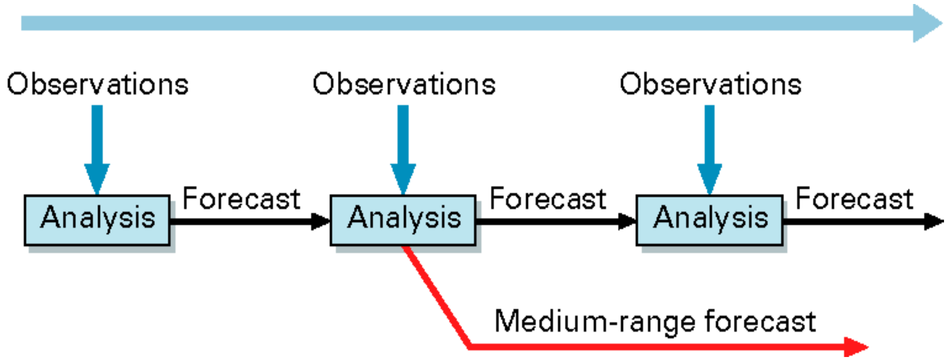
Coupled data assimilation for climate reanalysis

Dick Dee

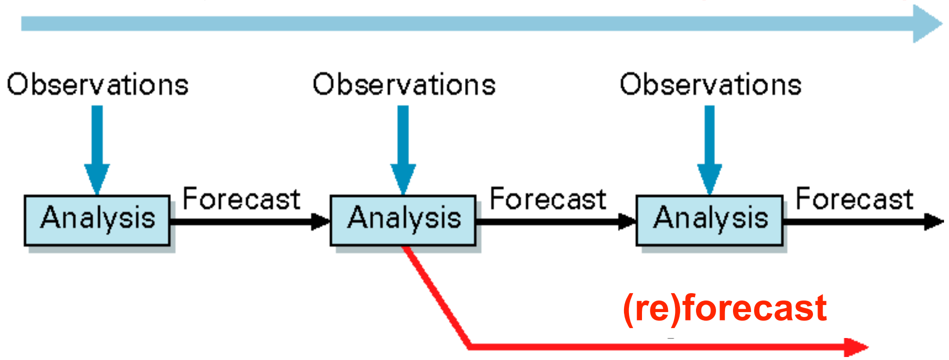
- Climate reanalysis
- Coupled data assimilation
- CERA: Incremental 4D-Var

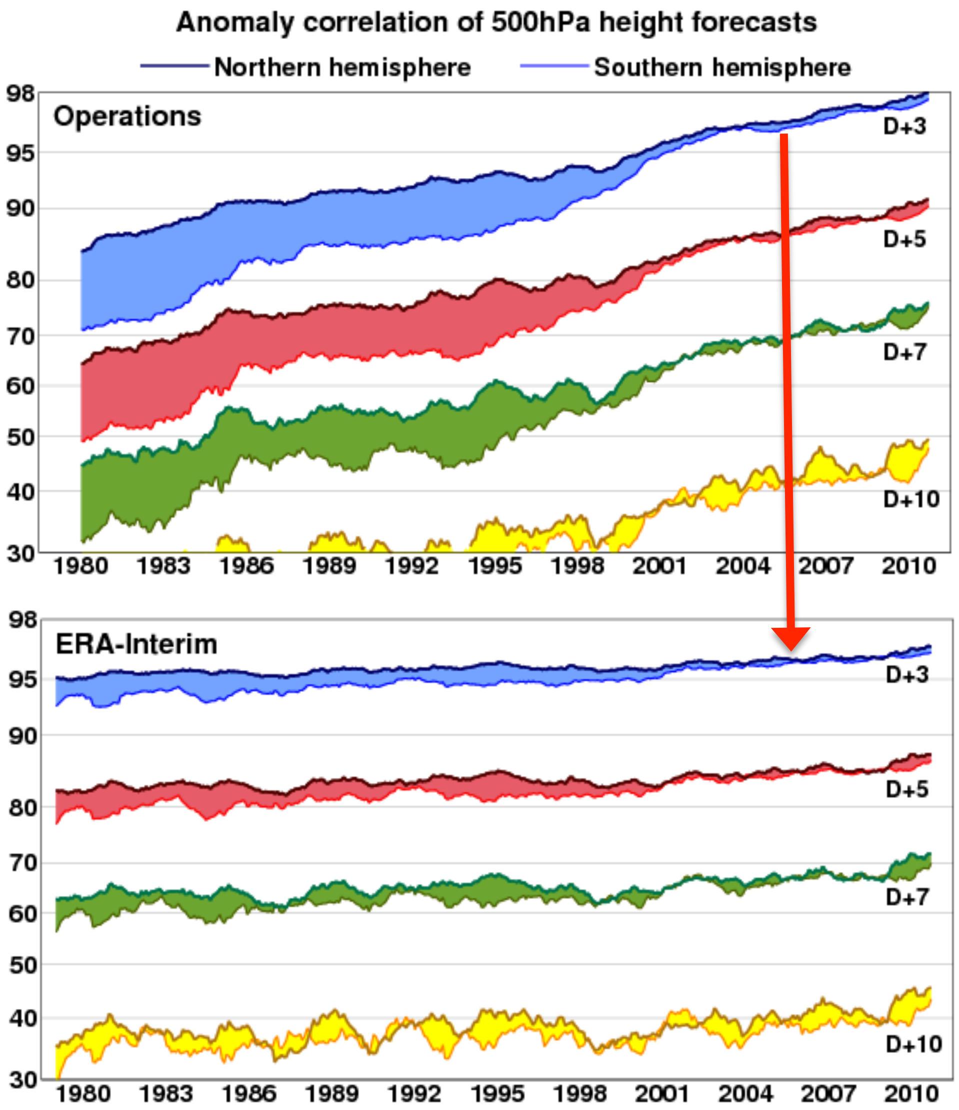
Tools from numerical weather prediction

Weather prediction *(real time)*



Reanalysis *(past time)*





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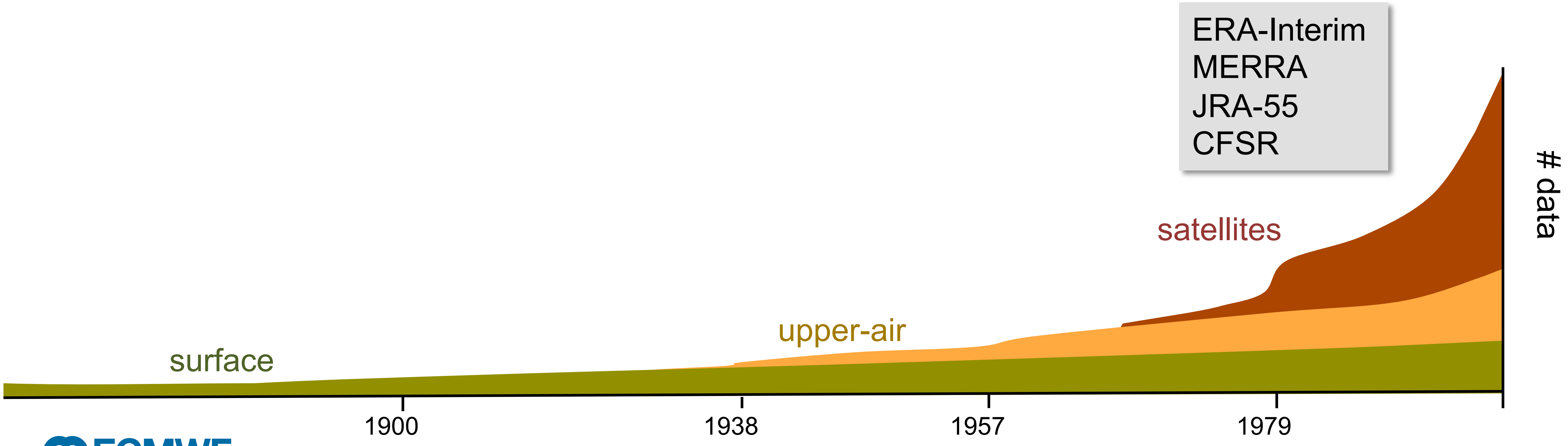
Reanalysis for climate studies

Reanalyses of the modern observing period (~30-50 years):

- Produce the best state estimate at any given time (as for NWP)
- Use as many observations as possible, including from satellites
- Closely tied to forecast system development and evaluation
- Can support product updates in near-real time



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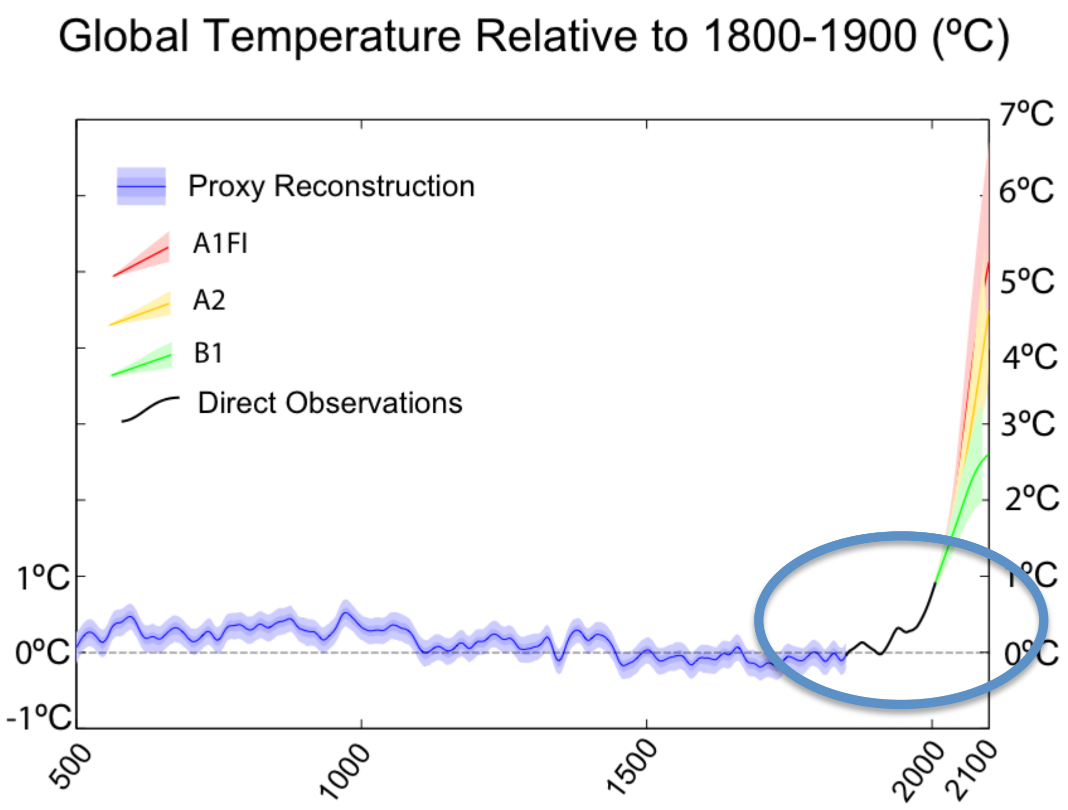
Climate reanalysis



Source: The Copenhagen Diagnosis, 2009

Goals:

- Detailed description of the recent climate consistent with the instrumental record
- Physically consistent estimates of essential climate variables
- Accurate representation of climate change and variability
- Useful information about uncertainties

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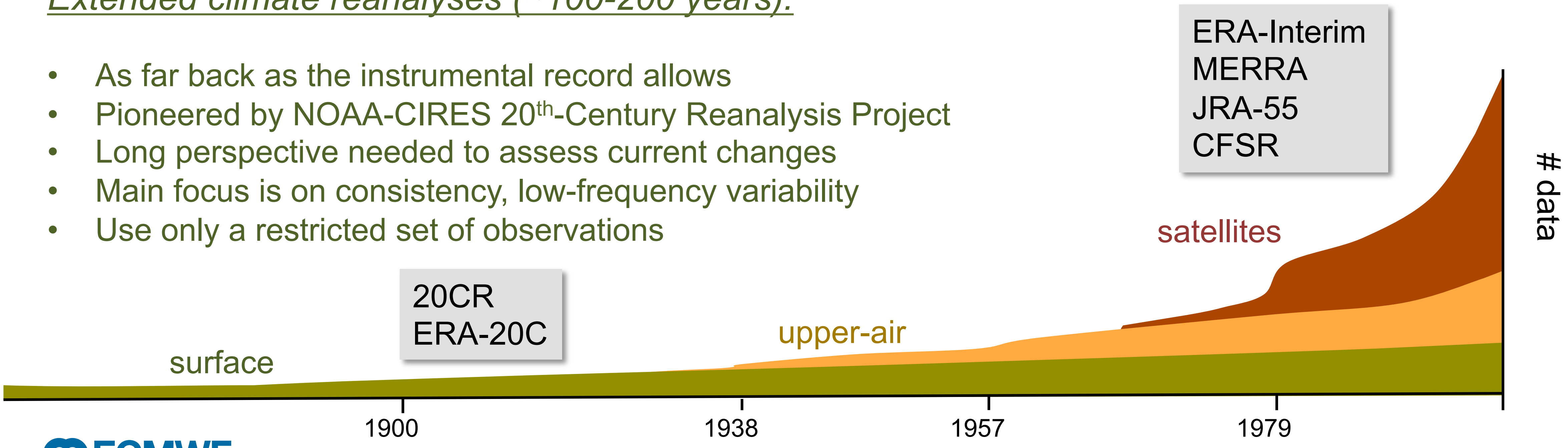
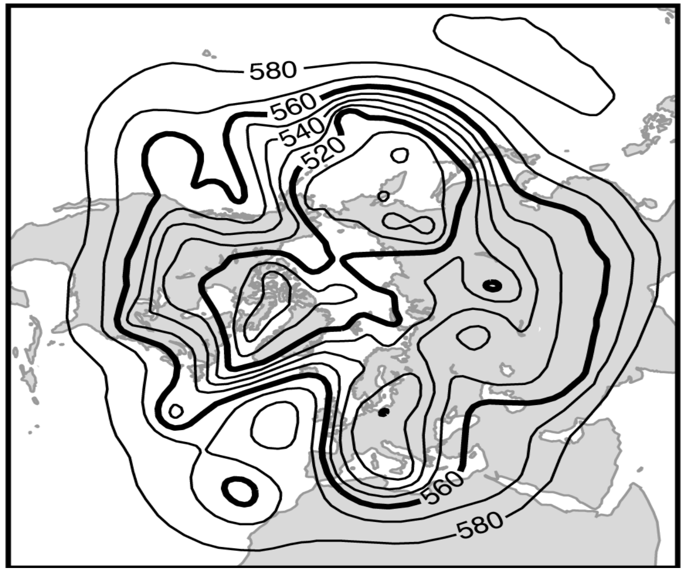
Extended climate reanalyses (~100-200 years):

- As far back as the instrumental record allows
- Pioneered by NOAA-CIRES 20th-Century Reanalysis Project
- Long perspective needed to assess current changes
- Main focus is on consistency, low-frequency variability
- Use only a restricted set of observations

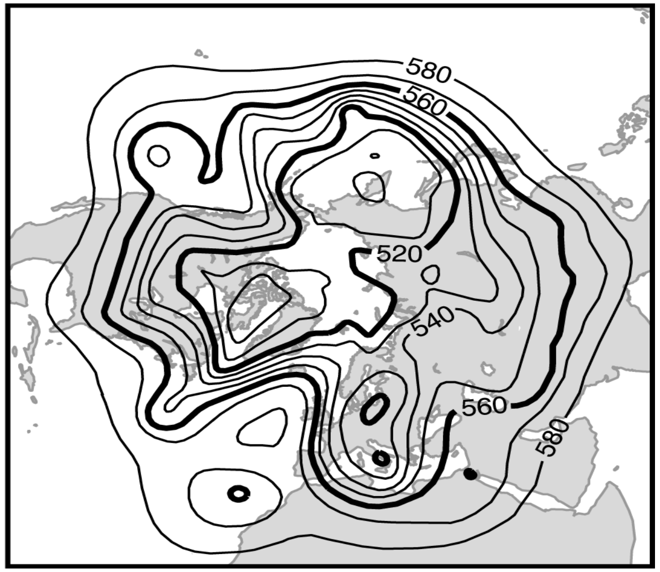


Utilising the early observing system

Two modern analyses of NH geopotential height at 500hPa

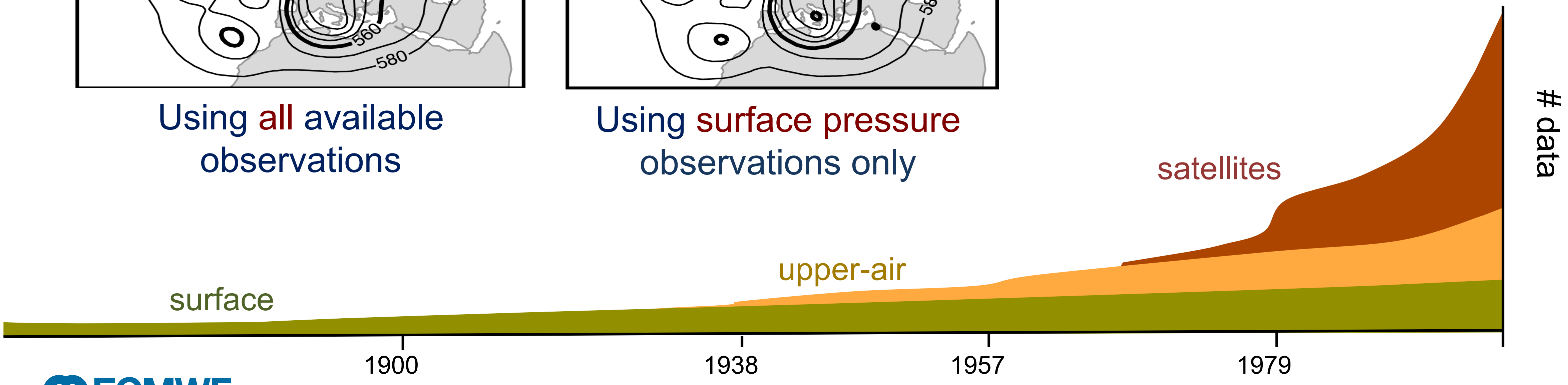


Using all available observations



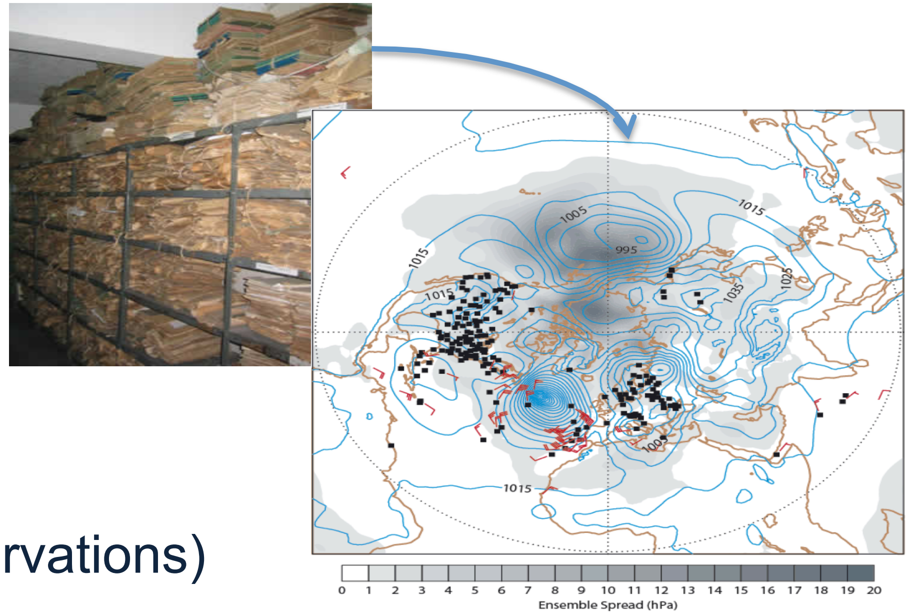
Using surface pressure observations only

Whitaker, Compo, and Thépaut 2009



The FP7 ERA-CLIM project (2011-2013)

Goal: Preparing input observations, model data, and data assimilation systems for a global atmospheric reanalysis of the 20th century



Main components:

- Data rescue (in-situ upper-air and satellite observations)
- Incremental development of new **20C reanalysis** products
- Use of reanalysis feedback to improve the historic data record
- Access to reanalysis data and observation quality information

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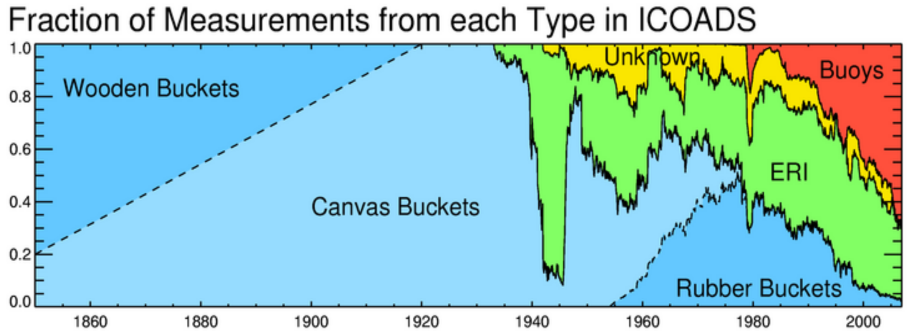
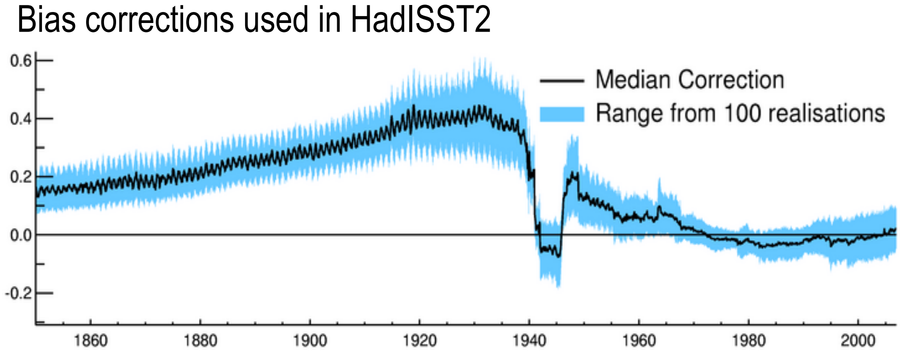
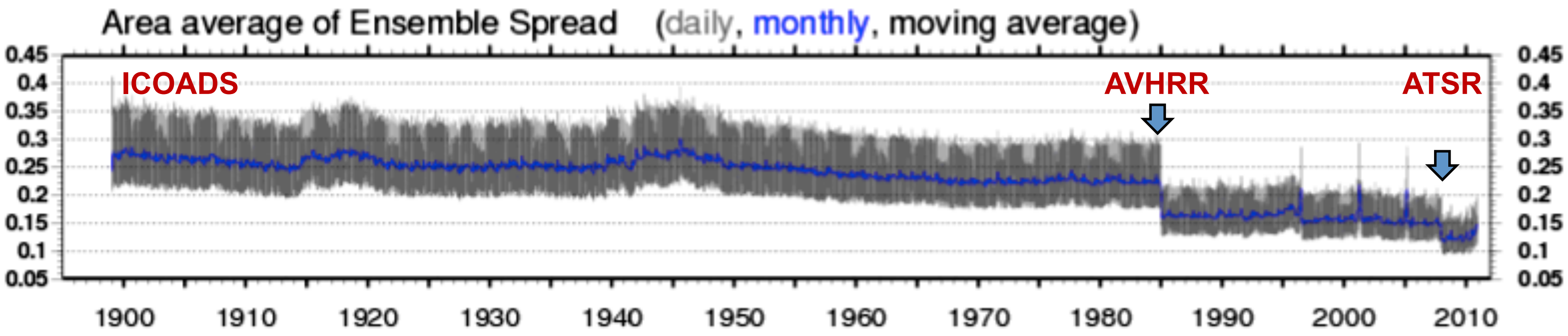
Model data for production of ERA-20C

- From 1900-2010, spatial resolution 125 km
- 10 members, each with plausible SST/ sea-ice evolutions from HadISST2
- Radiative forcing and land surface parameters as specified for CMIP5 experiments

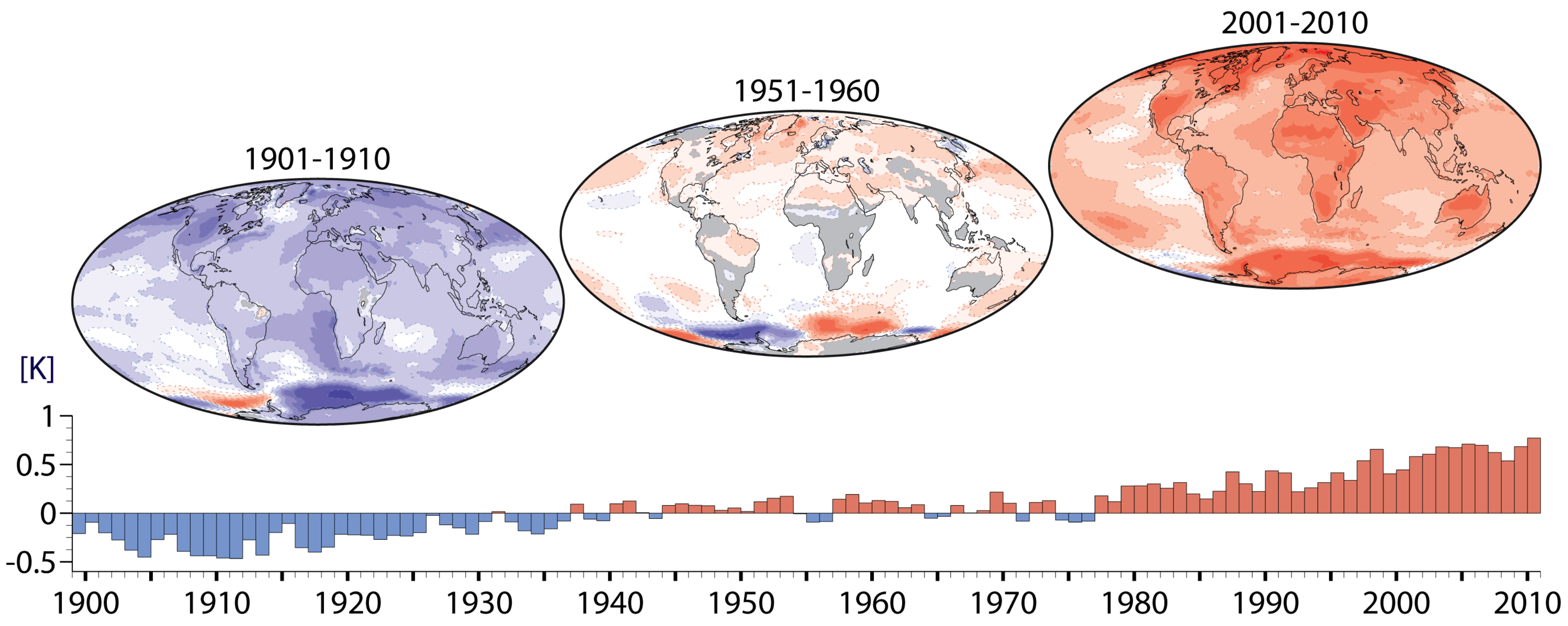




Kennedy, Rev. Geophys. 2014

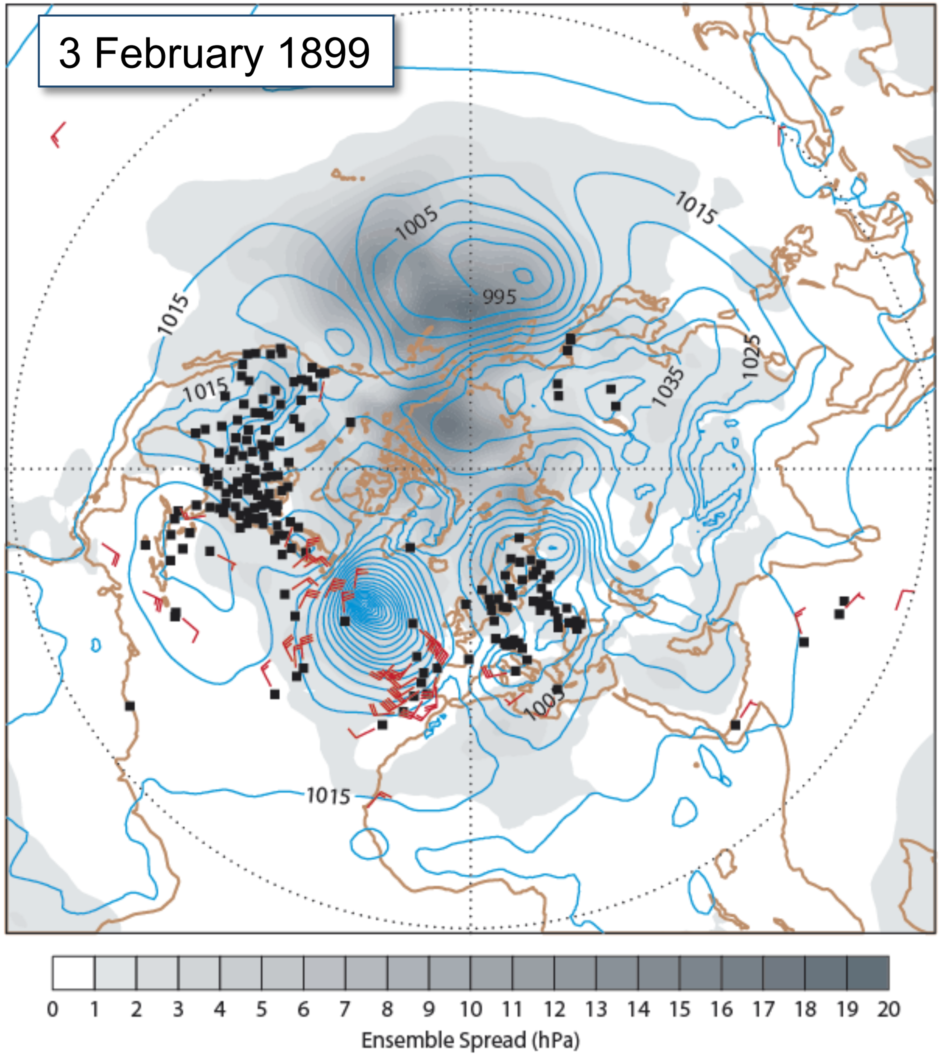


ERA-20CM: Ensemble of atmospheric model integrations *(climate)*



Hersbach et al, QJ 2015

ERA-20C: Reanalysis of surface observations *(weather)*



TERRIFIC STORMS AT SEA

Steamships from All Quarters Report Extremely Rough Voyages.

ALL MORE OR LESS BATTERED

Vessels Sighted in Distress and Abandoned — Blinding Snow and Waves Like Mountains.

All the steamers that came in yesterday were coated with ice from the tops of the masts down to the water line, and all had passed through storms of blinding snow and mountainous waves. The British steamer Ethelgonda, from Bristol and Swansea, which left the latter port on Jan. 19, ran into a gale of hurricane force, and seas swept her decks repeatedly. So fierce was the wind that the boat drifted before the gales and was barely able to keep steerage way. She anchored outside the bar late Sunday afternoon. The cable parted and she lost her anchor, together with 100 fathoms of chain. Then the great snowstorm drove her 150 miles off the shore. She succeeded in getting back late on Tuesday night.

The French liner La Bretagne, from Havre, came in a little before noon yesterday, with 58 cabin and 225 steerage passen-

The New York Times

Published: February 16, 1899

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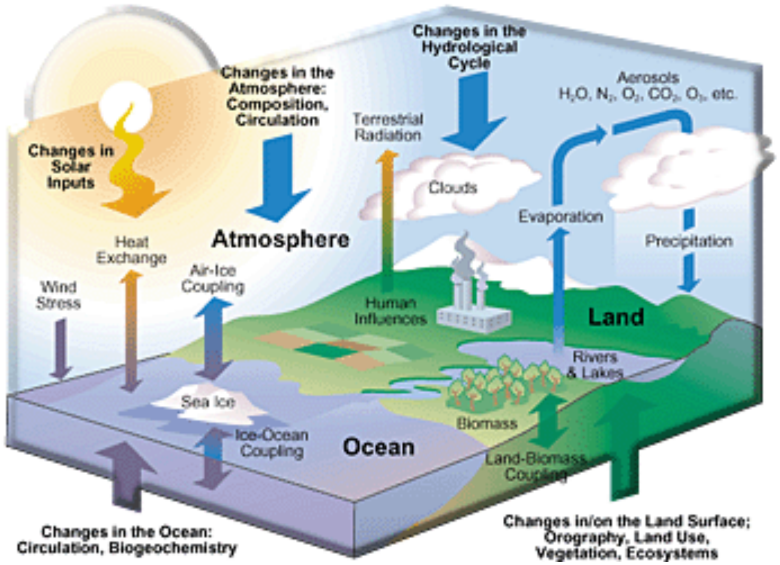
The FP7 ERA-CLIM2 project (2014-2016)

Goal: Production of a consistent 20th-century reanalysis of the coupled Earth-system: *atmosphere, land surface, ocean, sea-ice, and the carbon cycle*



Main components:

- Production of coupled reanalyses, for 20C and the modern era
- Research and development in **coupled data assimilation**
- Earth system observations for extended climate reanalyses
- Evaluation of uncertainties in observations and reanalyses

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What do we mean by “coupled” data assimilation?

Coupled model = A model that combines multiple components, each of which could also be used as a standalone model

Coupled data assimilation = Data assimilation in a coupled model

Weakly coupled data assimilation = Background produced with coupled model, analyses performed separately for each component

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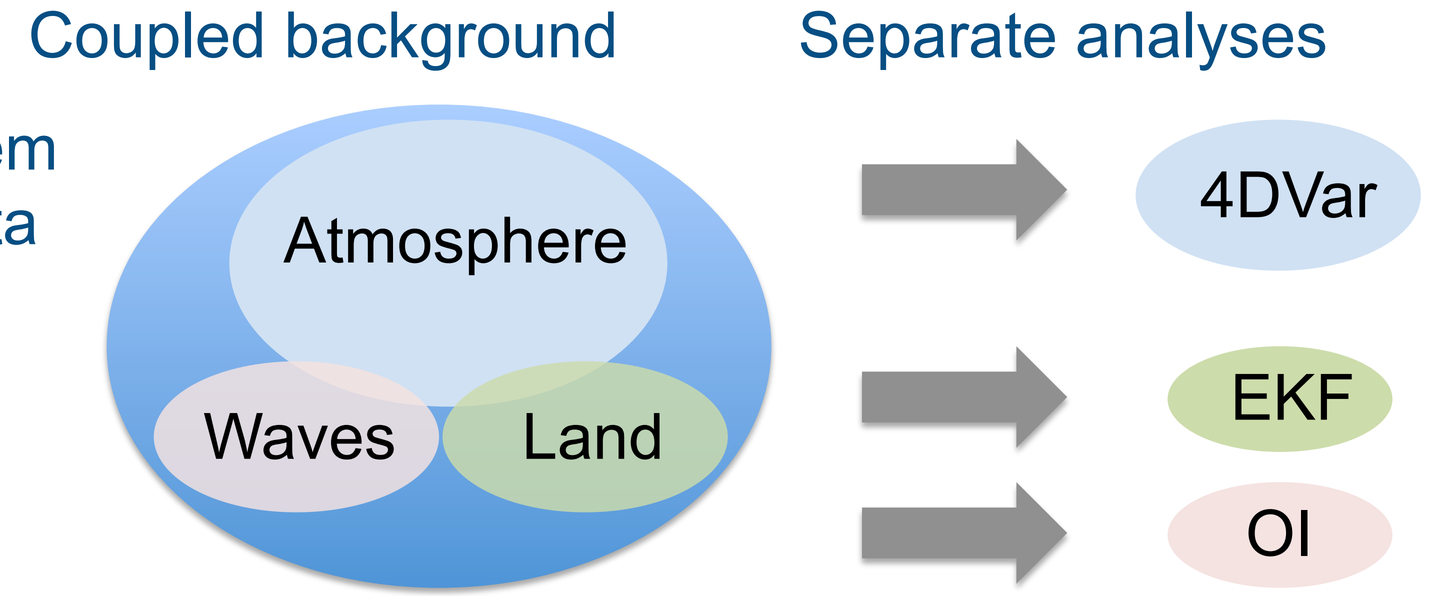
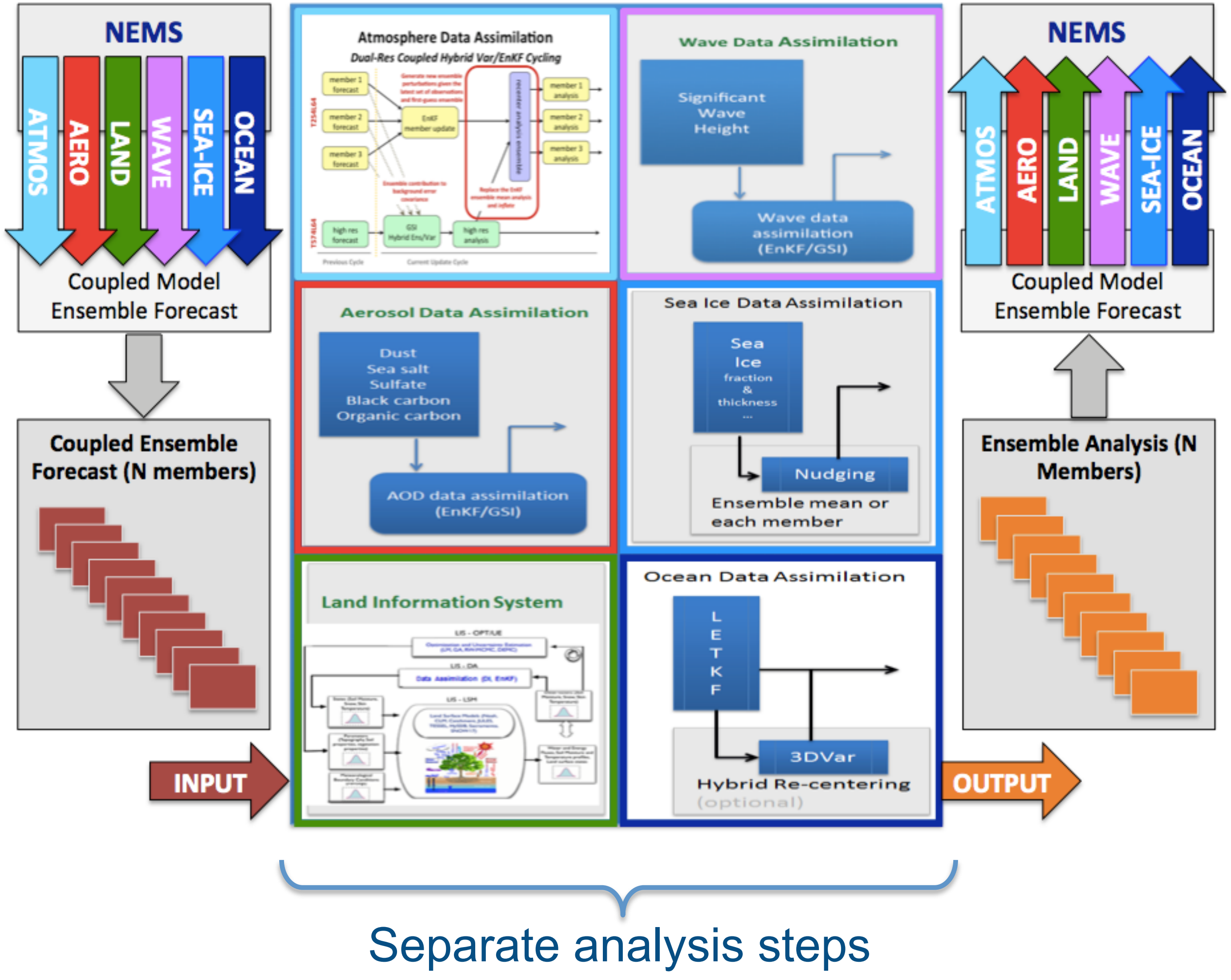
ECMWF's forecast system uses weakly coupled data assimilation:



NCEP's hybrid-EnKF data assimilation system is weakly coupled:



Physical consistence

Weakly coupled data assimilation = Coupled first guess, **separate analyses**

In a weakly coupled system:

- An observation in one component cannot have an immediate impact on the state of the other components
- Therefore the analysed state of the coupled system cannot be physically consistent

To get consistent fluxes across the interface, the analysis must be coupled as well.

Strongly coupled data assimilation = Coupled first guess, **coupled analysis**

Coupling defined in terms of observation impact

Weakly coupled data assimilation = Coupled first guess, separate analyses

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Strongly coupled data assimilation = Coupled first guess, coupled analysis

A natural definition of 'strong coupling' is in terms of observation impact:

Weakly coupled: instantaneous impact of any observation in a single model component only

Strongly coupled: simultaneous impact of an observation in multiple components

Especially relevant for fast processes *(land surface, chemistry)* but also to ensure consistent energy and water budgets *(reanalysis)*

Coupling the analysis step

$$J(\mathbf{x}) = (\mathbf{x}^{\mathrm{b}} - \mathbf{x})^{\mathrm{T}}\mathbf{B}^{-1}(\mathbf{x}^{\mathrm{b}} - \mathbf{x}) + \{\mathbf{y} - \mathbf{h}(\mathbf{x})\}^{\mathrm{T}}\mathbf{R}^{-1}\{\mathbf{y} - \mathbf{h}(\mathbf{x})\}$$

$\mathbf{x}$ is the coupled state.

At convergence:

$$\mathbf{x}^{\mathrm{a}} - \mathbf{x}^{\mathrm{b}} = \mathbf{B}\left(\left.\frac{\partial \mathbf{h}}{\partial \mathbf{x}}\right|_{\mathbf{x}=\mathbf{x}^{\mathrm{a}}}\right)^{\mathrm{T}}\mathbf{R}^{-1}\{\mathbf{y} - \mathbf{h}(\mathbf{x}^{\mathrm{a}})\}$$

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EnKF: Coupling is introduced explicitly by construction of B

4D-Var: Coupling is introduced implicitly by the coupled model *(embedded in h(x))*

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EnKF: Coupling is introduced explicitly by construction of B

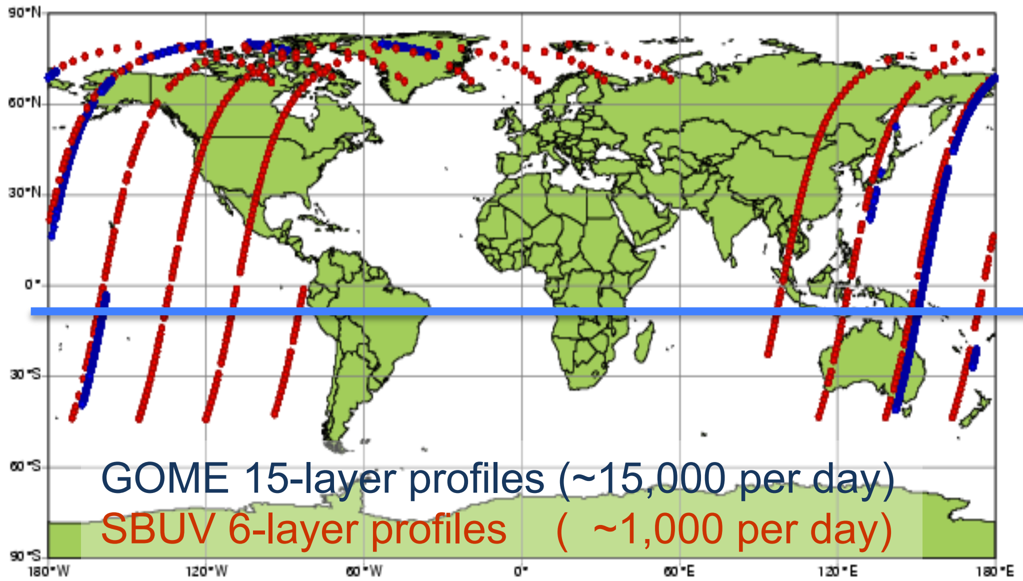
4D-Var: Coupling is introduced implicitly by the coupled model *(embedded in h(x))*

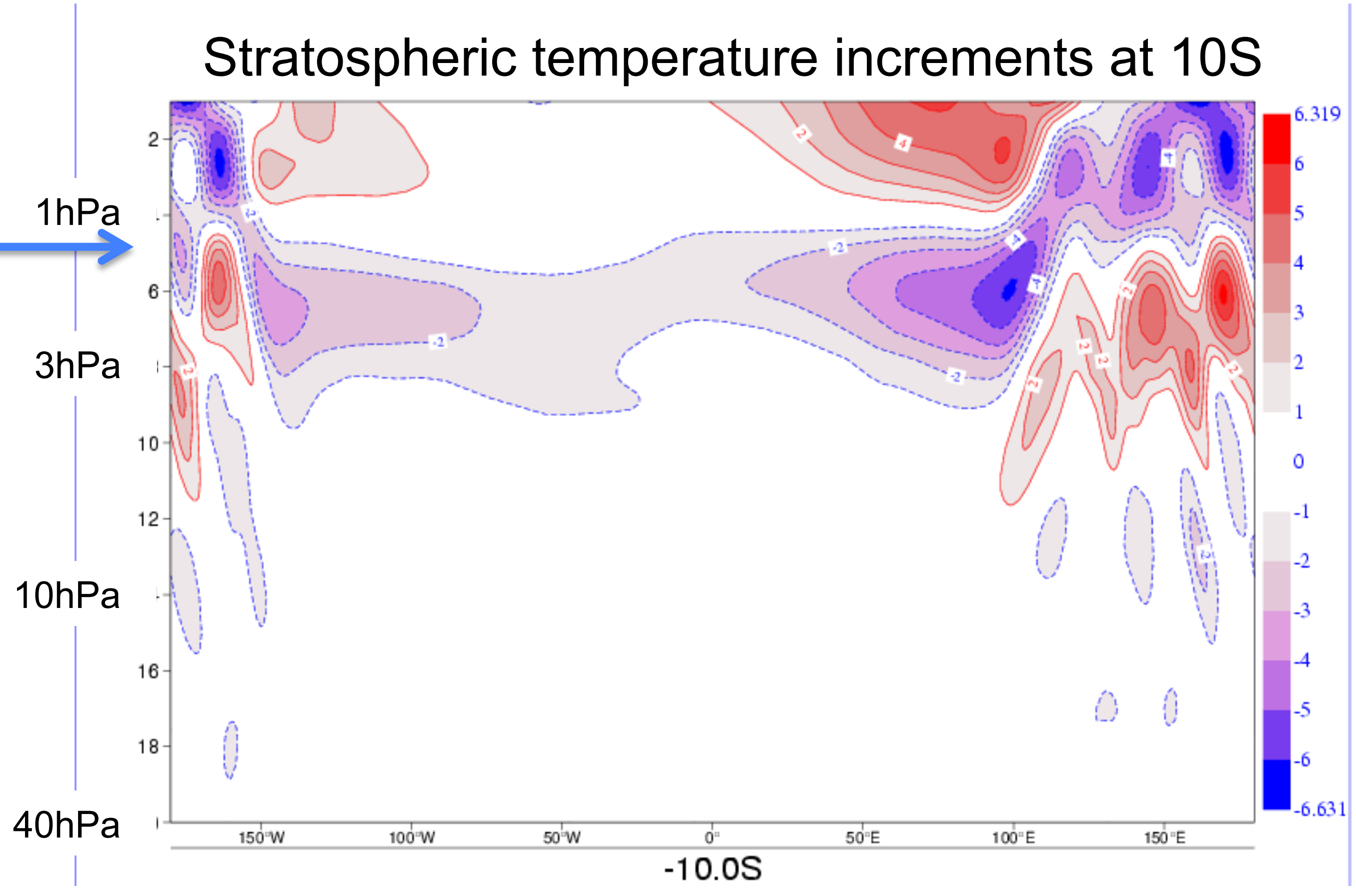
Main challenges: Observability; controlling model biases

In practice both are addressed by introducing additional constraints.

Impact of ozone profile data in a 12-hour 4D-Var analysis

(Ozone is included in the state vector)





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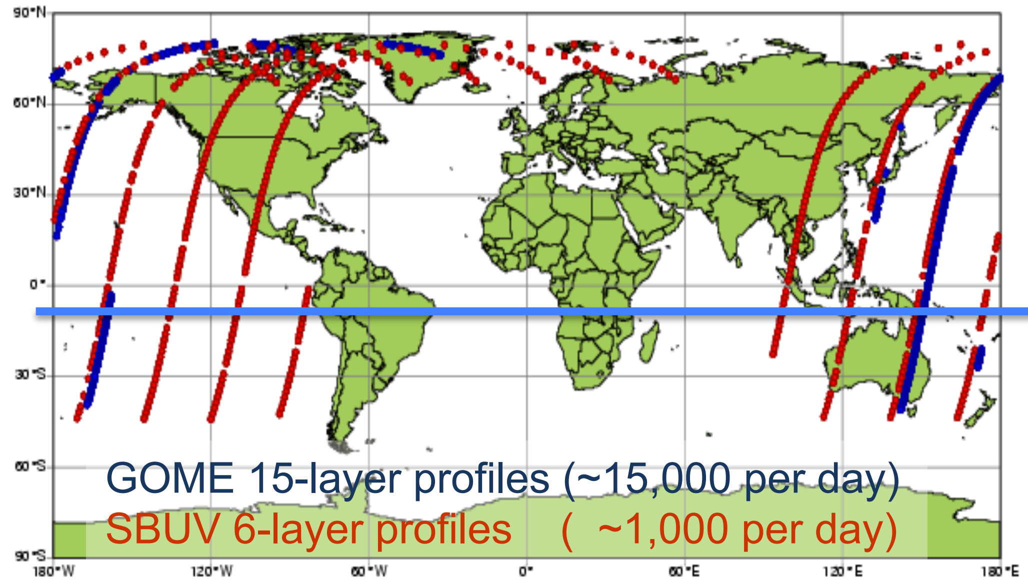

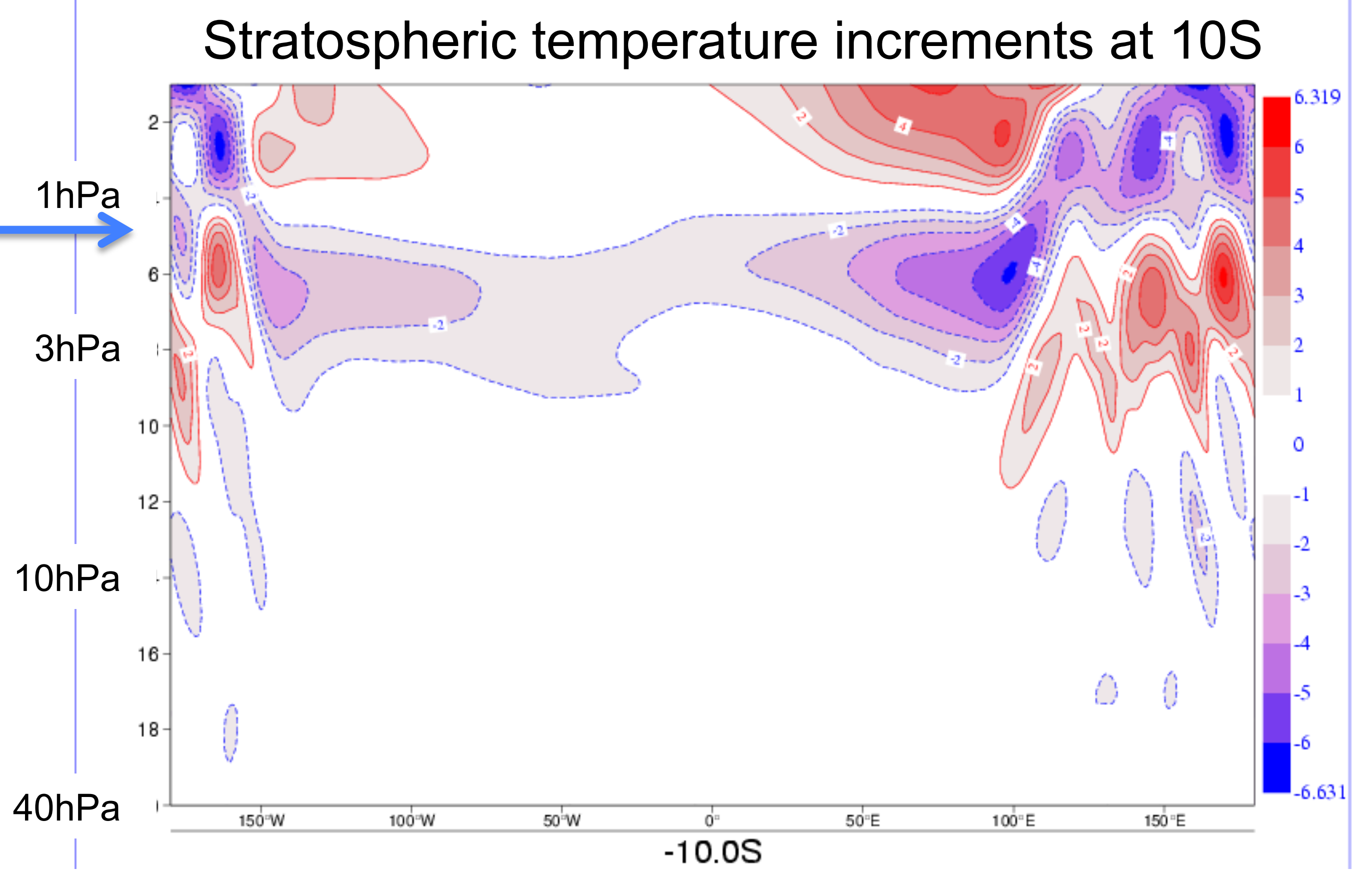

Practical solution: *weak coupling*

(long-term: *better models*)

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Toward a consistent reanalysis of the climate system *(Dee et al, BAMS 2014)*

Main challenges:

- Consistent means physically plausible, e.g. surface fluxes, energy budgets → need to use coupled atmosphere-ocean models with strongly coupled data assimilation
- Very poorly observed, especially the ocean → need to constrain model drifts and prevent spurious effects of data assimilation

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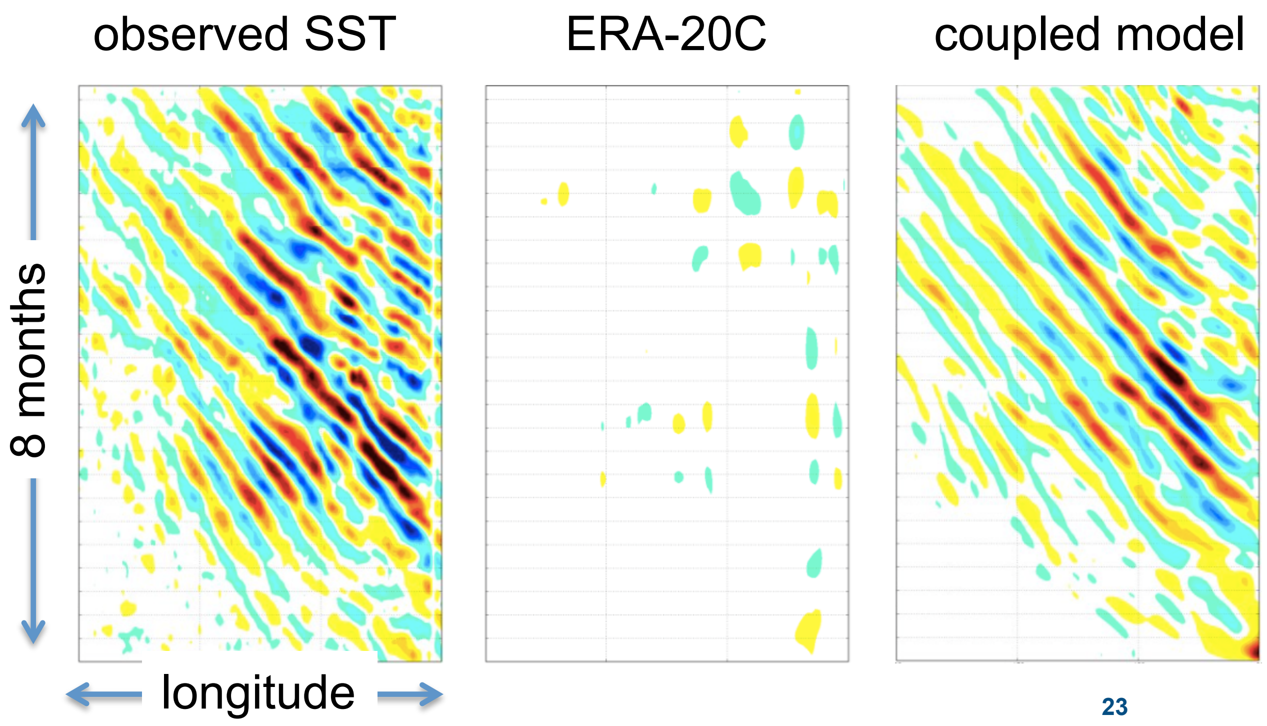
Illustration: Tropical instability waves
(De Boisseson, 2015)

- Equatorial Pacific from April-Dec 2010
- Westward propagation of SST anomalies
- Not captured in HadISST2 monthly, therefore not seen in ERA-20C
- Coupled model nudged to HadISST2 monthly is able to represent TIWs



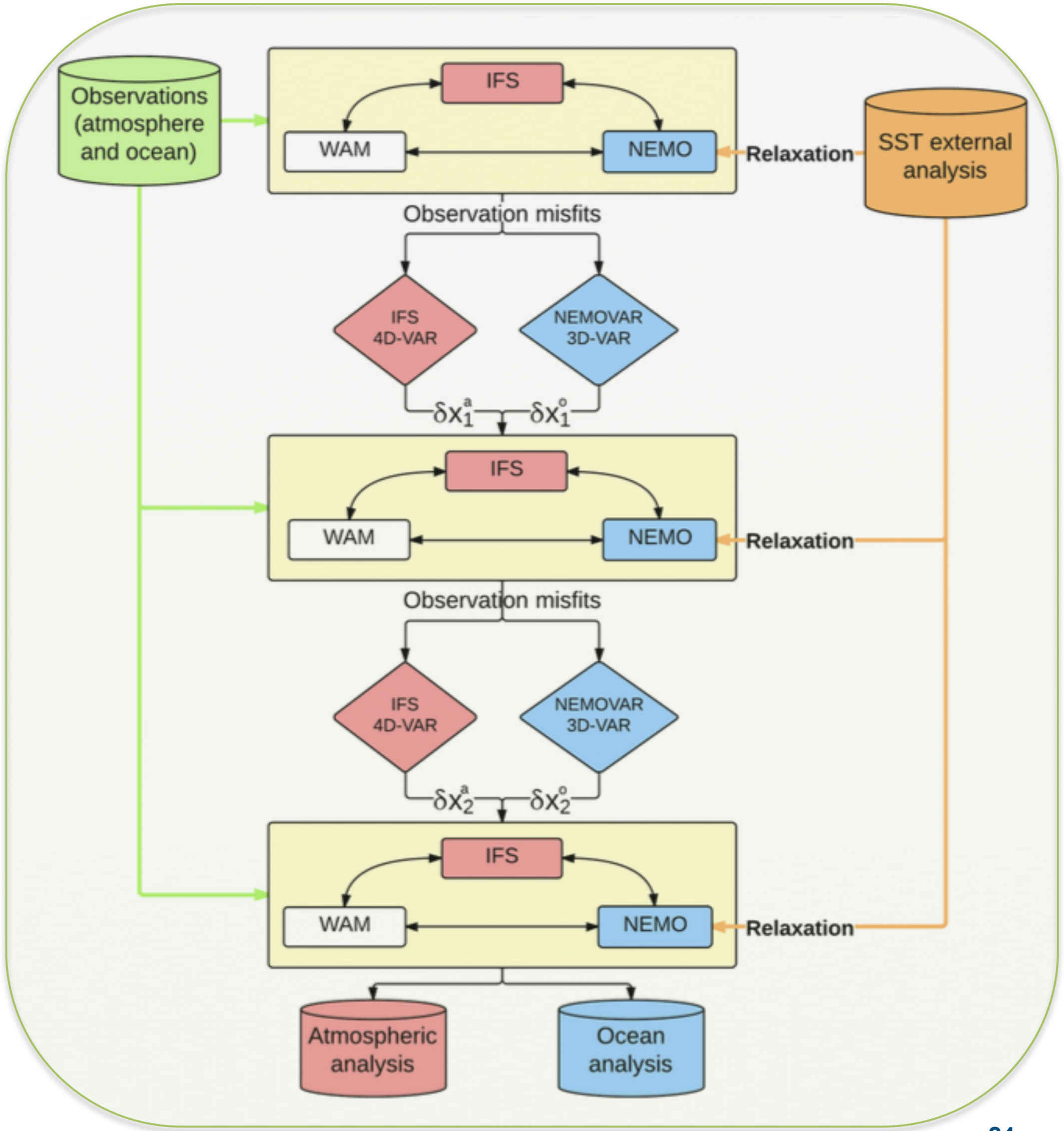
CERA: A coupled data assimilation system for climate reanalysis

Laloyaux et al 2015a

- Coupled variational analysis based on incremental 4D-Var *(Courtier et al 1994)*
- ***Outer loop:*** 24h coupled integration to evaluate the 4D-Var cost function
  - ***Inner loop****:* Linearised variational increments for atmosphere and ocean state components
- Converges toward coupled 4D-Var:

$$\mathbf{x}^a - \mathbf{x}^b = \mathbf{B}\left(\frac{\partial \mathbf{h}}{\partial \mathbf{x}}\bigg|_{\mathbf{x}=\mathbf{x}^a}\right)^T \mathbf{R}^{-1}\{\mathbf{y} - \mathbf{h}(\mathbf{x}^a)\}$$

- ***Bias constraint:*** Scale-selective nudging to monthly SST estimates

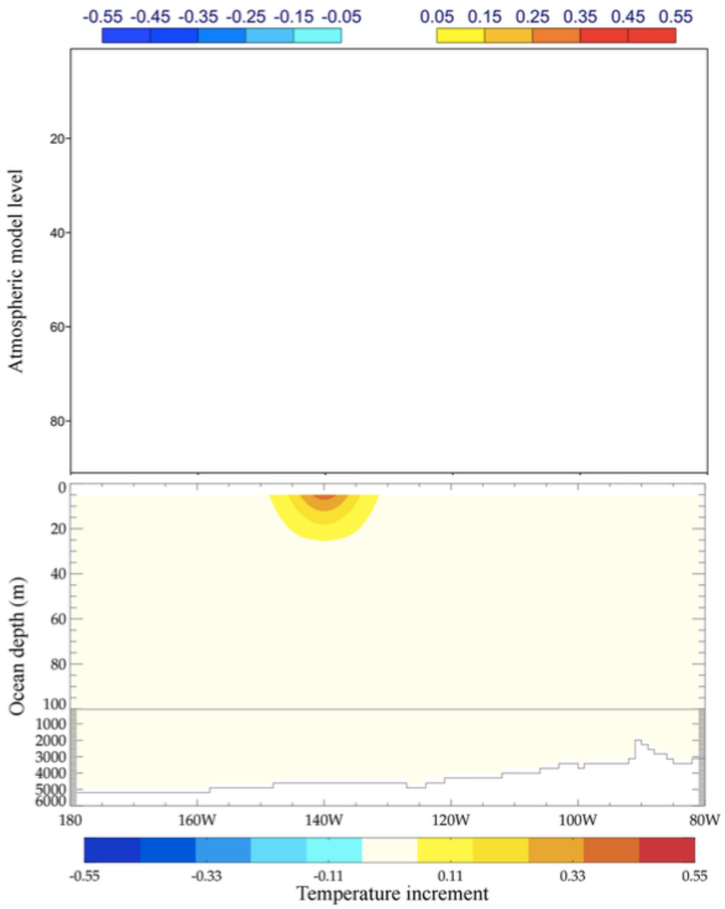


CERA: Impact of a single observation of ocean temperature at 5m depth

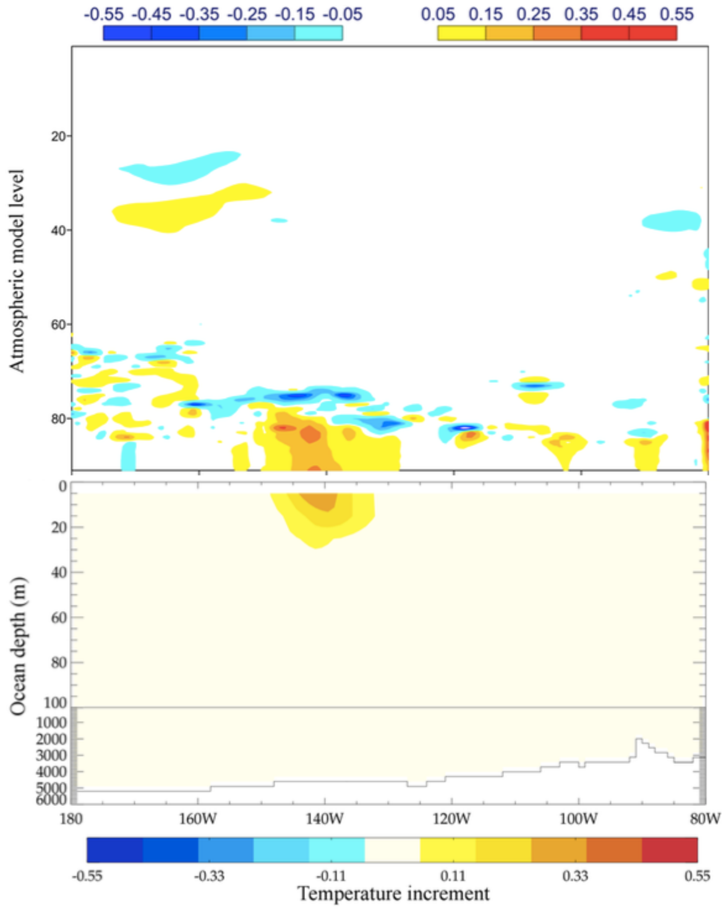
atmosphere

ocean

Temperature change at t=0h



Temperature change at t=24h



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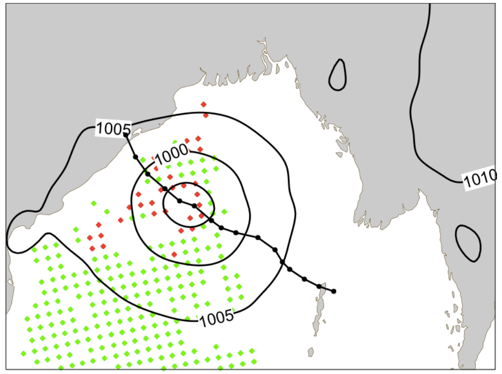
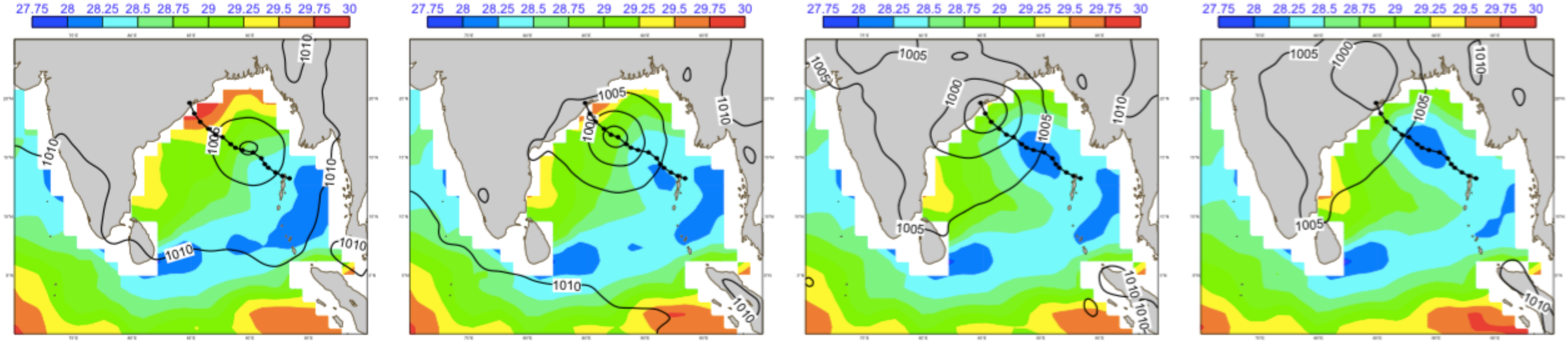
CERA: A case study

- Tropical Cyclone Phailin
- Assimilation of scatterometer wind data



Laloyaux et al 2015b

CERA analysis of the Sea Surface Temperature



10 October 2013 | 11 October 2013 | 12 October 2013 | 13 October 2013

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CERA: A case study

Laloyaux et al 2015b

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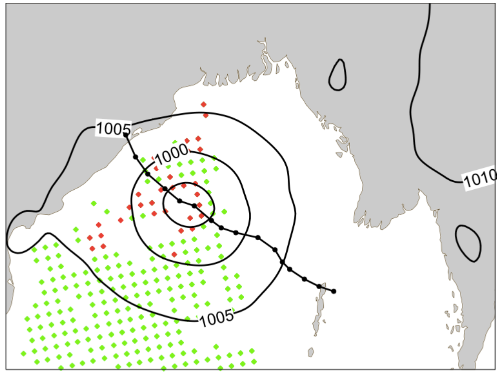
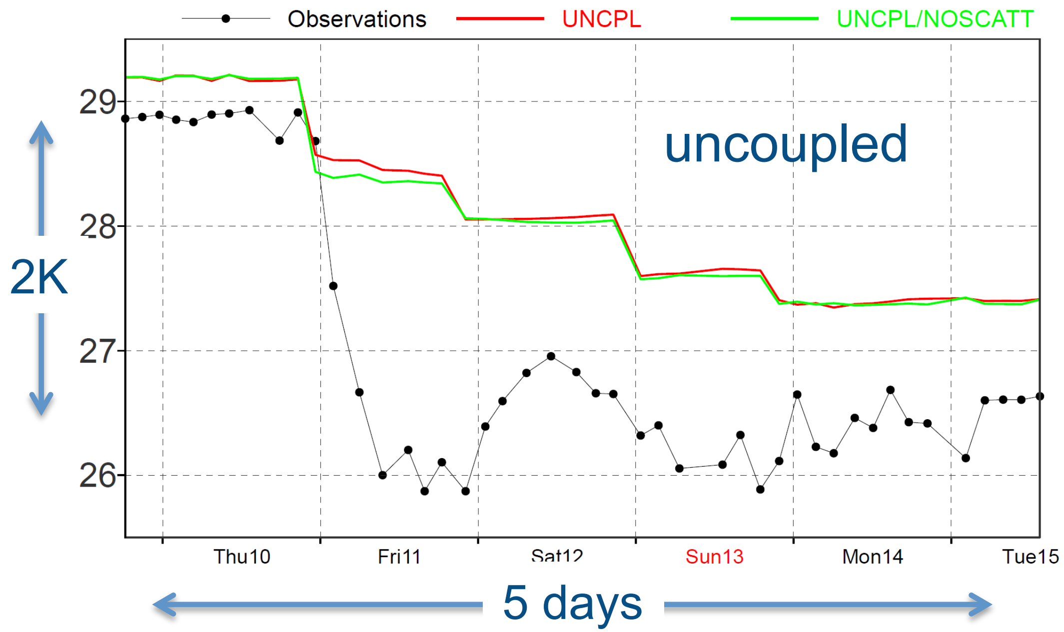
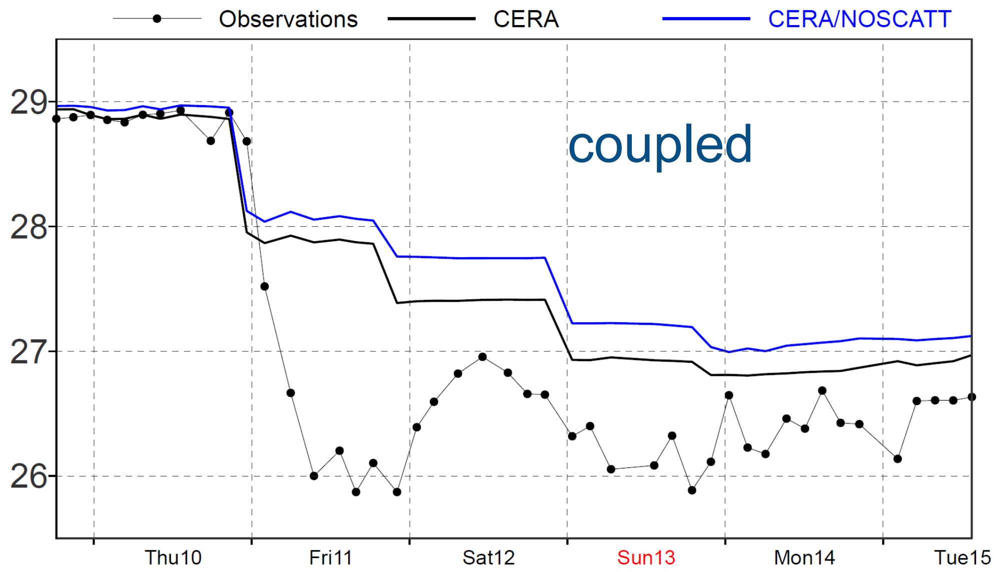


Impact of surface wind observations on ocean temperature at 40m depth





Summary

- The ultimate goal is to create a seamless reconstruction (reanalysis) of the climate system, making use of all available observations
- Requirements for climate science: Consistent surface fluxes; closed energy budgets
- In principle this requires coupled models and strongly coupled data assimilation
- In practice we need extra constraints in order to deal with lack of observability and model biases