Use of satellite data in reanalysis

Dick Dee

***Acknowledgements**:* Paul Poli, Adrian Simmons, Hans Hersbach, Carole Peubey, David Tan, Rossana Dragani, the rest of the reanalysis team and many others at ECMWF.

Outline

Reanalysis at ECMWF

The ERA-CLIM project

Satellite data in ERA-Interim

The next ECMWF reanalysis: ERA5

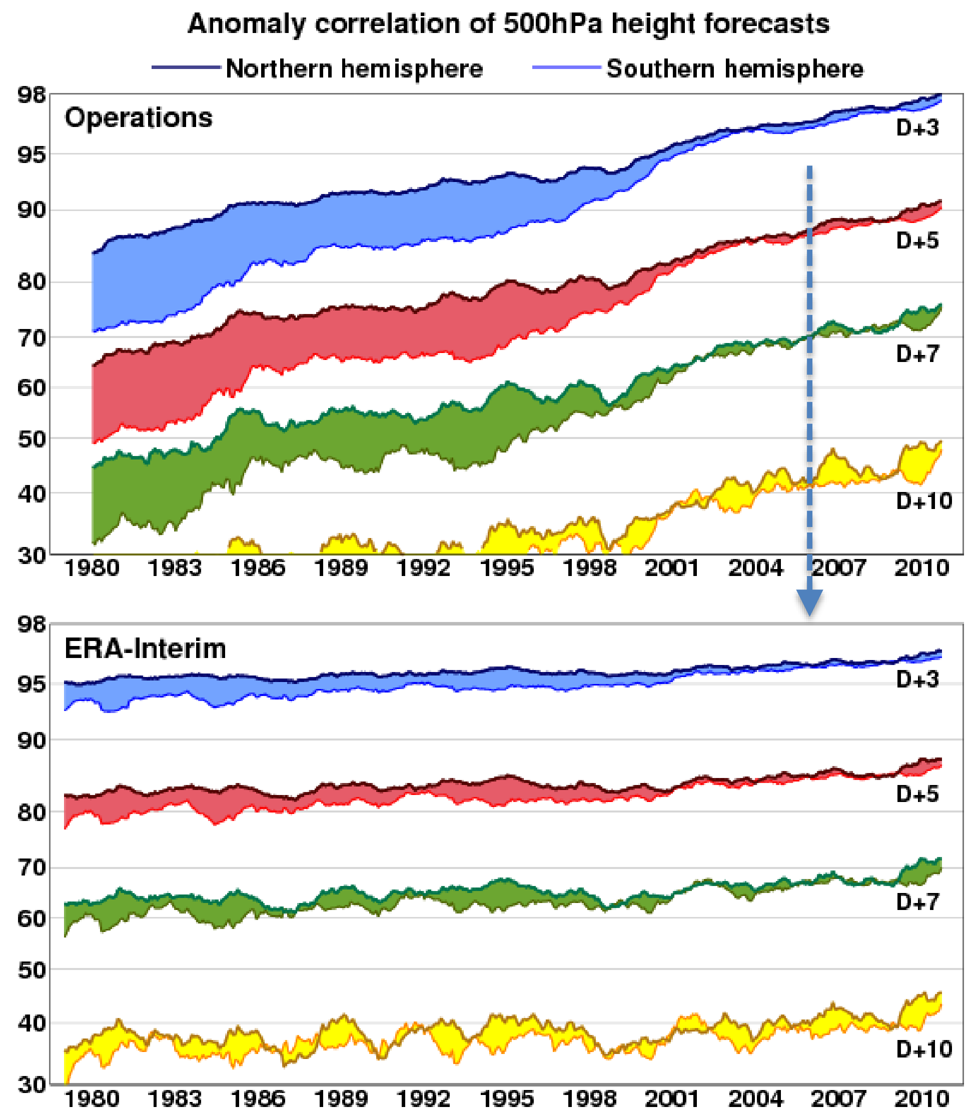
Reanalysis and numerical weather prediction

Reanalysis makes use of data assimilation systems designed for weather forecasting

It uses a single model and analysis method for a consistent re-analysis of past observations

Consistency in time is the key challenge for climate reanalysis

The difficulties are due to biases in models and observations



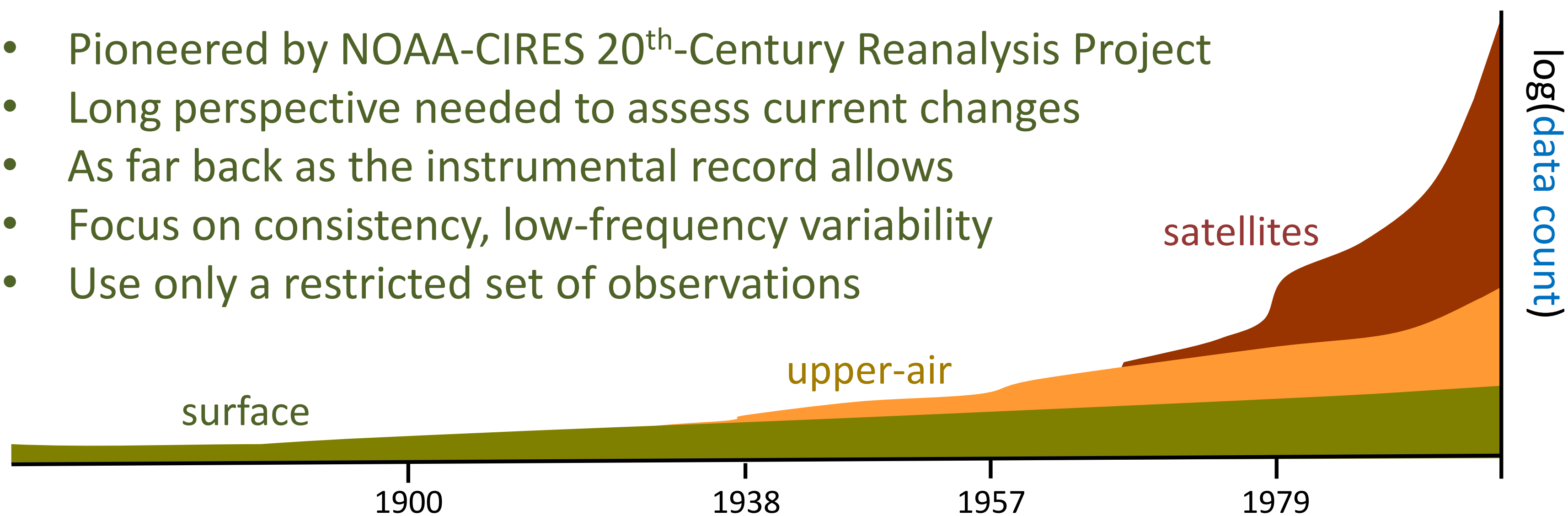
Two types of reanalyses for climate studies

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

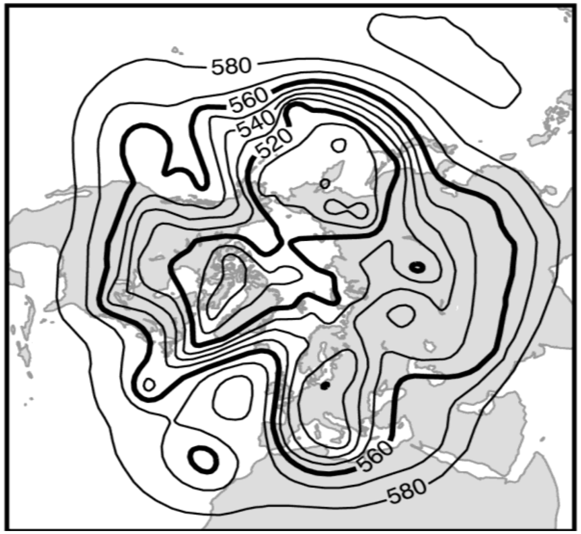
Extended climate reanalyses (~100-200 years):

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

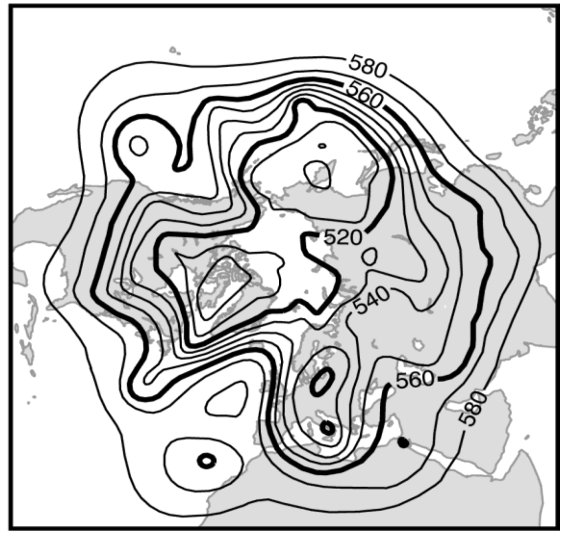


What can we do with limited observations?

Two modern analyses of NH geopotential height at 500hPa

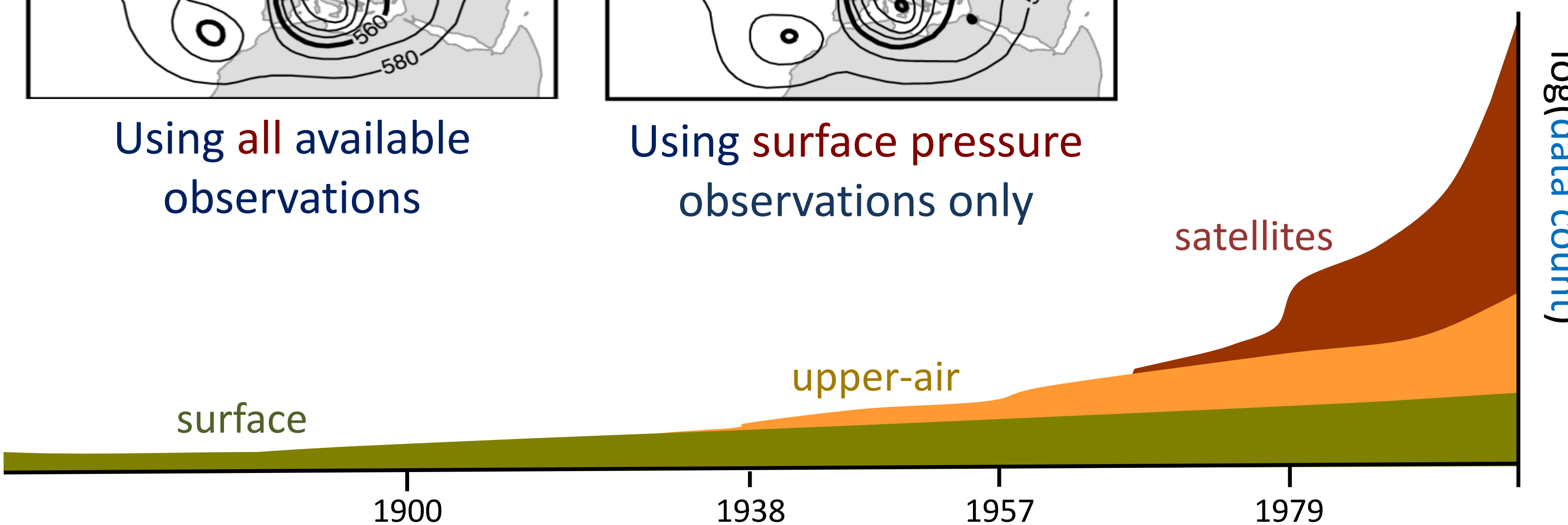


Using all available observations



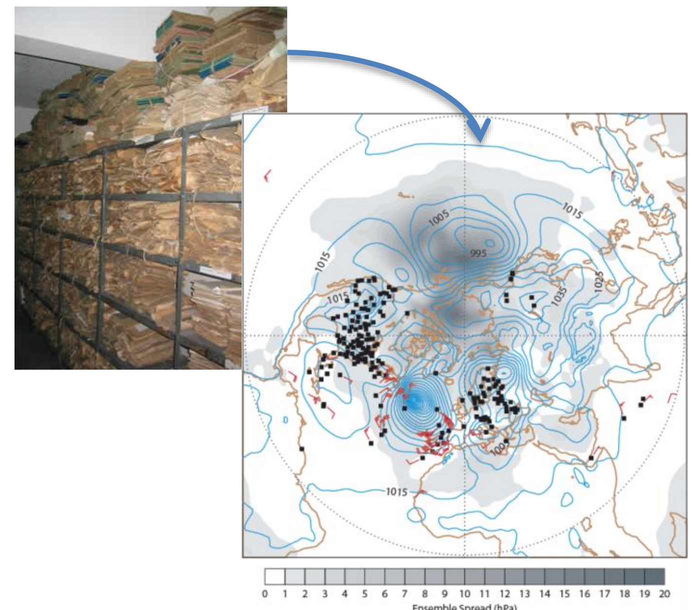
Using surface pressure observations only

Whitaker, Compo, and Thépaut 2009



The ERA-CLIM project

European FP7 collaborative research, 9 institutions, 2011-2013

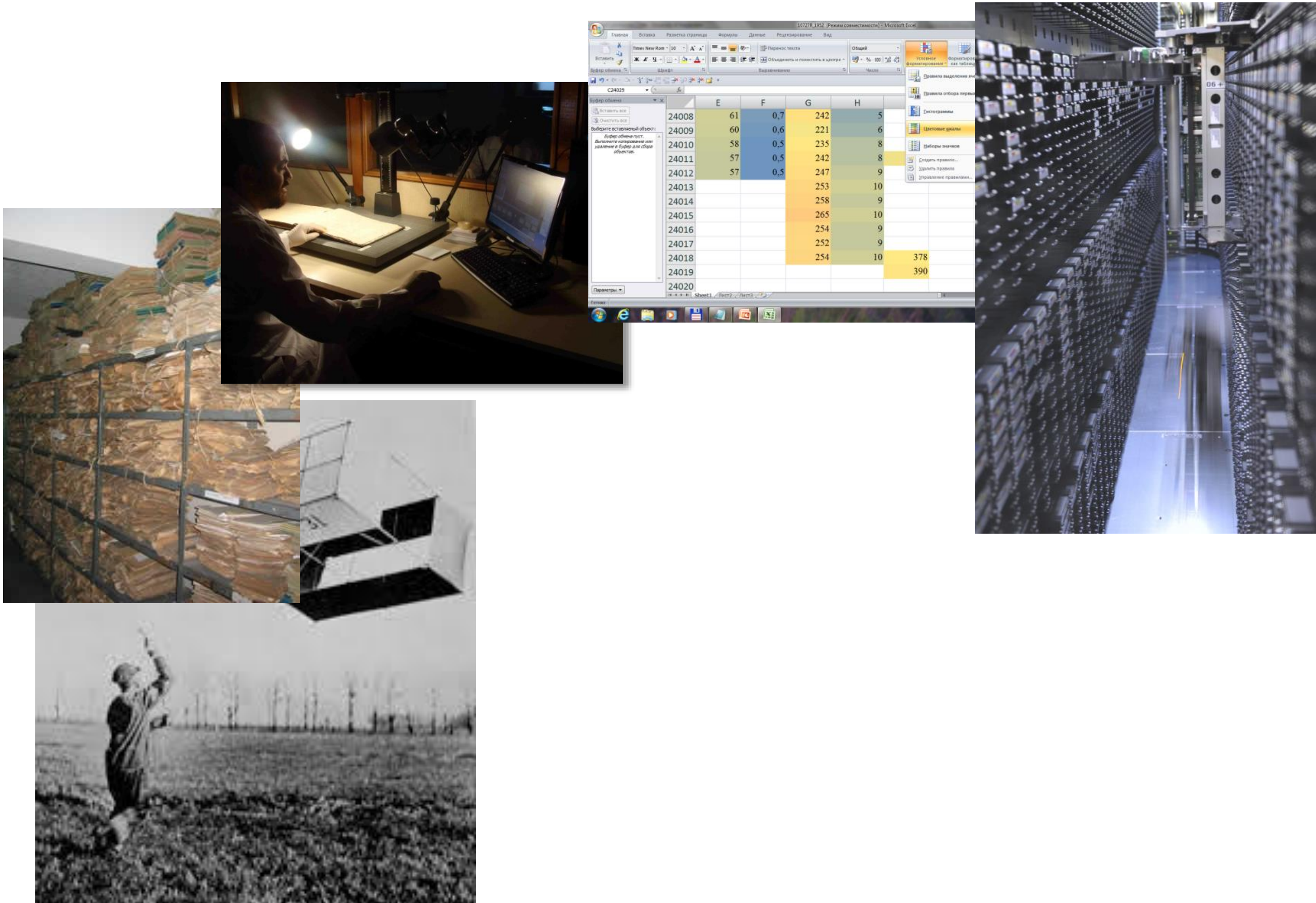


Goal: Preparing input observations, model data, and data assimilation systems for a global atmospheric reanalysis of the 20th century

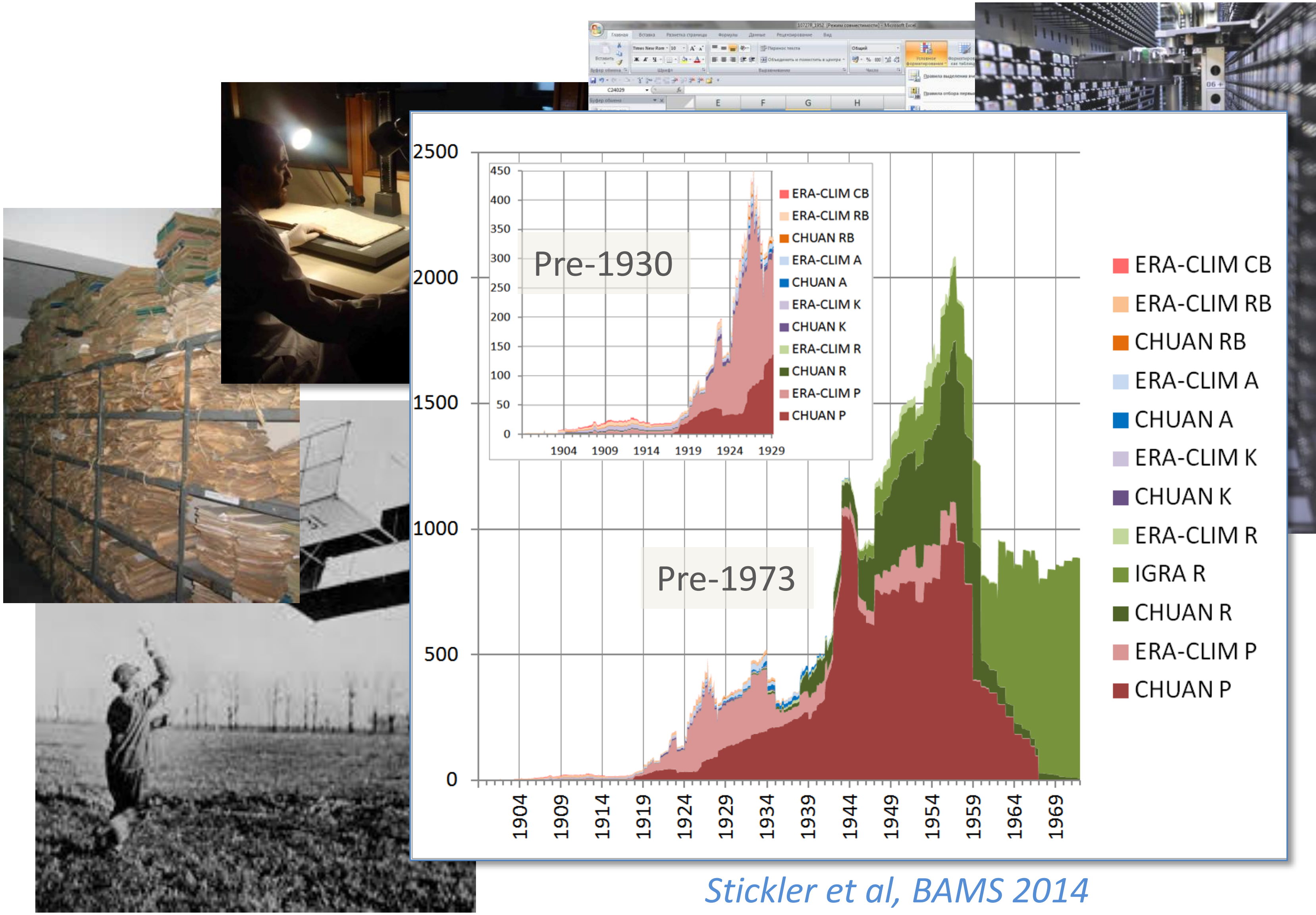
Main components:

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

Data rescue: *Upper-air observations pre-1957*

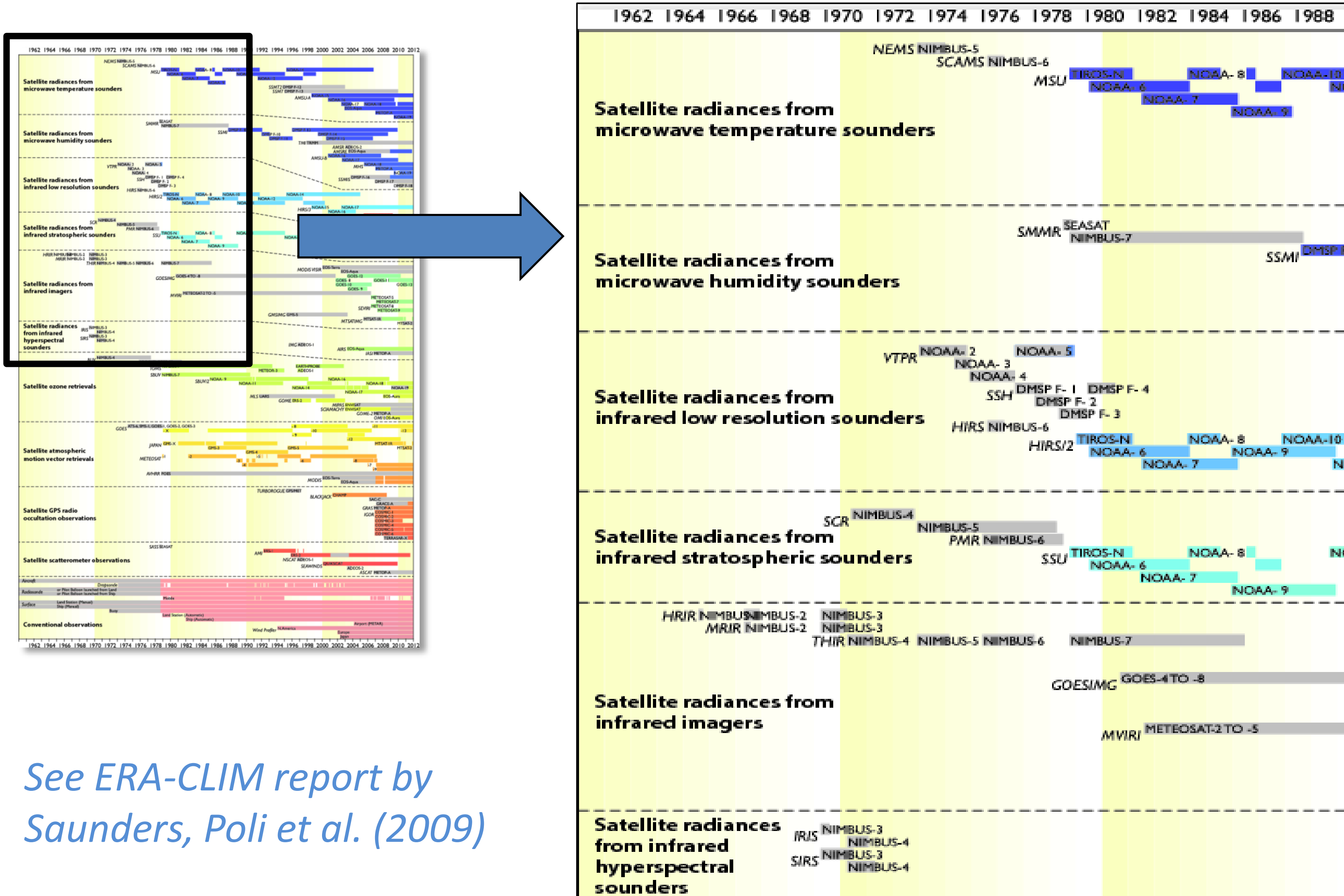


Data rescue: *Upper-air observations pre-1957*



Stickler et al, BAMS 2014

Data rescue: *Early meteorological satellites*



See ERA-CLIM report by Saunders, Poli et al. (2009)

Early instruments with potential for reanalysis

ERA-CLIM contribution:

- Detailed inventory of usable records
- Clear expression of requirements
- Efficient tools for data exploration and analysis

Active work on SMMR, PMR/SCR, SSM/T-2, IRIS, SCAM, …

See ITSC18 poster by Poli et al. 2012

Instru-ment	Characteristics	Immediate concern	Recom-mendation
NEMS	Microwave spectrometer, with two water vapour channels near 22 GHz (5 mm) and three channels near 59 GHz (10 mm), spatial resolution 180 km at nadir	Nadir-viewing only, data on microfiche	**Reject for now**
SCAMS	Microwave spectrometer, with one water vapour channel near 22 GHz (5 mm), three channels near 59 GHz (10 mm), one window channel, spatial resolution 150 km at nadir	Data recovery in process by NSSDC.	**Consider for assimilation**
SSM/T	Microwave temperature sounders precursors to AMSU-A and AMSU-B but with bigger fields-of-view. Met Office preparing a homogenized data for ERA-CLIM.	RT forward model needed for SSM/T	**Assimilate**
SMMR	Microwave radiometer, ten channels: dual-polarization measurements at 6.63, 10.69, 18.0, 21.0, and 37.0 GHz, spatial resolution 150 km at nadir	Raw radiance data not found	**Keep looking for data**
SSH	Discrete filter radiometer, six channels in the 15 micron CO_2 band, one window channel, eight water vapour channel in the 22–30 micron band, one channel in the 10 micron ozone band	Data lost forever?	**Keep looking for data**
HIRS on Nimbus-6	Discrete filter radiometer, seven channels in the 15 micron CO_2 band, two window channels, two water vapour channels, five channels in the 4.3 micron band, spatial resolution 25 km at nadir	Data recovery in process by NSSDC. Digital version of the SRF not found.	**Assimilate**
SCR	Radiometer observing through a pressurized optical cell, six channels in the 15 micron CO_2 band, spatial resolution 112–160 km at nadir (Nimbus-5: eight channels in the 15 micron CO_2 band, three window channels, one water vapour channel at 18.6 microns, spatial resolution 30 km at nadir)	RT coefficients challenging	**Validate**
PMR	Radiometer observing through a pressurized optical cell	RT coefficients challenging	**Assimilate**
HRIR	Visible and infrared imager, 8 km spatial resolution at nadir, 3.5–4 micron channel (and also 0.7–1.3 for Nimbus-3)	Digital version of SRF not found	**Validate**
MRIR	Infrared imager, five channels including a water vapour channel in the 6.7 micron band	Digital version of SRF not found	**Validate**
THIR	Infrared imager, one window channel and one water vapour channel in the 6.7 micron band	Only JPEG images available, raw radiance data lost forever?	**Keep looking for data**
IRIS	Michelson interferometer, covering 5–20 microns with 5 cm^{-1} normalized apodized spectral resolution (Nimbus-4: 6.25–25 microns, 2.8 cm^{-1} resolution), nadir spatial resolution 144 km	Short time period, calibration biases	**Validate**
SIRS	Grating spectrometer, covering 11–15 microns (Nimbus-4: 11–36 microns), nadir spatial resolution 220 km	Narrow swath (up to 12 degrees only from nadir)	**Consider for assimilation**
AVHRR	Imager on polar orbiters, atmospheric motion vector (wind) retrievals at the poles. EUMETSAT and CIMSS working on reprocessing.	Reprocessing not complete yet	**Assimilate**
SeaSat	First scatterometer ever. Suspicious end-of-life.	Very short dataset (97 days)	**Validate**
NSCAT	Scatterometer from U.S.	Short dataset (9 months)	**Assimilate**

Nimbus-4 IRIS: 862 channels

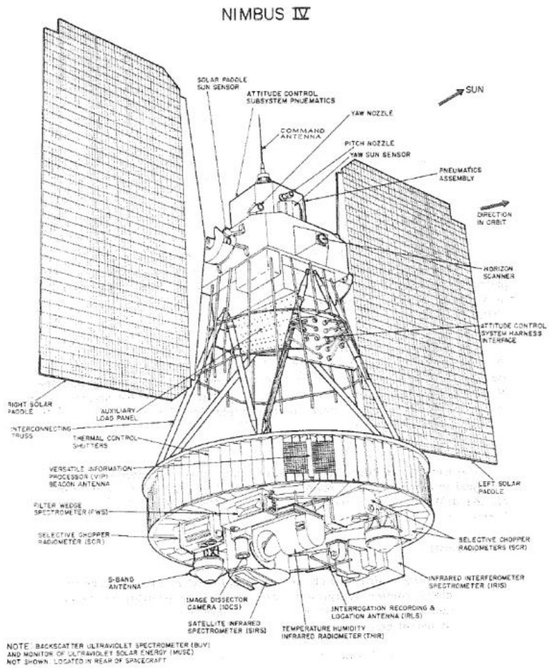


Figure 1-1. Basic Configuration of Spacecraft

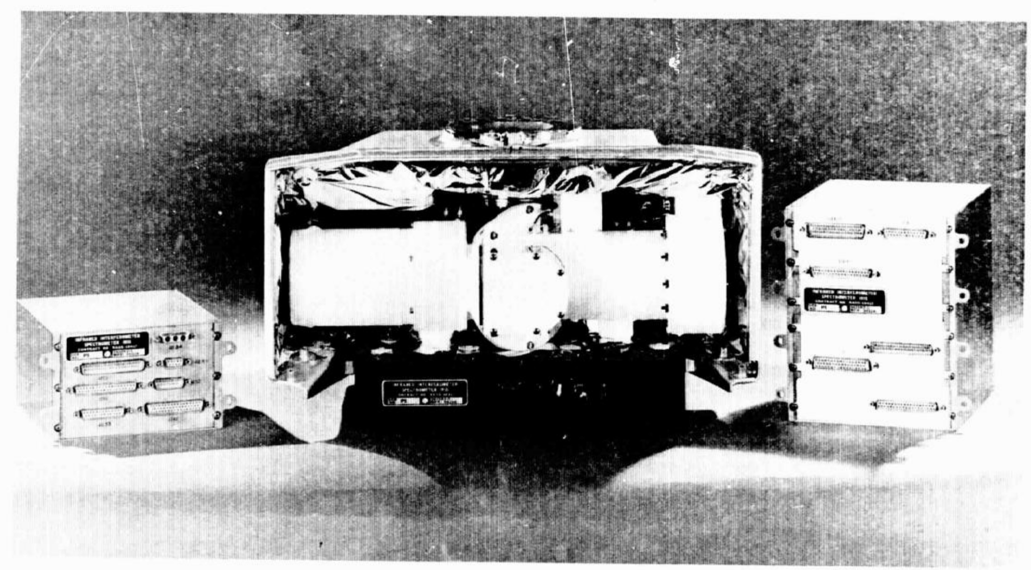


Figure 1. The infrared interferometer (IRIS-D) on Nimbus 4 consists of an optical module, shown enclosed by a thermal shroud in the center of the figure, and of two modules which contain electronic circuitry. The optical module is mounted below the Nimbus sensory ring (not shown), so that the port visible on top of the shroud views earth. The electronic modules fit into compartments within the sensory ring. The maximum dimension of the shroud across the exposed opening is 44 cm.

X-620-70-421
PREPRINT

NASA TM X-65375

THE NIMBUS 4 MICHELSON INTERFEROMETER

R. A. HANEL
B. SCHLACHMAN
D. ROGERS
D. VANOUS

DEC. 1970

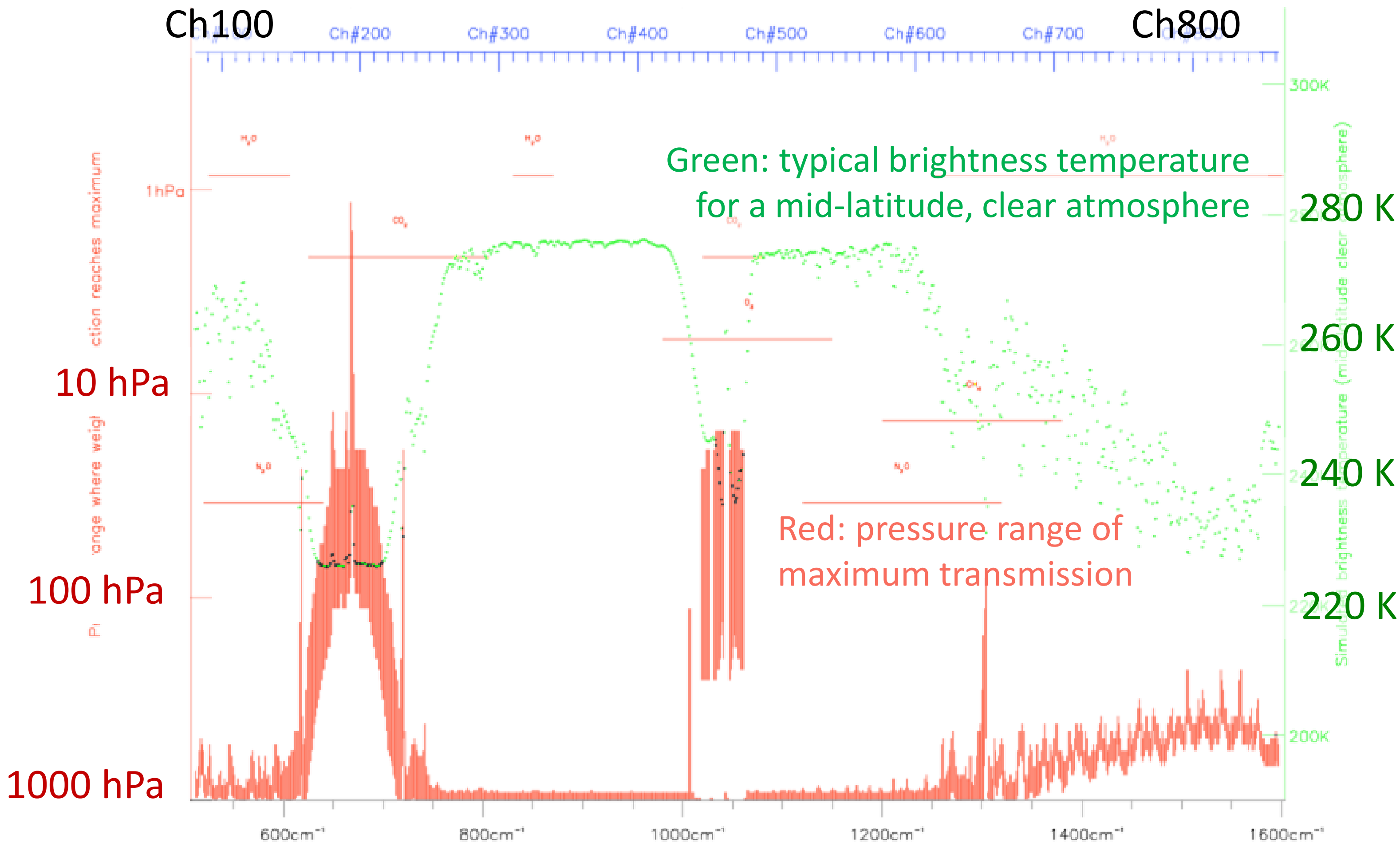
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

N71-14804

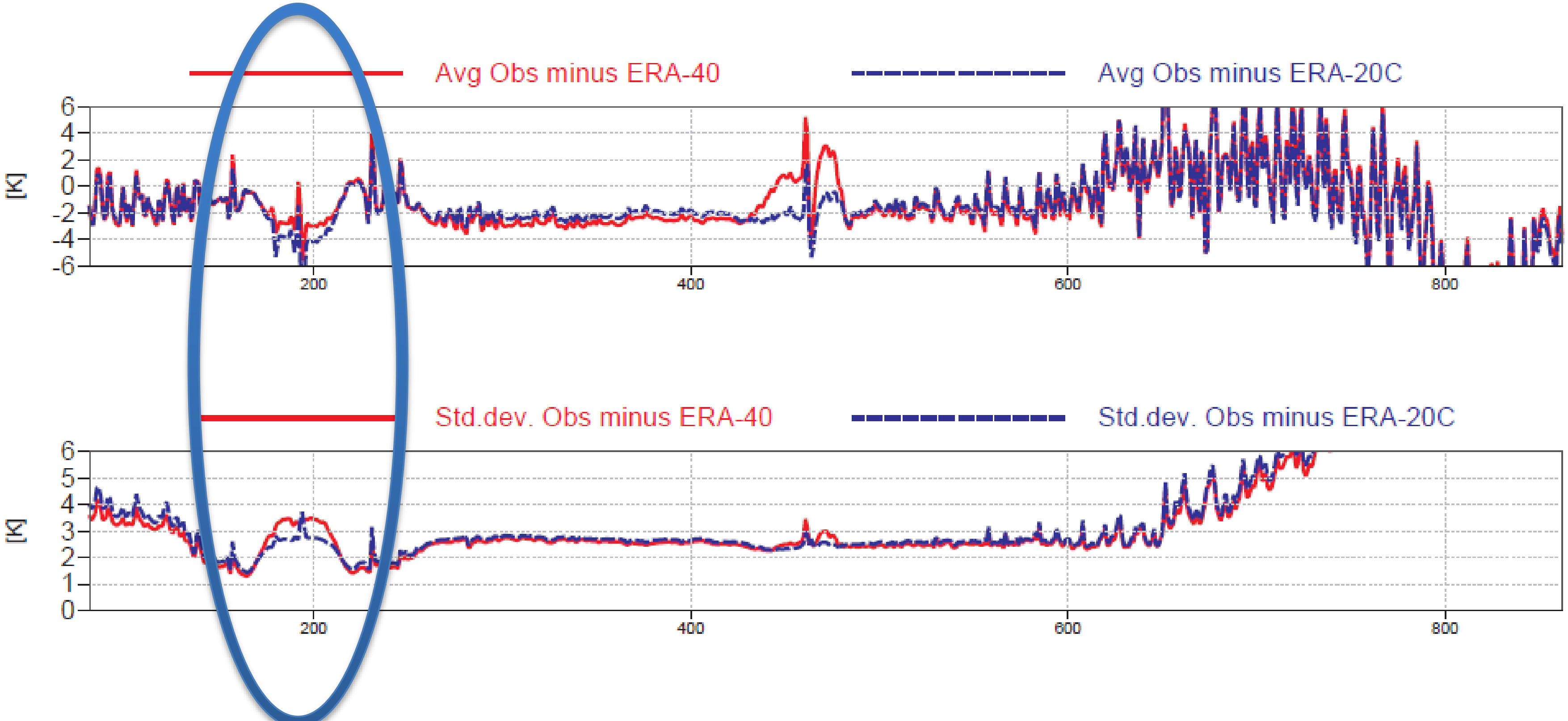
Plenty of scanned documents on the web, including recent studies: *Harries et al. (Nature 2001), Jiang et al. (Proc. SPIE 2011)*

Data were rescued from aging tapes recently by NASA, and are now available on the NSSDC website at http://nssdc.gsfc.nasa.gov

IRIS simulation using RTTOV
(mid-latitude, clear atmosphere profile)



Departure statistics relative to ERA-40 (1970-71)



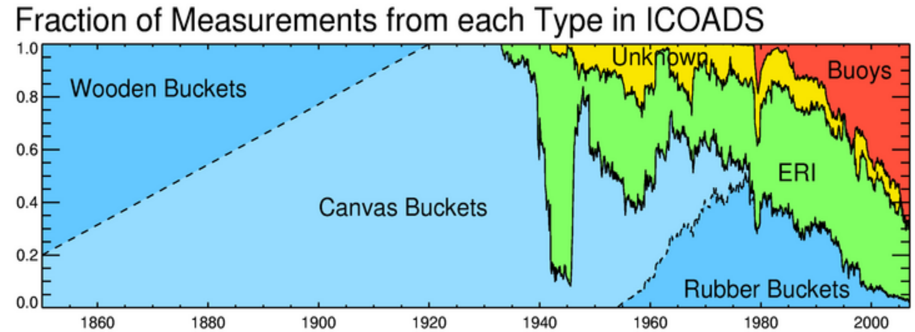
- Departures computed off-line: RRTOV using interpolated reanalysis fields
- Simple cloud screening based on window-channel departures
- Biases O(2K); standard deviation as low as 1.5K in tropospheric channels
- *Technical report by Poli and Brunel in preparation*

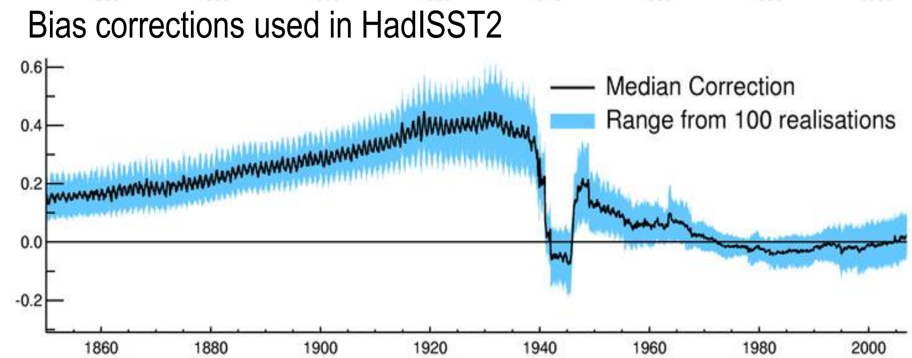
ERA-CLIM reanalysis products

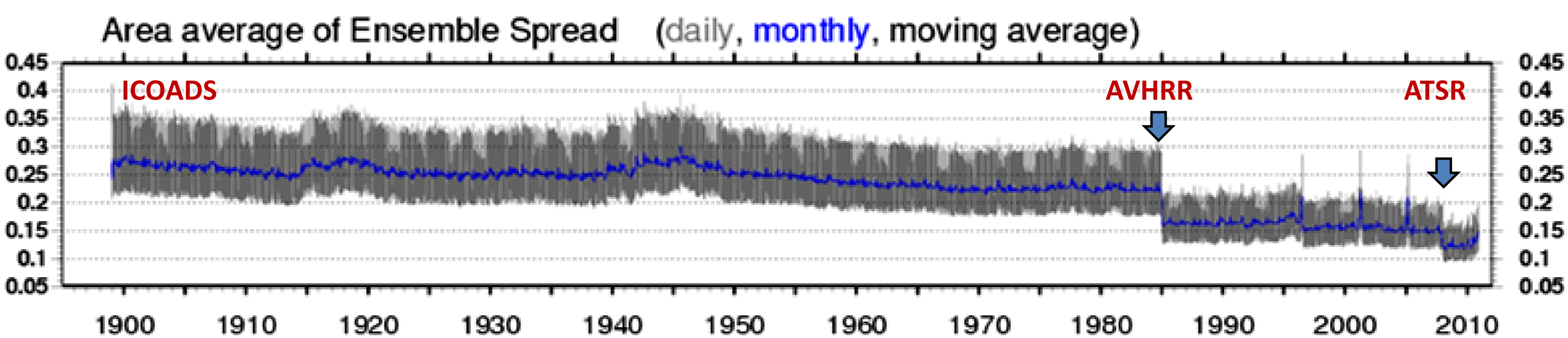
Atmospheric reanalysis for the 20th-century (1900-2010) Using an ensemble of 10 plausible SST/sea-ice evolutions Assimilating observations of surface pressure and marine wind 125/25 km global resolution, 91 vertical model levels		
ERA-20CM	Ensemble of model integrations *(mainly monthly products)*	IFS Cy38r1 + CMIP5 data + HadISST v2.1
ERA-20C	Assimilation of surface observations *(3-hourly products)*	+ ICOADS v2.5.1 + ISPD v3.2.6 *(incl. ERA-CLIM)*
ERA-20CL	High-resolution land surface *(25km global)*	+ CHTESSEL
Final ERA-20C/M/L datasets (~200 Tb) will be available at *http://www.ecmwf.int/en/research*		

Model data for production of ERA-20CM

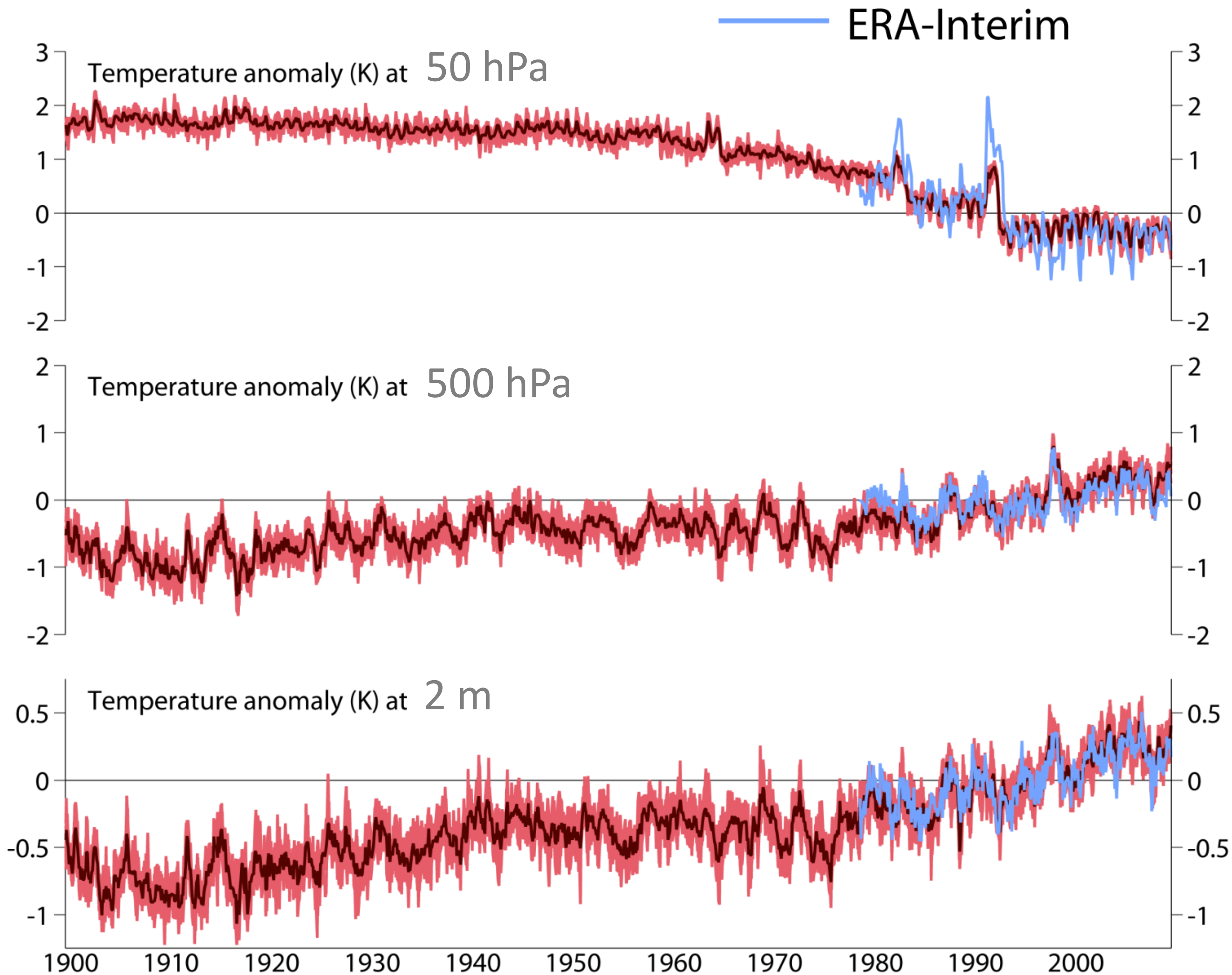
- From 1900-2010, spatial resolution 125 km
- 10 members, using equally plausible SST/sea-ice evolutions from HadISST2
- Radiative forcing and land surface parameters as in CMIP5







ERA-20CM global temperature anomalies

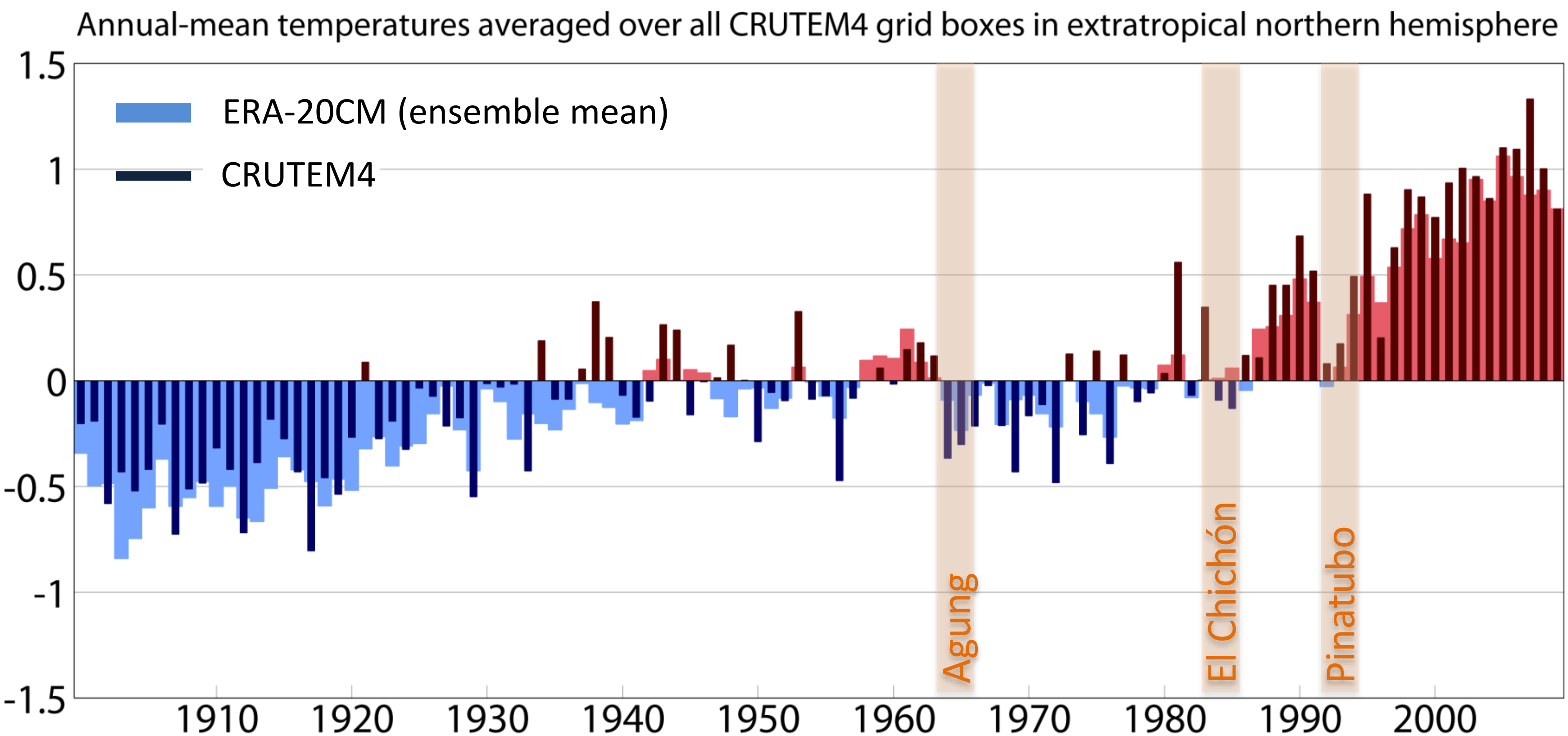


ECMWF EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

ERA-20CM (ensemble mean)

Animation of global warming in ERA-20CM

Verification of annual mean temperature changes



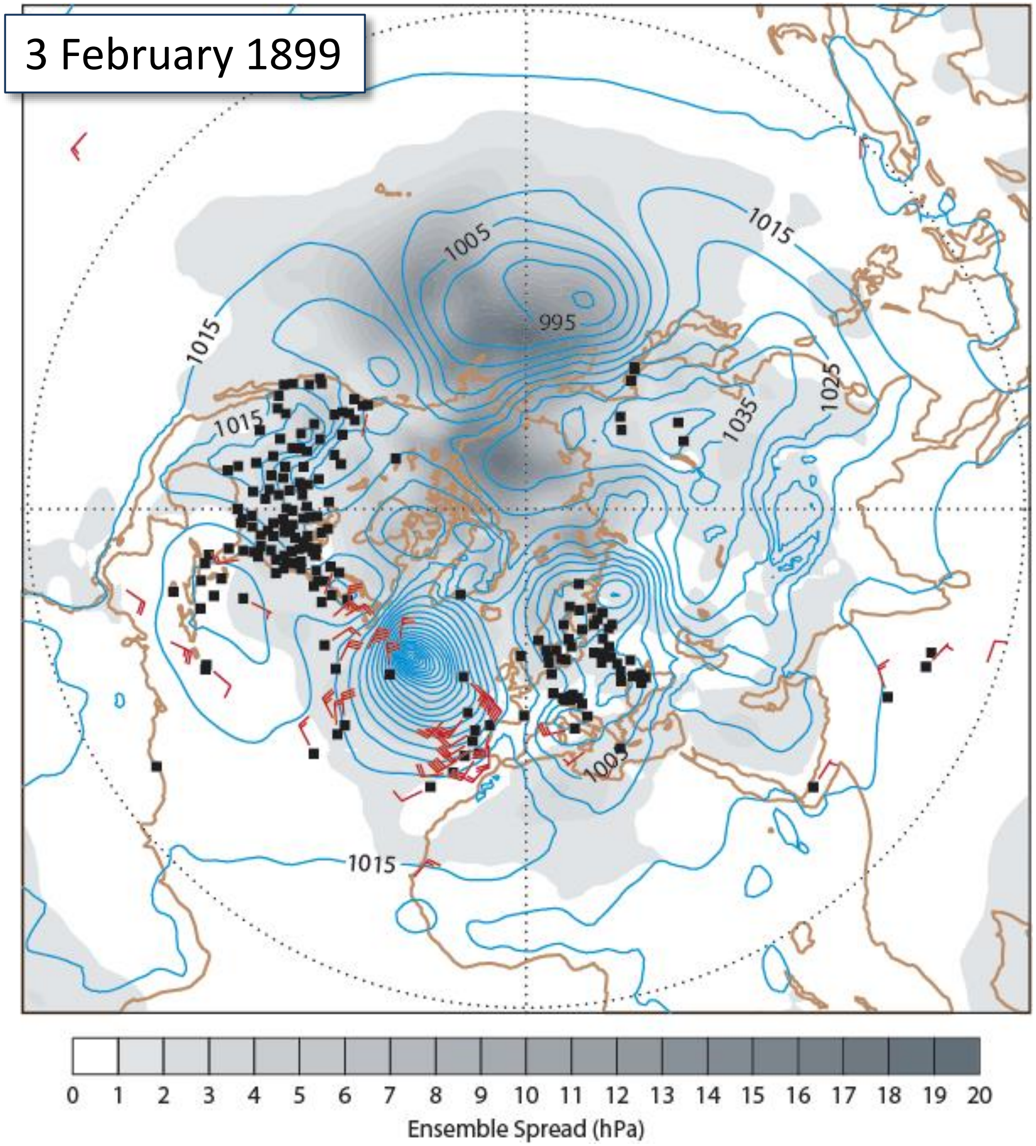
More details on ERA-20CM in *Hersbach et al 2014*, submitted to QJ

ERA-20C: reanalysis of surface observations

Animation of surface pressure data used in ERA-20C

- Sources: ICOADS 2.5.1 (surface pressure and marine winds)
  ISPD 3.2.6 (surface pressure)
- Approximately 1 billion observations from 2 million distinct platforms
- All time series analysed to identify likely breakpoints
- Details on data assimilation aspects in *Poli et al. 2013*

ERA-20C: A terrific storm at sea



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.

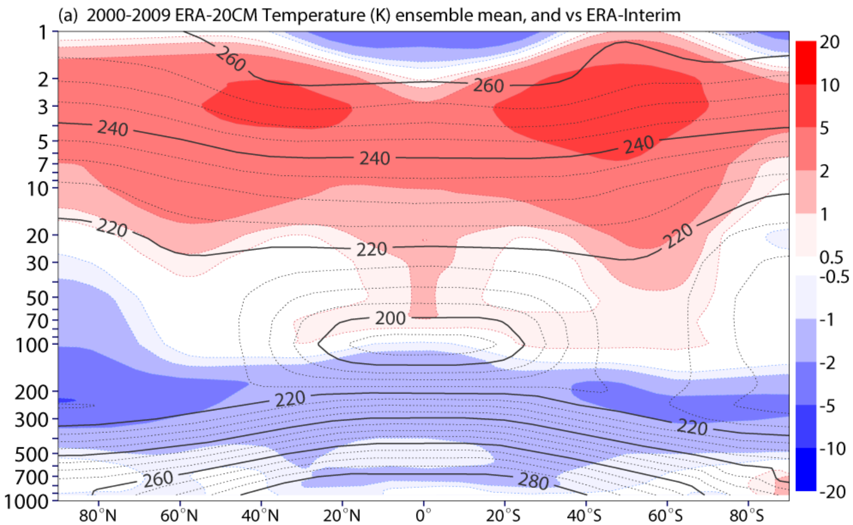
All the steamers that came in yesterday were coated with ice from the tops of the masts down to the water line, and all had passed through storms of blinding snow and mountainous waves. The British steamer Ethelgonda, from Bristol and Swansea, which left the latter port on Jan. 19, ran into a gale of 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

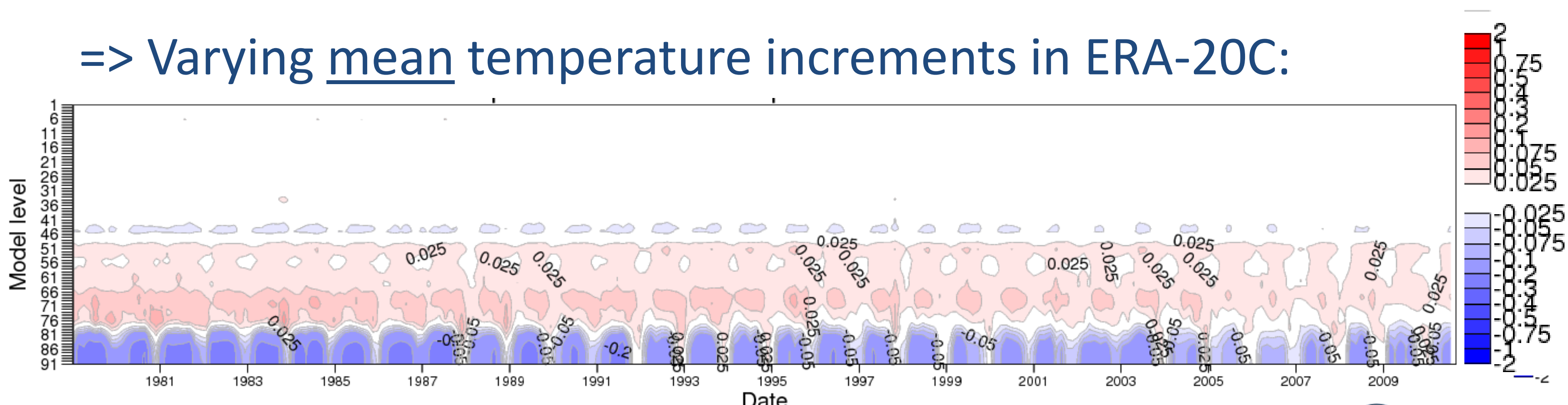
What about trends?

ERA-20CM model bias *(temperature 2000-2009 vs ERA-Interim)*



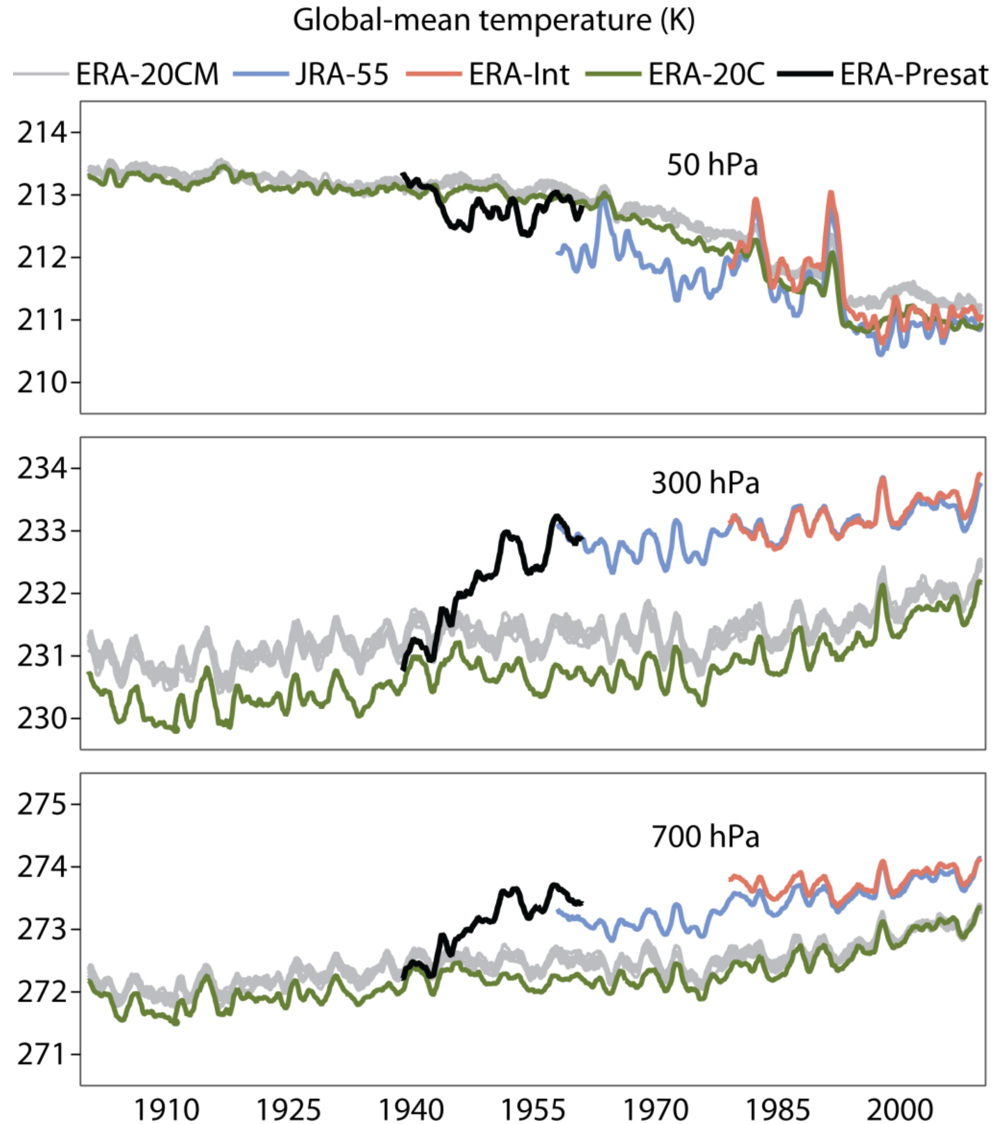
+ residual biases in observations
+ changes in observational coverage
+ changes in background error statistics

=> Varying <u>mean</u> temperature increments in ERA-20C:



20C global-mean temperature evolution

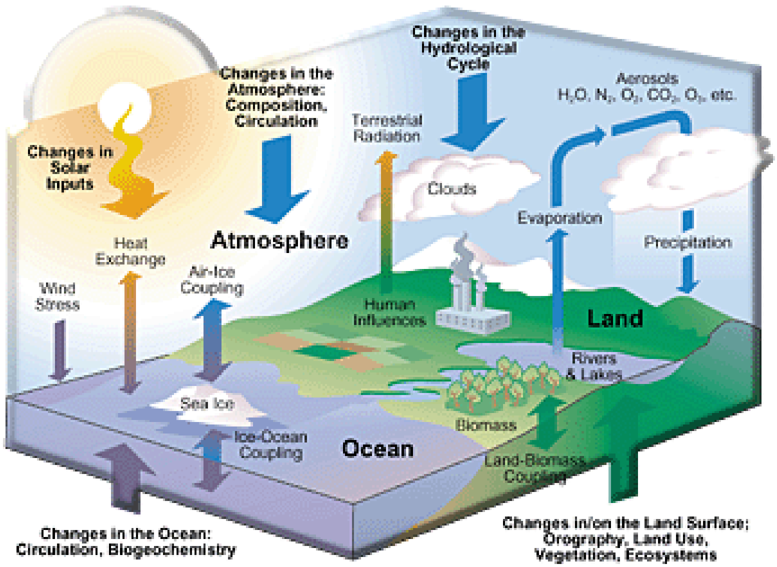
- ERA-20C slightly worse than ERA-20CM *(relative to CRUTEM4)*
- More warming than ERA-Interim in lower troposphere *(differences in model biases + SST data)*
- Promising results from first experiment with ERA-CLIM upper-air observations *(ERA-Presat, 1939-1959)*



ERA-CLIM2

EU collaborative research project, 16 institutions, 2014-2016

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

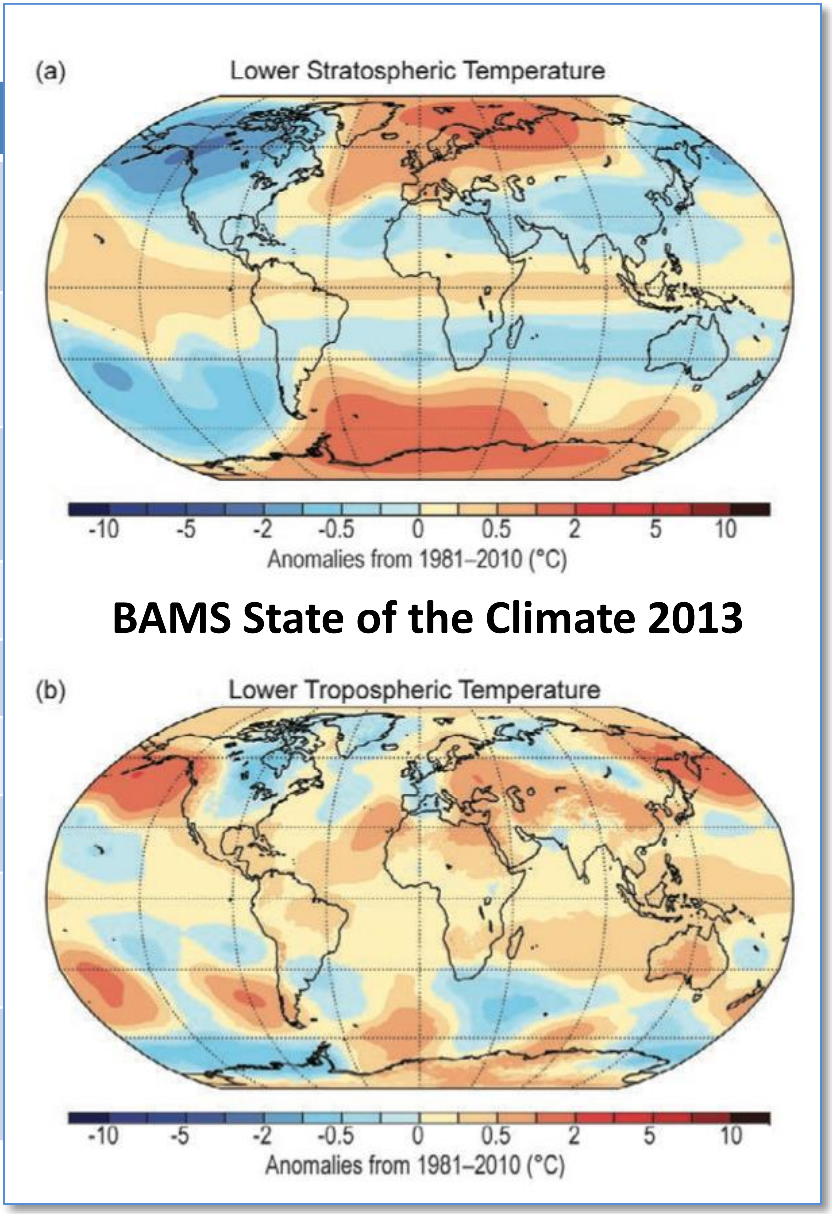


Main components:

1. Production of coupled reanalyses, for 20C and the modern era
2. Research and development in coupled data assimilation
3. Earth system observations for an extended climate reanalysis
4. Evaluation of uncertainties in observations and reanalyses

ERA-Interim

	ERA-Interim
Start of production	August 2006 IFS Cy31r2
Model input	As in operations *(inconsistent SST)*
Spatial resolution	79 km global 60 levels to 10 Pa
Time period	1979 - present
Dissemination	Monthly
Observations	Mostly ERA-40, GTS
Radiative transfer	RTTOV7
Analysis method	4D-Var 1D+4DVar rain
Variational bias corrections	Satellite radiances



Satellite data used in ERA-Interim

Microwave radiances
- temperature sounding
- water vapor sounding

Infrared radiances
- temperature and water vapor sounding
- stratospheric temperature sounding

Imagery — visible, near infrared, water vapor

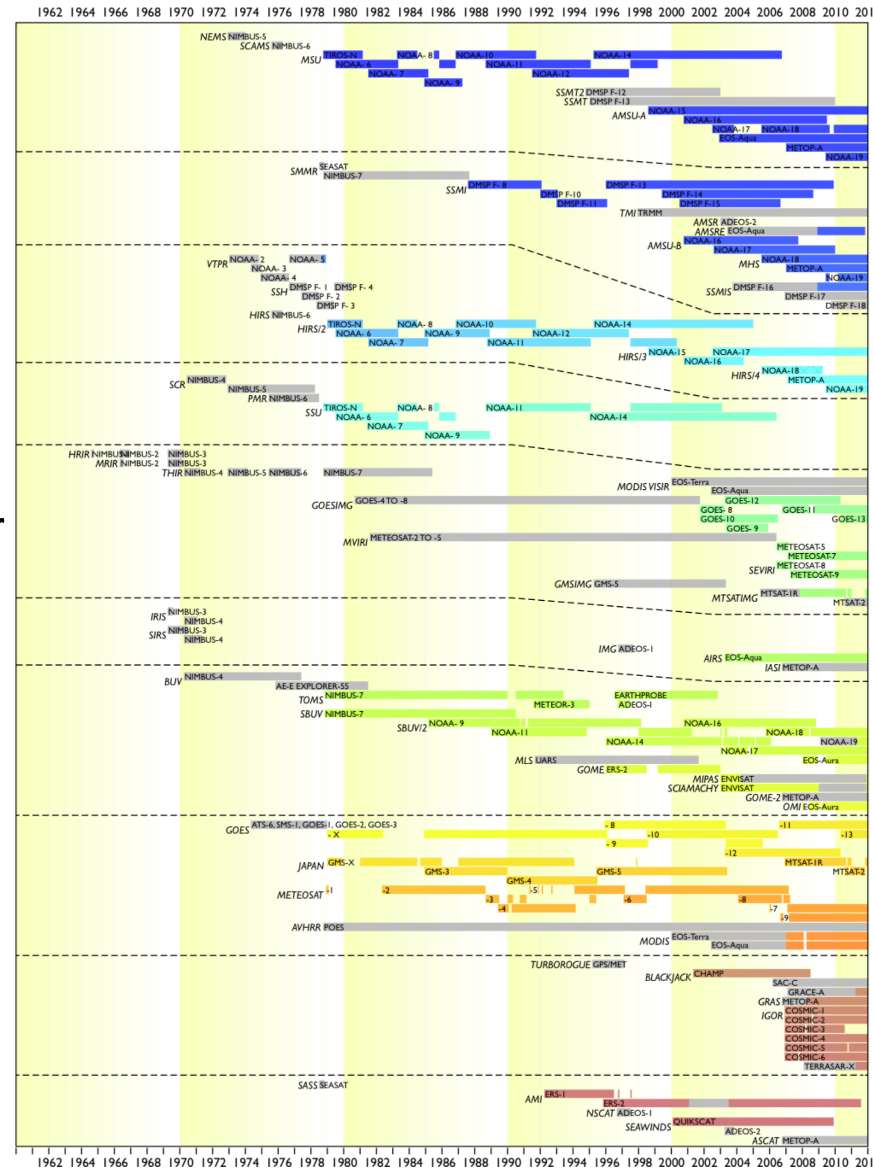
Hyper-spectral infrared

Ozone
- mostly ultra-violet, some limb-viewing infrared

Atmospheric motion vectors
- geostationary (GEO)
- low-earth orbit (LEO)

Bending angles from GPS radio occultation

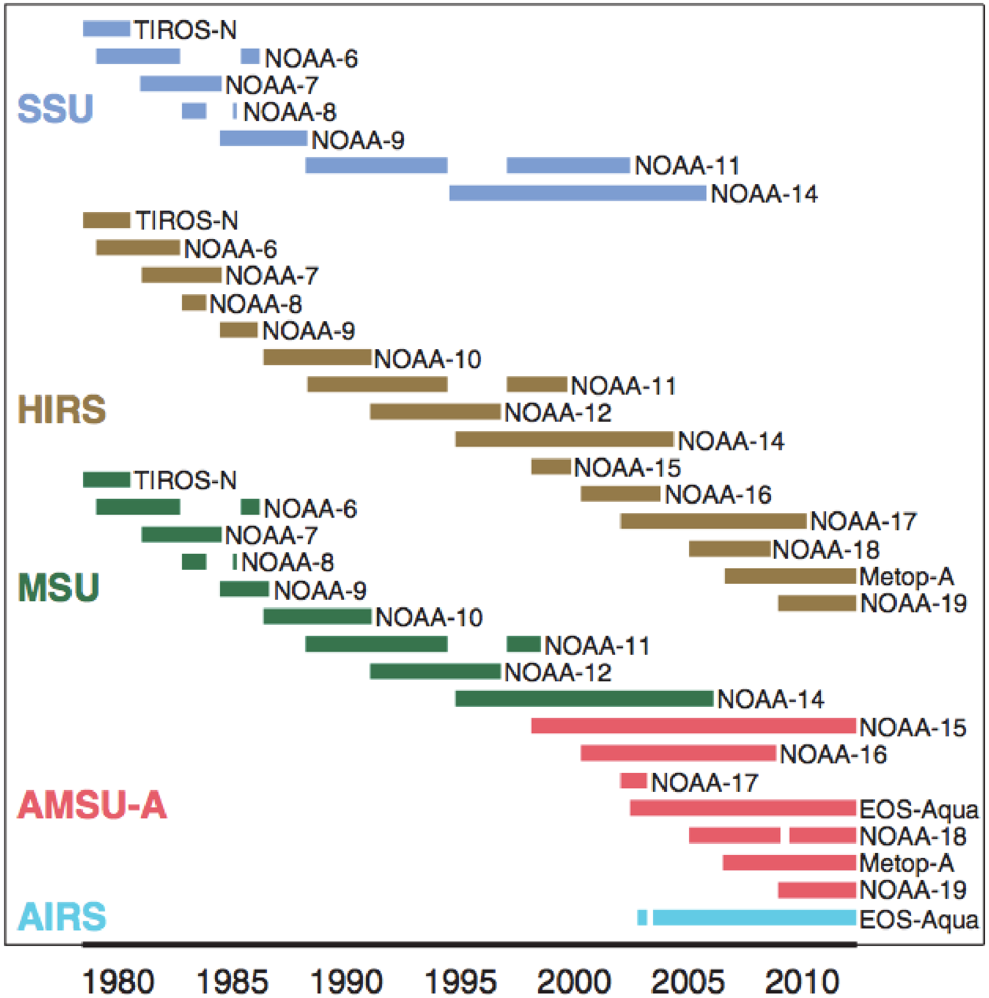
Backscatter — near-surface wind above ocean



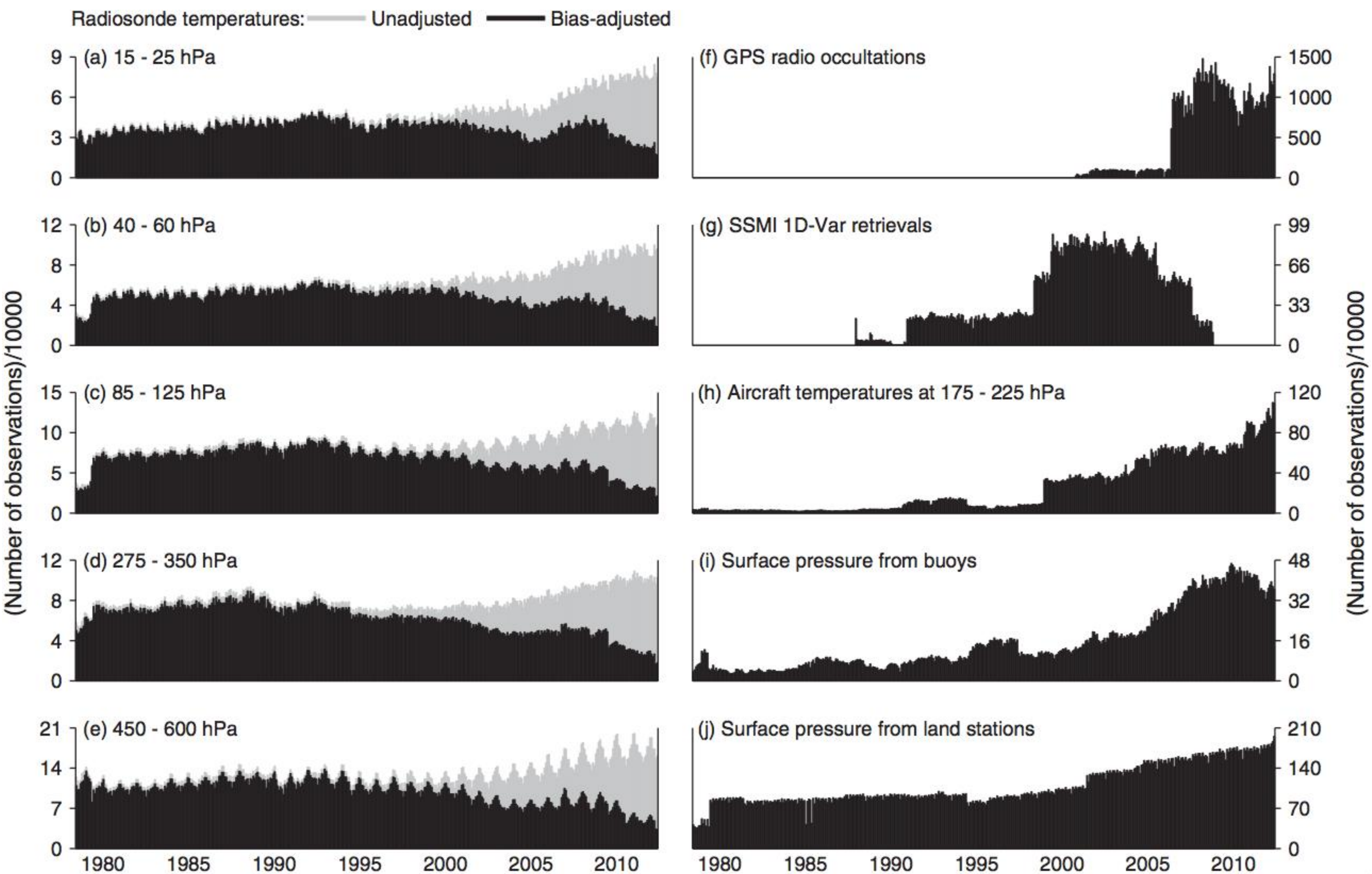
Temperature variability and trends in ERA-Interim

Simmons et al. QJ 2014

Temperature sounders used in ERA-Interim



Other key inputs affecting temperature estimates

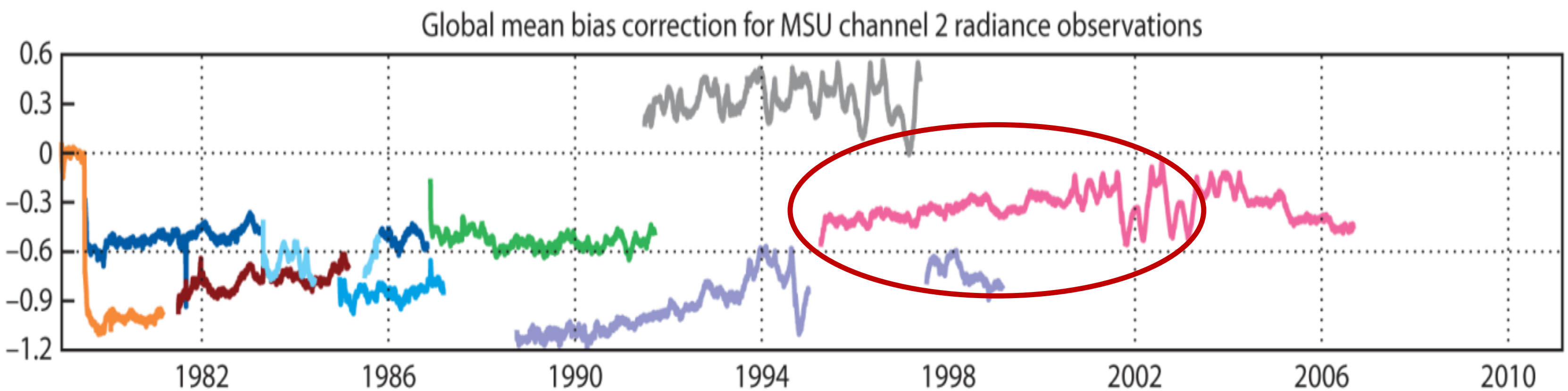


Variational bias adjustments for radiance data

Biases due to instrument errors, errors in radiative transfer, etc. are parameterized using global predictors *(Harris and Kelly 2001)*

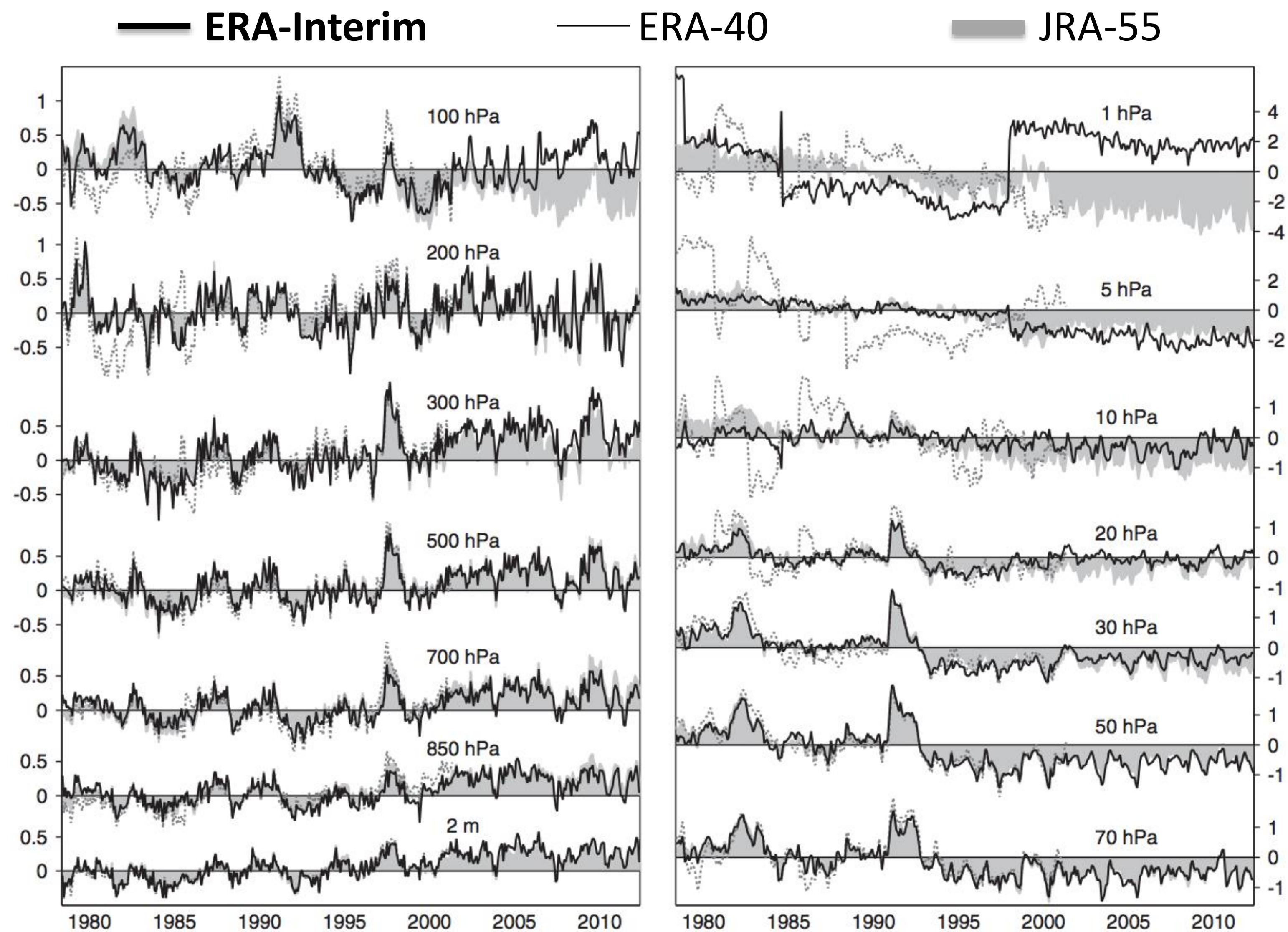
The bias parameters are then adjusted on the fly *(Derber and Wu 1998)*:

$$\mathbf{J}(\mathbf{x},\beta) = (\mathbf{x}_b - \mathbf{x})^T \mathbf{B}^{-1}(\mathbf{x}_b - \mathbf{x}) + [\mathbf{y} - \mathbf{h}(\mathbf{x},\beta)]^T \mathbf{R}^{-1}[\mathbf{y} - \mathbf{h}(\mathbf{x},\beta)]$$



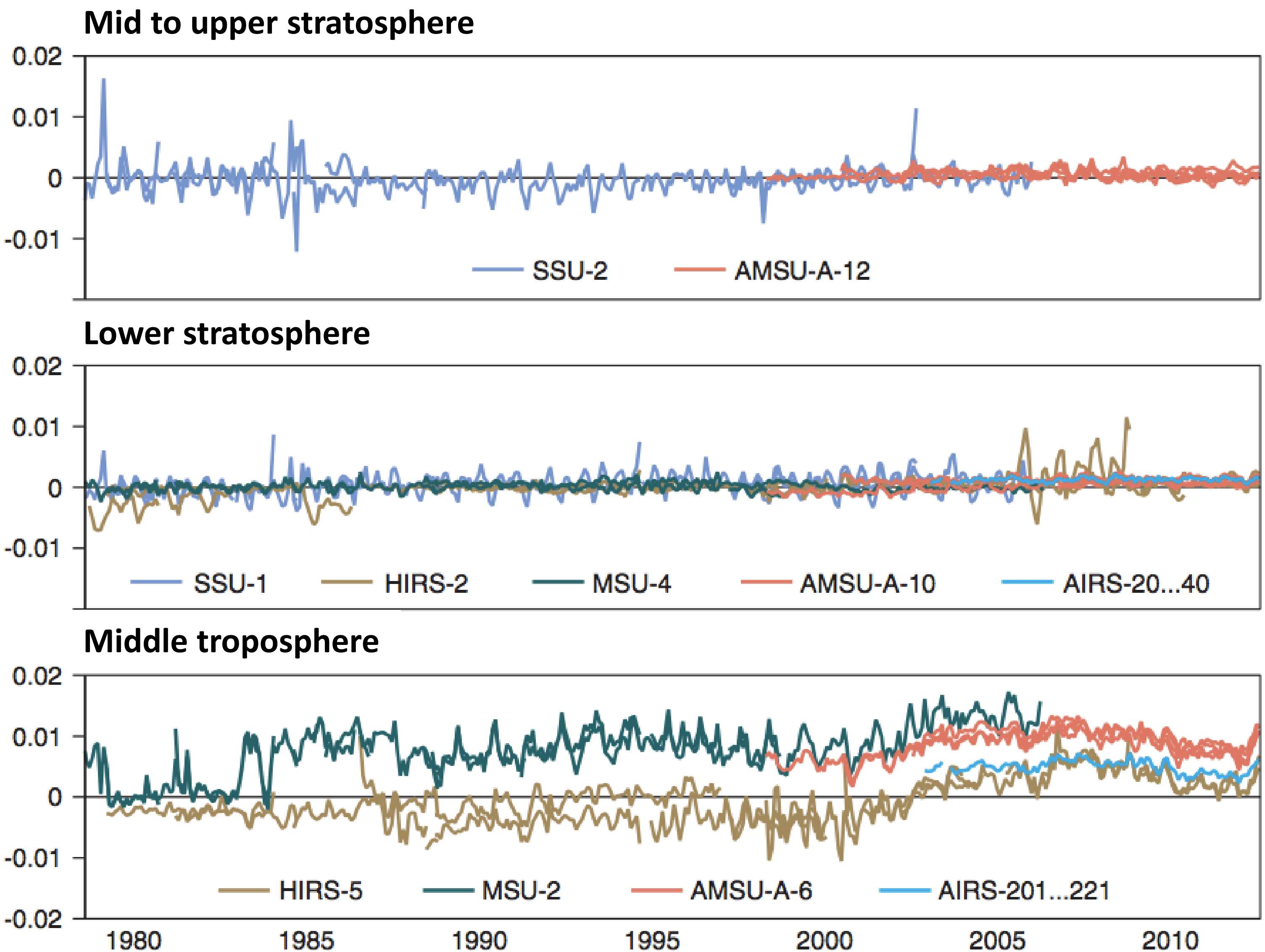
On-board warm target variations for MSU NOAA-14 *(Grody et al. 2004)*

Global temperature anomalies

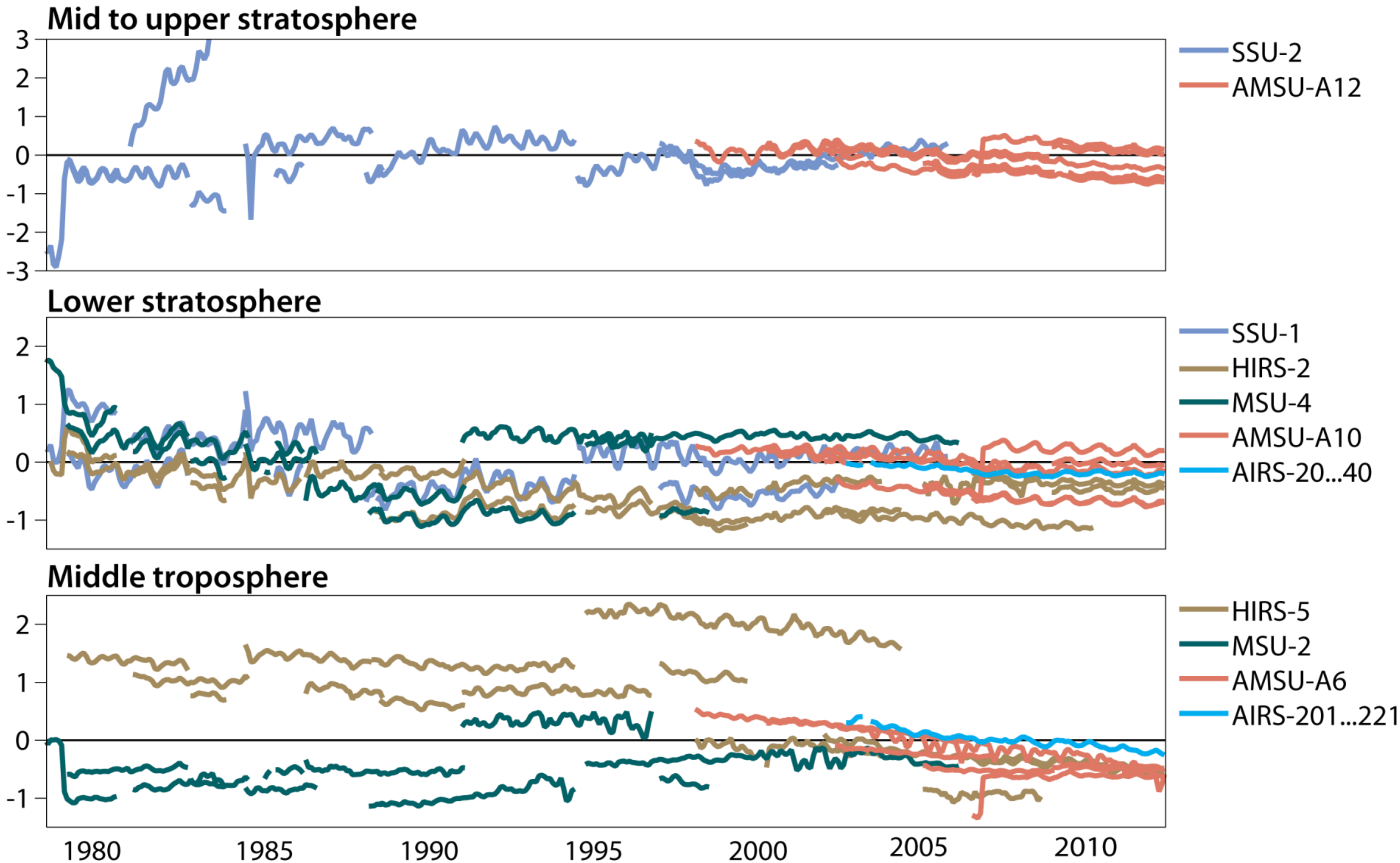


ECMWF EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

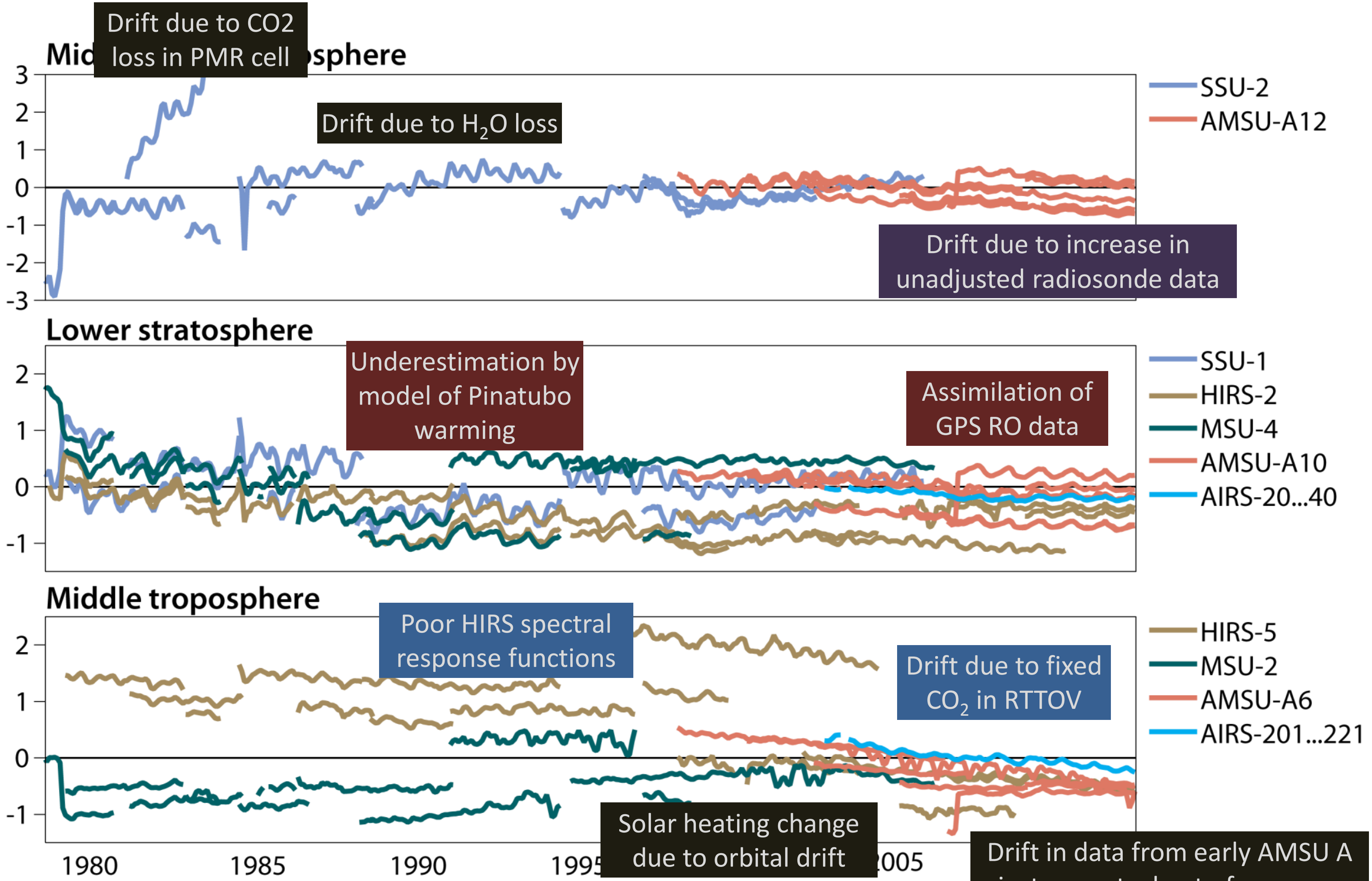
Mean fit to selected sounding channels [K]



Mean bias adjustments [K]



Mean bias adjustments [K]



ERA-Interim successor: ERA5

	ERA-Interim	ERA5
Start of production	August 2006 IFS Cy31r2	January 2015 IFS Cy40r3
Model input	As in operations *(inconsistent SST)*	Appropriate for climate (CMIP5, HadISST.2)
Spatial resolution	79 km global 60 levels to 10 Pa	39 km global (or 31 km) 91 levels to 1 Pa (or 137 levels)
Time period	1979 - present	1979 - present (extension to ~1950)
Dissemination	Monthly	Monthly for ERA5; daily for ERA5T
Observations	Mostly ERA-40, GTS	Various reprocessed CDRs
Radiative transfer	RTTOV7	RTTOV11
Analysis method	4D-Var 1D+4DVar rain	10-member ensemble 4D-Var (EDA) All-sky MW
Variational bias corrections	Satellite radiances	Also ozone, aircraft, surface pressure (radiosondes)

New input data sets for ERA5

- METEOSAT AMV (EUMETSAT)
- GOES AMV (CIMSS 1995-2013)
- GMS and GOES-9 AMV (Japan)
- AVHRR NOAA AMV (CIMSS 1982-2010)
- AVHRR METOP AMV (EUMETSAT)

- METEOSAT radiances (EUMETSAT)
- ASCAT L1 Sigma0 (EUMETSAT)
- SSM/I radiances (CM-SAF)

- SBUV and TOMS ozone (NASA v8.6)

- Upper-air in situ observations (NCAR DS 370.0)
- Surface pressures (ISPD 3.2.6)
- Marine surface reports (ICOADS 2.5.1)

Improved radiative transfer modelling:

- Microwave and infrared frequency shifts
- Time-varying SSU cell pressure
- Time-varying atmospheric CO_2 concentration

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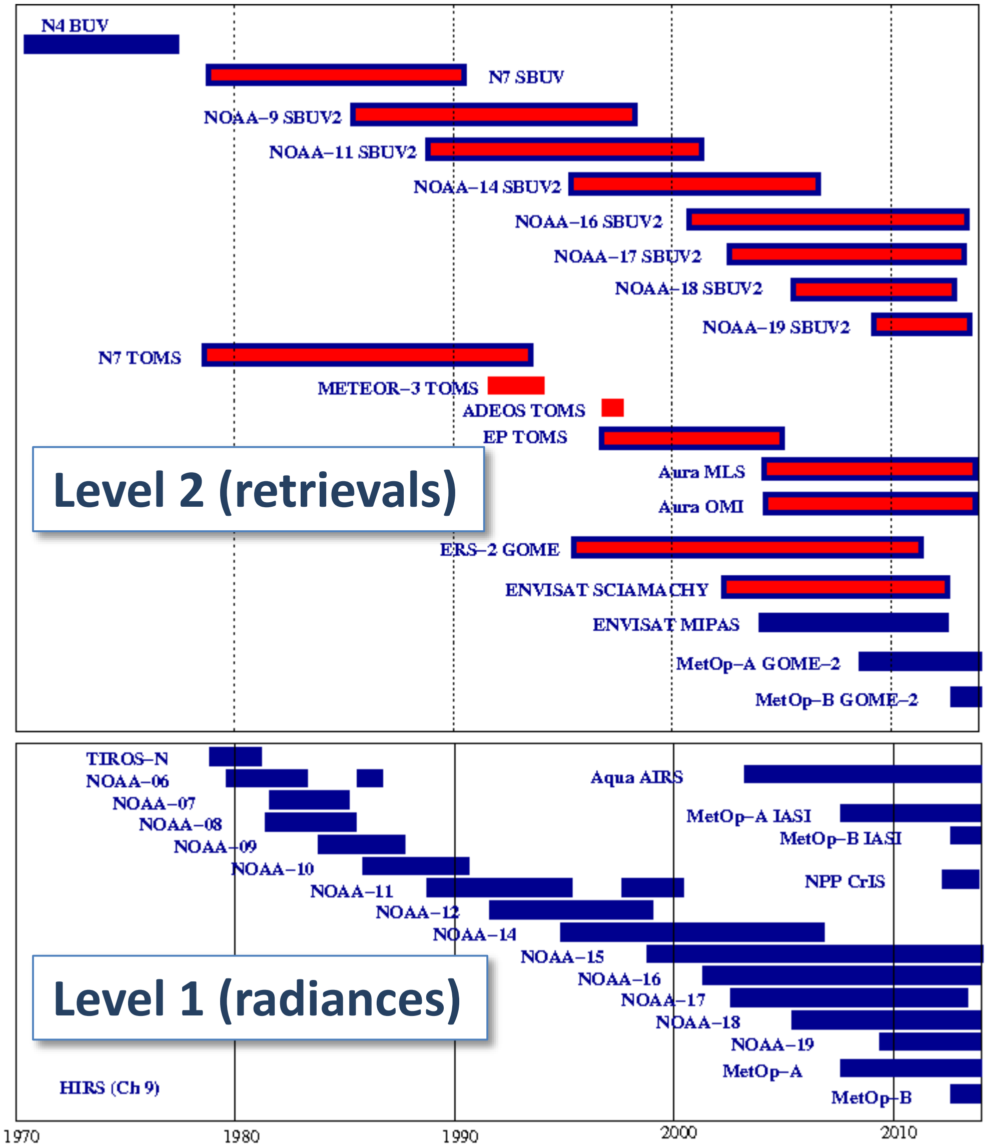
- Time-varying atmospheric CO2 concentration

Ozone observations for ERA5



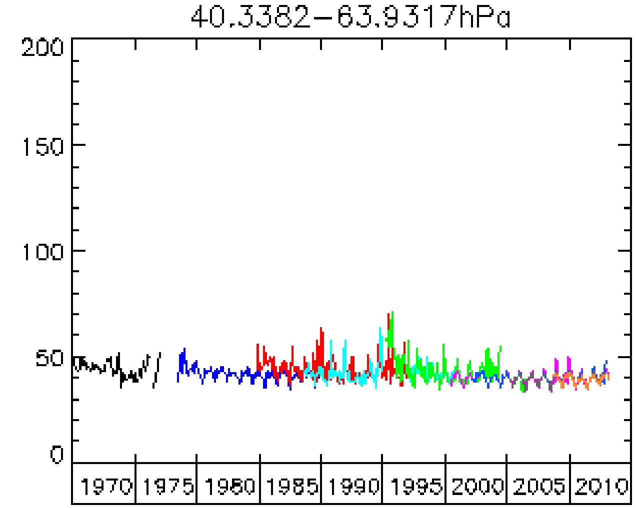
As used in ERA-Interim

New version

Not used in ERA-Interim

NASA v8.6 product

BUV-SBUV-SBUV2 (21 layers)



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- Microwave and infrared frequency shifts
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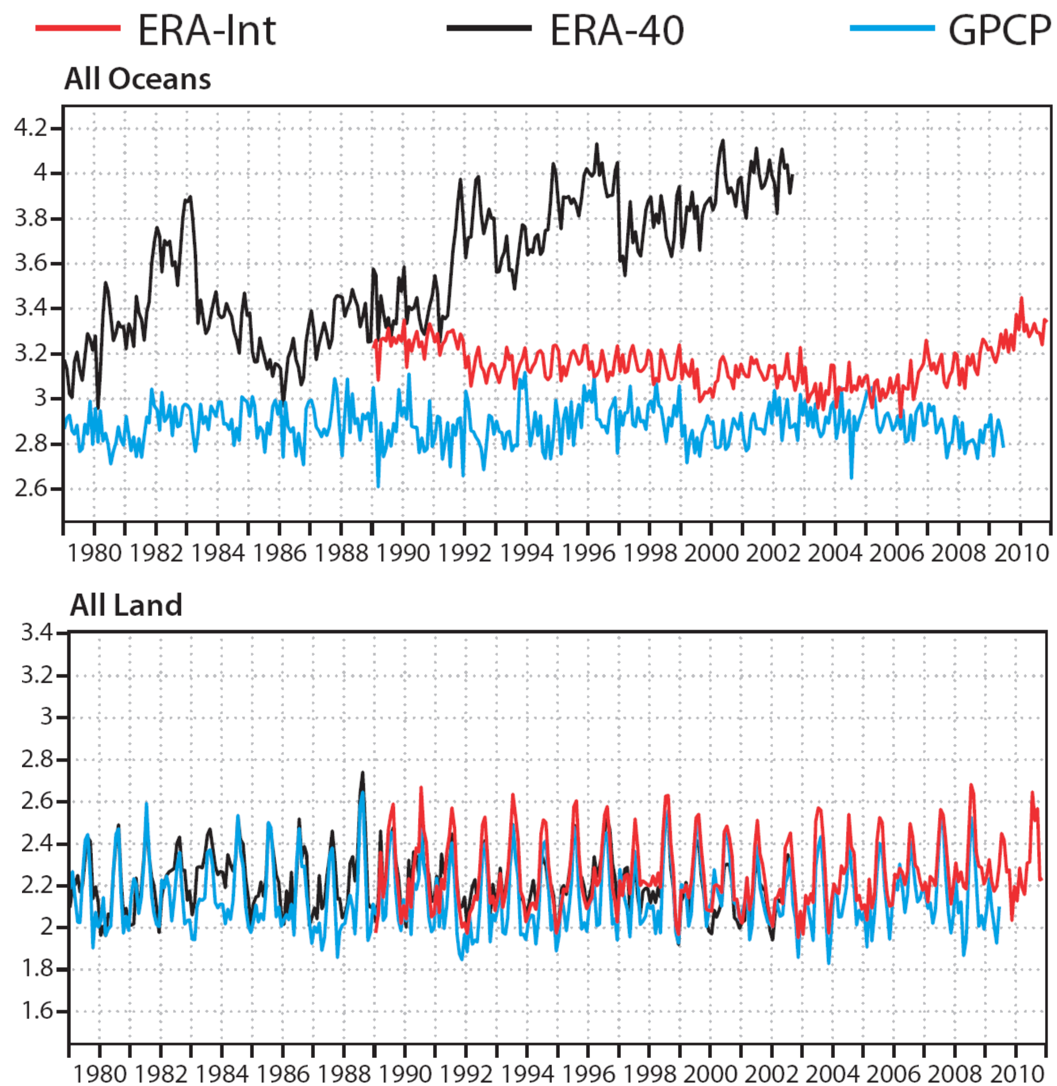
- Time-varying atmospheric CO2 concentration

Room for improvement: Hydrological cycle

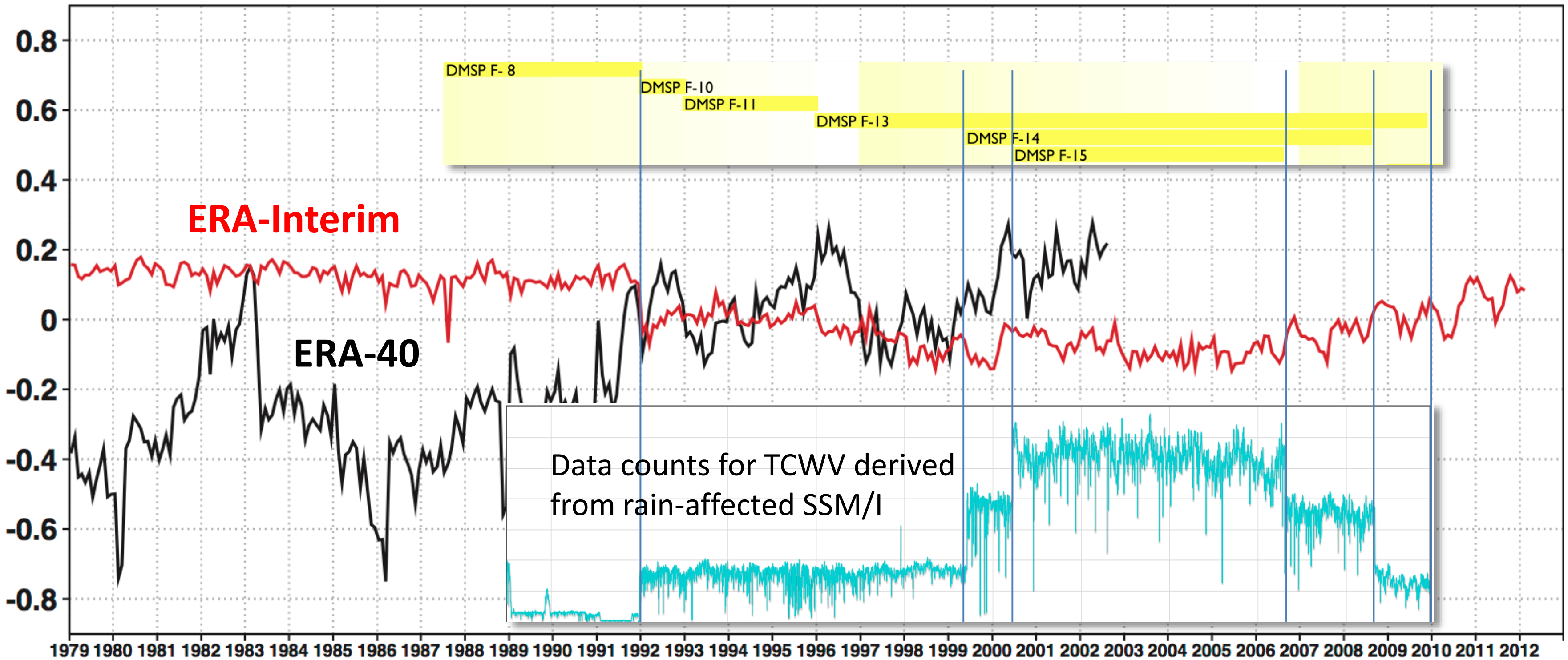
Monthly averaged rainfall from reanalyses, and combined rain gauge and satellite products (GPCP)

Reanalysis estimates of rainfall over ocean are still problematic

Results over land are generally better

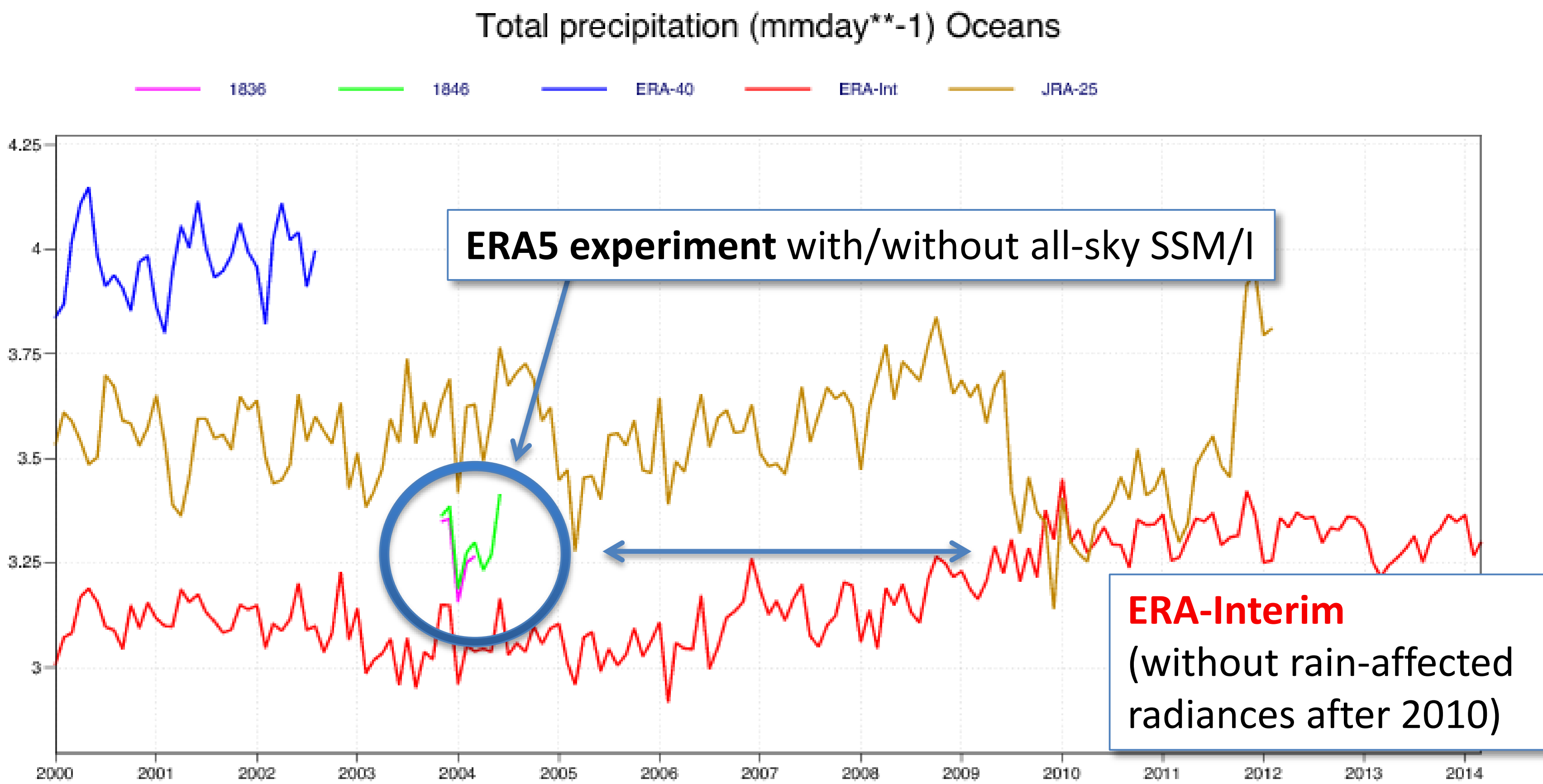


Shifts in ERA-Interim precipitation explained



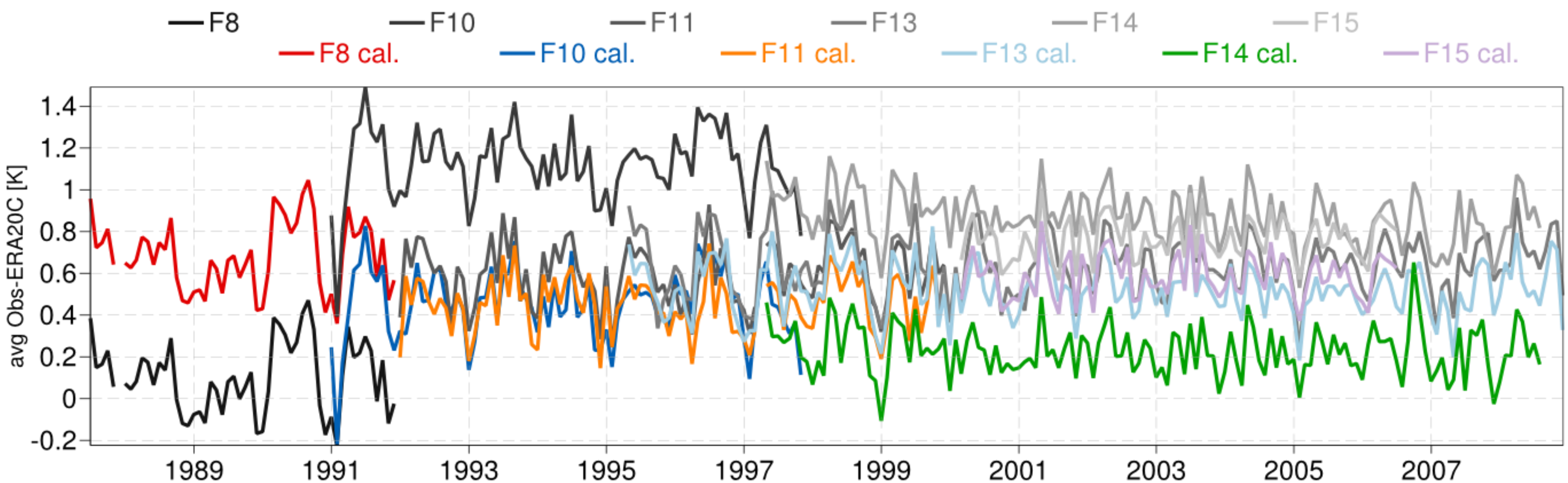
- Due to assimilation of rain-affected radiances from SSM/I over oceans
- Experimentally verified, and now fully understood *(Geer et al. 2008)*

Impact of all-sky SSM/I on mean precipitation



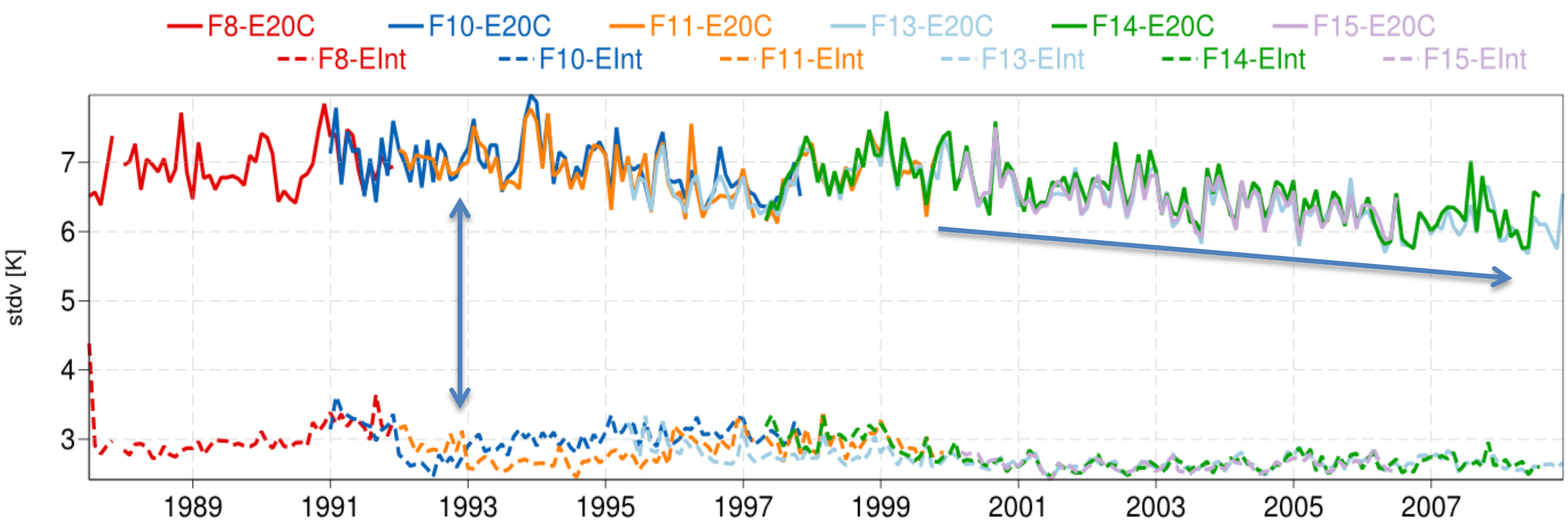
CM-SAF reprocessed SSMI (1)

- Ch 4 (37H): Ocean, ice-free and non-rainy scenes
- Mean differences [K] relative to RTTOV simulations, with/without inter-calibration offsets
- Calculated off-line using interpolated fields from ERA-20C



CM-SAF reprocessed SSMI (2)

- Ch 3 (22V): Ocean, ice-free and non-rainy scenes
- Standard deviation [K] of departures from ERA-20C, ERA-Interim computed off-line
- ERA-20C improves in last decade: Winds over southern oceans?



Additional details in technical report by *Poli et al. 2014*

New input data sets for ERA5

- METEOSAT AMV (EUMETSAT)
- GOES AMV (CIMSS 1995-2013)
- GMS and GOES-9 AMV (Japan)
- AVHRR NOAA AMV (CIMSS 1982-2010)
- AVHRR METOP AMV (EUMETSAT)

- METEOSAT radiances (EUMETSAT)
- ASCAT L1 Sigma0 (EUMETSAT)
- SSM/I radiances (CM-SAF)

- SBUV and TOMS ozone (NASA v8.6)

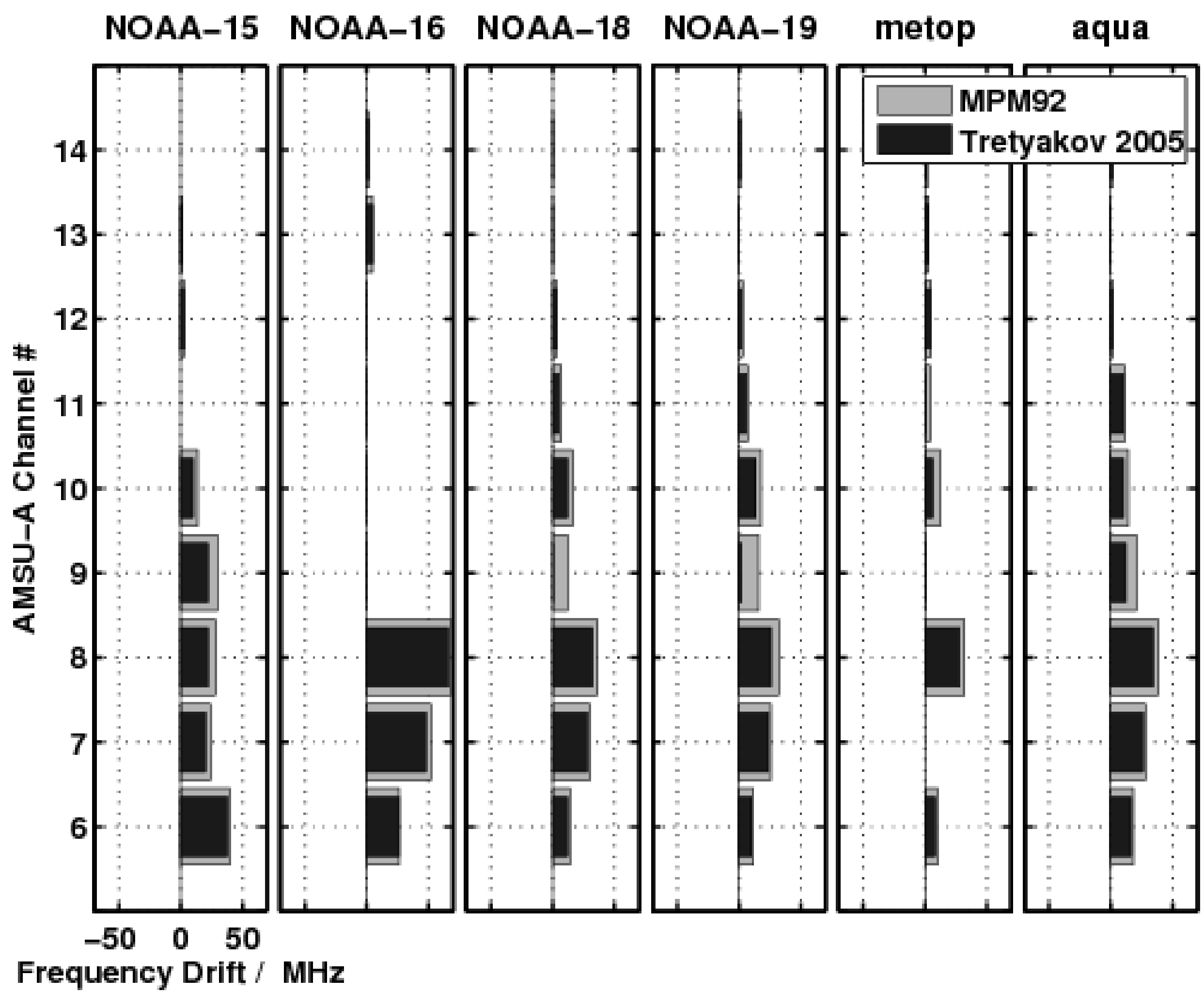
- Upper-air in situ observations (NCAR DS 370.0)
- Surface pressures (ISPD 3.2.6)
- Marine surface reports (ICOADS 2.5.1)

Improved radiative transfer modelling:

- Microwave and infrared frequency shifts
- Time-varying SSU cell pressure
- Time-varying atmospheric CO2 concentration

Estimates of AMSU pass band shifts

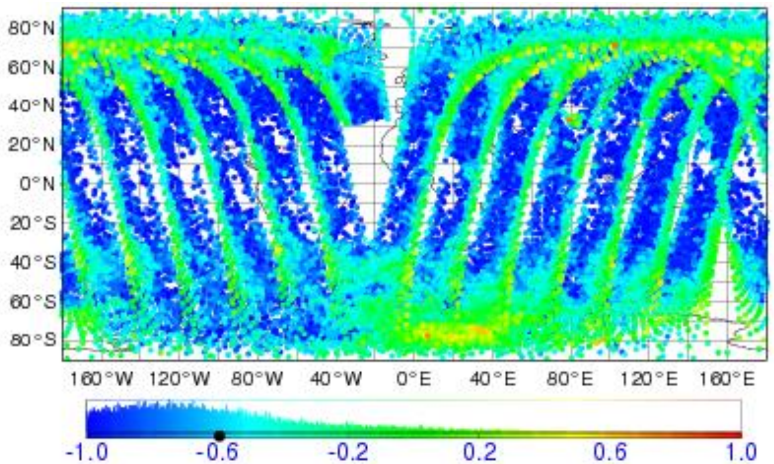
Lu and Bell, JTECH 2014



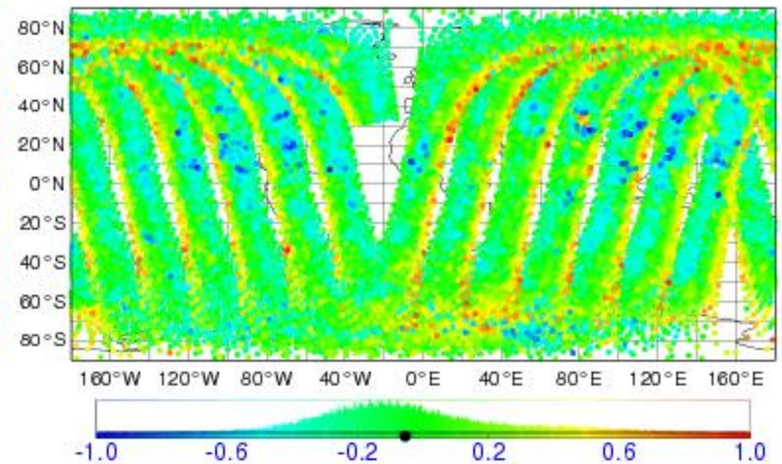
NOAA-16 AMSU-A ch 6

First-guess departures, 1200UTC 23 Aug 2011

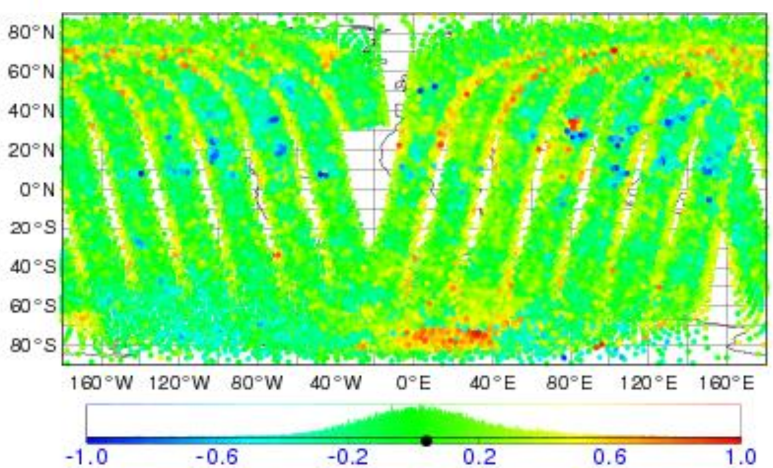
Nominal center frequency, pre-VarBC



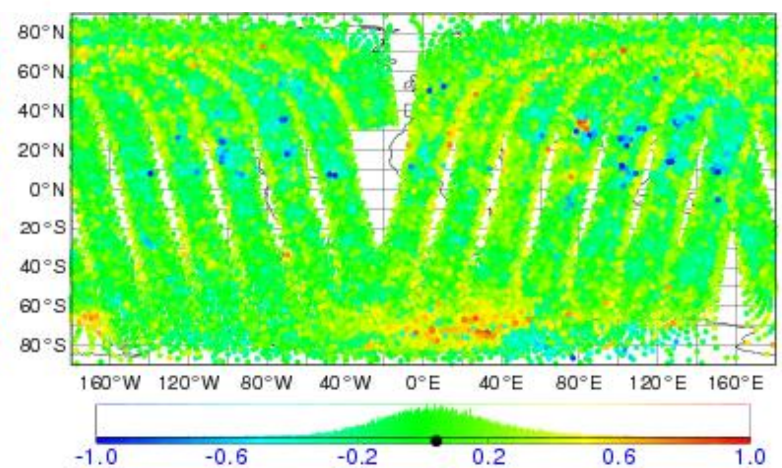
Adjusted center frequency, pre-VarBC



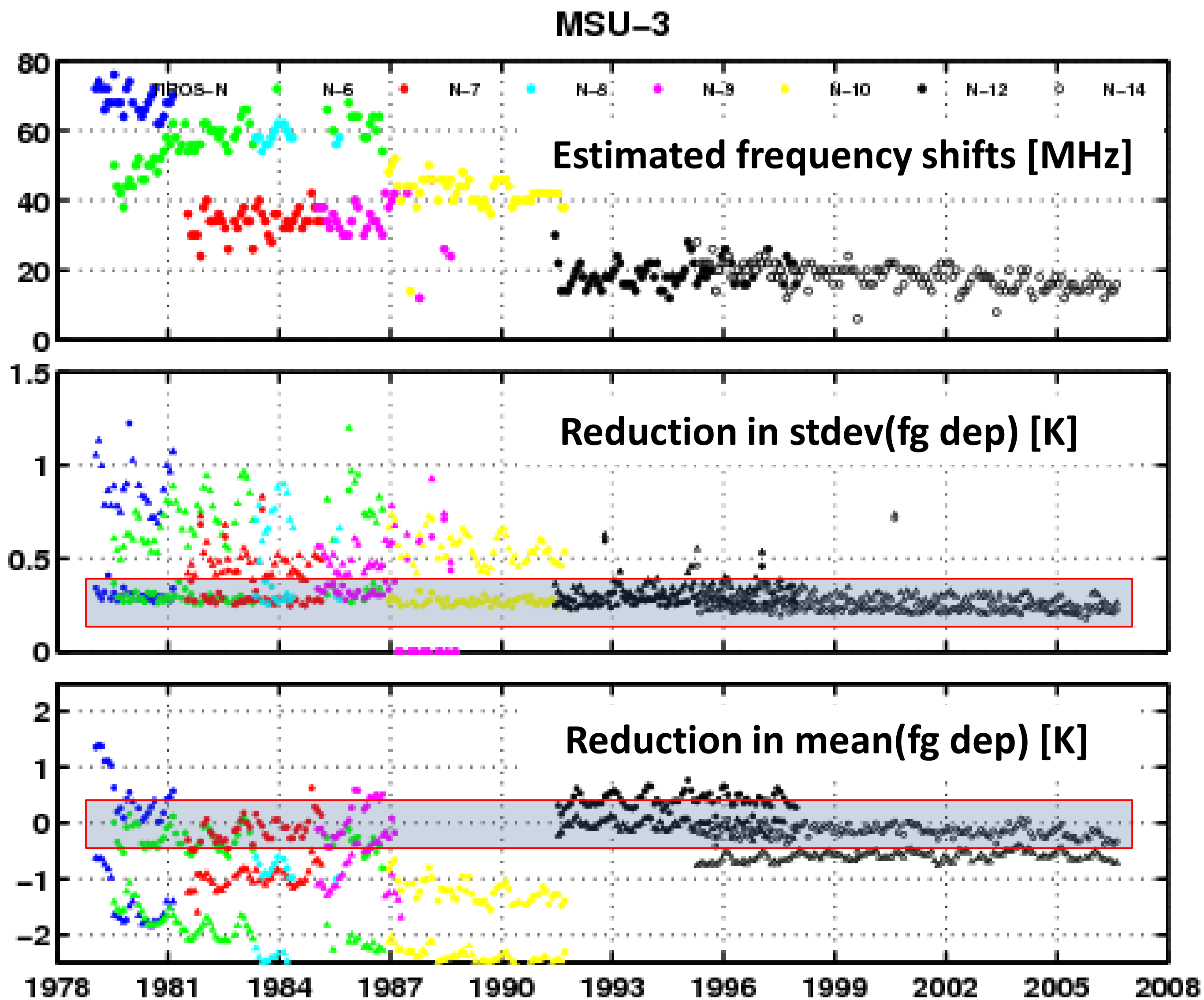
Nominal center frequency, post-VarBC



Adjusted center frequency, post-VarBC



MSU ch3 frequency shifts and departures



Final points

- Aim of reanalysis is to fully exploit the instrumental record
- Focus is increasingly on climate
- Trying to go back as far as possible
- Trying to couple atmosphere and ocean

- Importance of satellite data rescue and reprocessing of existing data records
- Still learning how to get the most from satellite data
- Improving the assimilating models is key

Satellite data assimilated in ERA-Interim

Animation of satellite data usage in ERA-Interim