Exploiting cloud-affected hyperspectral geostationary radiances

Alan Geer

Thanks to: Marco Matricardi, Stefano Migliorini, Massimo Bonavita, Philippe Chambon, Katrin Lonitz, Cristina Lupu

ECMWF

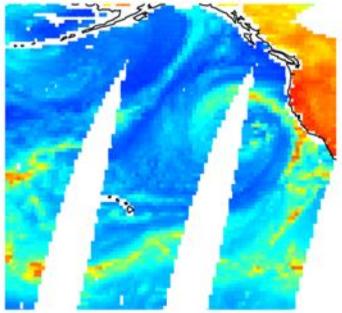
Overview

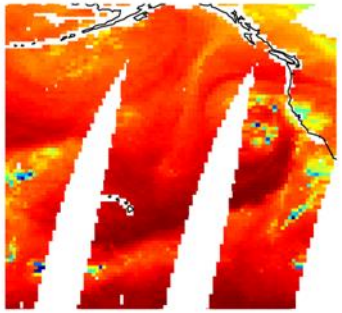
- All-sky assimilation of WV-sensitive microwave radiances
  - Currently supplying around 20% of all forecast impact in the ECMWF operational system
  - Tropical cyclone analysis
  - Benefits of higher temporal frequency (SAPHIR)
  - Prospects for geo-mw?
- All-sky infrared developments
- What can geostationary hyperspectral provide for cloud and precipitation assimilation?

Current benefit of all-sky microwave observations

Sensitivities and current sources of all-sky microwave data

- Imager channels (19 – 90 GHz):
  - Instruments: SSMIS, GMI, AMSR2
  - Total column water vapour
  - Rain and liquid water cloud, particularly at lower frequencies
  - (Large frozen particles (snow, graupel, hail) at higher frequencies)
- WV sounding channels (around 183 GHz)
  - Instruments: SSMIS (F-17, F-18); MHS (Metop-A,B, NOAA-18,19), SAPHIR, MWHS-2
  - Water vapour in the mid to upper-troposphere
  - Scattering from large frozen particles (snow, graupel, hail)
  - Ice cloud
- 118 GHz temperature/cloud channels (a developing capability)
  - Instruments: MWHS-2
  - Cloud, particularly over land?

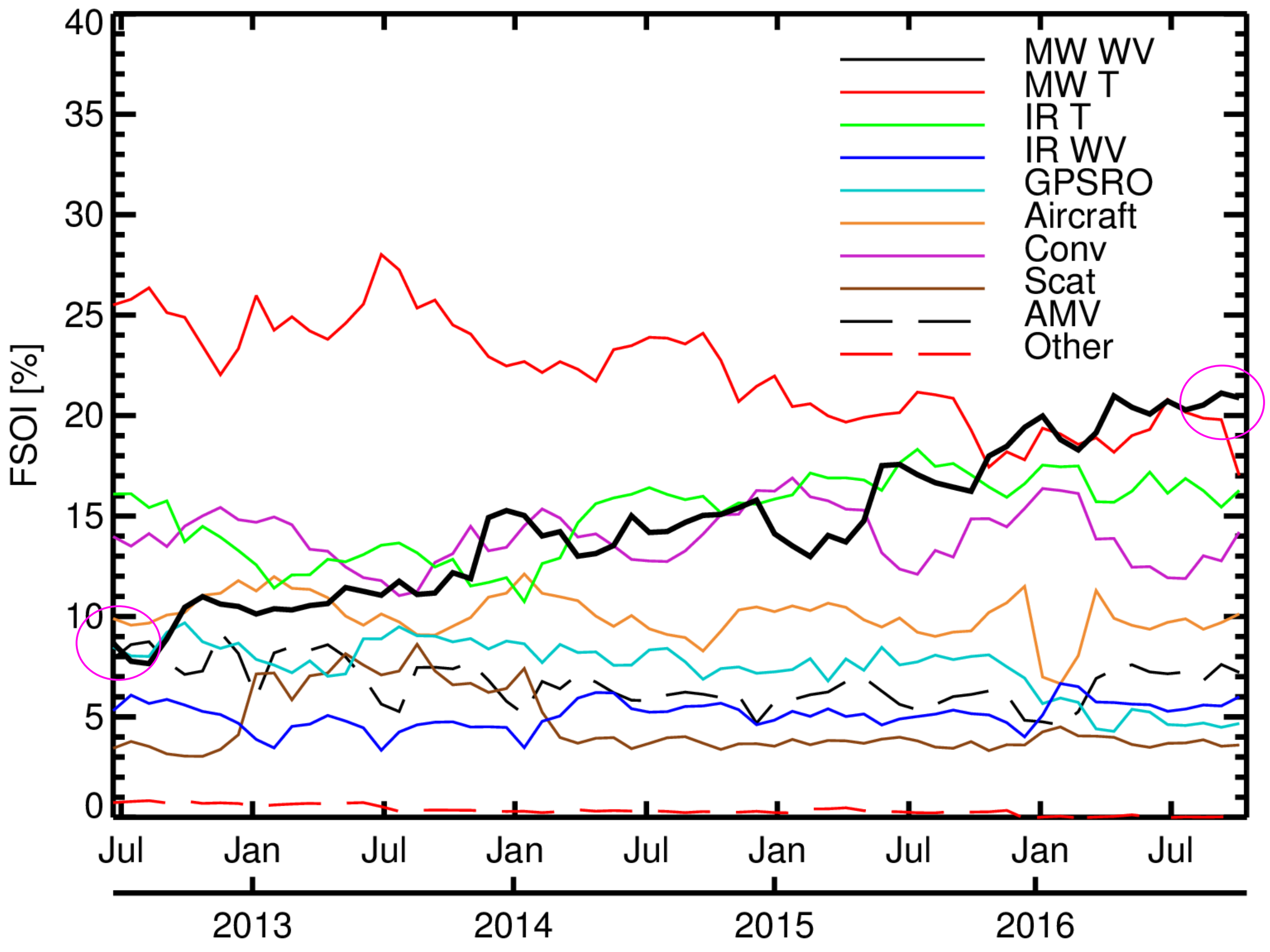




Forecast sensitivity (FSOI) of major observing systems in ECMWF operations

Summer 2006
(from Cardinali, 2009)

Microwave WV	6.2 %
Microwave T	35.5 %
Infrared T&WV	28.0 %



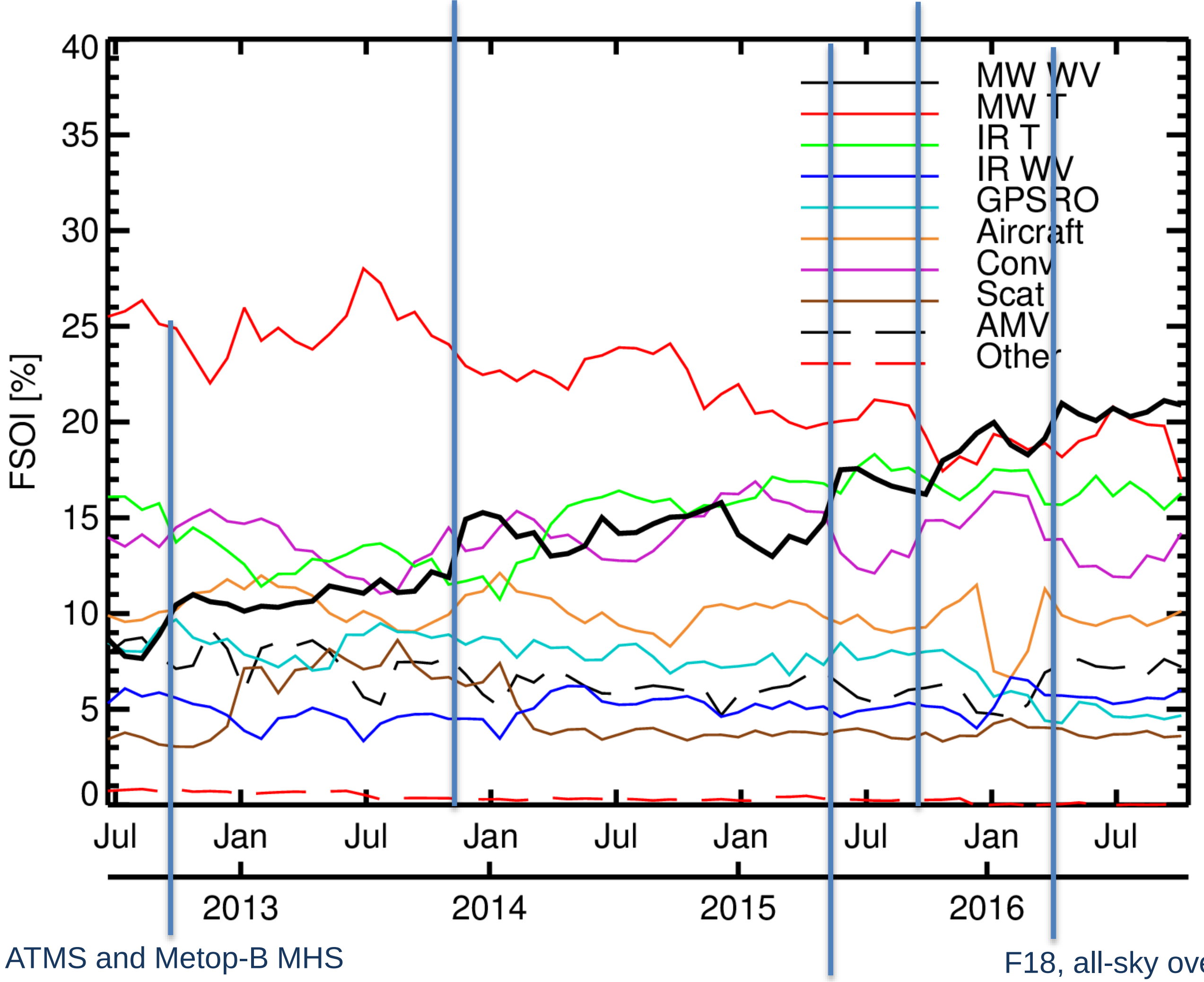
August 2016

Microwave WV	20.4%
Microwave T	20.1 %
Infrared T	16.5 %
Infrared WV	5.4 %

What's happened recently?

All-sky assimilation of humidity sounding channels on SSMIS

GMI and AMSR-2 added in all-sky



ATMS and Metop-B MHS added in clear skies

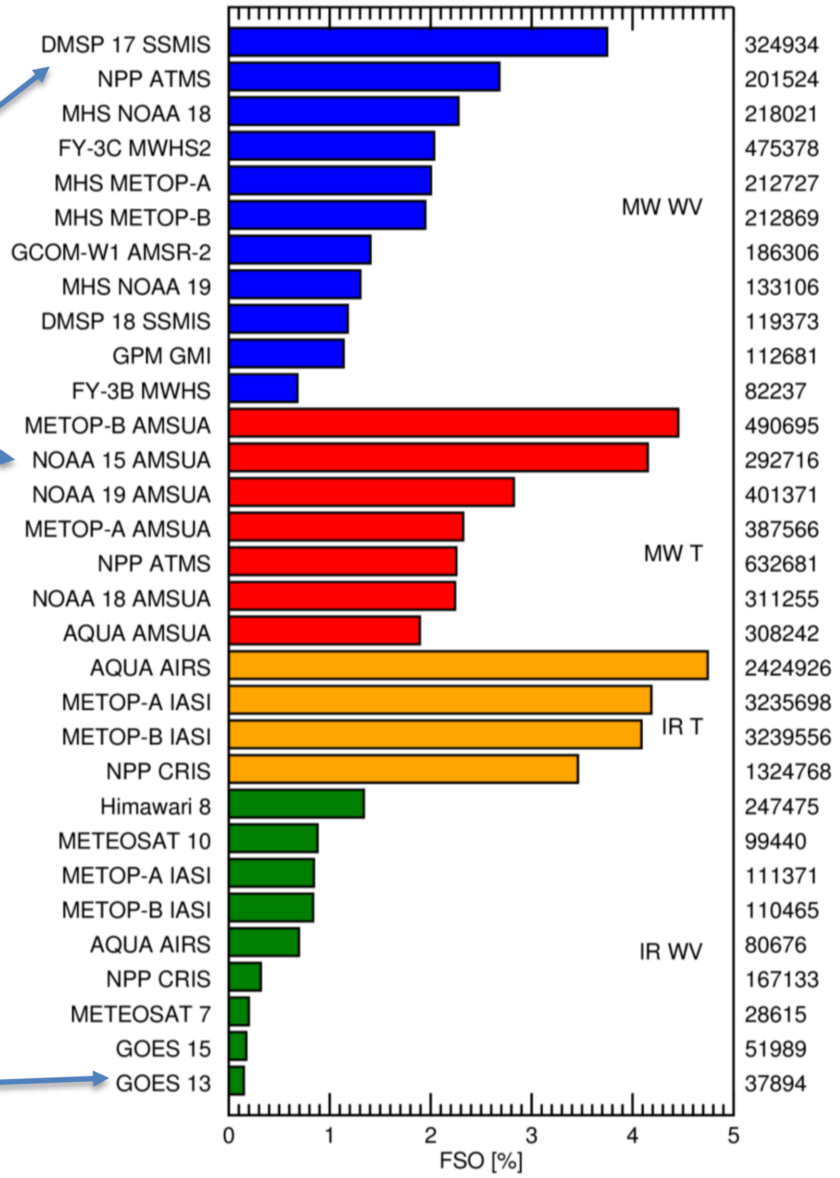
All-sky assimilation of all four MHS (transferred from clear-sky)

F18, all-sky over snow, MWHS-2

FSOI of satellite radiances, August 2016

100% = full operational observing system

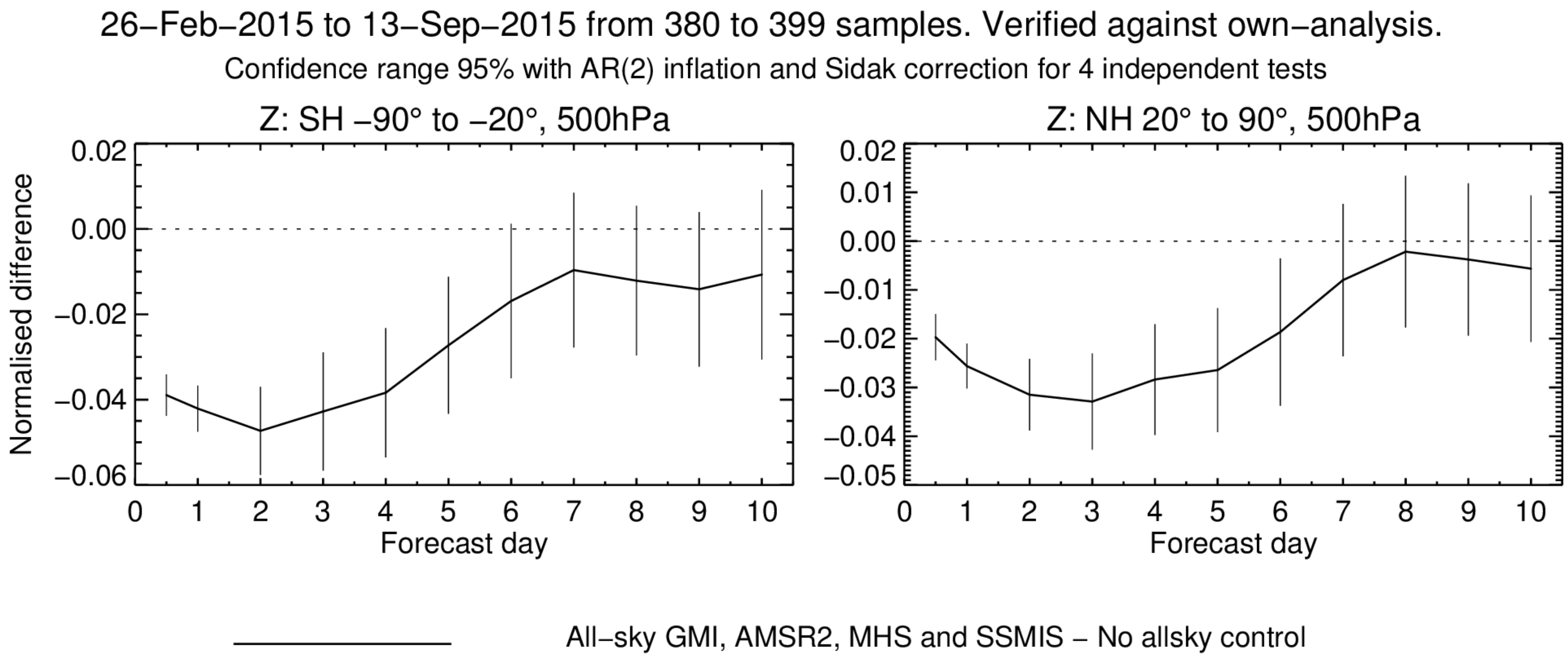
An SSMIS (combining imaging and humidity sounding channels; with its T channels not assimilated) is nearly equivalent to the best of the temperature-sounding AMSU-As



There is great potential for making better use of infrared WV channels: their sensitivities are not so different from their microwave equivalents

Microwave WV	20.4%
Microwave T	20.1%
Infrared T	16.5%
Infrared WV	5.4%

High FSOI => real improvements in medium-range synoptic forecasts

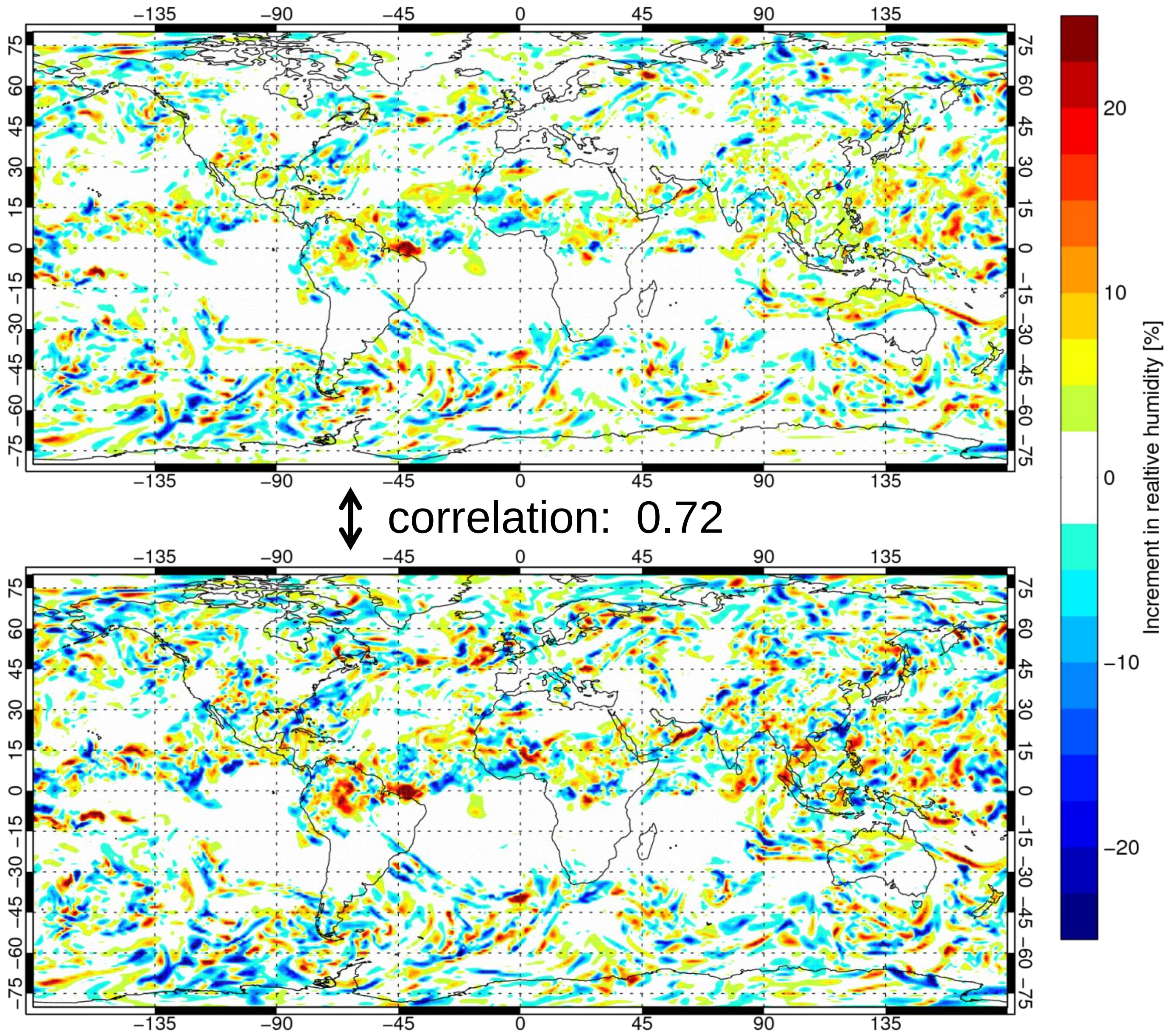


Humidity increments at 500hPa

06Z: 9h into the assimilation window

All-sky WV
sounding only:
4 MHS, 1 SSMIS

Full observing
system
Including all-sky
WV

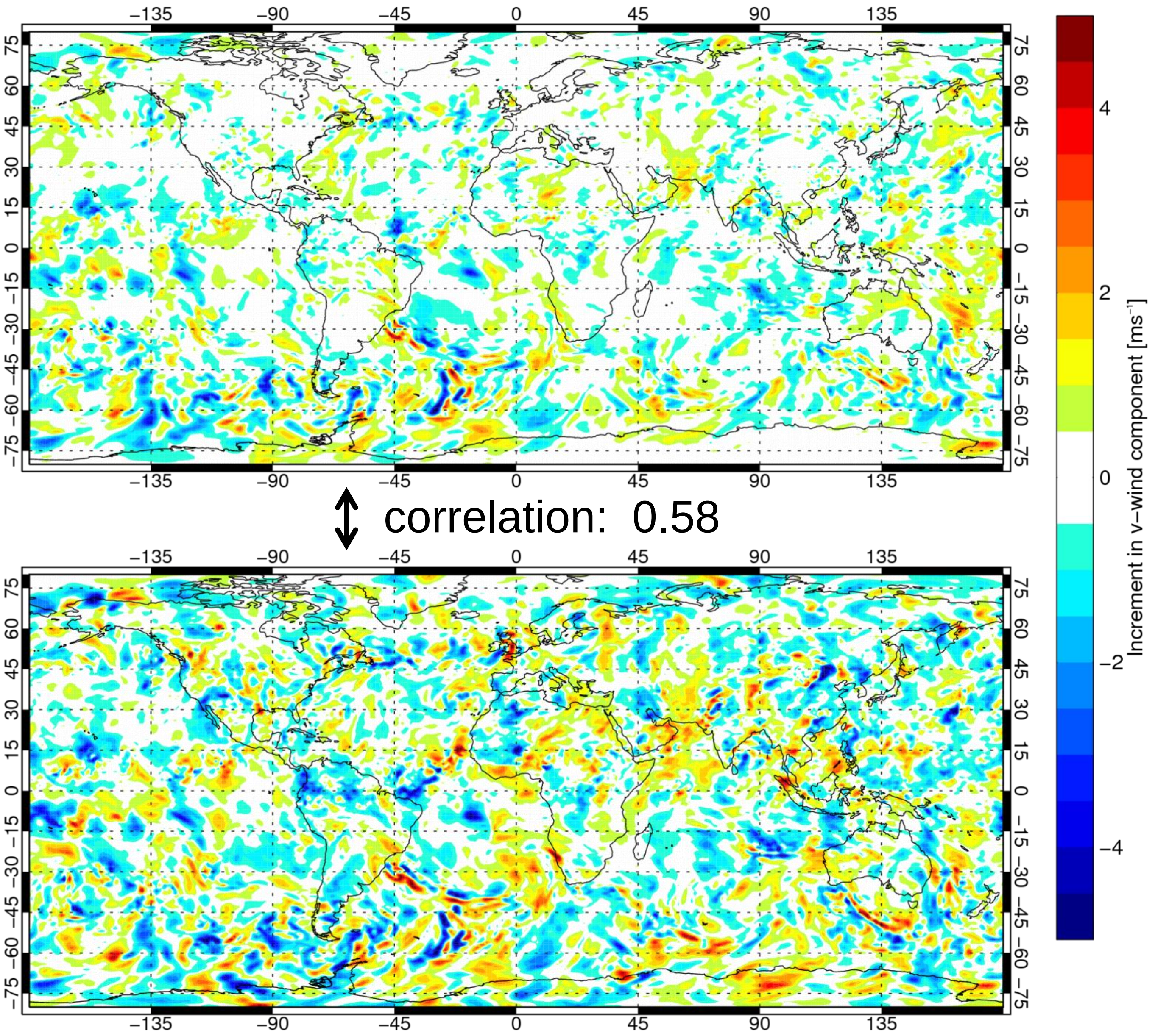


v-wind increments at 500hPa

06Z: 9h into the assimilation window

All-sky WV sounding only: 4 MHS, 1 SSMIS

Full observing system Including all-sky WV



Current benefit of all-sky microwave observations

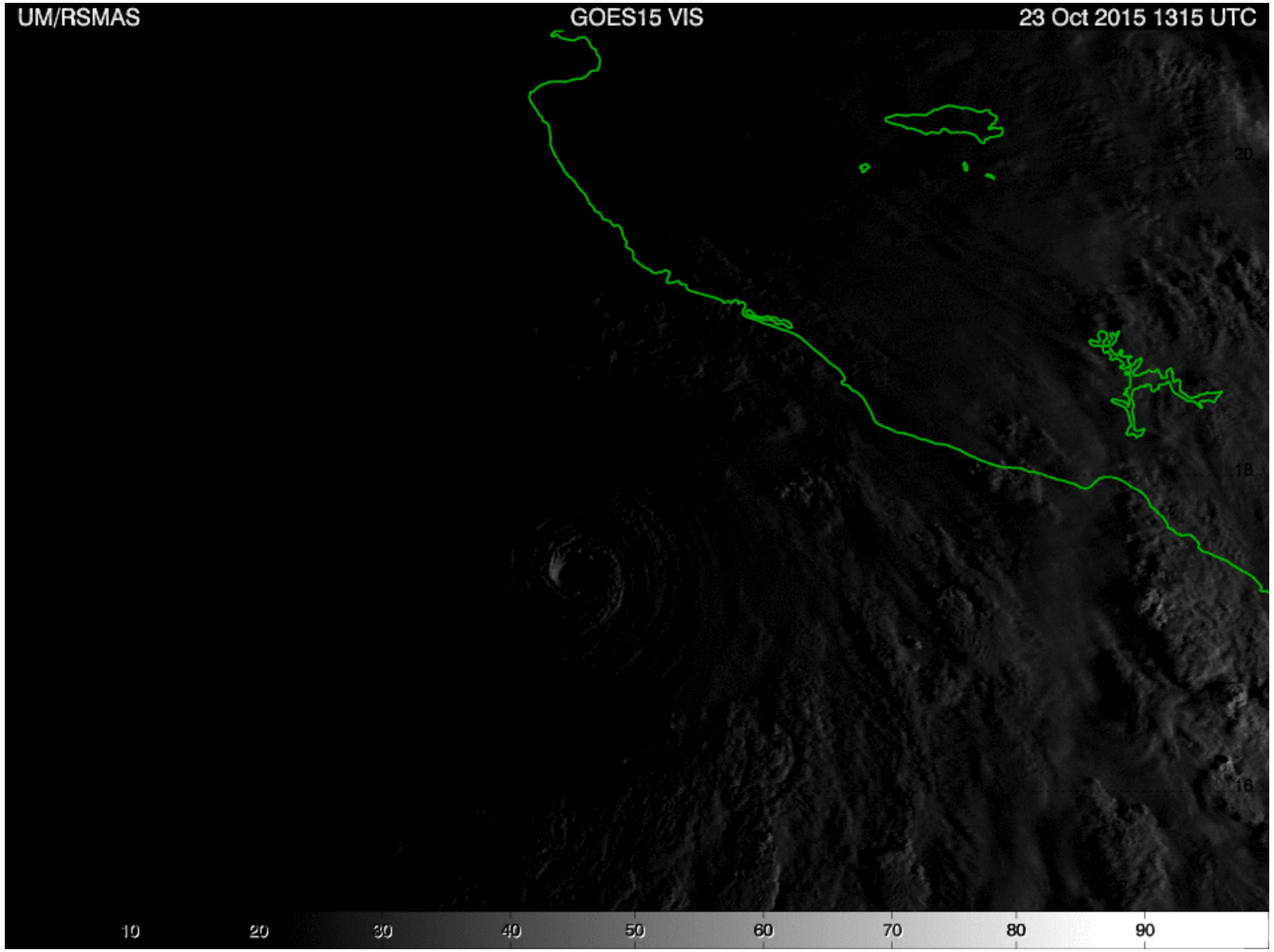
- Observations sensitive to water vapour, cloud and precipitation now provide around 20% of forecast impact at ECMWF
- 4D-Var tracing infers improved dynamical initial conditions to support improved WV, cloud and precipitation initial conditions
- Forecasts are improved into the medium range

→ **Water vapour and window frequencies are starting to become as important to NWP as the temperature-profiling frequencies**

Tropical cyclone analysis

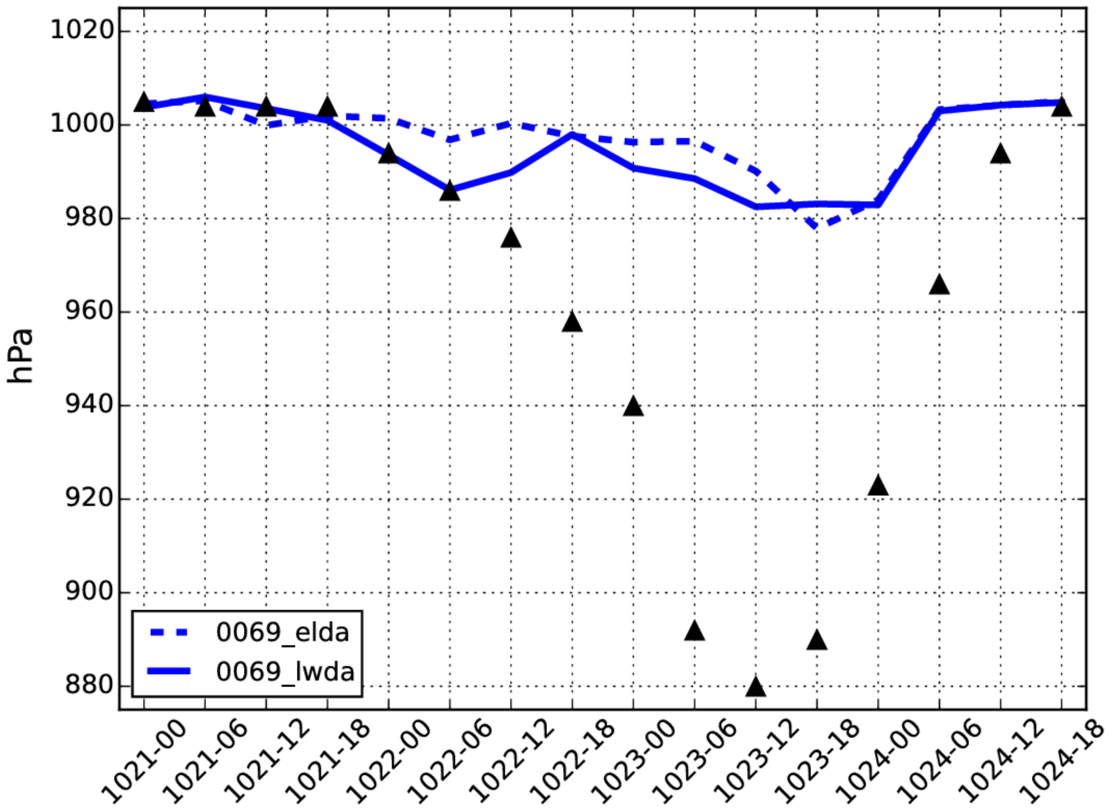
Thanks to Massimo Bonavita

TC Patricia, 23rd Oct 2015 – geo vis



National Oceanic and Atmospheric Administration (GOES-15 satellite); animation provided via the University of Miami's Rosenstiel School of Marine and Atmospheric Science

ECMWF analyses suffered large errors in central pressure



Blue: ECMWF analyses

Triangles: NHC best estimate

TC Patricia, 23rd Oct 2015

All-sky microwave

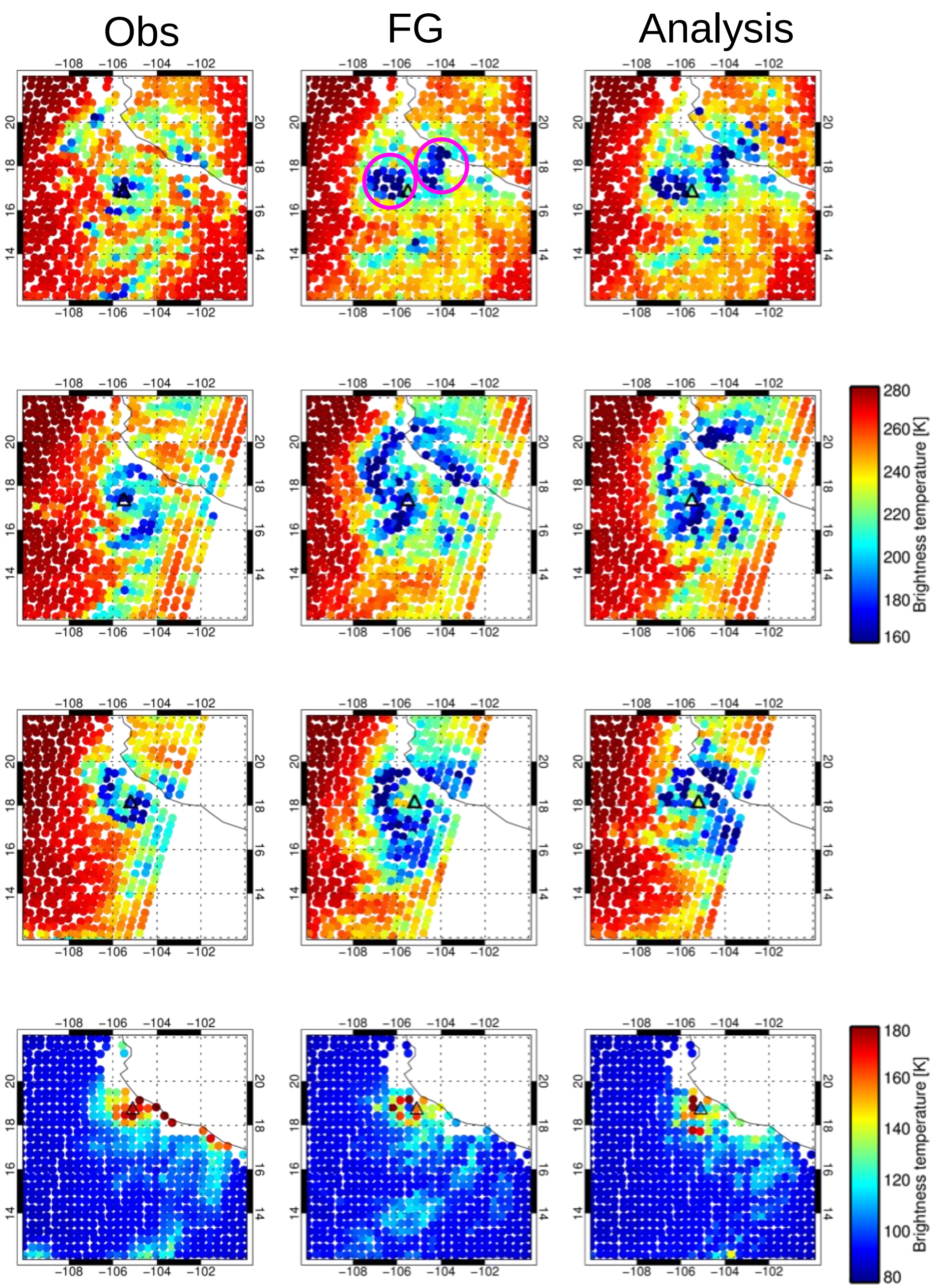
FG also has two low-pressure centres!

MHS NOAA-19 09:20

MHS NOAA-18 13:03

MHS Metop-A 17:13

AMSR-2 GCOM 20:30



183±7 GHz TB

6.9 GHz TB

TC analysis

- Some TC forecasts and analyses are good. Some are poor, like TC Patricia:
  - First guess:
    - Two low-pressure centres; both very weak compared to observations
    - Far too widespread and intense convection
  - Analysis:
    - Even additional weight given to all-sky observations does not significantly deepen the TC
    - Convective areas are moved around; intensity reduced, but still do not fully resemble reality
  - Are we struggling with basic data assimilation issues?
    - If the FG is too far away from the truth, DA cannot be expected to work (even with a very good model)
    - And if the forecast model cannot properly represent a process, it is even harder:
      - Forecast model is spreading convection too wide and not deepening the low pressure centre. Maybe the latent heating that should power the TC is being wasted elsewhere?
    - The complex processes that link dynamical initial conditions with observed precipitation need to be very well modelled in order to infer dynamical increments from observed TC convection

Tropical cyclone analysis – relevance to hyperspectral geo

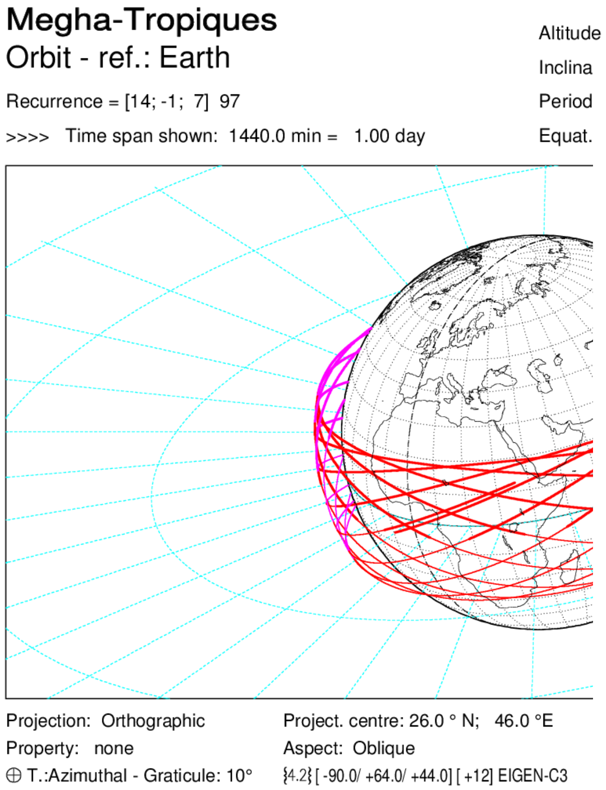
- Only microwave observations observe the driving forces behind the TC, i.e. the convective bands
  - And a combination of polar orbiting observations can already provide reasonable sampling of TCs (e.g. at least every 2-3 hours for TC Patricia)

- Infrared should be useful too:
  - Cloud top temperature indicates areas of deepest convection
  - Cloud motion can help track upper-level winds
  - TCs with well-developed eyes can be located quite precisely

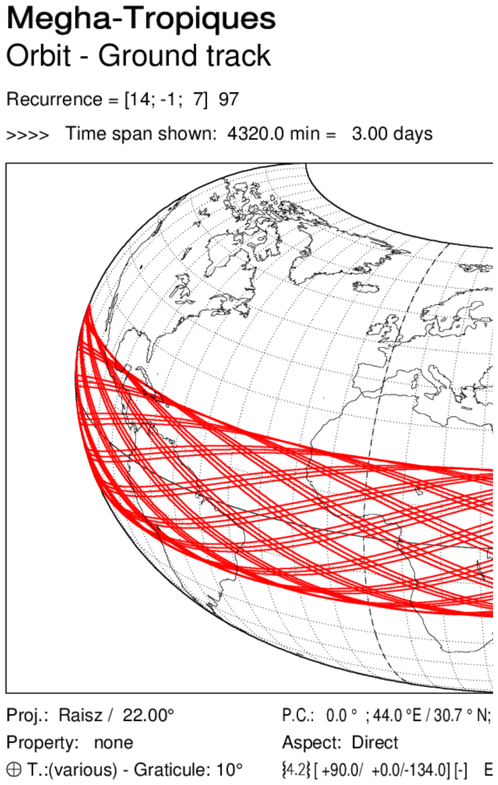
A non-sun synchronous orbit: MeghaTropiques

Thanks to Philippe Chambon

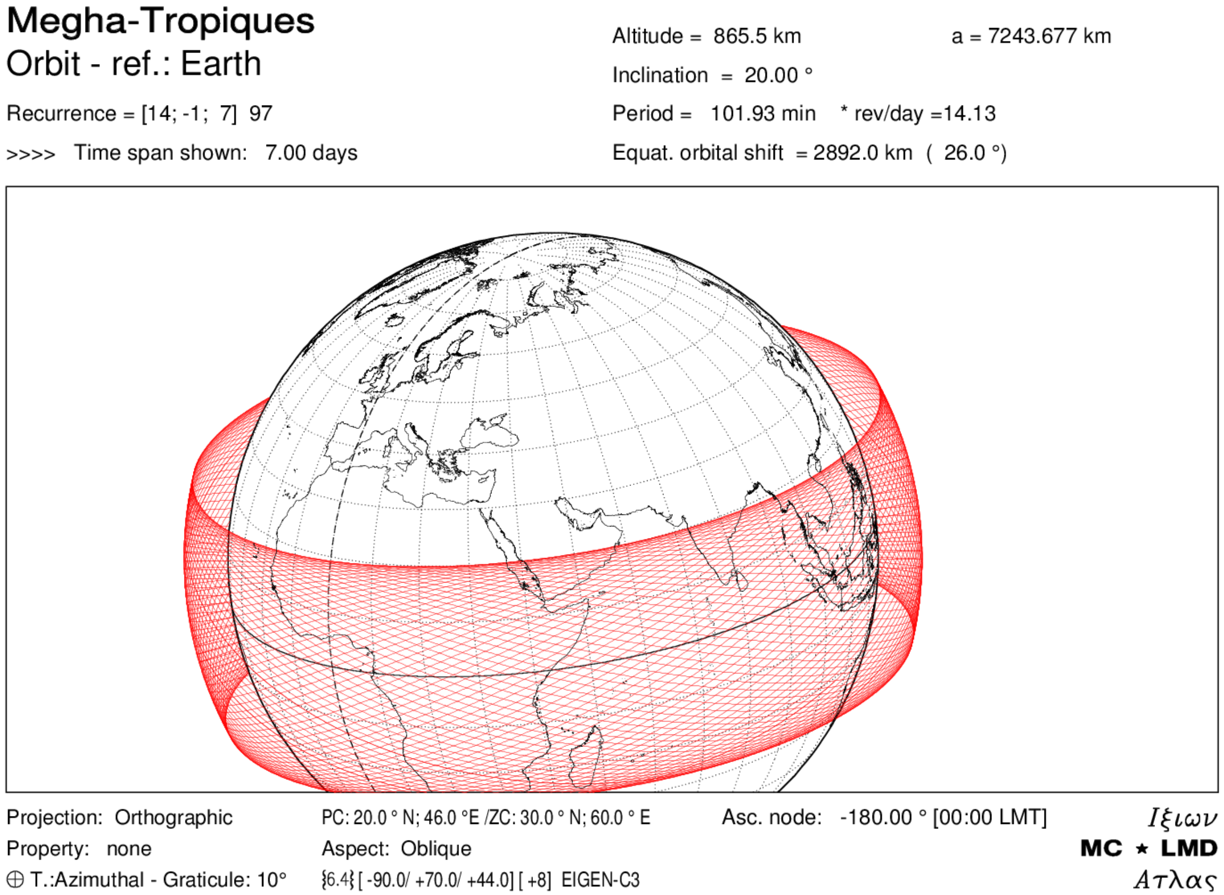
Meghatropiques sampling



1 day



4 days

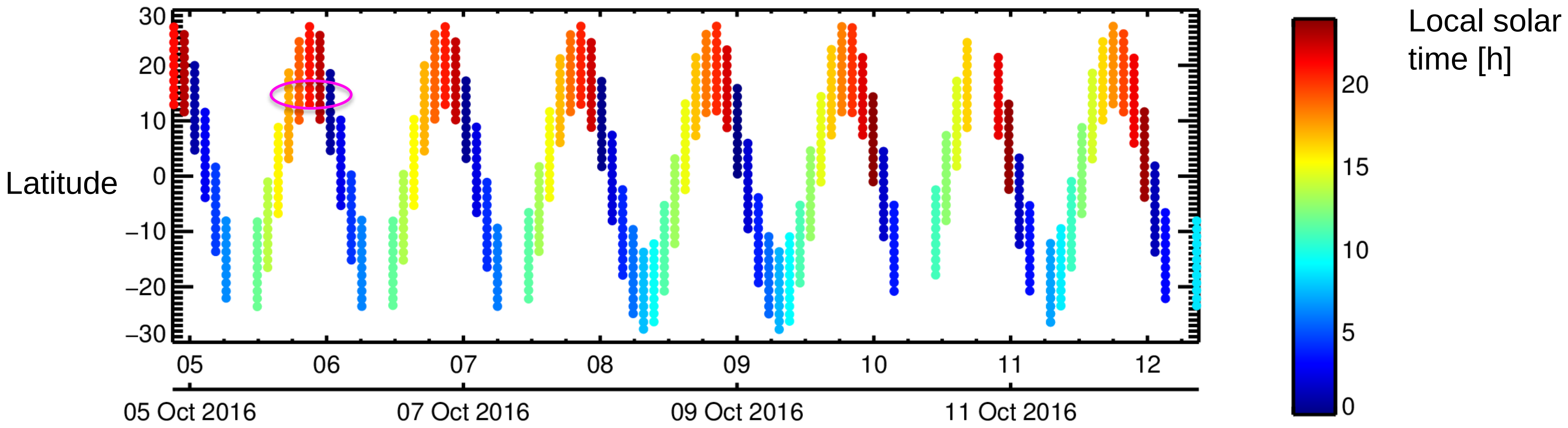


7 days

images from http://meghatropiques.ipsl.polytechnique.fr

SAPHIR sampling

Example: observations at longitude 0



Mesoscale convection

May 7th 2016

16.30

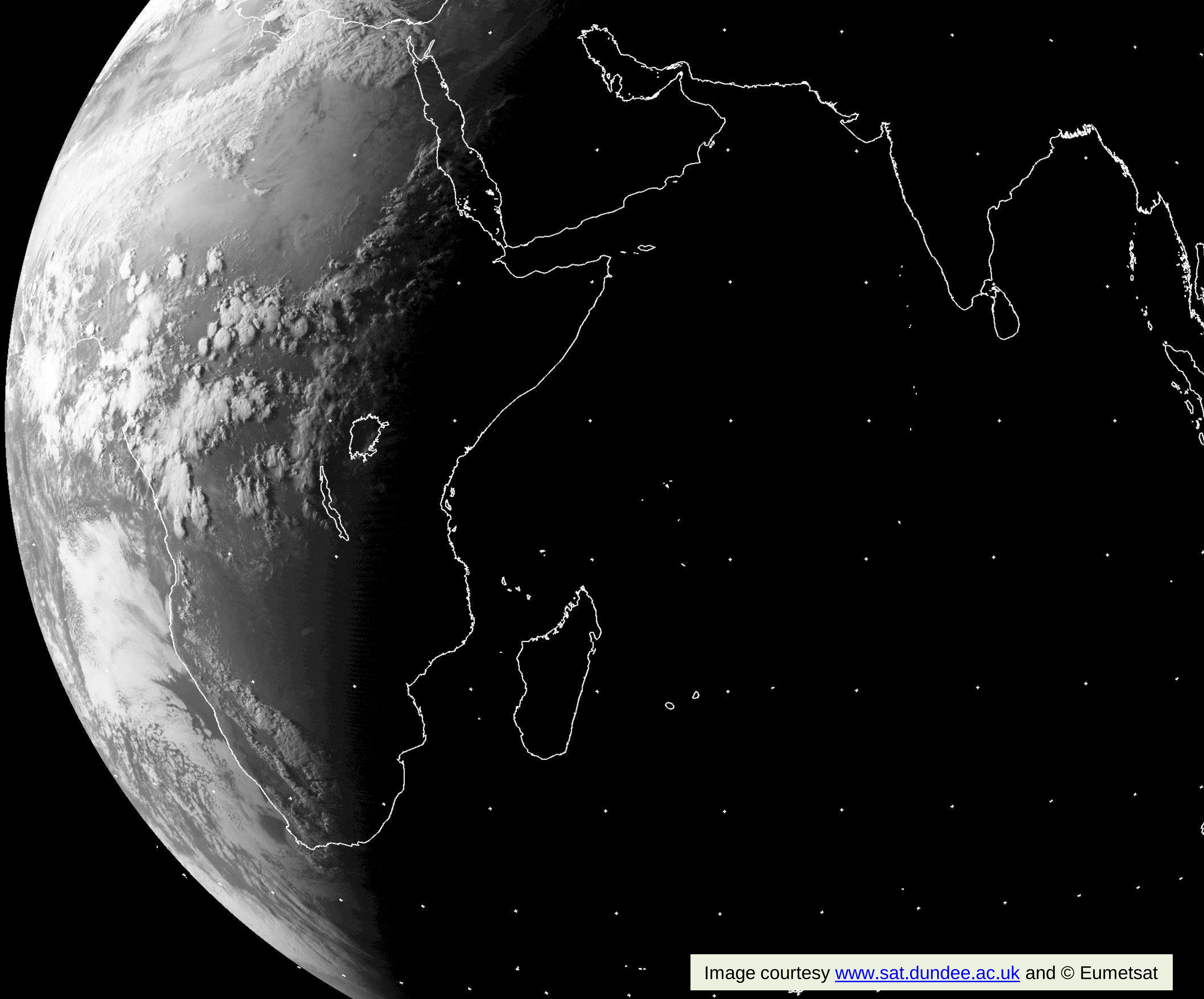


Image courtesy www.sat.dundee.ac.uk and © Eumetsat

Diurnal cycle with SAPHIR ch5 (183±7 GHz)

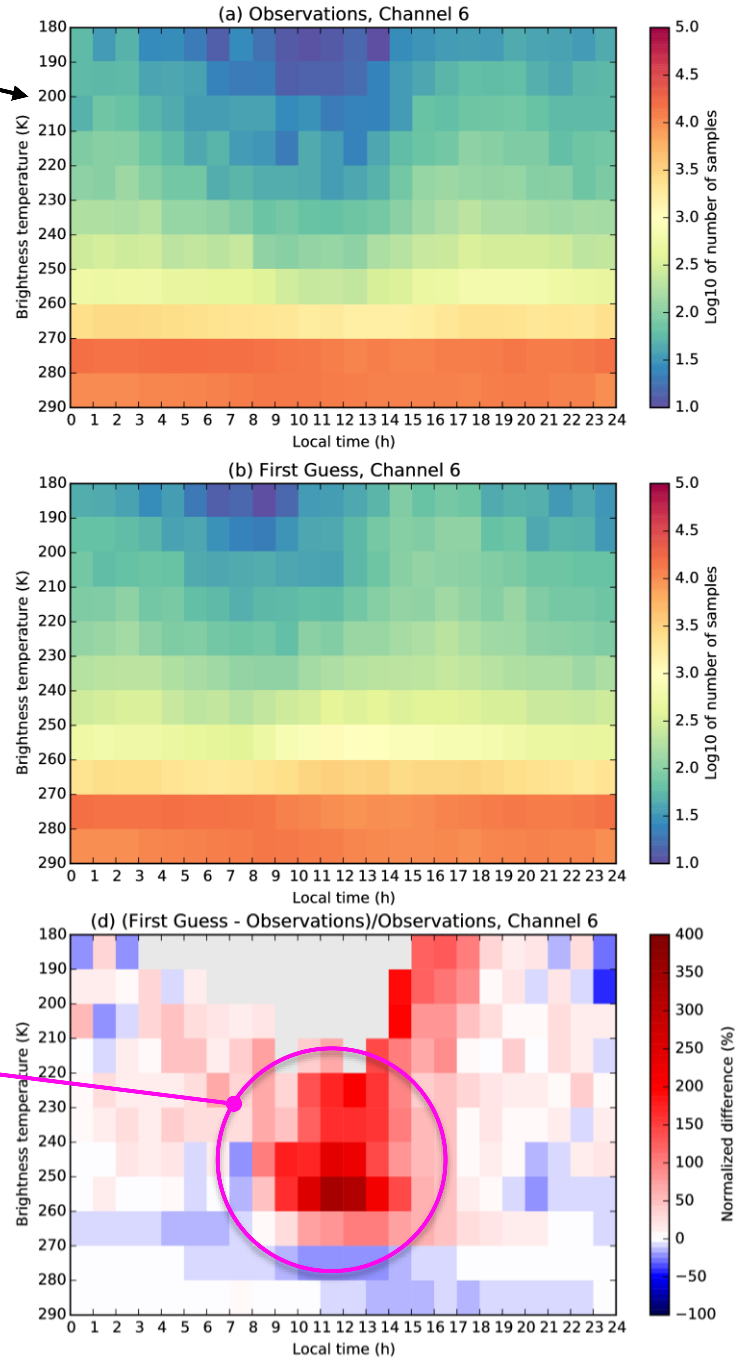
Chambon & Geer, TM in prep.

Land surfaces, 1st June – 29th August 2016

Low Tb = deep convection

Clear skies

Frequency of occurrence

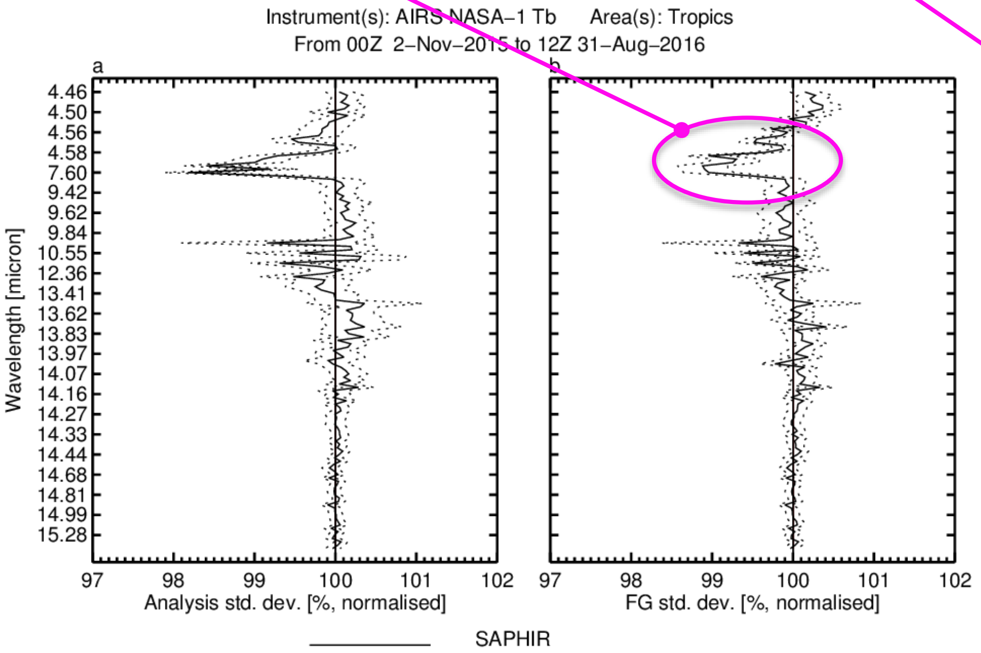


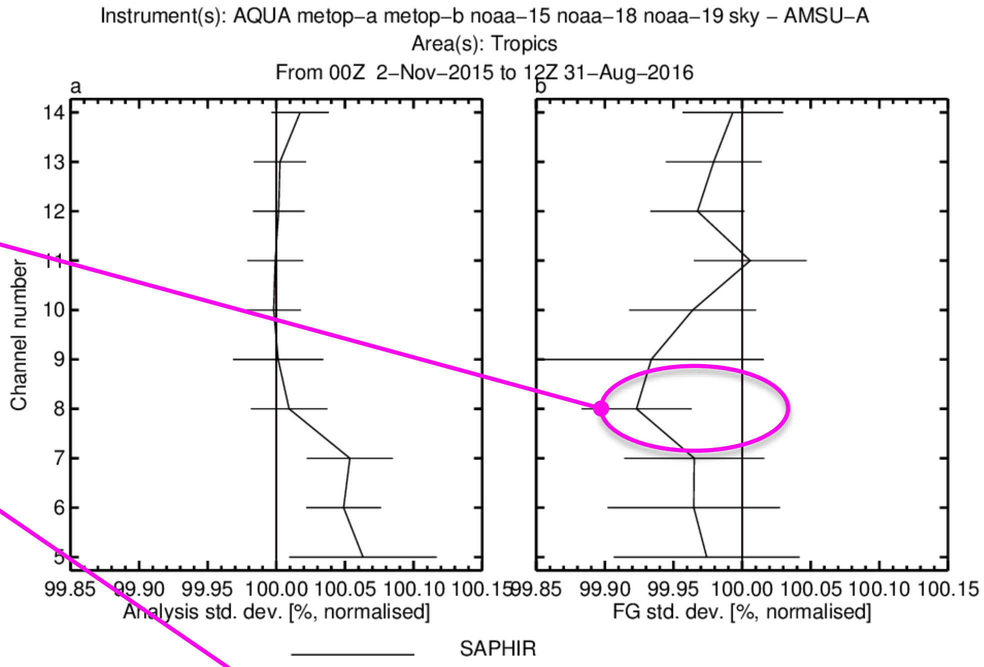
Convective onset in model is still too early

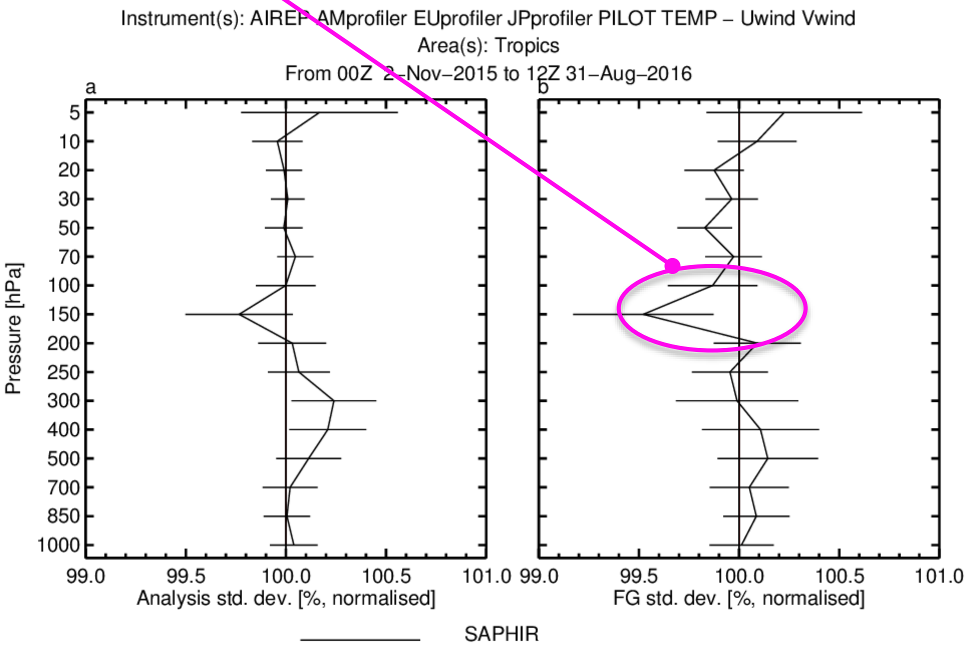
Normalised difference: FG - obs

SAPHIR activation for cycle 43r1

Improvements in water vapour, upper-tropospheric wind and temperature







SAPHIR summary

- All-sky microwave observations are already assimilated from 9 satellites (+2 that are still in clear-sky)
  - Activating SAPHIR observations helps improve short-range forecasts, despite the great amount of similar data already available

- Diurnal cycle of tropical convection is well-observed by SAPHIR.
  - There is still work needed to improve the forecast model (tropical land surfaces initiate convection too early)

How do we get even more frequent coverage of all-sky microwave observations?

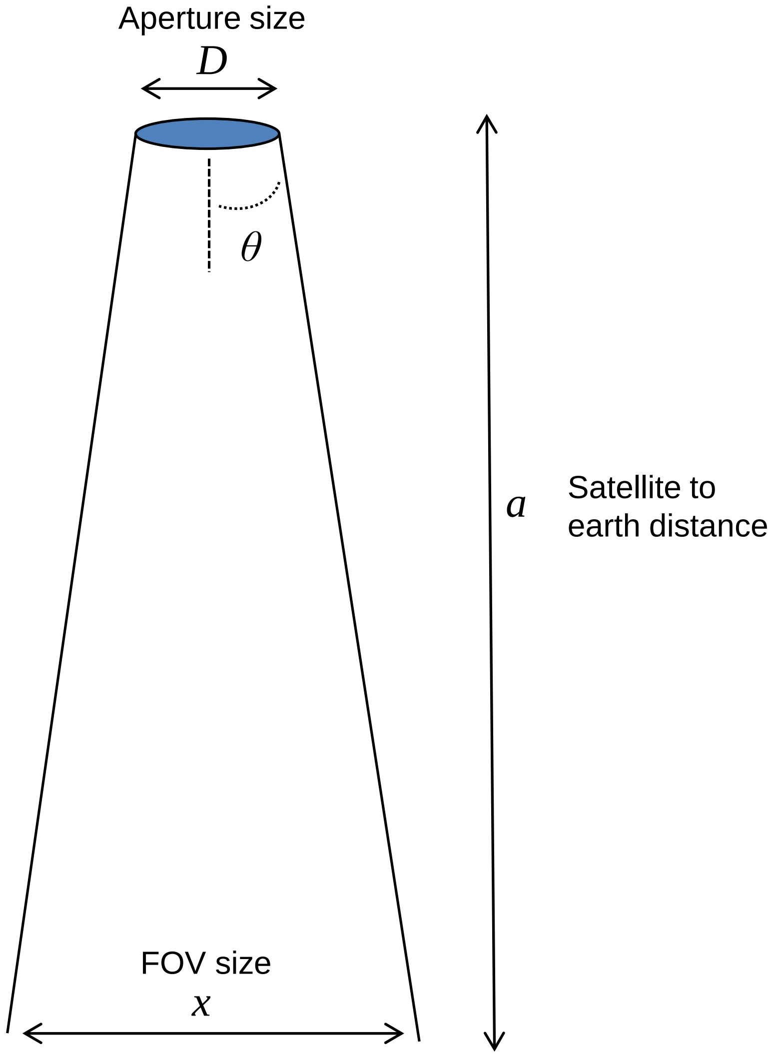
Effect of viewing altitude (LEO vs. GEO)

Approximate calculations in a diffraction-limited system

Airy disk size:

$$\sin\theta = 1.22\frac{\lambda}{D}$$ Wavelength

$$x \approx a\,2.44\frac{\lambda}{D}$$



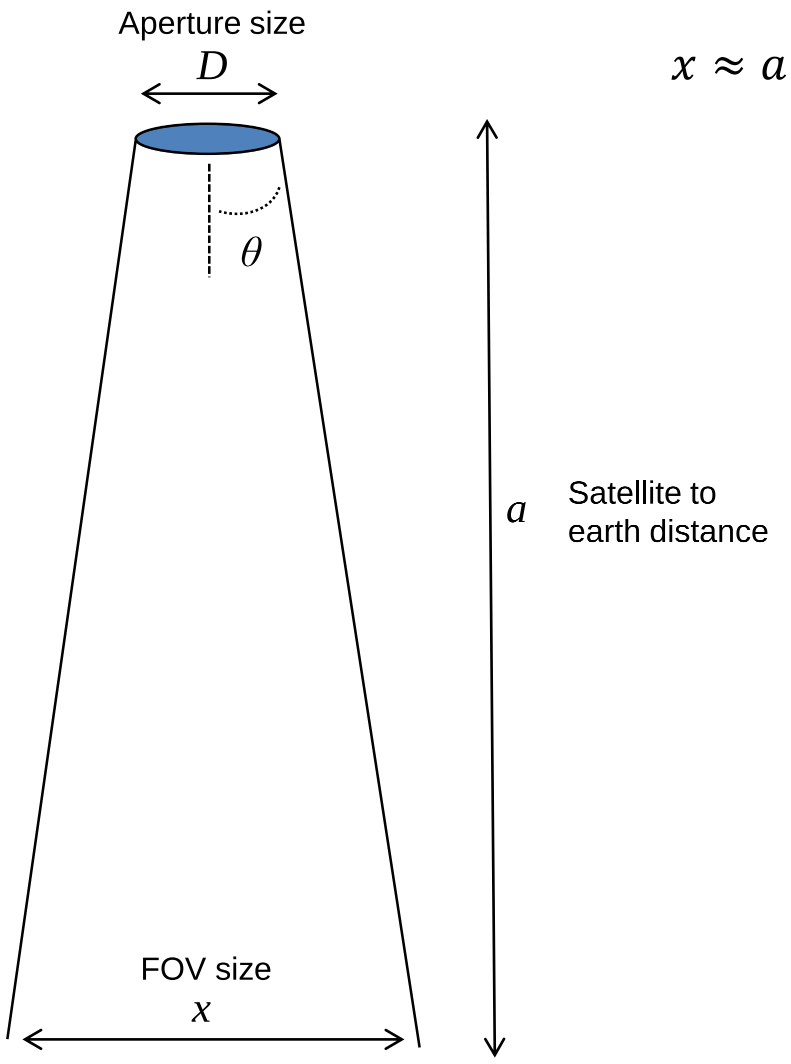
Aperture size [m] needed to achieve 20km FOV size

approximate calculations in a diffraction-limited system

	LEO (a~700km)	GEO (a~35,800km)
19 GHz	1.4	73.0
50 GHz	0.53	27.8
183 GHz	0.14	7.6
448 GHz	0.06	3.1

Note – reducing altitude to 400km (e.g. GPM/GMI) can increase FOV size but reduces swath width, so less of the earth is covered

$$x \approx a\,2.44\frac{\lambda}{D}$$

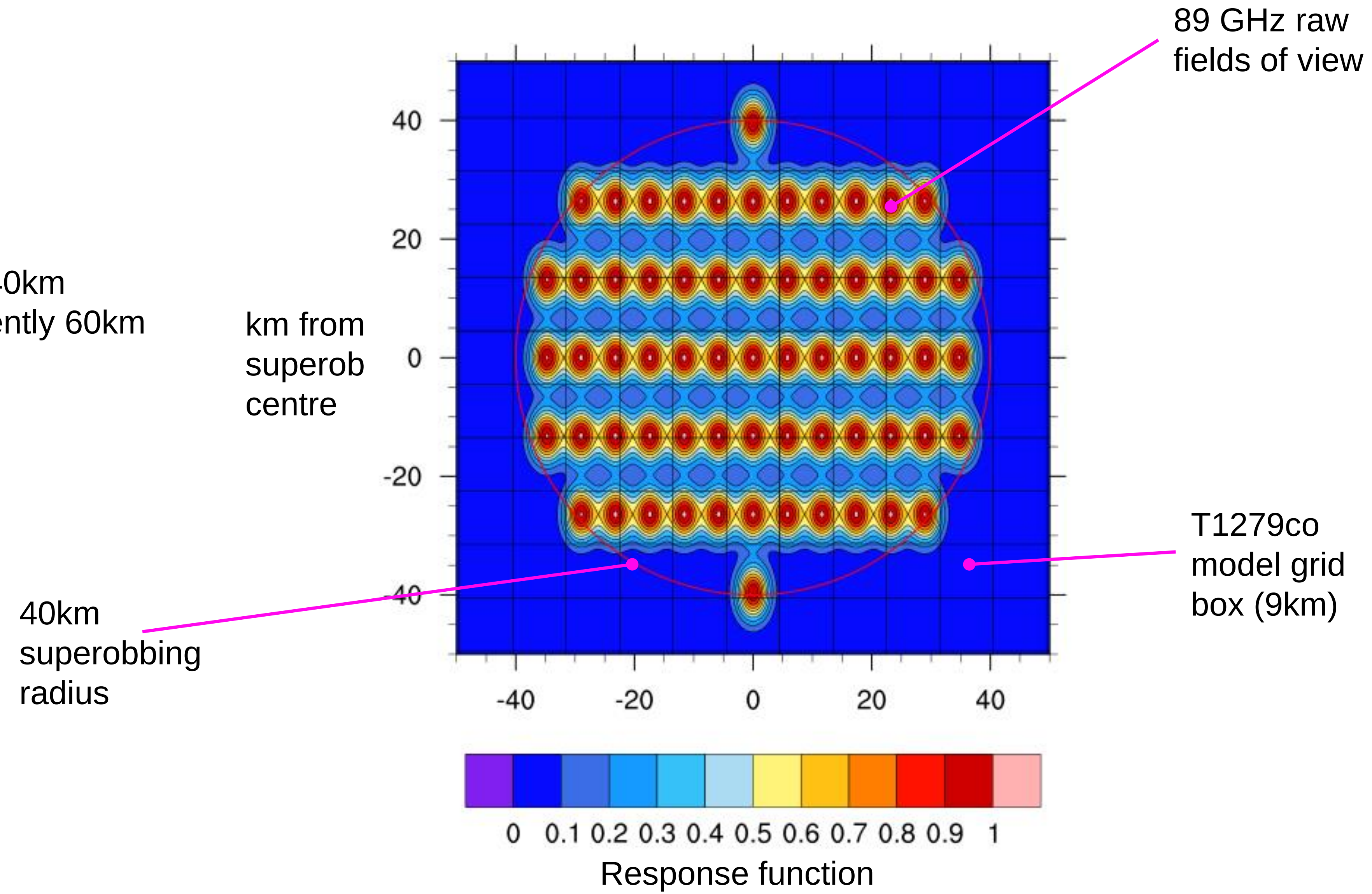


Do we need a 20km FOV for all-sky assimilation?

Currently we use superobbing: because models cannot predict cloud/precip features at small scales

Thanks to Katrin Lonitz

Idealised example shows a 40km radius for superobbing (currently 60km is used operationally)



Increasing the sampling frequency of microwave observations

- All-sky assimilation currently uses approximately 120km resolution superobs
  - Hence it would be possible to make use of quite low-resolution observations
  - Hence geostationary microwave at high frequencies (> 183 GHz) might be just about be viable (low spatial resolution => more reasonable aperture sizes)

- However, the future is moving only towards higher resolution:
  - TC Patricia case study used 60km sampling. Much higher resolution would be needed to properly resolve rain bands, eyewall.
  - ECMWF model currently at 8-9km resolution; we hope to reduce to size of all-sky superobs in the near future.
  - All-sky assimilation for regional and short-range modelling will need cloud and precipitation-resolving resolution.

Development of all-sky infrared assimilation

ECMWF

Lots of work, but no operational implementation yet

Developments in ECMWF system (but see also Météo France, DWD, JMA, NCEP …)

- Chevallier and Kelly (2002); Chevallier et al. (2004):
  - Showed reasonable agreement between all-sky IR observations and simulated radiances from ECMWF forecasts
- Marco Matricardi (2005)
  - RTTOV extended to provide scattering R/T (Chou scaling) using representative scattering optical properties for various cloud types.
- McNally (2009), Lupu And McNally (2012)
  - Operational implementation of “overcast” IR assimilation – limited scenes available
- Bill Bell
  - Framework for all-sky IR 4D-Var assimilation
- Kozo Okamato (2014)
  - Observation error model using a symmetric cloud predictor, similar to what is used for all-sky microwave
- Stefano Migliorini
  - Experiments with IASI WV channels, and possible additional WV channels

Promising results from all-sky assimilation of HIRS

- Focus on HIRS channels 11 and 12 (upper-troposphere WV channels)
- Control:
  - Full observing system minus HIRS
- Experiment = control +
  - Assimilation of HIRS channels 11 and 12 in all-sky situations
    - Metop-A, NOAA-19
  - RTTOV complex IR cloud with 1 cloud-column and 1 clear.
  - Constant observation error: 6K in channel 11, 4K in channel 12
  - 1 month duration

- Note: experiments carried out a few years ago, when all-sky microwave was not so well developed.

Fit to observations

(std. dev. of departures, global)

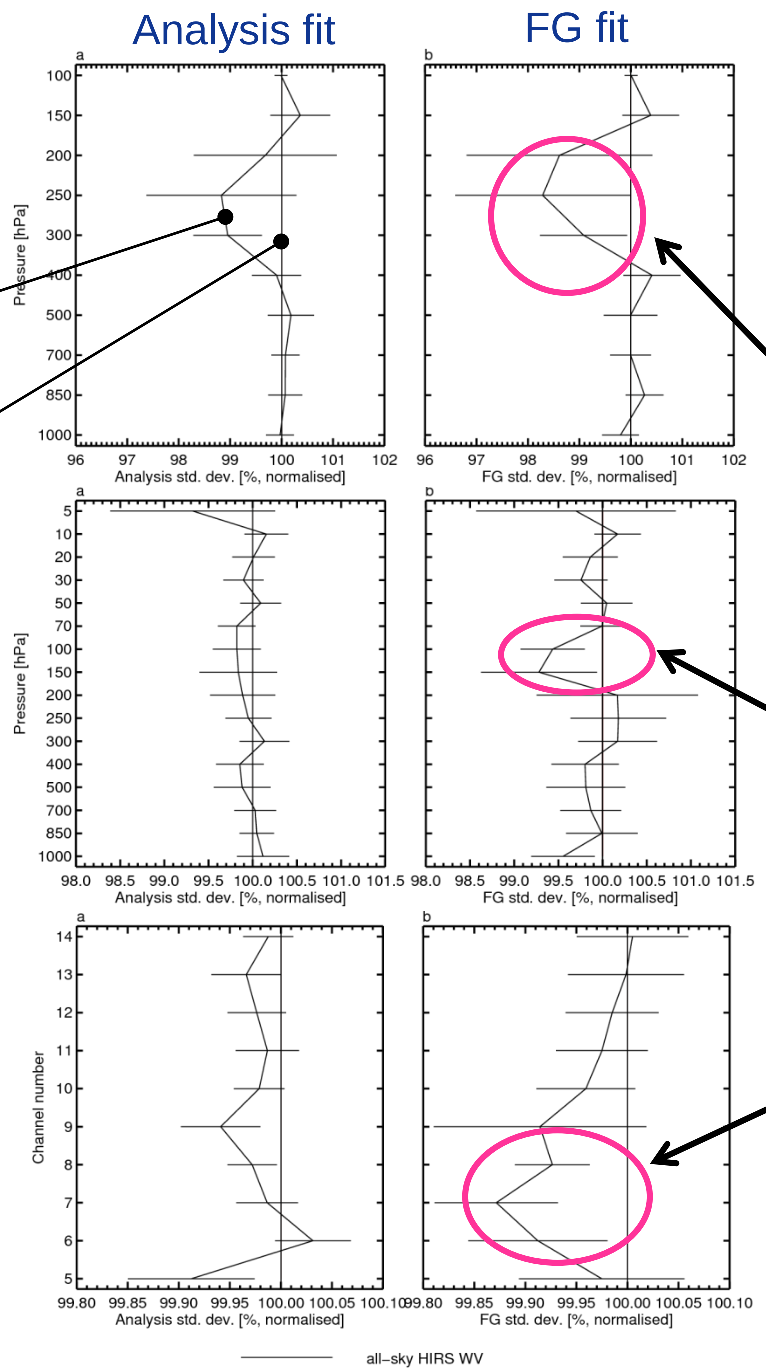
Sonde humidity

Control+ All-sky HIRS

100=Control (no HIRS)

In-situ u-wind

AMSU-A



Upper tropospheric humidity improved by 1.5%

UTLS wind improved by 0.5%

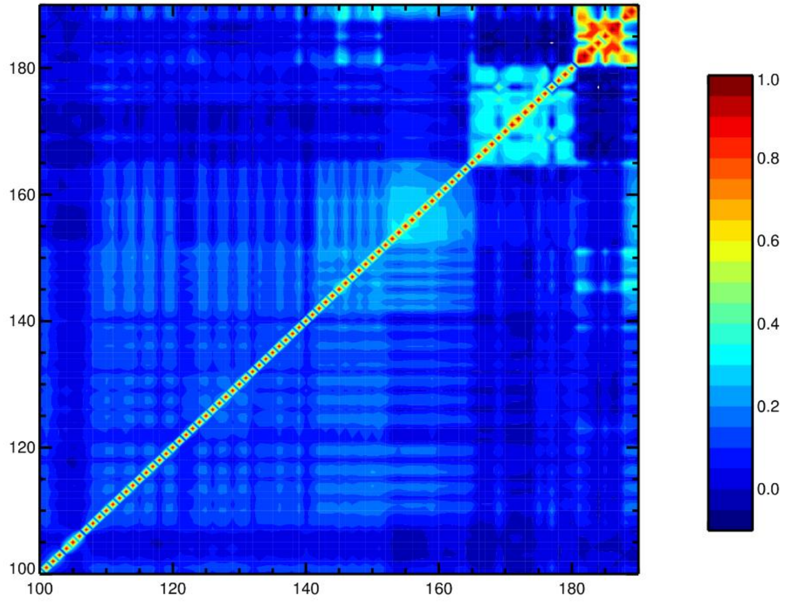
UTLS temperature improved by 0.1%

All-sky assimilation of hyperspectral IR sounders

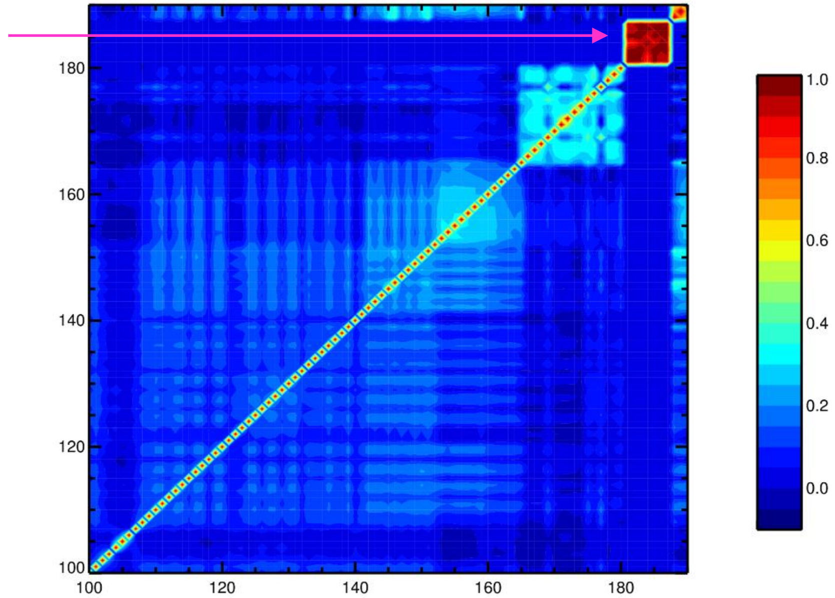
Current strategy:

- Start with 7 UTH channels
  - Currently under-exploited
  - Similar channels are a vital to all-sky microwave impact

- All-sky observation error modelling must respect the correlated nature of hyperspectral channels



Current IASI observation error correlation matrix



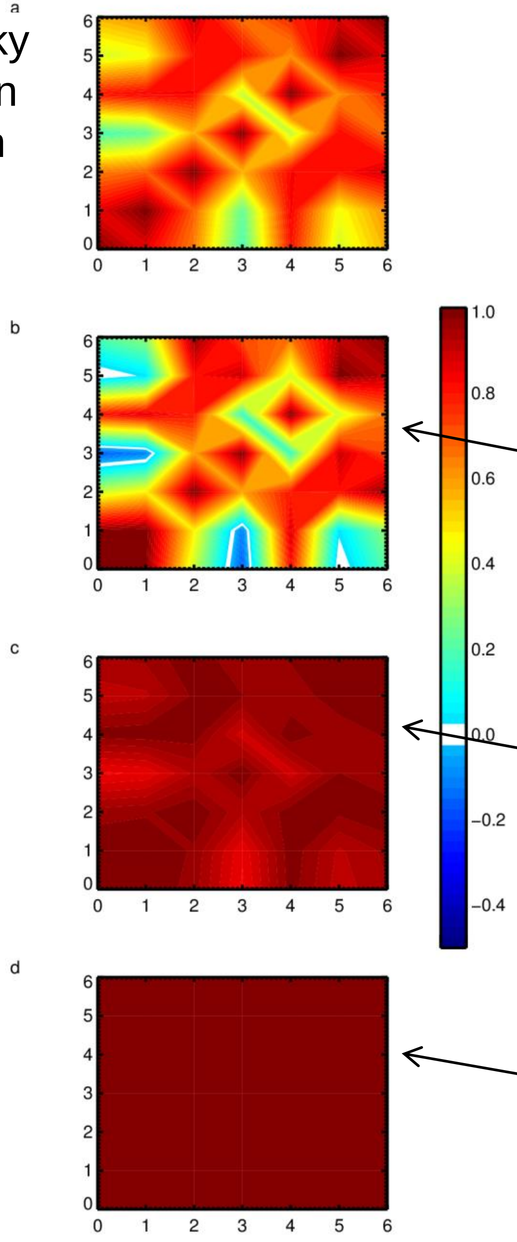
New matrix for all-sky assimilation of water vapour channels

ECMWF

Correlated observation error as a function of error scaling parameter “s”

Current clear-sky IASI observation error correlation matrix (7 WV channels)

Proposed all-sky error covariance matrix

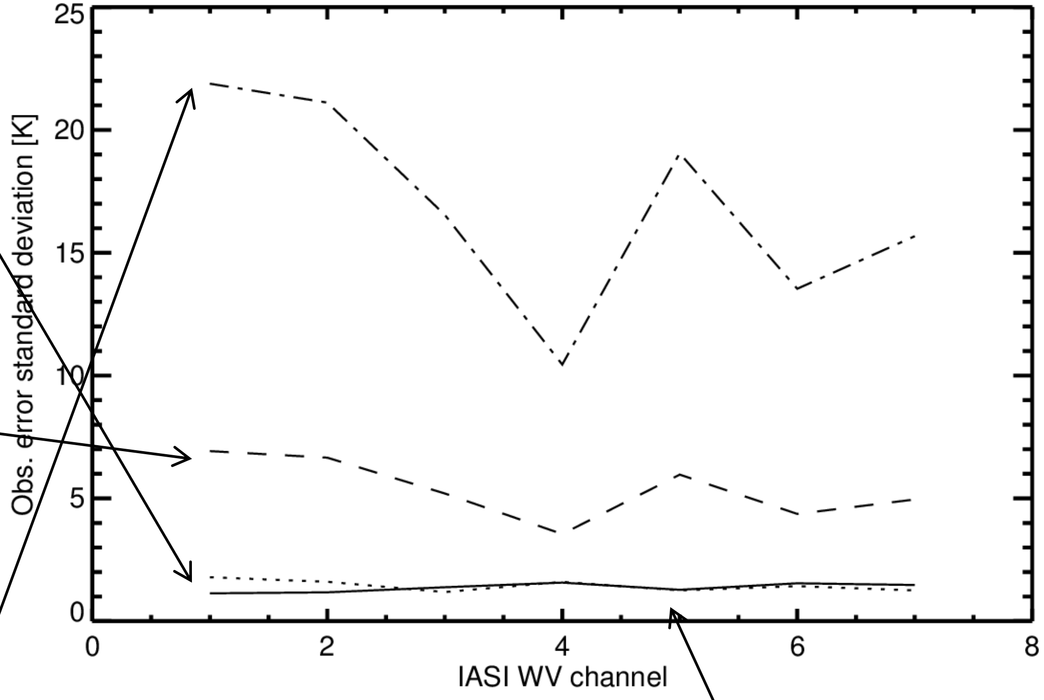


s=0.2 (clear skies)

s=1.0 (mostly cloudy)

s=3.2 (fully cloudy)

Observation error standard deviation



Current clear-sky error std. dev. (Bormann et al., 2016)

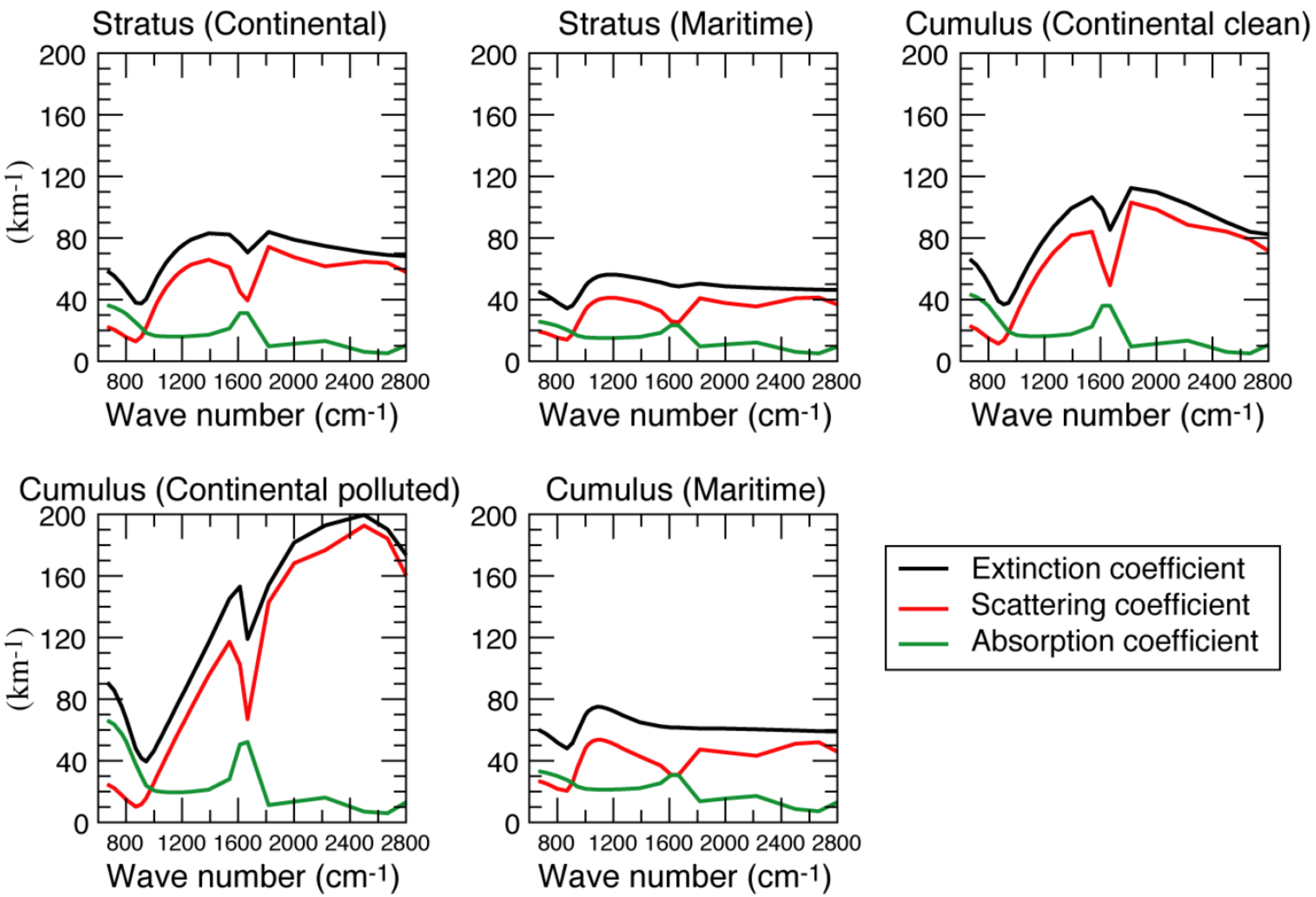
Development of all-sky infrared assimilation

- Best starting point:
  - Upper-troposphere WV channels (following success assimilating similar microwave channels)
- Issues:
  - Multi-stream (i.e. sub-grid cloud resolving) radiative transfer models can be slow, especially with hyperspectral instruments
    - Temporarily solved with “simple streams” approximation, valid only for upper-tropospheric channels
  - Observation error
    - Hyperspectral observation errors are correlated
    - All-sky observation errors are even more correlated, and also situation (i.e. cloud) dependent
    - Given that in cloudy situations, observation errors are nearly 100% correlated, what is the extra spectral resolution for?

What can hyperspectral infrared bring to all-sky assimilation?

Spectral variation of water cloud optical properties

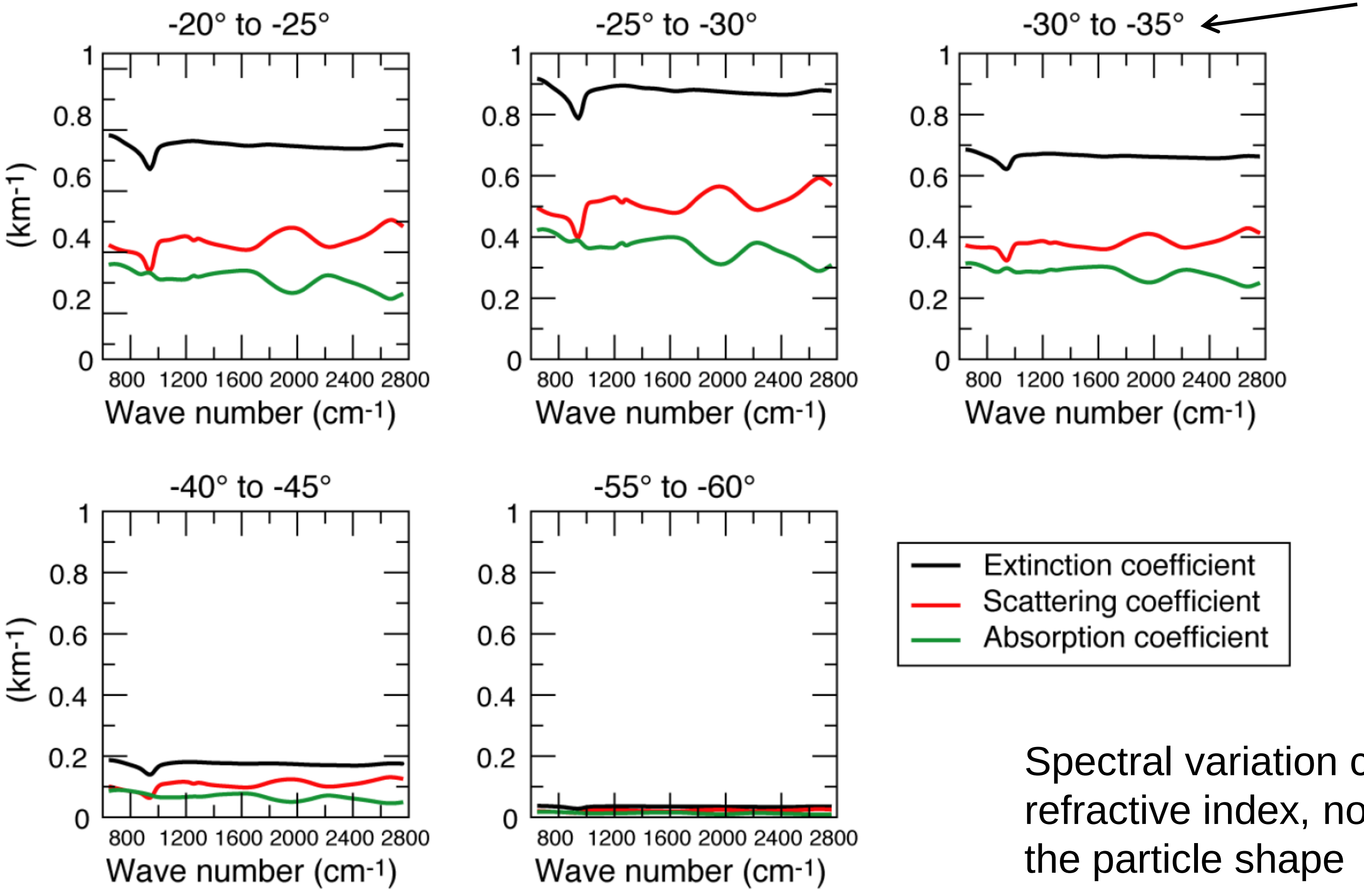
Spheres - Matricardi (ECMWF TM 474, 2005)



Spectral variation of ice cloud optical properties

Randomly oriented hexagons - Matricardi (ECMWF TM 474, 2005)

Temperature [°C]



Spectral variation comes from the refractive index, not the details of the particle shape

Summary: exploiting cloud-affected hyperspectral geostationary observations

Summary: exploiting cloud-affected hyperspectral geostationary observations

- Does **hyperspectral resolution** benefit the assimilation of cloud and precipitation?
  - When cloud is present, observation errors are highly correlated between channels
  - Spectral features of cloud optical properties are present at IR wavelengths, but most details could be well-sampled with a $10cm^{-1}$ spectral resolution
  - Vertical localisation of cloud tops?

- But all-sky assimilation aims to assimilate both the clear-air signal (temperature, moisture) and the hydrometeor information:
  - High spectral resolution should help separate the cloud (relatively smooth) and the clear-air (high spectral resolution) information

Summary: exploiting cloud-affected hyperspectral geostationary observations

- Can **high temporal sampling** benefit cloud and precipitation assimilation? Yes, e.g:
  - Diurnal cycles of tropical convection
  - Tropical cyclone observations at high temporal resolution

- But putting microwave sensors on geostationary platforms is difficult.
  - Even at 183 GHz, a 20km FOV size is achieved only by a 7.6m aperture

- For microwave, instead:
  - The current polar constellation provides frequent overpasses, even for TCs:
    - TC Patricia was observed approximately every 2-3 hrs
  - Non sun-synchronous satellites add even more coverage, e.g. MeghaTropiques

  → **What would I suggest? A constellation of AMSR2 and SSMIS-like instruments**

  - mostly polar orbits; some non-synchronous to improve tropical and midlatitude coverage frequencies
  - at 700km altitude (swath wide enough that one polar satellite covers most of the earth in 12h)

Prospects for all-sky hyperspectral geostationary assimilation

- All-sky assimilation
  - is already benefitting global medium-range weather forecasts
    - 4D-Var tracing to infer winds
  - is being developed for infrared WV channels (others to follow)
    - All-sky hyperspectral infrared assimilation
  - is being developed for cloud-resolving NWP (short-range, local area forecasting, e.g. DWD, MF)
    - All-sky geostationary assimilation: geostationary observations give the high-temporal resolution needed for cloud-resolving NWP
- In the next few years:
  - all-sky geo IR assimilation will likely first be applied to SEVIRI-like instruments
  - a priority order for resolution enhancements for cloud and precipitation assimilation:
    1. temporal 2. spatial 3. spectral

→ all-sky assimilation will be used to extract information from hyperspectral geo in the future – maybe in time for MTG-IRS launch?