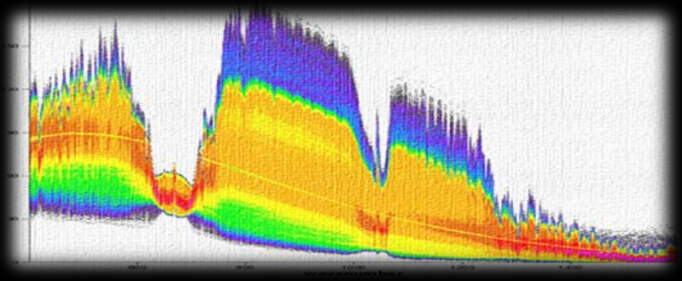


Use of hyperspectral infra-red observations in reanalyses

Paul Poli

Acknowledgments to
NASA NSSDC for rescuing tapes from Nimbus-4 IRIS
Pascal Brunel for computing new RTTOV coefficients for an old instrument
Hans Hersbach for his all-purpose visualization tool & interpolation program
Qifeng Lu for a visit in January 2013 during which we collaborated to implement
a fast satellite simulator, a modified version of which I used in this talk

ECMWF

Outline

1. **Global atmospheric reanalyses**
2. **Use and impact of sounder data in reanalyses**
3. **The special case of hyperspectral infrared data**
4. **Historical hyperspectral infrared observations**
5. **Conclusions**

ECMWF

The three pillars of Geosciences

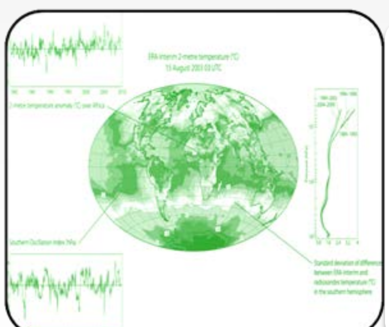
- 100+ years of observations
- Meteorology and climate "big data"

Observations

- Predictability & variability
- Grasp uncertainties
- State-of-the-art data services
- Thousands of users

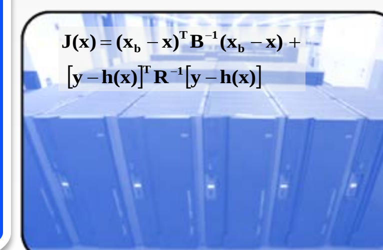
Reanalysis

- State-of-the-art numerical schemes representing physical laws and uncertainties
- Tie geophysical variables, enforce balance & conservation



Understanding & Applications

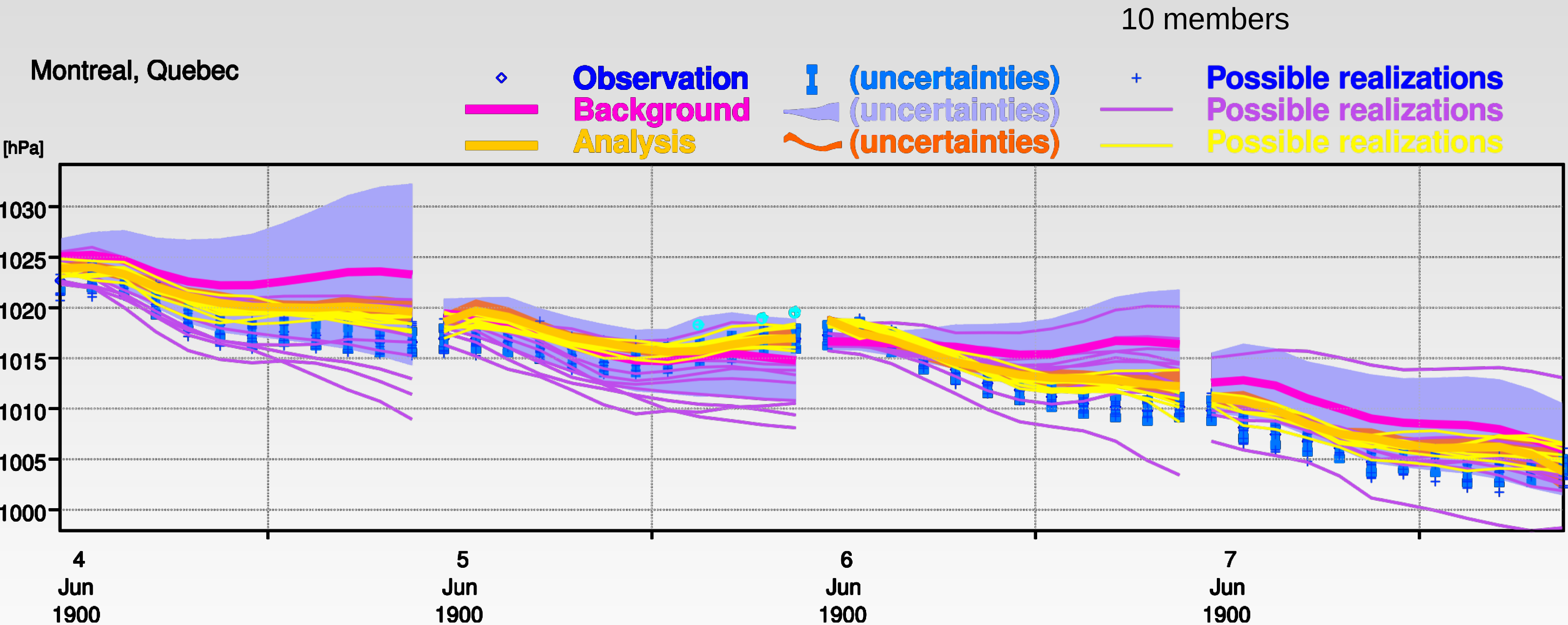
Models



ECMWF

Dealing with an uncertain past

Traditional reanalysis approach reconstructs the weather history in a forward-propagating way



Observation feedback from ERA-20C 10-member ensemble of 4DVAR

Note: This observation feedback is accessible on ECMWF MARS archive

Variational data assimilation, *as used by NWP & Reanalysis*

For each analysis, define a cost function & find its minimum:

$$\mathbf{J}(\mathbf{x},\boldsymbol{\beta}) =$$

$$(\mathbf{x_b}-\mathbf{x})^{\mathrm{T}}\cdot\mathbf{B}_x^{-1}\cdot(\mathbf{x_b}-\mathbf{x})+$$

$$(\boldsymbol{\beta}_\mathbf{b}-\boldsymbol{\beta})^{\mathrm{T}}\cdot\mathbf{B}_\beta^{-1}\cdot(\boldsymbol{\beta}_\mathbf{b}-\boldsymbol{\beta})+$$

$$\left[\mathbf{y}^0-h(M(\mathbf{x}))-b(M(\mathbf{x}),\boldsymbol{\beta})\right]^{\mathrm{T}}\cdot\mathbf{R}^{-1}\cdot$$

$$\left[\mathbf{y}^0-h(M(\mathbf{x}))-b(M(\mathbf{x}),\boldsymbol{\beta})\right]$$

Constraints: must fit:
State prior estimates
Bias correction prior estimates
Observations

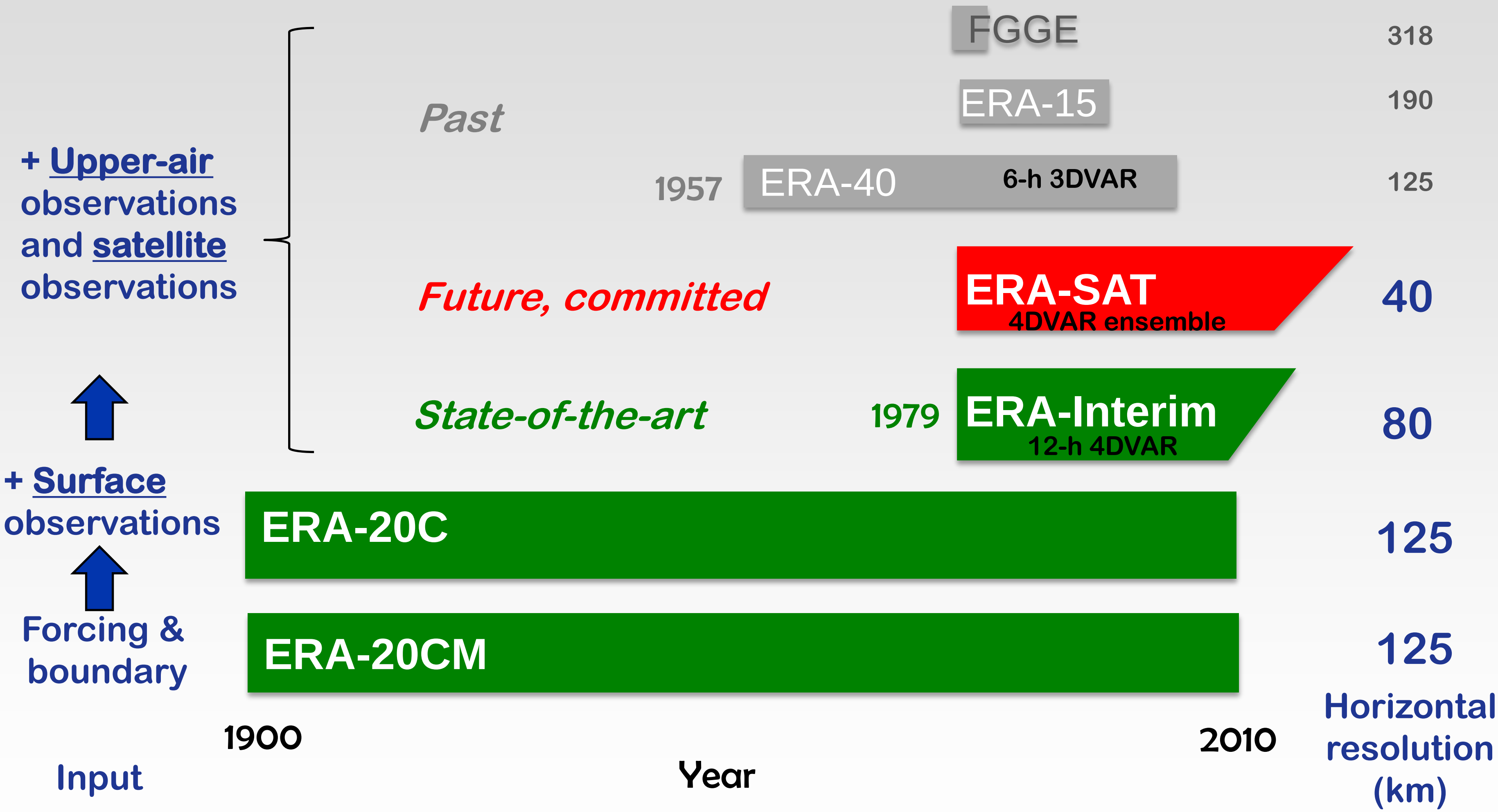
Statistical models of uncertainties:
Error covariances of:
R = observation
B_β = observation bias prior estimate
B_x = state prior estimate

Models of the physics of the atmospheric and instruments:
M = simulates state evolution
h = simulates observations
b = simulates observation biases

This produces the "most probable" atmospheric state *

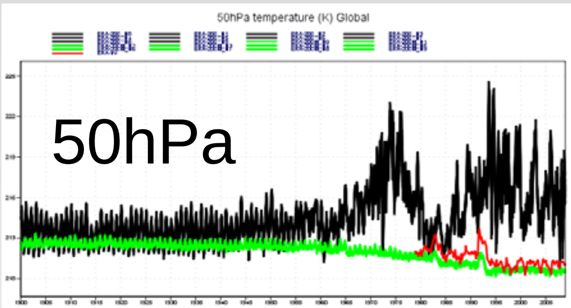
* In a maximum-likelihood sense, which is equivalent to the minimum variance, provided that **background and observation errors are Gaussian**, **unbiased**, **uncorrelated with each other**; all error covariances are correctly specified; model errors are negligible within the analysis window

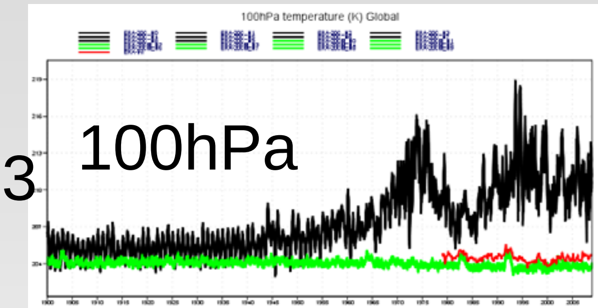
ECMWF atmospheric reanalyses



ECMWF

1900-2008 temperature trends from reanalyses

3


3


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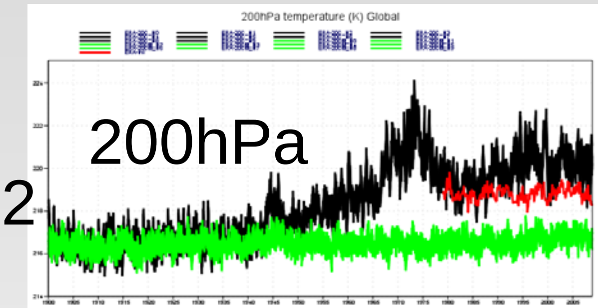
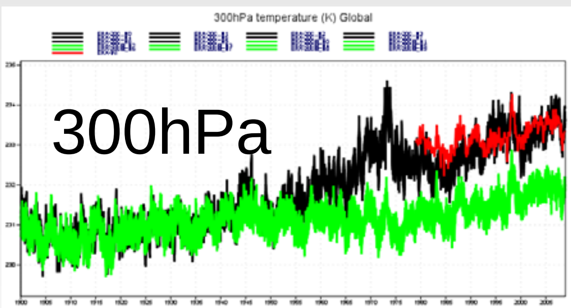
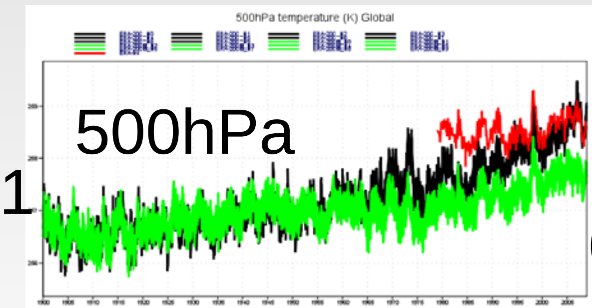
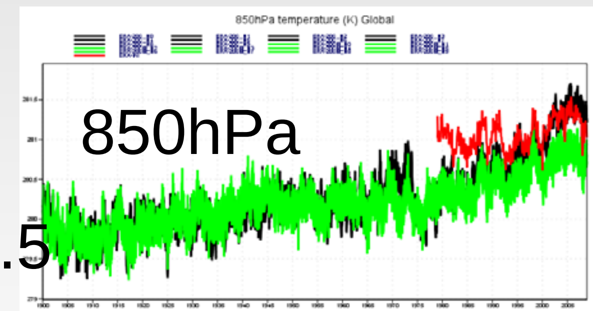
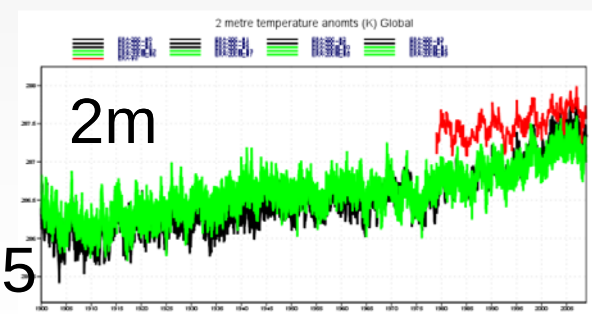


1


1


0.5


ERA-Interim
ERA-20CM
ERA-20C

0.5


Figures from Paul Berrisford

ECMWF

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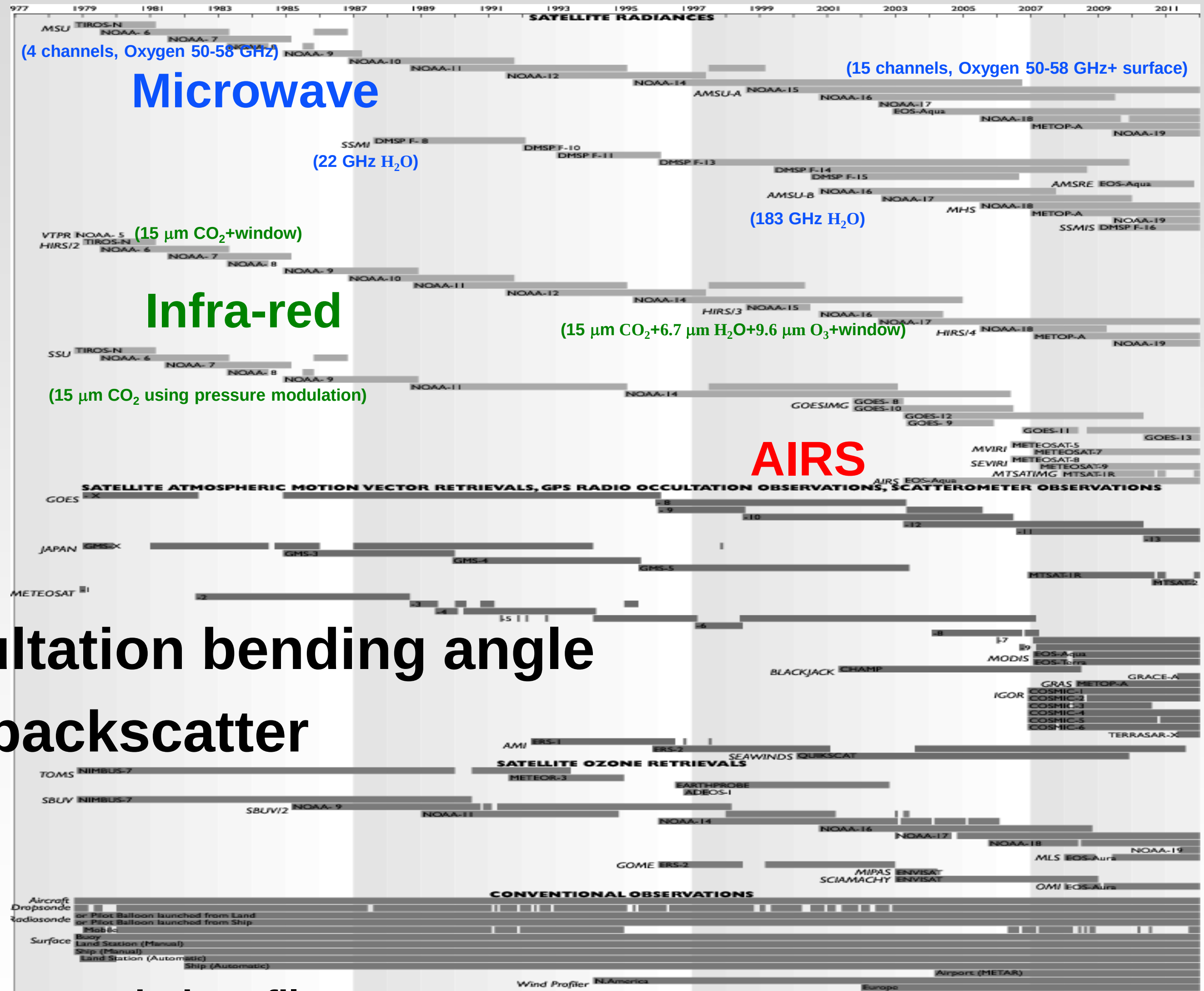
Reanalyses use the widest variety of observations

Observations used in ERA-Interim 1979-2012

Radiance



Atmospheric motion vector

GPS radio occultation bending angle

Scatterometer backscatter

Ozone

Radiosonde,

aircraft, station, buoy, wind profiler, dropsonde

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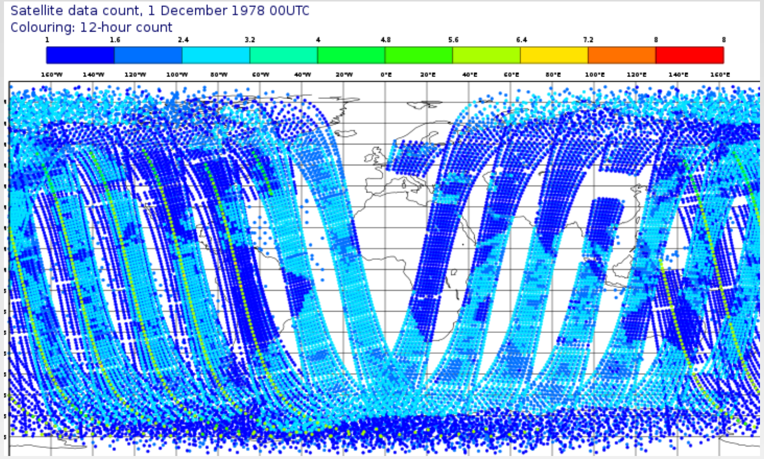
Satellite data input to atmospheric reanalysis

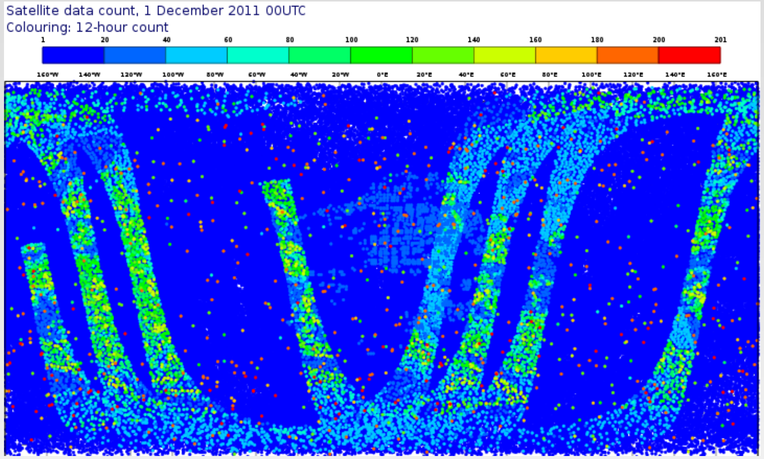
Number of satellite data used, 1 deg x 1 deg 12-hour count

1 Dec 1978, 00UTC



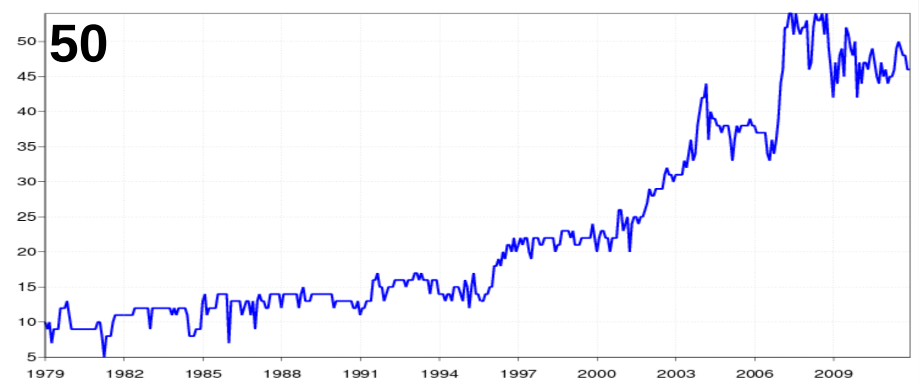
8

1 Dec 2011, 00UTC

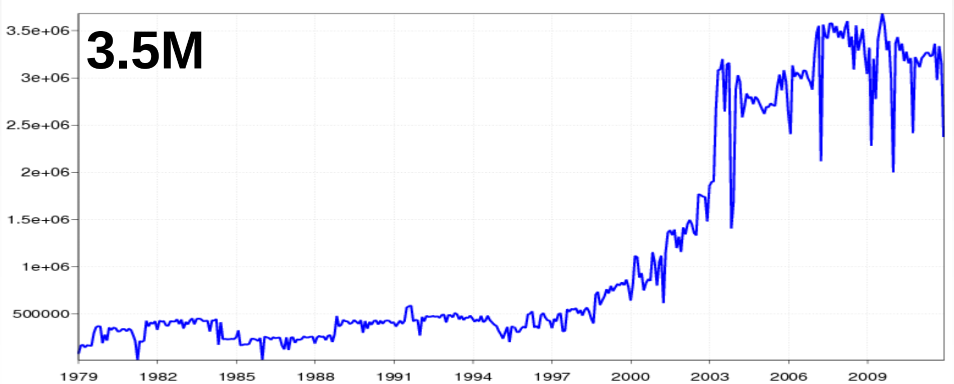


201

Number of satellite sensors/ AMV retrieval types



Number of observations every 12 hours



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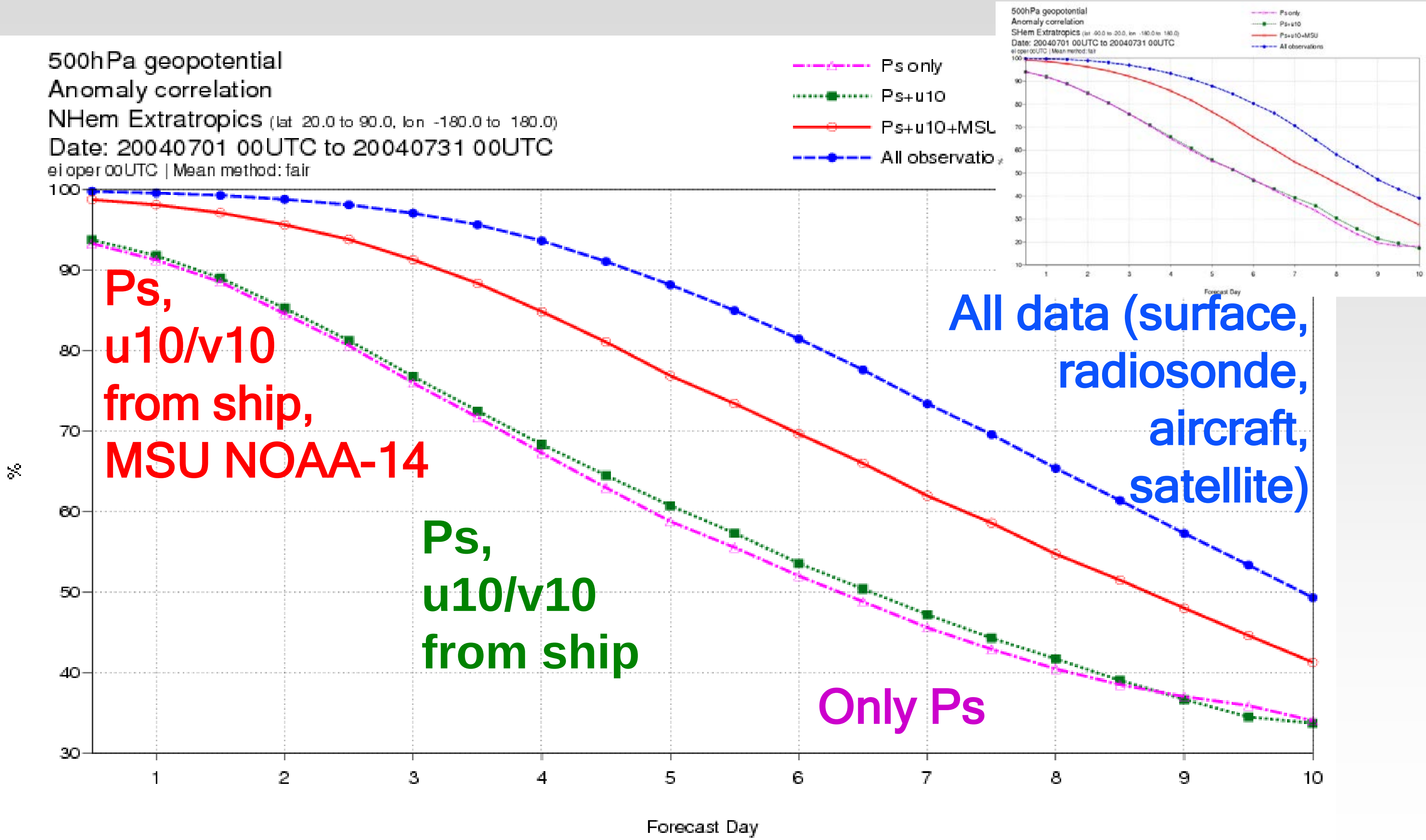
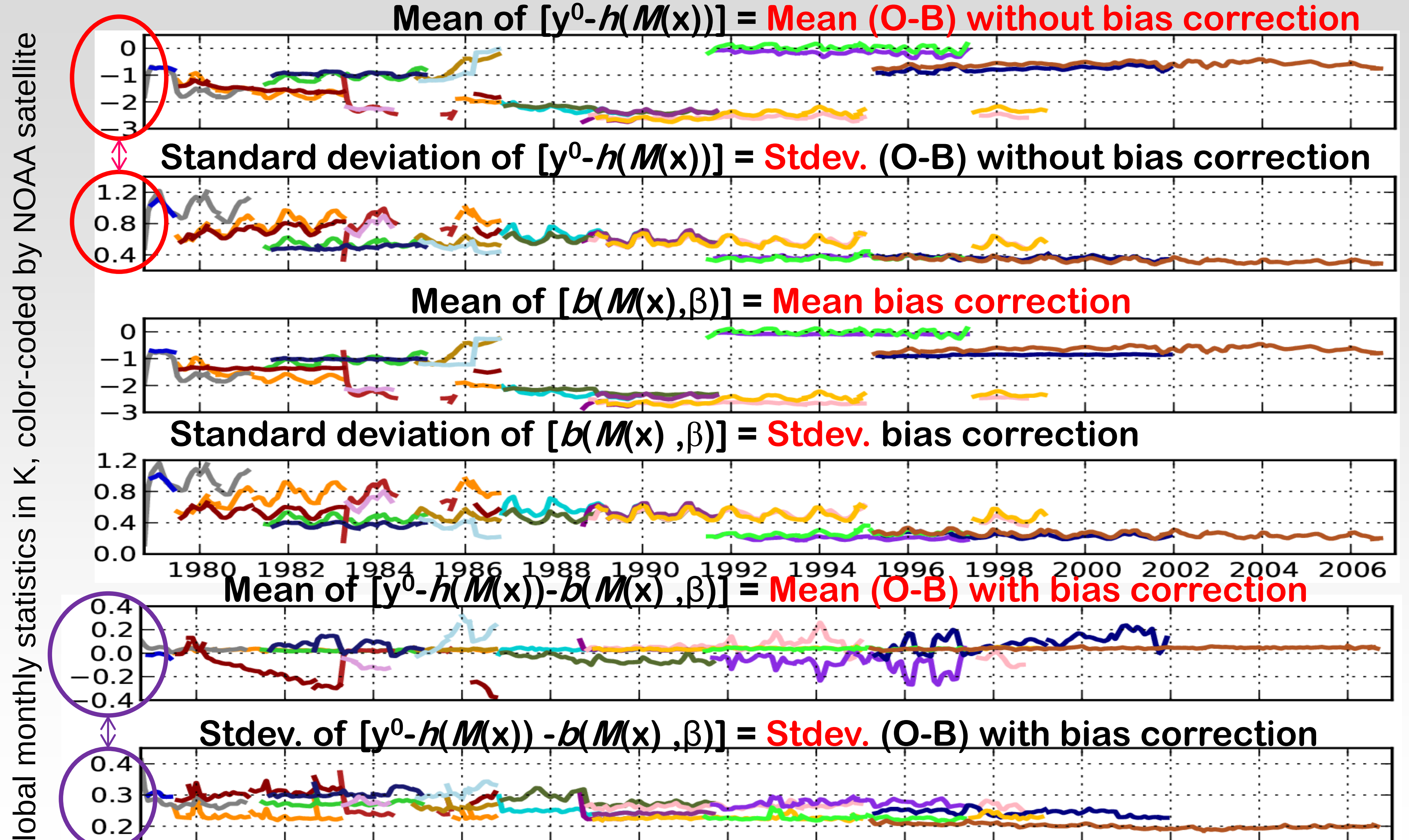
Impact of a 4-channel microwave sounder NOAA-14 MSU



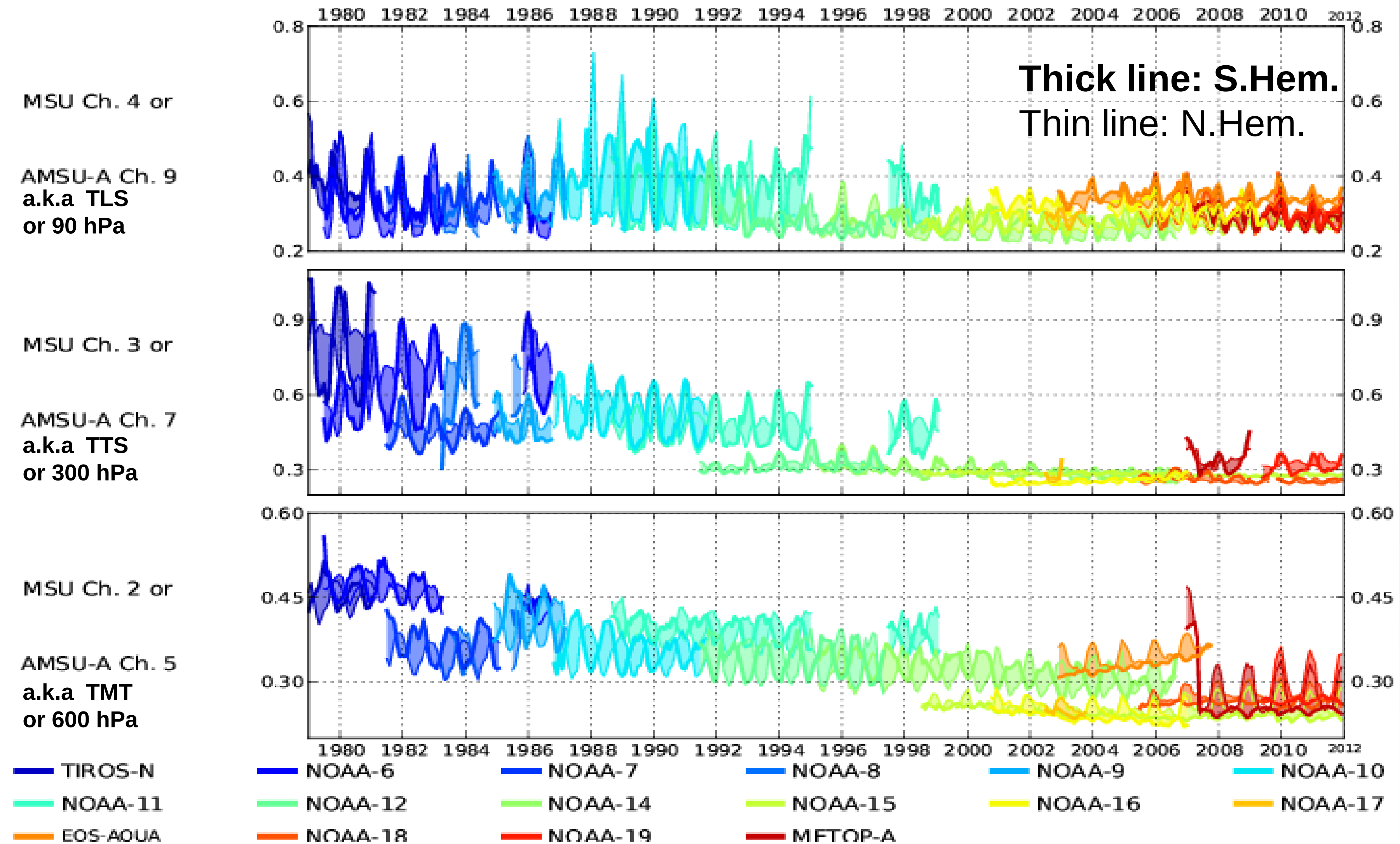
ECMWF

MSU channel 3 minus ERA-Interim: 1979-2006
h = RTTOV8 at the time and location of obs.



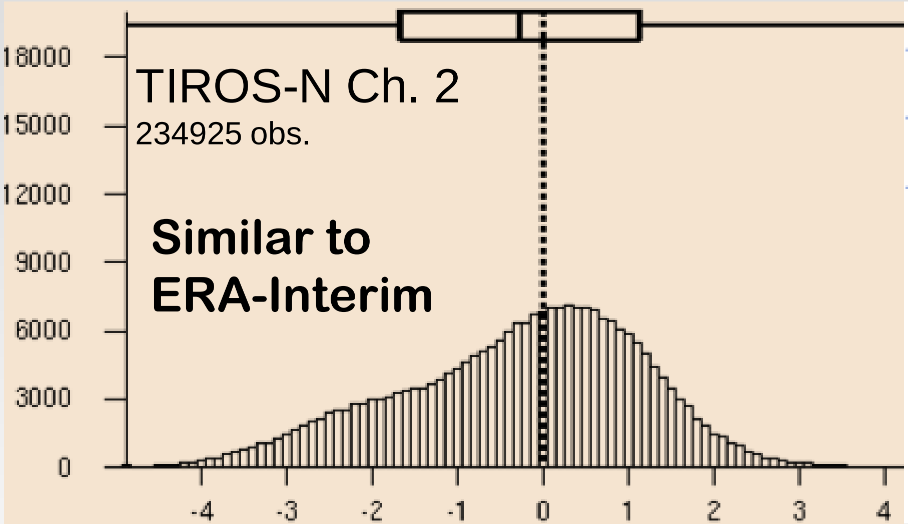
33 years of passive microwave vertical sounding

Stdev(O-B), without bias correction (in K)



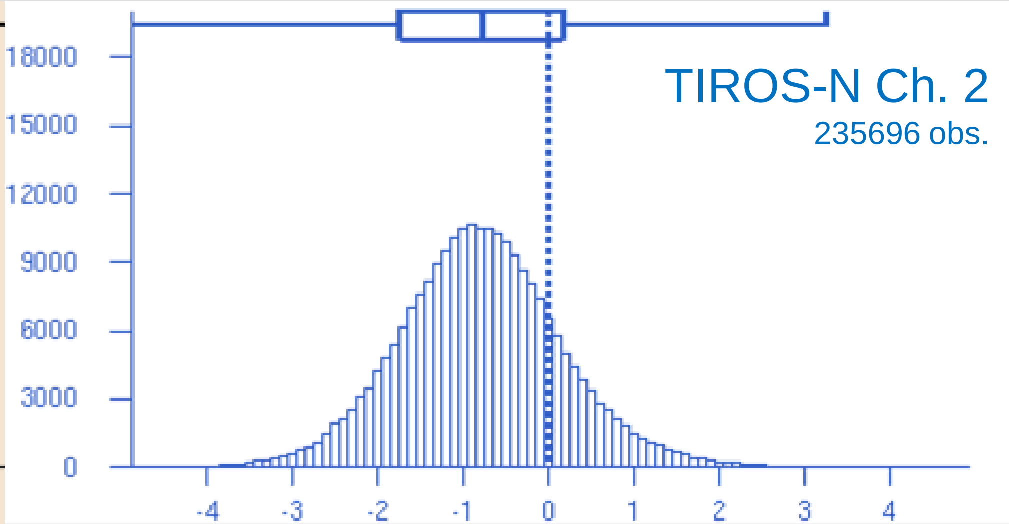
Impact of improving the radiative transfer model

OLD



O-B (without bias correction), in K

NEW



O-B (without bias correction), in K

DIFFERENCES:

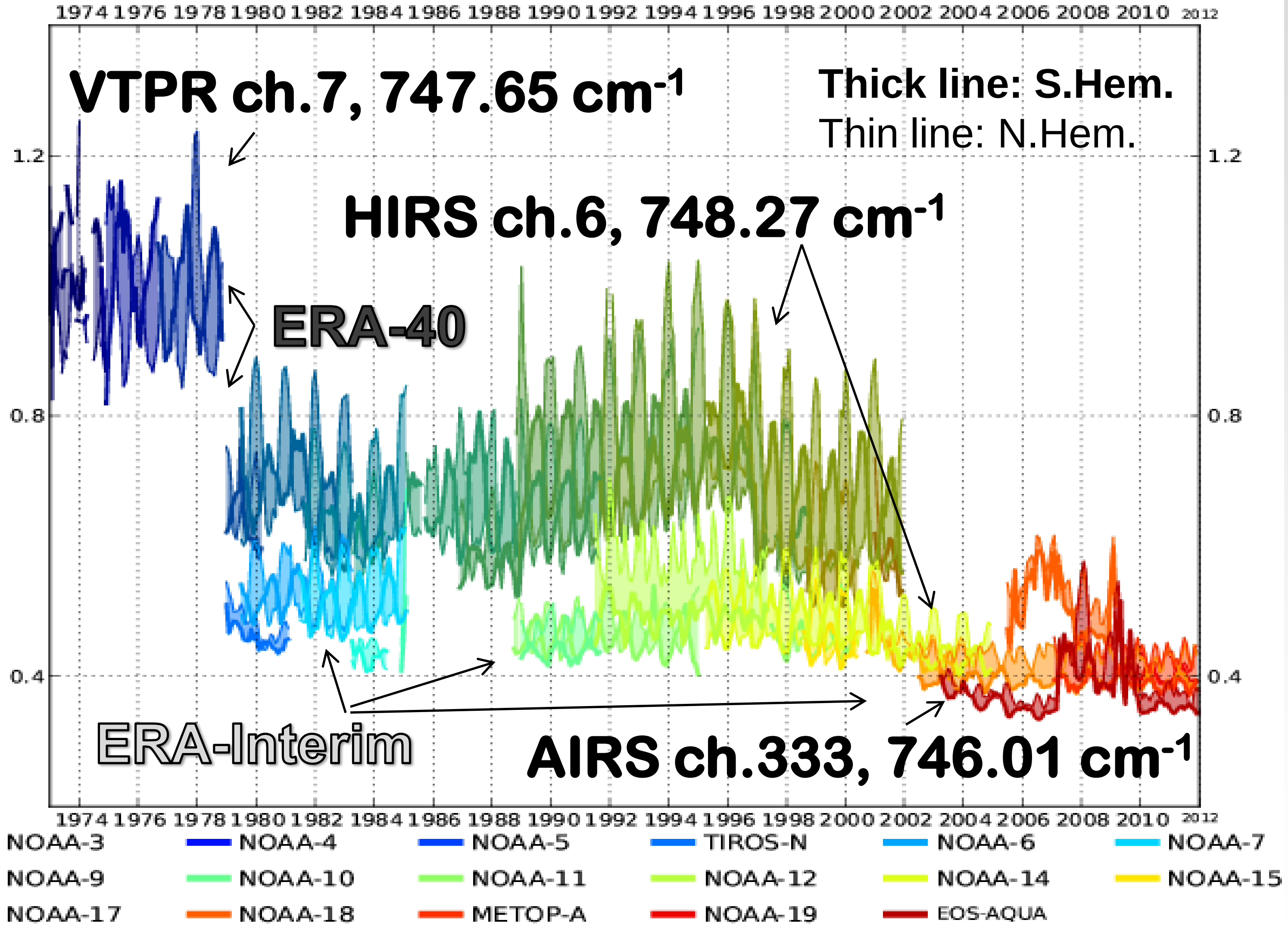
1. **Spectroscopy: Hitran 1978 → Hitran 2004**
2. **CO_2 profile now used as predictor**
3. **SSU cell pressure better characterized**

Full assimilation run, 1 Feb 1981 – 17 Mar 1981, ECMWF IFS CY36R4, NWP-SAF RTTOV-10

ECMWF

39 years of observations ~747 cm^{-1} compared with ERA-40 and ERA-Interim

Stdev(O-B), without bias correction, in K



ECMWF

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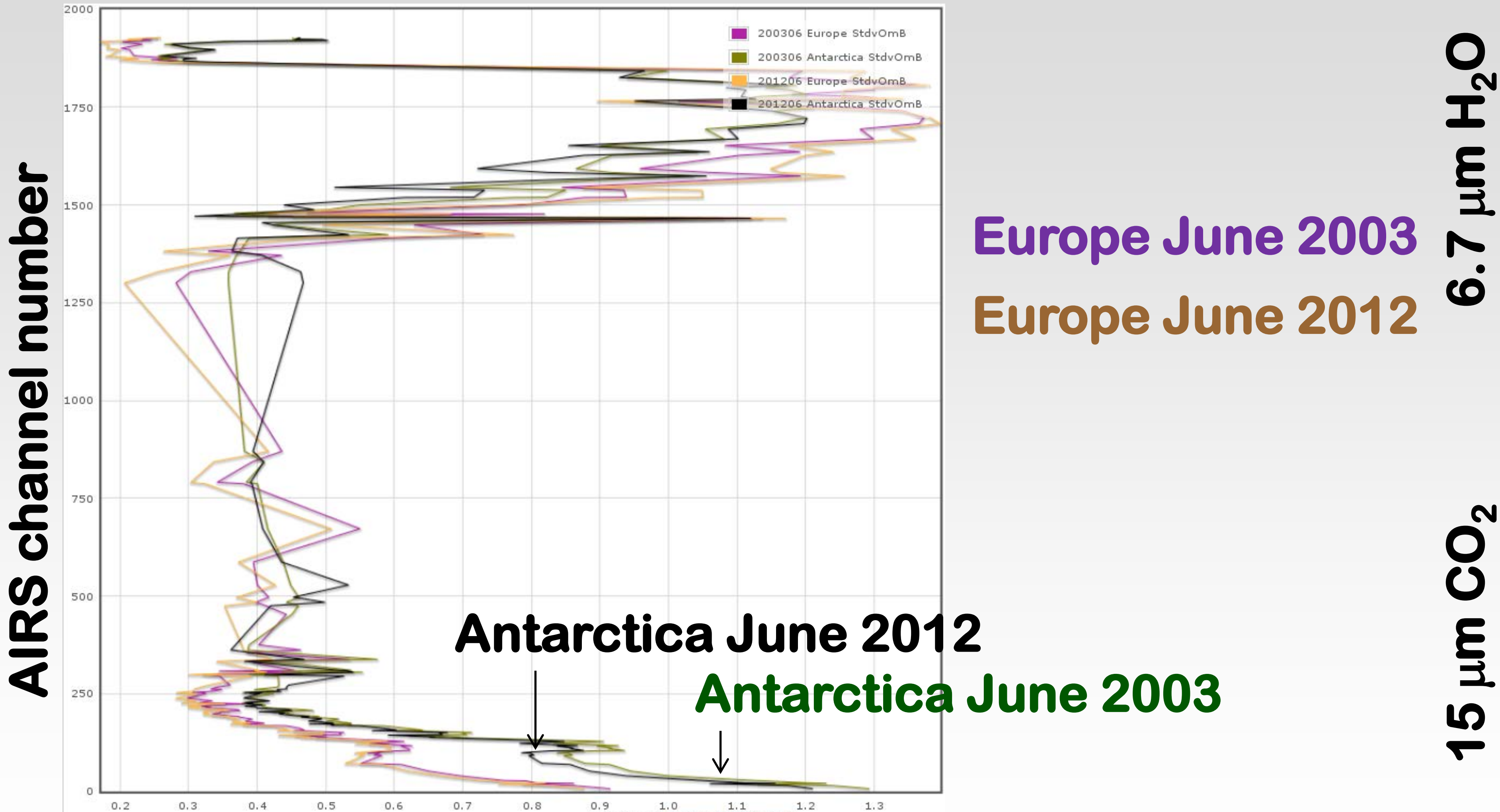
Hyperspectral infrared assimilation in modern reanalyses

Percentage of channels assimilated

Satellite Instrument	Time period	NCEP CFSR	NASA MERRA	JMA JRA-25	JMA JRA-55	ECMWF ERA-Interim	MACC
EOS-Aqua AIRS	2002-present	***5%*** (121/2378)	***5%*** (121/2378)	*No*	*No*	***6%*** (156/2378)	***8%*** (185/2378)
MetOp-A IASI	2006-present	***2%*** (165/8461)	*No*	*No*	*No*	*No*	***2%*** (175/8461)
MetOp-B IASI	2012-present	*No*	*No*	*No*	*No*	*No*	*No*
Suomi NPP CrIS	2011-present	*No*	*No*	*No*	*No*	*No*	*No*

ERA-Interim use of AIRS: as in ECMWF OPS in 2006



Output JSON: Download JSON output

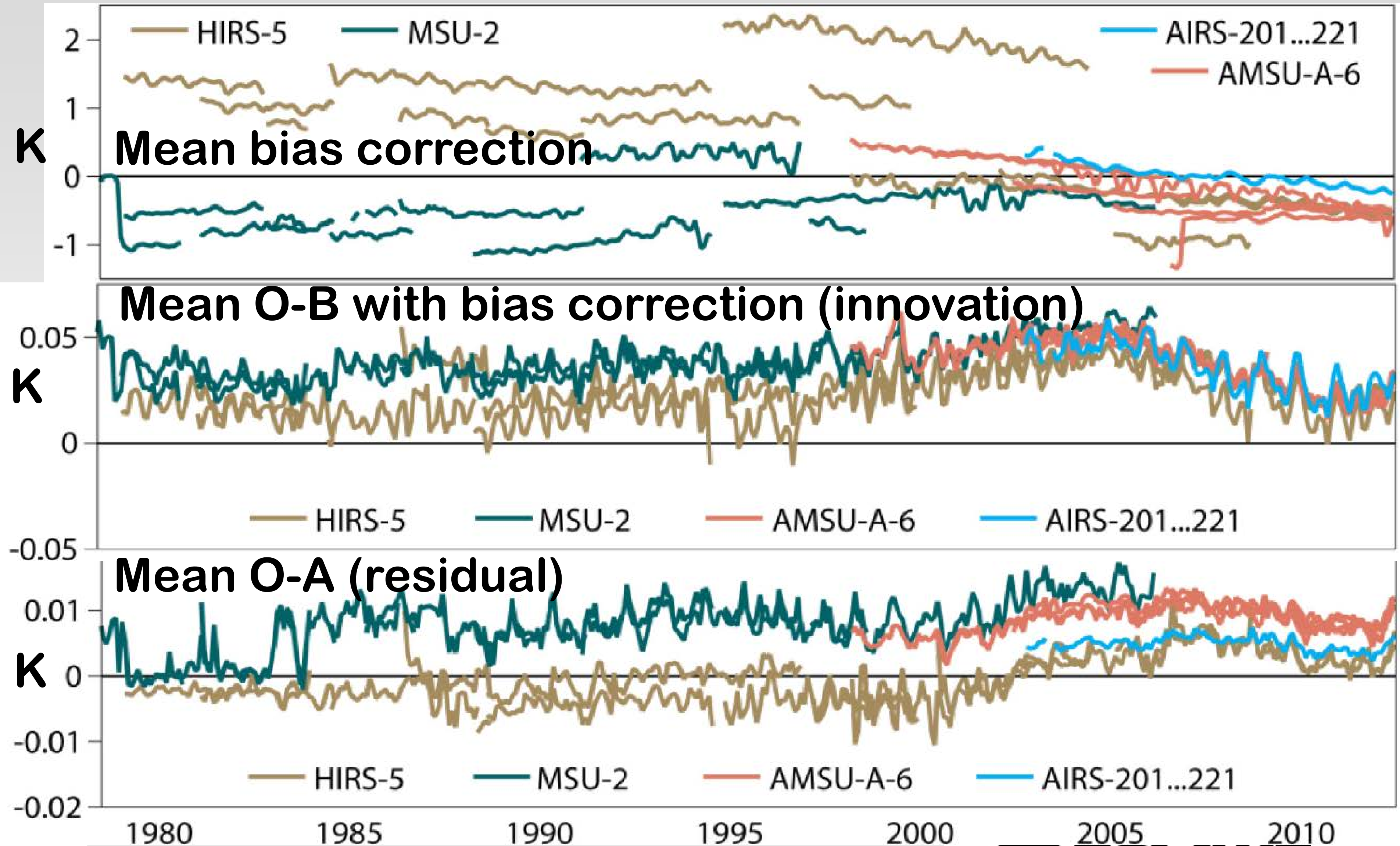
Query time: 2.44s

Query command: DROP TABLE IF EXISTS sch_stats5.tempdateti

Stdev(O-B) with b.corr.

ECMWF

Tropospheric AIRS monthly time-series



ECMWF

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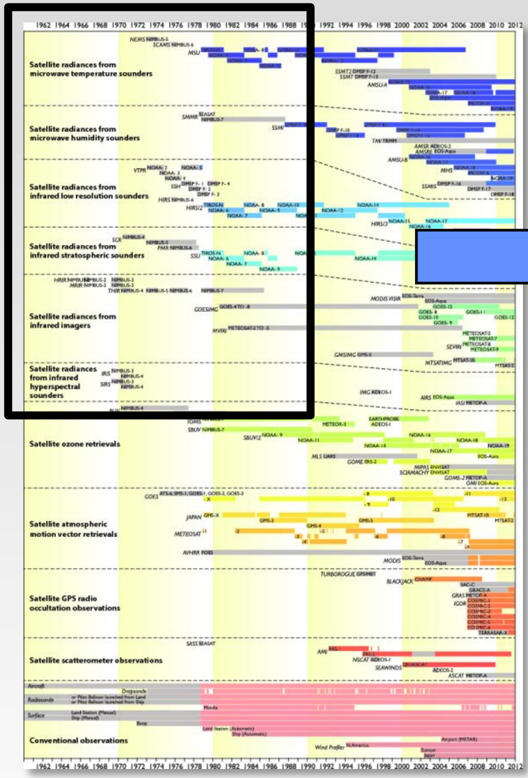
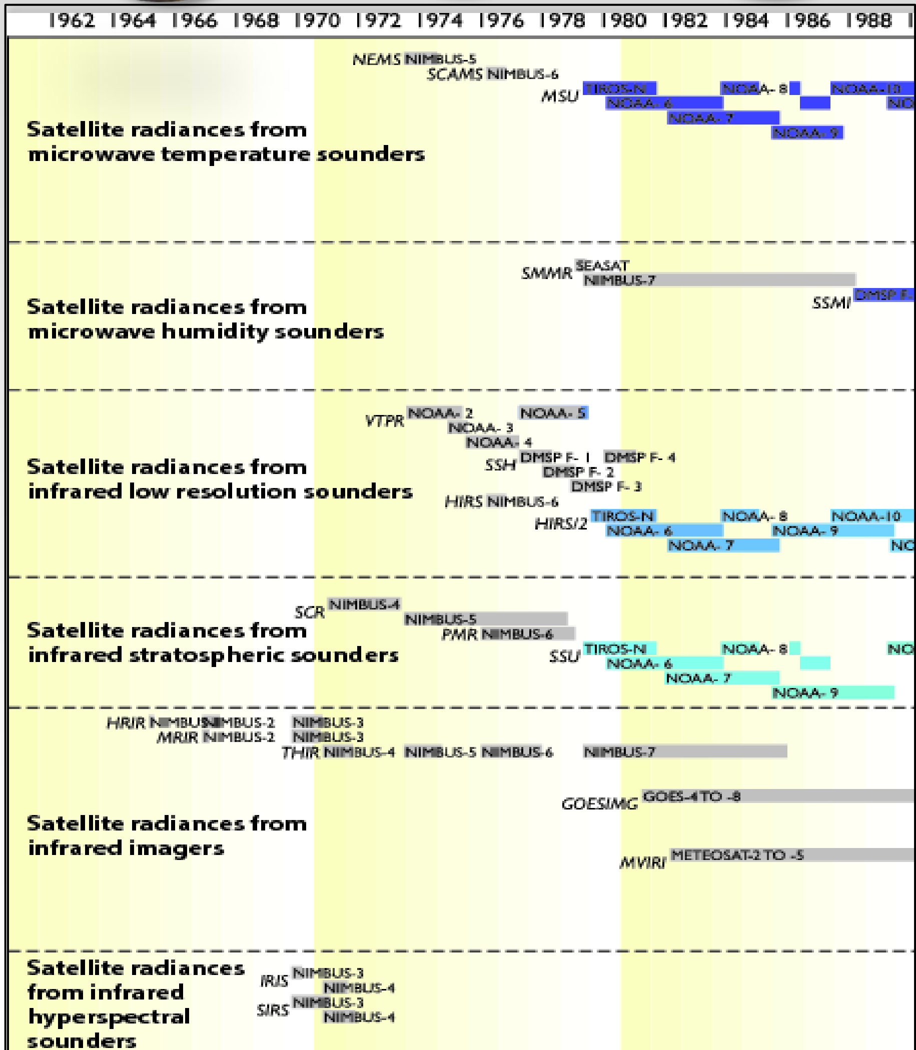
ECMWF

Satellite data since the 1960s





More details about these early instruments, though without the present visuals, can be found in the ERA-CLIM deliverable "Satellite Datasets for use in ERACLIM" by Roger Saunders, Paul Poli, Viju John and Graeme Kelly (2011)

ECMWF

Historical interferometers in space

Instrument	Satellite & Agency	Time period	Viewing geometry	Resolution (cm^{-1})	Spectral domain (cm^{-1})
IRIS-B	Nimbus-3 NASA	April 1969—July 1969	Nadir (no cross-scanning)	5.000	500—2000
IRIS-D	Nimbus-4 NASA	April 1970—January 1971	Nadir (no cross-scanning)	2.800	400—1600
IMG	ADEOS-1 JAXA	August 1996—June 1997	Nadir (no cross-scanning)	0.100	700—2000, 2000—2500, 2500—3000
MIPAS	Envisat ESA	July 2002—April 2012	Limb	0.035	685—970
ACE-FTS	Scisat-1 CSA	August 2003—present (as of Oct. 2013)	Limb	0.020	750—4400

Versions flew later on planetary explorers: Mariner-9, Voyager-1, Voyager-2

Nimbus-4 IRIS: 862 channels

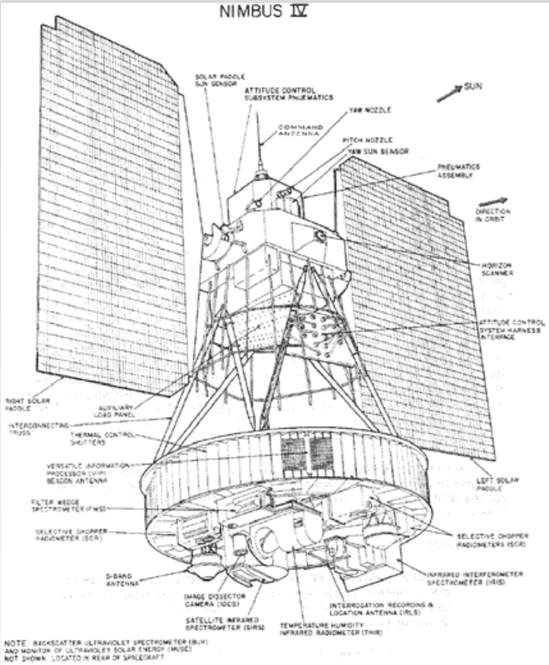


Figure 1-1. Basic Configuration of Spacecraft

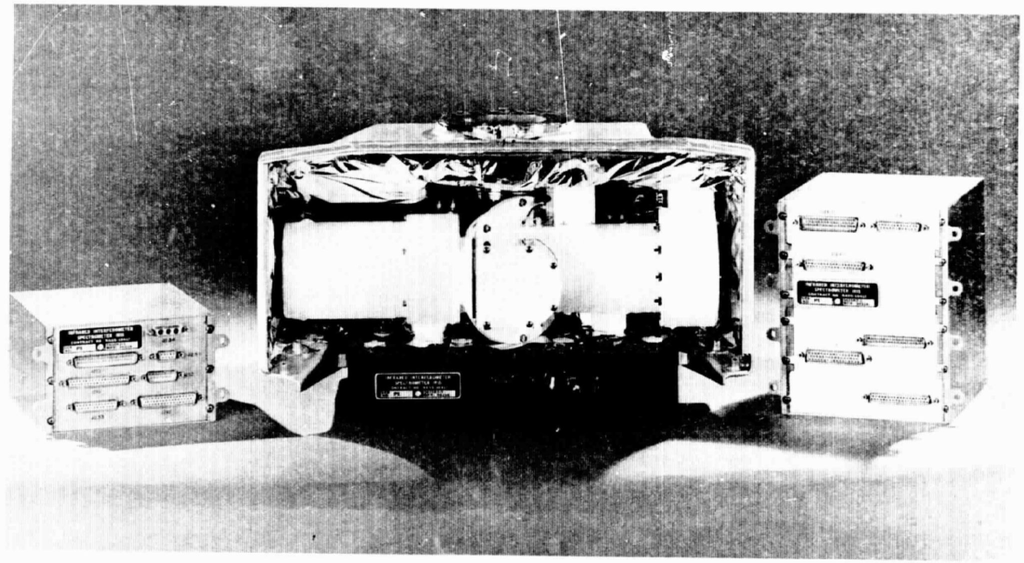


Figure 1. The infrared interferometer (IRIS-D) on Nimbus 4 consists of an optical module, shown enclosed by a thermal shroud in the center of the figure, and of two modules which contain electronic circuitry. The optical module is mounted below the Nimbus sensory ring (not shown), so that the port visible 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- 65395

THE NIMBUS 4 MICHELSON
INTERFEROMETER

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

DEC. 1970

GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

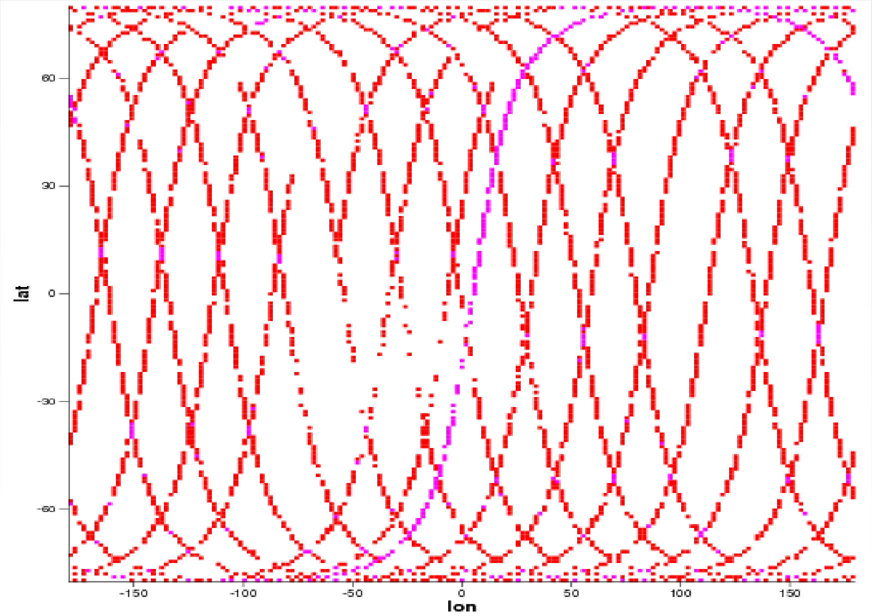
N71-14804

- Plenty of imaged documents on the web, even some fairly recent papers
- Unfortunately the experimenters are not necessarily longer available to take questions
- Data were rescued from ageing tapes recently by NASA, and are now available on the NSSDC website http://nssdc.gsfc.nasa.gov

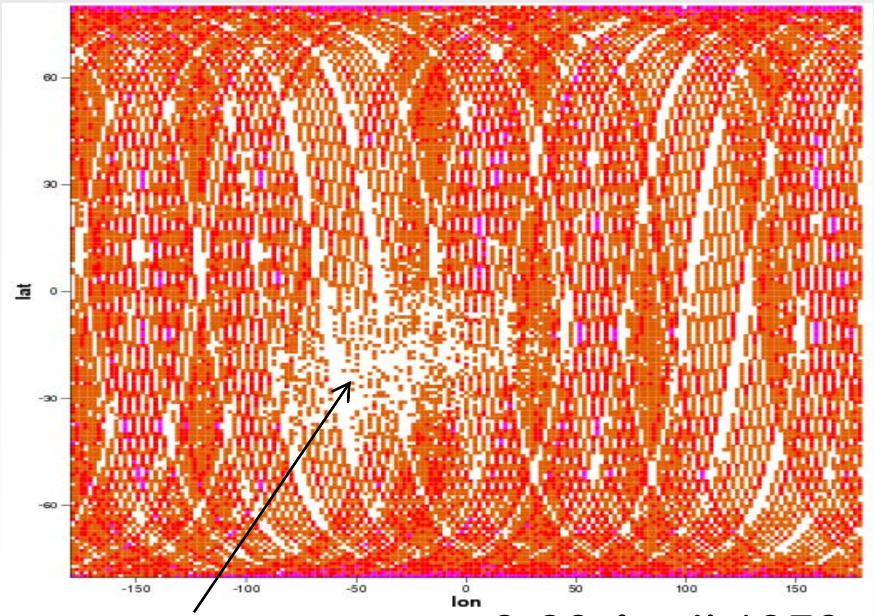
First step: Read the data

- **Awkward / ancient file formats.**
  Nearly makes you wish for BUFR, though note quite.
- **Read the data with some Fortran**
- **Convert to brightness temperatures & usual date format**
- **Import into ECMWF ODB-2 format the following information:**

date, time, lat, lon, orbit no., profile no., channel no., wavenumber, radiance, b.t.



Map of soundings for 14 April 1970

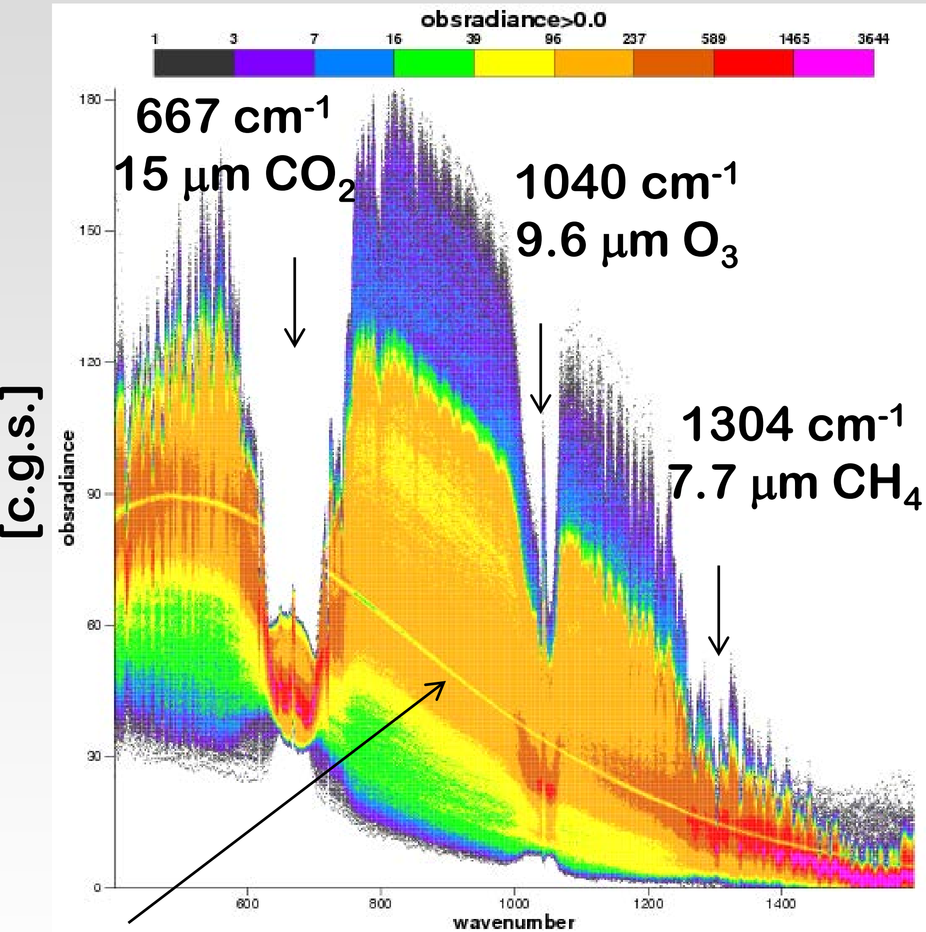


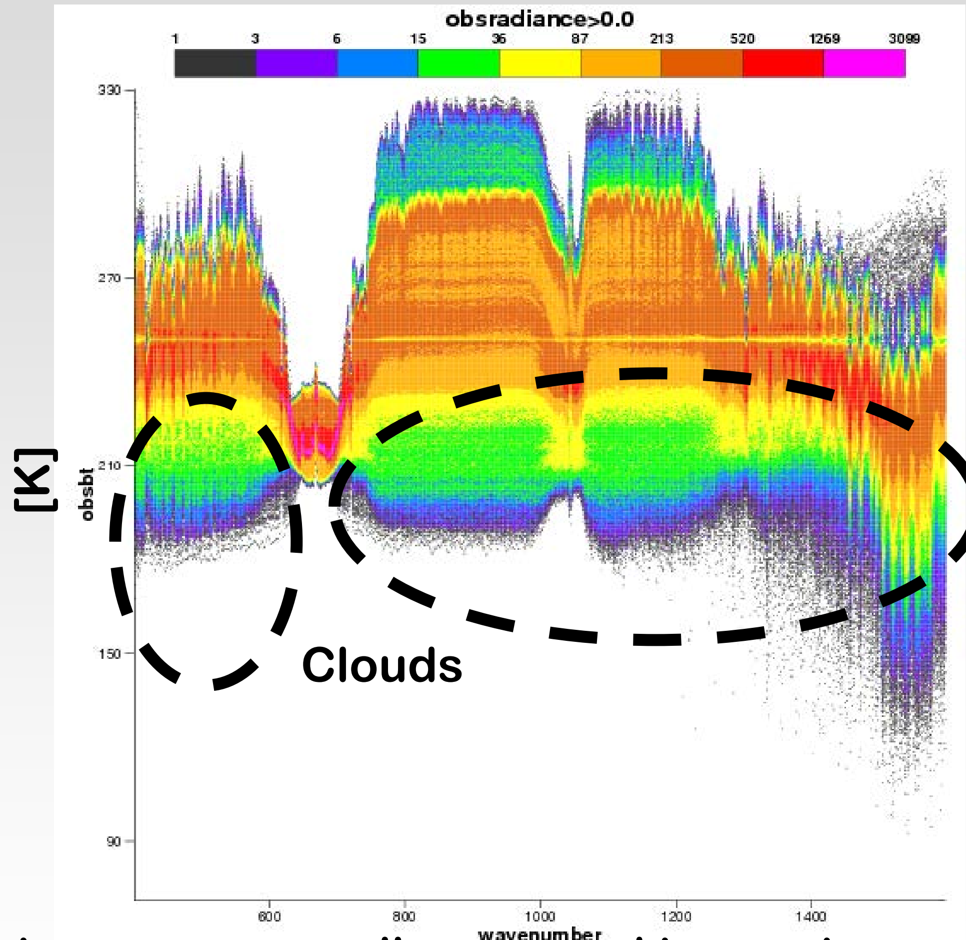
9-30 April 1970

ECMWF

Second step: Visualize the observations

All spectra found in the radiance files, 9-30 April 1970





From documentation: calibration spectra were manually removed to create this radiance dataset – some actual good spectra were wrongly removed?
→ Will need to go back to the actual raw data, also thankfully recovered.

Third step: Compare with model calculations

ERA-40 field extraction

Acquire 6-hourly 3D fields of T,q,O_3 and 2D fields of surface parameters

↓

For each observation

Interpolate horizontally the reanalysis fields to observation location, taking the nearest field in time

↓

Call RTTOV10 with interpolated profile of T,q,O_3 and surface parameters

Specifying we want radiances simulated for IASI

↓

Re-sample high spectral resolution output to IRIS lower spectral resolution

For each IRIS channel in the IASI spectral range (>=645cm-1),
find all the IASI channels (resol 0.25 cm^{-1}) falling within +/1.39 cm^{-1} and average

↓

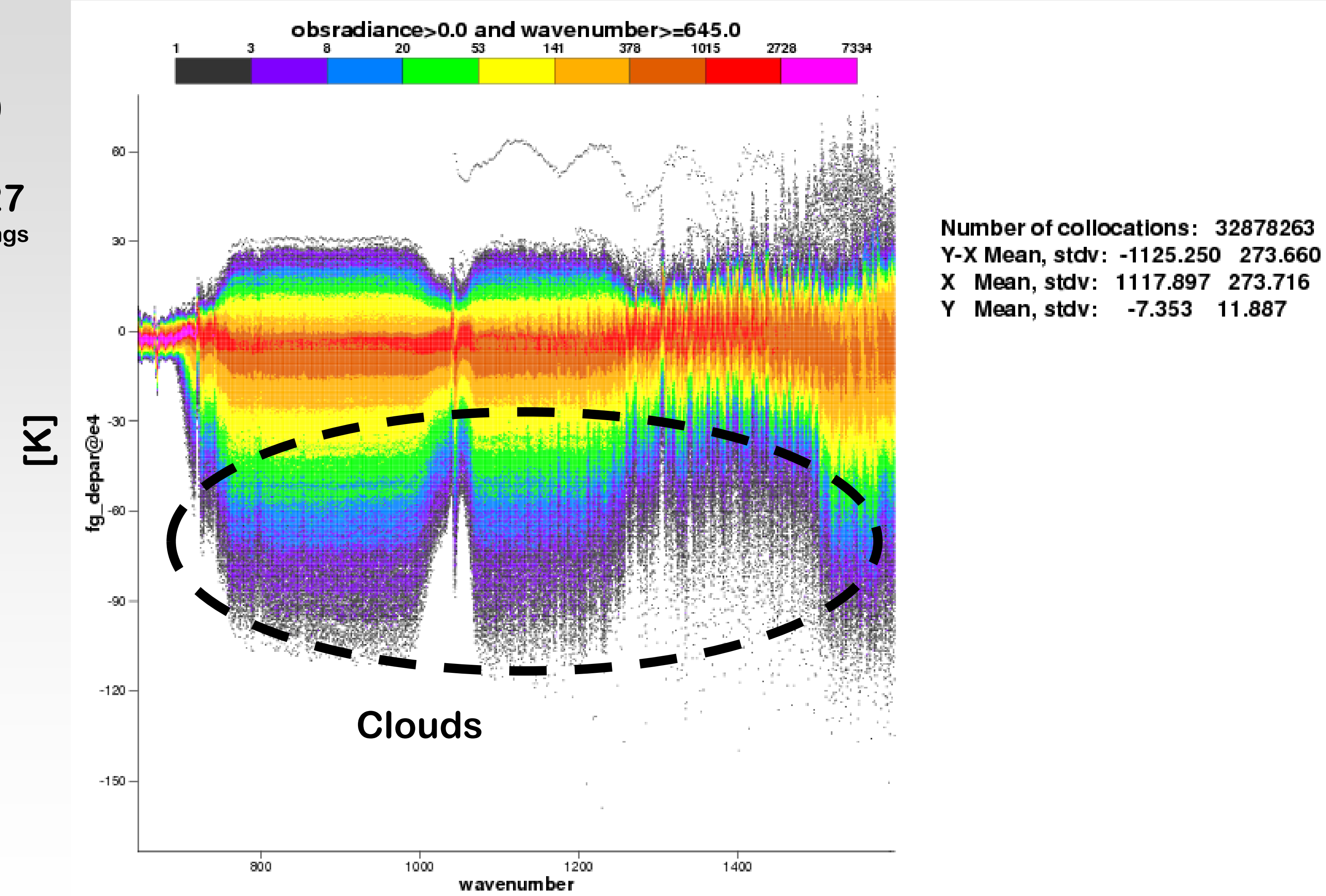
Append departure information

Into the ODB file, as an extra column

Differences IRIS minus ERA-40, for all channels>645 cm^{-1}

9-30 April 1970

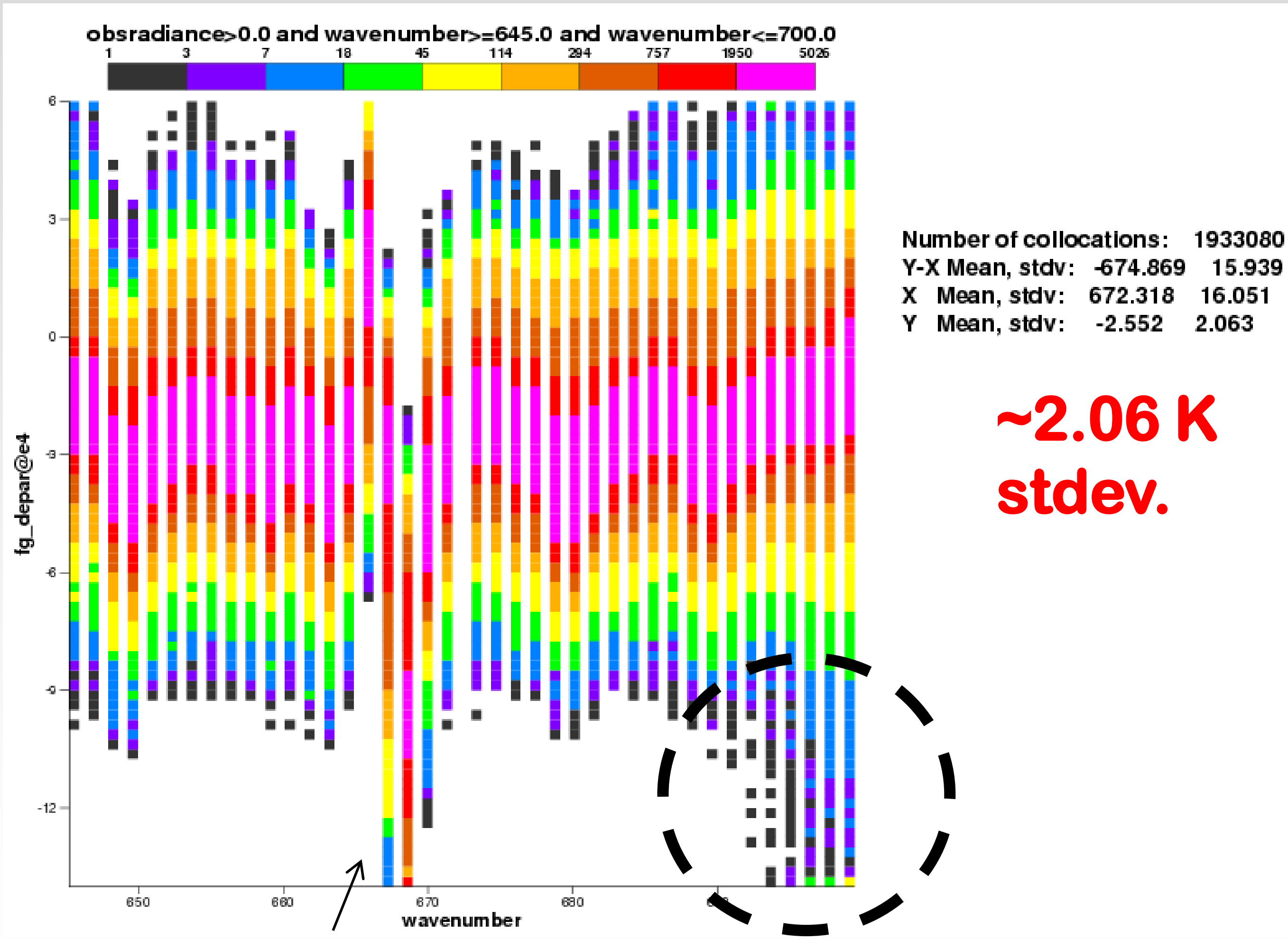
48327 soundings



Zoom on upper-peaking channels in 15µm CO2 band

9-30
April
1970

[K]

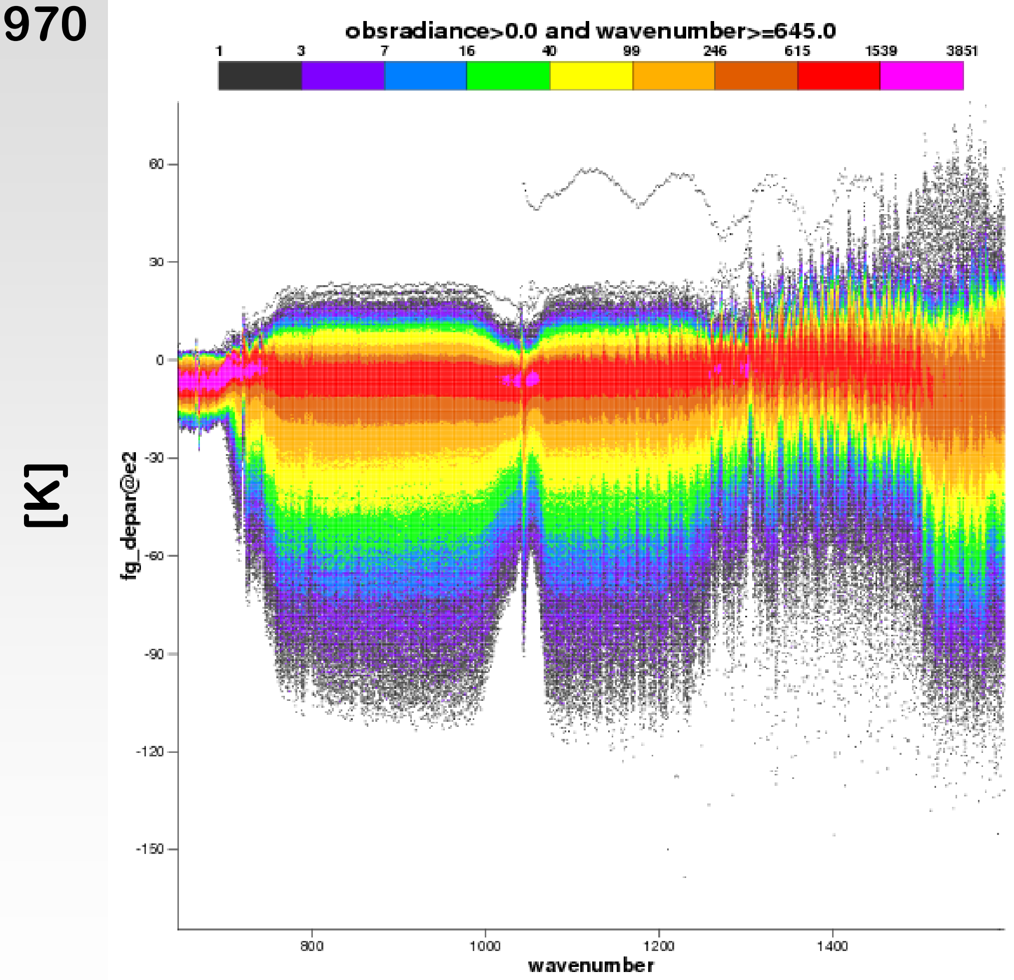


667 cm-1 Q-branch

Clouds

Same as earlier but with 3-hourly ERA-20C fields

9-30 April 1970



Number of collocations: 32878263
Y-X Mean, stdv: -1126.225 273.376
X Mean, stdv: 1117.897 273.716
Y Mean, stdv: -8.328 11.604

Clearly larger departures than ERA-40.
Not surprising: ERA-20C did not assimilate *any* upper-air observations

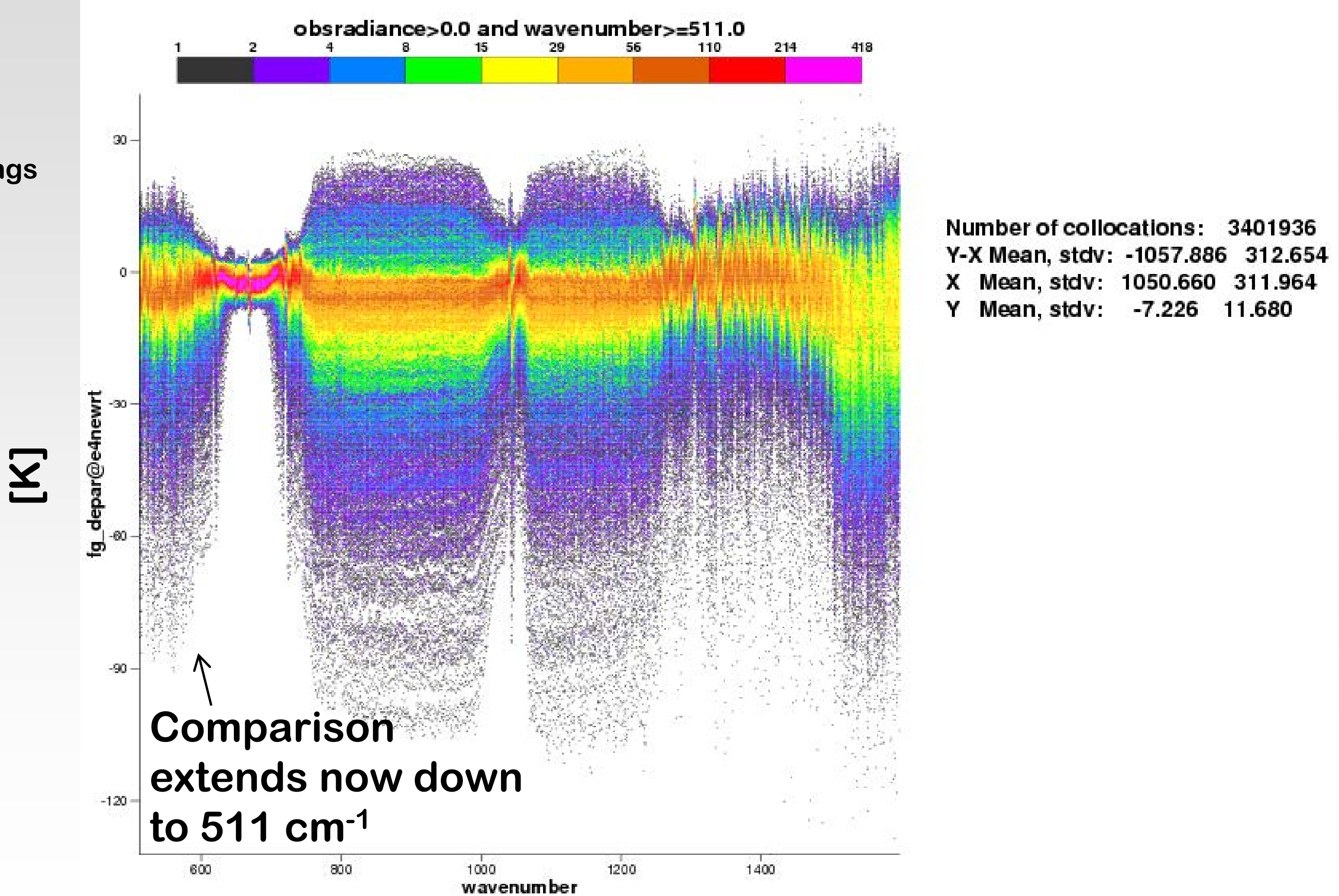
ECMWF

With RTTOV coefficients computed especially for IRIS

14 April 1970

4386 soundings

RTTOV v8 coefficients computed by Pascal Brunel NWP-SAF/Meteo-France, given IRIS wavenumbers, apodisation function, and mirror displacement



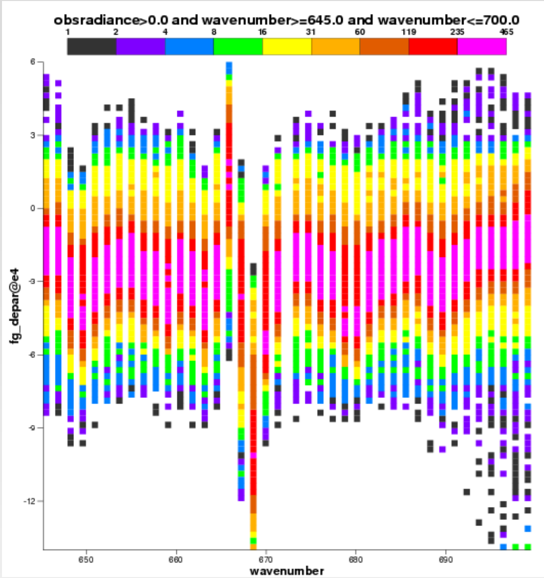
ECMWF

Zoom on the 645-700 cm^{-1} band

14 April 1970

4386 soundings

[K]

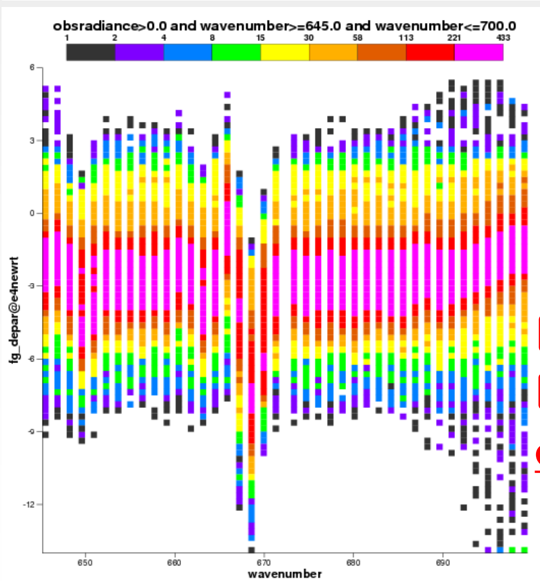


Number of collocations: 175440
Y-X Mean, stdv: -674.881 15.957
X Mean, stdv: 672.318 16.051
Y Mean, stdv: -2.564 2.102

IASI v7L54 RT coeffs.:
σ = 2.1 K

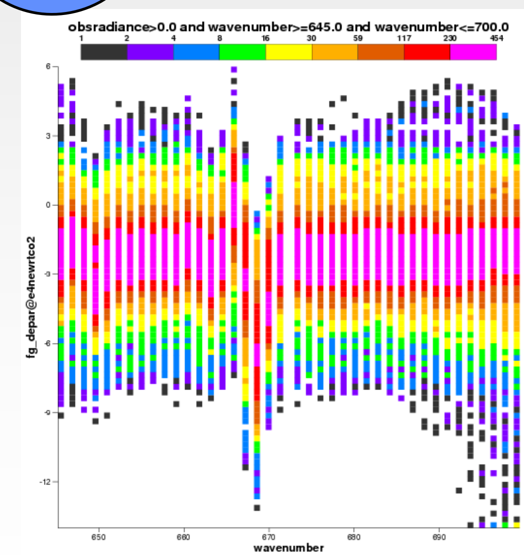
Smaller residuals allow for more accurate retrievals & applications. This illustrates how much more information can potentially be extracted from +40-year old satellite data, thanks to ongoing development in (radiative transfer and NWP) models.

[K]



Number of collocations: 175440
Y-X Mean, stdv: -674.982 15.944
X Mean, stdv: 672.318 16.051
Y Mean, stdv: -2.665 1.840

IRIS v8L101 RT coeffs.:
σ = 1.8 K



Number of collocations: 175440
Y-X Mean, stdv: -674.622 16.102
X Mean, stdv: 672.318 16.051
Y Mean, stdv: -2.305 1.712

IRIS v8L101 RT coeffs. & adjusting for 1970 CO_2 (325 ppmv)
σ = 1.7 K

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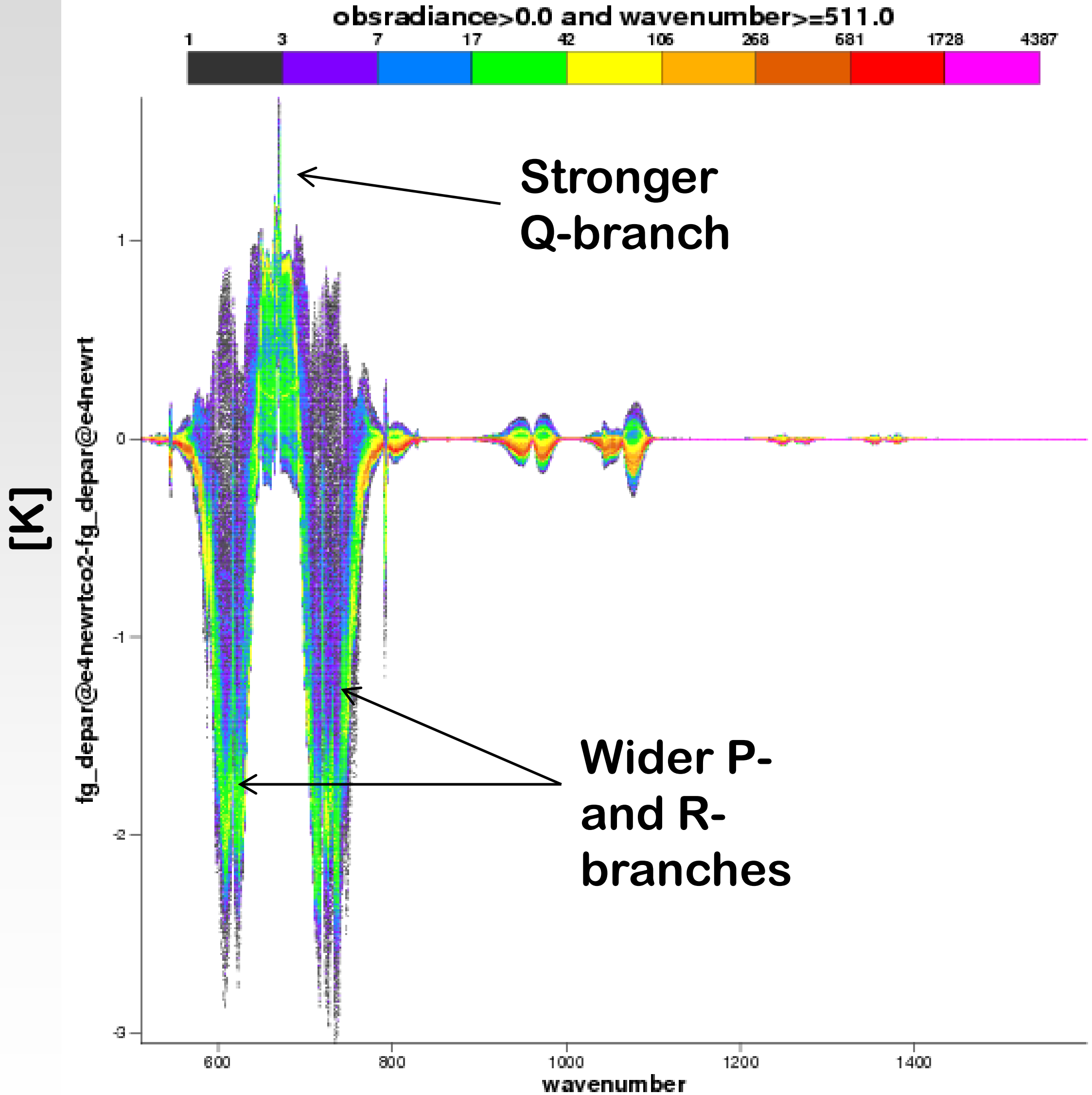
Impact of CO_2 325 ppmv in 1970 → 384 ppmv in 1983

14 April 1970

4386 soundings simulated with RTTOV



Nice to be able to see the P and R branches.
➔ Benefits for CO2 retrievals?

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Conclusions 1/2

Last page of NASA TM on Nimbus-4 IRIS

ACKNOWLEDGEMENTS

The authors are grateful to C. Kruger and M. Rhodes of Texas Instruments for their invaluable assistance in the development of the IRIS-D instrument and to G. Wolfard of GSFC for his efforts in the area of data reduction. Mr. Milton Sing, GSFC, helped in the preparations of the figures.

- **Data reduction already an important topic in 1970.**
- **Reanalyses, lagging behind state-of-the-art NWP in terms of current satellite data usage, use at most**
  - **1 or 2, of the current 4 hyperspectral infrared sounders**
  - **fewer than 10% of the channels**
- **The 'relatively new' sensors, and the large amount of data probably explain why hyperspectral data haven't been used more in current reanalyses.**

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Conclusions 2/2

- **Based on earlier examples, *with much poorer sounders*, we found that the corresponding data still managed to make a huge impact on today's weather and climate reconstruction**
- **The promise is much greater with hyperspectral infrared, probing details of spectral regions otherwise unmonitored on a systematic basis, which could in the future tell us about unforeseen changes in constituents and aerosols**
- **Overall the potential for climate use hasn't been realized yet**
- **Reanalysis can help, making comparisons between observations and model accessible**
- **All original raw data must be preserved, along with meta-data for future users to understand data quality, calibration, and its time evolution**