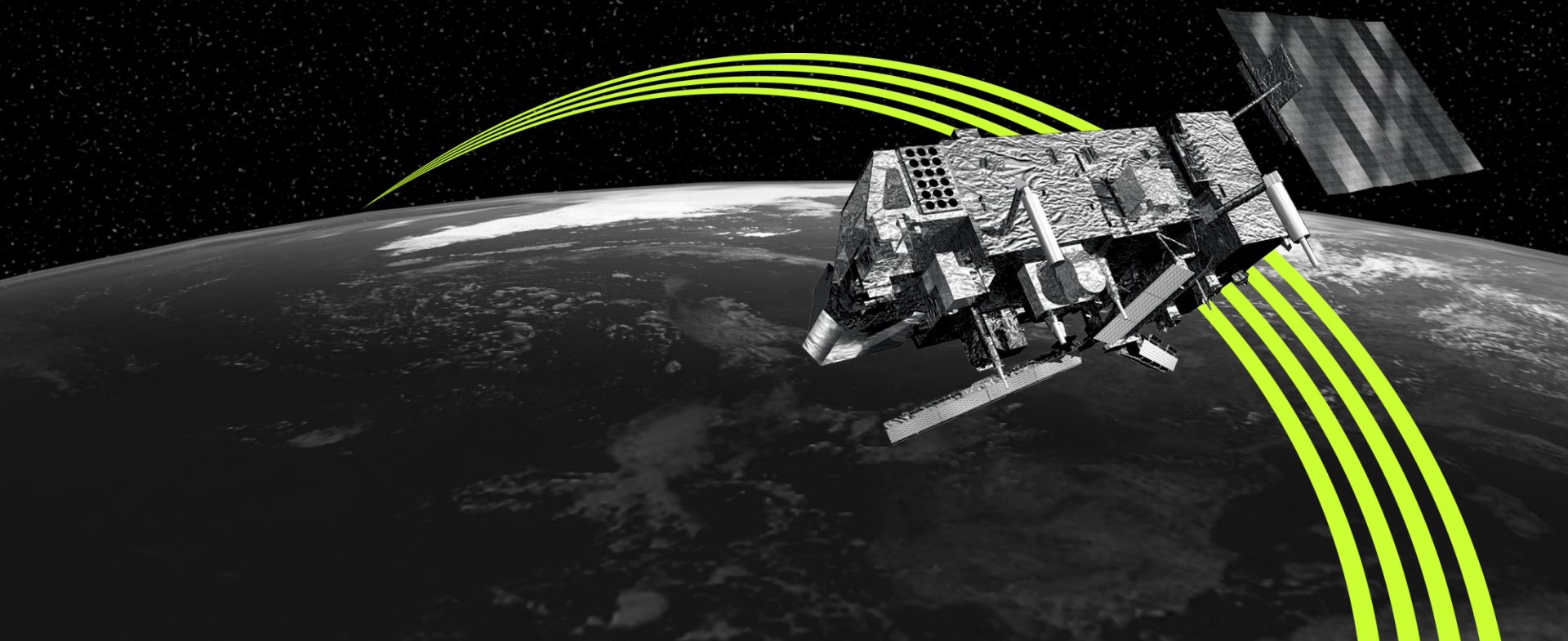
Use of satellite climate data for numerical modelling

Roger Saunders
Met Office and
ESA-CCI Climate Modelling User Group

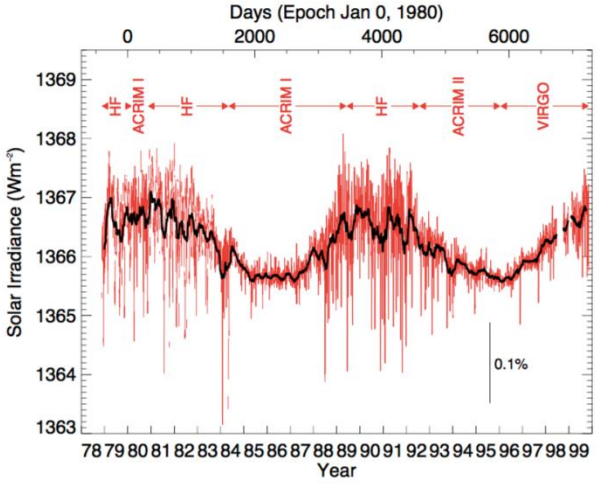


Talk outline

- Some history
- Satellite climate datasets for modellers
- Requirements of modellers
- Some examples of modellers exploiting climate datasets
- Future perspectives

Creation of Early Satellite Climate Datasets

NASA

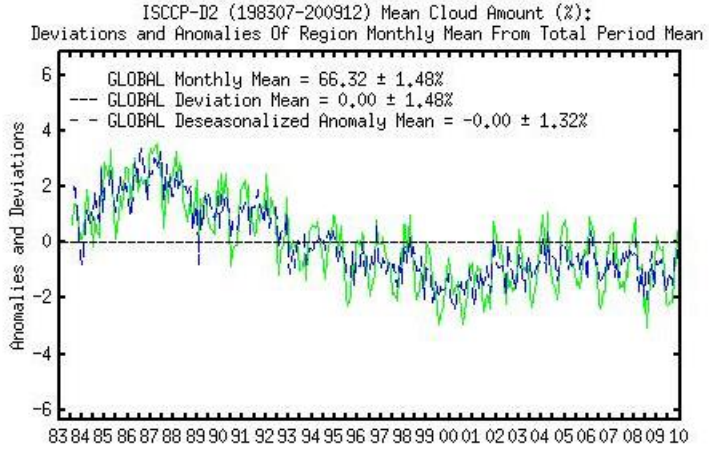


First Satellite data used to validate climate models

Earth Radiation Budget Measurements

Nimbus-6 ERB 1975 → S-NPP CERES 2016

ESA/NASA/JMA



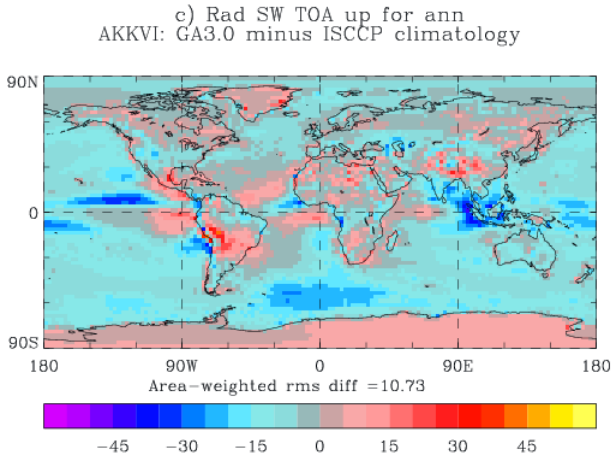
ISCCP Project started in 1982 but it took 15 years for modellers to use ISCCP data from Geo imagers 1983 – 2009 thanks to COSP ISCCP simulator

Model development: The early days

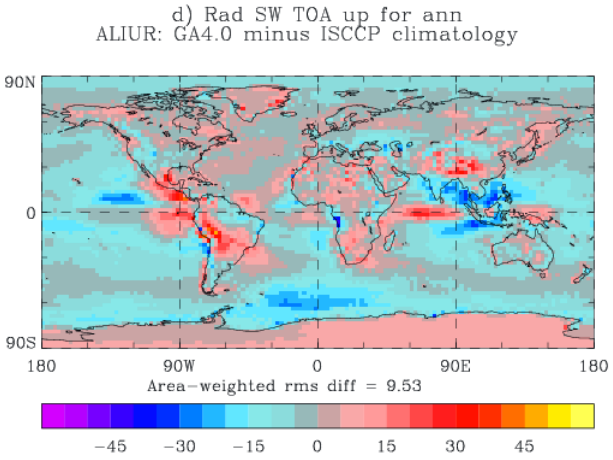
Development of Hadley Centre climate model

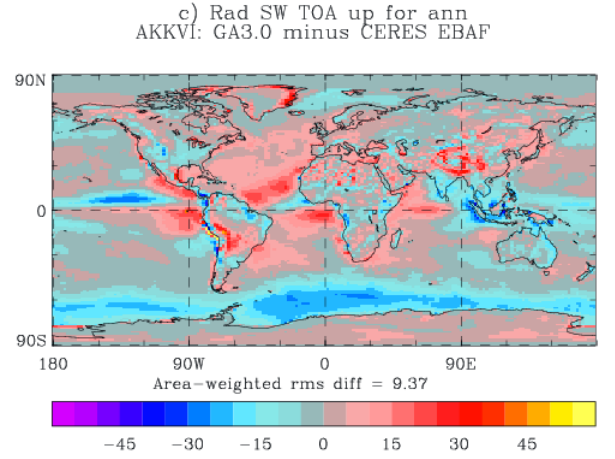
- Shortwave radiation at TOA
- ISCCP → model improves
- CERES → model gets worse

Model 1-ISCCP

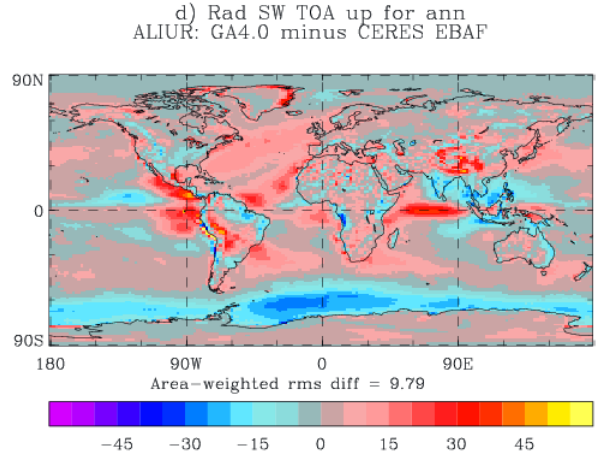


Model 2-ISCCP





Model 1-CERES



Model 2-CERES

Dataset definitions

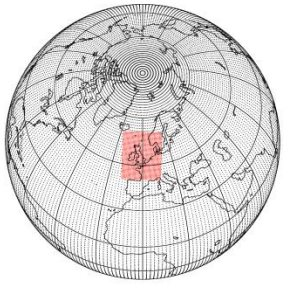
Operational Weather Prediction

Raw Satellite Data

Level 1b

Level 1c

NWP



Fundamental Climate Data Record

(Thematic) Climate Data Records

Climate Services

Climate Models

Reanalyses

Climate monitoring

Climate Dataset Production

Reprocessing Activities
Fundamental Climate Data Records

- NASA (especially very old satellites)
- NOAA STAR
- ESA
- EUMETSAT (CAF, CM-SAF)
- JMA

Reprocessing Activities Climate Data Records

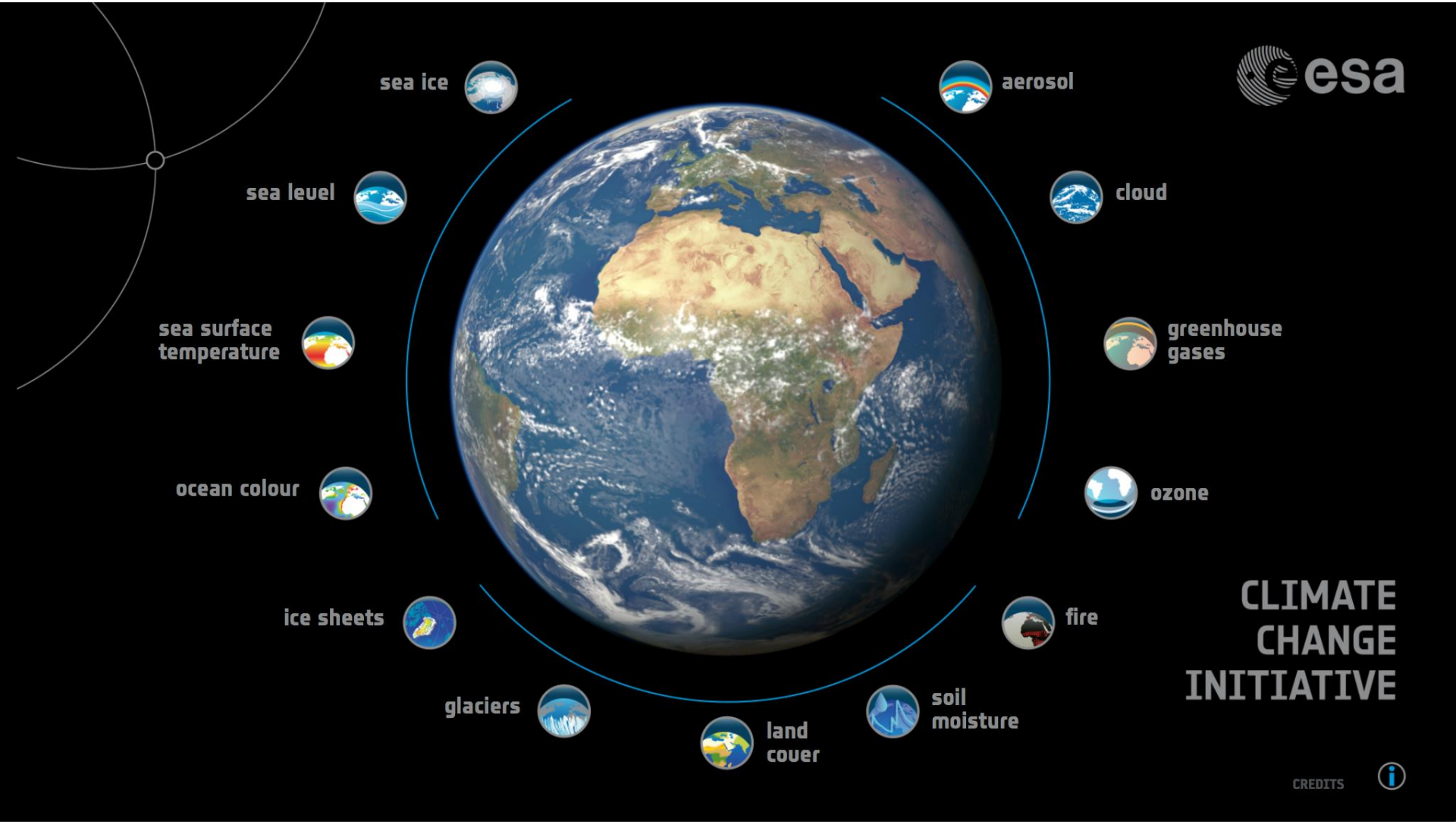
- NASA MEaSUREs Program
- NOAA STAR (…)
- ESA (GlobXXX, Climate Change Initiative)
- EUMETSAT (CAF, CM-SAF)
- SCOPE-CM

Satellite climate data records

- **ESA CCI**
- EUMETSAT CM-SAF
- NASA Obs4MIPS
- NOAA-NCDC

cci

Climate Change Initiative



CCI Key Benefits

- **User requirements determined for all ECVs including GCOS input.**
- **Open process of algorithm inter-comparison and selection to define best techniques**
- **Uncertainty provided with data**
- **Long term preservation of data archives and seamless access for users (e.g. Earth System Grid Federation for modelers)**
- **CDRs will be openly and independently verified, validated and assessed for their utility**

Satellite climate data records

- ESA CCI
- **EUMETSAT CM-SAF**
- NASA Obs4MIPS
- NOAA-NCDC

Deutscher Wetterdienst

Swedish Meteorological and Hydrological

Royal Netherlands Meteorological Institute

Royal Meteorological Institute Belgium

Federal Office of Meteorology and Climatology

Finnish Meteorological Institute

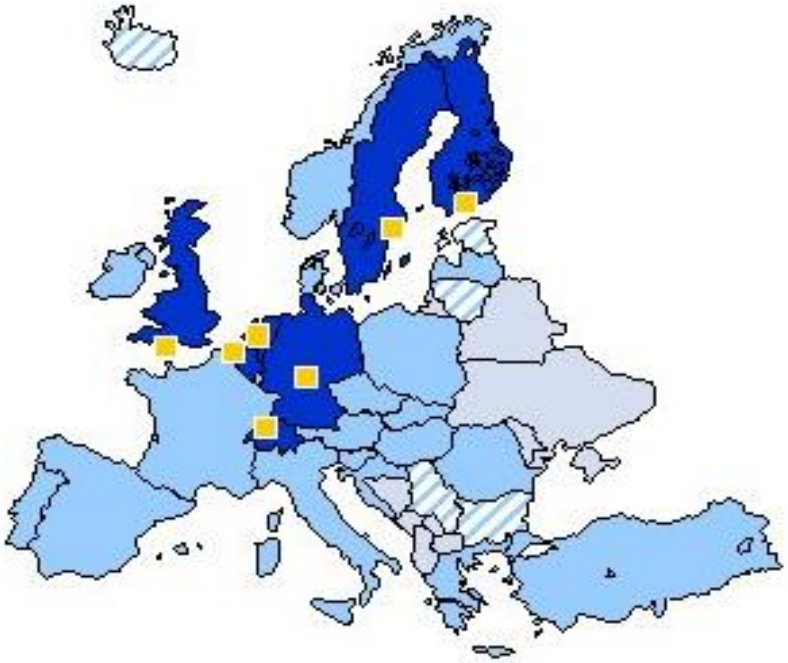
UK MetOffice

CM SAF
Climate Monitoring

The CM SAF is part of the EUMETSAT Satellite Application Network

and is a joint effort of six European National Meteorological and

Hydrological Services, led by Deutscher Wetterdienst.



Deutscher Wetterdienst

Swedish Meteorological and Hydrological

Royal Netherlands Meteorological Institute

Royal Meteorological Institute Belgium

Federal Office of Meteorology and Climatology

Finnish Meteorological Institute

UK MetOffice

Planned CM SAF CDR's until 2022

Sensor, Satellite resp.	Parameter	CDR length Period	Coverage
Fundamental **C**limate **D**ata **R**ecord (FCDR)			
SMMR, SSM/I, SSMIS	**Microwave Radiances**	1978 – 2013	global
Climate Data Record (CDR)			
SEVIRI	**Cloud parameters (frac., height, opt. dep., phase, eff. Rad., LWP, IWP)**	2004 – 2015	Regional
GERB/SEVIRI	**Top of atmosphere radiative fluxes**	2004 – 2015	
MVIRI/SEVIRI	**TOA, surface radiation & Cloud frac.** **land surface temp** **Free tropospheric humidity**	1983 – 2015 1991 – 2015 1983 – 2009	
AVHRR GAC	**Cloud parameters, surface radiation parameters, incl. albedo**	1982 – 2015	Global
SSM/I, SSMIS	**HOAPS 4 (precip, evap, hum., wind, ..)** **Ice free ocean only**	1987 – 2014	
ATOVS	**Water vapour and Temperature profile**	1998 – 2008	
MSU, AMSU, SSM/T2, MHS	**Upper troposphere humidity**	1993 – 2013	

Satellite climate data records

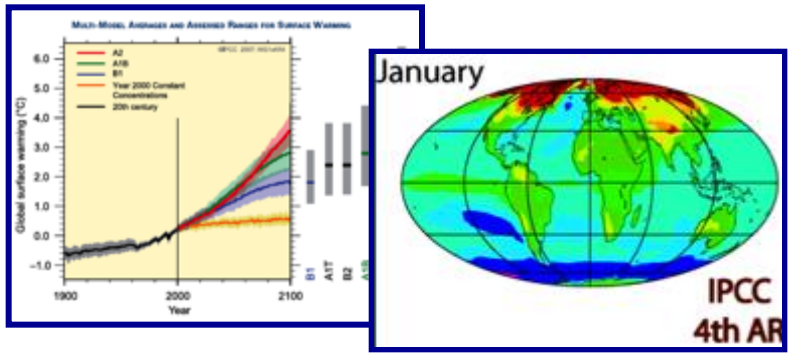
- ESA CCI
- EUMETSAT CM-SAF
- **NASA Obs4MIPS**
- NOAA-NCDC

Under-Exploited Observations for Model Evaluation

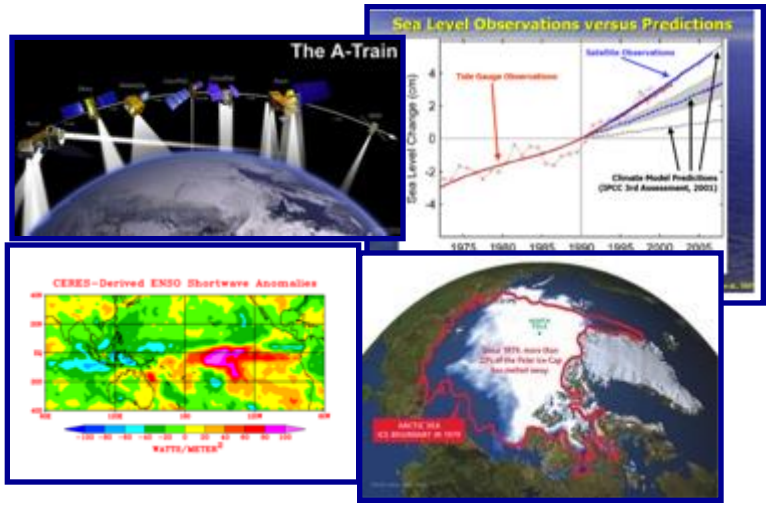
Observations for Model Intercomparison Projects (obs4MIPs)

WDAC Task Team on Observations for Model Evaluation

CMIP6



How to bring as much observational scrutiny as possible to the CMIP/IPCC process?



How to best utilize the wealth of satellite observations for the CMIP/IPCC process?

- Obs4MIPs has defined a set of technical specifications and criteria for developing observational data sets that are technically aligned with CMIP model output (with common file format, data and metadata structure).
- Over 50 datasets that conform to these standards are now archived on the ESGF alongside CMIP model output (Teixeira et al., 2014), including ESA CCI data
- Data users have enthusiastically received Obs4MIPs

DLR

How do modellers use satellite climate datasets ?

1. Assimilation in reanalyses (atmosphere, ocean or land)
2. Validating and improving parametrisations in climate models (e.g. radiation budget, hydrological cycle carbon cycle)
3. Initialising seasonal to centennial model predictions
4. Provide observational constraint for model intercomparisons (e.g. CMIP)
5. Constraining climate model projections and attribution studies

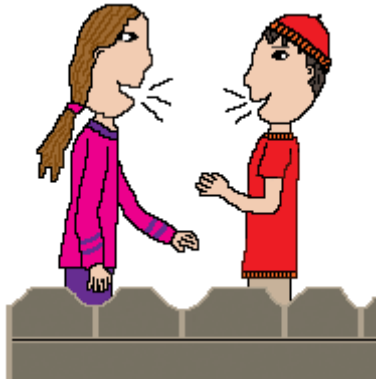
Applications of climate datasets

GCOS ECV	Model Initialisation	Prescribe Boundary Conditions	Re-analyses	Data Assimilation	Model Development and Validation	Climate Monitoring/ Attribution	Q/C in situ data	Climate process study
Atmospheric								
Cloud properties	X	X					X	X
Ozone	X	X	X	X	X	X	X	
Greenhouse gases	X	X	X	X	X	X	X	
Aerosols	X	X	X	X	X	X		
Oceanic								
SST	X	X	X		X	X		
Sea level	X	X	X	X	X	X		
Sea-ice	X	X	X		X	X		
Ocean colour				X	X	X		
Terrestrial								
Glaciers and ice caps	X	X			X	X		X
Ice sheets	X	X			X	X		X
Land cover	X	X	X		X	X	X	
Fire	X	X		X	X	X	X	
Soil Moisture	X	X	X	X	X	X	X	X
Users responses								
Declared uses	36	34	23	22	71	39	11	7

Observations and modellers

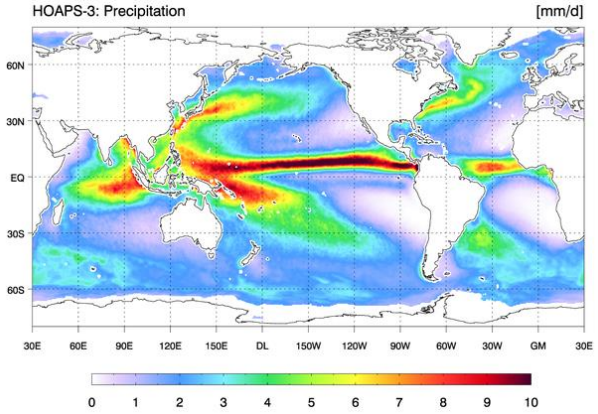
New satellite data

Observer Modeller



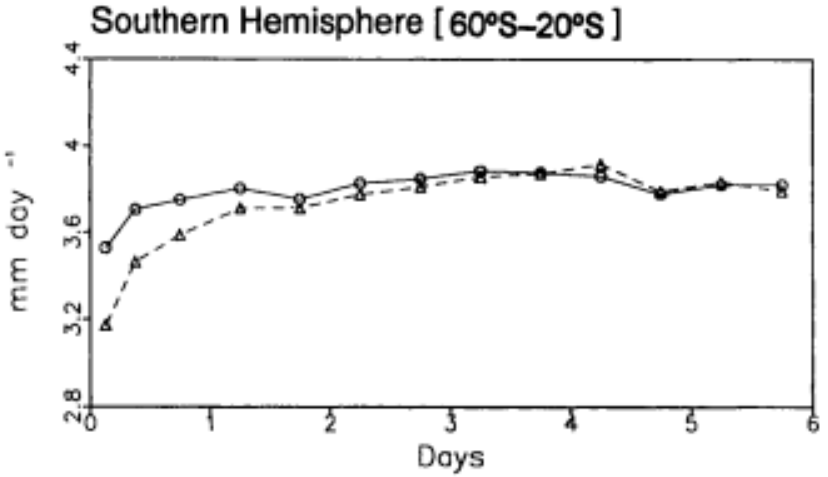
Poor forecasts

Increased spin up



Improved analysis

Forecast expts



What do modellers need?

1. ECVs which can be related to model variables (e.g. Temp, TCWV, wind, AoD, Radiation, Clouds, Precipitation,….)
2. Observation simulators (e.g. COSP)
3. Accurate uncertainty estimates (i.e. bias, rms, stability)
4. Consistency between ECV datasets
5. Common formats easy to read (e.g. NetCDF-CF, Obs4MIPS)
6. Easy to use tools to assess the models (e.g. ESMValtool, AutoAssess, …)

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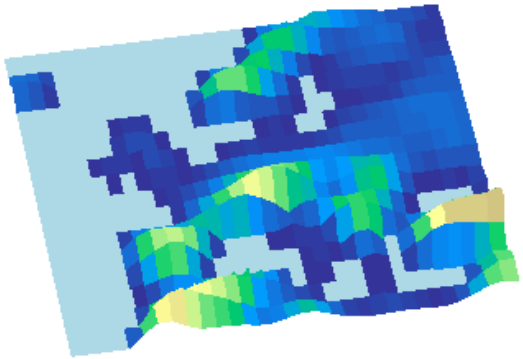
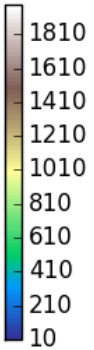
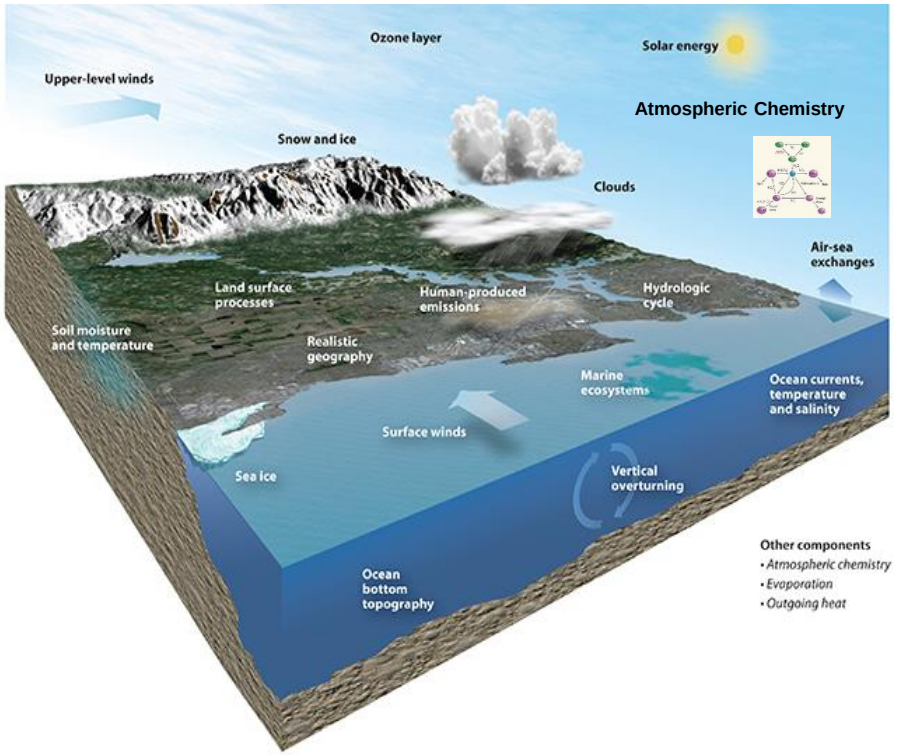
Models are increasing in complexity and resolution

- From AOGCMs to Earth System Models with biogeochemical cycles -

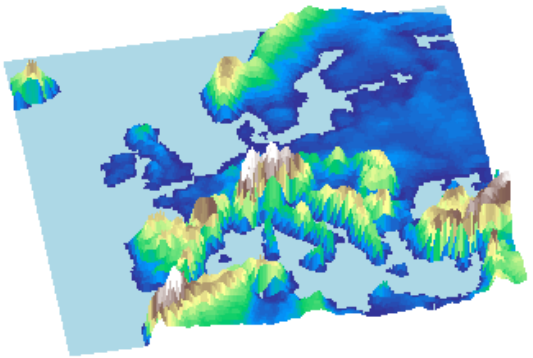
130 km resolution orography

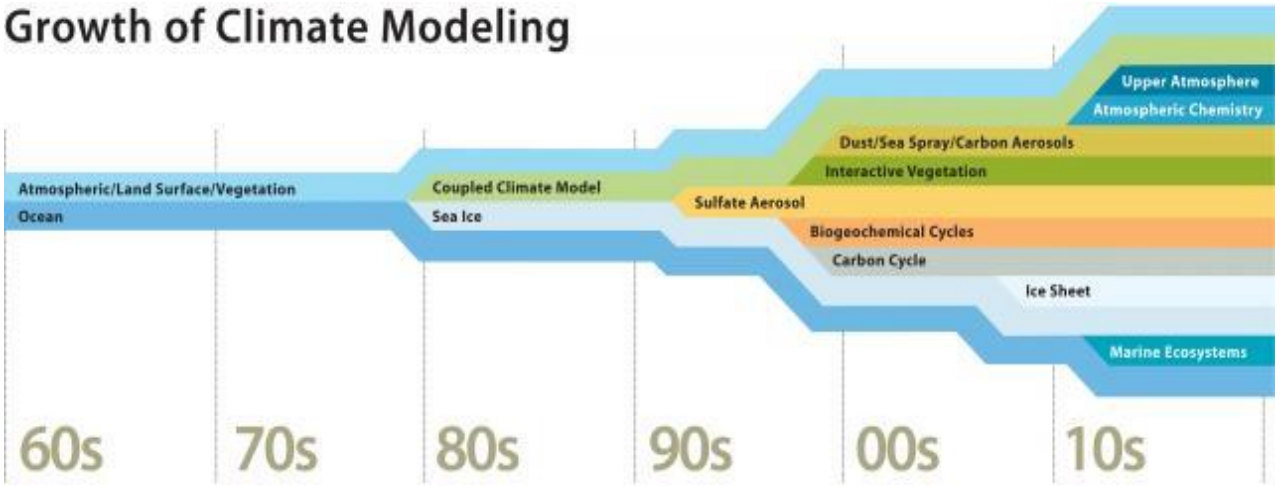






25 km resolution orography

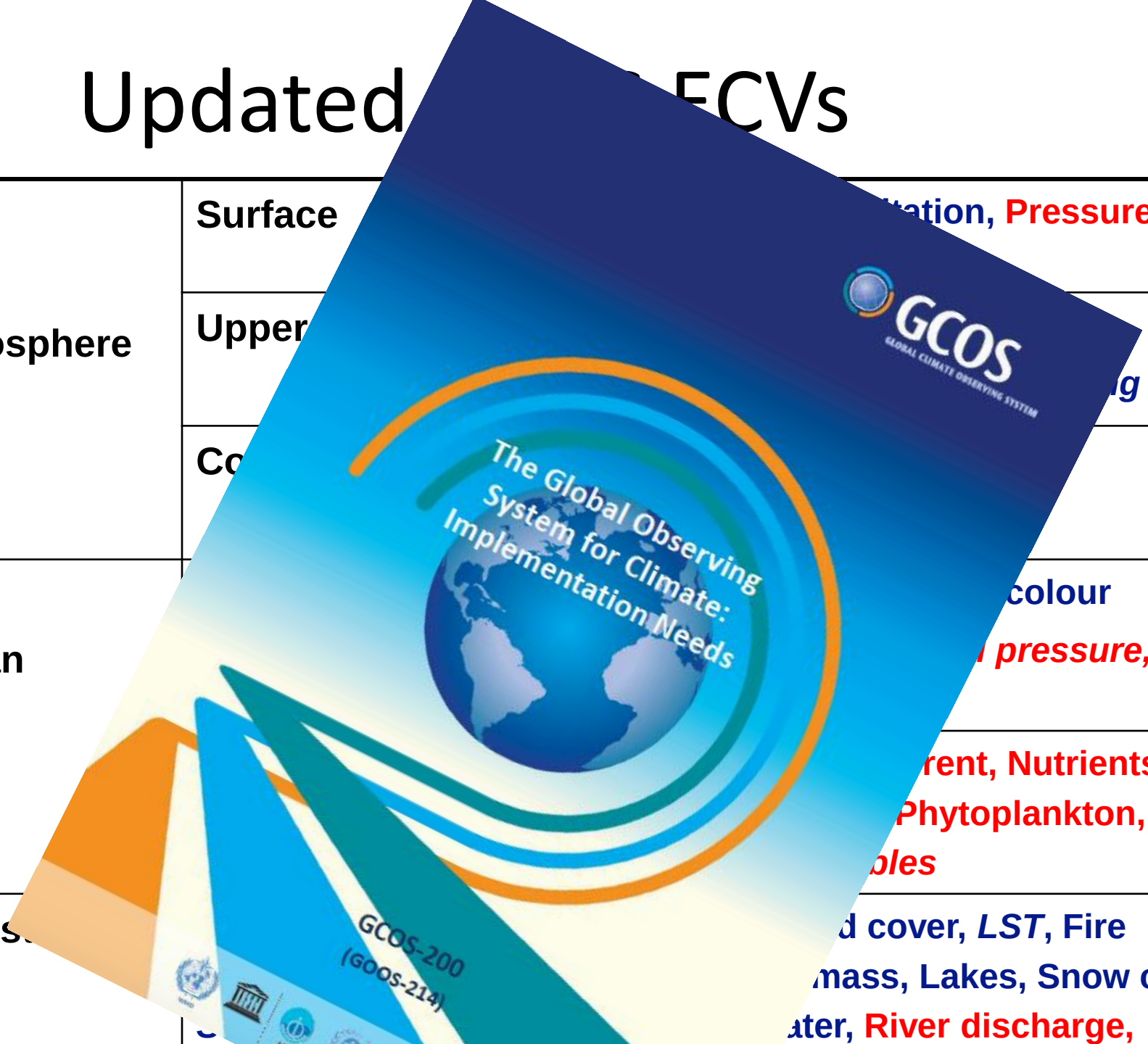




https://www2.ucar.edu/news/understanding-climate-change-multimedia-gallery

Updated ECVs

Atmosphere	Surface	tation, Pressure,
	Upper	g
	Co	
Ocean		colour
		pressure,
		rent, Nutrients,
		Phytoplankton,
		bles
Terres		d cover, *LST*, Fire
		mass, Lakes, Snow cover,
		ater, River discharge,



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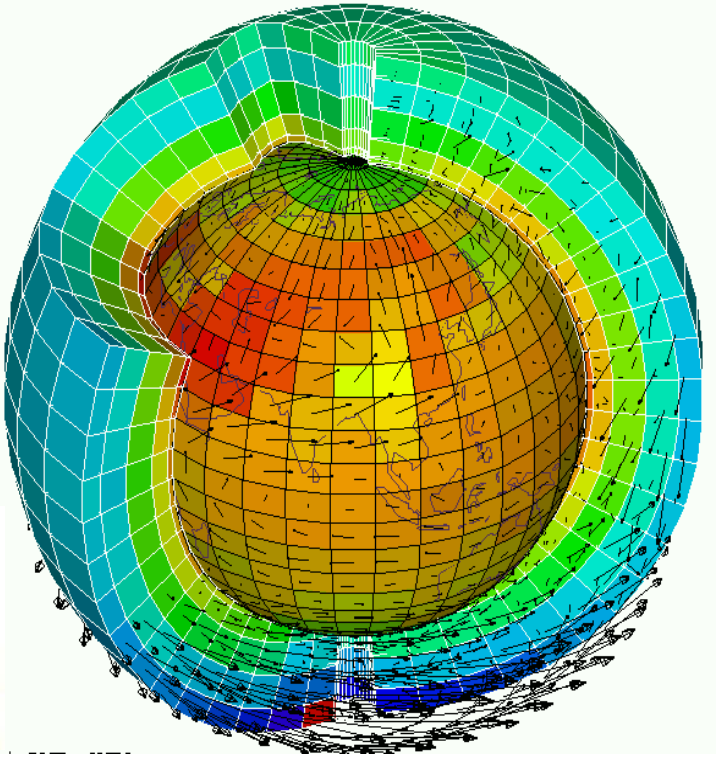
Need for Obs Simulators

Geophysical measurements
(e.g. radiance, bending angle)

?



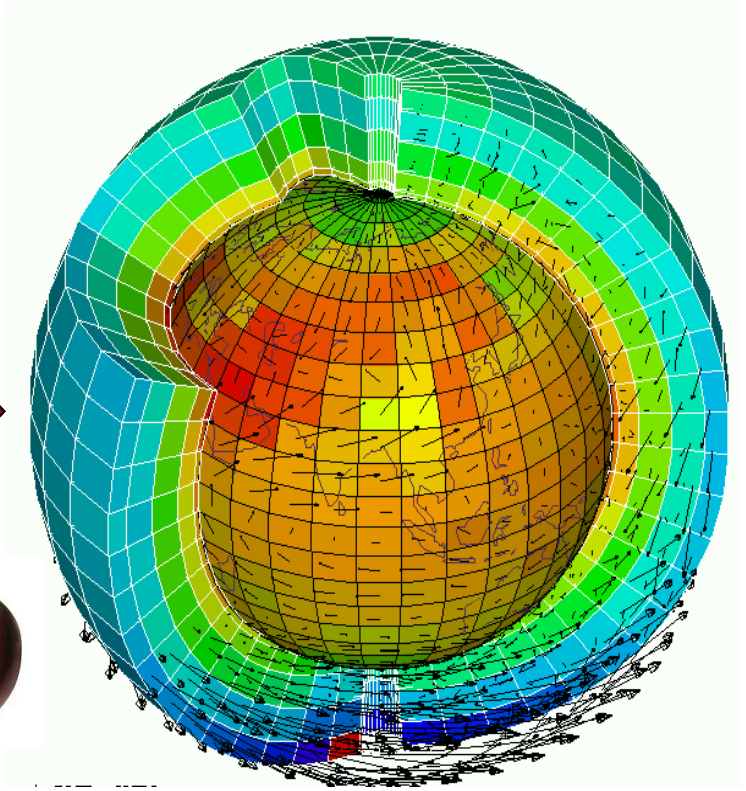
Model grid variables
(e.g. temp, water vapour, wind, etc)

Retrieve model variables

Compare in model space

Need for Obs Simulators

?



Geophysical measurements (e.g. radiance, bending angle)

Model grid variables (e.g. temp, water vapour, wind, etc)

Compare measured and simulated measurements

Compute satellite measurements using simulator (e.g. COSP)

Need for Obs Simulators

Geophysical measurements
(e.g. radiance, bending angle)

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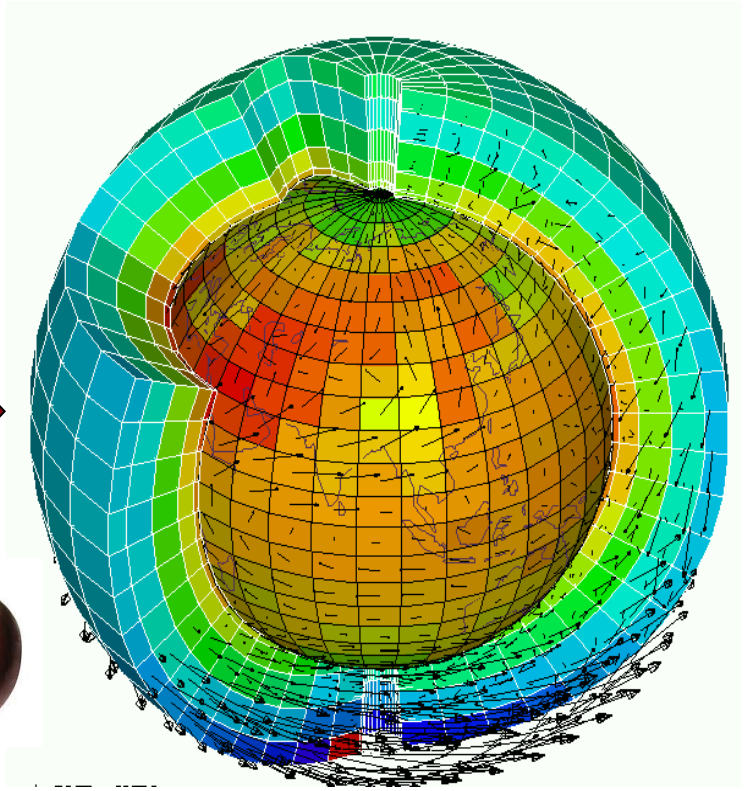


Model grid variables
(e.g. temp, water vapour, wind, etc)

Both approaches are useful depending on the ECV

CFMIP Observation Simulator Package

COSP

Satellite simulation software for model assessment

BY A. BODAS-SALCEDO, M. J. WEBB, S. BONY, H. CHEPFER, J.-L. DUFRESNE, S. A. KLEIN, Y. ZHANG, R. MARCHAND, J. M. HAYNES, R. PINCUS, AND V. O. JOHN

By simulating the observations of multiple satellite instruments, COSP enables quantitative evaluation of clouds, humidity, and precipitation processes in diverse numerical models.

CFMIP web: https://www.earthsystemcog.org/projects/cfmip/

User group: http://groups.google.com/group/cosp-user

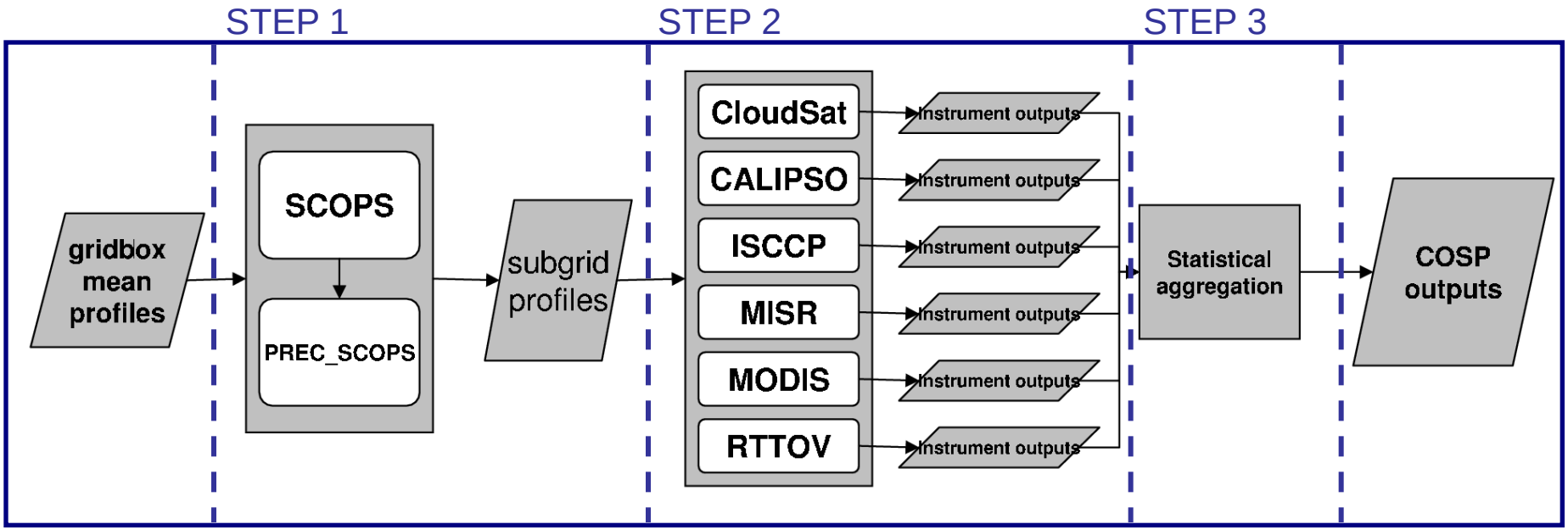
Code: : https://github.com/CFMIP/

(Bodas-Salcedo et al., BAMS, 2011)

COSP

CFMIP Observation Simulator Package

- Used in the CFMIP2 and CMIP5 experiments



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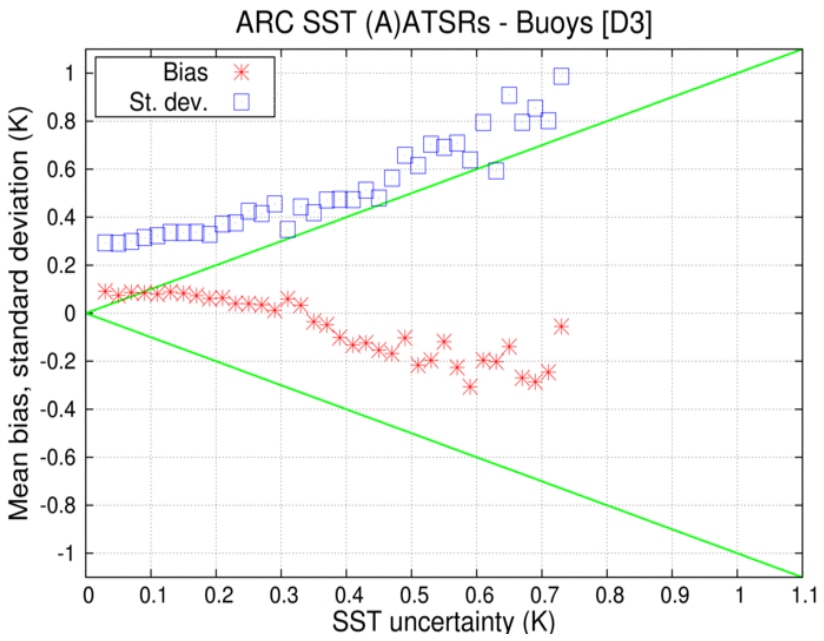
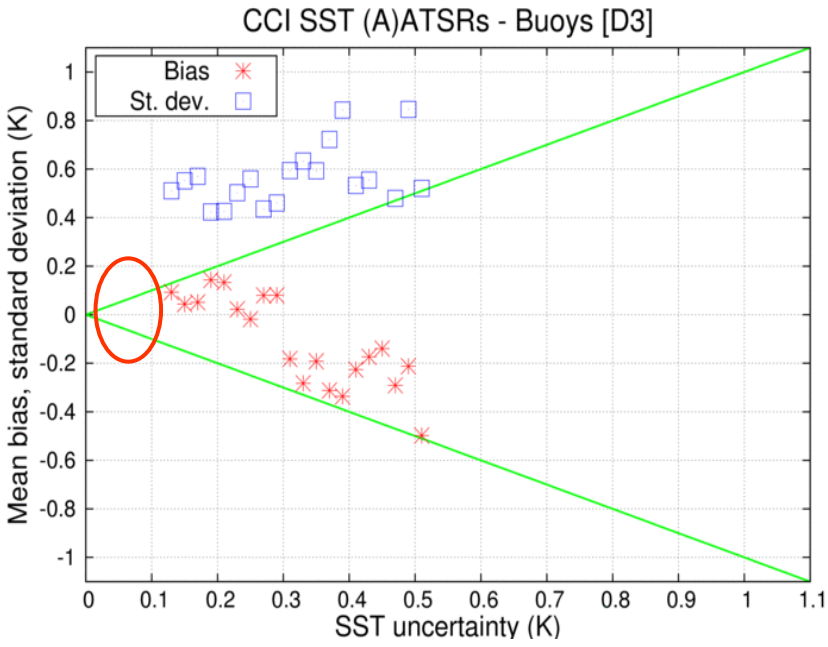
Validate observational uncertainty

Use Buoy SSTs to validate uncertainties provided with ATSR record

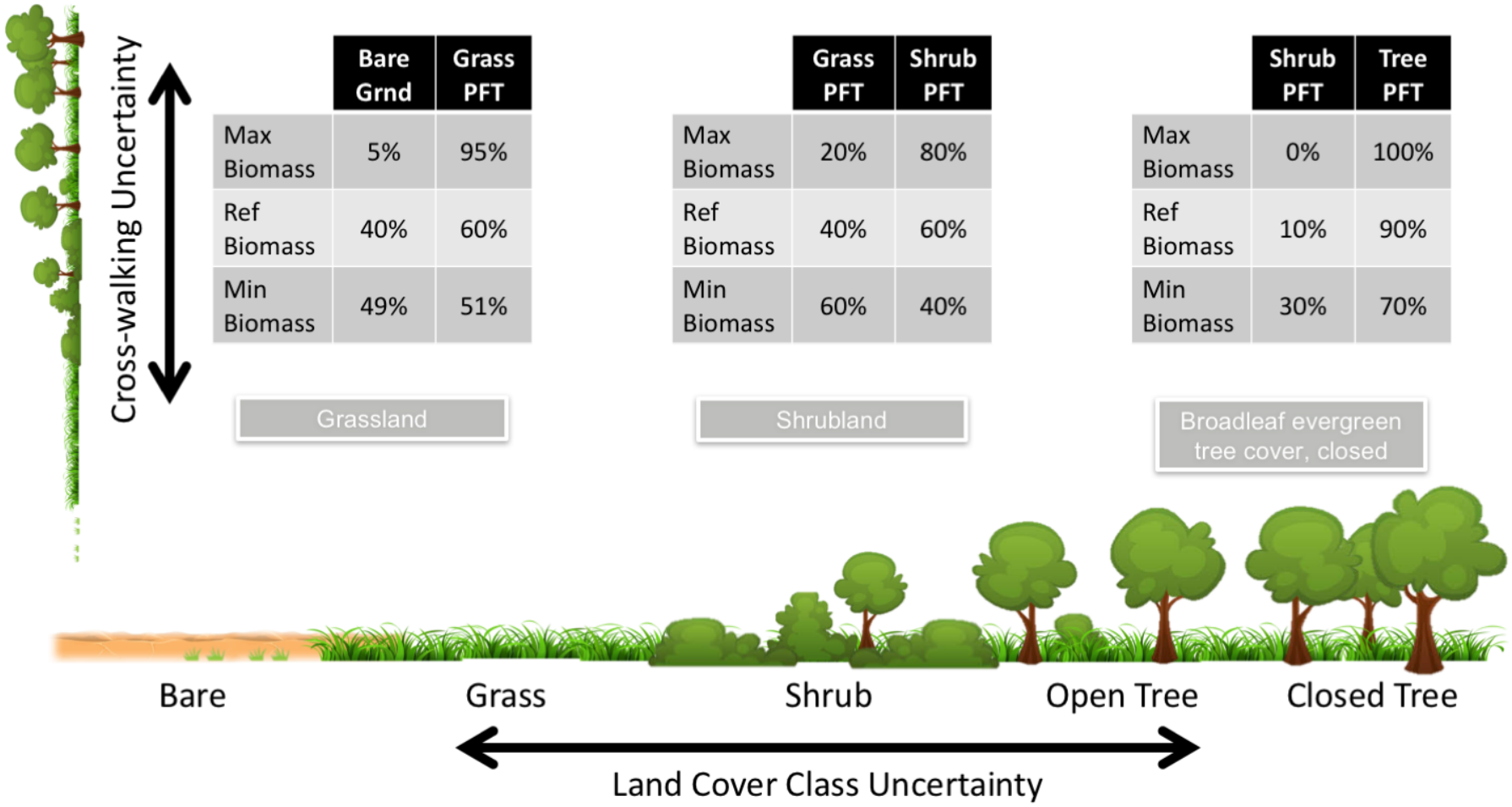


Uncertainty in ARC ATSR SST



Uncertainty in CCI ATSR SST

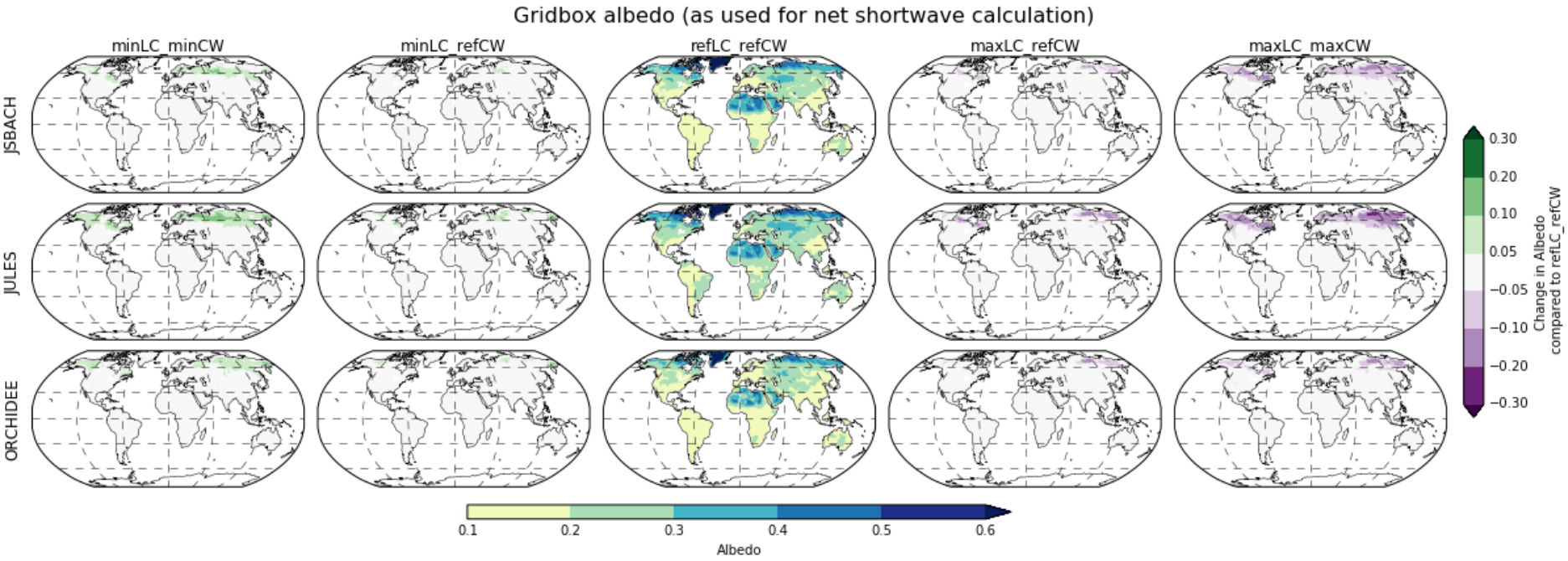
Land cover class: Better uncertainties



Hartley et al 2016 Uncertainty in plant functional type distributions and impact on land surface models *Submitted.*

Land cover: Better uncertainties

Sensitivities in Albedo of Land Cover Fractions



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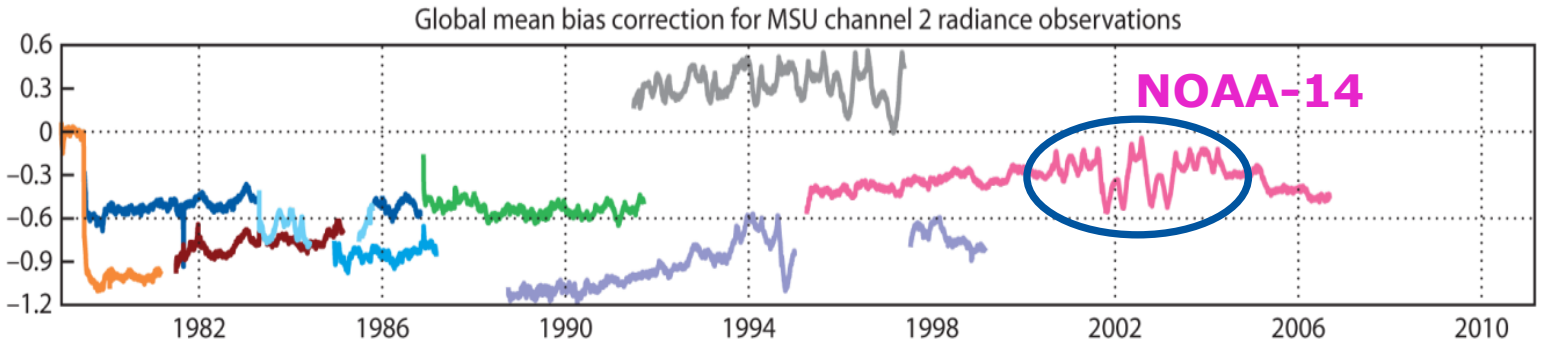
Integrated view of ECVs

1. **Ensuring common input datasets are used for CDR creation and in some cases common pre-processing (e.g. geolocation, land/sea mask, cloud detection)**
2. **Comparisons of CDRs for different ECVs (e.g. SST, sea-level, sea-ice and ocean colour) are consistent**
3. **Comparisons of CDRs with model fields (e.g. GHG and Ozone CDRs and MACC model profiles/total column amounts)**
4. **Through studying teleconnections (e.g. El-Nino SST shows consistent impact on cloud fields, fires).**
5. **Through assimilation of CDRs and to assess impact on analyses and predictions (e.g. SST in ERA-Interim)**

Biases in Measurements

- MSU level 1B radiances assimilated in ERA-Interim
- Bias corrections have to be made to ensure consistency

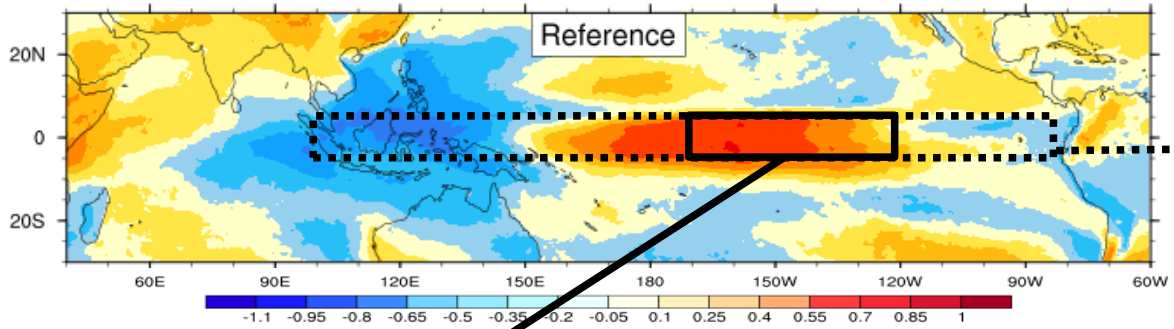


- A Data Assimilation System (DAS) can be used to assess both the consistency between datasets of the same ECV and that across ECVs

Cross-assessment of ECV's for global climate variability

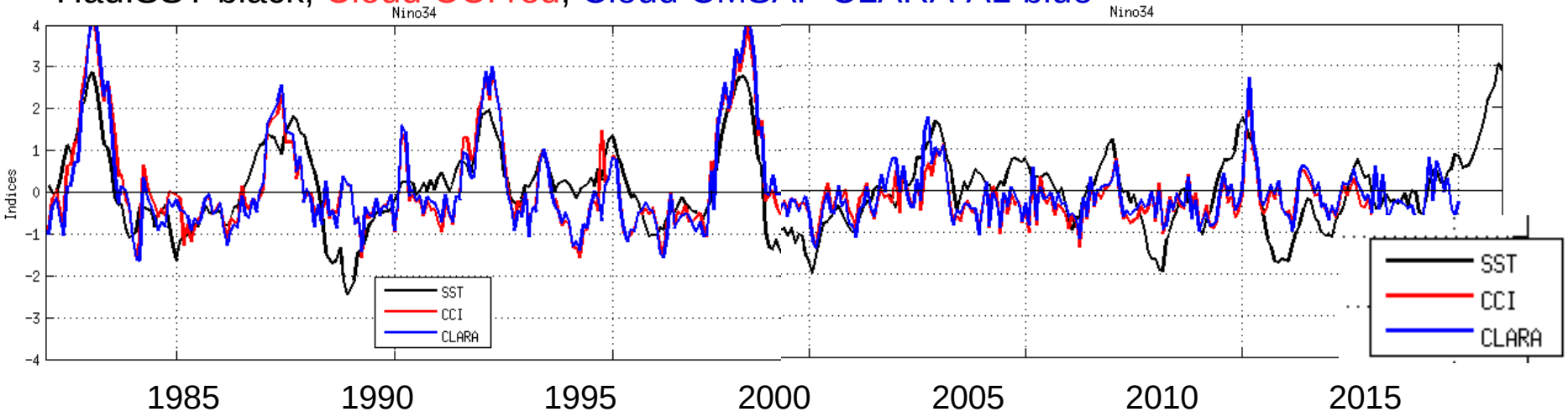
SMHI

1. Correlation CCI SST Nino3.4 timeseries and CCI Clouds globally



3. Next slide
Mean Index for 5S/5N
Time/longitude
Hovmöller plots

2. Timeseries: Niño3.4 (5S-5N,190E-240E), X=SST, Clouds: Index=Anomaly(X)/std(X)
HadISST black, Cloud CCI red, Cloud CMSAF CLARA-A1 blue



Consistency between different cloud data sets
Variability analysis reveal instrument problems

SMHI

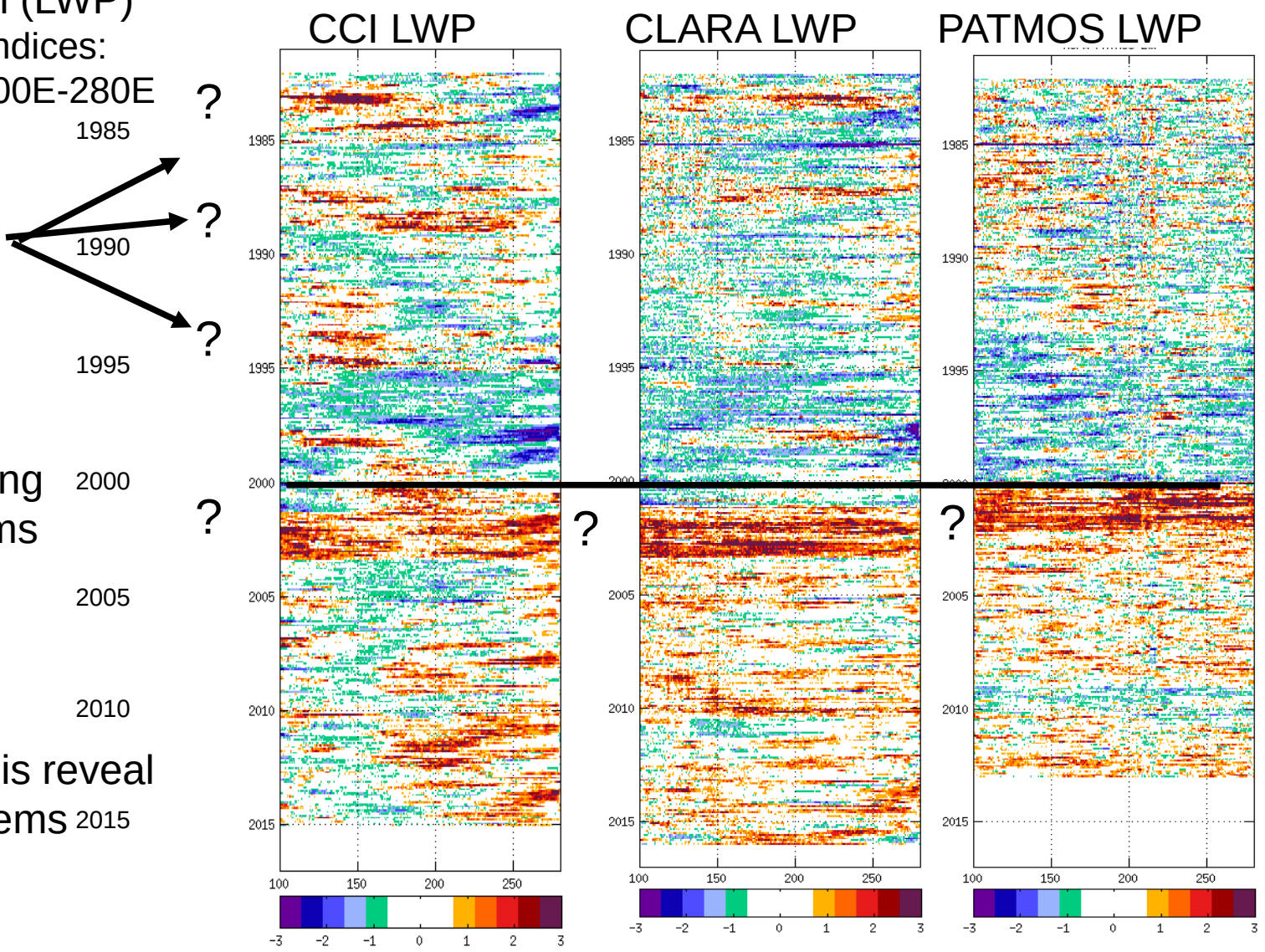
Liquid Water Path (LWP)

Hovmöller Pacific Indices:
Mean 5S/5N, lon 100E-280E

NIR Channel issues

NOAA scanning motor problems

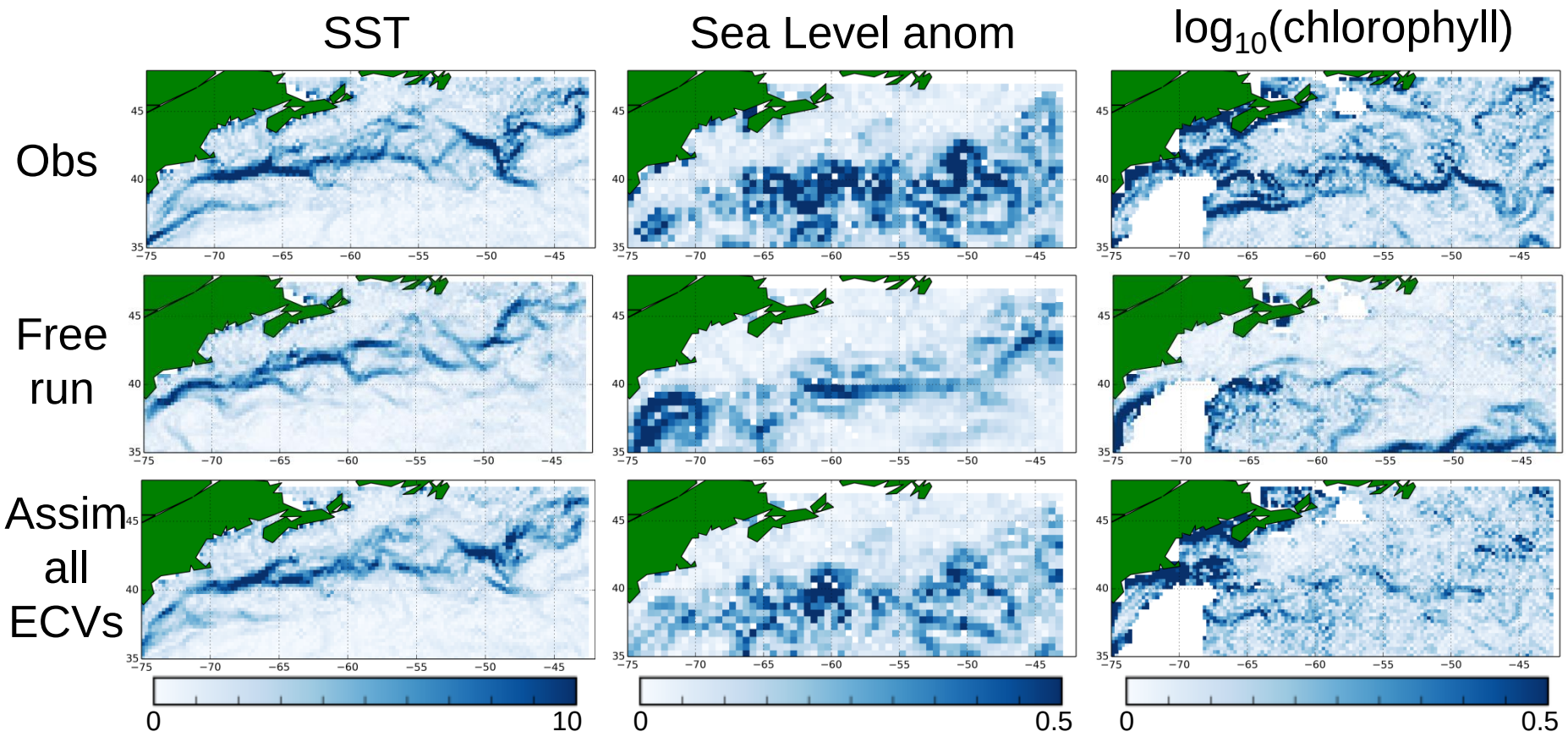
Variability analysis reveal instrument problems



Assessing consistency

Horizontal gradients in ocean - June 2009

Calculated at binned observation locations



Observed SST and SLA gradients seem consistent

Observed OC gradients likely consistent given expected nutrient concentrations, but further investigation needed

Model better matches observed gradients for all fields with assimilation

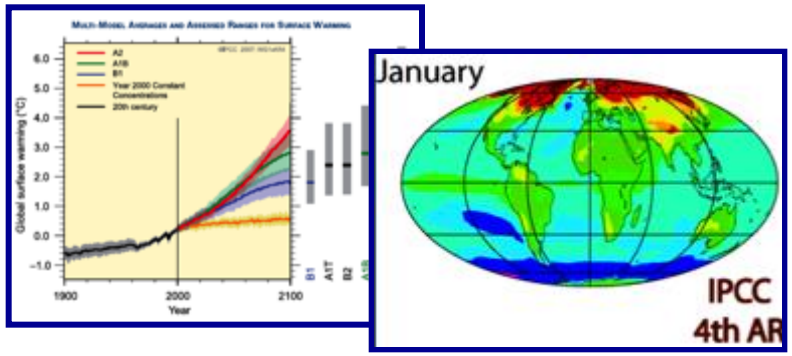
What do modellers need?

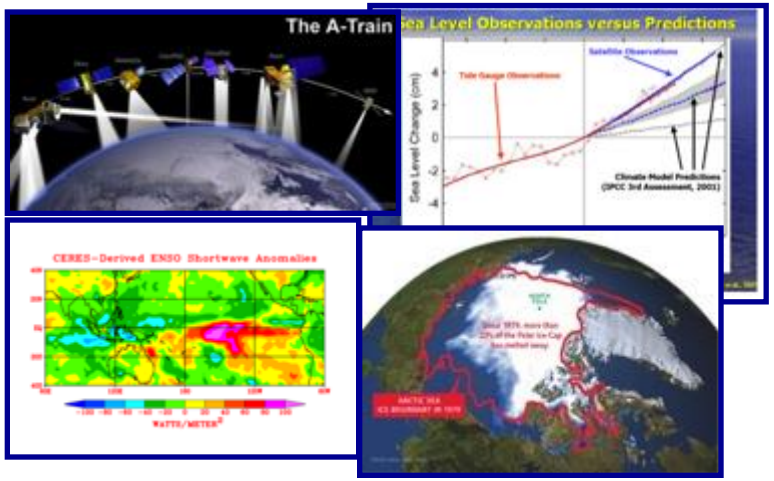
1. ECVs which can be related to model variables (e.g. Temp, TCWV, wind, AoD, Radiation, Clouds, Precipitation,….)
2. Observation simulators (e.g. COSP)
3. Accurate uncertainty estimates (i.e. bias, rms, stability)
4. Consistency between ECV datasets
5. Common formats easy to read (e.g. NetCDF-CF, Obs4MIPS)
6. Easy to use tools to assess the models (e.g. ESMValtool, AutoAssess, …)

Observations for Model Intercomparison Projects (obs4MIPs)

WDAC Task Team on Observations for Model Evaluation

CMIP6





How to bring as much observational scrutiny as possible to the CMIP/IPCC process?

How to best utilize the wealth of satellite observations for the CMIP/IPCC process?

- Obs4MIPs has defined a set of technical specifications and criteria for developing observational data sets that are technically aligned with CMIP model output (with common file format, data and metadata structure).
- Over 50 datasets that conform to these standards are now archived on the ESGF alongside CMIP model output (Teixeira et al., 2014), including ESA CCI data
- Data users have enthusiastically received Obs4MIPs ☺☺☺

DLR

What do modellers need?

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Development of an Earth System Model Evaluation Tool

Within EMBRACE: DLR, SMHI & EMBRACE partners in collaboration with NCAR, PCMDI, GFDL

- **Open Source:** **Python** Script that calls **NCL (NCAR Command Language)** and **other languages (e.g. R, Python)**
- **Input:** CF compliant netCDF model output (CMIP standards)
- **Observations:** can be easily added
- **Extensible:** easy to (a) read models (b) process output [diagnostic] with observations and (c) use standard plot types (e.g. lat-lon map)

EMBRACE

Current developments include for example

- Essential Climate Variables, e.g.
  - Sea-Ice
  - Temperatures & water vapor
  - Radiation
  - CO2
  - Ozone
- Tropical variability (incl. monsoon, ENSO, MJO)
- Southern ocean
- Continental dry biases and soil-hydrology-climate interactions (e.g. standardized precipitation index)
- Atmospheric CO_2 and NO_2 budget
- Aerosol, clouds
- Stratospheric ozone

Release as open-source software

Goal: **Standard namelists to reproduce certain reports or papers** (e.g., IPCC AR5 Chapter 9, Massonnet et al., 2012; Anav et al., 2012; Wenzel et al. 2014; Eyring et al., 2013)

DLR

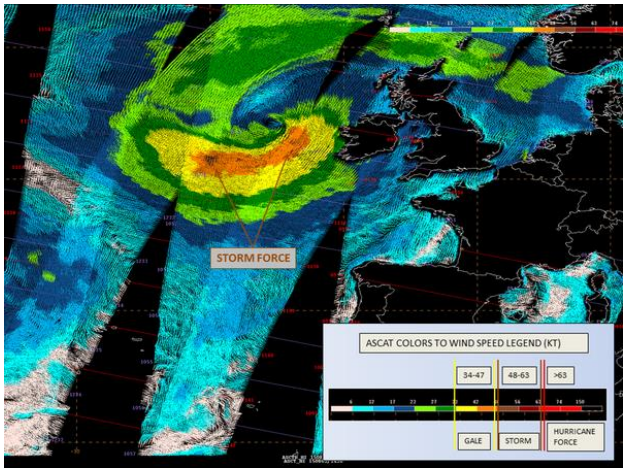
Some Examples of use of satellite climate data

- Assimilation in reanalyses
- Specification of initial state
- Model validation
- Validating model processes
- Verification for MIPs (CMIP6)
- Trends and attribution, models vs obs

Use of Observations in UERRA

- Satellite Radiances (level 1b) – at least TOVS, ATOVS, AIRS, IASI from ECMWF
- Reprocessed (consistent) satwinds – EUMETSAT & CIMSS
- Reprocessed (consistent) scatterometer winds – KNMI (Ocean SAF)
- Reprocessed (consistent) GPSRO - UCAR
- Reprocessed (consistent) Ground based GPS
- TOVS - capability restored to assimilate TOVS radiances
- VarBC - automation is ideal for reanalysis
- System to reject satellite radiances during instrument problems

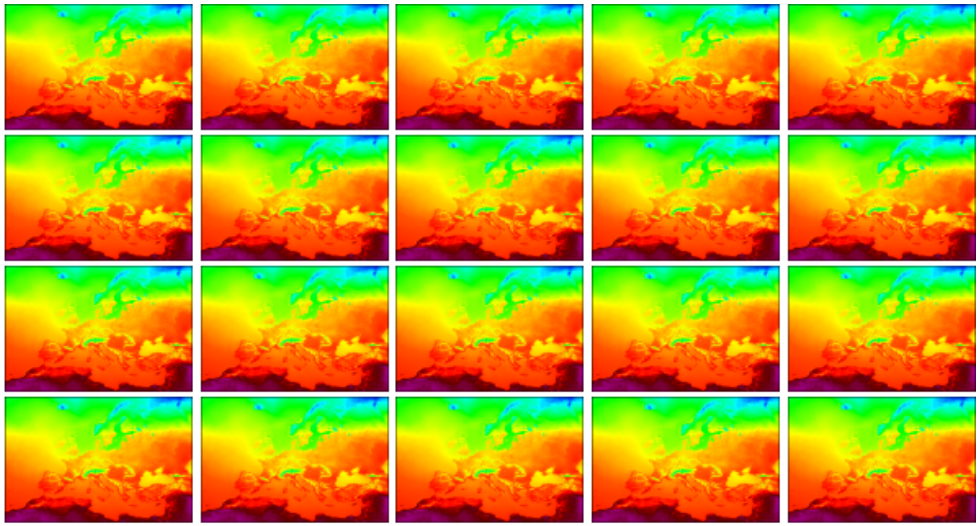
  (>100 individual instances based on ERA-40 & MERRA)



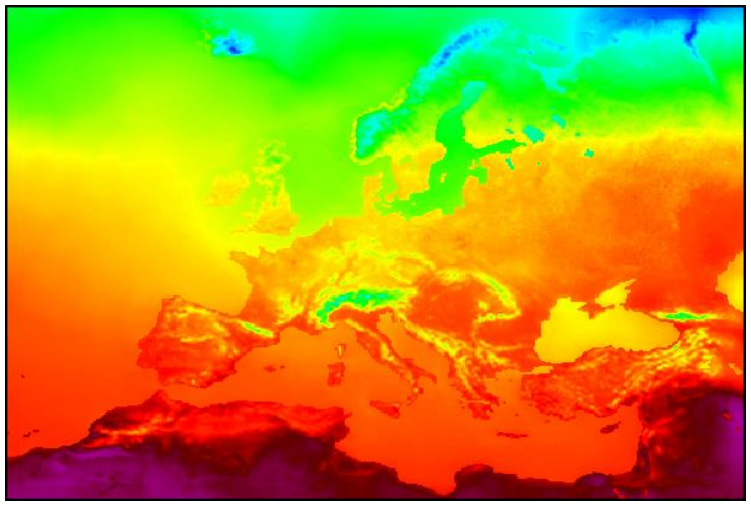
Met Office UERRA reanalyses

- **Satellite era (1978 – present)**

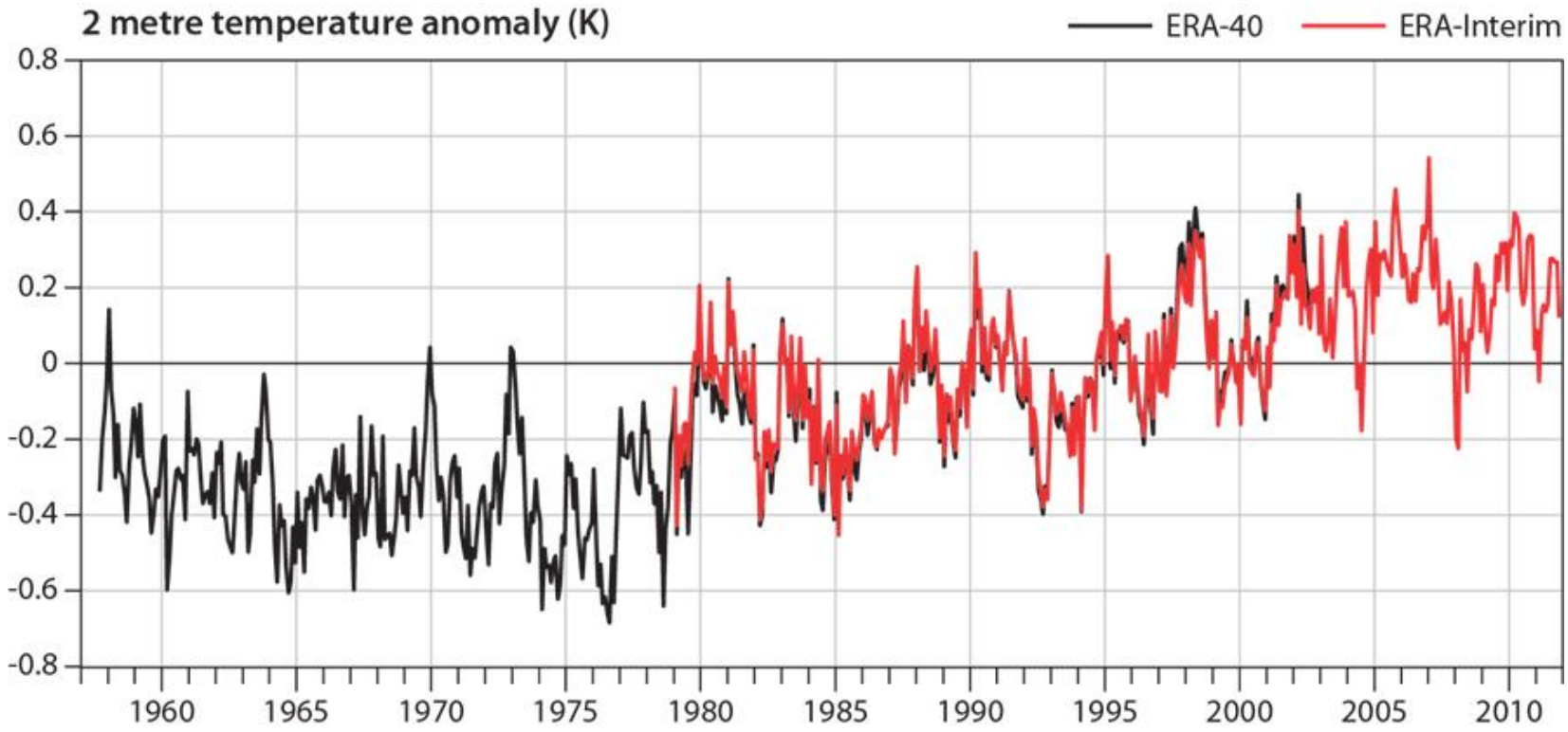
- **Ensemble using static 4DVAR**
- Provides lower resolution fields with uncertainty estimation
- i.e. mean and spread at 24km
- **Production start: Oct 2016**



- **Deterministic reanalysis using hybrid 4DVAR**
- Uses ensemble reanalysis uncertainty to improve assimilation (B)
- Provides higher resolution deterministic fields at 12km
- **Production start: end 2016**

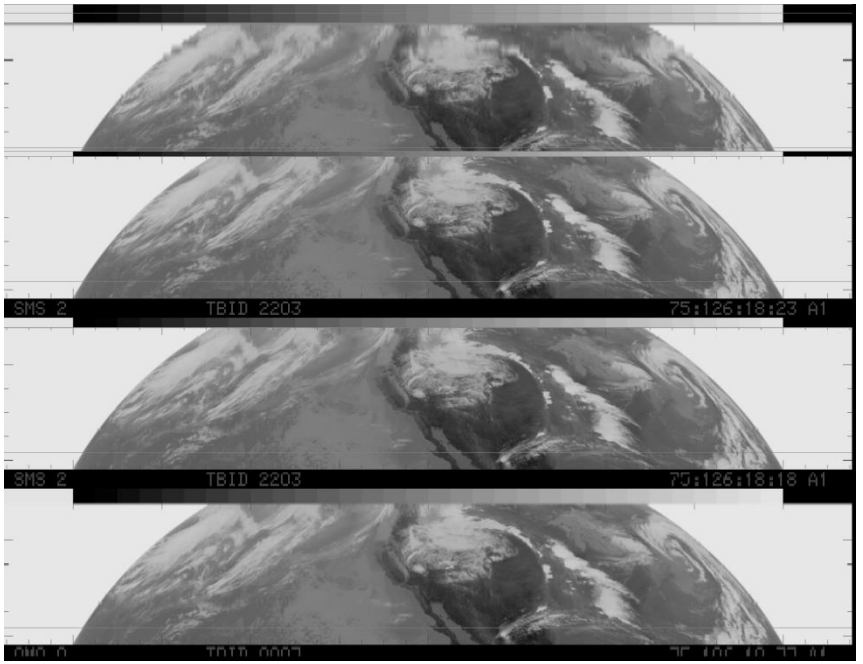


Reanalysis for climate monitoring



Data rescue

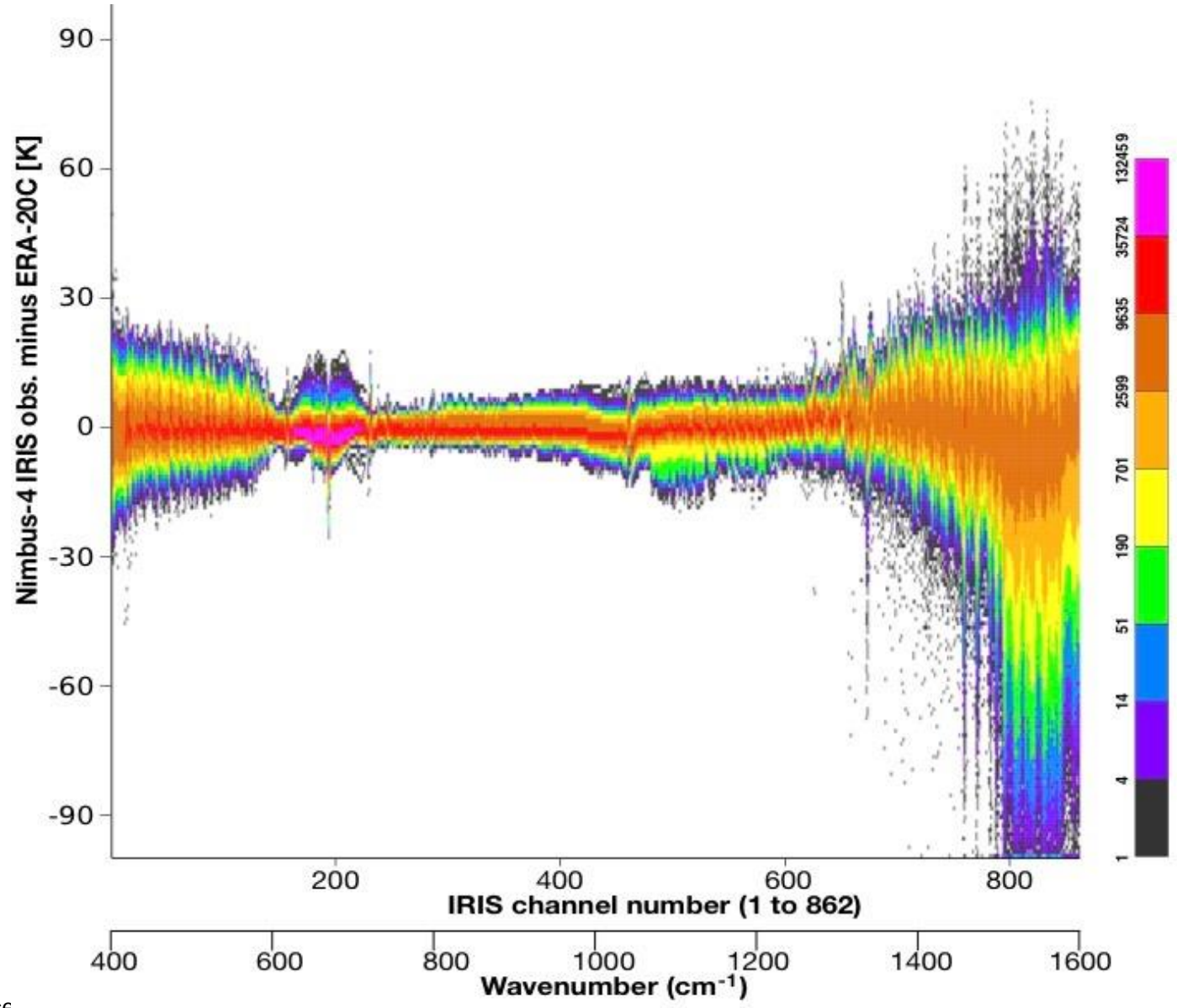
A 9-track tape, holding historic geostationary data, with the corresponding player underneath.



A series of four 5-minute SMS-2 satellite images from 6 May 1975

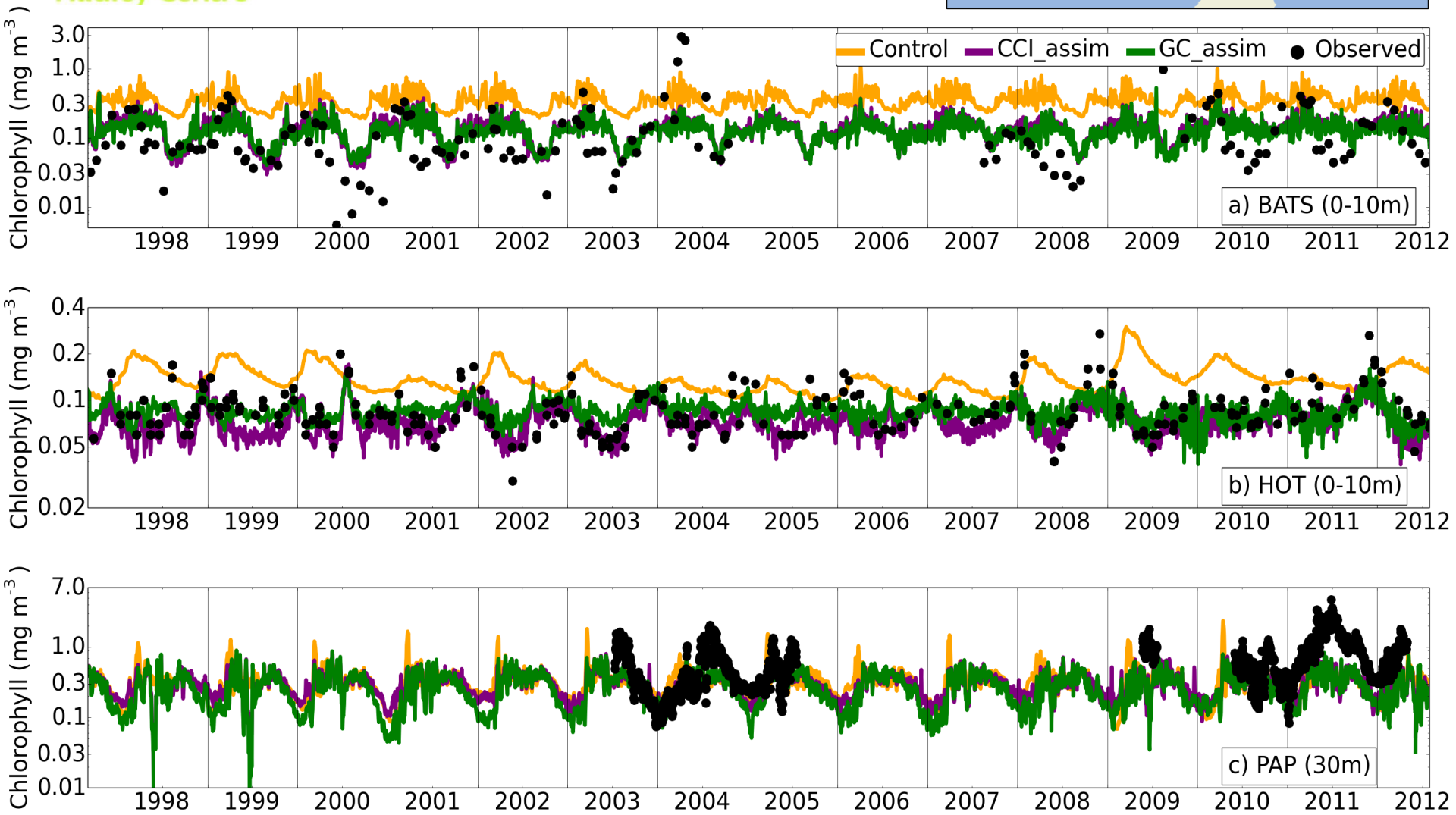
Ancient satellite data

Spectra of Nimbus-4 IRIS (April 1970-January 1971) brightness temperatures, quality controlled to retain only clear channels departures with ERA-20C.



Met Office
Hadley Centre

Chlorophyll time series

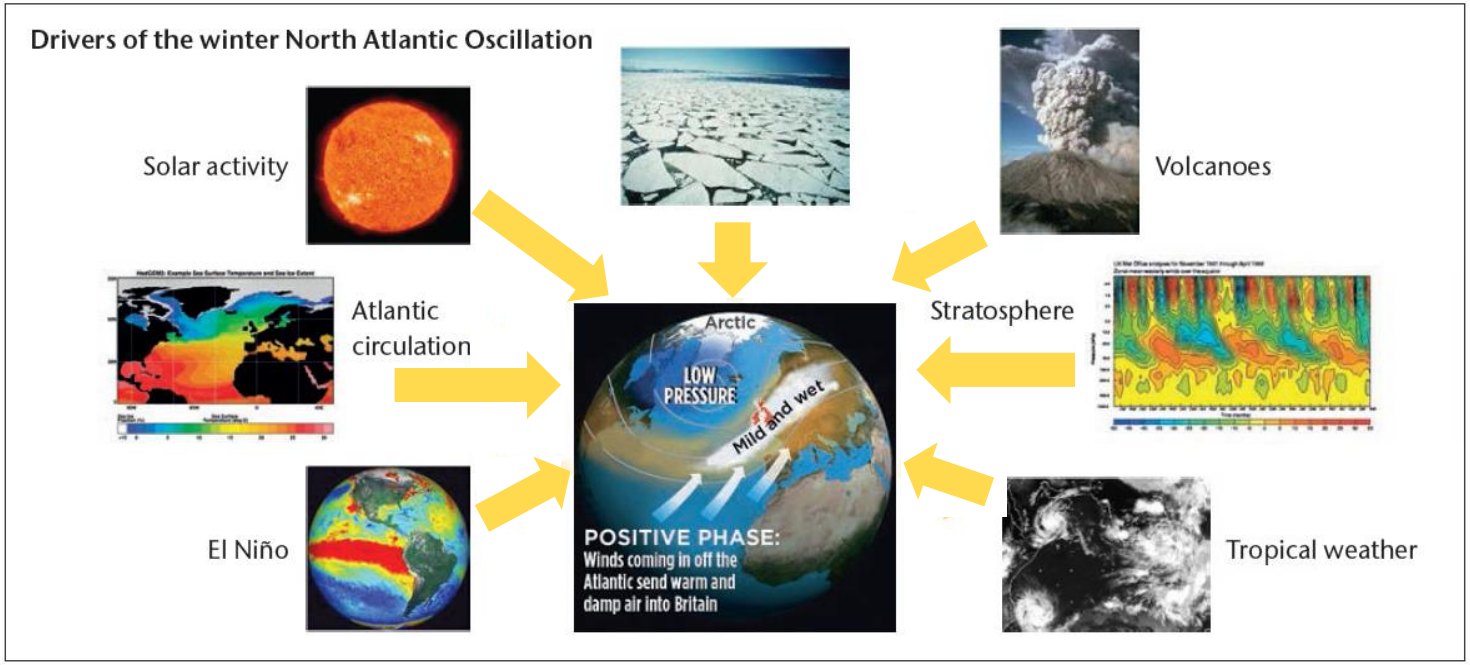


Some Examples

- Assimilation in reanalyses
- Specification of initial state for seasonal and decadal forecasts
- Model validation
- Validating model processes
- Verification for MIPs (CMIP6)
- Trends and attribution, models vs obs

North Atlantic Oscillation

The North Atlantic Oscillation (NAO) is a climatic phenomenon in the North Atlantic Ocean of fluctuations in the difference of atmospheric pressure at sea level between the Icelandic low and the Azores high. Many things trigger the NAO.



Initialisation for seasonal and decadal forecasts

- Ocean and atmosphere analyses are currently the main source of initialisation
- SST from assimilation in ocean model
- Hence satellite data are only indirectly used
- Moving to coupled DA and models
- The key variables are:
  - Sub-surface ocean temperatures
  - SST, Salinity, Sea-Ice (cover & thickness)
  - Stratospheric state
  - Solar spectral irradiance, Soil moisture, Snow cover

Some Examples

- Assimilation in reanalyses
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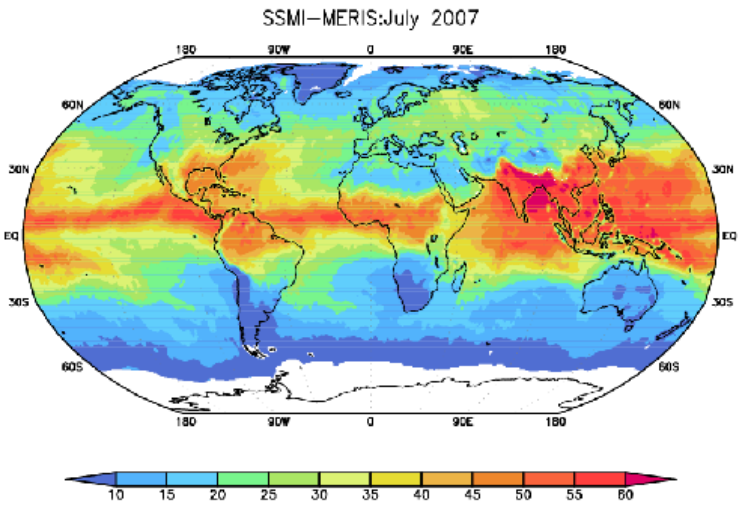
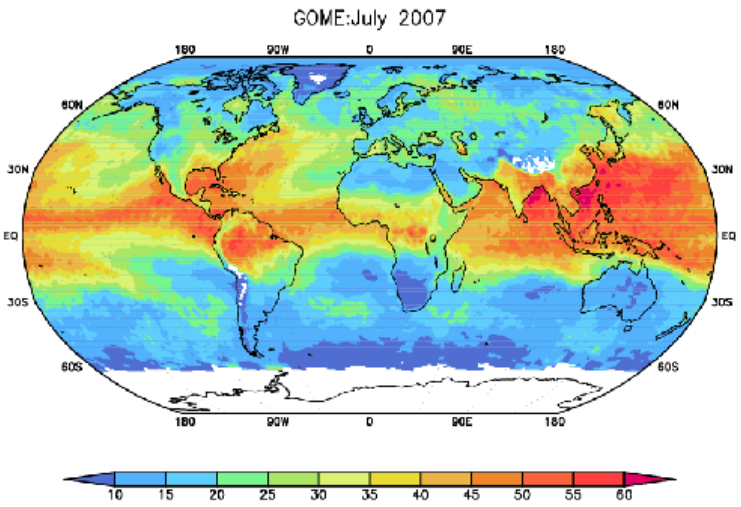
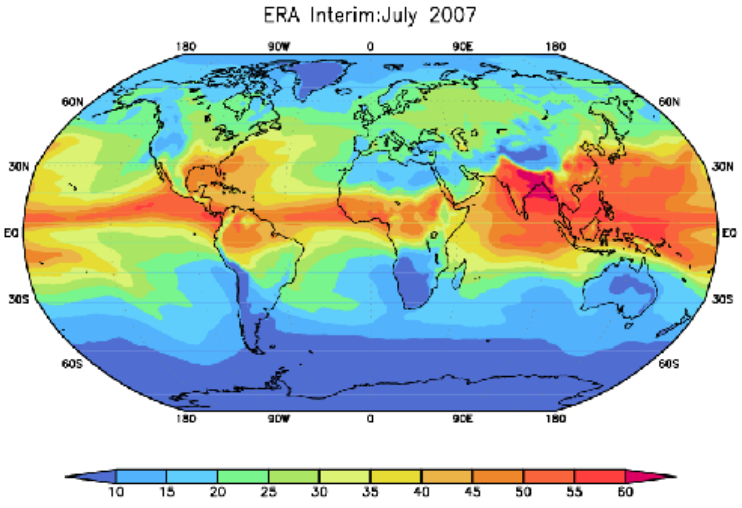
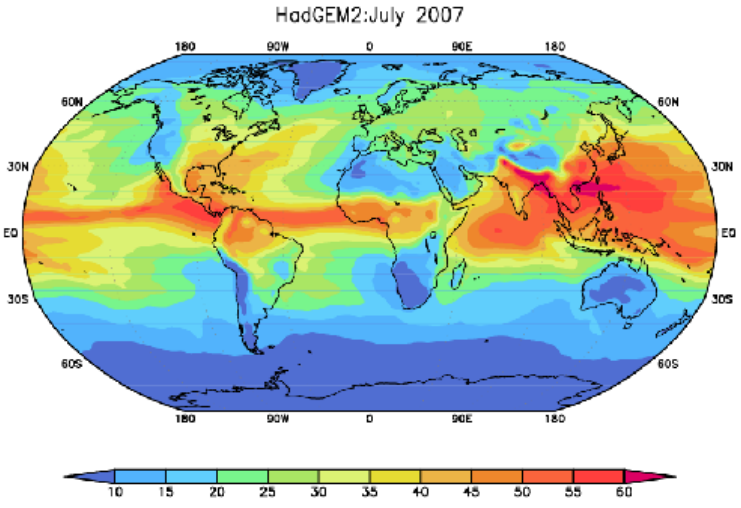
Total column water vapour

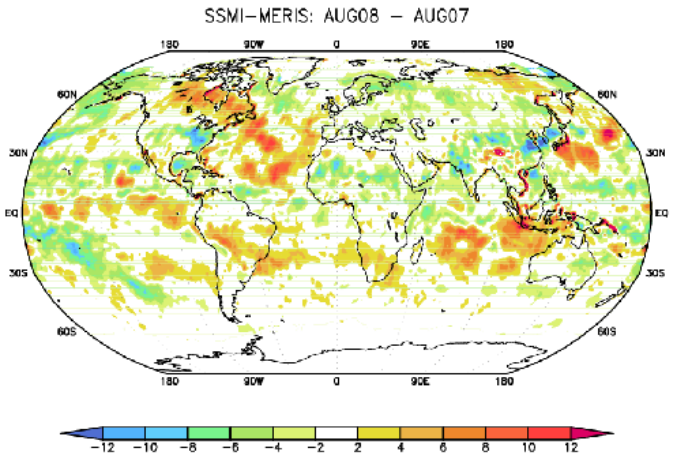


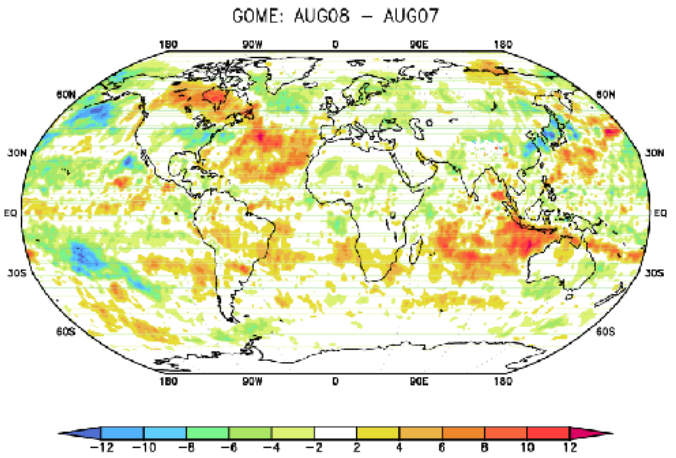


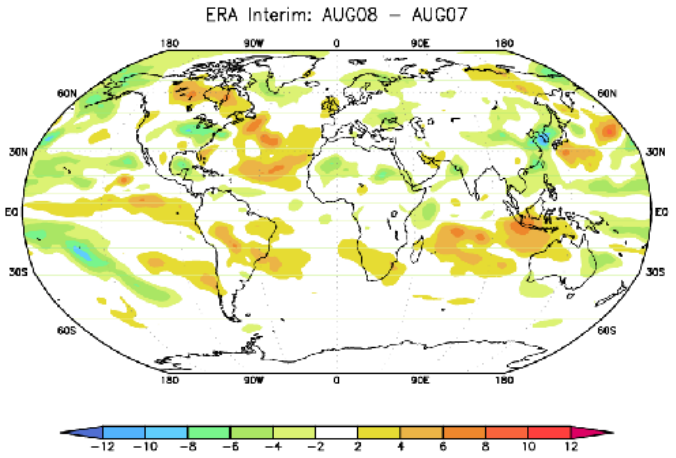


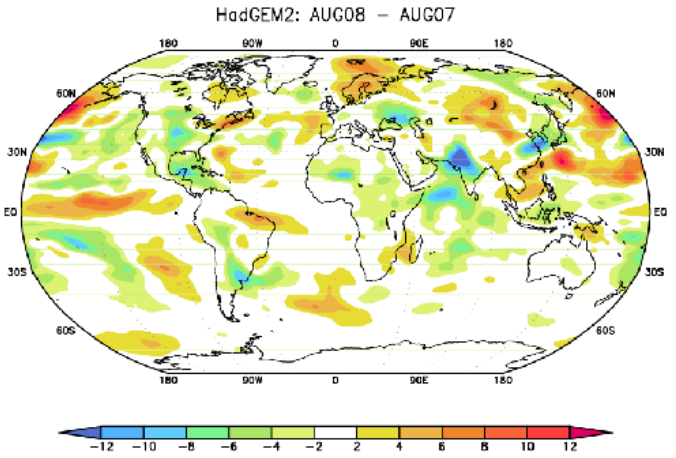


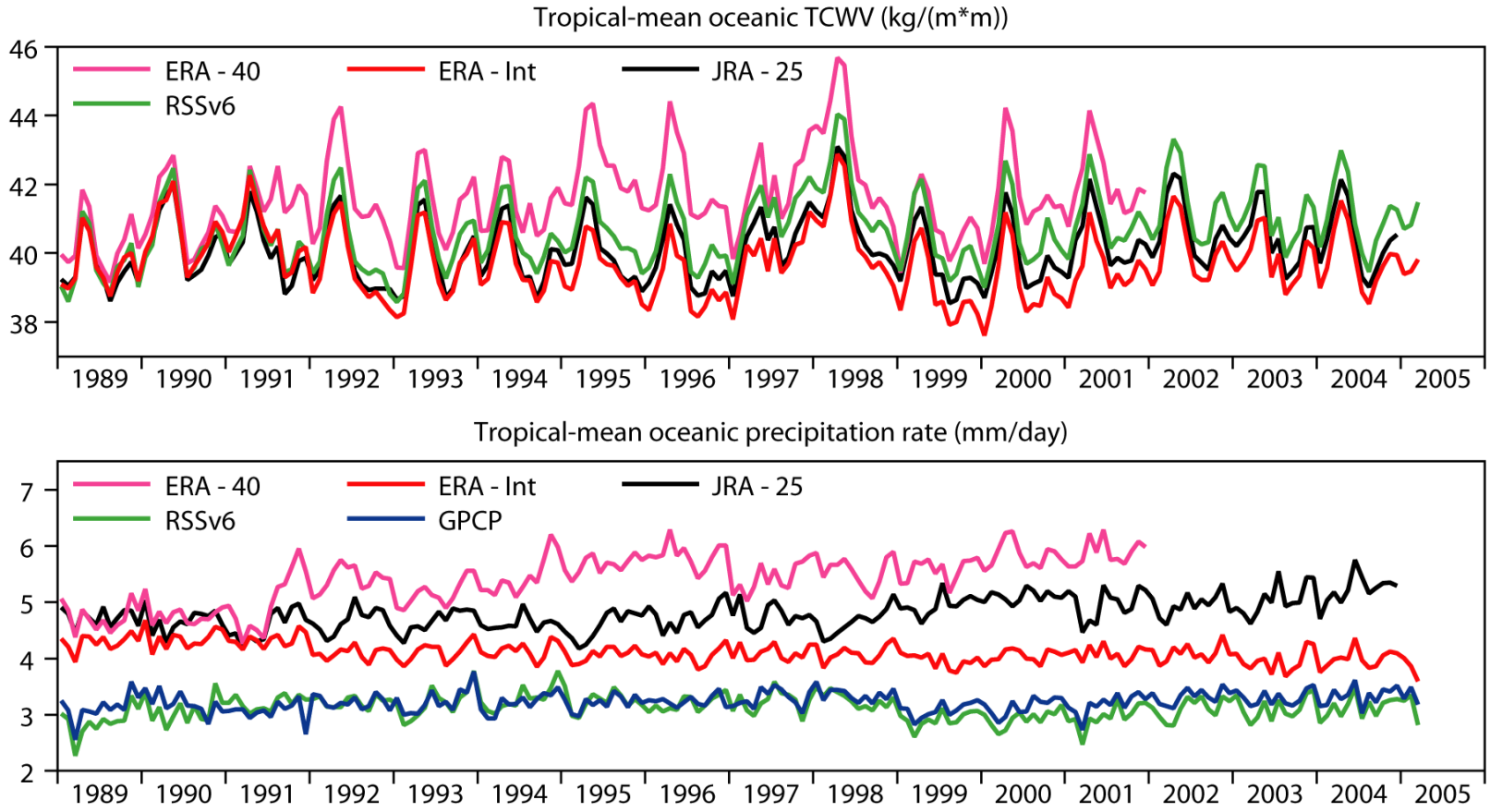
Total column water vapour









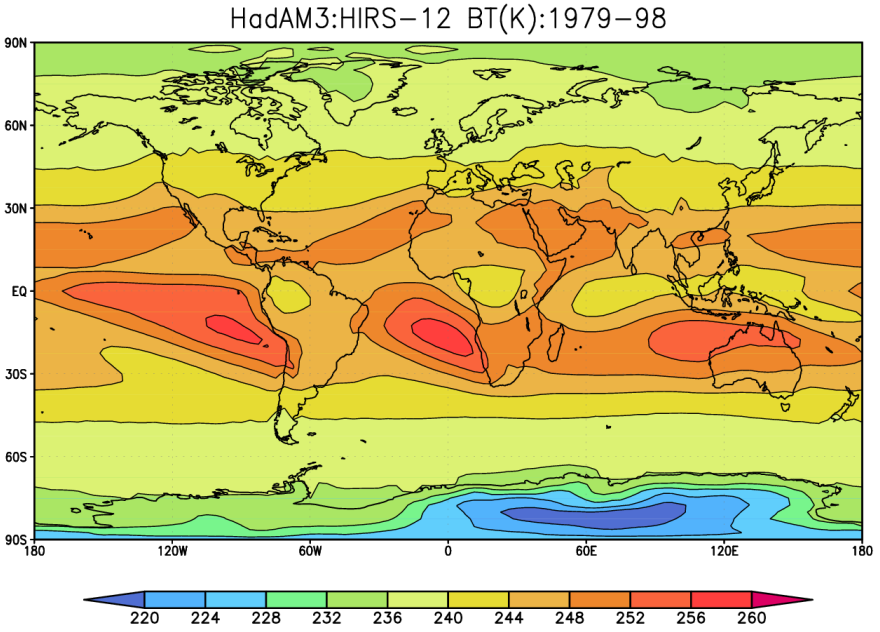


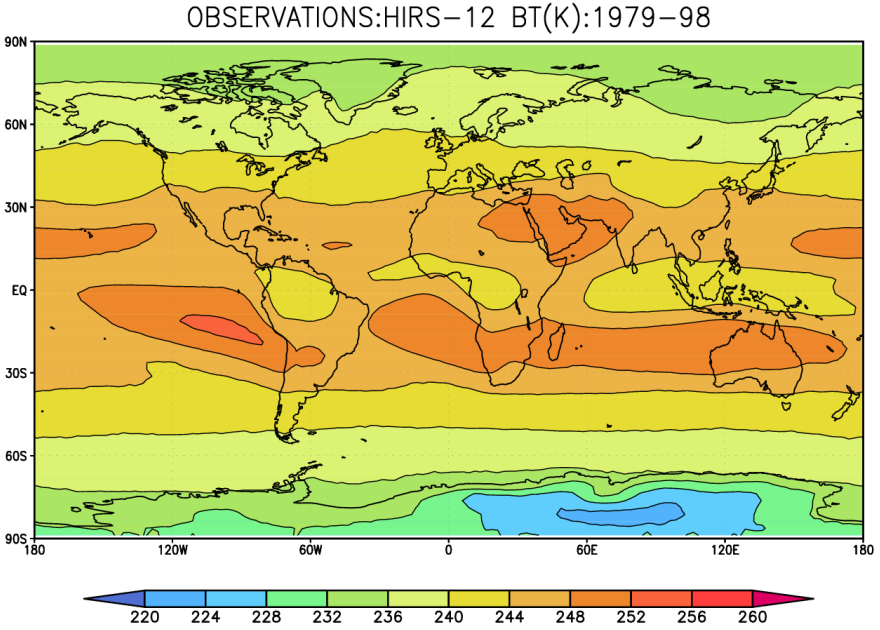
Improvements in ERA-Interim, due to:

- Revised humidity analysis
- Better model physics
- 4D-Var
- Improved bias corrections for radiance data

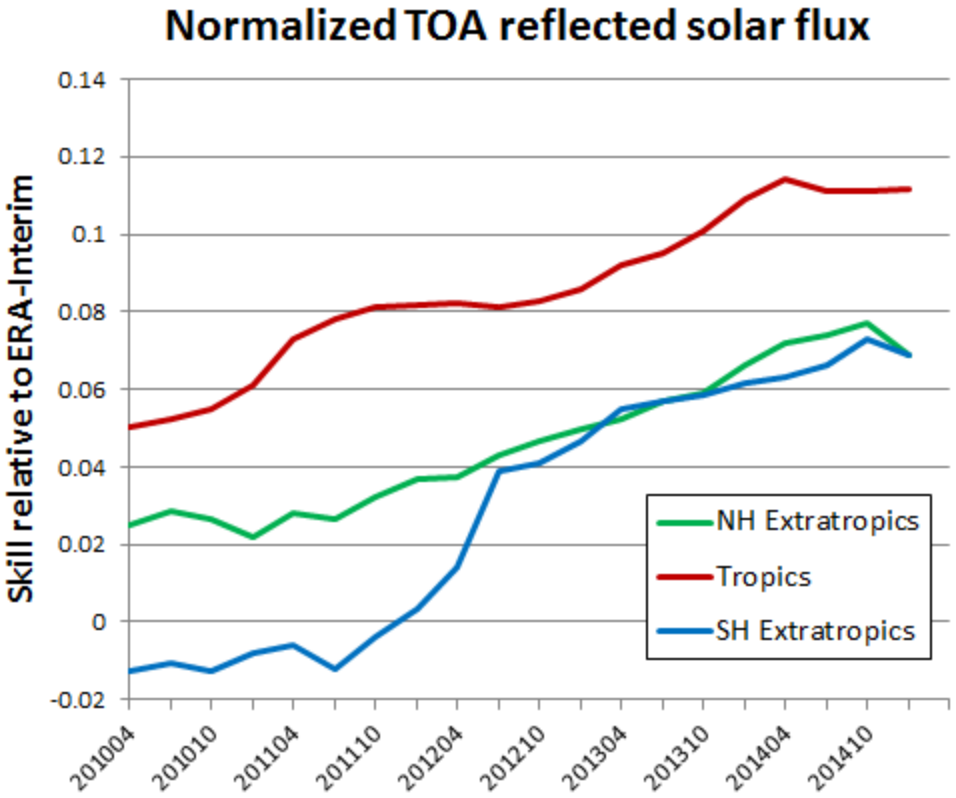
Comparisons in radiance space

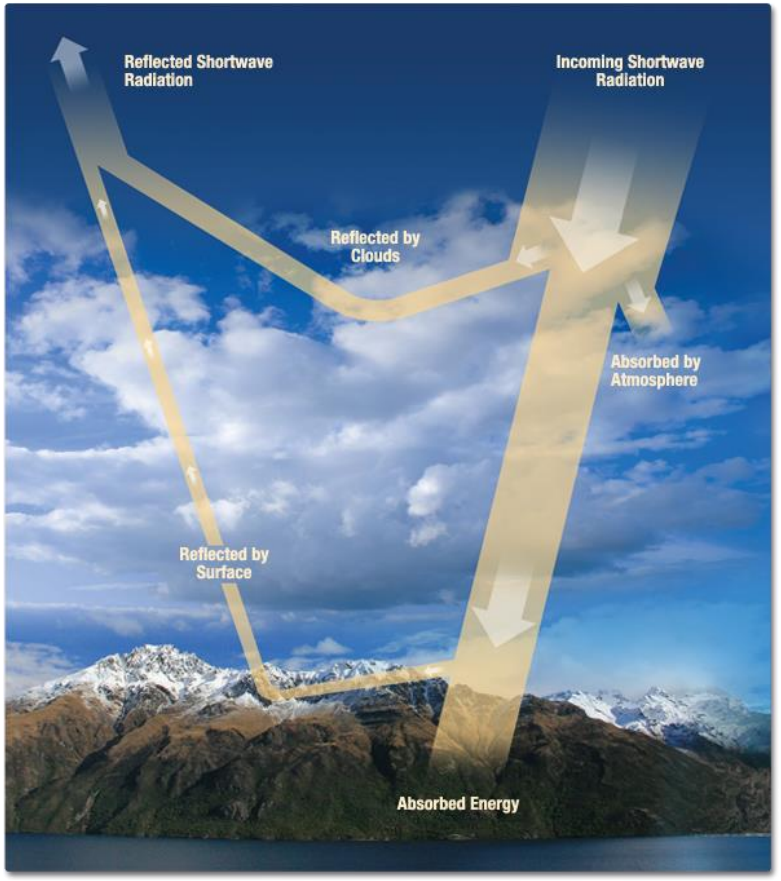
- Avoids ambiguities associated with comparing to retrieved quantities
- Example shows HIRS Channel 12 in previous version of Hadley Centre model
- RTTOV is now part of the COSP simulator





Radiation budget





12-month running average of the day 3 forecast skill relative to ERA-Interim of normalized TOA reflected solar flux (daily totals), verified against satellite data. The verification has been carried out for those parts of the northern hemisphere extratropics (green), tropics (red), and southern hemisphere extratropics (blue) which are covered by the CM-SAF product (approximately 70 S to 70 N, and 70 W to 70 E).

Some Examples

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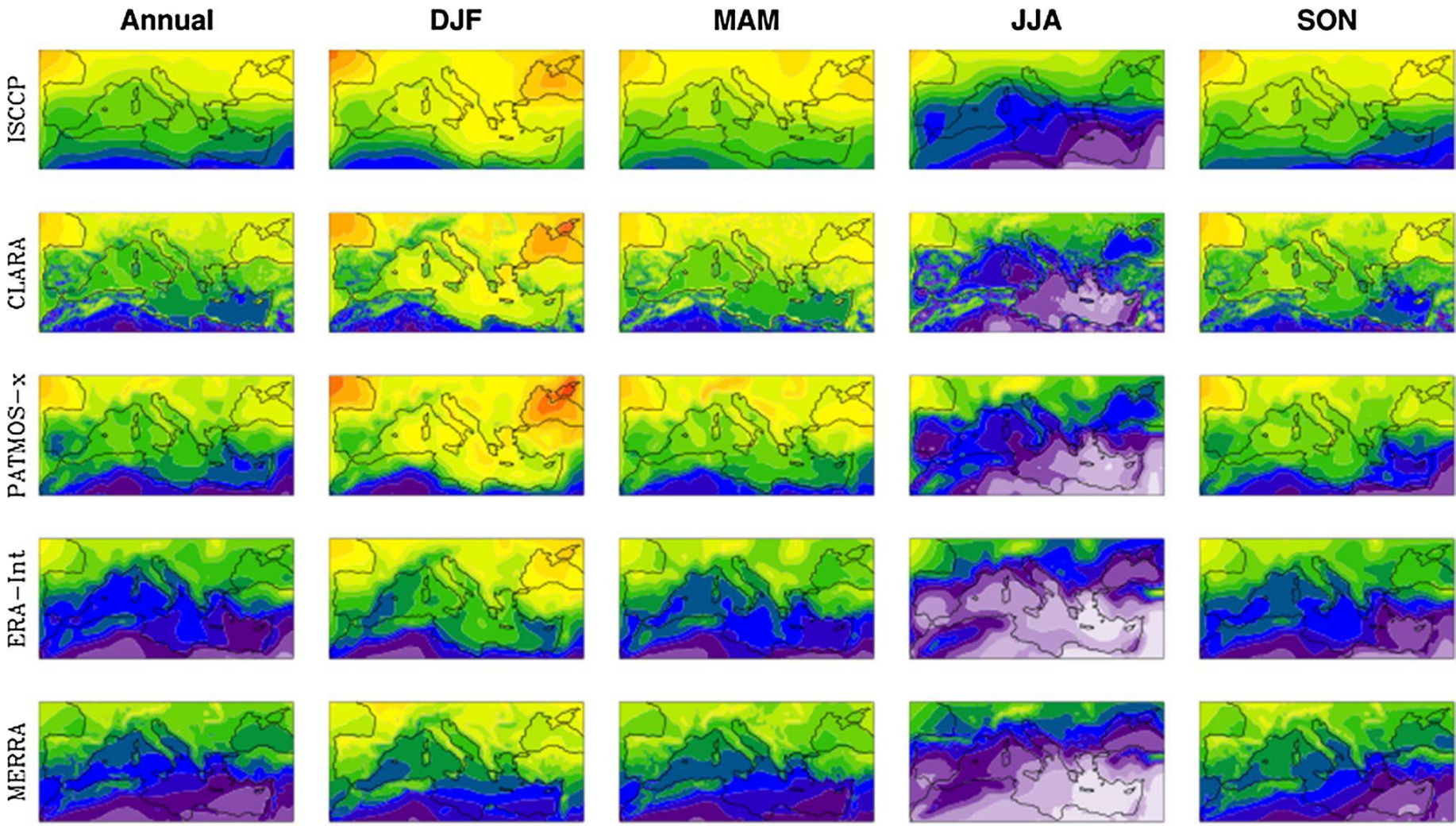


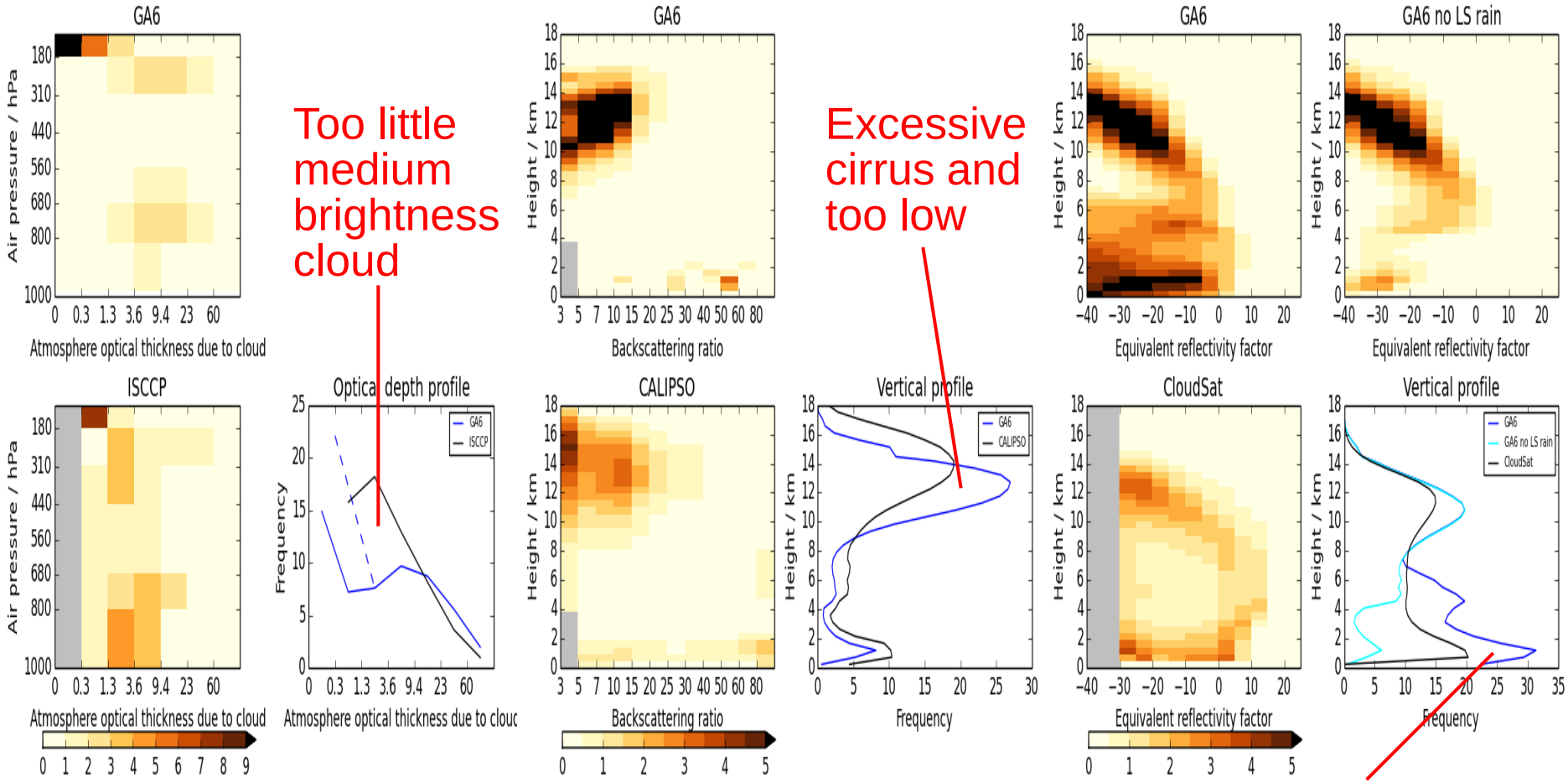
Mean annual and seasonal TCC (%) in the Mediterranean region from remote sensing (i.e., ISCCP, CLARA, and PATMOS-x), reanalyses (ERA-Int and MERRA) and surface observations (EECRA and ICOADS). The means are estimated for the common period. Area shown is from 10°W to 40°E and from 30 to 48°N

Comparison against satellite data over the tropics

ISCCP

CALIPSO

CloudSat



 (Courtesy K. Williams)

Some Examples

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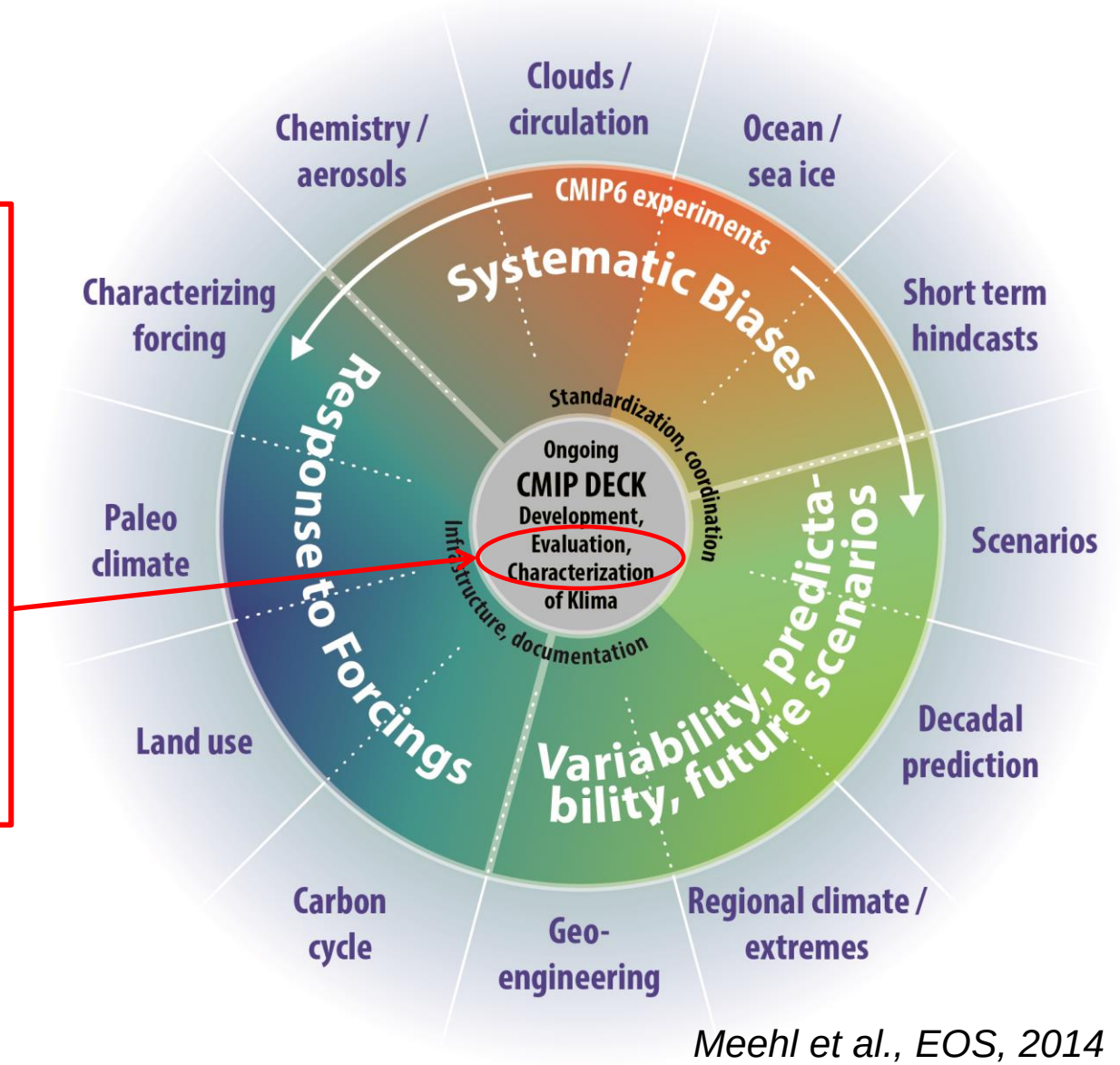
WCRP Grand Challenges: (1) Clouds, circulation and climate sensitivity, (2) Changes in cryosphere, (3) Climate extremes, (4) Regional climate information, (5) Regional sea-level rise, and (6) Water availability, plus an additional theme on **“**biospheric forcings and feedbacks”

Goal

ESMValTool as one of the CMIP documentation functions to routinely assess the performance of CMIP DECK and CMIP6 simulations running alongside the ESGF

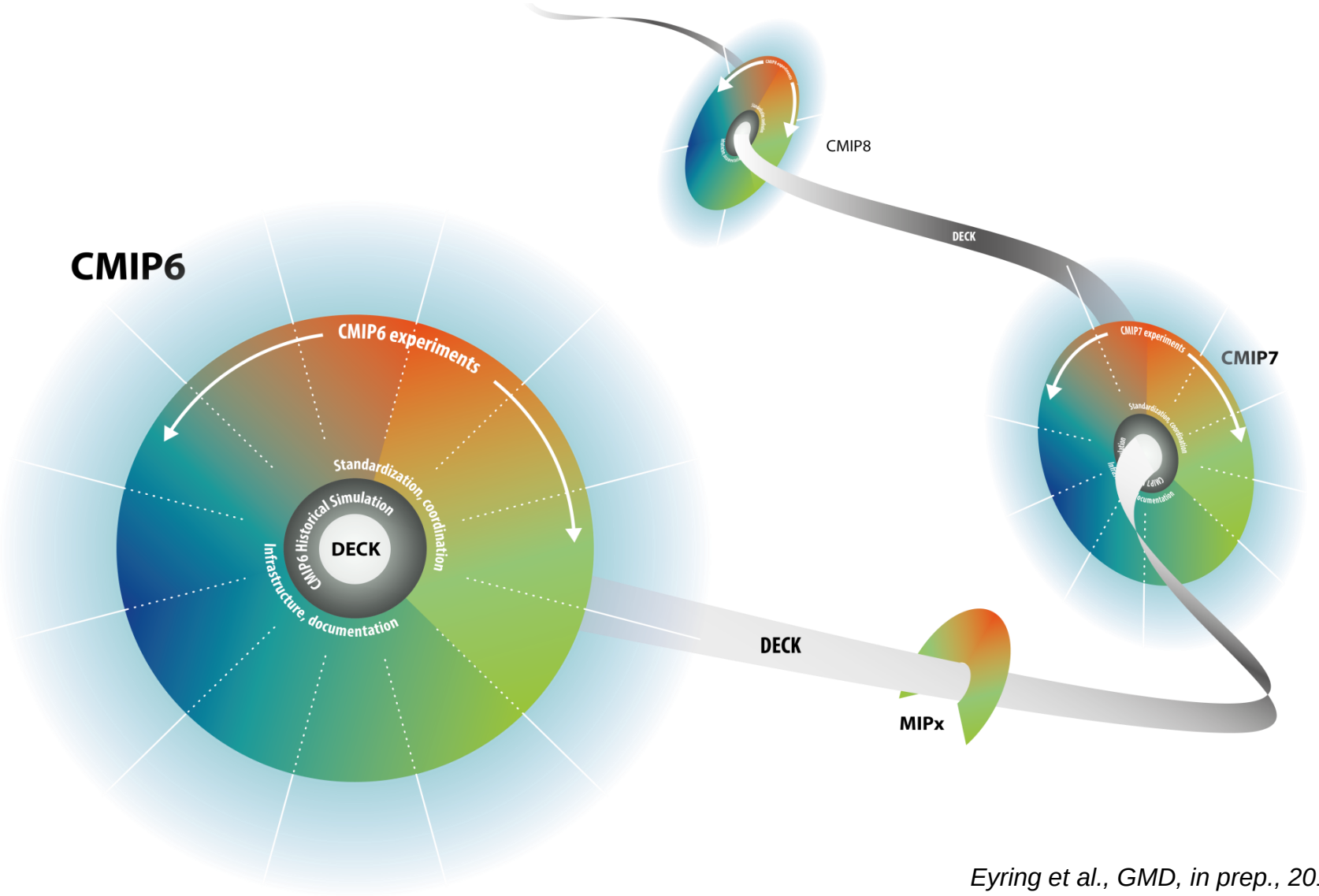


Meehl et al., EOS, 2014

DLR

CMIP Continuity

A common suite of experiments for each phase of CMIP provides an opportunity to construct a multi-model ensemble using model output from various phases of CMIP



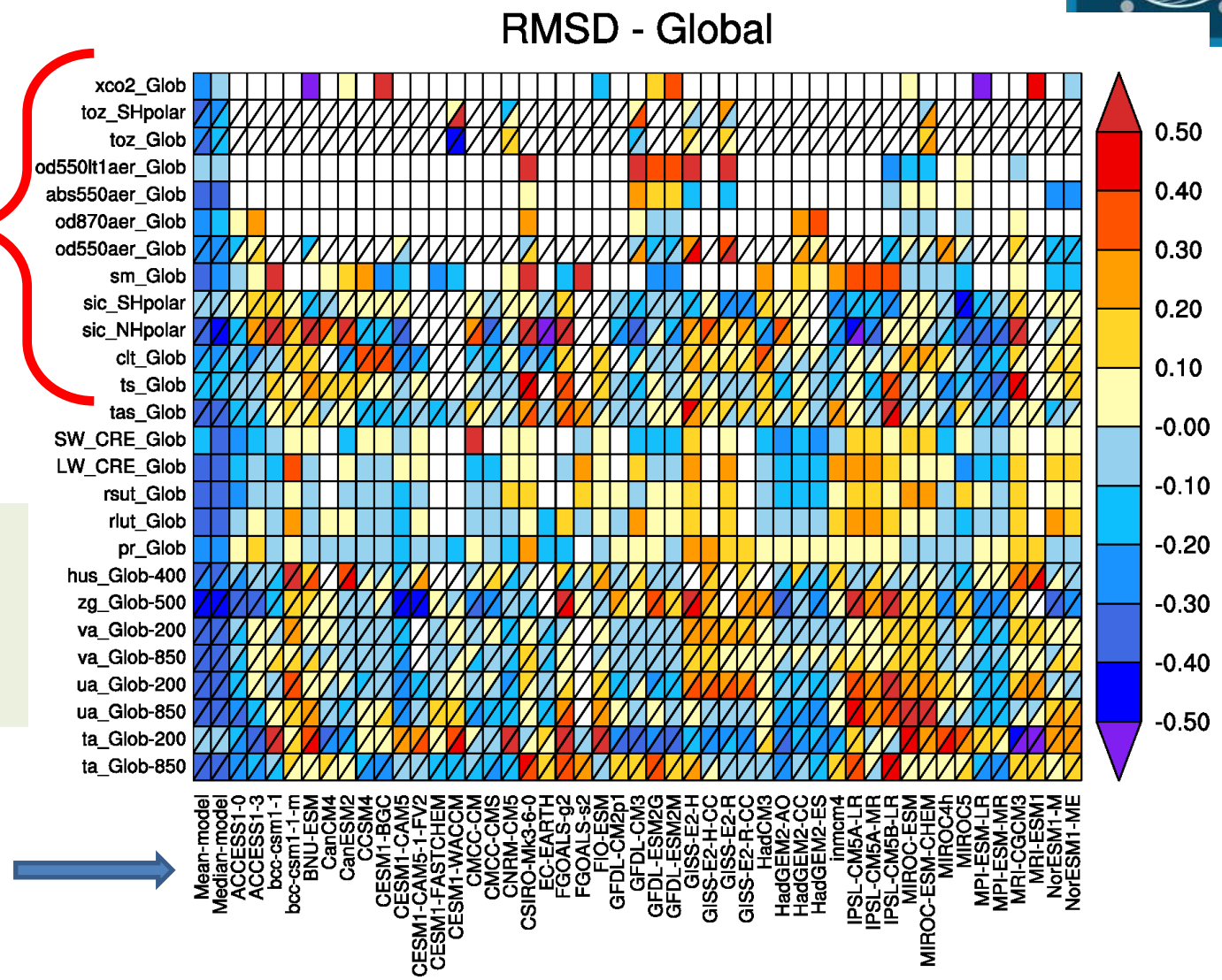
Eyring et al., GMD, in prep., 2015

Where we are now: Model assessment

ESA CCI datasets

greenhouse gases
ozone
aerosol
soil moisture
sea ice
cloud
SST

Assessment of climate models using ESMVal tool for several CCI datasets



Climate models

From: Lauer et al. (2016), Remote Sensing of Environment (manuscript in preparation)

Some Examples

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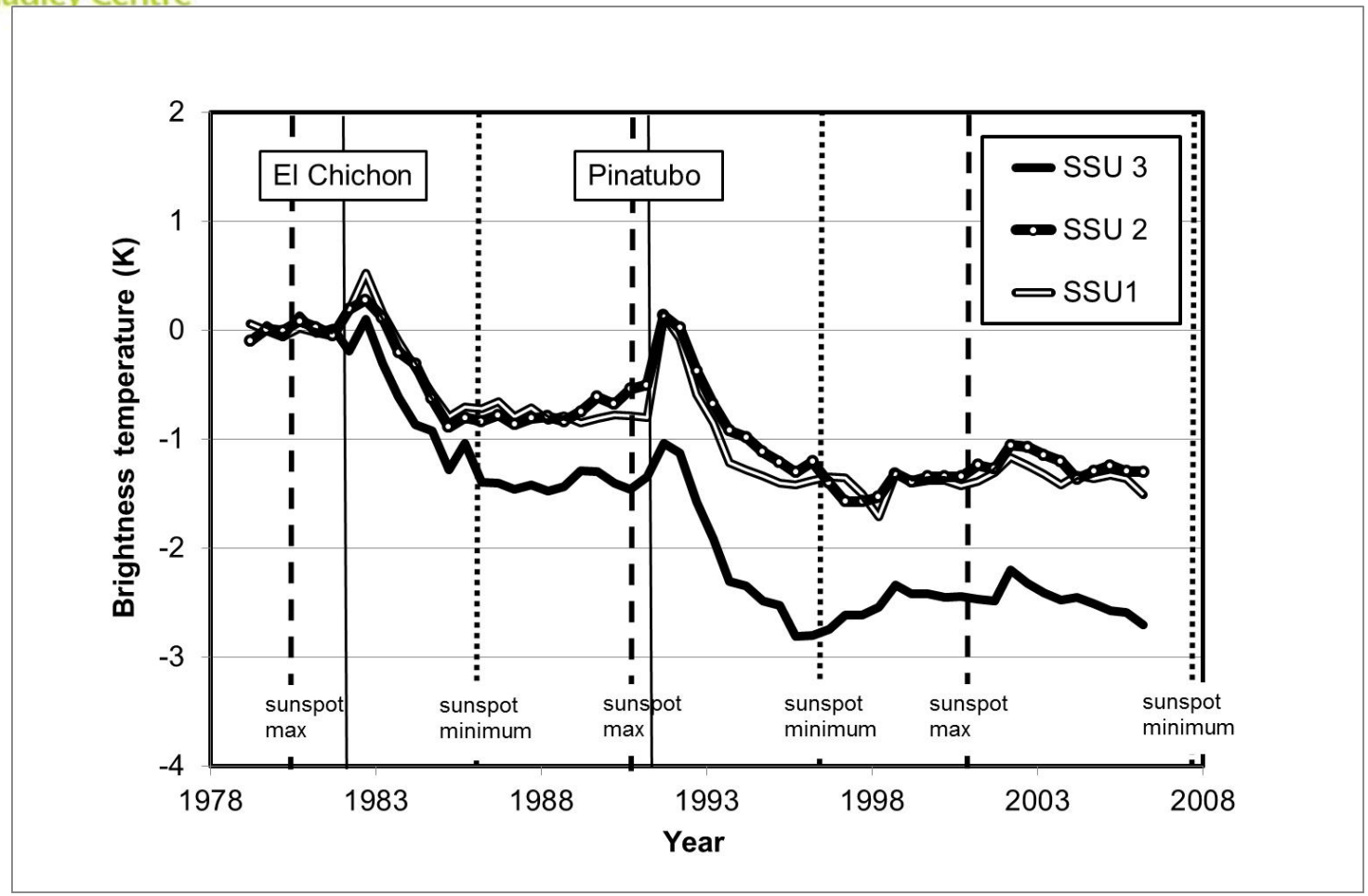
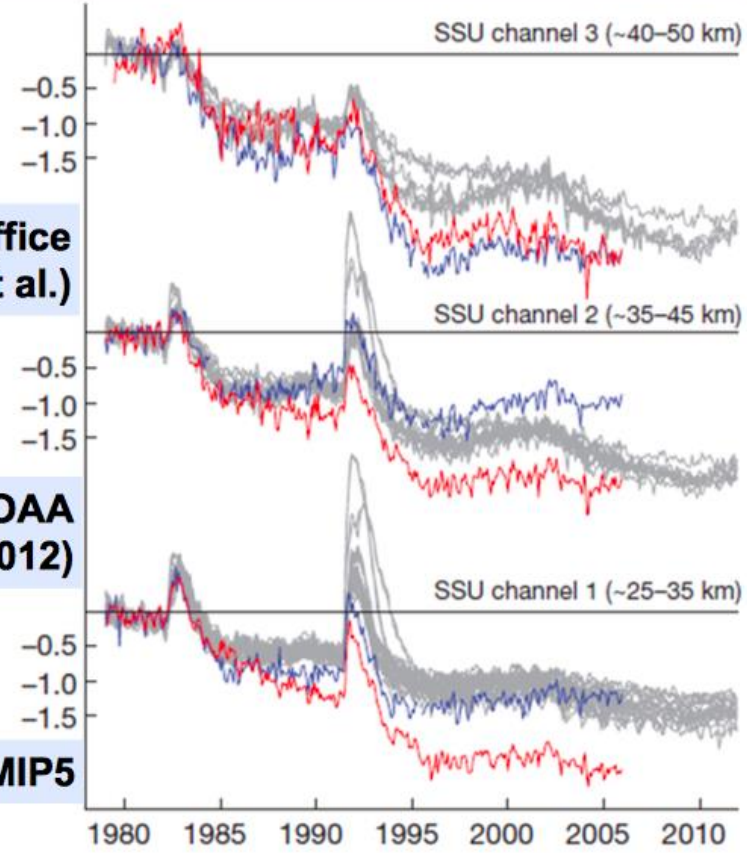
SSU monitors the stratosphere



Nash, J. and Saunders, R. (2015), A review of Stratospheric Sounding Unit radiance observations for climate trends and reanalyses. Q.J.R. Meteorol. Soc, 141: 2103–2113. doi:10.1002/qj.2505

Monitoring and attribution

Thompson et al. (2012) Nature Research Perspective: The mystery of recent stratospheric temperature trends



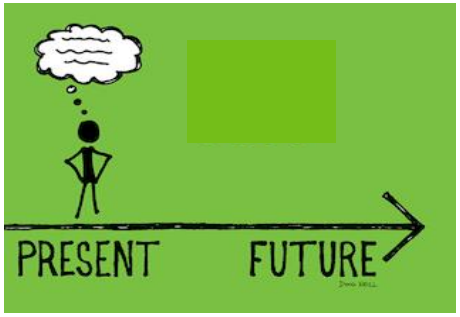
Blue: Met Office (Nash et al.)

Red: NOAA (Wang et al., 2012)

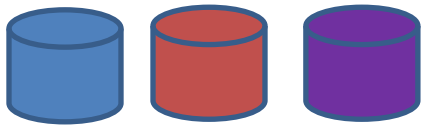
Grey CMIP5

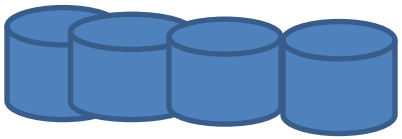
1. Differences between 2 independently processed satellite datasets
2. CMIP5 models differ from observations
3. Impact of Pinatubo well modelled
4. Post eruption change in stratospheric temperature not so well modelled

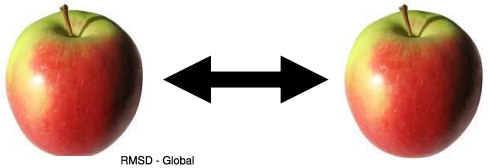
Future prospects

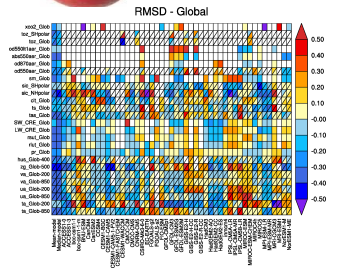


- More satellite based climate data records (variables, time span,..)
- Better climate data records via re-reprocessing *including* modellers needs
- Need for observation simulators
- Defined metrics for climate model assessments (sat + in-situ)
- Better tools for confronting models with observations

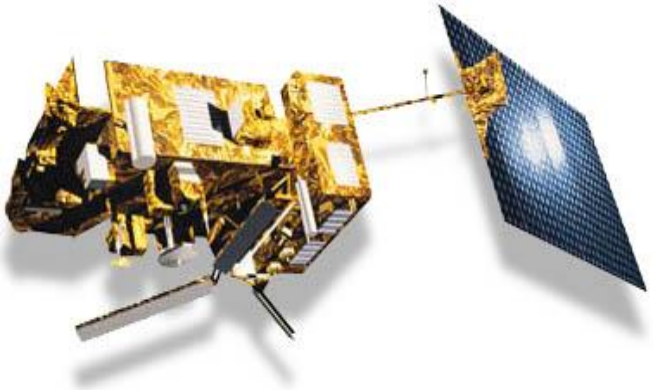








EMBRACE



Our climate modellers can now access good datasets to evaluate their models thanks to the many FCDR and TCDRs now available