APPLICATIONS OF RO DATA IN CLIMATE

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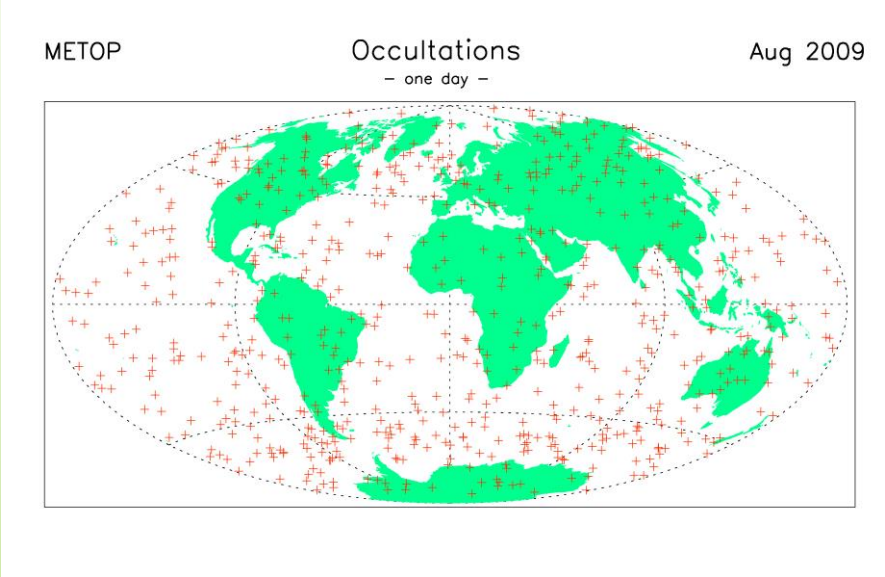
Outline

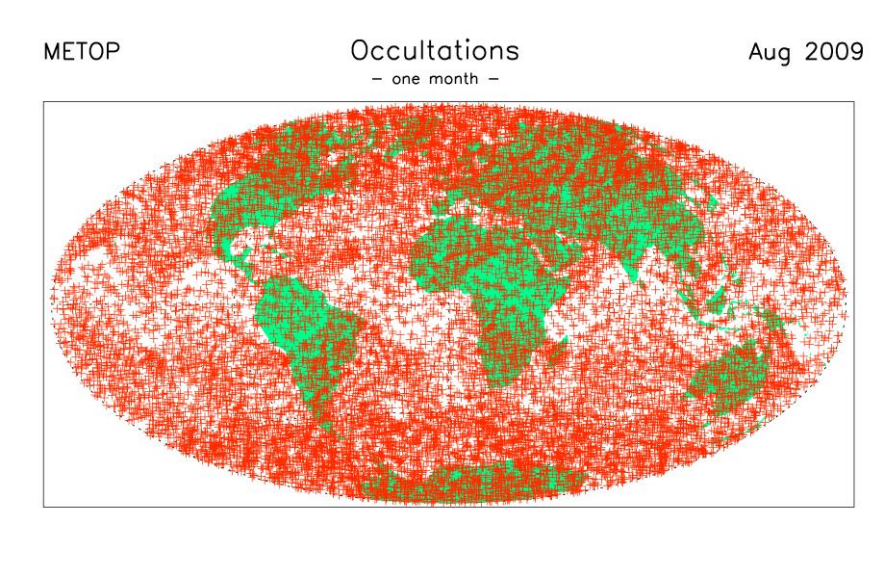
- Characteristics of RO data important for Climate
- Examples of RO data use in Climate
- Conclusions & where to find data

Sampling

– by a single satellite –



A single satellite tracking GPS signals (setting and rising) provides about 700 occultations per day (~20000 per month).

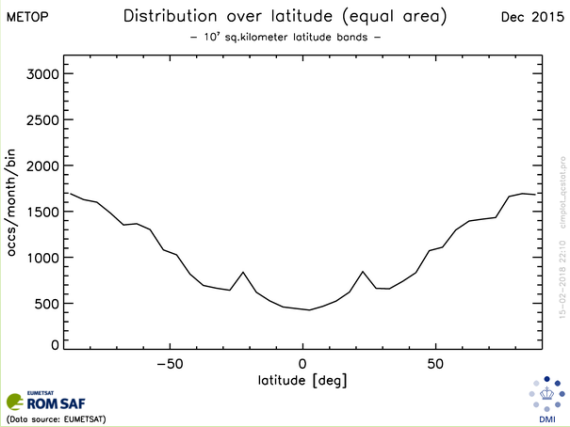


- quasi-random spatial distribution
- independent of clouds
- independent of underlying surface
- no land-sea differences

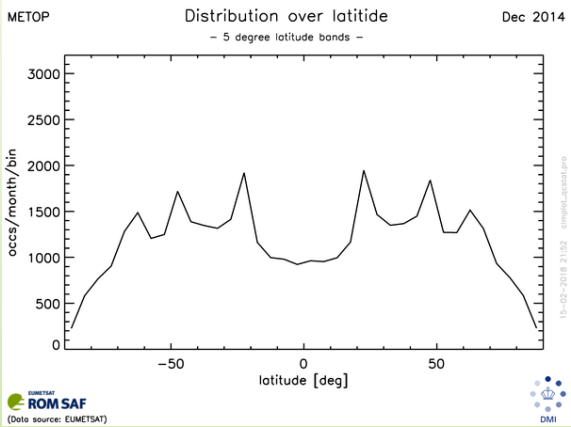
Sampling

– Distribution in latitude and longitude –

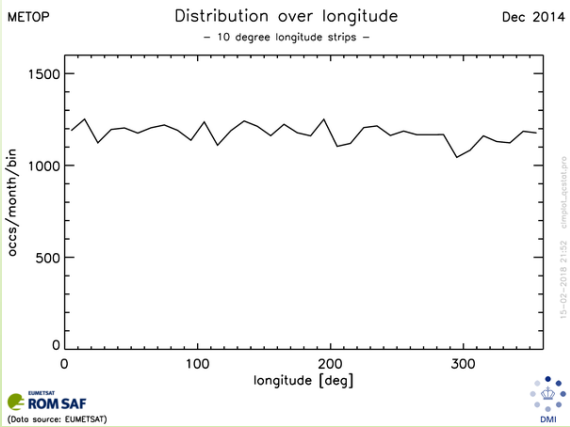
Latitude, equal area bins



Latitude, equal angle bins



Longitude



The distribution of observations is mainly governed by the LEO satellite orbits (inclination, altitude), but with a finer structure influenced by the GNSS satellite orbits.

Data numbers vary with latitude, generally denser towards the poles. Data numbers are roughly uniform in longitude.

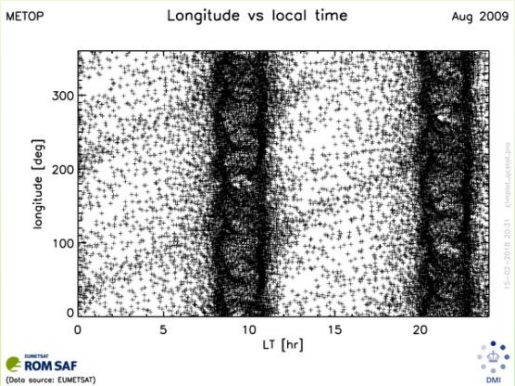
Sampling

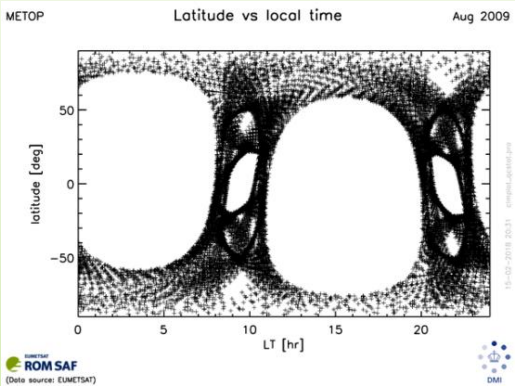
– Local solar time / diurnal cycle –

Longitude vs. local time

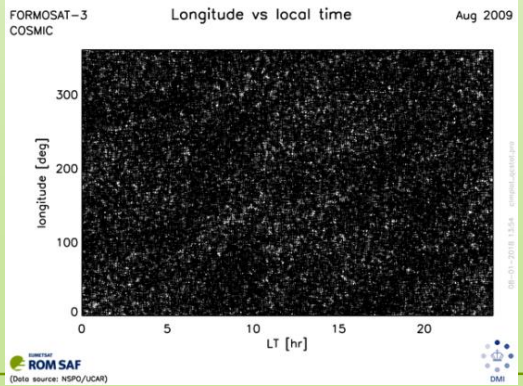
Latitude vs. local time

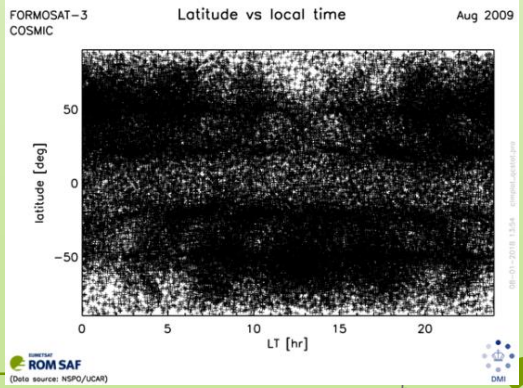
Sun-synchronous orbits:
e.g., Metop, Metop-SG





Precessing orbits:
e.g., COSMIC-1, -2, CHAMP, GRACE





RO mission differences

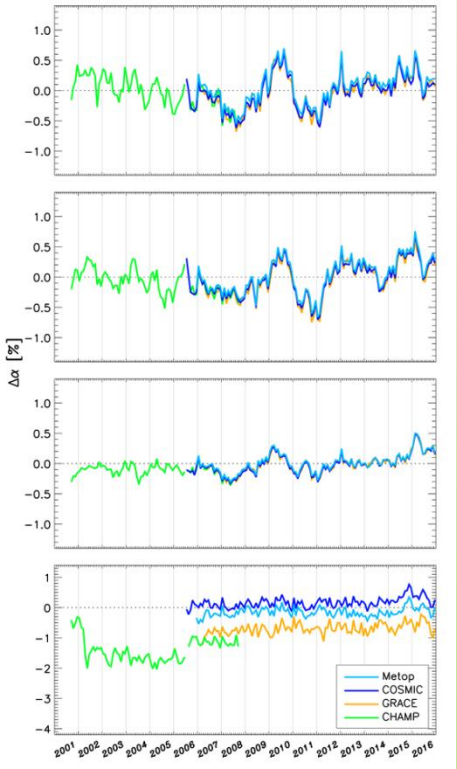
Bending angle ***Refractivity*** ***Dry temperature***

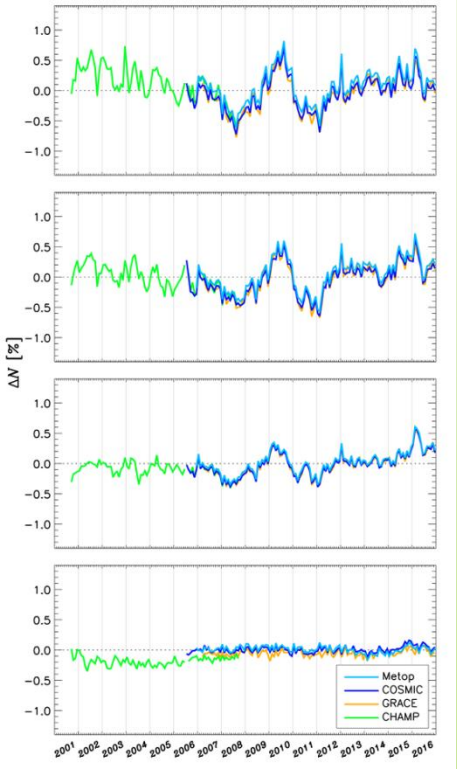
35-40 km

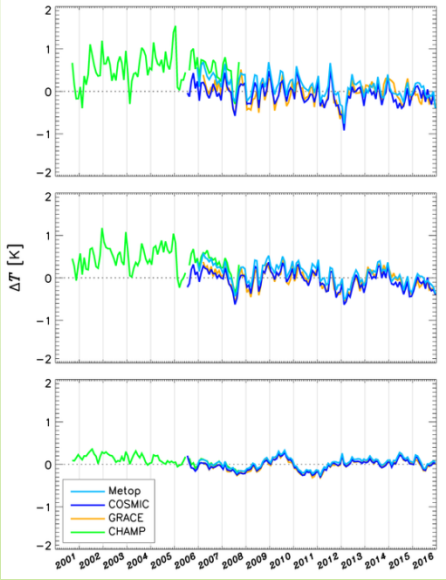
30-35 km

8-30 km

4-8 km







Excellent mission consistency 8-30 km.

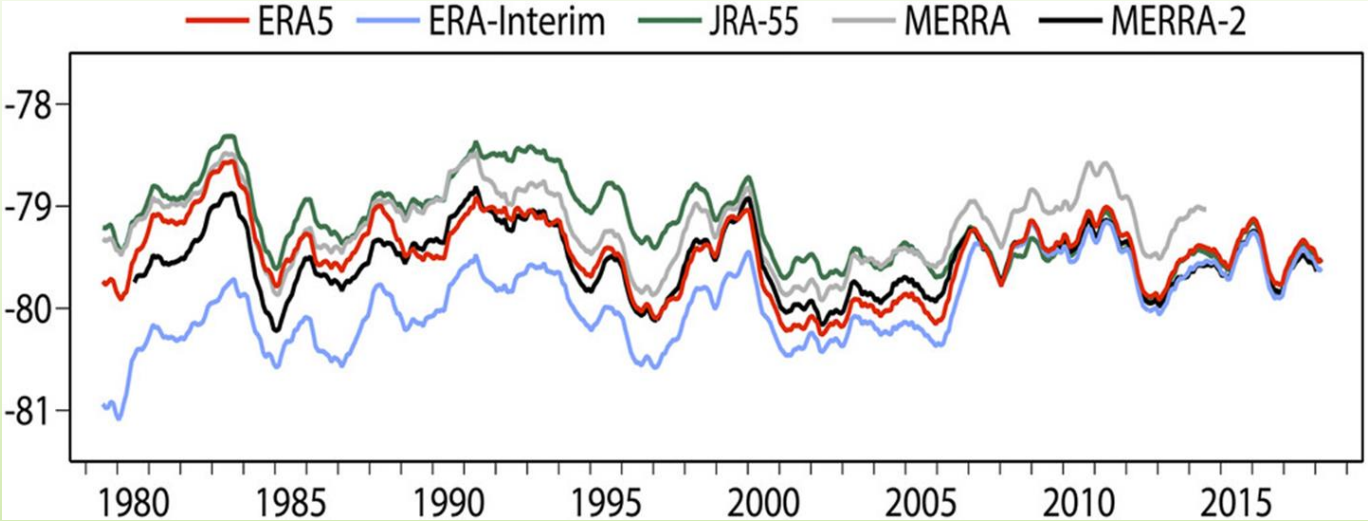
Consistency for bending angle and refractivity up to 40 km.

Examples of RO climate applications

A few examples of RO data in climate related applications:

- *climate reanalysis*
- *atmospheric monitoring, climate time series*
- *equatorial stratosphere: ENSO, QBO, mean zonal winds*
- *polar stratosphere: polar vortex variability, SSW events*
- *atmospheric trends, contributions to the IPCC AR6 WG1 report*
- *climate model testing*
- *migrating diurnal tides in the stratosphere*

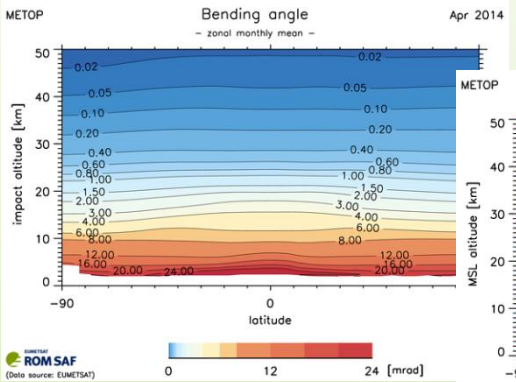
Assimilation of RO in climate reanalyses

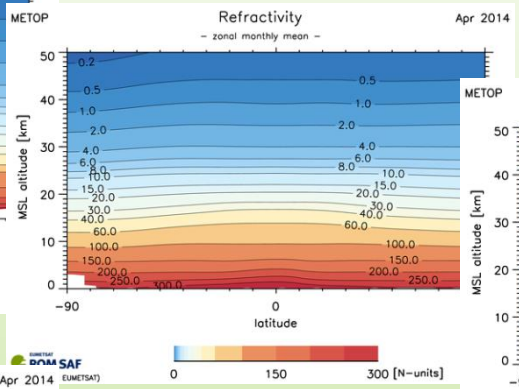


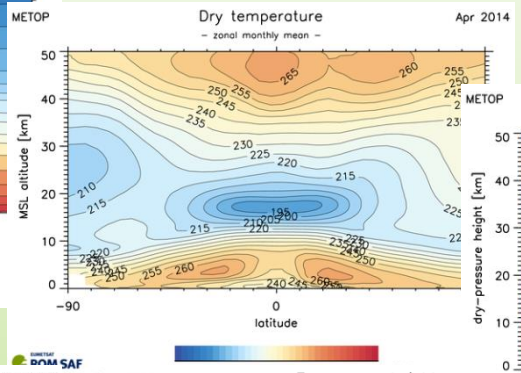
Tropical 100 hPa temperatures from five global reanalyses. All assimilate RO data after 2006, except *MERRA* (gray line). Data from the *COSMIC* mission were available from mid-2006 and *Metop* data from end of 2006. Other contributing RO missions are *CHAMP*, *GRACE*, *SAC-C*, *TerraSAR-X*, *FY-3C*, and *TanDEM-X* RO missions.

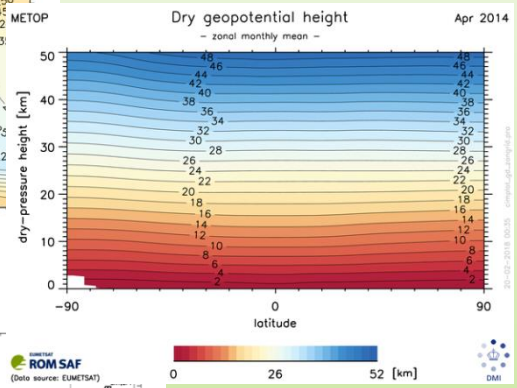
From the time RO data begin to be assimilated, the temperatures of four reanalyses begin to converge, while the *MERRA* temperatures remain significantly higher.

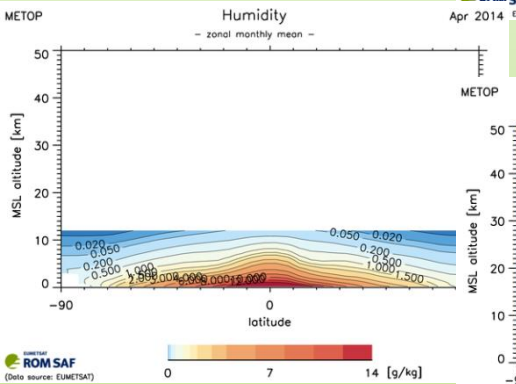
Climate monitoring: gridded monthly mean data

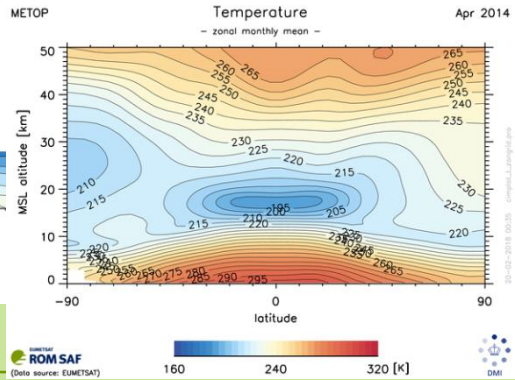


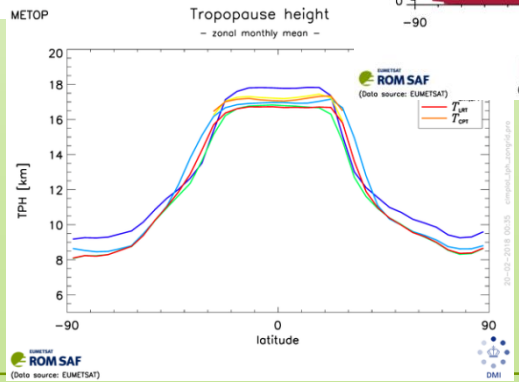






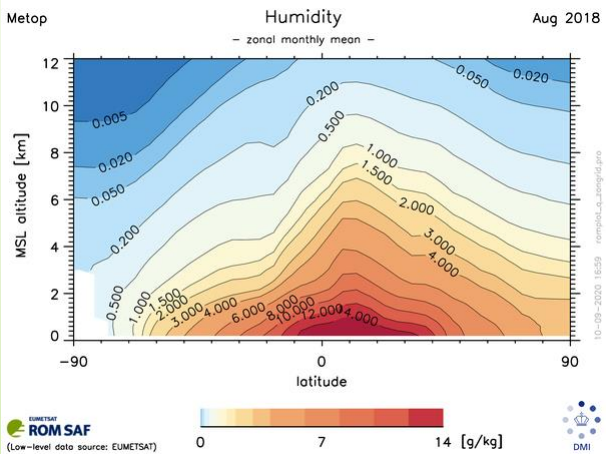




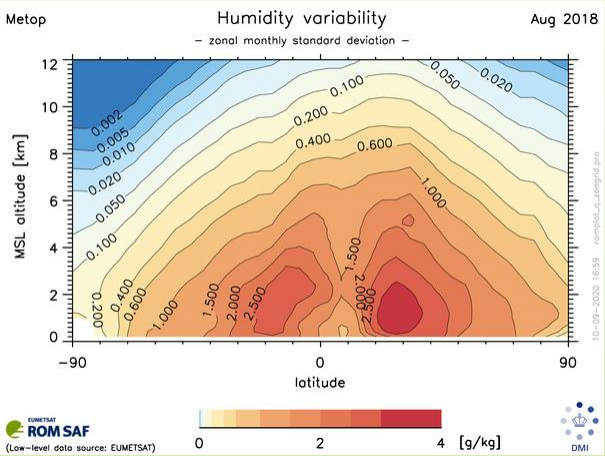


Tropospheric humidity

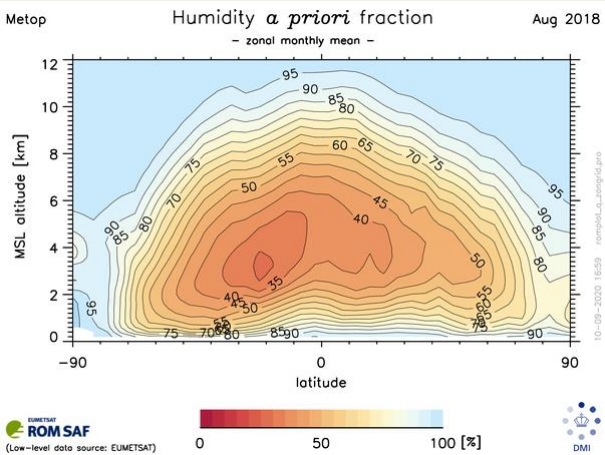
through 1D Variational processing



Mean



Standard deviation



A priori fraction

Humidity climatologies can be obtained by combined RO measurements with model data – here using 1D-Var processing and ERA5 as *a priori*.

Observational information in the retrieved humidity largest around 4 km.

Very little observational information above 10-12 km.

Temperature time series at low latitudes

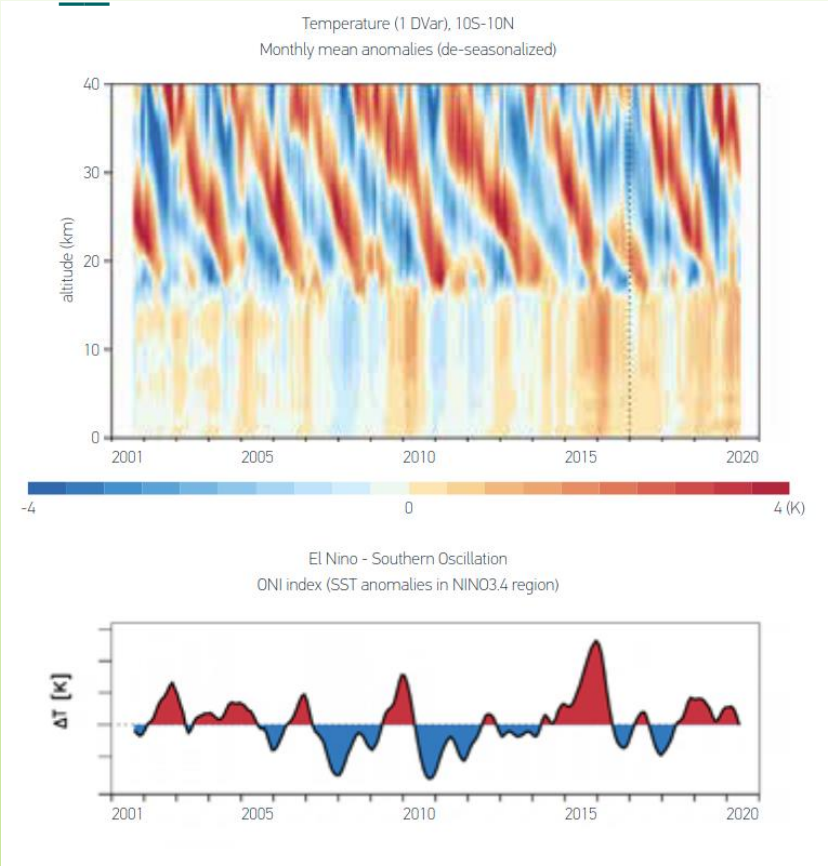
Time series of monthly mean data

- Temperature
- Equatorial monthly means
- De-seasonalized

Low-latitude tropopause clearly visible

Semi-annual variability dominated by:

- Quasi-Biennal Oscillation (QBO) in the stratosphere
- El Nino-Southern Oscillation (ENSO) in the troposphere

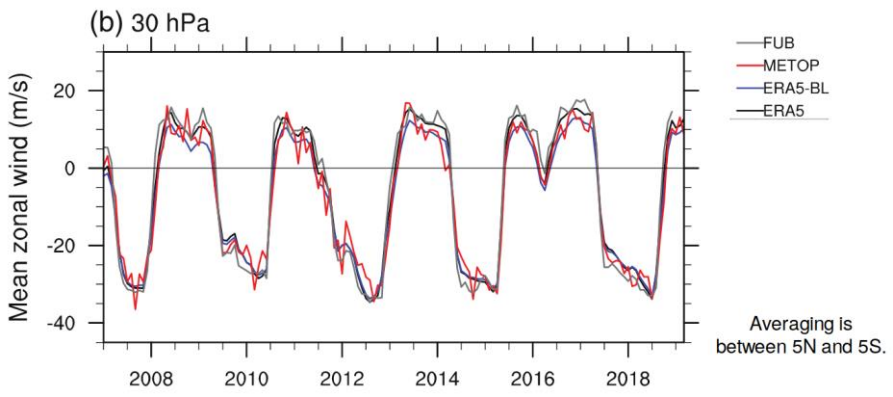


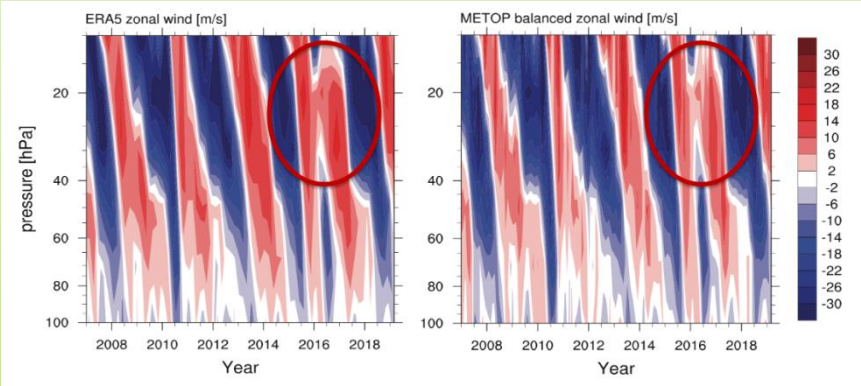
Zonal winds in the equatorial stratosphere

Healy, Polichtchouk, and Horanyi (2020) showed that the equatorial zonal winds associated with the QBO can be derived from RO geopotential observations, using a formulation of the geostrophic balance applicable at the equator:

$$\overline{U} \simeq -\frac{1}{\beta}\frac{\partial^2 \overline{\Phi}}{\partial y^2},$$

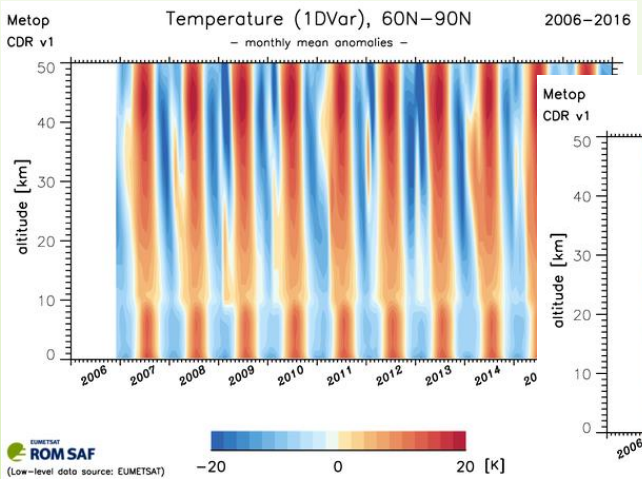
One consequence is that assimilation of RO data appears to improve the zonal winds in reanalyses.



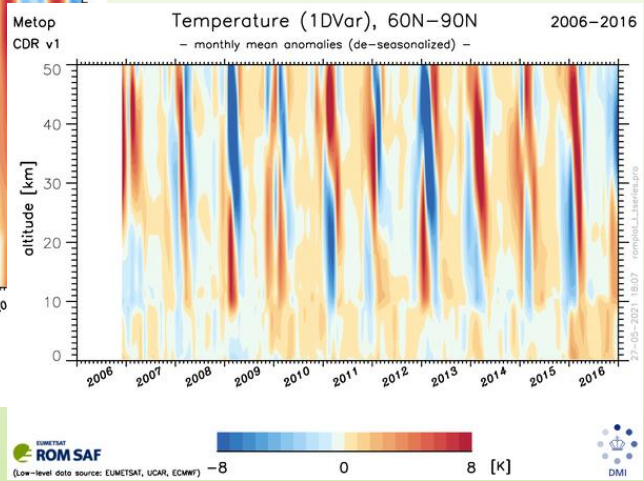


Adapted from Healy, Polichtchouk, and Horanyi (QJRMS, 2020)

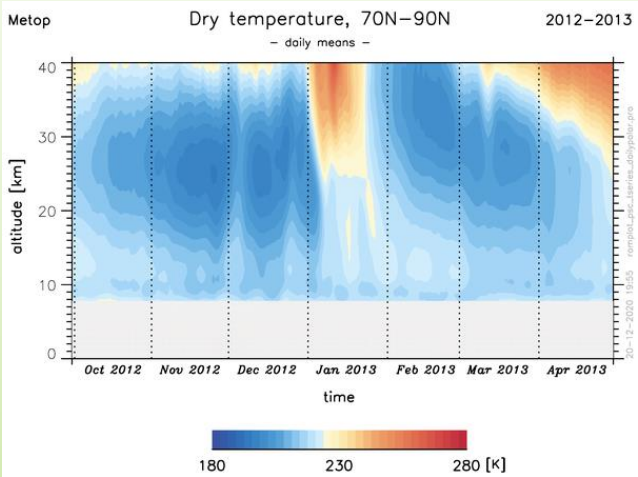
Temperature time series at high latitudes



***Anomalies relative to long-term means*,** dominated by seasonal cycle.

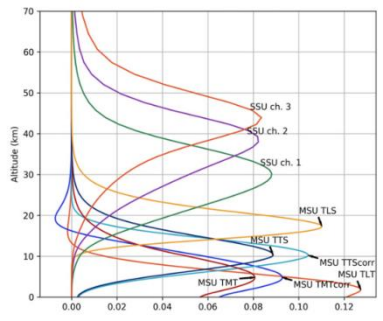


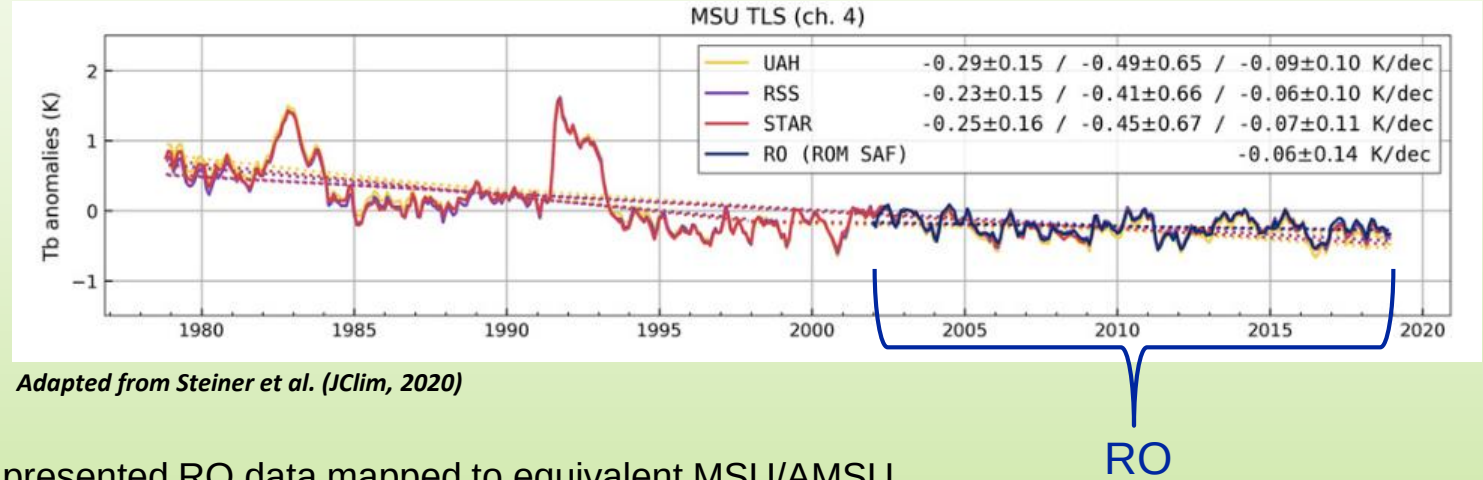
***Anomalies relative to seasonal cycle*,** dominated by polar vortex build-up and breakdown, and Sudden Stratospheric Warmings.



Sudden Stratospheric Warming in the winter of 2012-13 associated with rapid break up of a polar vortex and build-up of a new vortex.

Comparison of RO with MSU/AMSU temperatures

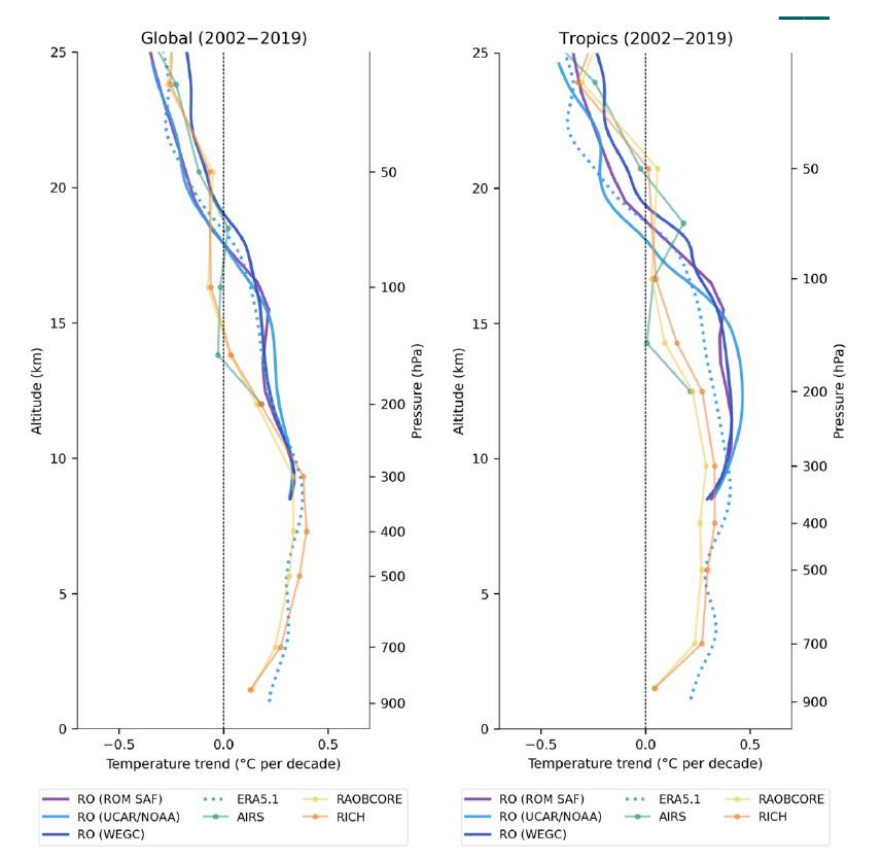




Adapted from Steiner et al. (JClim, 2020)

Steiner et al. (2020) presented RO data mapped to equivalent MSU/AMSU brightness temperatures. The mapping reduces the high vertical resolution of RO to the lower resolution of MSU/AMSU.

Decadal trends: contribution to IPCC WG1 AR6

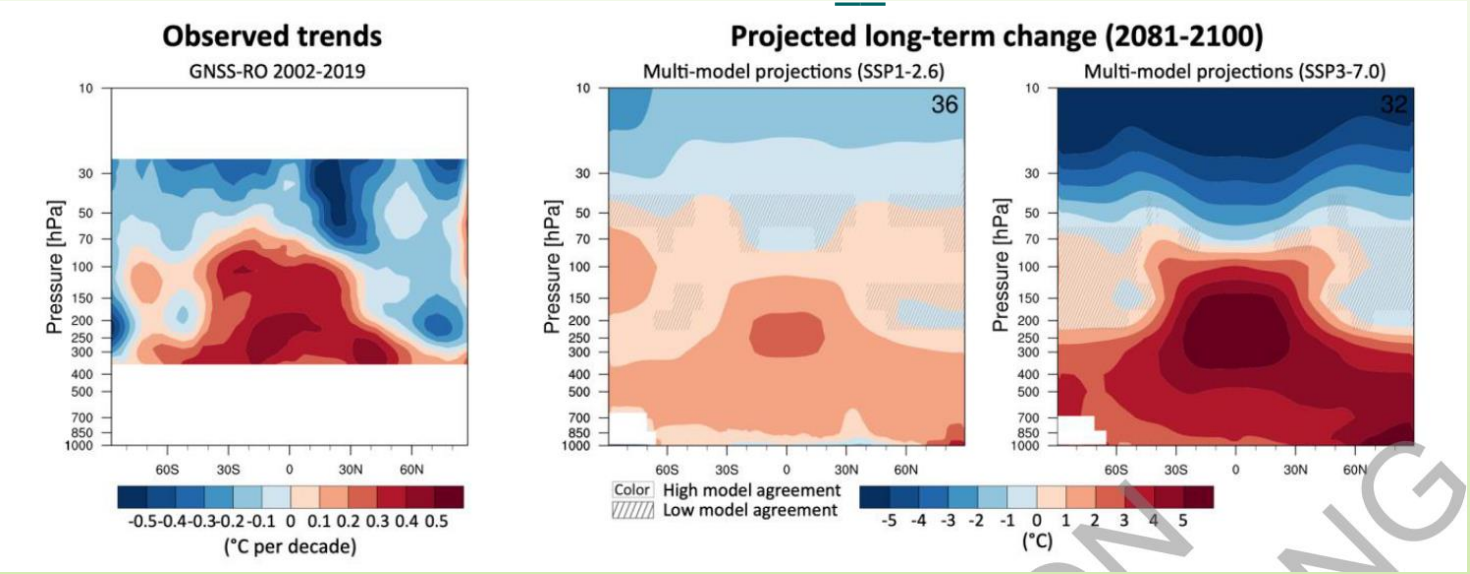


Decadal temperature trends as function of altitude from:

- *RO data from: ROM SAF, UCAR/NOAA, Wegener Center, Graz (WEGC)*
- *Radiosonde datasets: RAOBCORE, RICH*
- *AIRS data*
- *ERA5 data*

From ROM SAF VS40 report (Florian Ladstädter)

Decadal trends: contribution to IPCC WG1 AR6

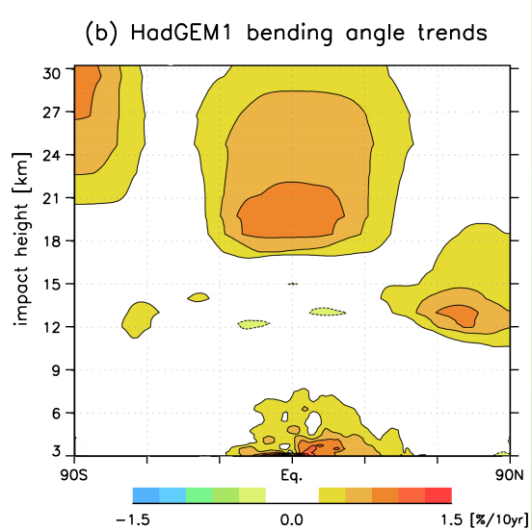


From IPCC AR6 WG 1, Technical Summary

Observed temperature trends in ROM SAF RO data (left) in K/decade compared to to projected temperature changes in two different CMIP6 scenarios over a roughly 85-year time period up to the end of the present century.
The two CMIP6 scenarios are *SSP1-2.6* (middle panel) and *SSP3-7.0* (right-hand panel).

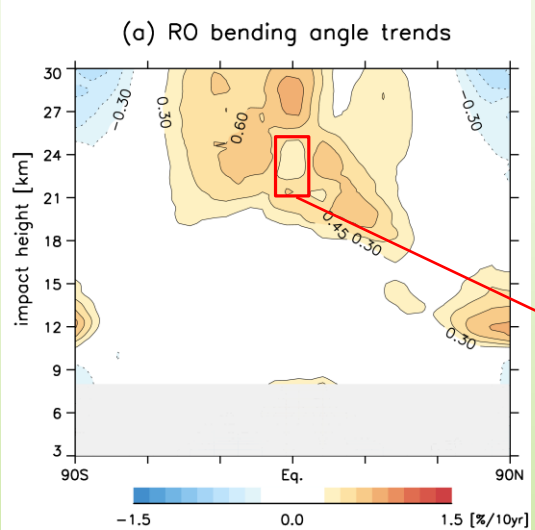
Climate model testing

– HadGEM1 model integrations against RO data –



From Ringer and Healy (GRL, 2008)

Bending angle changes per decade early 2000s to early 2020s from HadGEM1 climate model scenario integrations made 15 years ago.

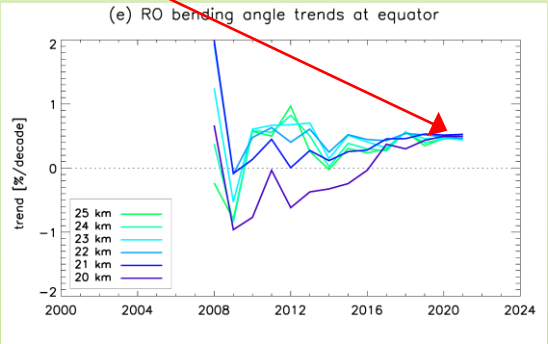


From ROM SAF data (2021)

Observed bending angle trends based on ROM SAF climate data records 2002–2020.

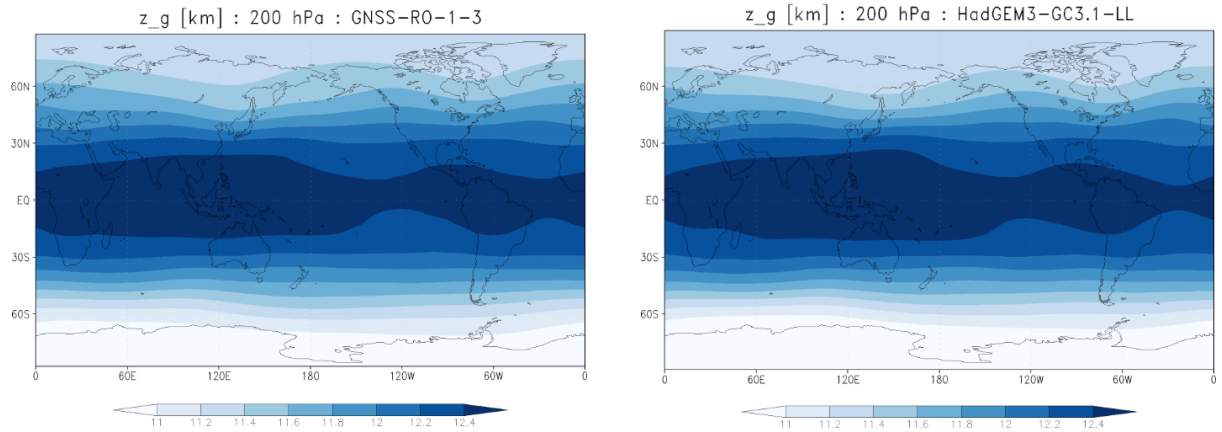
***Ringer and* Healy** (2008) suggested, based on climate model data, that climate trends in the tropical stratosphere bending angles would be clearly detected from 11–16 years of data.

Observed trends seems to have converged with the currently available 19 years of data.



Climate model testing

– HadGEM3 model integrations against RO observations –



- Annual mean 200 hPa geopotential height 2002 – 2014
- Obs4MIPS data produced by NASA-JPL on the ESGF (CHAMP+COSMIC)
- Met Office model forced with observed SSTs and sea ice (AMIP simulation)
- HadGEM3-GC3.1 is the Met Office model submitted to CMIP6

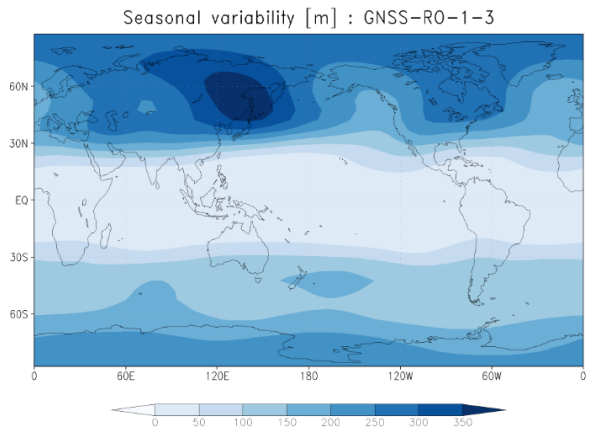
From a presentation by Mark Ringer at the 7th ROM SAF User Workshop

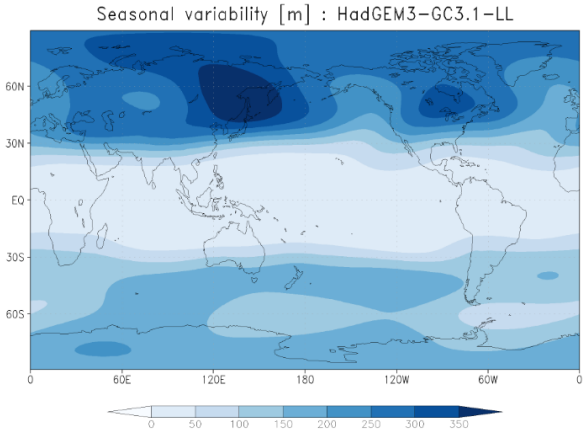
Data from the Met Office Hadley Center HadGEM3 model and RO data from NASA/JPL.

Similar comparisons with several CMIP5 models were made by *Ao et al. (2015)*.

Climate model testing

– HadGEM3 model integrations against RO observations –





- Amplitude of the seasonal cycle: standard deviation about the annual mean
- Model overestimates seasonal variability over NH mid and high latitudes
- In the SH: overestimate over sub-tropics, underestimate at high latitudes

Data from the Met Office Hadley Center HadGEM3 model and RO data from NASA/JPL.

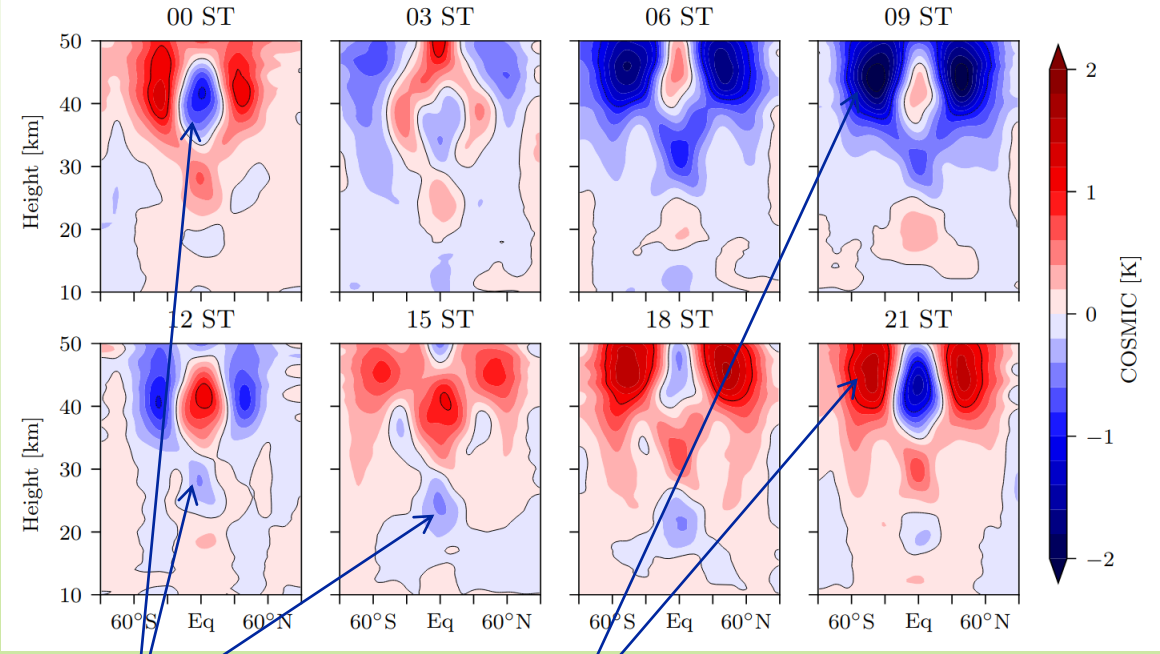
From a presentation by Mark Ringer at the 7th ROM SAF User Workshop

Migrating diurnal tides in the stratosphere

Atmospheric thermal tides can be studied with RO data that samples the whole diurnal cycle (i.e., not Metop-SG alone).

Leroy et al. (2021) fitted spherical harmonics to globally distributed RO data, including basis functions for representation of the local solar time domain.

Plots of the diurnal cycle, at 3-hour intervals, show a) the vertically propagating tides near the equator, and b) a vertically trapped oscillation in the mid-latitude upper stratosphere.



From ROM SAF VS38 report (Stephen Leroy)

Vertically propagating wave

Vertically trapped oscillation

Conclusions

- Nearly 20 years of RO data available for generation of climate data records. Metop-SG will continue to provide RO data well into the 2040's.
- RO data provide uniquely long-term stable remote sensing data with global coverage. High consistency between different RO missions between about 8 and 30–35 km (bending angle consistent up to 40–45 km).
- RO is important for climate reanalyses, providing bias-free ("anchor") data constraining upper-air temperatures (troposphere and stratosphere)
- RO provides important information for monitoring the climate, e.g., the rate of warming in the atmosphere. Complementary to that of other observation types because of the high vertical resolution. Testing climate models using RO is still somewhat unexplored.
- RO decadal trends as function of latitude and altitude included in IPCC Assessment Report 6, Working Group I (The physical science basis)
- RO data contributing to a range of applications important for climate: stratospheric winds (QBO), polar stratosphere, diurnal tides, static stability and gravity waves, etc.
- Firm commitment from the EUMETSAT ROM SAF to make RO based climate data records available, including regular updates addressing recent scientific developments.

RO data available at the ROM SAF web site

Climate Data Records (CDRs)

Mission	Time period	DOI	Product ID	Data access
Metop	200610 - 201612 200612 - 201612	10.15770/EUM_SAF_GRM_0002	GRM-29-R1	Profile data Gridded data
COSMIC	200604 - 201612 200607 - 201612	10.15770/EUM_SAF_GRM_0003	GRM-30-R1	Profile data Gridded data
CHAMP	200109 - 200809 200109 - 200809	10.15770/EUM_SAF_GRM_0004	GRM-32-R1	Profile data Gridded data
GRACE	200703 - 201612 200703 - 201612	10.15770/EUM_SAF_GRM_0005	GRM-33-R1	Profile data Gridded data
Multi	200109 - 201612	10.15770/EUM_SAF_GRM_0001	GRM-28-R1	Gridded data

Information and limitations: README_CDR

Interim Climate Data Records (ICDRs) - *extending the CDRs in time*

Mission	Time period	DOI	Product ID	Data access
Metop	201701 - 202106 201701 - 202105	10.15770/EUM_SAF_GRM_0006	GRM-29-I1	Profile data Gridded data

Information and limitations: README_ICDR

https://www.romsaf.org

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