Applications of Data Assimilation in Earth System Science

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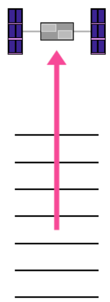
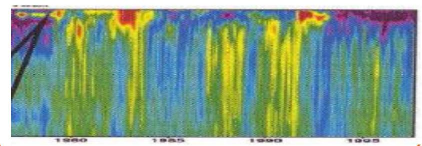
University of Reading, UK

Applications of data assimilation in the geosciences

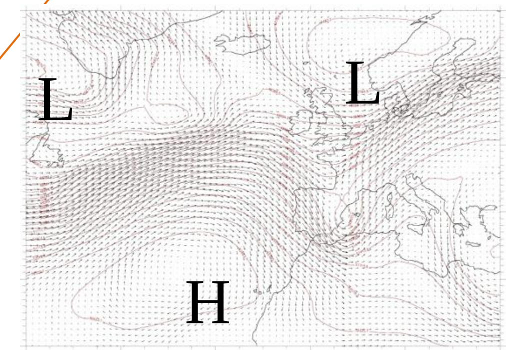
Atmospheric retrievals

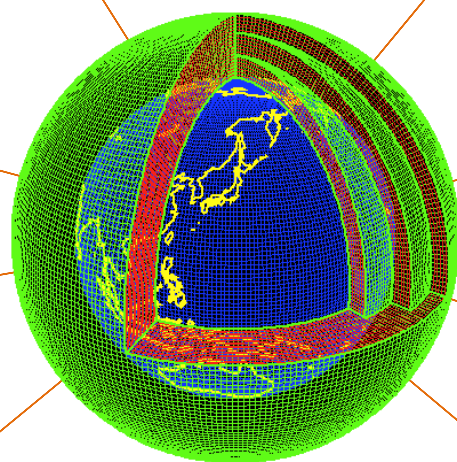


Reanalysis

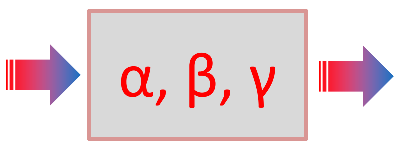


Atmospheric dynamics / NWP

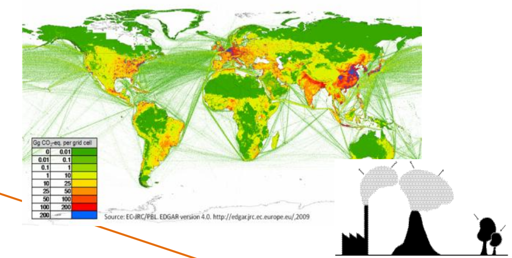




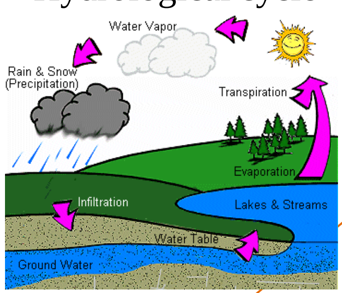
Parameter estimation



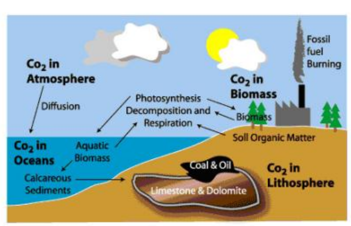
Inverse modelling for sources/sinks



Hydrological cycle

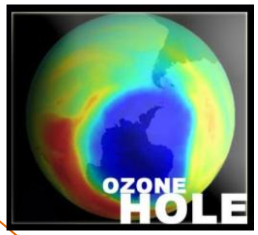


Carbon cycle



Oceanography

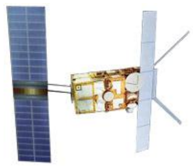
Atmospheric chemistry

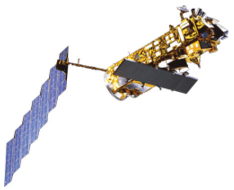


2050 VISION

- By 2050 the Earth will be viewed from space with better than 1km/1min resolution
- Computer power will be over 100,000 times greater than it is today
- To exploit this technological revolution, the world must be digitised

Digital World





What users get

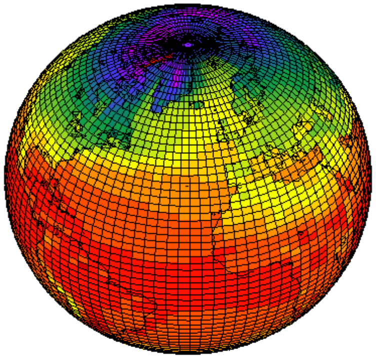
High-tech Sampler

What end-users want

Level 2 for individual sensor

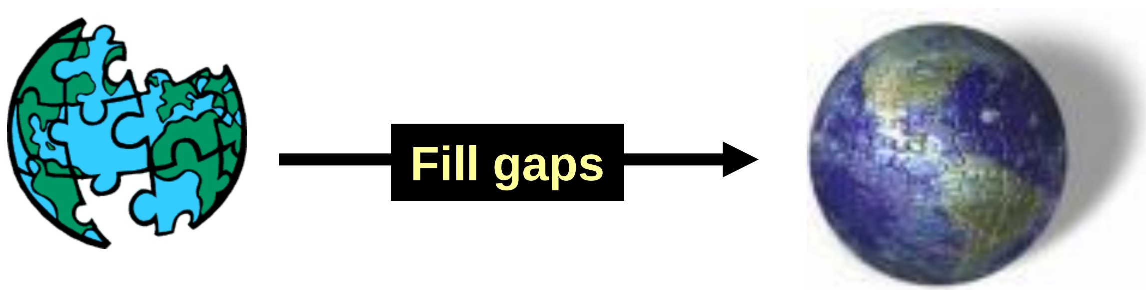
Synthesis via Assimilation of EO data into Earth System Model

4D digital movie of the Earth System



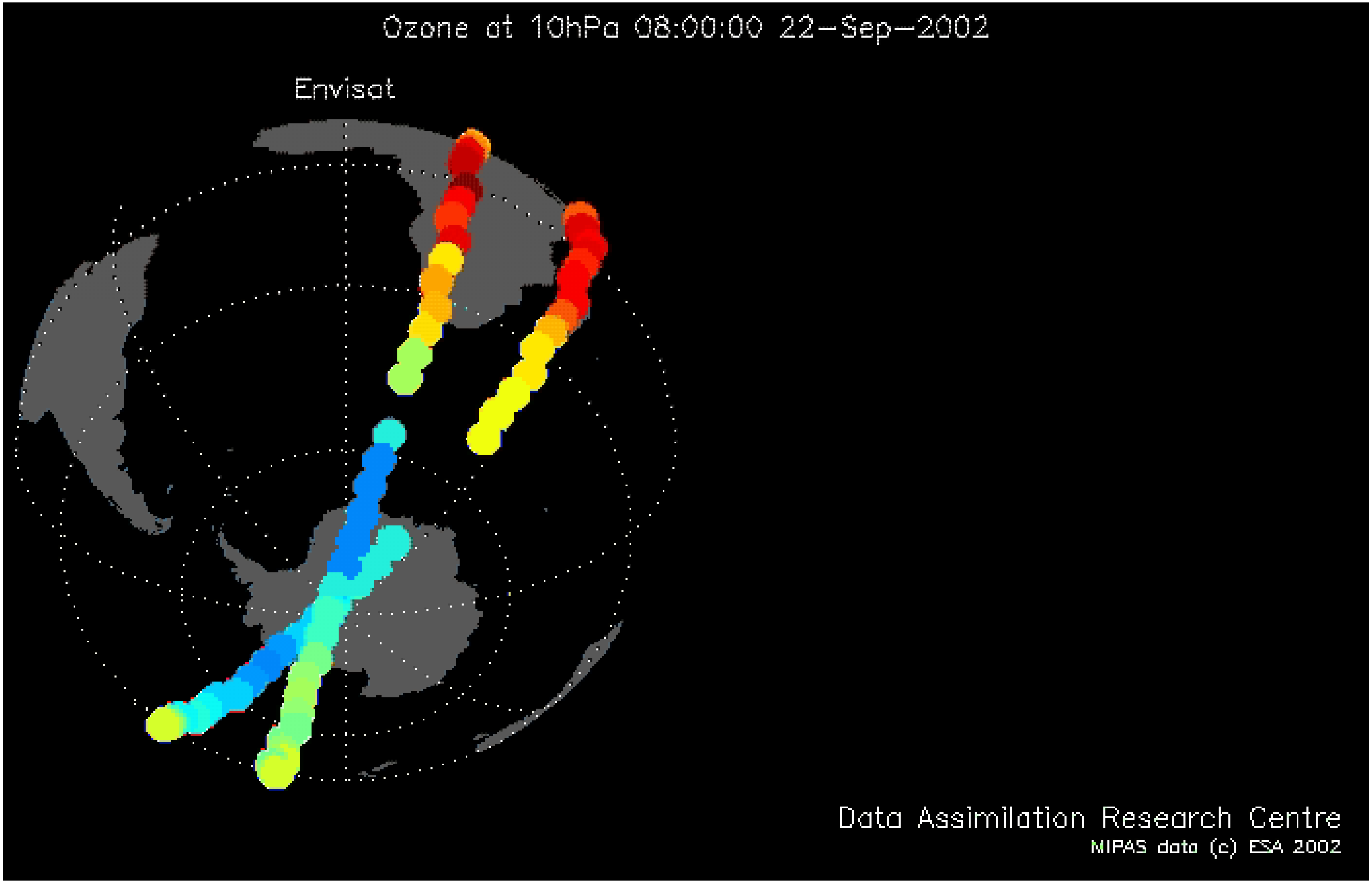
State Estimations & Physical Interpolation

**EO data provide a global view ……
but have a limited & sequential sampling …..**



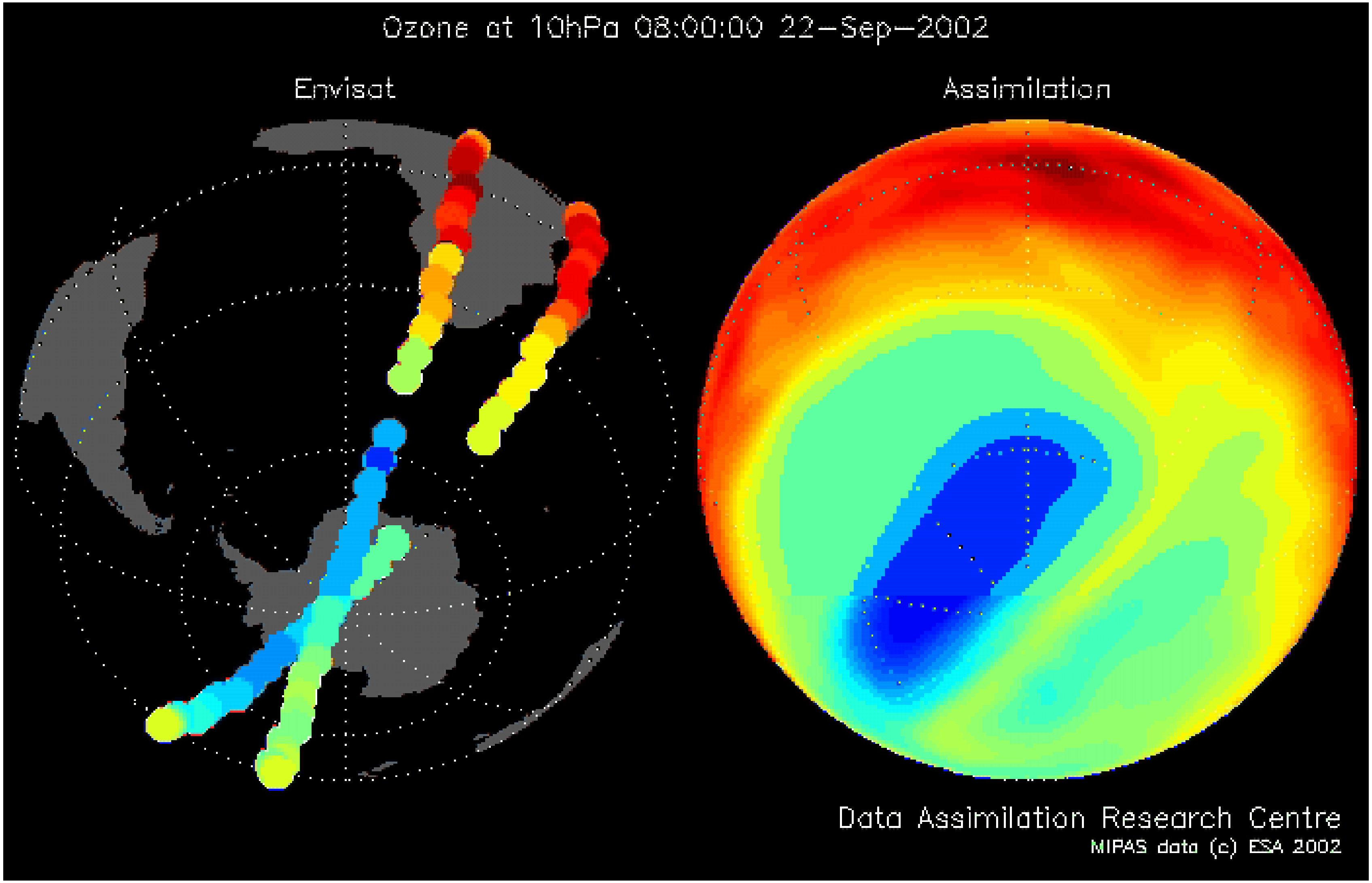
Assimilation of data into models provides an optimal synthesis of heterogeneous observations taking account of errors and dynamical principles …

Chemical analysis

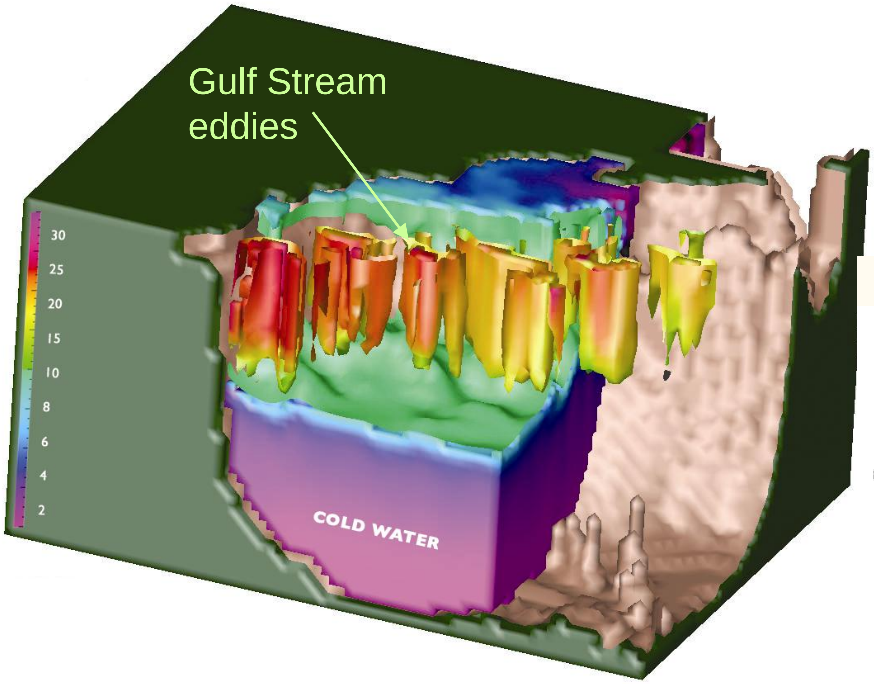


O_3 measured by MIPAS/Envisat

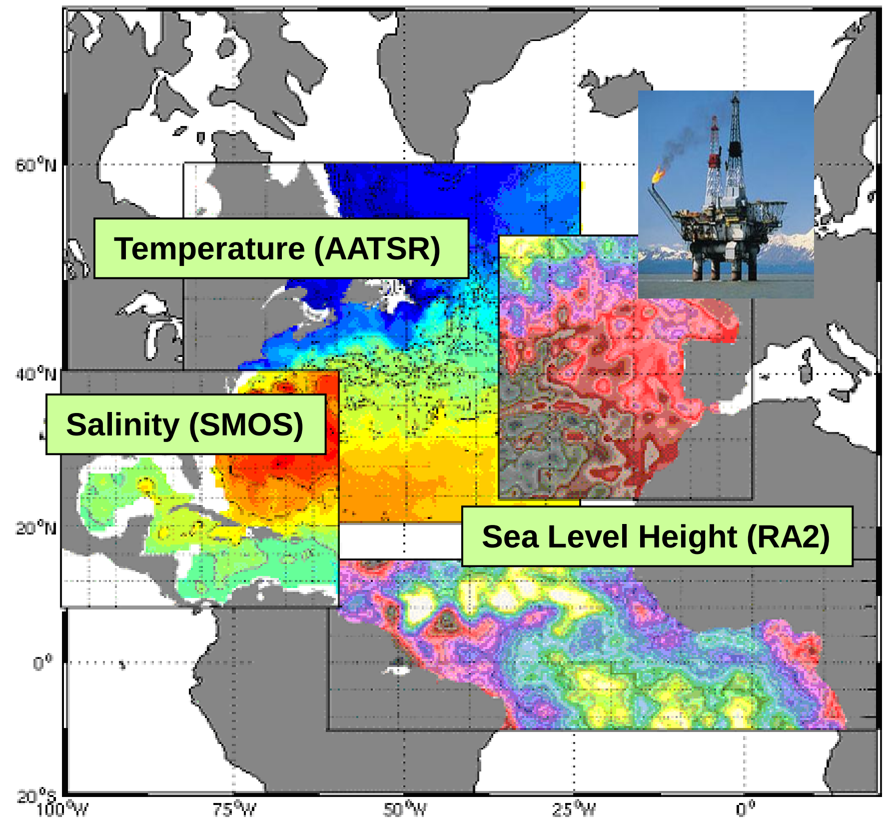
Assimilation of O3 data into GCM



Operational oceanography



Model dynamics transports EO information from surface (data-rich region) to depth (data-poor region).

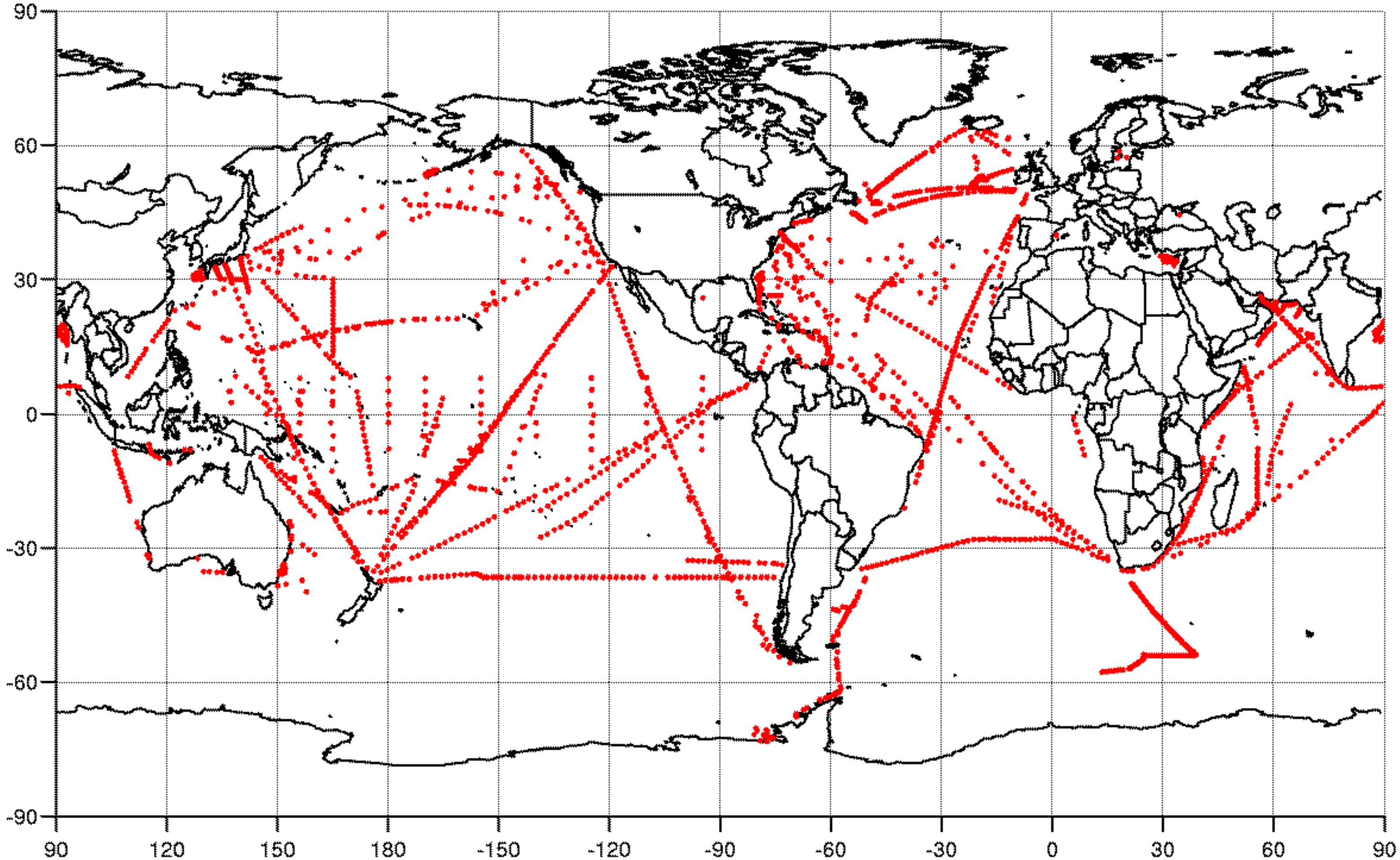


Assimilation of EO data into ocean models provides the best available quantitative picture of the ocean state.

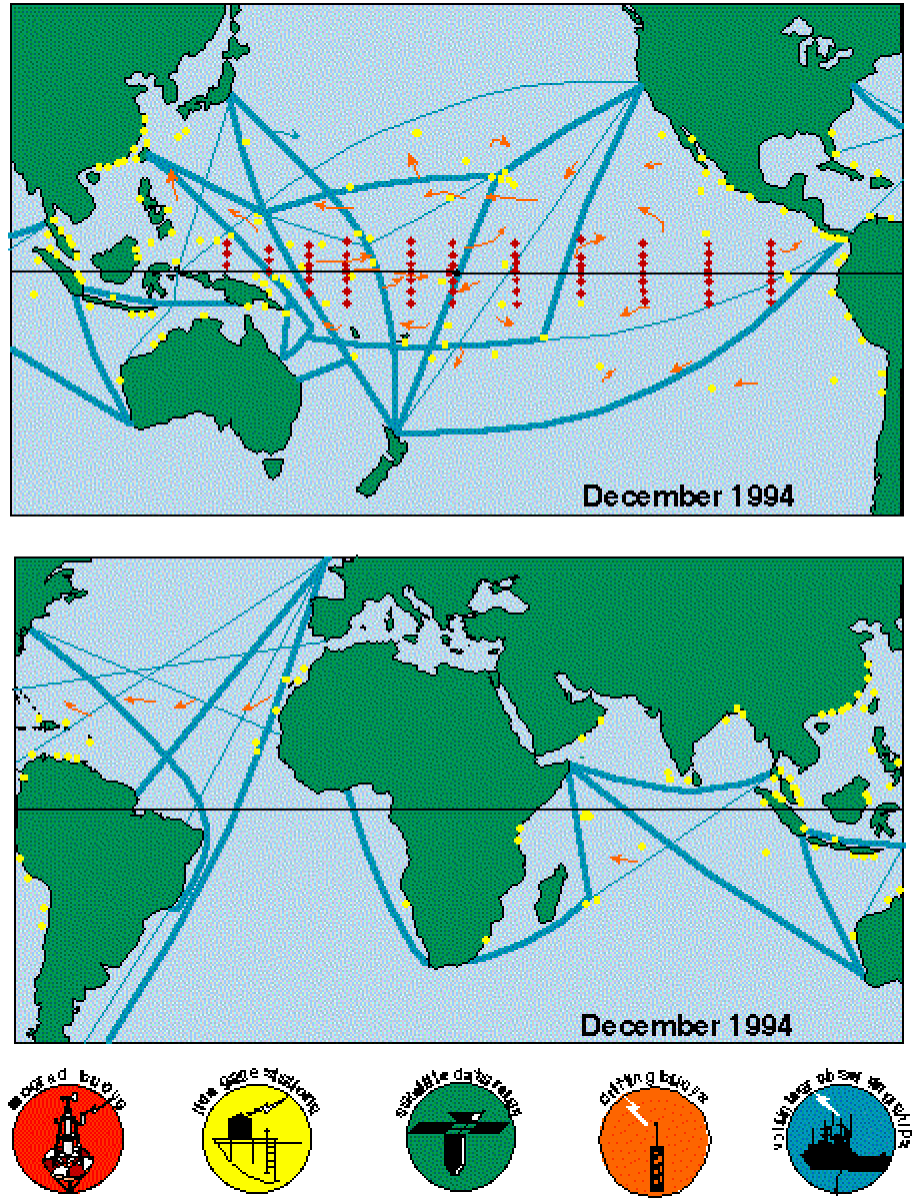
Essential building block for the development of operational marine services (ROSES).

Courtesy LEGI

XBT data assimilated in March 1996.

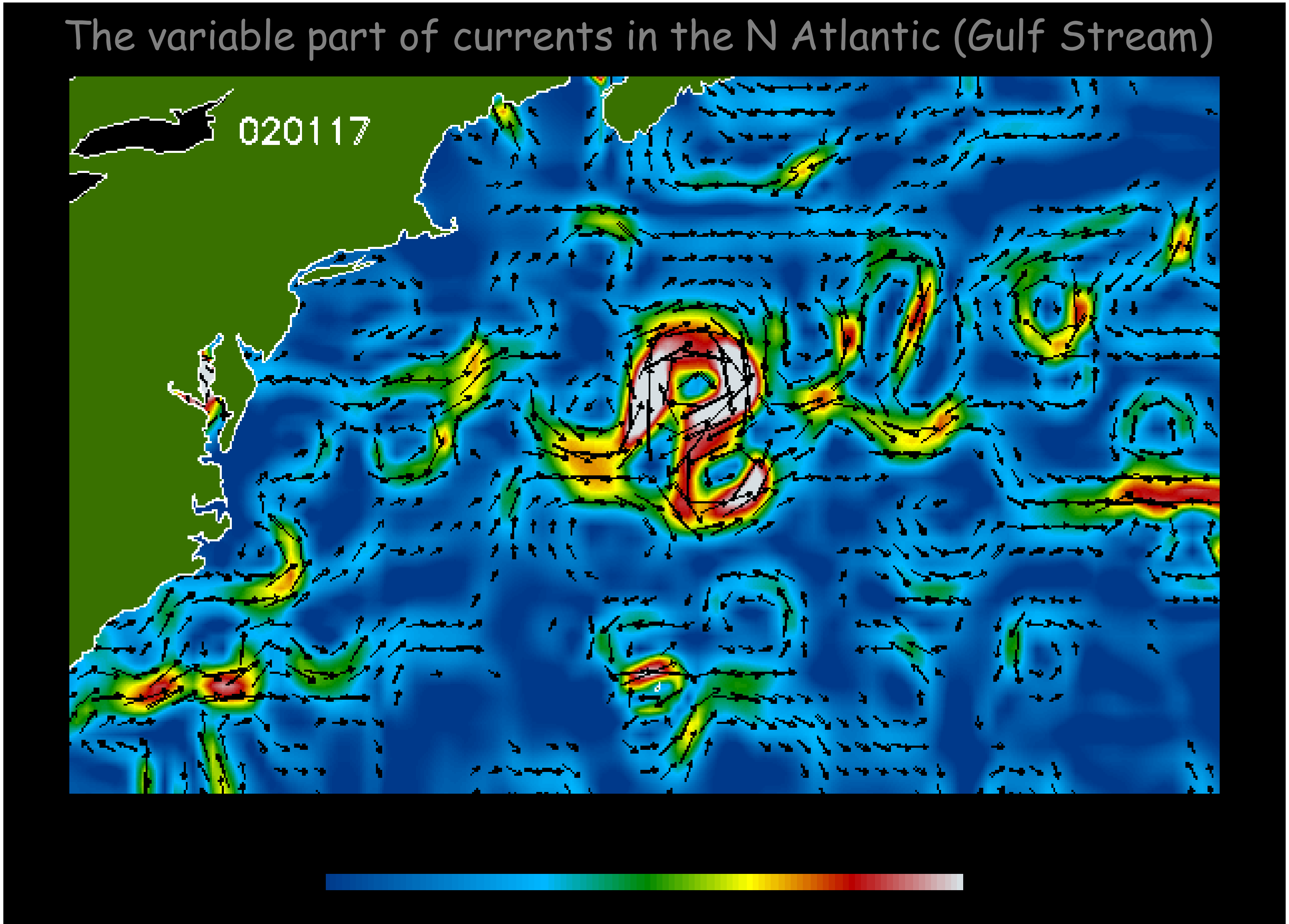


TOGA In Situ Ocean Observing System
Global Tropics

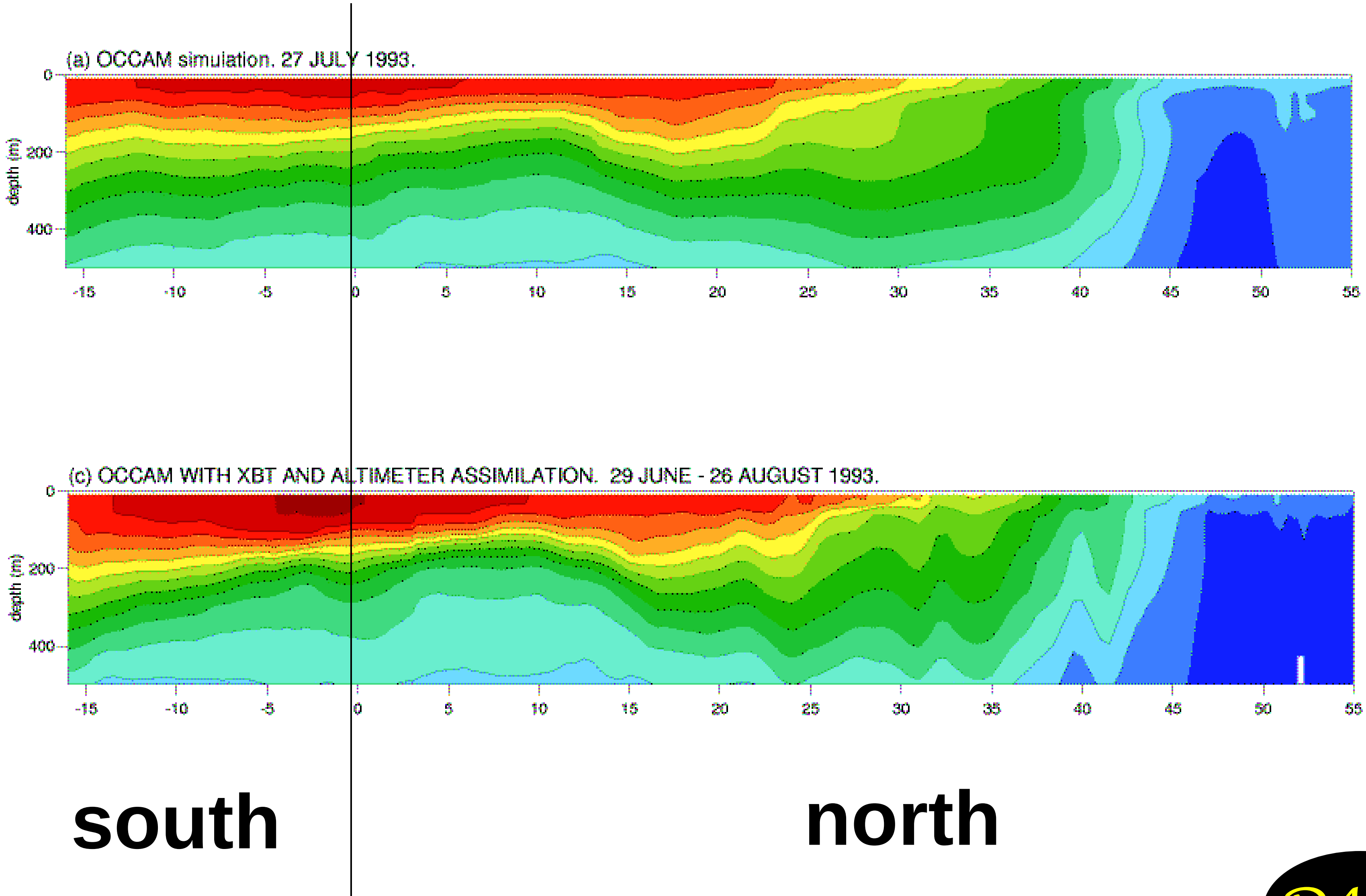


- Note that absolute currents (the non-variable field) will be measurable once the ocean Geoid is known

Geoid from GOCE

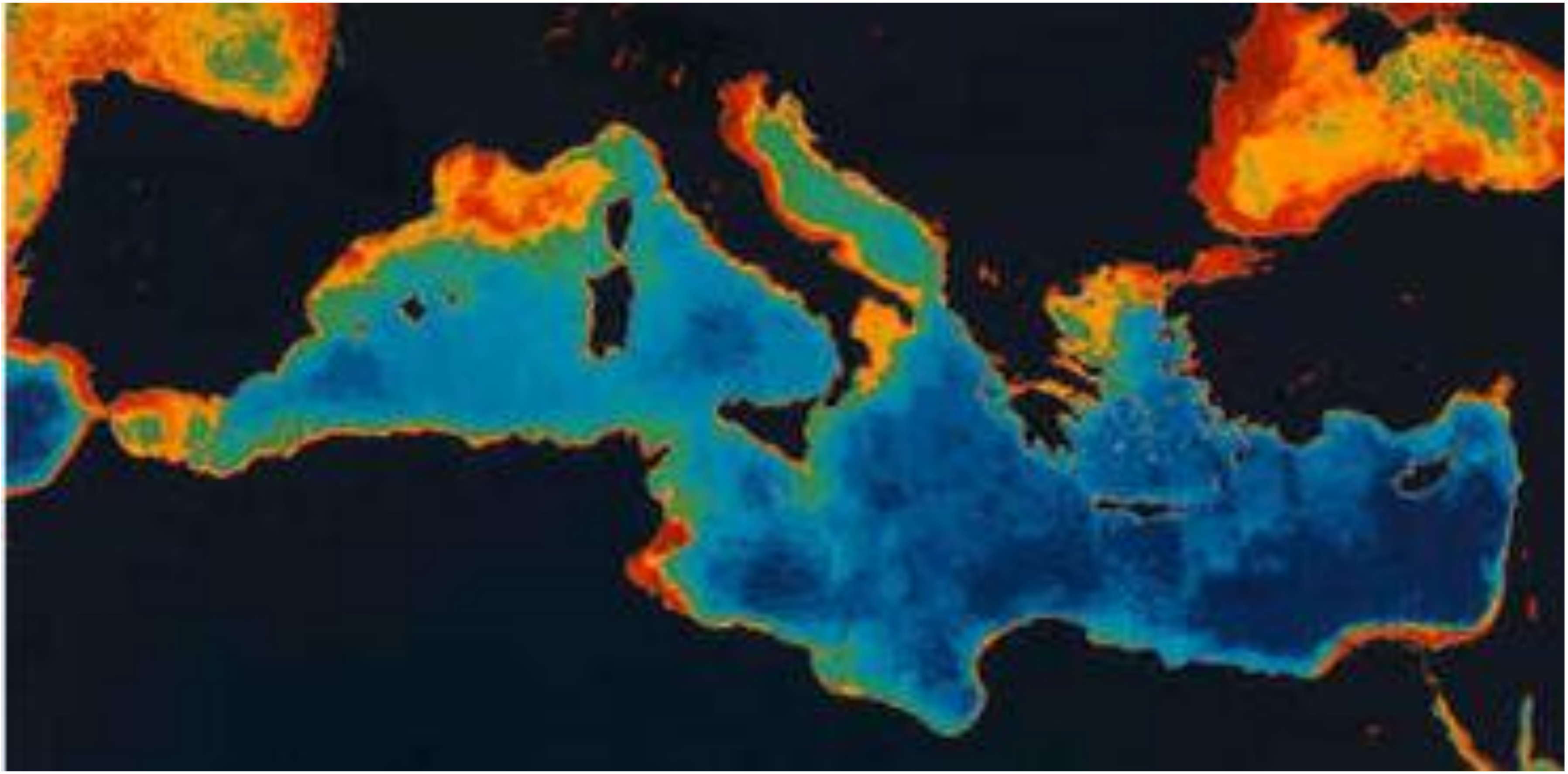


Cross-section in mid Atlantic

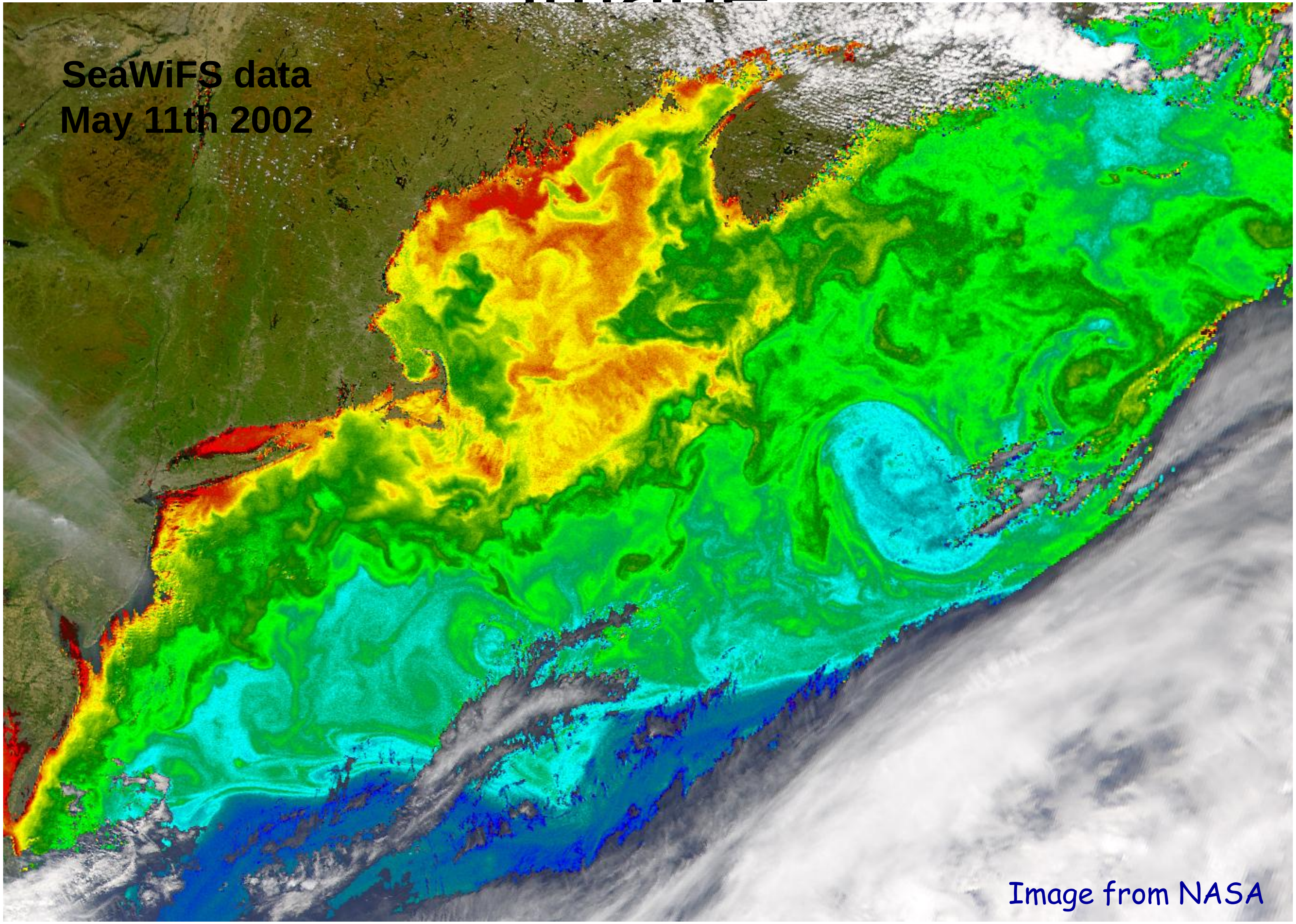


DARC

MERIS ocean colour

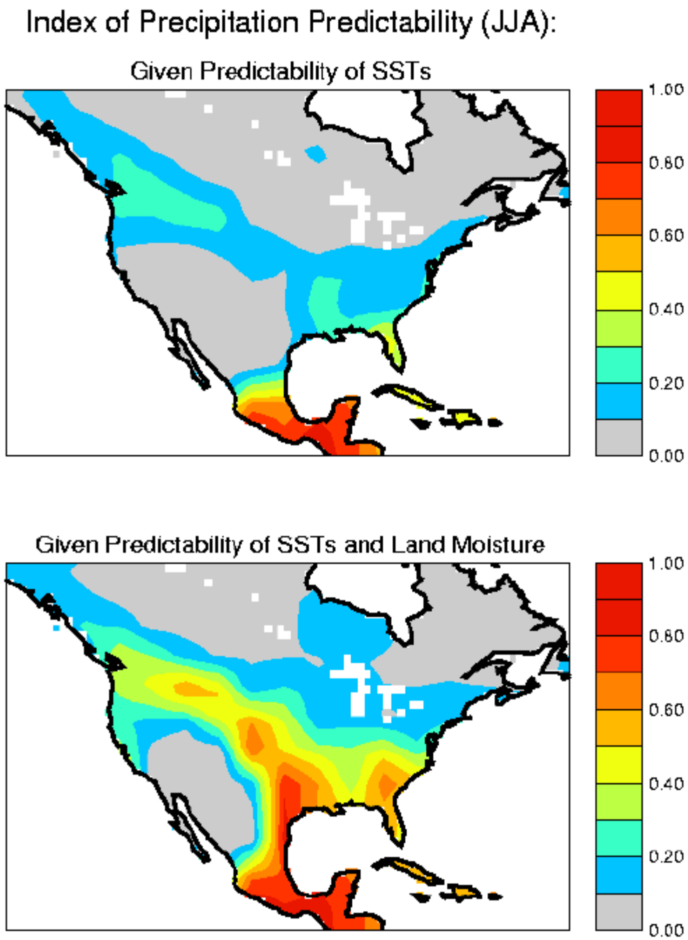


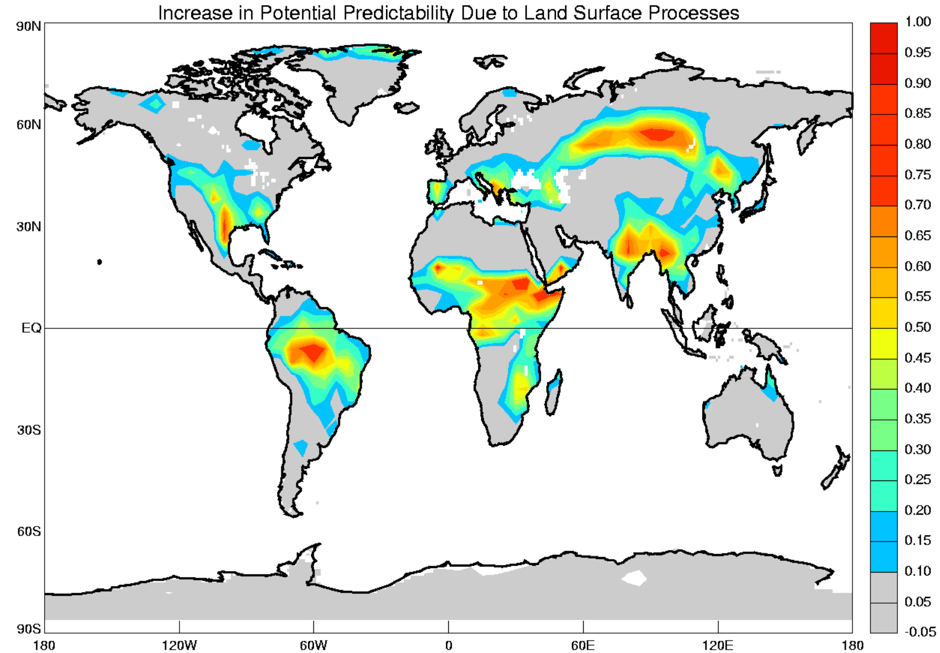
Ocean eddies in a chlorophyll image

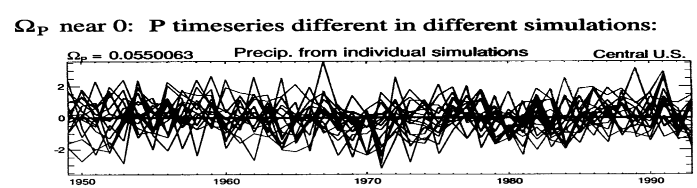


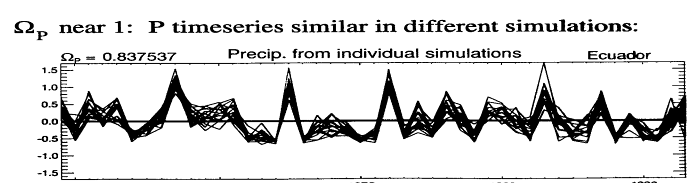
Land Initialization: Motivation

- Knowledge of soil moisture has a greater impact on the predictability of summertime precipitation over land at mid-latitudes than Sea Surface Temperature (SST).



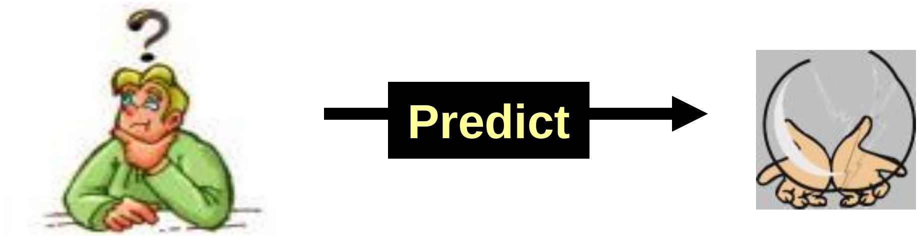




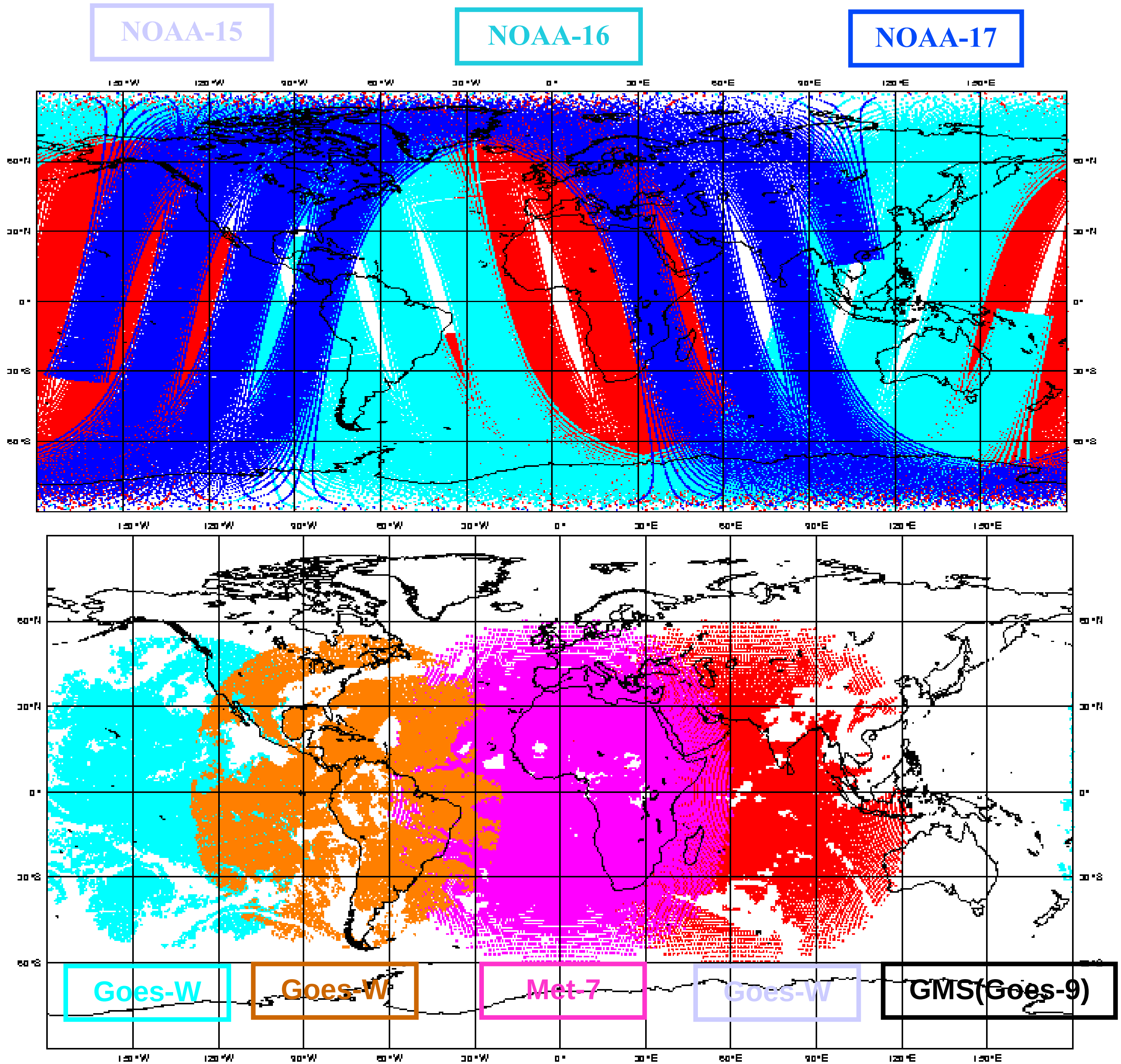


Environmental Forecasting

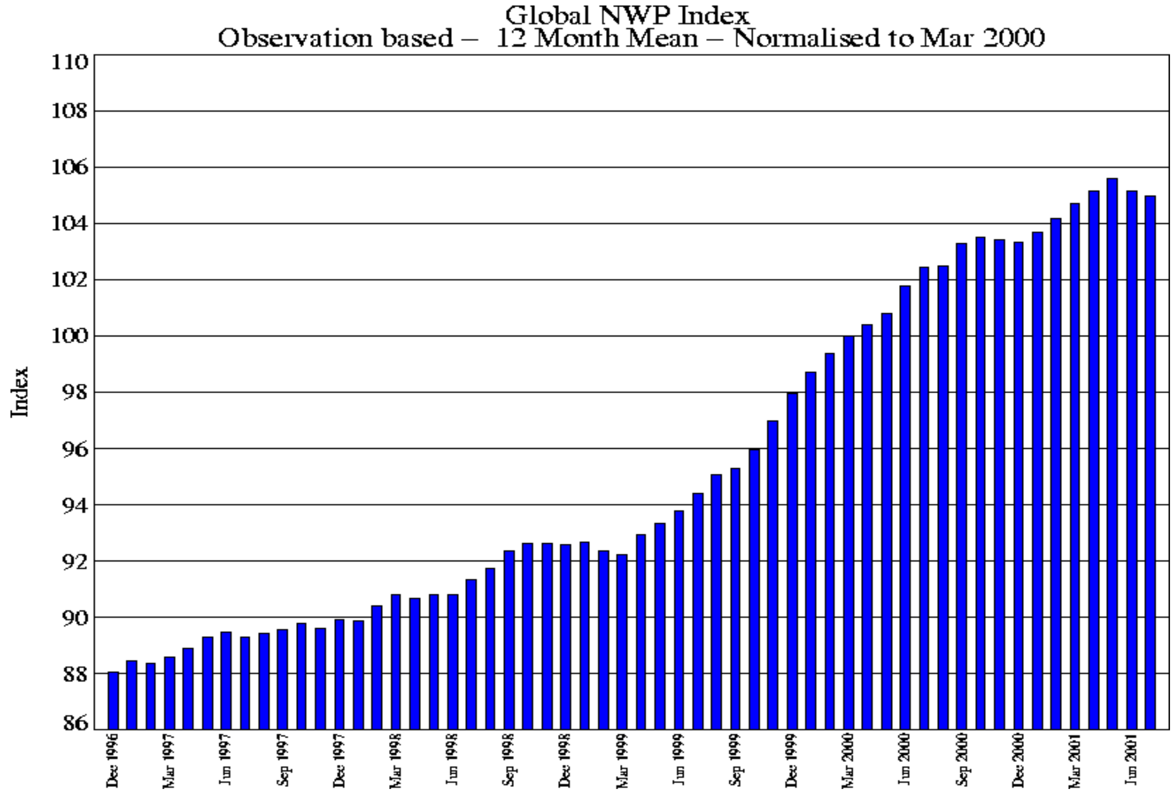
EO data are critical for monitoring the global environment but managing risks requires forecasts .....



Assimilation of data into models is at the heart of operational prediction ....


NOAA-15
NOAA-16
NOAA-17
Goes-W
Goes-W
Met-7
Goes-W
GMS(Goes-9)

Impact on NWP at the Met Office



Mar 99. 3D-Var
and ATOVS

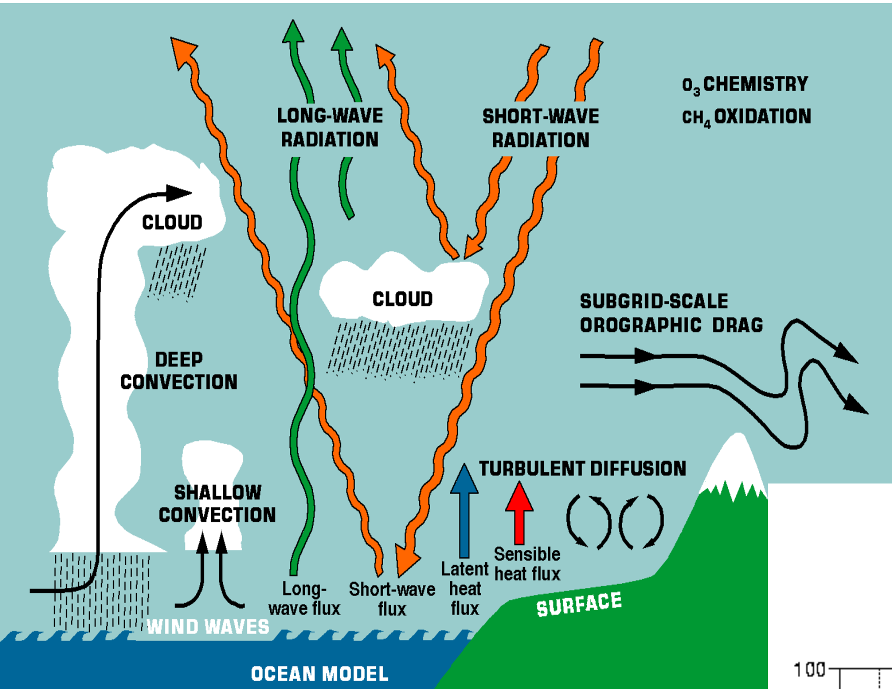
Oct 99. ATOVS as radiances,
SSM/I winds

Feb/Apr 01. 2nd satellites,
ATOVS + SSM/I

Jul 99. ATOVS over Siberia,
sea-ice from SSM/I

May 00. Retune
3D-Var

Weather forecasting

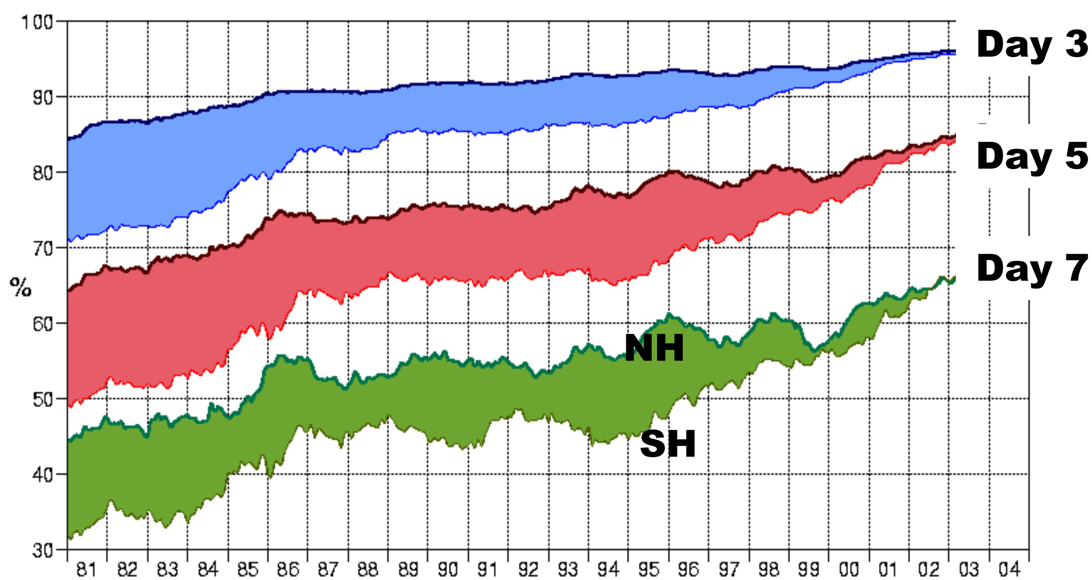


Numerical Weather Prediction:

- Sophisticated atmospheric models.
- Most mature assimilation techniques (able to ingest sounding radiances).
- Very big user of EO data.

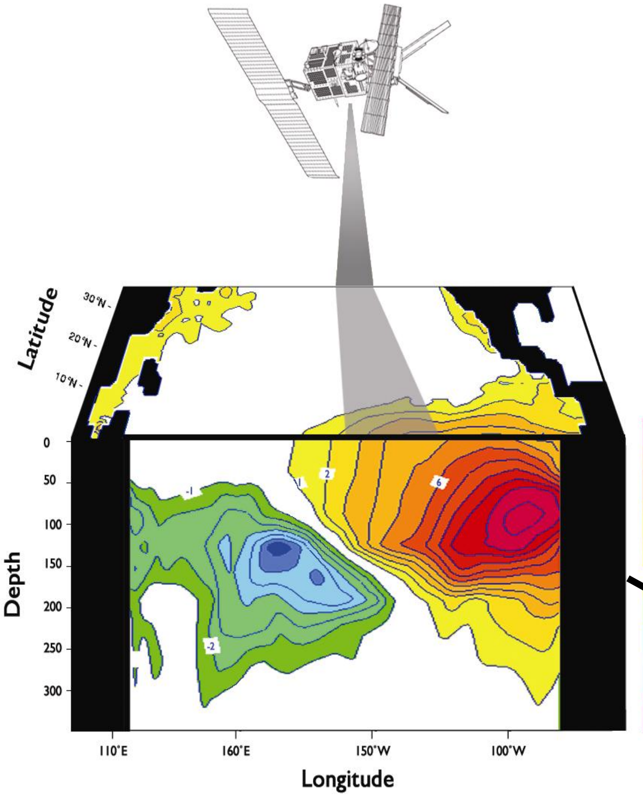
Satellite data have contributed to the continuous improvement of forecast quality with enormous benefits for society.

NWP Forecast Skill

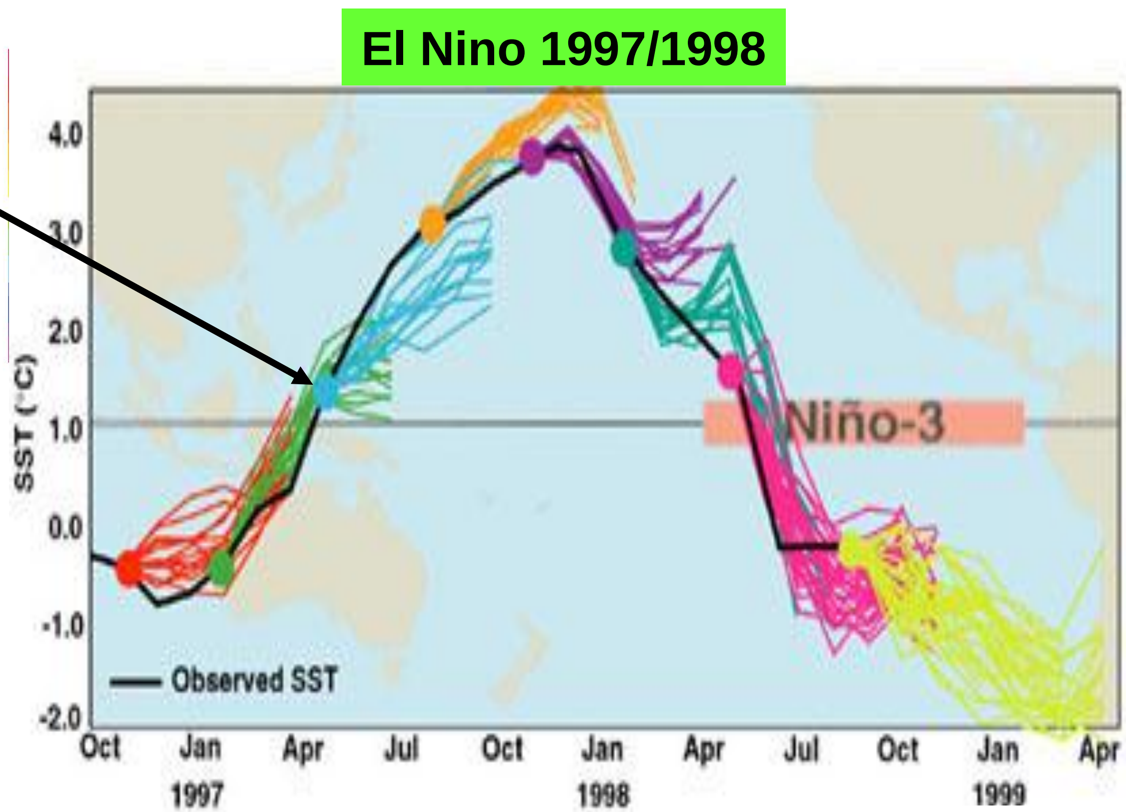


Seasonal Prediction

Coupled models are now routinely used to make probabilistic prediction of the mean state of climate several months ahead. Enormous potential for EO!.



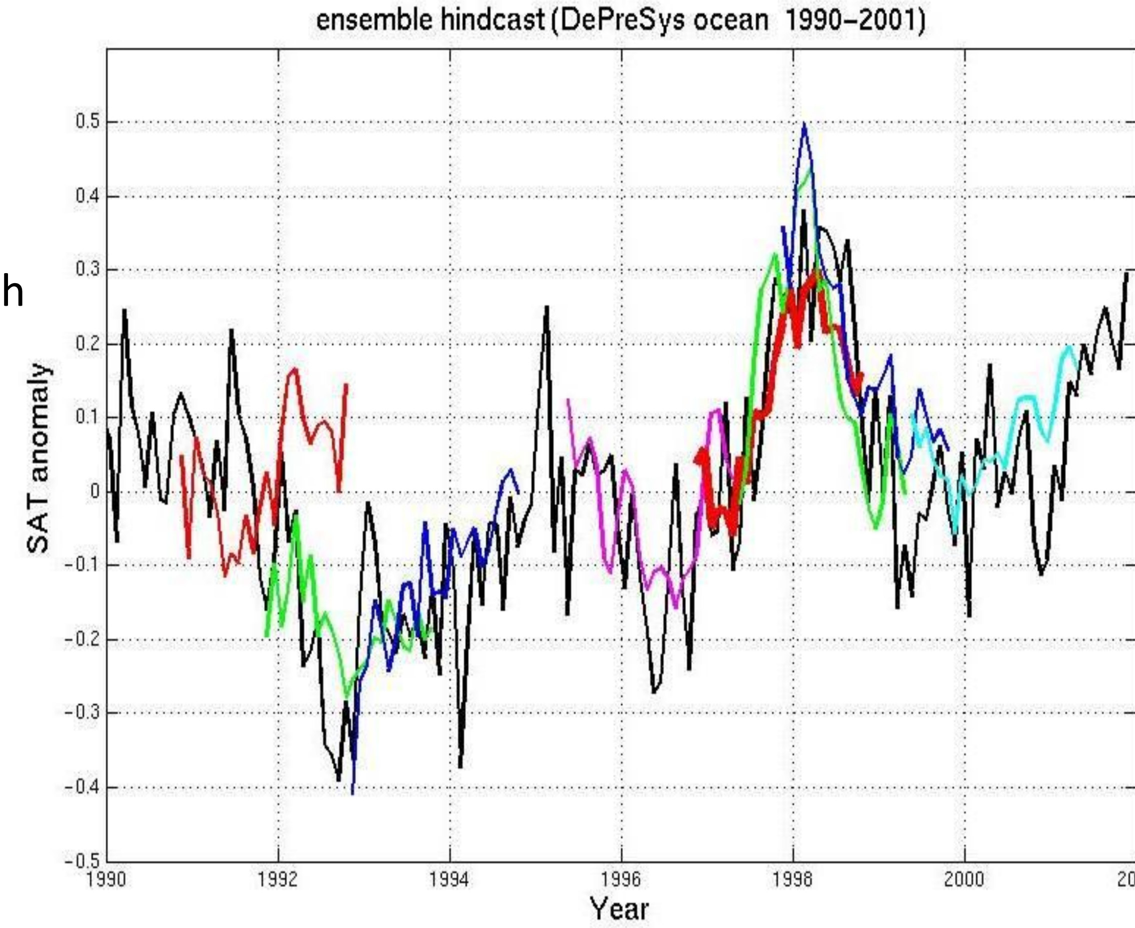
High-quality ocean analysis are vital to initialise coupled models and make accurate ensemble predictions.



Courtesy ECMWF

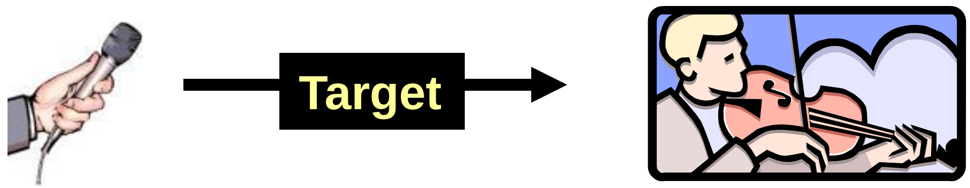
Initialised Climate predictions

- Global Surface Air Temperature hindcasts from HadCM3 (following Smith et al 2007 Science)
  - Black line Obs.
  - Ensemble mean of Nov 2-year hindcasts



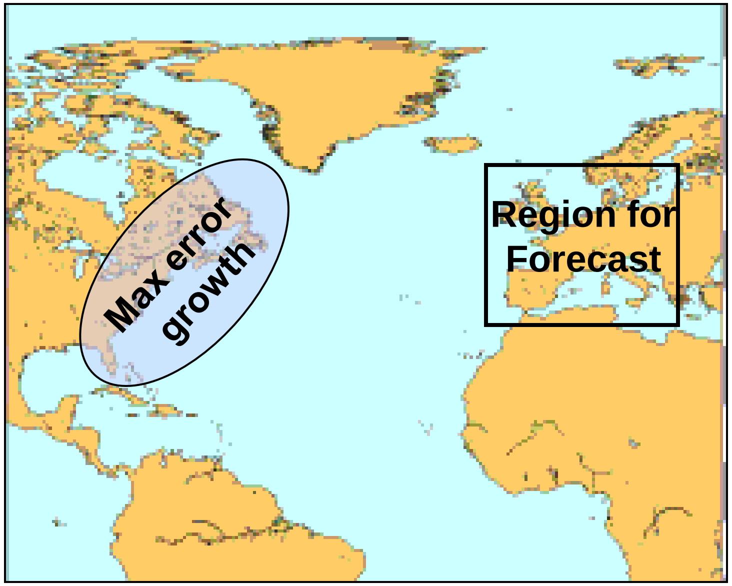
Observing System Design

Observing systems should help to advance our current state of knowledge …..



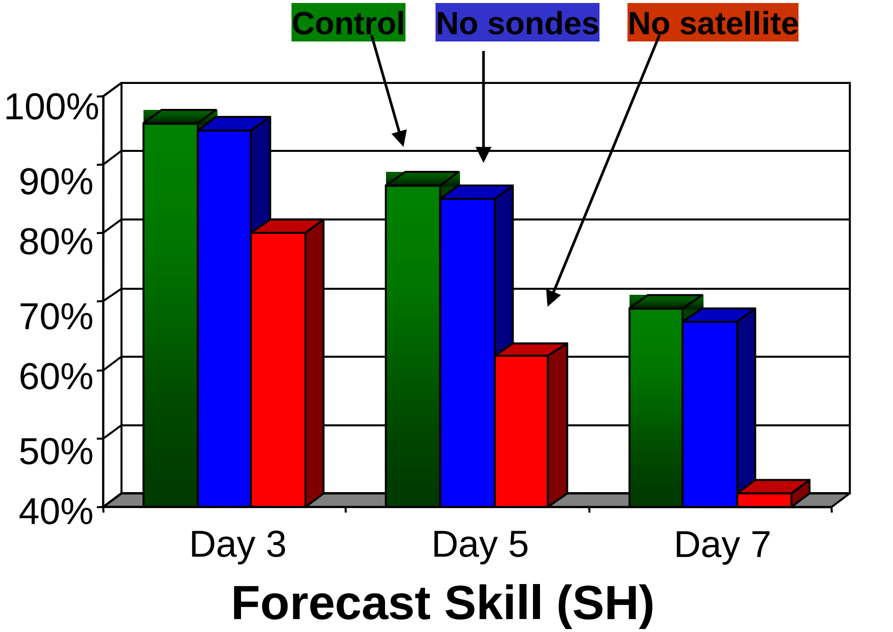
Model sensitivity experiments allow us to target observations and to evaluate objectively the incremental value of EO data. Potential cost savings!

Numerical Laboratory



Where/What should we measure?
Data Assimilation helps to identify sensitive regions where observations would maximise benefits for forecast.

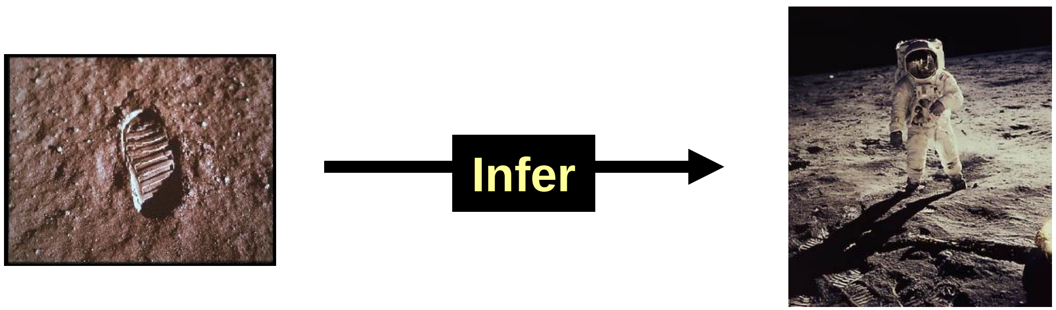
What is the added value of EO?
Observing System experiments help to quantify the impact of withdrawing various (synthetic) data streams on forecast skill (e.g. evaluation of Swift mission before launch!).



Courtesy ECMWF

Inverse Modelling

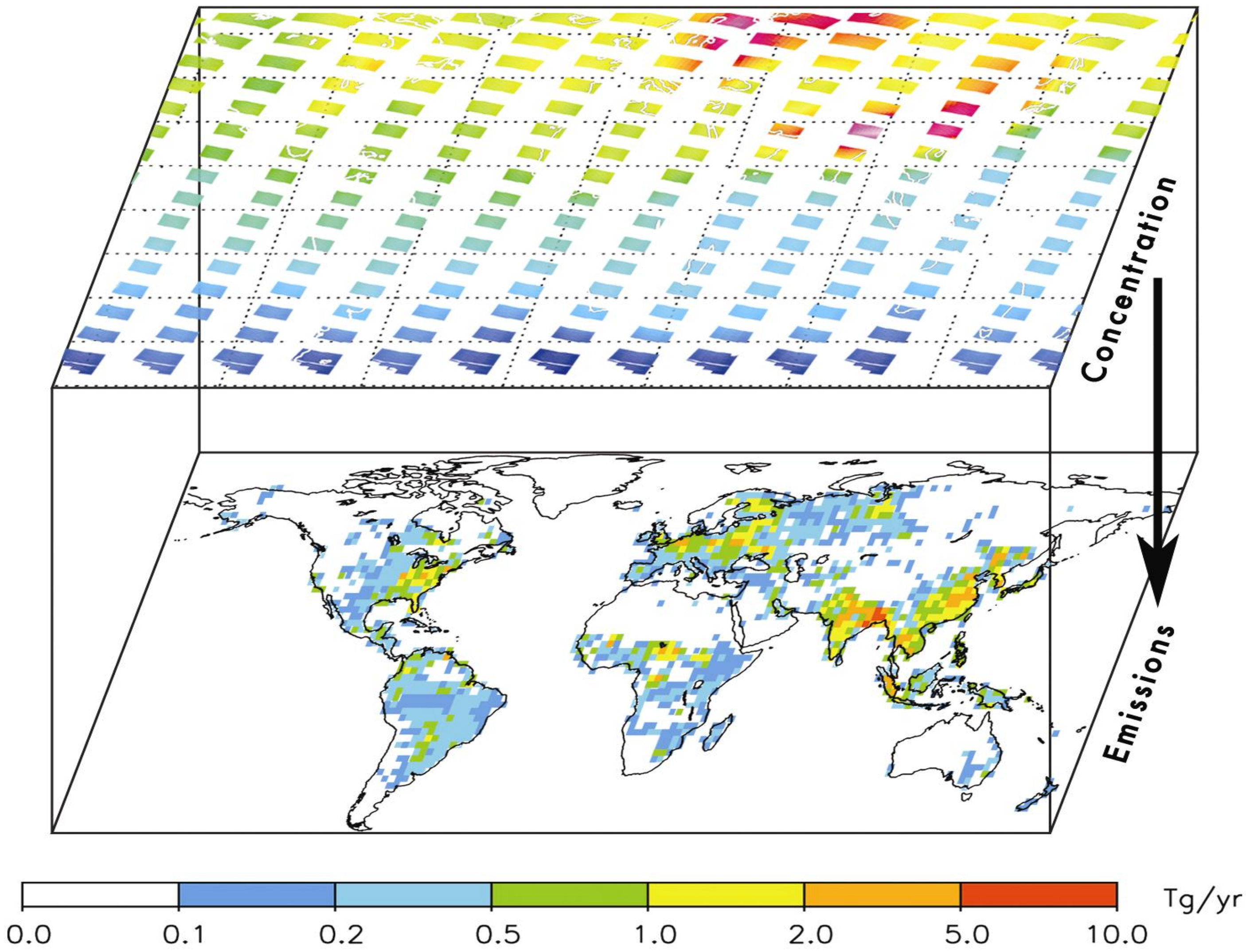
EO provides an indirect measure of the quantity of interest .....



Assimilation of data into models enables to one to infer [non-observable] geophysical quantities of interest by exploiting physical/chemical linkages in the system.

GHG sources & sinks

Models play a diagnostic role by helping to interpret observations (e.g. causal relationships)



Synthetic SCIAMACHY measurements of CH_4 total column

Assimilation into a Chemical Transport model

Methane Emissions (critical for Kyoto inventories)

Courtesy KNMI

Re-analysis

Reanalysis

The need for long atmospheric/oceanic data sets

- Researchers need long, consistent, global 4-d data sets for scientific studies.
- Most researchers do not have access to NWP systems to make data sets for specific needs.

Why reanalysis?

- Over time, models, assimilation systems and available observations change.
- Use observation sets from history and assimilate with one state-of-the-art system.

Reanalysis is good for

- Large-scale variability studies (e.g.)
  - El-Nino, La-Nina, MJO, NAO, monsoons, storm tracks.
- Studies of quantities well modelled and well observed.

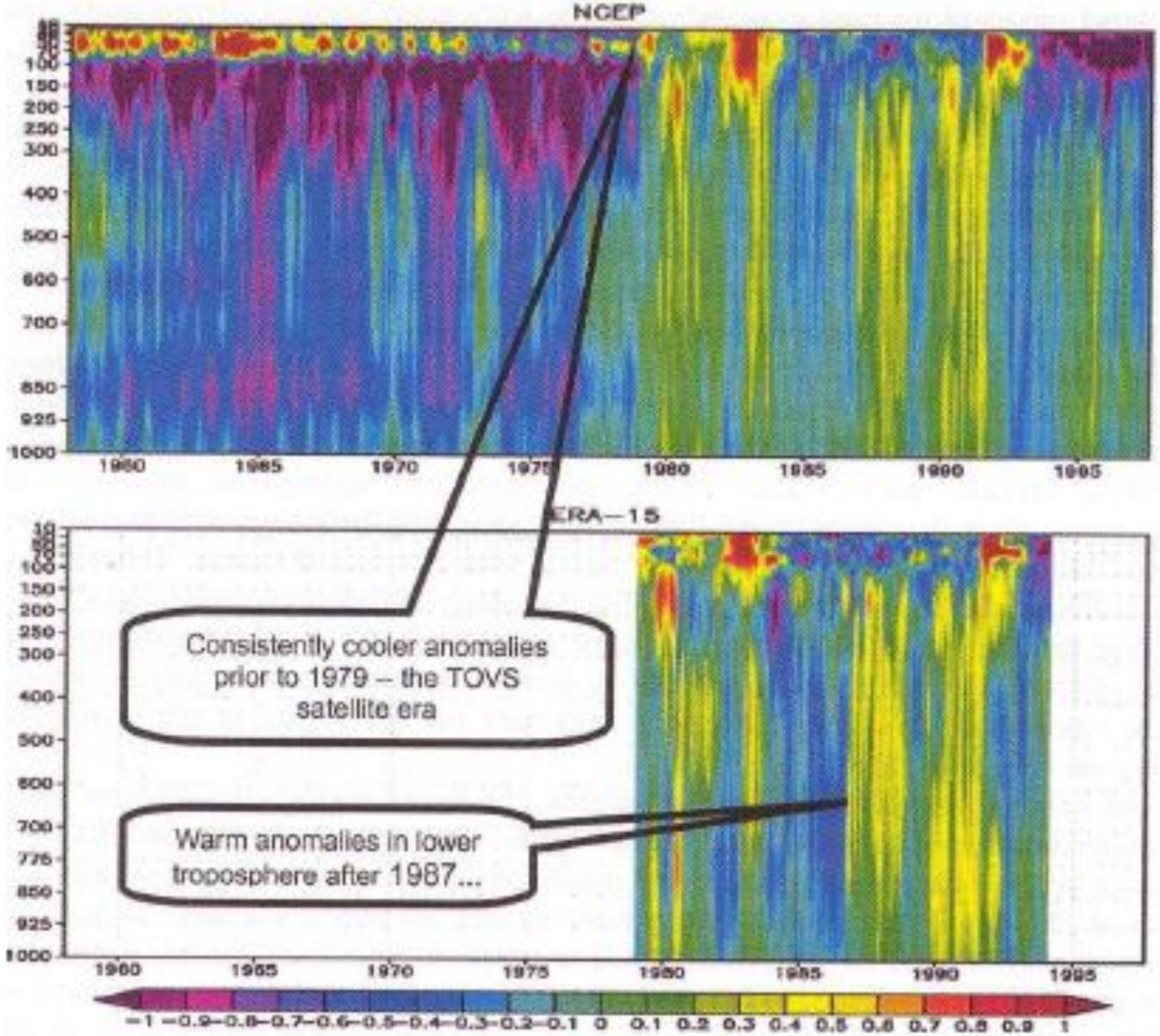
Reanalysis is not good for

- Trend studies (due to changes in observing systems).
- Studies of poorly observed quantities (e.g.)
  - stratospheric water vapour.
- Studies of derived quantities, not constrained by observations (e.g.)
  - divergent wind, clouds, hydrological cycle, surface fluxes, vertical wind.

Leading reanalysis data sets

- NCEP/DOE - atmosphere.
- ECMWF (ERA-15, ERA-40) - atmosphere.
- NASA/DAO - atmosphere.
- JMA (JRA-25) - atmosphere.
- GODAE - planned ocean reanalysis.

Biases cause problems with reanalysis 1



Courtesy, R.Rood (2003)

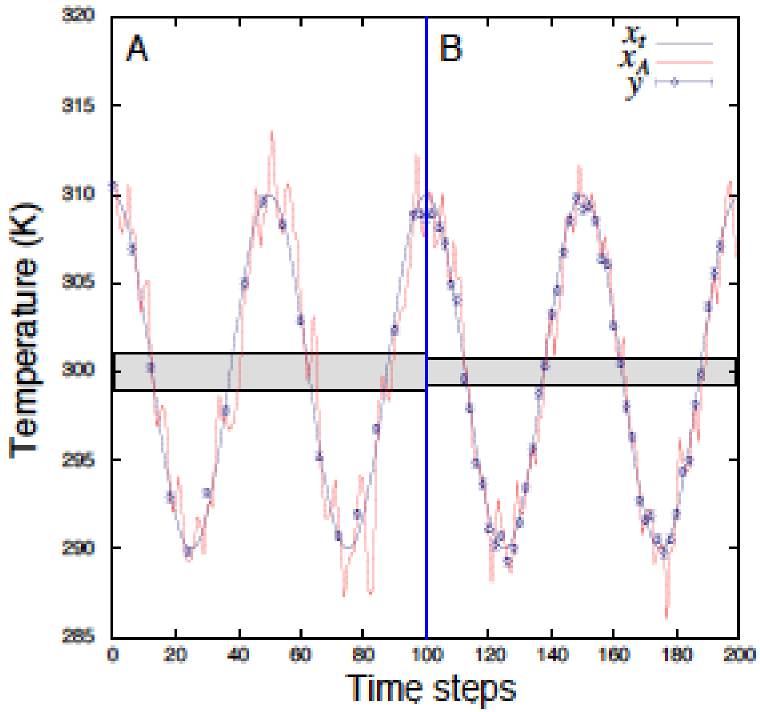
Reanalysis is inappropriate for climate trend studies

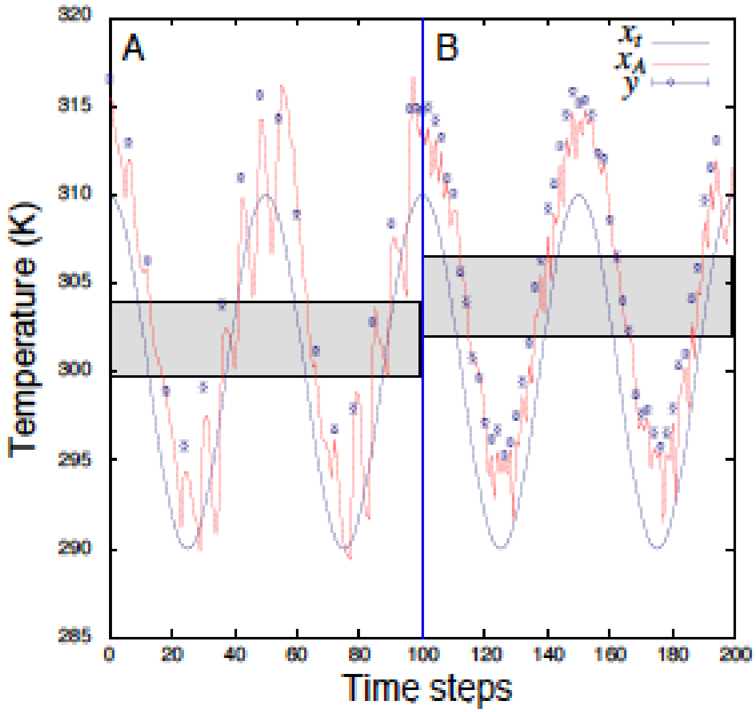
Biases cause problems with reanalysis 2

Consider a jump in frequency of the assimilation of an observation type

If the obs are unbiased, the mean error reduces.

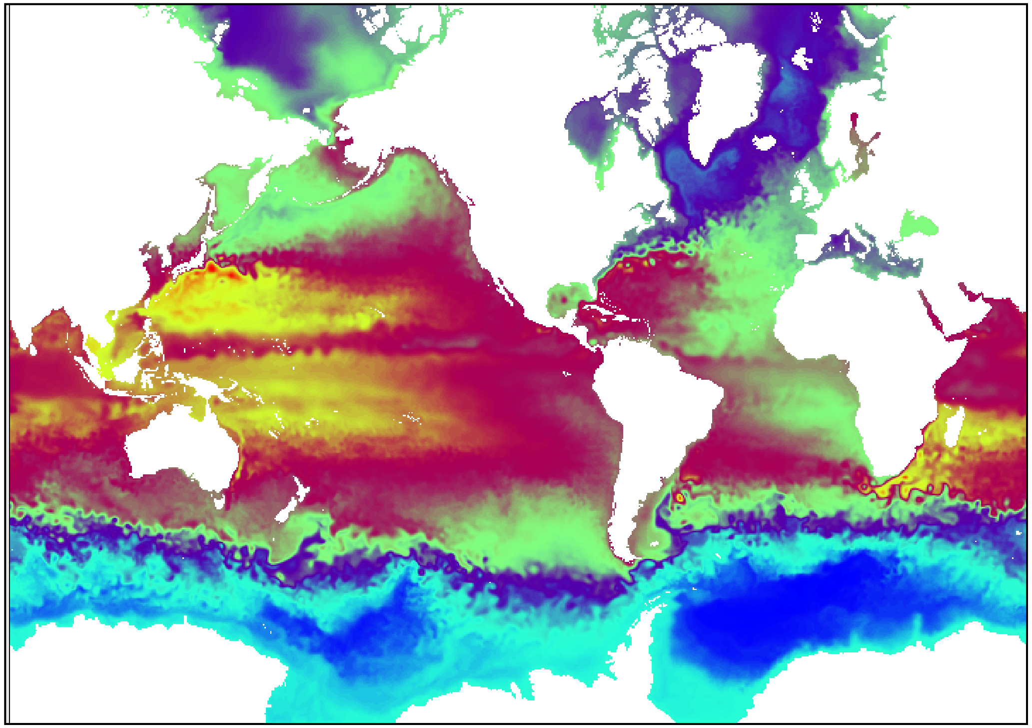
If the obs are biased (6K) , the mean error can increase.

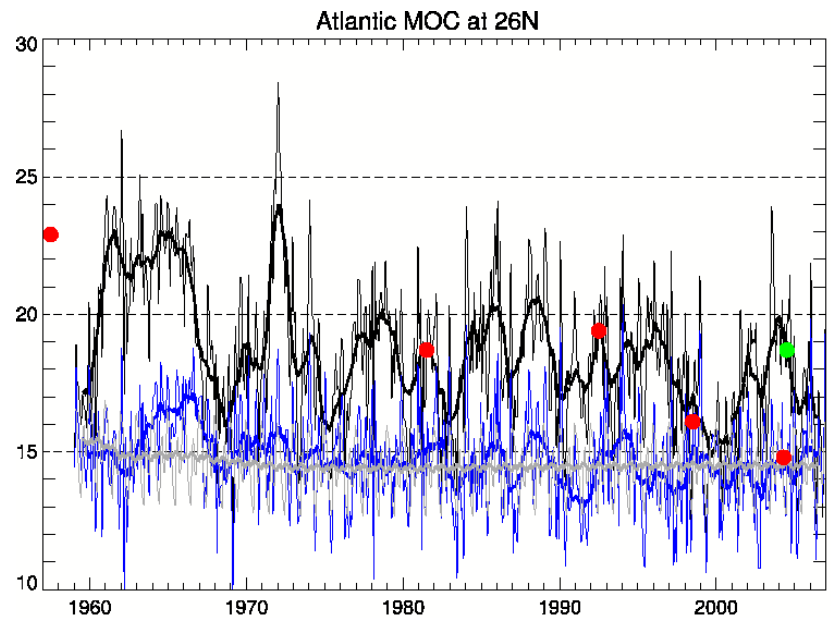




Biases (in observations or models) can lead to artefacts (e.g. apparent trends).

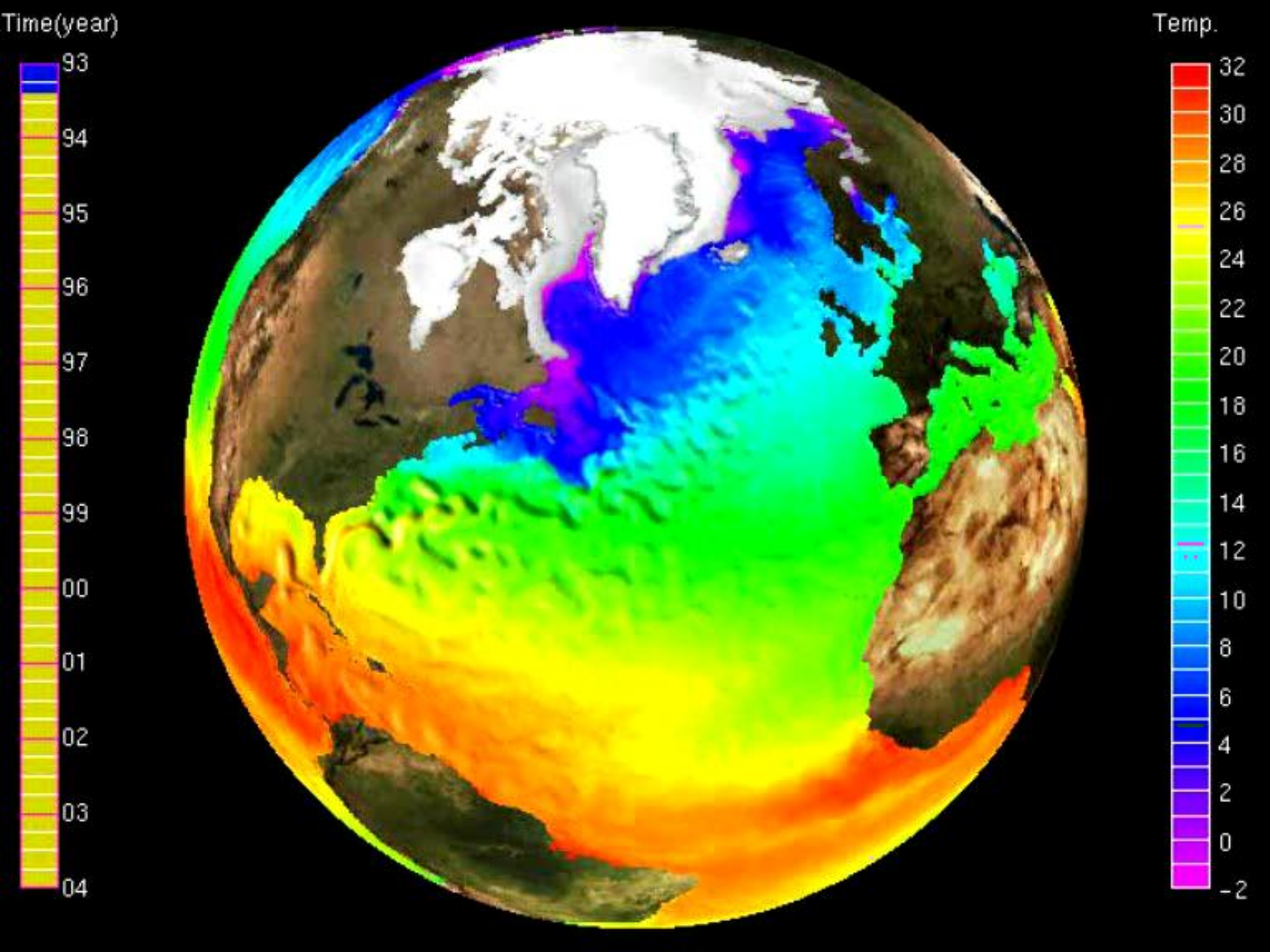
Uses of Ocean Reanalysis



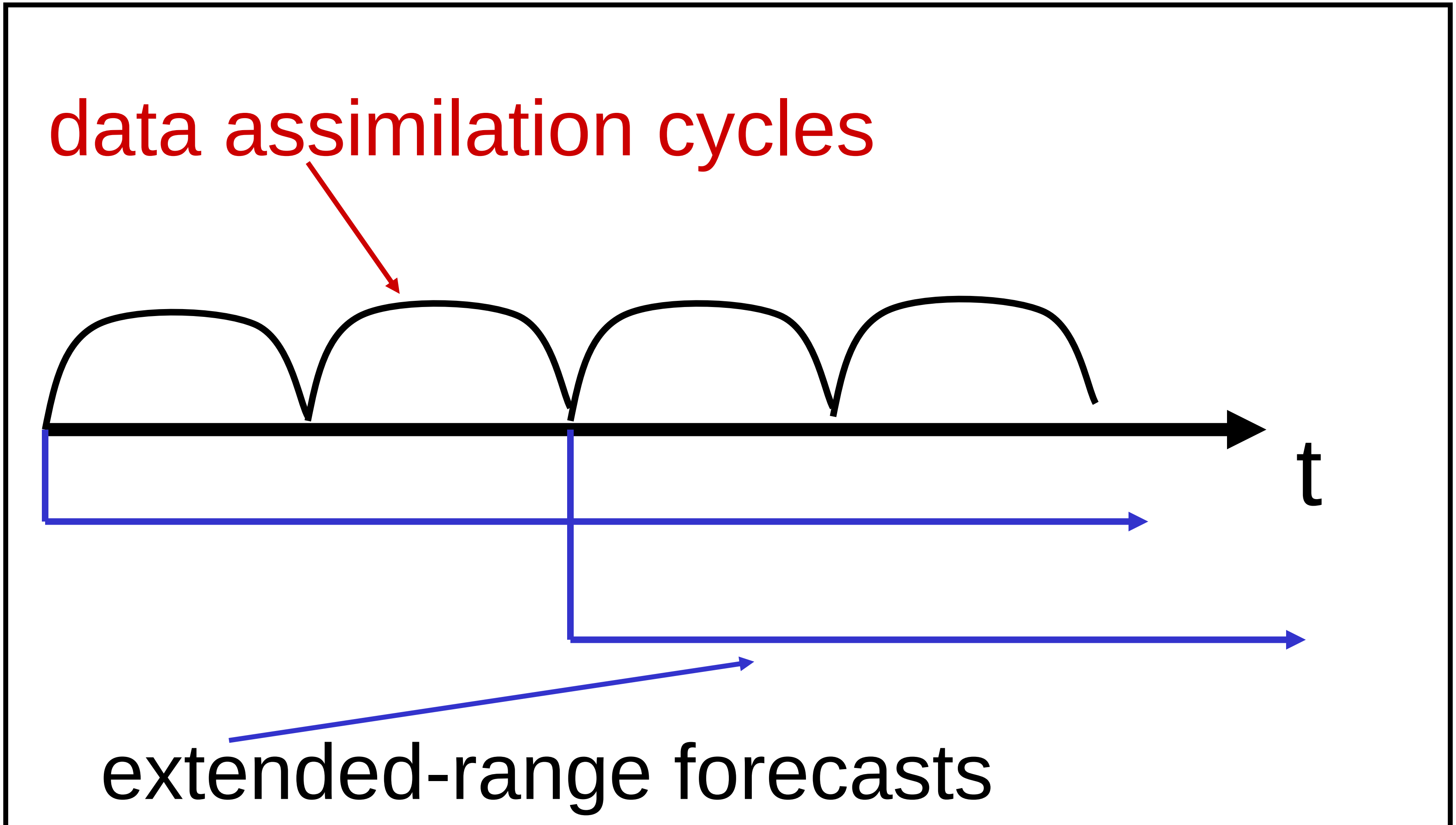


Analysed sea level 26-31 Dec 2004
Global ¼ NEMO 18 yr Synthesis with assimilation
Eg. Better Gulf Stream separation here aids
Altimeter and GOCE assimilation for NCEO)

Thermohaline MOC transports
ECMWF reanalysis compared t
Bryden section based annual r
(Black line is assimilation)
Balmaseda et al 2007

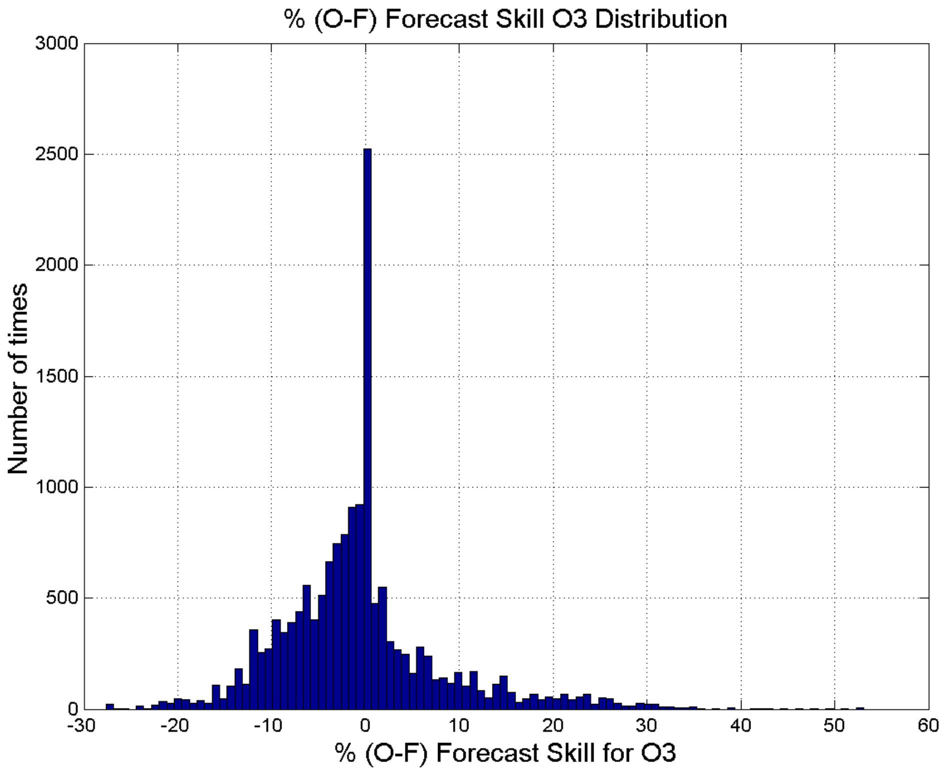

Time(year)
93
94
95
96
97
98
99
00
01
02
03
04
Temp.
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2

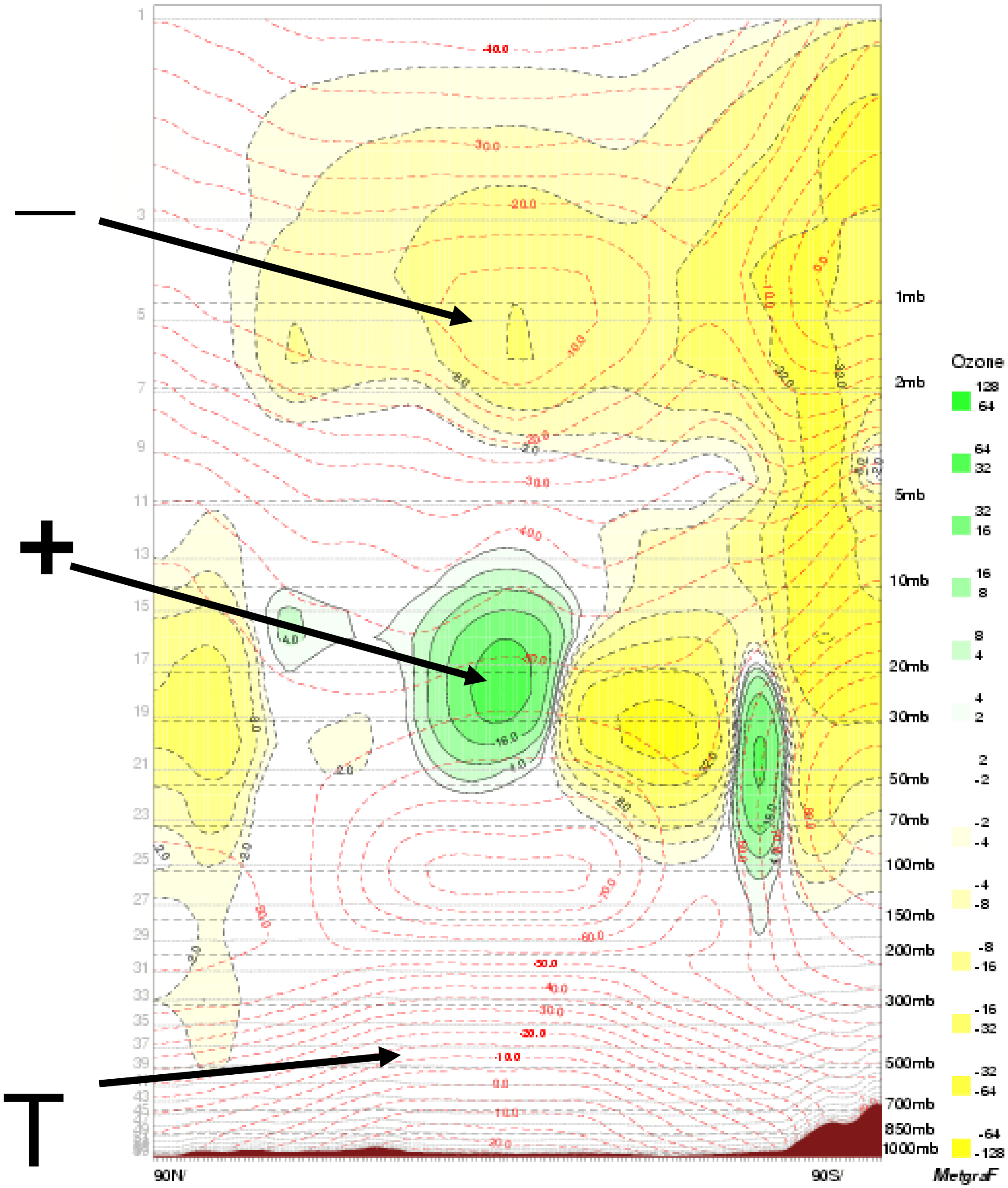
Testing Earth System Models



Skill Measures: Observation Increment, (O-F)

- The difference between the forecast from the first guess, F, and the observations, O, also known as observed-minus-background differences or the innovation vector.
- This is probably the best measure of forecast skill.

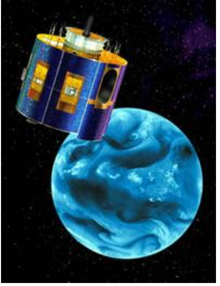




ECMWF

Ozone monthly-mean analysis increment.

Sept. 1986



Systematic biases in the UK's Unified Model

LW Model minus GERB 1200 UTC
SW

ITCZ

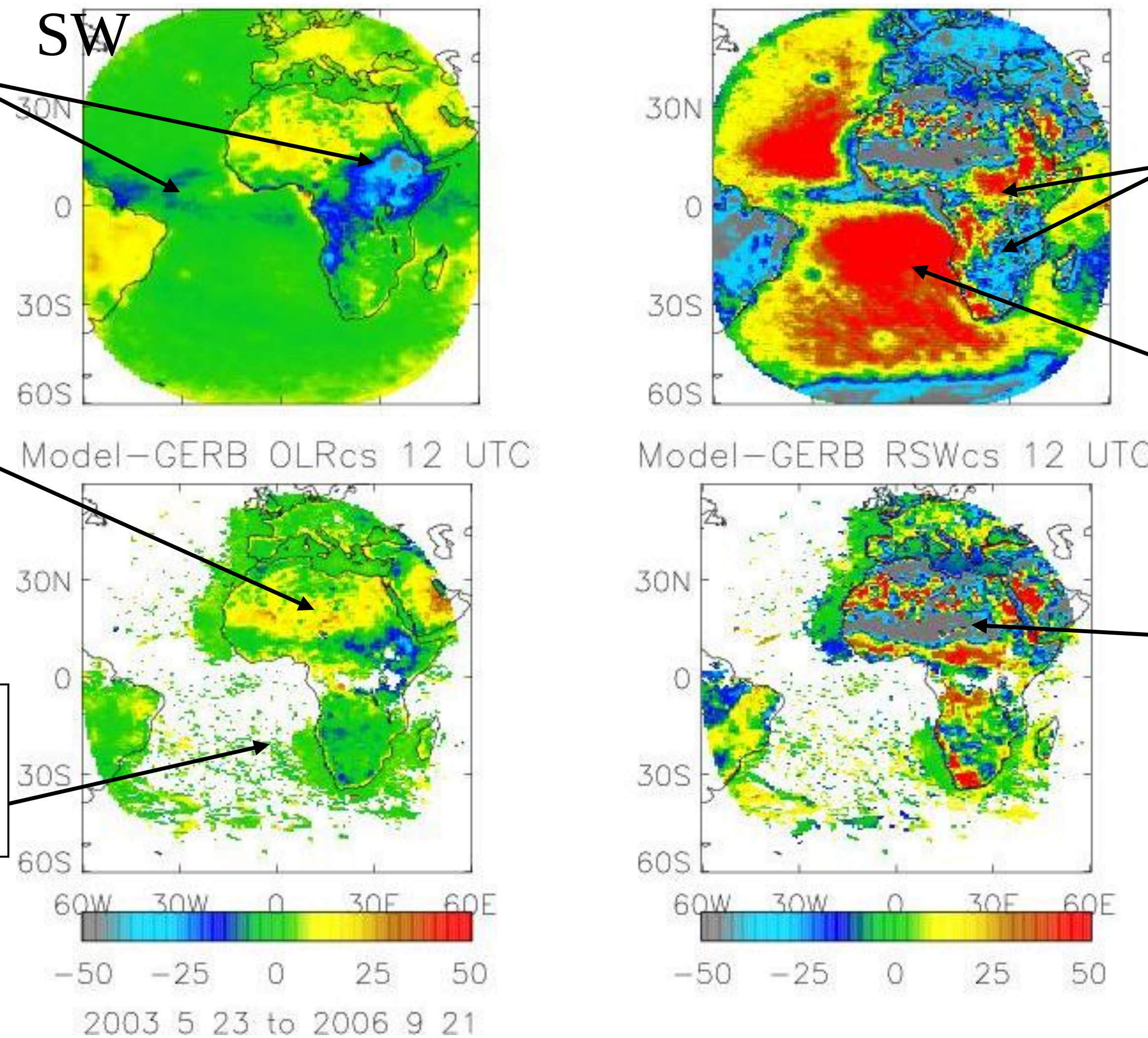
Convective cloud

Low cloud

Desert dust aerosol

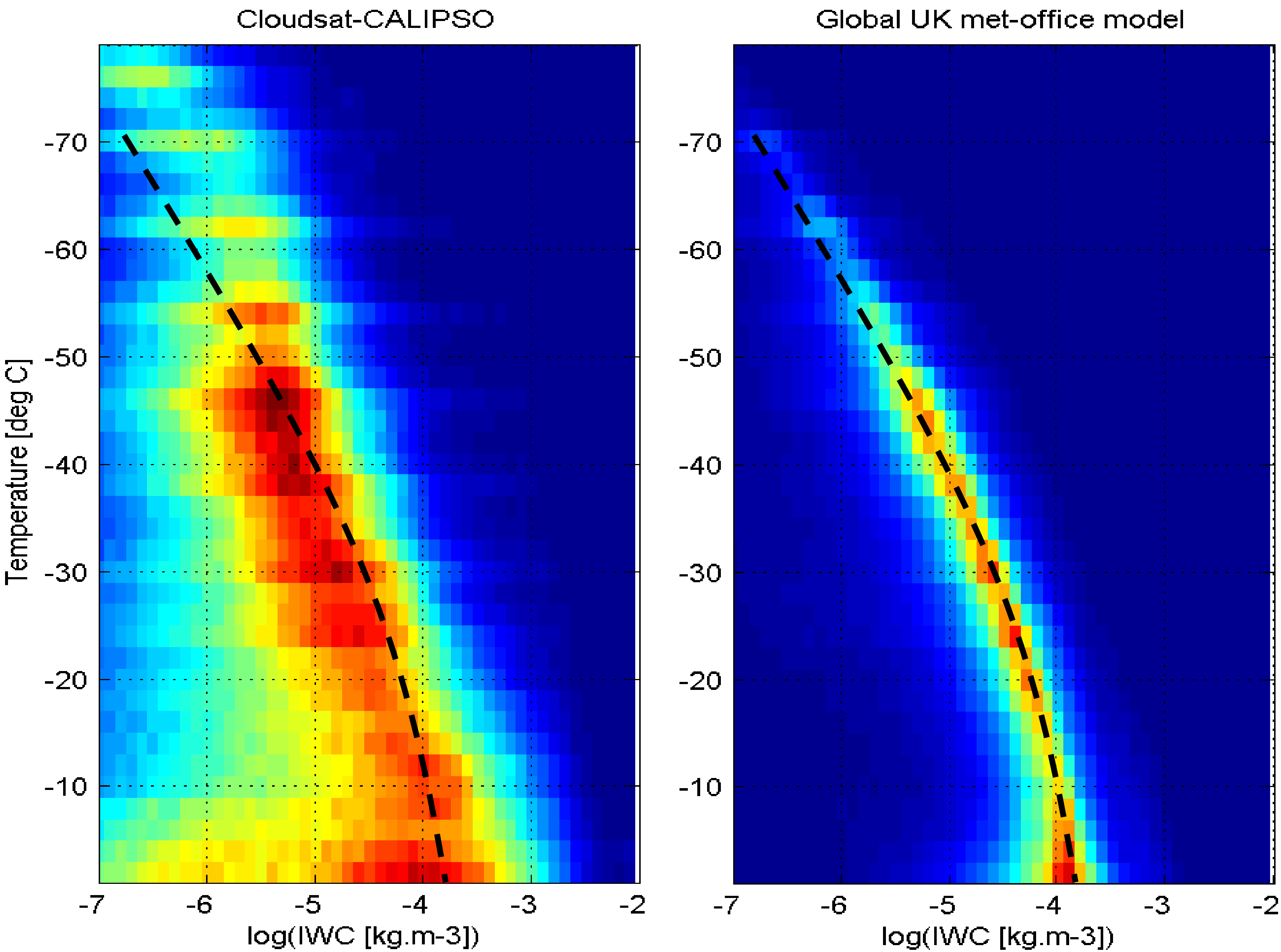
Water vapour

Surface albedo



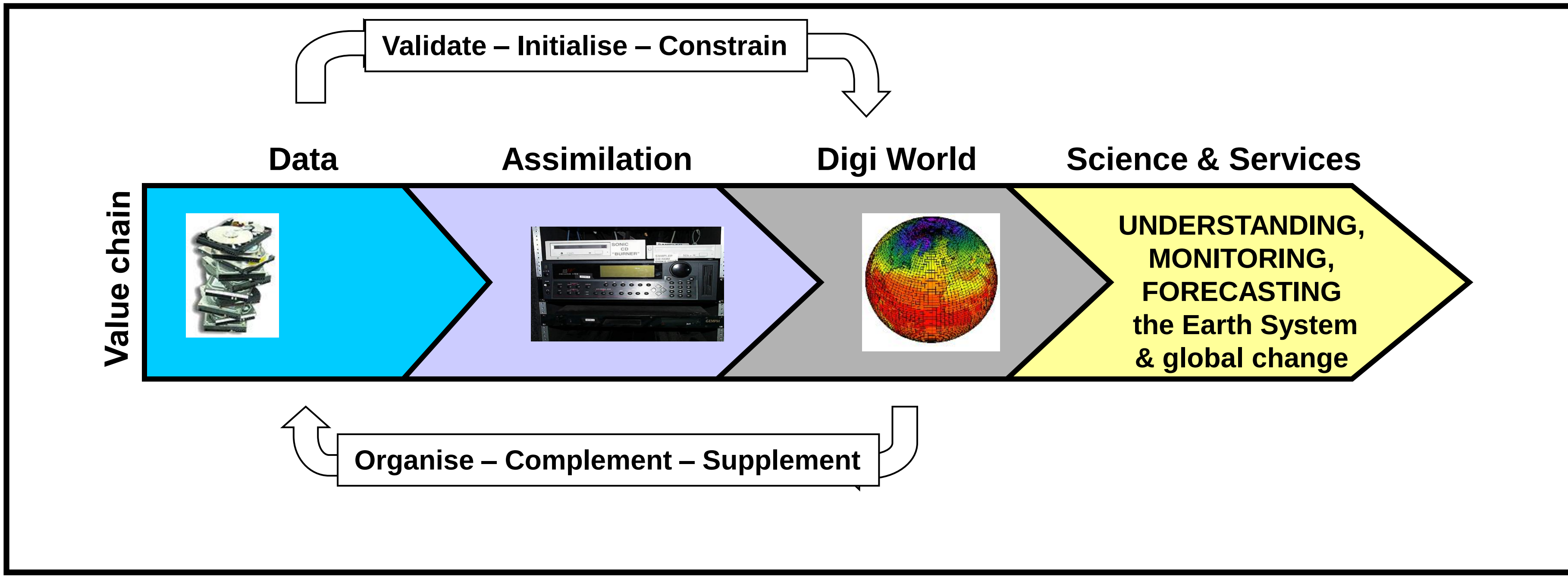
Top: all-sky differences

Bottom: clear-sky differences


Cloudsat-CALIPSO
Global UK met-office model
Temperature [deg C]
-70
-60
-50
-40
-30
-20
-10
-7
-6
-5
-4
-3
-2
log(IWC [kg.m-3])

Hogan &

Conclusion


Validate – Initialise – Constrain
Data
Assimilation
Digi World
Science & Services
Value chain
UNDERSTANDING,
MONITORING,
FORECASTING
the Earth System
& global change
Organise – Complement – Supplement