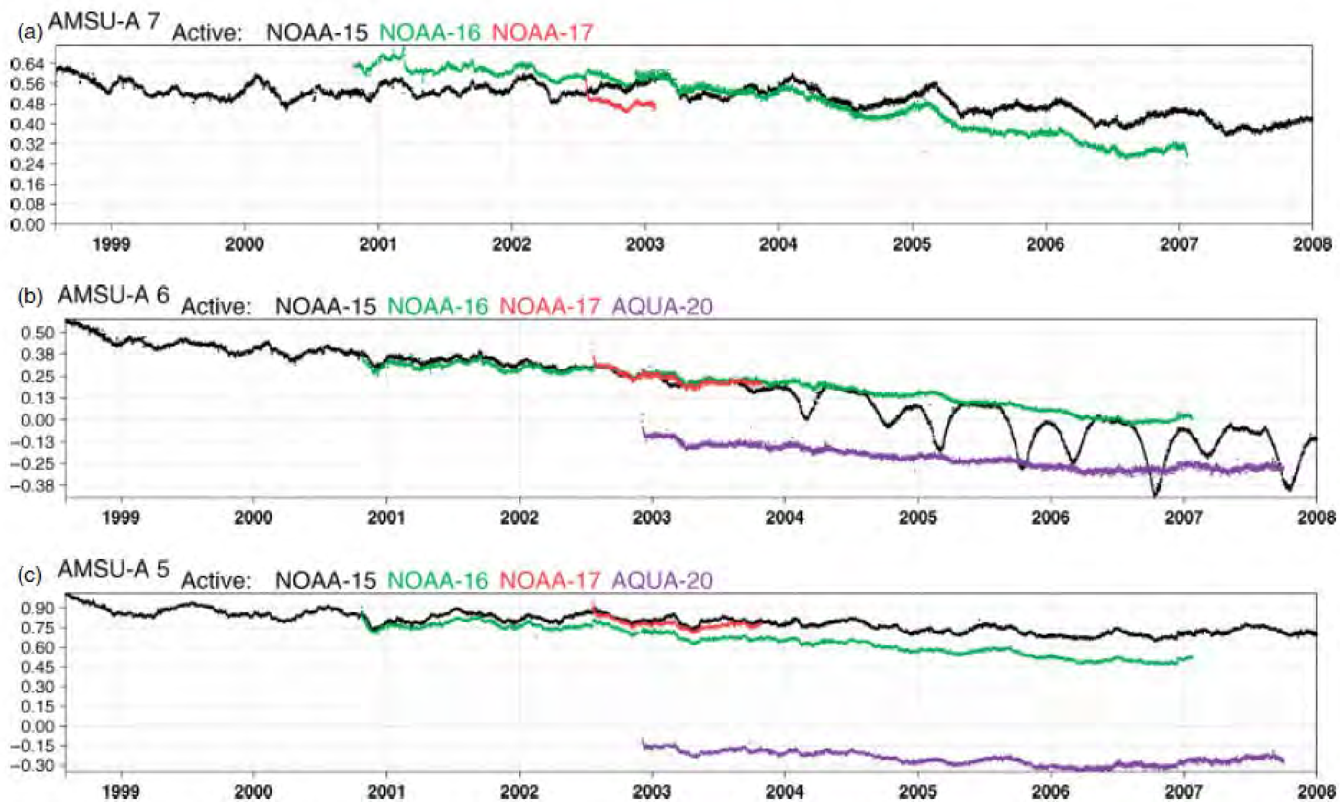

Figure 7. Globally averaged 12-hourly bias estimates (K) from NOAA-15, NOAA-16, NOAA-17, and AQUA for AMSU-A (a) channel 7, (b) channel 6, and (c) channel 5.

From *Dee and Uppala (2009)*

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Challenges: Model error

We consider that the model has unknown errors:

$$\mathbf{x}_{i+1} = \mathcal{M}_i(\mathbf{x}_i) + \boldsymbol{\eta}_i, \qquad \boldsymbol{\eta}_i \sim \mathcal{N}(0, \mathbf{Q}_i)$$

State formulation

$$\begin{aligned} & \mathcal{J}(\mathbf{x}_0, \mathbf{x}_1, \ldots, \mathbf{x}_N) \\ = \; & \mathcal{J}_b + \mathcal{J}_o + \frac{1}{2}\sum_{i=0}^{N-1}(\mathbf{x}_{i+1} - \mathcal{M}_i(\mathbf{x}_i))^T \mathbf{Q}_i^{-1}(\mathbf{x}_{i+1} - \mathcal{M}_i(\mathbf{x}_i)) \end{aligned}$$

Error formulation

$$\mathcal{J}(\mathbf{x}_0, \boldsymbol{\eta}_0, \ldots, \boldsymbol{\eta}_{N-1}) = \mathcal{J}_b + \mathcal{J}_o + \frac{1}{2}\sum_{i=0}^{N-1}\boldsymbol{\eta}_i^T \mathbf{Q}_i^{-1}\boldsymbol{\eta}_i$$

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Implementation of weak-constraint formulation

- Size of the control vector is greatly increased.
- The two formulations may behave quite differently, even though they appear to be equivalent.
- We need to specify the model error covariances **Q**. It is not obvious how this should be done.

Can we distinguish model and observation bias?

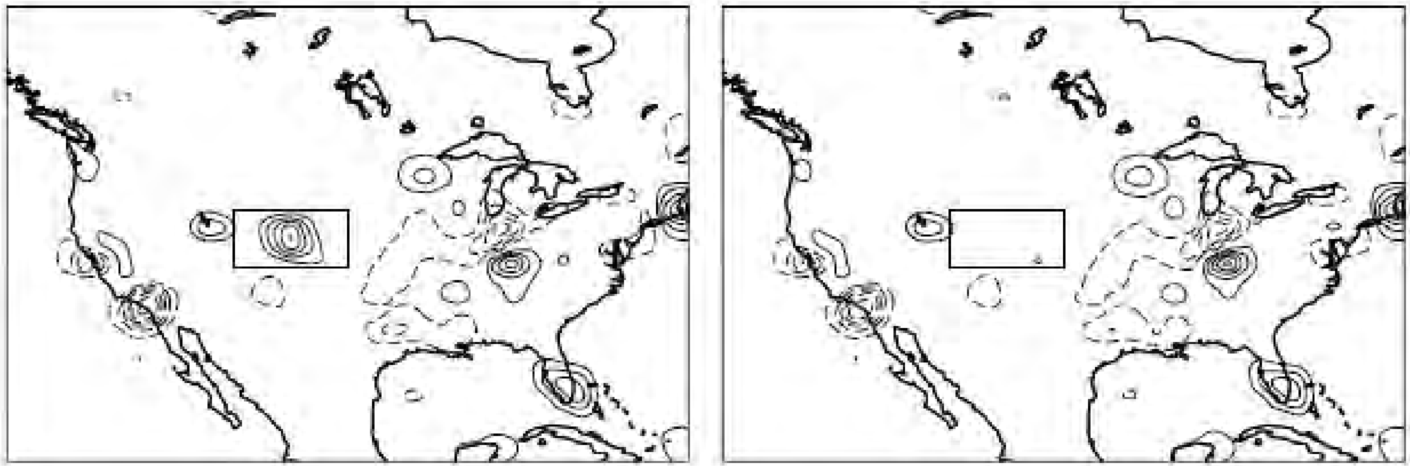

Figure 11. Average temperature forcing at the lowest model level over North America: with all data (left panel), and without aircraft data in the marked area (right panel). The contour interval is 0.01 Kh^{-1}.

Estimated model bias using all data (left) and without aircraft data (right).
Trémolet (2007)

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Challenges: New algorithms

- Data assimilation of the future will have to take account of new computer architectures.
- Massively parallel architectures seem more suited to ensemble-based methods.
- Desire to move to non-Gaussian methods such as particle filters.
- The best algorithm will depend on your application.

Concluding remarks

- Data assimilation is potentially useful whenever you have data and a model.
- DA is now being applied to many different areas of Earth science.
- Launch of new satellites will provide many more data available for assimilation, but this brings its own challenges.
- Many research questions remain as to how best to implement DA for different applications.

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