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Recovering historical observations for climate reanalysis

Bill Bell, Paul Poli, Dinand Schepers, Liam Steele, Hans Hersbach, Cornel Soci, Mikael Kaandorp, Dave Duncan, Alan Geer, Ethel Villeneuve @ ESAS, RD, ECMWF

Roberto Ribas, Martin Suttie @ FSD, ECMWF

Jörg Schulz, Viju John, Timo Hanschmann, Roger Huckle, Oliver Sus, Alessio Lattanzio & Collegues, Climate Team, EUMETSAT

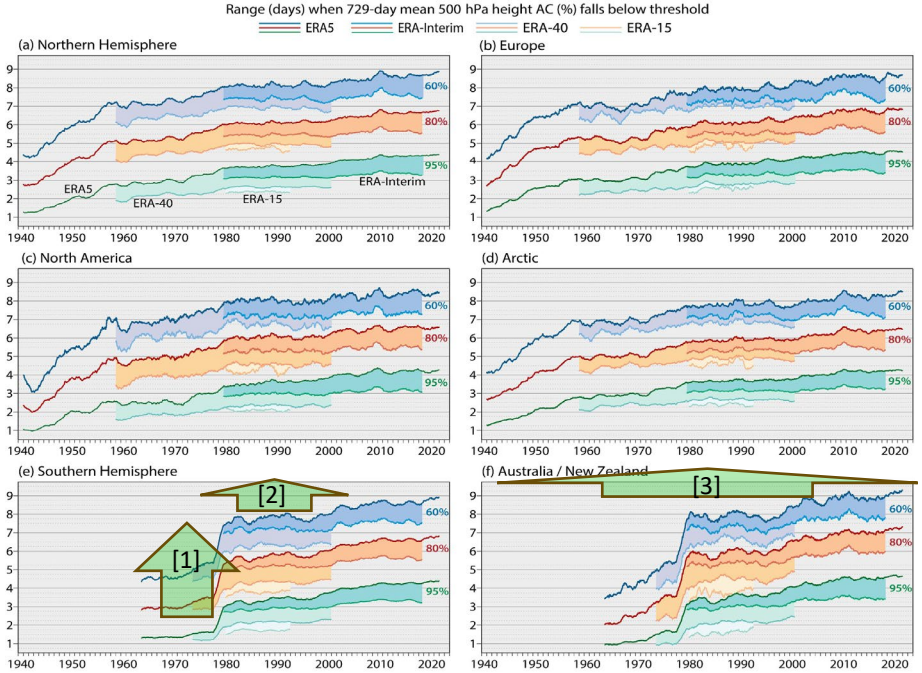
Andrzej Klonecki, Tom Hall, Jon Mittaz, Jerôme Vidot, Jean-Marie Lalande & collegues from Spascia, University of Reading, ICARE & Météo-France

Karsten Fennig & Marc Schröder, EUMETSAT-CMSAF, DWD, Offenbach

ECMWF Annual Seminar 2026

Motivation

Re-forecast skill of ERA5 & previous ECMWF reanalyses



From Soci *et al*, 2024

For more details on ERA5:
- Hersbach *et al*, QJ, 2020
- Bell *et al*, QJ, 2021
- Soci *et al*, QJ, 2024

Aim is to improve reanalysis quality by exploiting observations never before assimilated, or assimilating reprocessed versions of observational data already used:

[1] exploit early satellite observations from the late 1960s & through the 1970s (early satellite, data-sparse, era)

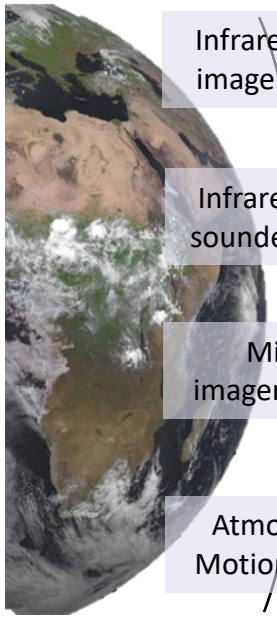
[2] exploit additional satellite observations in *early modern era (~ 1979 - 2000)*, when we have TOVS (MSU / HIRS / SSU)

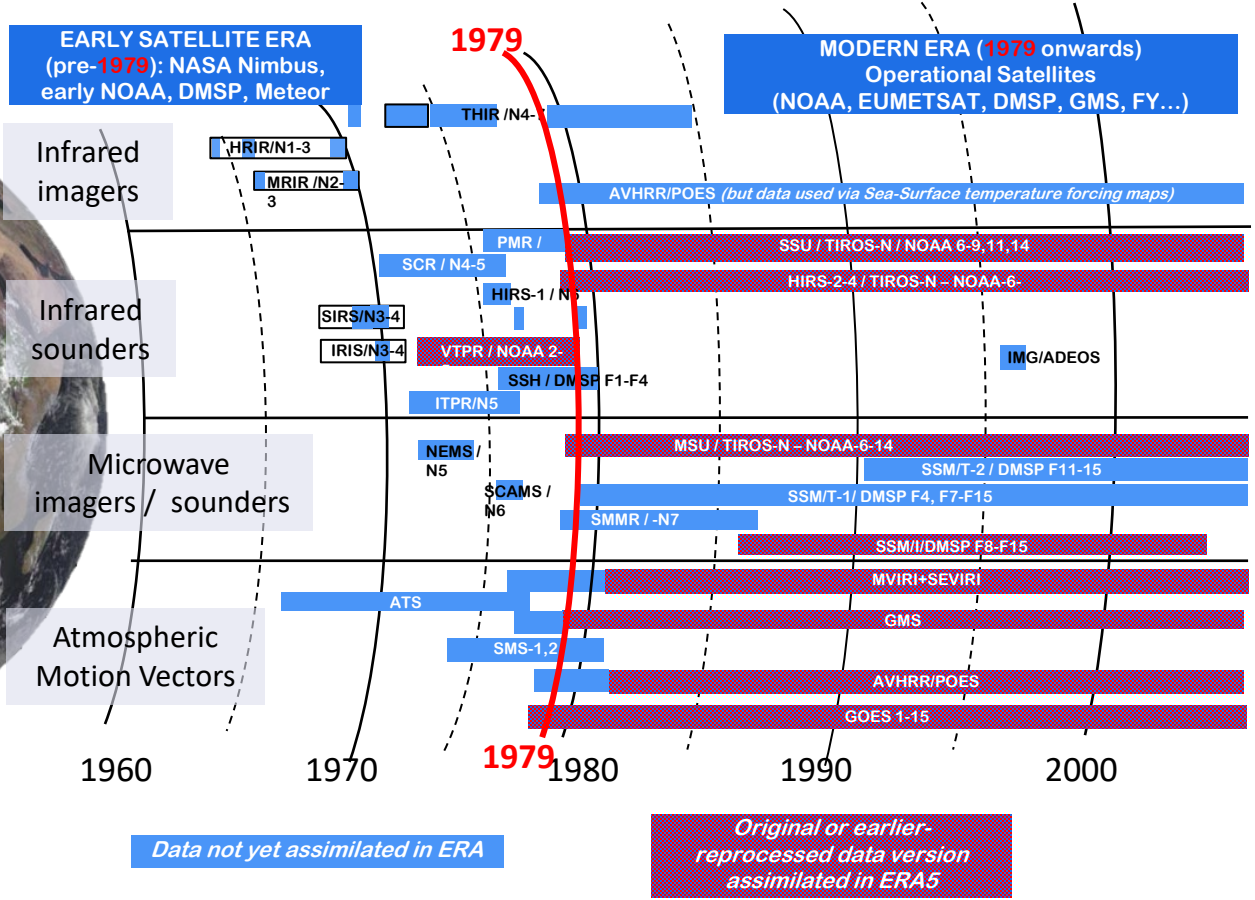
[3] Recover & exploit rescued conventional observations throughout the reanalysis period

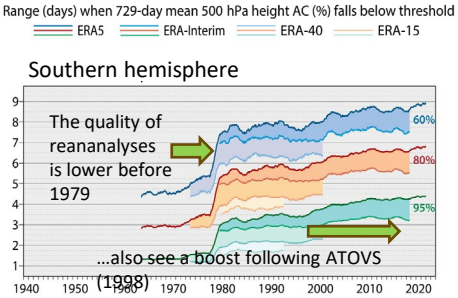
Overview

- **The Early Satellite era (1969 – 1979)**
  - NASA's Nimbus program
  - Hierarchy of Aims: ' *curation* ' → ' *validation* ' → ' *assimilate*'
  - **Nimbus** - IRIS / SIRS / SCR / NEMS / SCAMS / SMMR & **NOAA** - VTPR
- **The Early Modern era (1977 - 2005)**
  - **DMSP**: SSH / SSM/T-1 / SSM/T-2 & **MFG** MVIRI
- **Conventional Observations**
- **Future Work** (PMR & SSMIS, MLS & early limb sounders, ASRs & Geo-ring)
- **Summary & Conclusions**

Rescued and reprocessed satellite data for ERA6







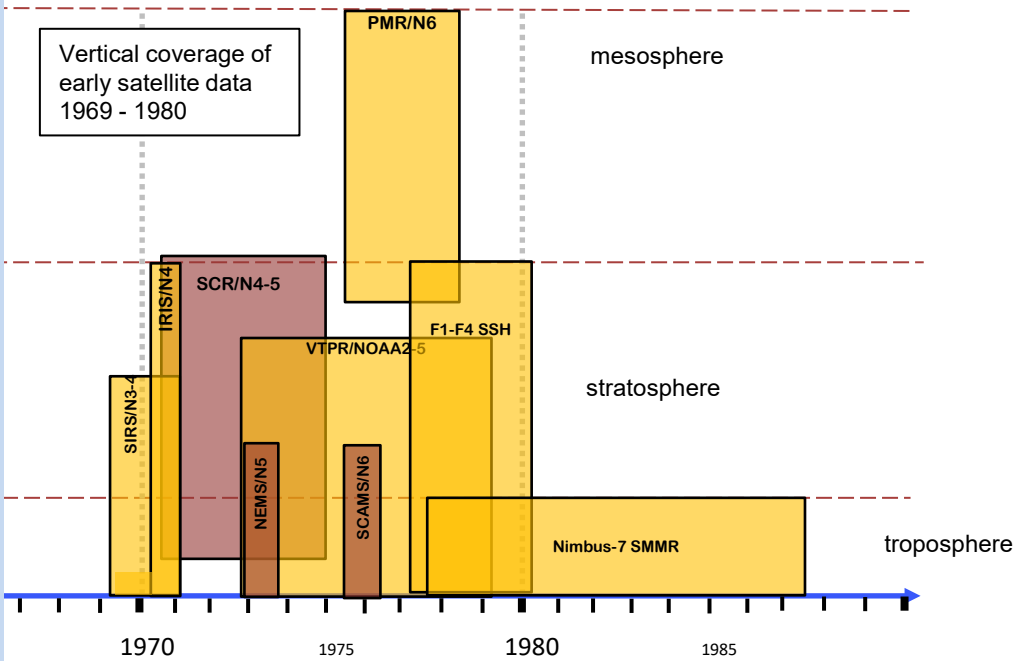
In preparation for ERA6 significant efforts have been made by ECMWF / EUMETSAT / Spascia:

- To recover, assess and prepare early (pre-1979) satellite data, and;
- To reprocess operational mission data from the post-1979 era

All of these datasets bring new information to the ERA6 reanalysis & will be available for **all future C3S reanalyses**

Temporal coverage and vertical sensitivity of the data from early satellites

- **Nimbus-4 IRIS**: demonstration of analysis benefits & validation of model error forcing in 1970
- **SIRS-A & -B** extends the sounding era back to April 1969
- **SCR** bridges the gap between IRIS & SIRS (April 1969 - April 1971) & VTPR (November 1972)
- **Re-navigated VTPR** significantly improves impact 1972-1979
- **NEMS & SCAMS** - the first microwave sounding missions
- **SSH** - IR & FIR sounding of temperature & humidity
- **SMMR** – First microwave imaging mission – extends SSM/I record back to 1978
- **PMR** - validation of reanalysis performance in upper stratosphere and lower mesosphere (TBC !)



Andrzej Klonecki & colleagues, Spascia
Jörg Schulz & colleagues, EUMETSAT

Climate Change Service

HOME ABOUT INSTRUMENTS RESCUED DOCUMENTATION DATA-ACCESS

https://satellite-datarescue.climate.copernicus.eu

Culmination of detailed C3S work 2019-2006 & covers :

- instrument characteristics
- original data characteristics
- rescued / reprocessed data characteristics
- timing errors / geolocation / renavigation
- analysis of O-A wrt ERA5
- bias and noise characteristics, uncertainties
- evaluation of VarBC bias models

Analogous documentation on EUMETSAT's reprocessing (SSM/T-1, SSM/T-2, SSH, SMMR …) available from EUMETSAT & CMSAF



NASA's Nimbus Series (1 – 7, 1964 - 1978)

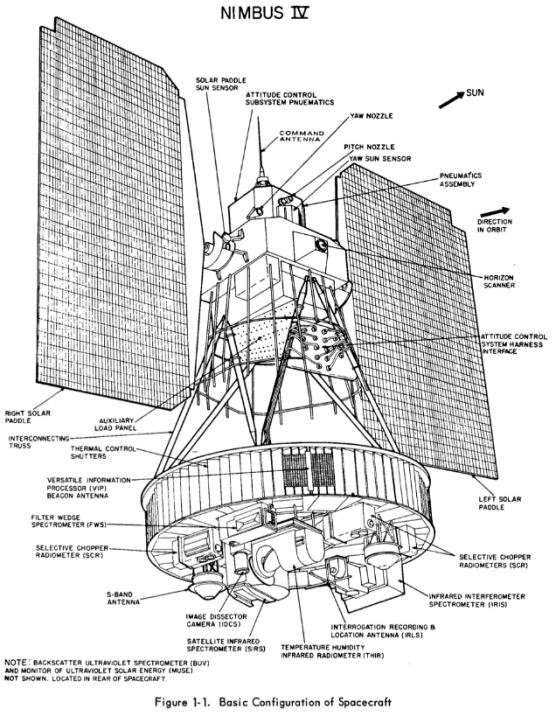


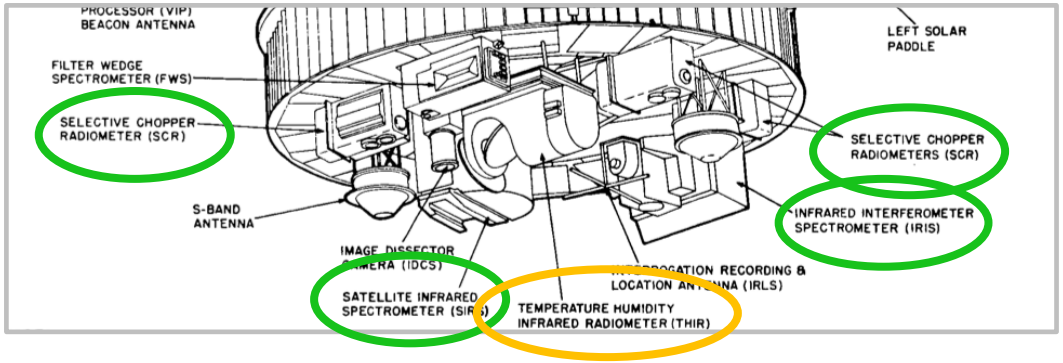
Figure 1-1. Basic Configuration of Spacecraft

Aimed to prototype and evaluate remote sensing technologies for operational weather forecasting, *e.g.* in the IR :

multi-spectral SIRS ⇩ SSH / HIRS

/ **hyperspectral** / IRIS ⇩ IASI / CRIS / IASI-NG / MTG-IRS ….

selective-filtering & pressure modulation SCR & PMR ⇩ SSU



The Incredible Nimbus Program

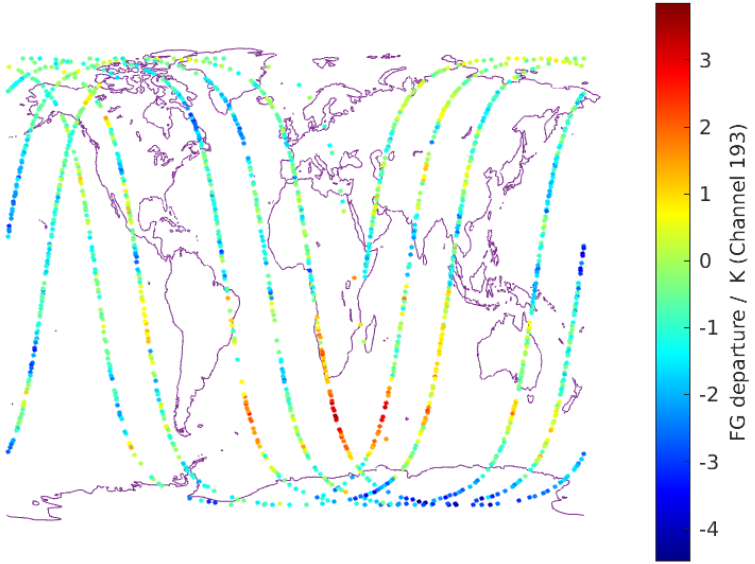
The first Nimbus contract, for the controls subsystem, was placed in October 1960; the final major contractor, for integration and testing, was selected in February 1961.

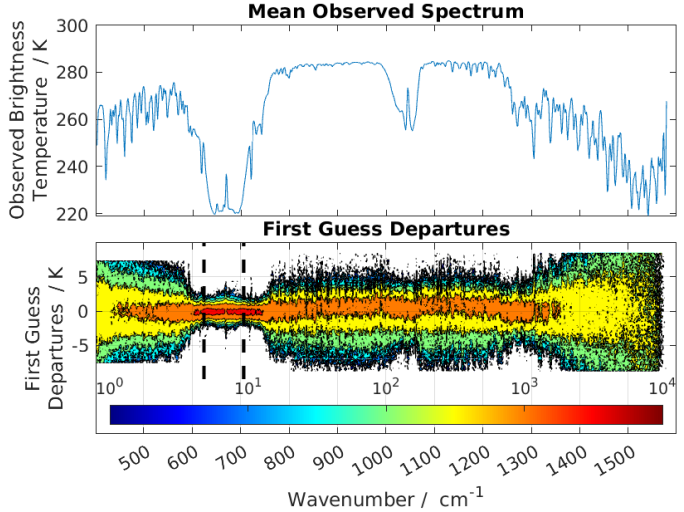
During a 6-month period, the GSFC group prepared specifications for some fifteen subsystems, put them out for bid, evaluated the responses, and put the contractors to work. Some of these specifications were good, some were poor; some of our contractors were good, others were poor; some of the GSFC technical management was good, some was poor.

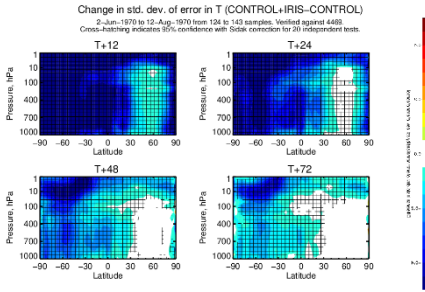
W.G. Stroud
Proceedings of the Nimbus Program Review
November 14-16, 1962

Assimilating Nimbus-4 IRIS Observations

Typical 12 hour coverage







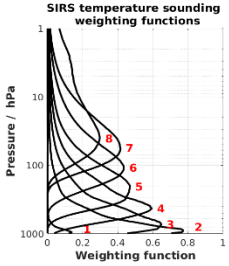
FTS-based hyperspectral IR sounder on Nimbus-4 • Apr 1970–Jan 1971 • 36 years before IASI
Resolution: 2.53–2.69 cm^{-1} • 94 km footprint
Identified southern-polar biases up to 20 K; tested WC 4D-Var model-error forcing.
Further reading: Poli & Brunel (2018); W. Bell seminar (2023); ECMWF newsletter article.

Significant improvements

Southern Hemisphere and stratosphere

Better fits to radiosonde temperature and winds (~5%) and surface pressure observations (7%)

Extending the satellite sounding record back to 1969 : Assimilating data from the *Satellite Infrared Spectrometer* (SIRS)



Vertical coverage of early satellite data 1969 - 1980

PMR/N6

SCR/N4-5

IRIS/N4

SIRS/N3-4

VTPR/NOAA2-5

NEMS/N5

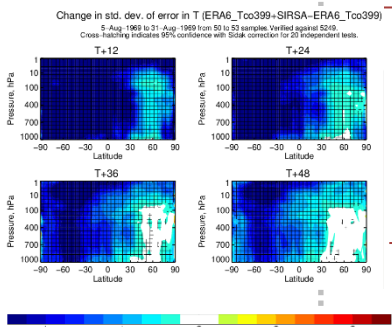
SCAMS/N6

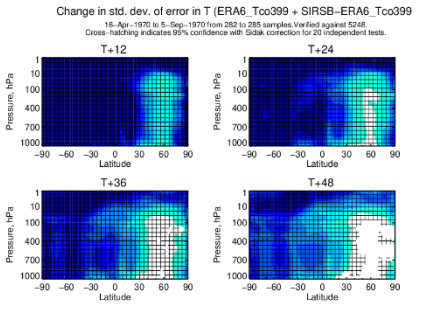
mesosphere

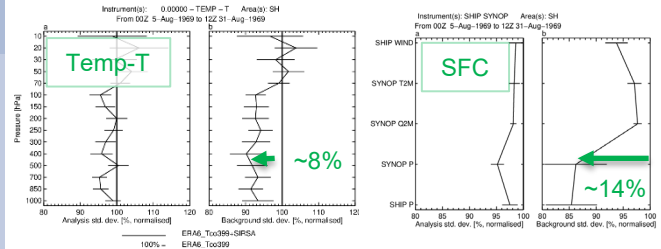
stratosphere

troposphere

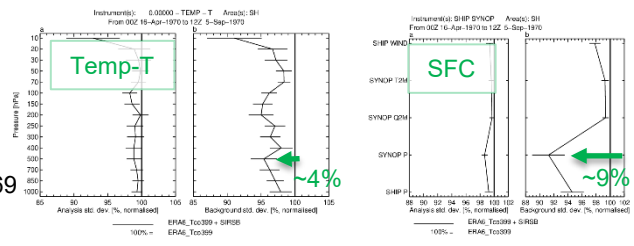
1970 1975 1980







- **VTPR** assimilated in ERA5 (& ERA6) 72-79
- **SIRS** extends the sounding record back to April 1969
- If **SCR** can be used
  → continuous sounding observations from 1969



The assimilation of observations for the Vertical Temperature Profiling Radiometer (VTPR) in **ERA5**

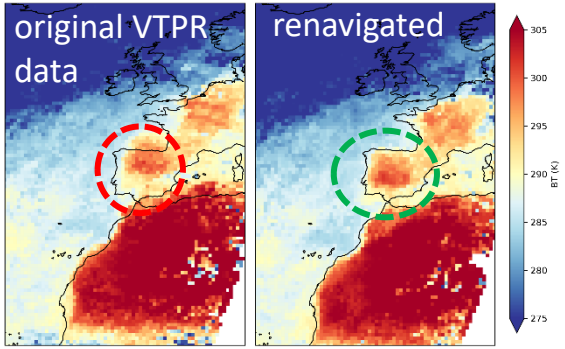
ERA5 background fits to surface pressure observations. Southern Hemisphere.



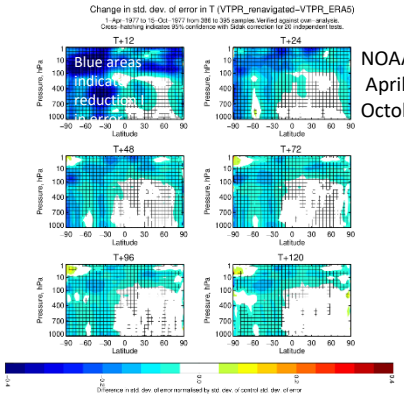
- Multi-spectral IR sounder carried on NOAA -2 / -3 / -4 & -5: Nov 1972 – Feb 1979
- Assimilated in ERA-40 – based on earlier reprocessing / rescue efforts
- Relatively small biases (~1K) and STDEV(fg_deps) ~0.5K
- Improved re-forecasts & background fits to independent observations

Reprocessed VTPR data for ERA6

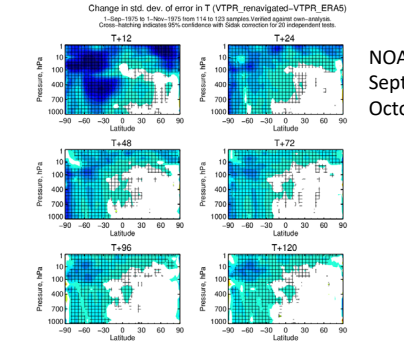
Renavigated VTPR data
(1972-1979)



Channel 8 (window channel) observations

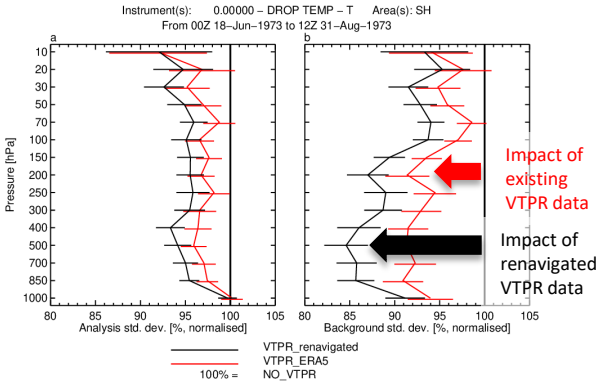


NOAA-5 VTPR
April –
October 1977



NOAA-4 VTPR
September –
October 1975

NOAA-2 VTPR test
June - August 1973
Background and analysis fits to radiosonde temperatures



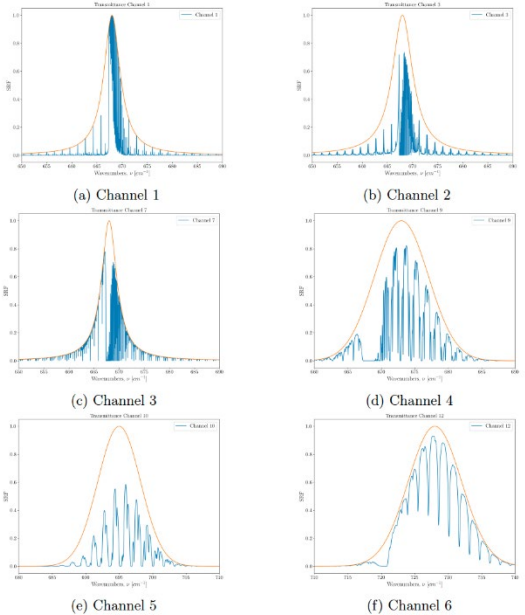
New data doubles the impact of assimilating VTPR observations from 1972 to 1979

- Original VTPR data was found to exhibit large geolocation errors. Typically 200km – as large as 400km
- Traced to a timing error in the original data
- Timing error rectified and the observations re-navigated
- Impact of assimilating the VTPR observations doubled

Tom Hall,
Spascia

The Selective Chopper Radiometer (SCR) on Nimbus-4 & Nimbus-5: bridging the gap between Nimbus-4 IRIS & SIRS & NOAA VTPR technical & scientific challenges

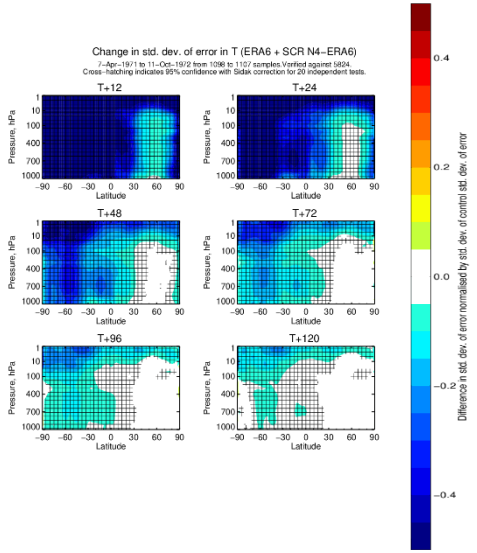
- Nimbus- & Nimbus-5 SCR were quite different instruments in terms of spectral response functions / channel sets
- → Challenge to develop a common path through IFS (*e.g.* cloud detection)



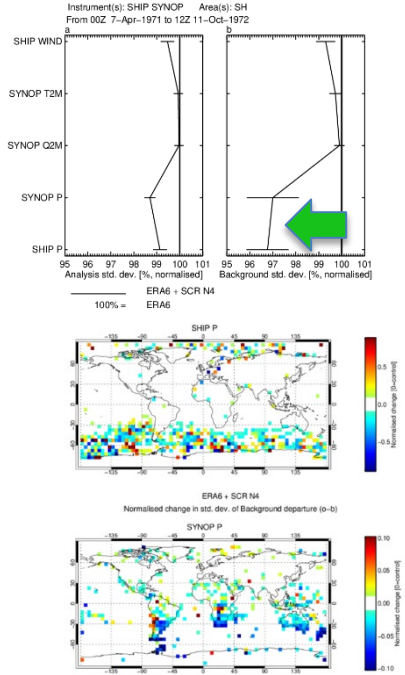
Tom Hall, Spascia & Jean-Marie Lalande, Météo-France

- Calculating the SRFs more complex than for multi-spectral instruments – comprising components associated with: (1) interference filters, and; (2) the cell transmission.
- Literature gave conflicting values for key cell parameters

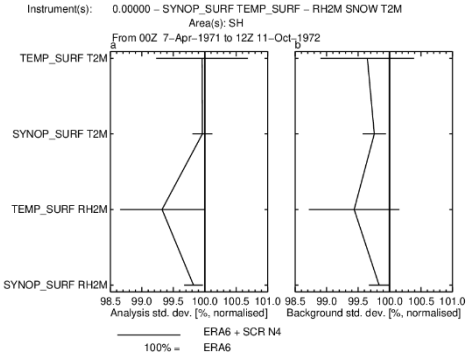
Nimbus-4 SCR April 1971- October 1972 Impacts

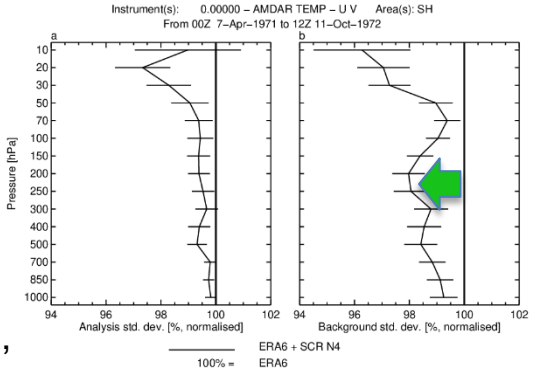


Analysis based verification very positive in SH & stratosphere



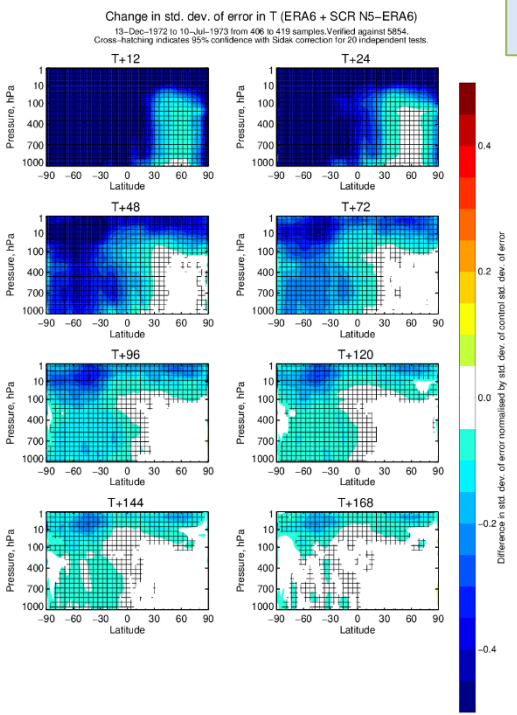
Background fits to surface pressure, T2m & RH2m improved – as expected (SH)



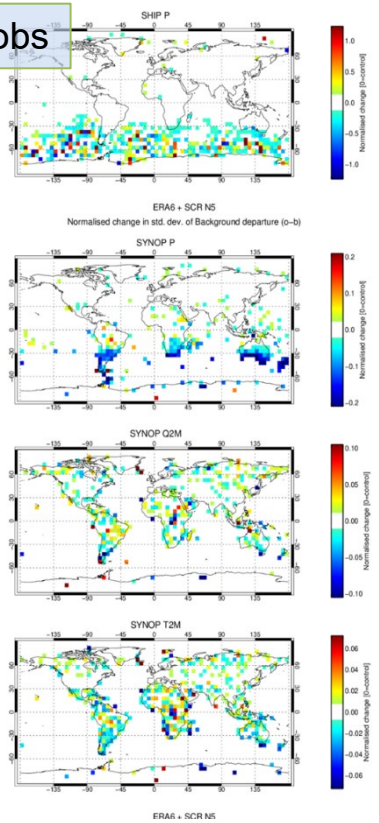


Background fits to upper level wind observations improved

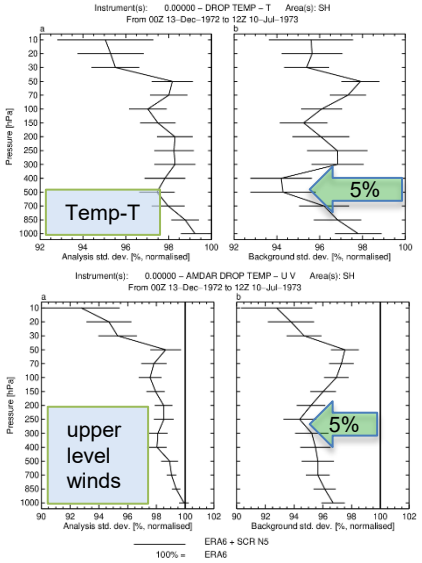
SCR Nimbus-5 impacts: December 1972 - July 1973



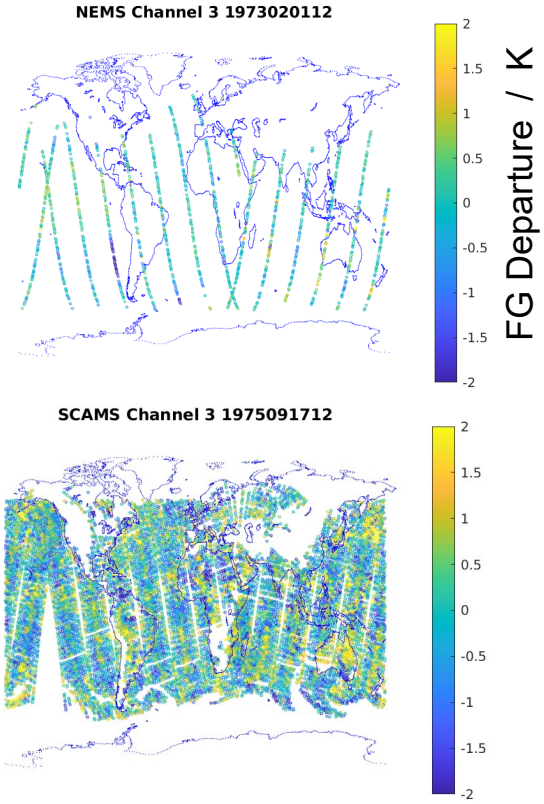
Surface obs



- Similarly positive impacts from Nimbus-5 SCR in 1973
- Improved analysis-based verification &
- Improved background fits to independent observations



The Nimbus-E Microwave Spectrometer (NEMS) on Nimbus-5 & The Scanning Microwave Spectrometer (SCAMS) on Nimbus-6



Assimilated using MW All-Sky path in IFS

Obs errors per channel ~ *f*(cloud proxy*)

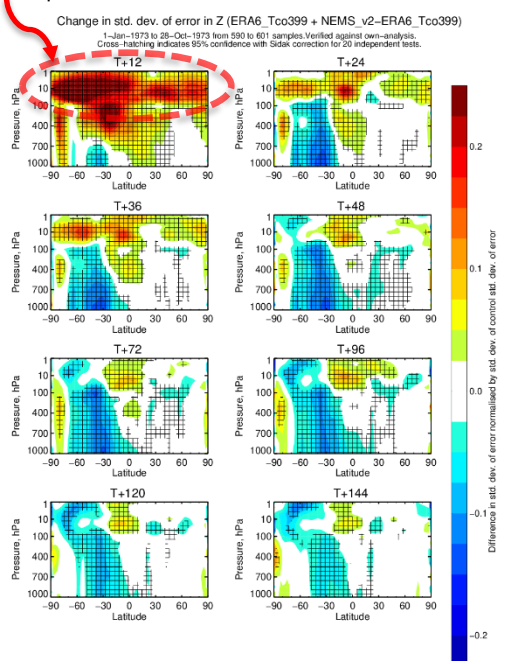
* Based on ch 3

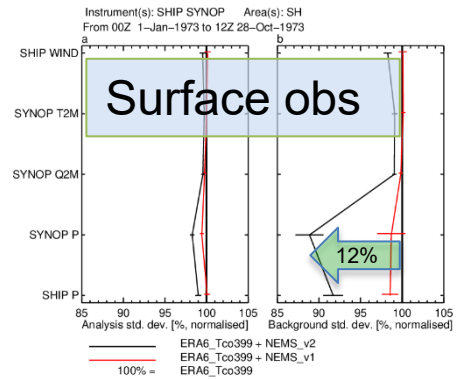
- First MW sounding instruments
- T-sounding (50GHz) channels assimilated in initial experiments

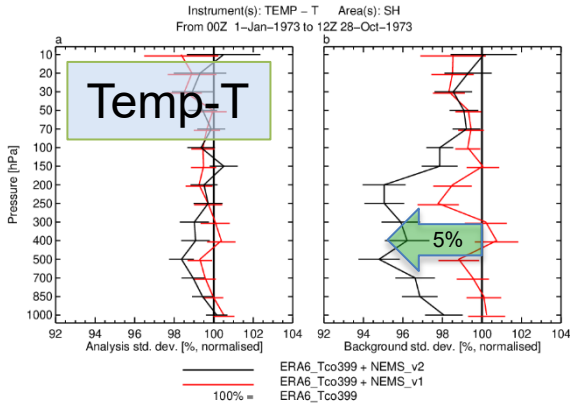
Jon Mittaz,
Tom Hall,
Liam Steele,
Alan Geer

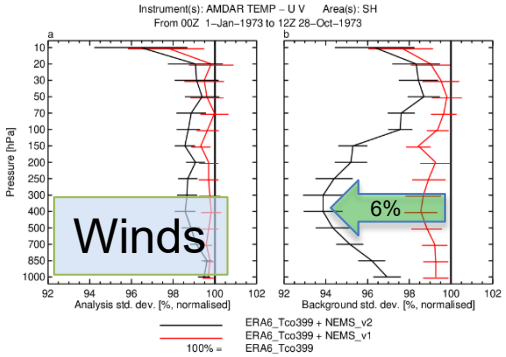
Impact of NEMS (test period 1st Jan 1973 – 28th October 1973)

Artefact if own analysis verification when there are no/few observations in the control experiment









Background fits to surface & upper air temperatures and winds improved

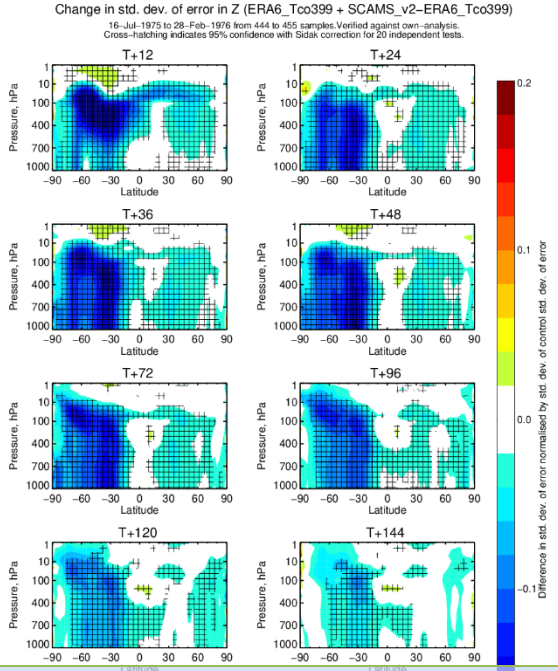
SH & stratosphere improved

Note: VTPR assimilated during this period

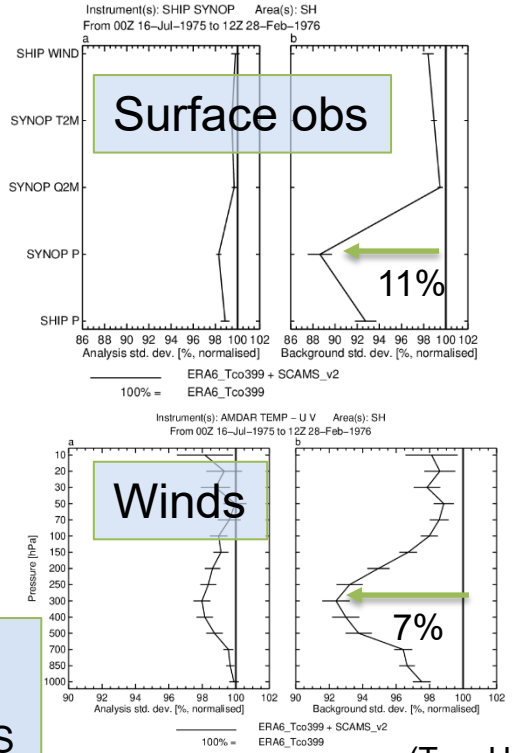
(Jon Mittaz, Liam Steele)

Impact of Assimilating Nimbus-6 SCAMS

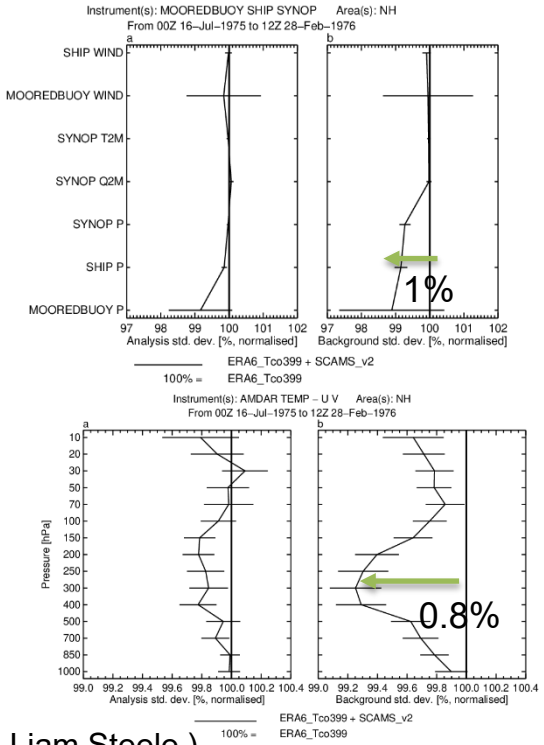
(July 1975 – February 1976)



Southern Hemisphere



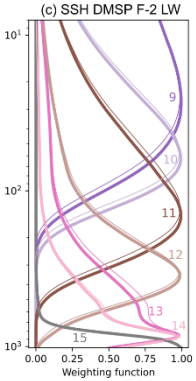
Northern Hemisphere



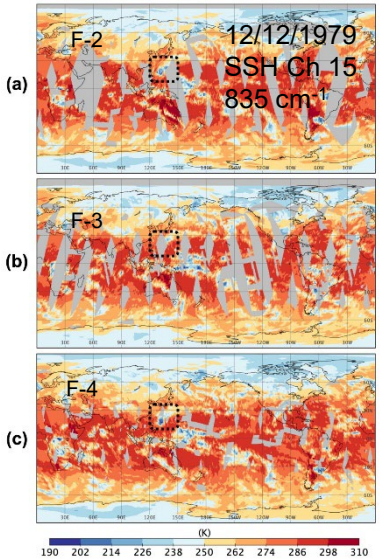
- Significant benefit in SH & NH
- Assimilated in addition to VTPR
- More benefit than obtained from NEMS

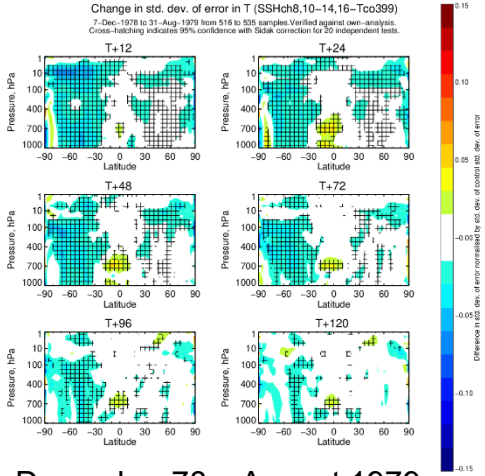
(Tom Hall, Liam Steele)

Special Sensor H (SSH) 1977-1980

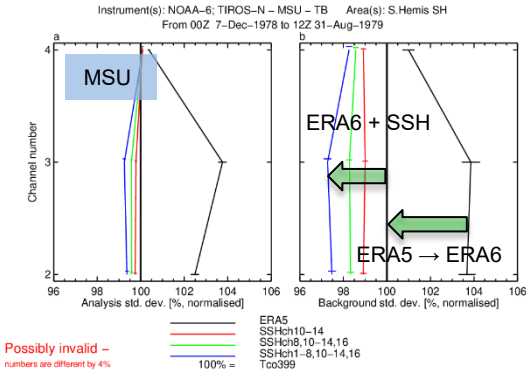


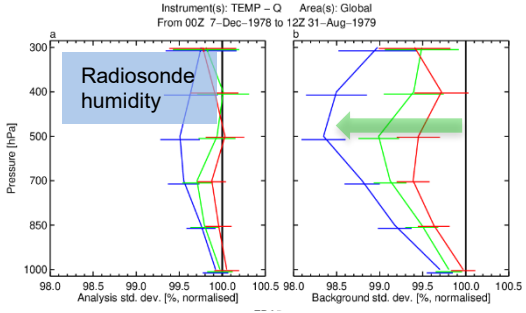
- Cross track multi-spectral IR instrument
- Flown on US DMSP F1-F4 satellites: March 1977 – Feb 1980
- Temperature, humidity and ozone sounding channels
- First use of FIR water vapour channels (1-8) at 19-28 μm





December 78 – August 1979





Paul Poli

The Scanning Multichannel Microwave Radiometer (SMMR)

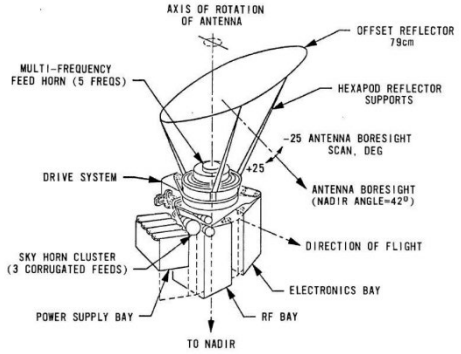
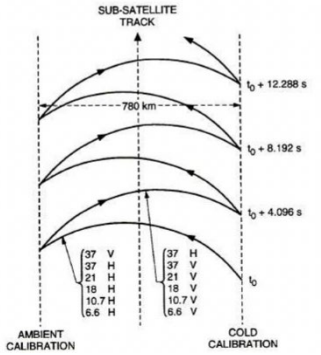
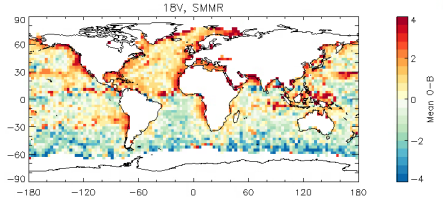


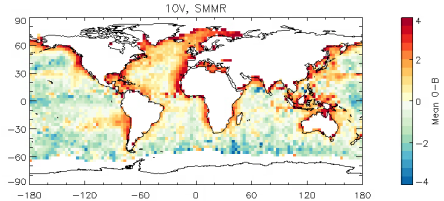
Figure II-2: SMMR Instrument configuration (from Nimbus 7 Users Guide, 1978).



- Conical scanning microwave imager, Nimbus-7 Oct. 1978 – Aug. 1987
- Predecessor of SSM/I / SSM/IS
- Extends MWI observations 8 years
- Dataset produced & provided by EUMETSAT CMSAF @ DWD
- Challenges along the way !

Coverage in 12 hr assimilation window

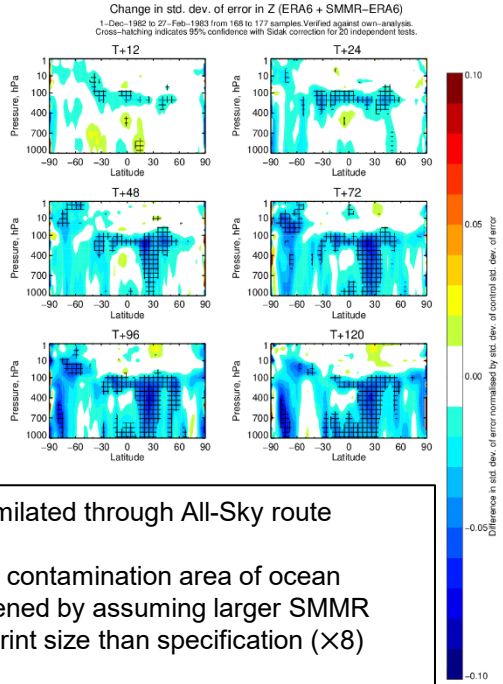




Significant land emission contamination, worse at lower frequencies, extending many 100s km into oceans regions

Karsten Fennig (DWD / CMSAF), Liam Steele & Alan Geer

The Scanning Multichannel Microwave Radiometer (SMMR)



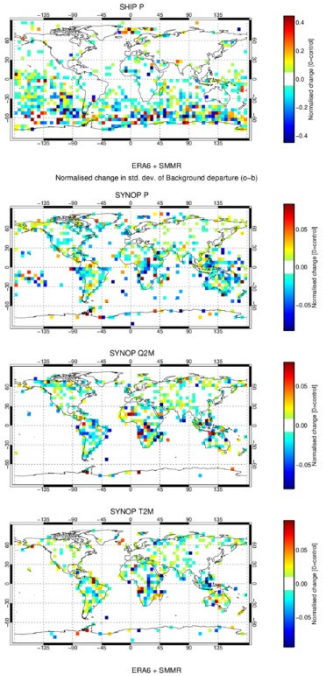
Assimilated through All-Sky route

Land contamination area of ocean screened by assuming larger SMMR footprint size than specification (×8)

Significant improvements in analysis & reforecast quality

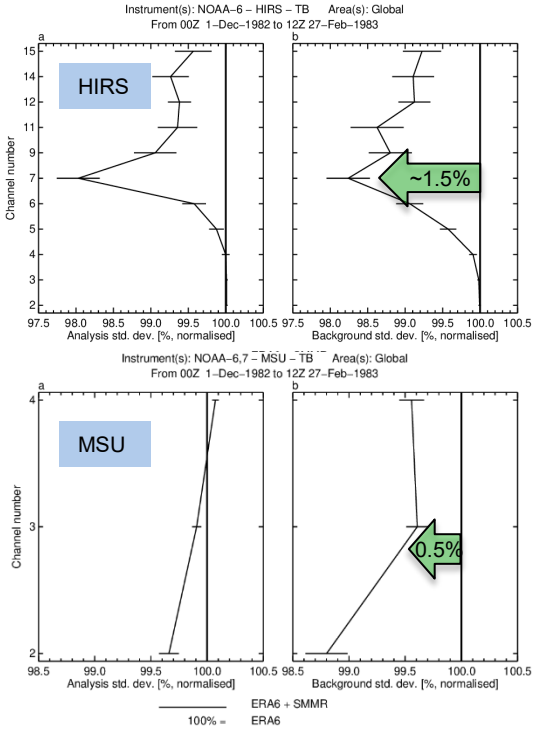
Surface Impacts

Change in background fits to independent surface observations



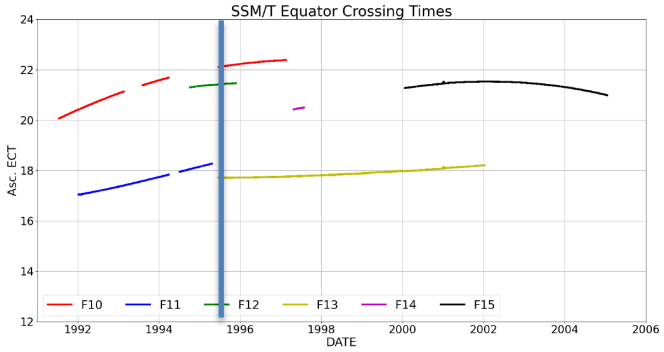
Upper Air Impacts

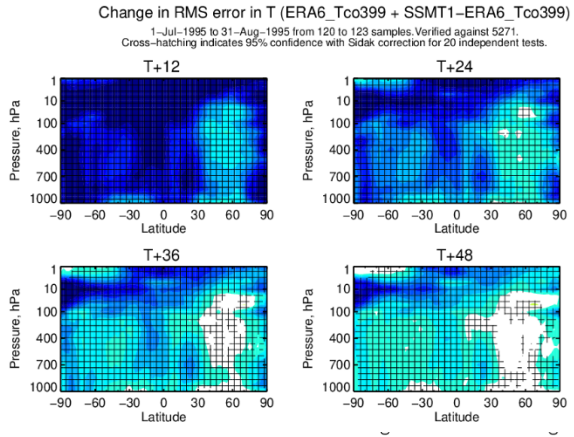
Change in background & analysis fits to independent satellite observations (HIRS & MSU)

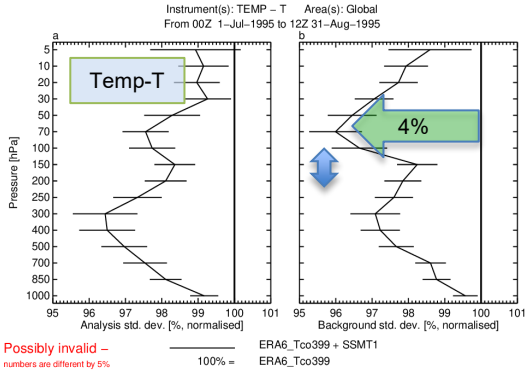


Special Sensor Microwave – Temperature (SSM/T)

- Flown on DMSP-F04, F07-15 (1979-1980, 1984-2020)
- FCDR produced by EUMETSAT for C3S :
  - DMSP F10 – F15
  - July 1991 – January 2005
- Positive impacts from testing in 1991, 1995 (below) and 2000

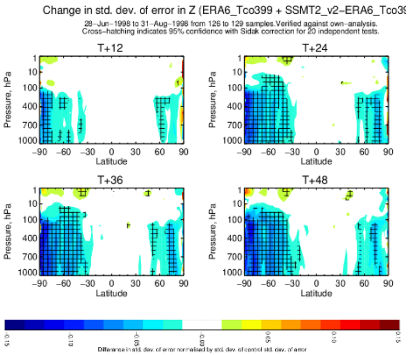




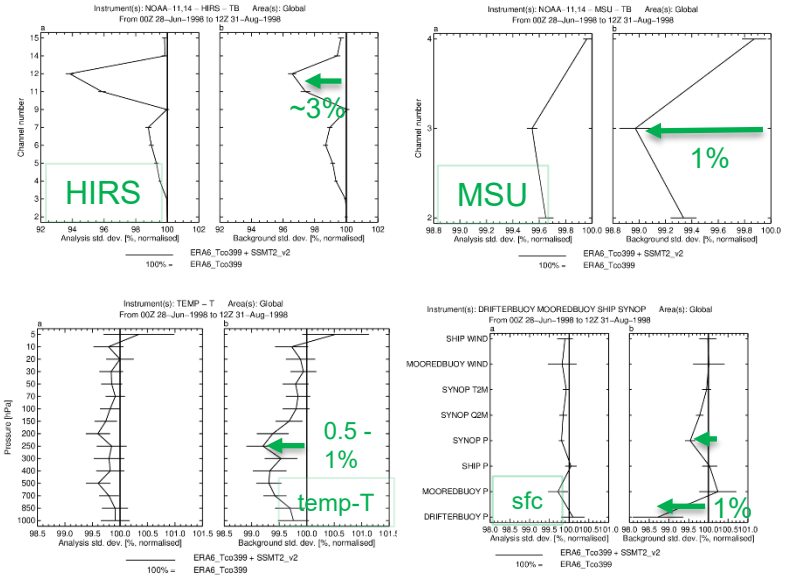


Dinand Schepers,
Dave Duncan & Liam Steele

SSM/T-2 (a microwave humidity sounder)
Tests assimilating F-12 SSM/T-2 data



Background and analysis fits
to independent observations



- ERA5 used AMSU-B 2001 onwards (NOAA-16)
- SSM/T-2 : an ‘MHS / AMSU-B – *like’* humidity sounder
- Data 1994 - 2005 reprocessed by EUMETSAT (4 sats)

- ERA5 assimilated AMSU-B data from 2001 (N-16)
  → SSM/T-2 (& NOAA-15 AMSU-B) extends ERA6
- Assimilated through all-sky route
- 2-month experiment shown here

In-situ observation records

- Scattered across hundreds (thousands?) of institutions, world-wide
- Structured approach, for a comprehensive & global solution, under the umbrella of GCOS

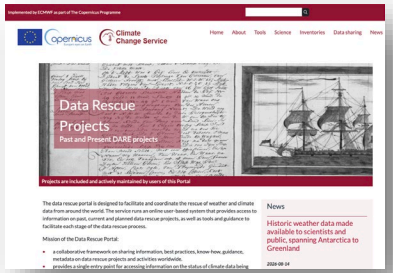
01

Data rescue

Authenticity

Grounding

Ownership



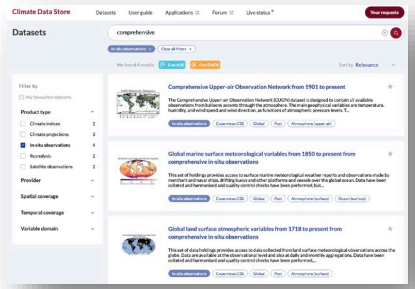
02

Data repositories

Provenance, credits

Consistency, e.g. physical units

Data license



03

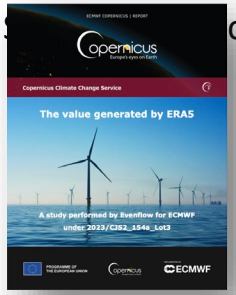
Reanalysis

Assimilation, with feedback

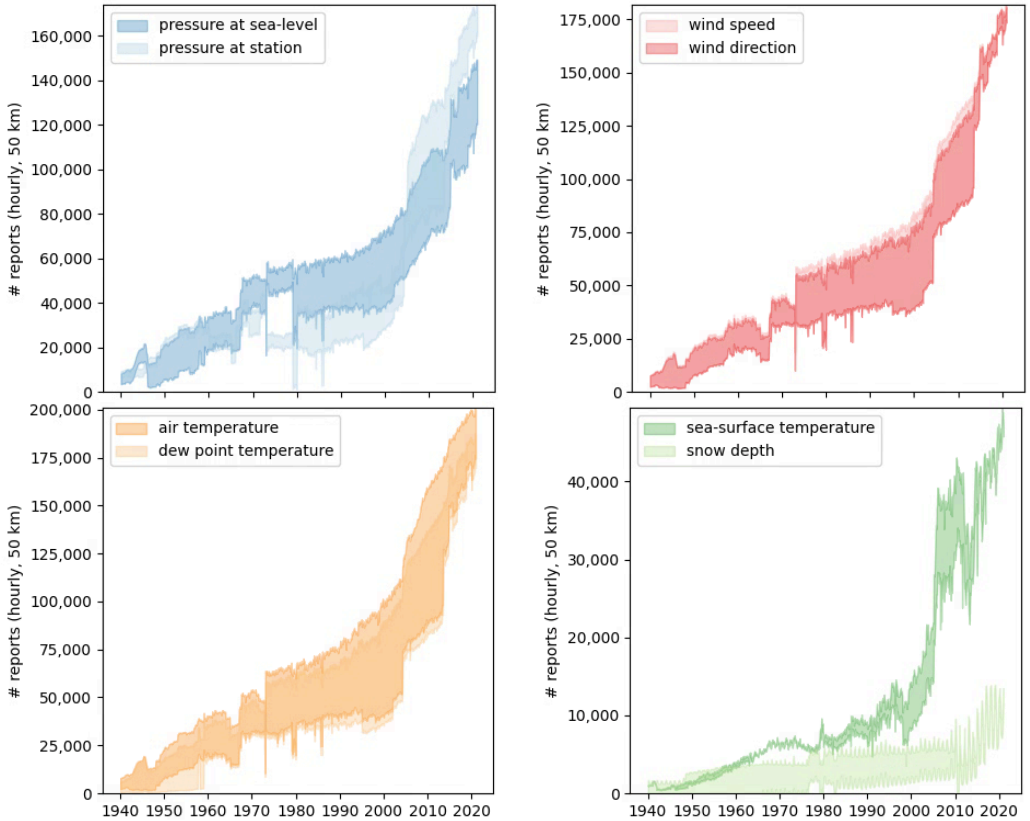
Visibility

Applications

c benefits



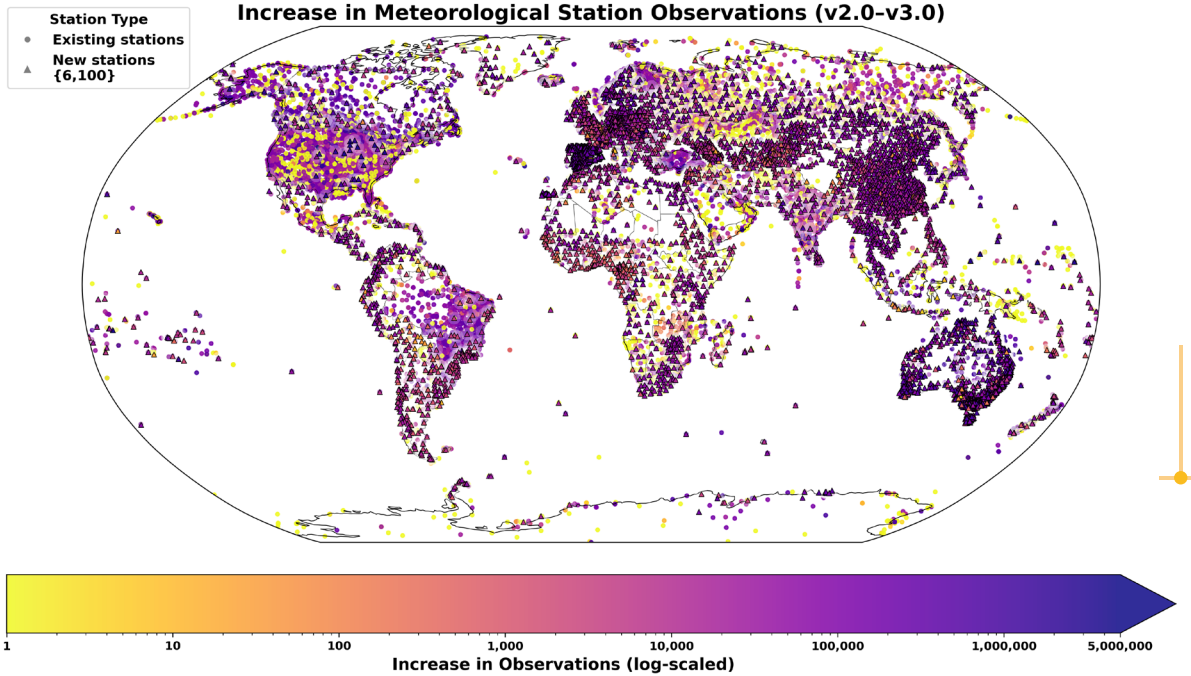
In-situ observations: Additional reports in ERA6, as compared to ERA5



- Bottom curves show **numbers of reports available to ERA5, at hourly, 50-km equal-area grid resolution**.
- Top curves show **numbers of reports available to ERA6**.
- Shading shows the additional reports, between +50% to more than doubling, for key variables.
- Final counts of data used will only be known after ERA6 is produced!

(Paul Poli)

Advances between *two successive versions* of the surface-land comprehensive data holdings



Ingestion timeline

11 March 2026
✅ V3.0.0 received

27 April 2026
✅ BUFR conversion

Now...
⏳ Pre-production screening

23 March 2026
✅ Obs. repository

28 May 2026
✅ CDS publication

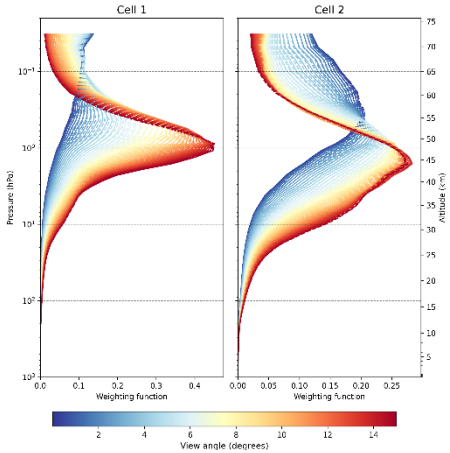
ERA6 (ongoing) production streams use the former version; Later streams (prior ~2006) will use the latter (more complete) version

Future Work :
Improved representation of the stratosphere in future reanalyses

channels 19-24 never assimilated in ECMWF NWP - due to biases & RT challenges

- Assimilate UAS channels from SSMIS 2003 – 2025
- Use weak constraint 4D-Var to determine model error in stratosphere/mesosphere
- Train neural net to estimate state dependent model error forcing
- Apply in early epochs & evaluate performance of the analysis using Nimbus-6 Pressure Modulator Radiometer (PMR)
- In addition - evaluate PMR for active assimilation in ERA6

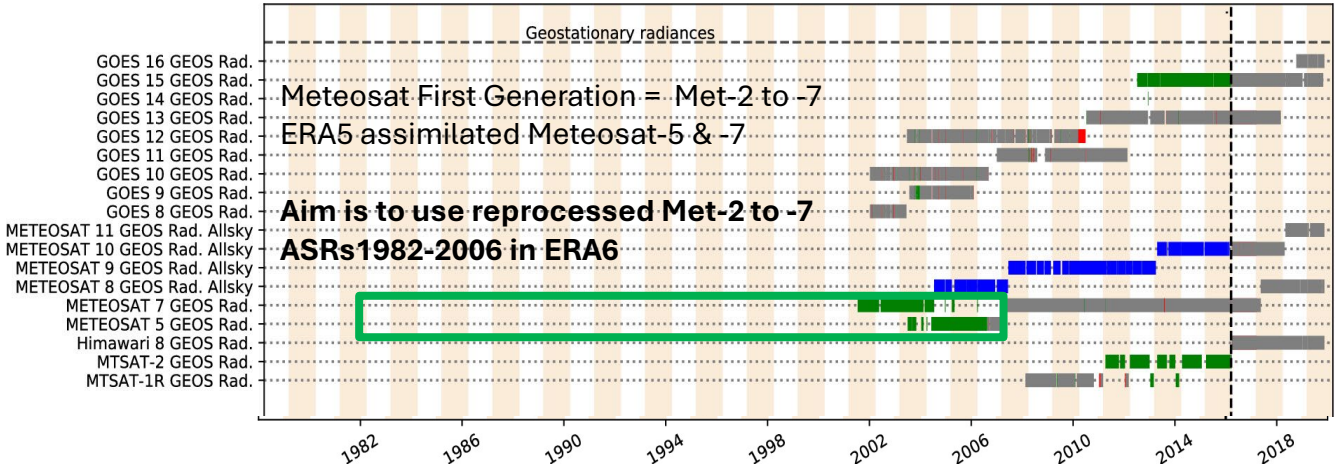
- Nimbus-6 (197X-197Y) Pressure Modulator Radiometer
- scans along track
- employs low pressure CO_2 cells and Doppler scanning
- to produce multi-spectral (188 channels) IR observations



- Analogous approach for water vapour (Aura & UARS MLS WV retrievals in modern era, early limb sounding data in 1970s)

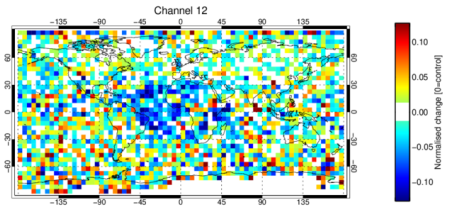
Roger Huckle & Timo Hanschmann (EUMETSAT)
Tom Hall (Spascia) &
Jean-Marie Lalande (Météo-France CNRM)

Future Work : Assessing Meteosat First Generation All-Sky Radiances for ERA6 (1987-2006)



Initial experiments assimilating Meteosat-2 ASRs in 1982

→ improved background fits for HIRS WV channel (Ch 12)



- The aim is to improve humidity analyses in the Meteosat disk (normally centred on 0°)
- The geo IR radiances present some challenges compared to IR radiances from polar orbiters, *e.g.*:
  - No onboard calibration for Meteosat-2 to -6 MVIRI
  - EUM Calibration is achieved through matchups with HIRS
  - EUMETSAT reprocessing involved a large effort to detect & correct anomalies in the IR & WV channels
  - First steps towards exploiting observations (visible & IR) from the *Geo-Ring* initiative

Summary and concluding remarks

- **Satellite Data Rescue** involves more than simply reformatting, documenting & gross error checking. It involves refining RT modeling, renavigating, investigating bias & noise characteristics over mission lifetimes, partitioning biases between model, the observation operator and instrument, assessing bias models, establishing uncertainties in observations, …

- **Impacts.** After several years of work (by C3S partners – EUMETSAT, Spascia & partners & ECMWF) we're confident most of the relevant Nimbus observations (1969-1987) and early DMSP mission data (1977-2005) will be assimilated in ERA6. Based on testing to date the impacts of this data are already overwhelmingly positive. Further optimization may yield further benefits in ERA6 (1967-1986 streams due to start Q2 2027).

- **Enhanced IFS capability.** 10 new instruments tested, across 22 satellites (not counting reprocessed data from > 40 satellites)

- **Conventional Observations.** Similar C3S coordinated activities mean the number of observations assimilated in ERA6 will be significantly higher in ERA6 (cf ERA5). 3 Billion new observations !

- **These observations will be assimilated in future generations of reanalysis (whatever form that may take!)**

- **Future Work.** Building on ongoing developments (*e.g.* temperature & humidity assimilation in the stratosphere & mesosphere, the assimilation of visible radiances / Geo-Ring initiatives, ML-based Earth System Reanalyses, …) the requirement for data rescue activities will remain, and can build on a healthy eco-system of expert partners, supported in the first two phases of Copernicus.

ECMWF

Thanks for your time !

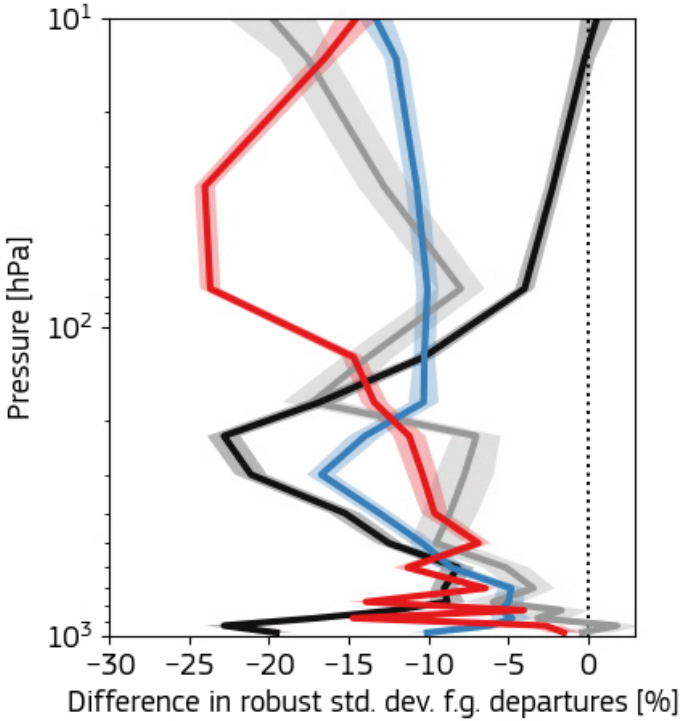
Extra Slides

What difference do the rescued/reprocessed in-situ obs. make?

Impact of rescued/reprocessed in-situ obs. in ERA6 system (red), and successive improvements between ERA generations:

6 ↑ 5 ↑ 4 ↑ 3

- From GTS to In-Situ obs. for ERA6 (2006)
- From ERA5 to Pre-ERA6 (2020)
- From ERA-Interim to ERA5 (2006)
- From ERA-40 to ERA-Interim (2000)



Each pair of experiments:

- Radiosonde temperature observations assimilated
- 15 July to 15 August
- Year indicated in legend

Blue: "Pre-ERA6" is the **second** pre-ERA6 prototype test dataset (https://doi.org/10.21957/1qyd-ep25)

Red: Last pair of experiments is at standard IFS "research" resolution (Tco399)