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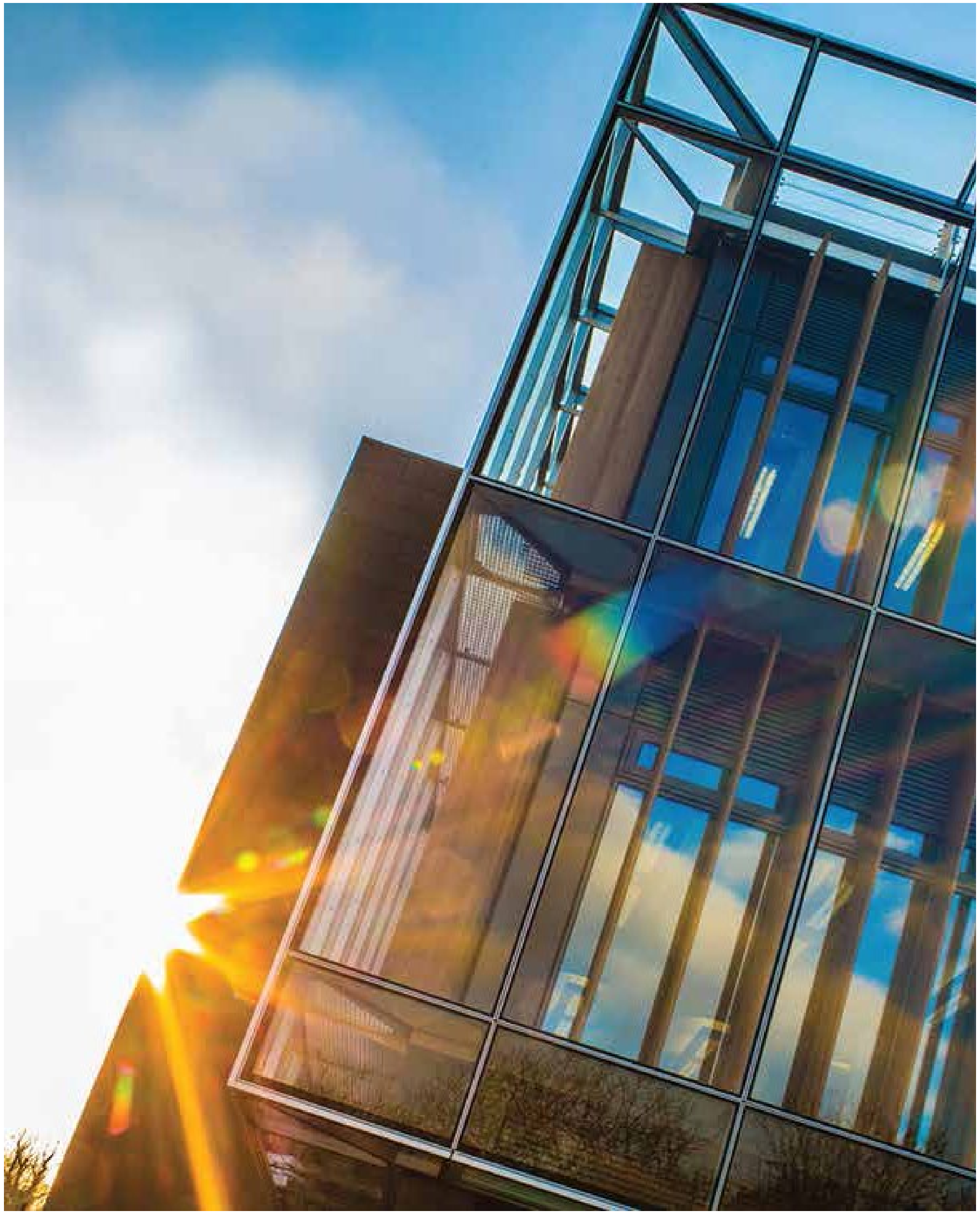
Current and potential future applications of RO measurements in climate applications

Peter Thorne



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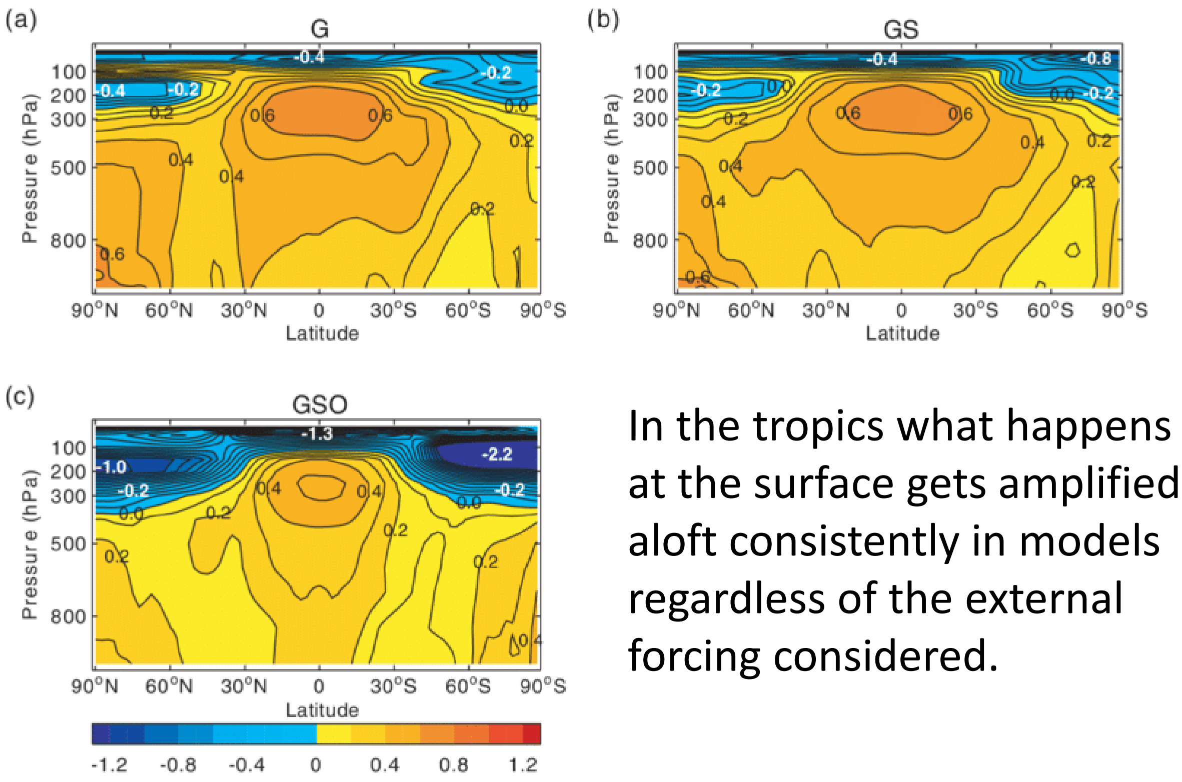
1. Past use

A case study application: RO has helped to start to resolve issues around tropical amplification

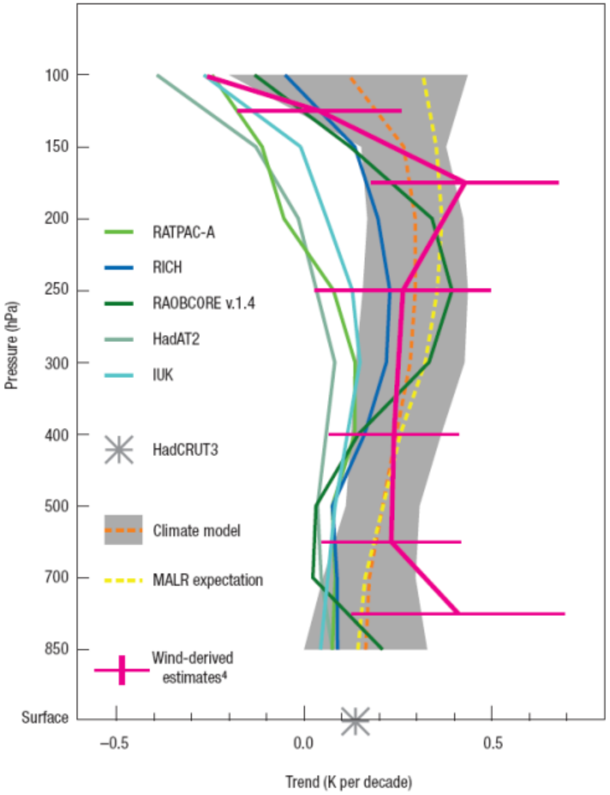


In the tropics what happens at the surface gets amplified aloft consistently in models regardless of the external forcing considered.

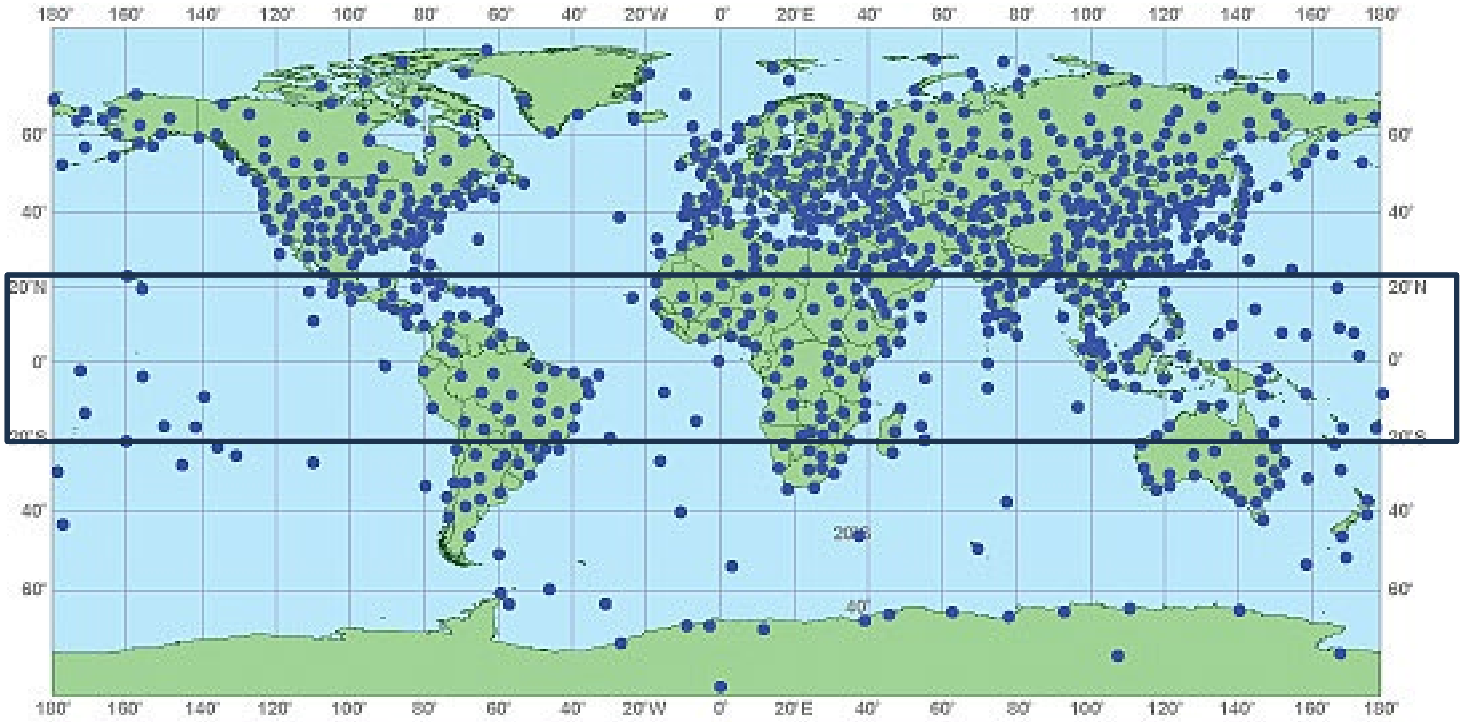
Historical ambiguity in whether models and observations agree

Some radiosonde observations have agreed with models whereas others have not.

Radiosondes are sparse in the tropics.



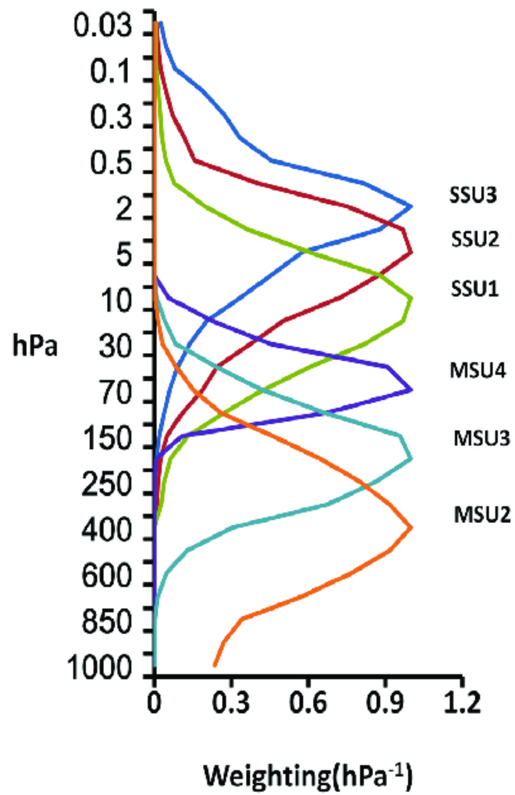
Sparsity of radiosondes



Current global radiosonde network – not all sites here fly regularly. Flights are generally once or twice daily at 00 or 12 UTC. Unsurprisingly a huge land bias.

Microwave sounding channels are far too broad to elucidate vertical structure changes

The long-term microwave measurements do not have the necessary fidelity even with 'novel' recombinations

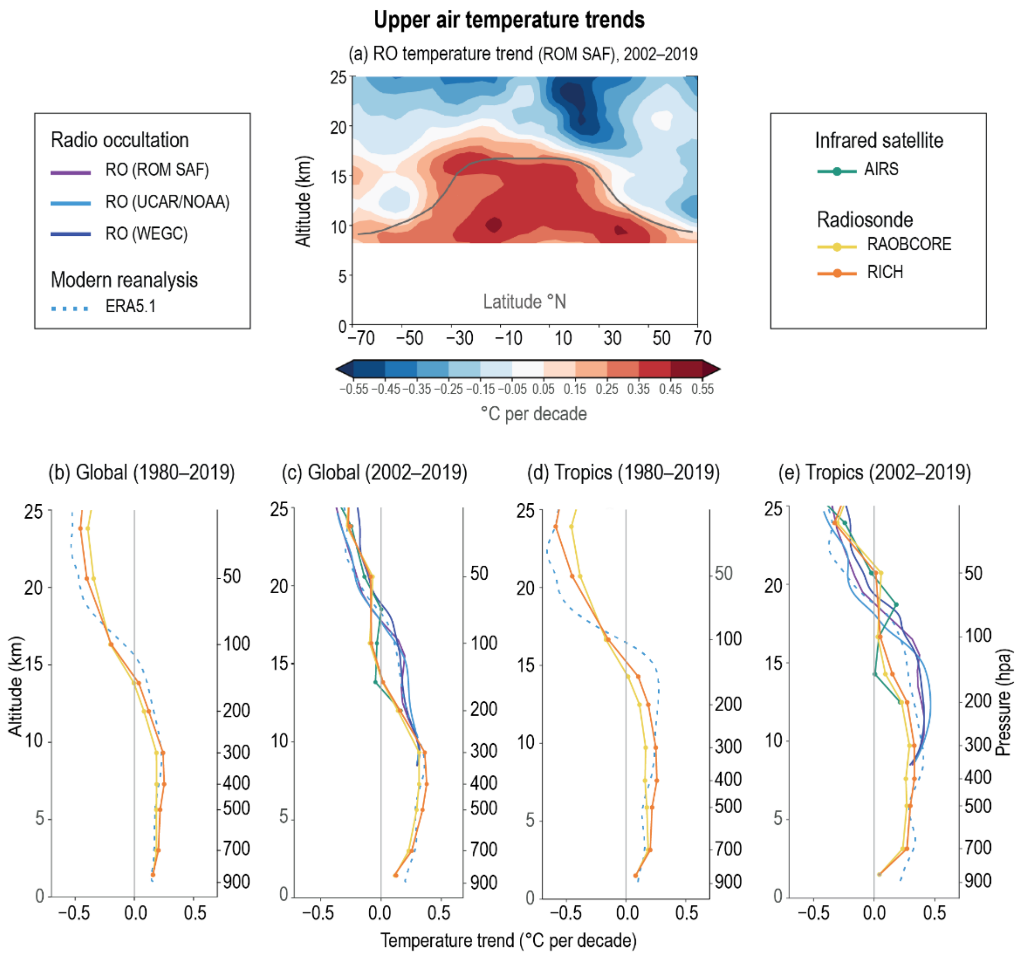


This is also an issue in reanalyses in regions where there is insufficient radiosonde (vertically resolved) constraint – the model potentially overfits leading a 'wave train' vertically – RO helps here (as does better conditioning the model).

See Gravesen et al and responses https://www.nature.com/articles/nature06502

[Assuming that Bill Bell will talk more generally about use in reanalyses]

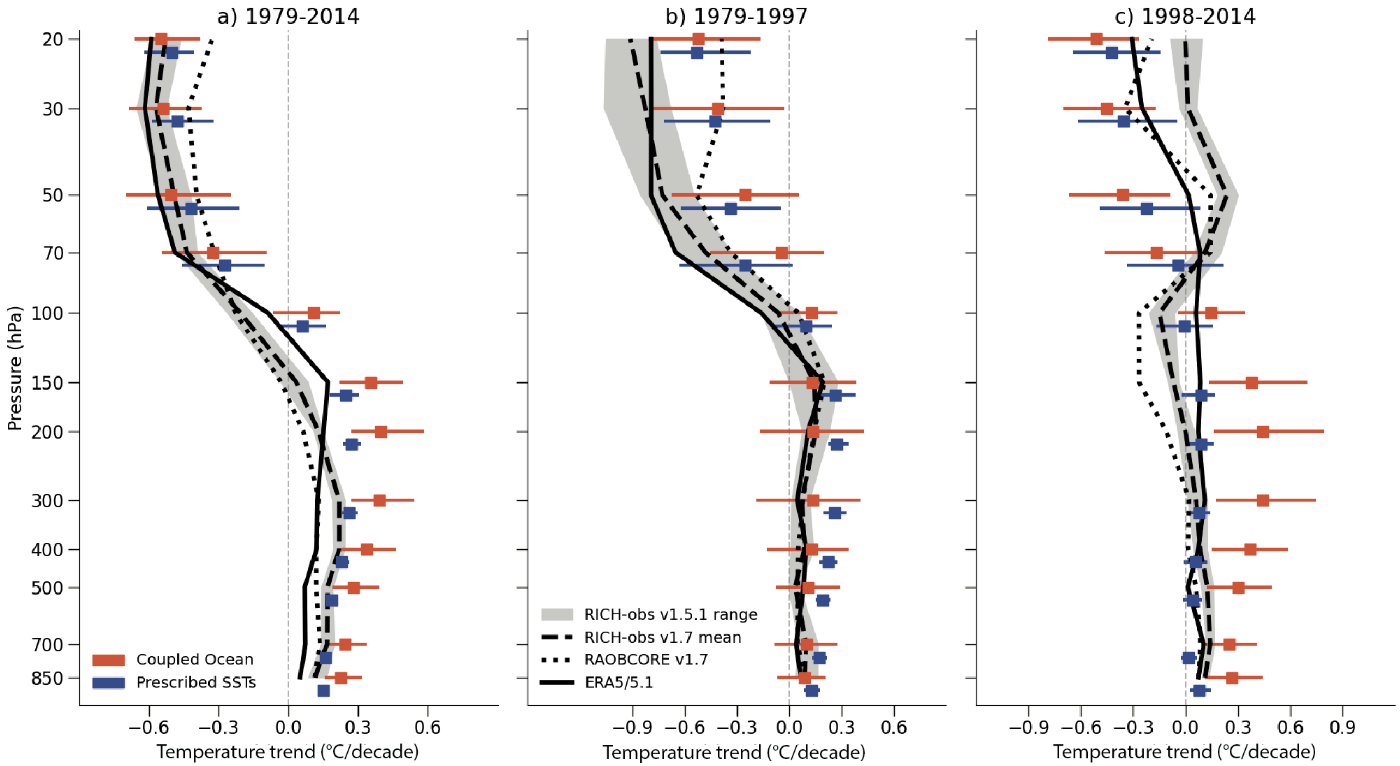
IPCC AR6: Enter the Radio Occultation



Although only available for a shorter period than radiosondes a combination of RO and hyperspectral IR was deemed of high value.

RO consistently exhibit tropical amplification with a peak in the upper troposphere

But not quite all the way through the value chain …



In the chapter looking at model validation and detection and attribution RO was not used because there were no published studies and because RO only started higher up.

One can 'mind-meld' the two but its not ideal

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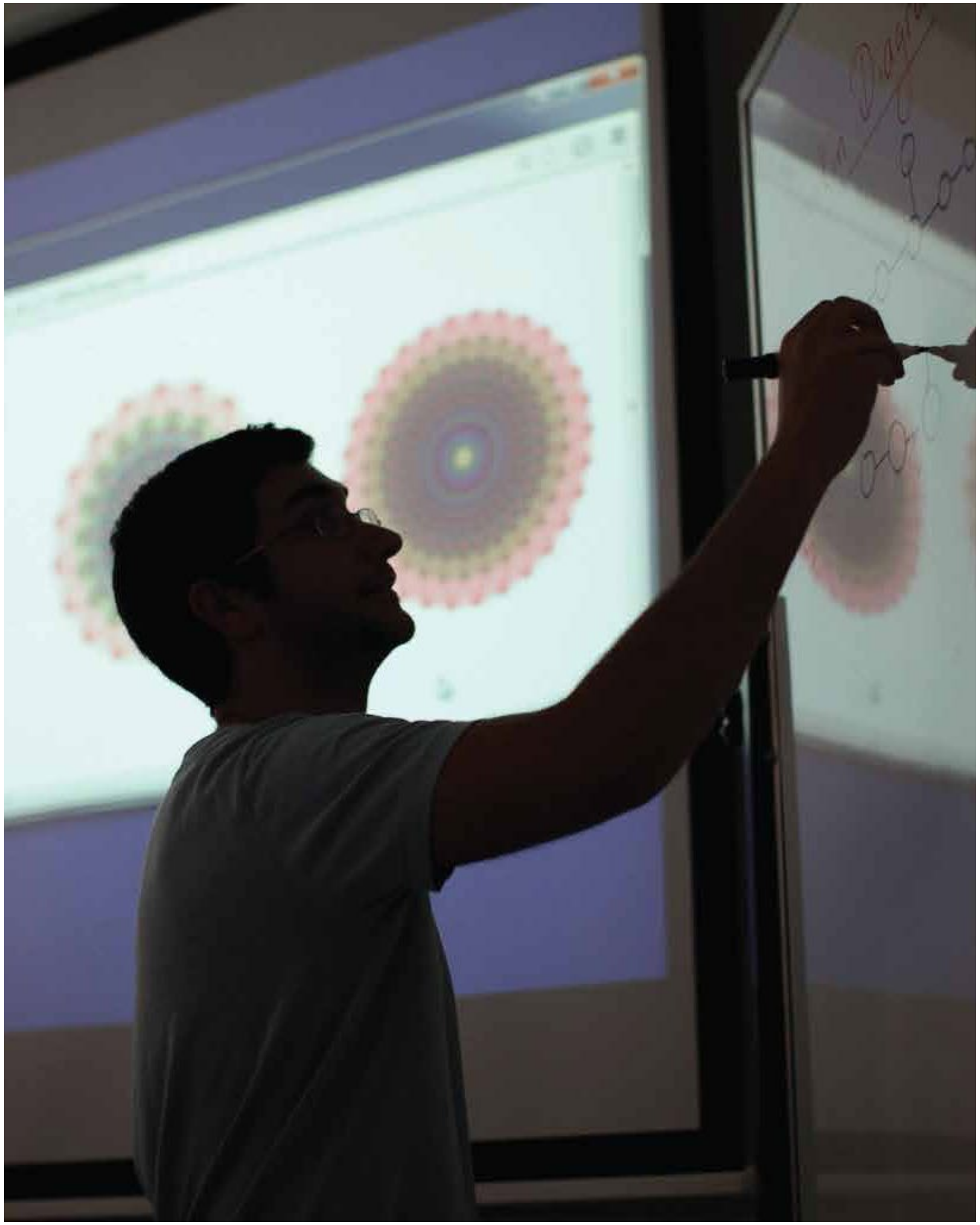
2. Potential applications / future developments



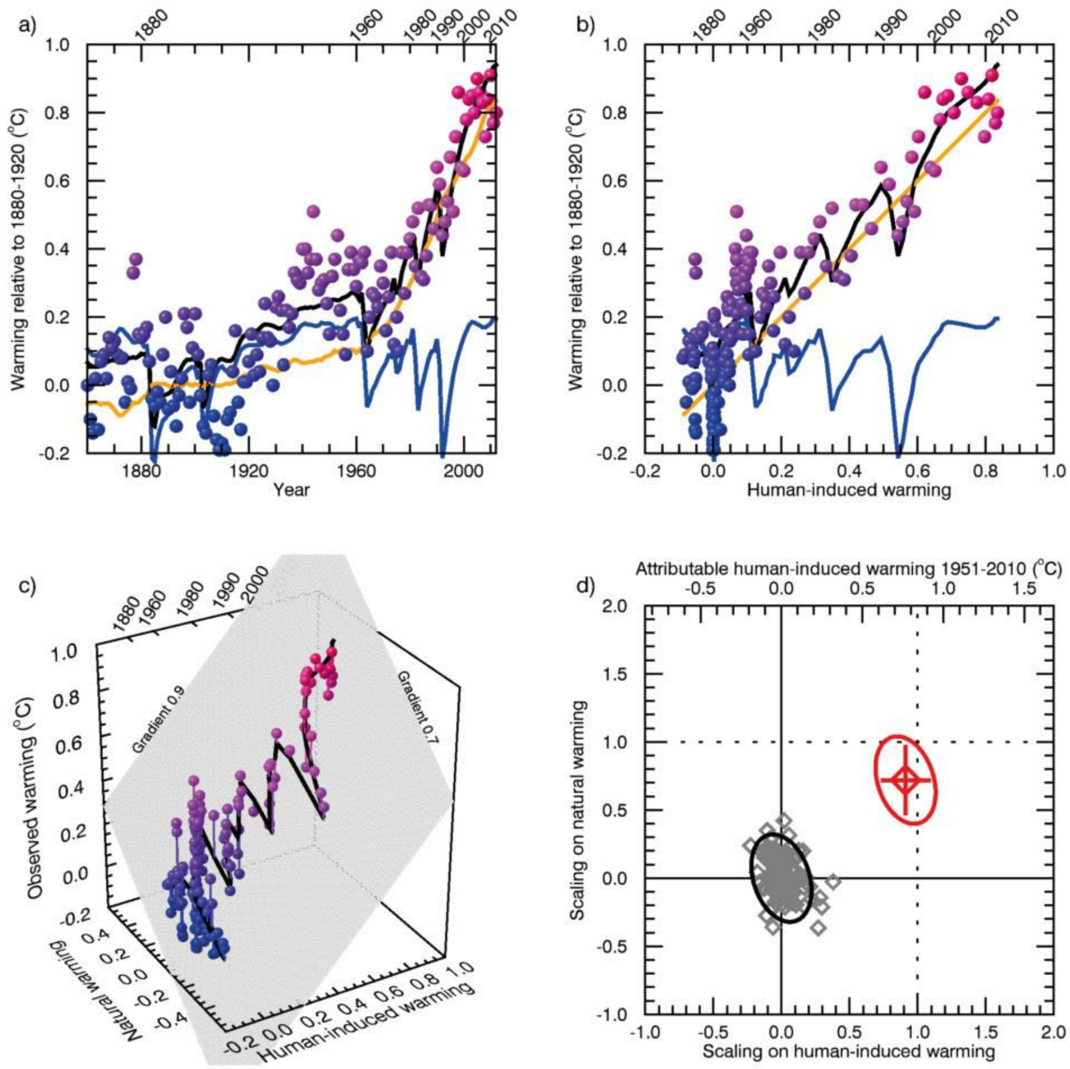
There remain many open questions where RO could help

- Formal detection and attribution
- Tropopause height
- Boundary layer height?
- Resolving diurnal cycle effects for long-term MSU

- This list is not comprehensive …

Formal detection and attribution

- Ringer and Healy (2008) suggested that the signal should become detectable after about 16 years
- There have been some model-observation comparisons confirming this
- But not, yet, a formal detection and attribution study using modern fingerprinting techniques


a)
Warming relative to 1880-1920 (°C)
Year
b)
Human-induced warming
c)
Observed warming (°C)
Gradient 0.9
Gradient 0.7
Natural warming
Human-induced warming
d)
Attributable human-induced warming 1951-2010 (°C)
Scaling on natural warming
Scaling on human-induced warming

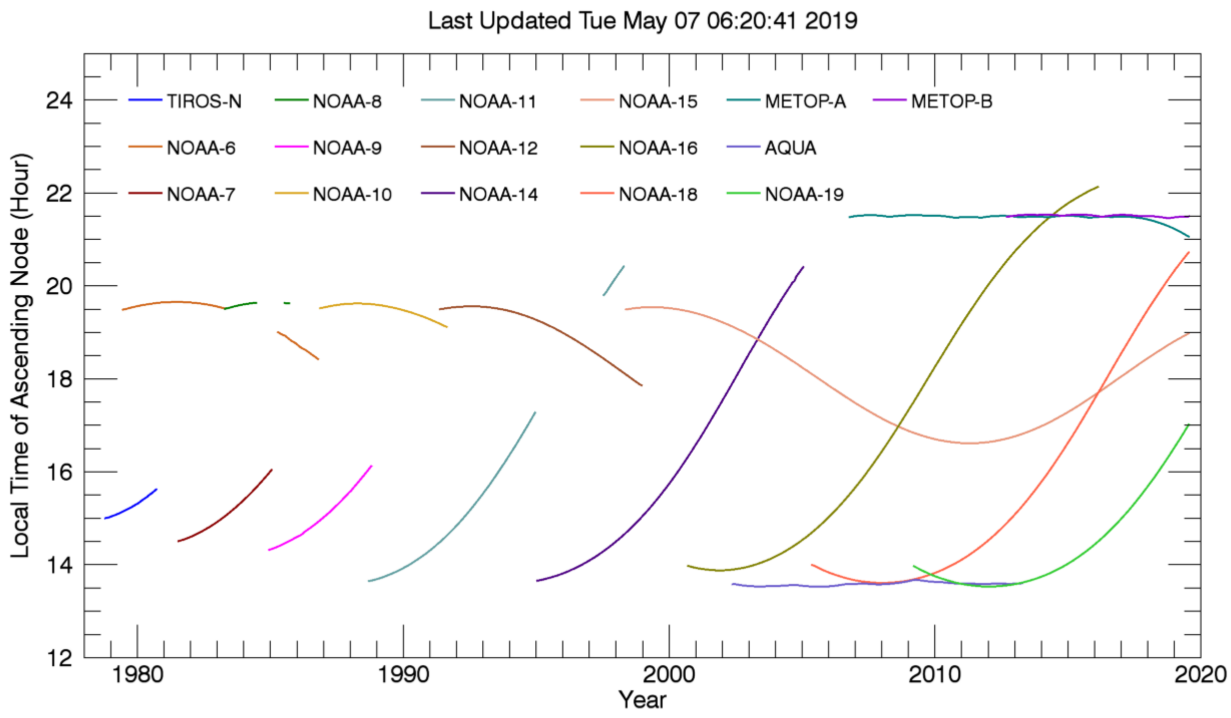
Tropopause height

- The tropopause height is an integrative measure of both changes in the troposphere and the stratosphere
- But it is really under-considered in the literature
- Most recent literature uses RO data (unsurprisingly) but is thus far largely from a literature search describing observed trends. Largely missing to my knowledge:
  - Formal model comparisons / validation
  - Understanding causes (D&A)
  - Process understanding e.g. changing statistics of double tropopause and implications

Boundary layer height

- Boundary layer is where we all live so changes in boundary layer are important
- Boundary layer height is a useful indicator
- Some occultations can see what is likely to be the top of boundary layer inversion
  - Is the BLH a well-posed diagnostic?
  - Is some occultations ‘enough’?
  - Do we understand why some do and some do not? Is it because of conditions aloft or conditions below or both?
  - If it preferentially is sampled in certain states how useful is RO for monitoring BLH changes?

Historical polar orbiter station keeping issues



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Ambiguity in MSU/AMSU/ATMS records

- Largest when satellites were drifting rapidly as alias in diurnal effects
- Largest in tropics where repeat frequency is 3 days
- No robust estimate of the diurnal cycle
  - For lowermost channels need estimate of skin surface cycle
  - Most radiosondes at 00 and / or 12Z
  - Reanalyses will suffer from this
  - Climate models are imperfect

RO (increasingly) samples the diurnal cycle

- As the number of GNSS satellites and RO receiver platforms increases (particularly with commercial smallsats) we get more and more samples across a broader range of LSTs (still not homogeneous)
- Sufficient samples to determine diurnal and semi-diurnal and even higher order moments seasonally at least from recent record?
- Can we use this to provide better estimates of the required diurnal adjustments?

Bottom line

- If you want RO to be more used and visible in IPCC AR7
- Yes, you need to continue to develop RO products
- BUT …
- To be more widely applied need to go from dataset development and deployment to using as a tool to answer questions that are IPCC relevant
- These need to be published in the peer reviewed literature
- Also, there will be a literature cut-off probably some time in 2027 (TBC)

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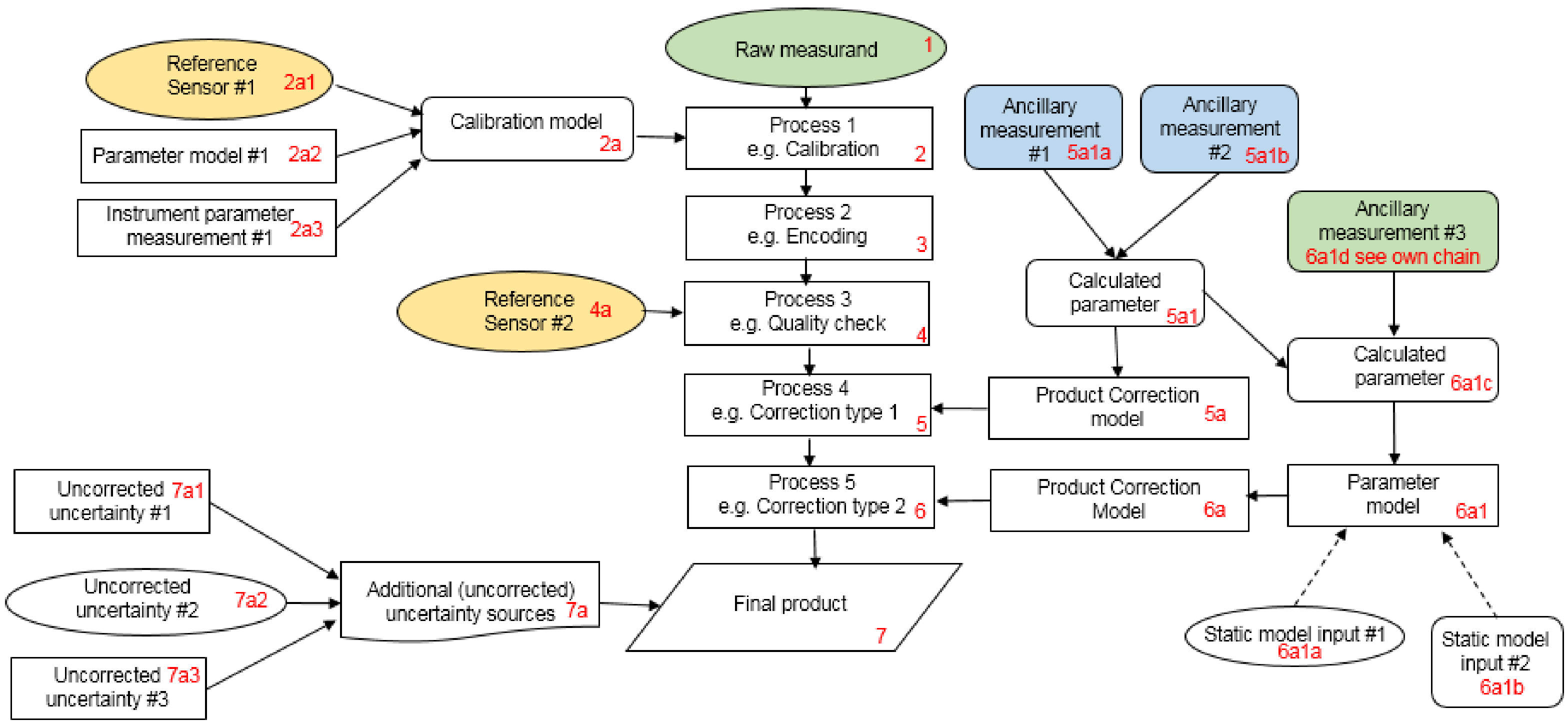
3. Metrological rigor in climate datasets?

Can we get really robust uncertainty estimates on RO datasets?

- We know that the fundamental measurement of time delay is SI traceable and stable
- BUT …
  - There are several subsequent processing steps
  - Which will add uncertainty which may be systematic, structured random or random in nature
  - And may interact
- It would be valuable to more metrologically robustly quantify the uncertainty.

Traceability chains



Information / data	**Type / value / equation**	**Notes / description**
Name of effect	IGS Final Products clock error	
Contribution identifier	2	
Measurement equation parameter(s) subject to effect	$\Delta ZTD = t_{clock}/c$ $u_{ZTD} = u_{Psat(x,y,z)}$	
Contribution subject to effect (final product or sub-tree intermediate product)	ZTD	Note that the satellite and receiver clock errors get canceled out while using Double Differenced strategy in GNSS data processing (Bernese, GAMIT).
Time correlation extent & form	Between 15 mins & 1 day depending on application	
Other (non-time) correlation extent & form	None	
Uncertainty PDF shape	Normal	
Uncertainty & units	Typically, clocks accurate to ~75 ps (1σ) RMS (~20 ps SDev)	See Table 2
Sensitivity coefficient	c^{-1} (speed of light)	
Correlation(s) between affected parameters	None	
Element/step common for all sites/users?	Yes	
Traceable to …		
Validation	Inter-comparison studies.	

Element identifier	Contribution name	Uncertainty contribution form	Typical value	Traceability level (L/M/H)	random, structured random, quasi-systematic or systematic?	Correlated to? (Use element identifier)
1	IGS Final Orbits	Statistical	~2.5 cm	H	systematic	Antenna pos., ZTD, σ_{ZTD}
2	IGS clocks	Statistical	75 ps	H	systematic	Antenna pos., ZTD, σ_{ZTD}
3	Uncertainty contributors to GNSS observations					
3a1	Antenna type and radome	N/A	±0 mm	L	systematic	GNSS obs., ZTD, σ_{ZTD}
3a2	Antenna cut-off	N/A	±0 mm	L	systematic	GNSS obs., ZTD, σ_{ZTD}
3a3	Multipath	N/A	±0 mm	L/M	systematic	GNSS obs., ZTD, σ_{ZTD}
3a4	Unmodelled environmental effects	N/A	±0 mm	L	random	GNSS obs., ZTD, σ_{ZTD}
5	Uncertainty of ZTD, σ_{ZTD}	constant	± 4 mm (1σ)		random	σ_{IPW}
6	Uncertainty of surface temperature, T_s	constant	± 0.1 K (1σ)	H	systematic	T_m
7	Uncertainty of surface pressure, σ_{P0}	constant	± 0.2 hPa (1σ)	H	systematic	ZHD, ZTD
8	Uncertainty of Tm	constant	± 1-2 K	H	systematic	σ_Q

Realising robust uncertainty estimates

- FIDUCEO H2020 project did this for a subset of satellite missions so there is precedent
- Need to quantify uncertainty through the entire processing chain
- Generally did it using monte carlo simulation to allow expression of correlation between terms

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Conclusions

To conclude

- Great to see greater use of RO data including in IPCC
- If you want to see more use really need to animate applications that use RO data and products to inform critical science questions
- Can the uncertainties be handled with greater metrological rigor using established techniques in EU H2020 projects?