Imperial College London

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

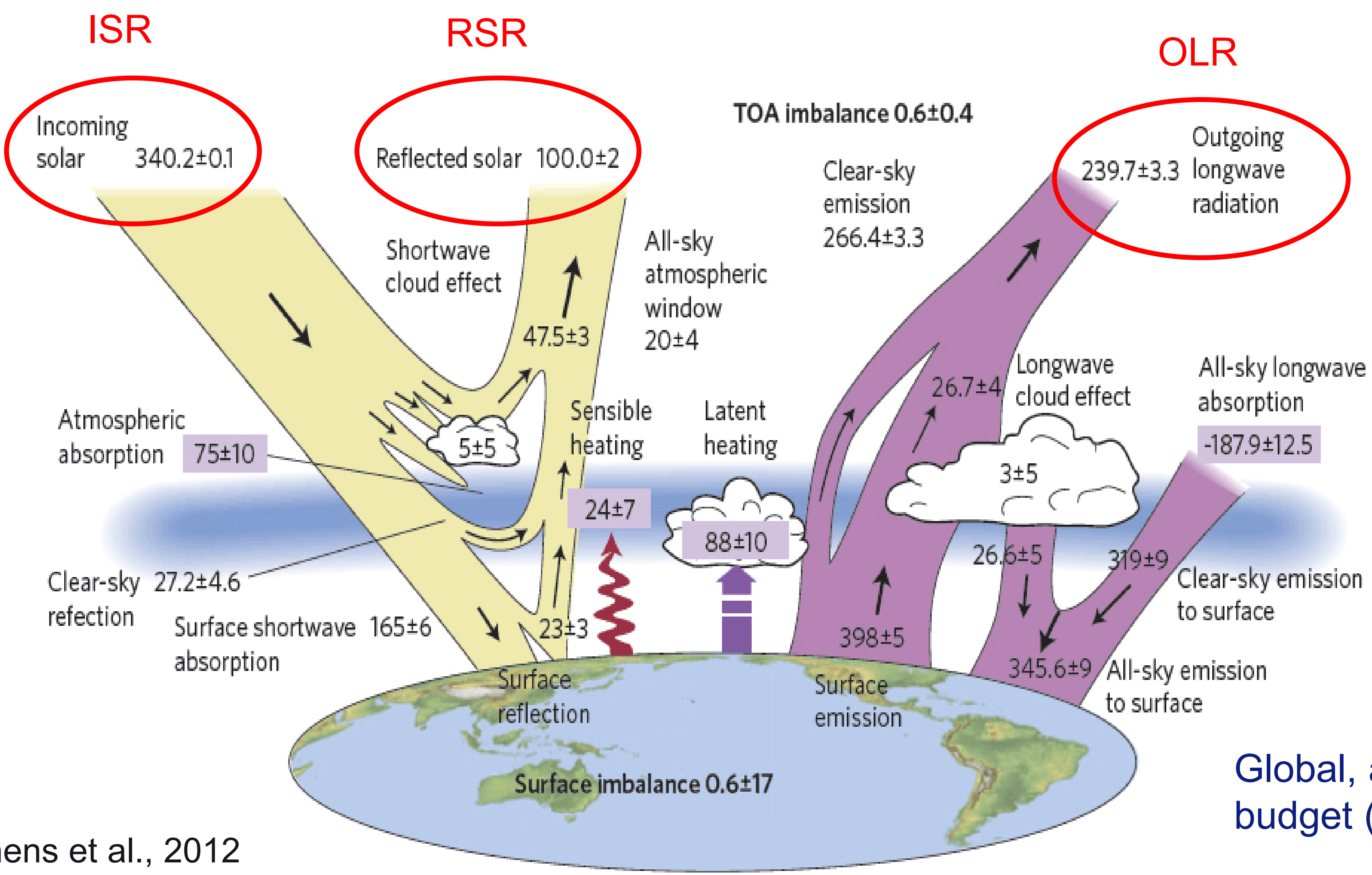
Unlocking the potential of spectrally resolved radiation observations for Earth System Model evaluation

Helen Brindley
Space and Atmospheric Physics Group &
National Centre for Earth Observation
Imperial College London

ECMWF Annual meeting, 14th September 2022

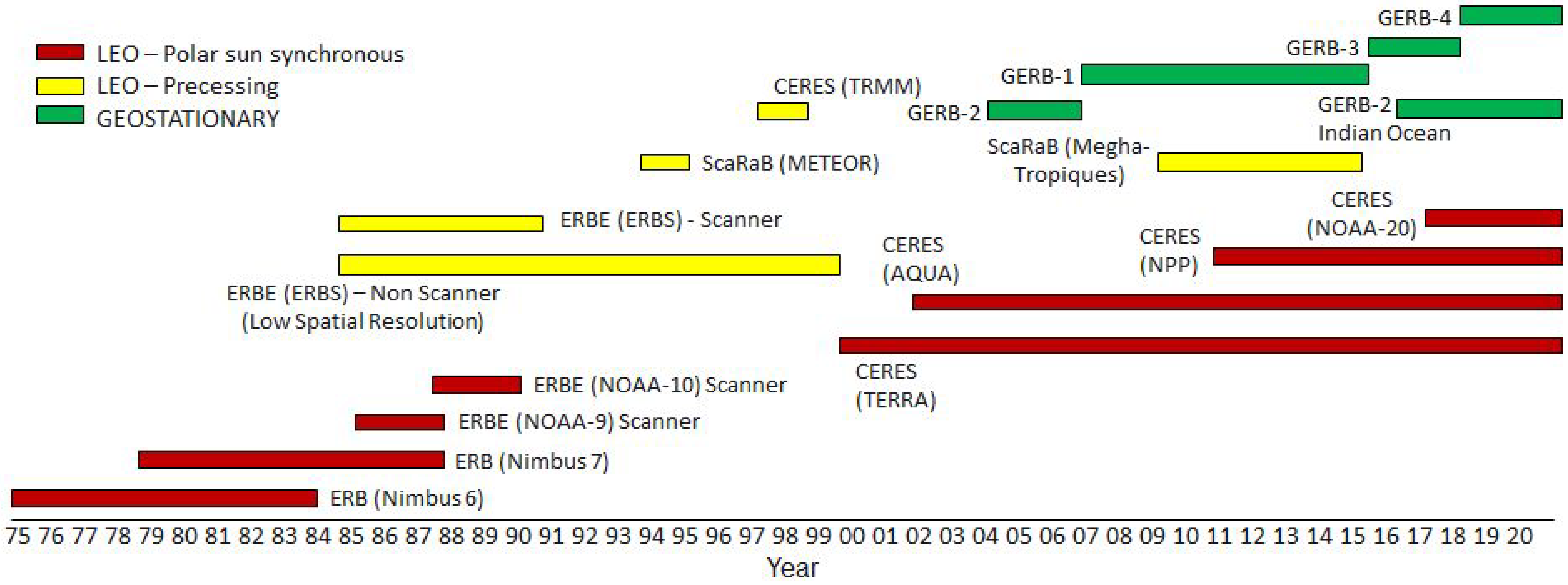
The Earth's Energy Budget

The (im)balance between net incoming solar radiation and outgoing longwave radiation fundamentally drives our climate system



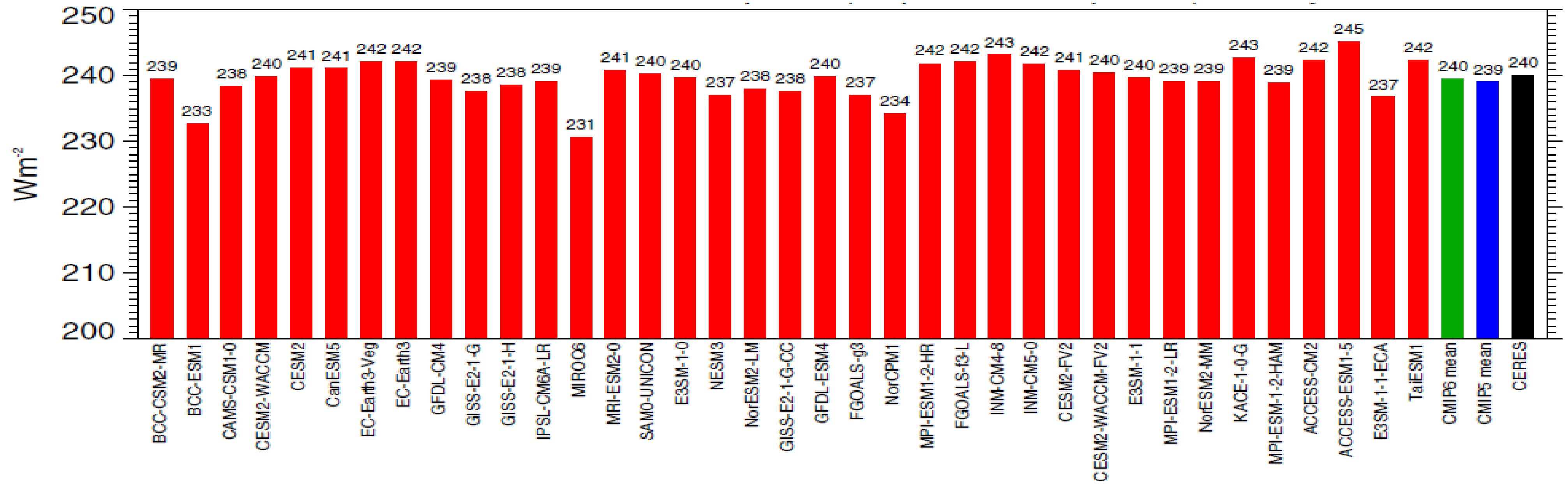
Global, annual mean energy budget (2000-2010)

Stephens et al., 2012

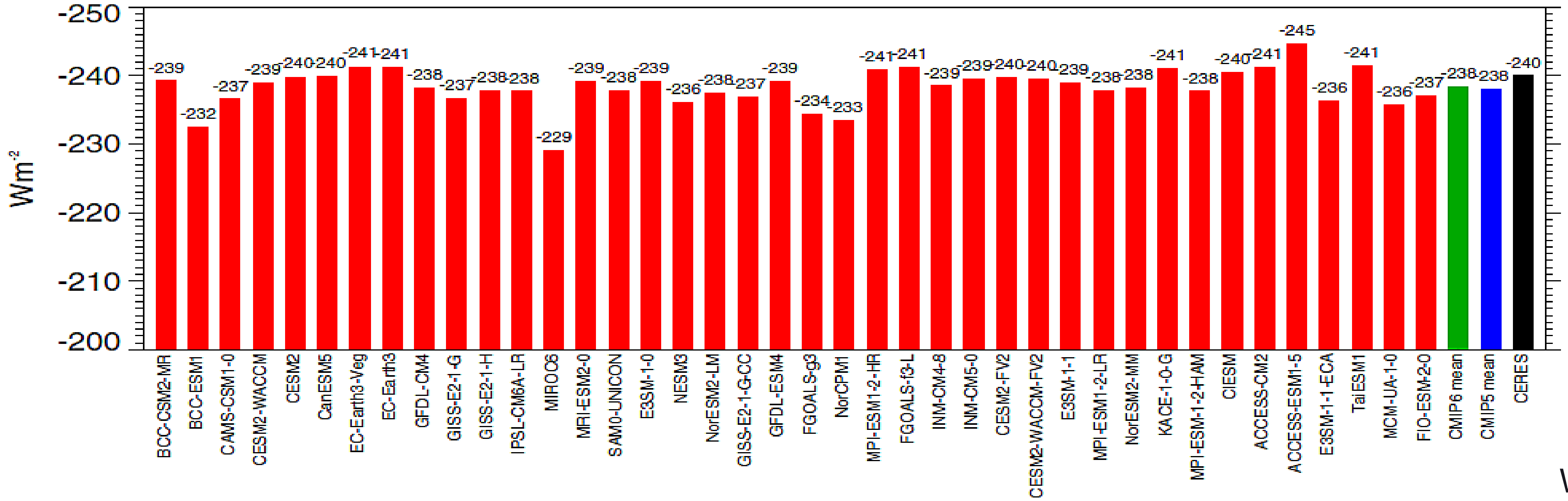


- Continuous satellite-based measurements of the reflected shortwave radiation and the outgoing longwave radiation have been made for almost 50 years from a variety of platform types

Model evaluation: Global annual mean flux



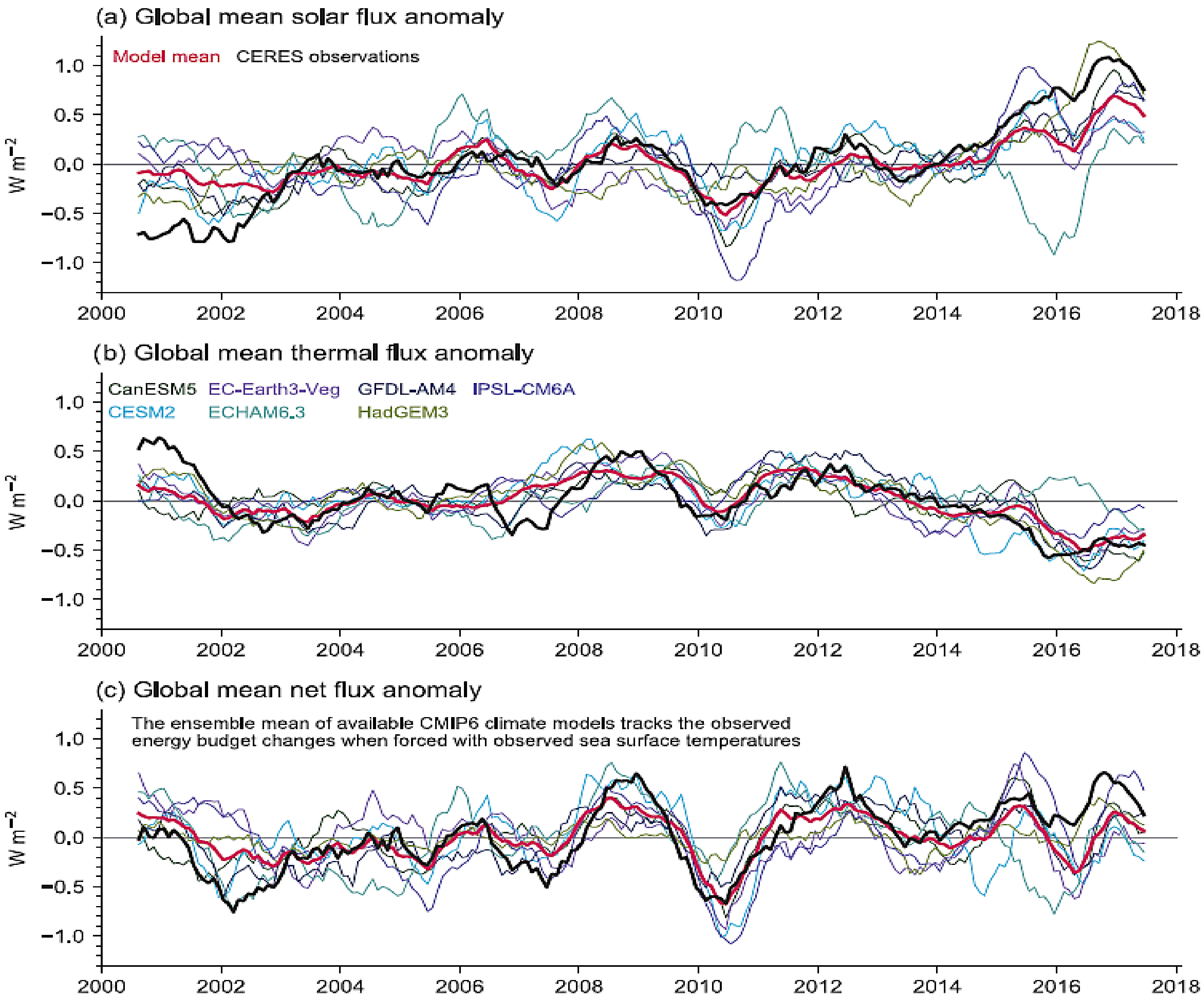
Total Absorbed SW flux



TOA Outgoing longwave flux

Wild, 2020

Model evaluation: Global mean flux anomalies



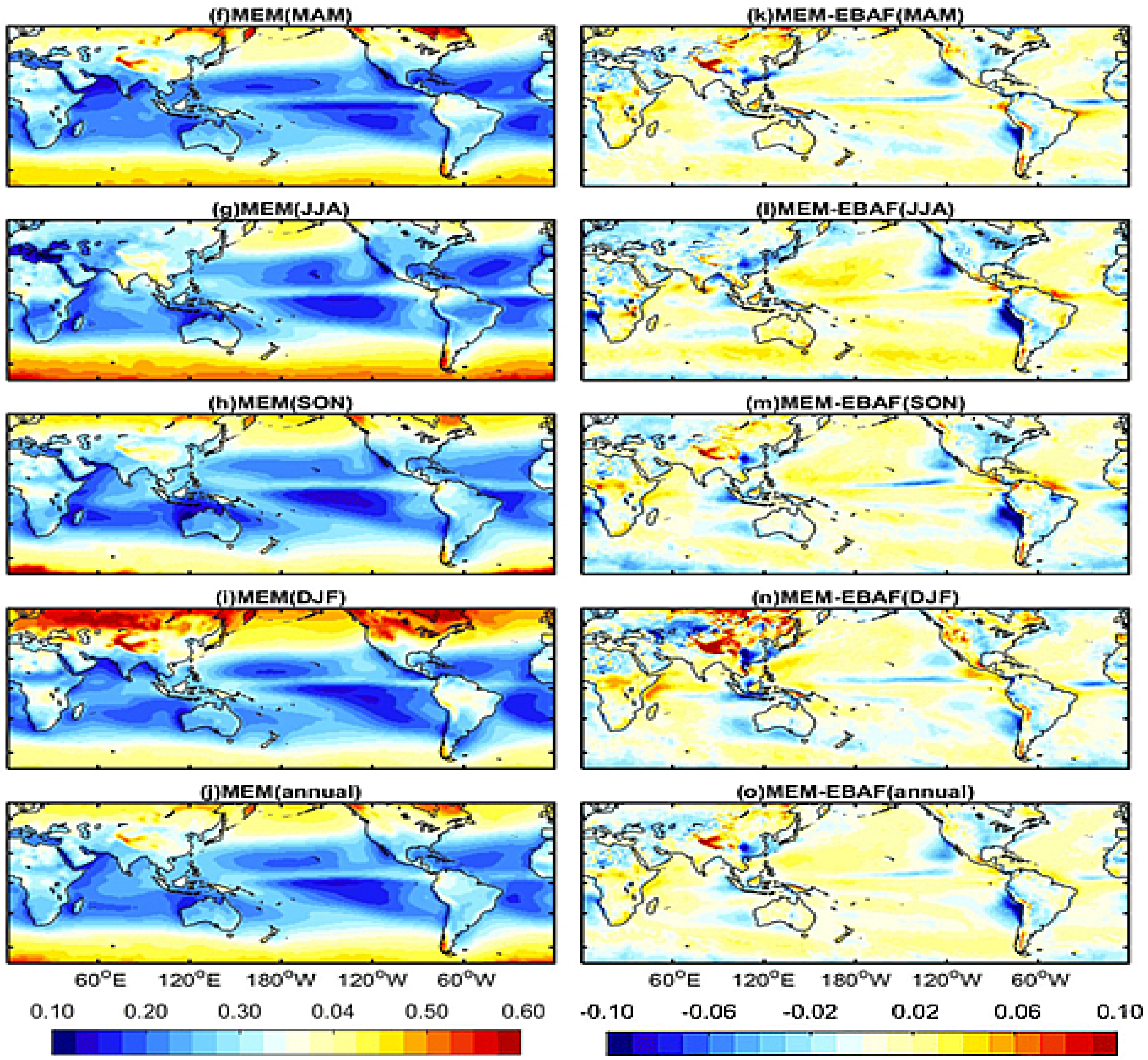
Comparison of CERES-EBAF and AMIP6 type simulations from a subset of CMIP6 models

Fluxes defined positive downwards

Forster et al., 2021 (adapted from Loeb et al., 2020)

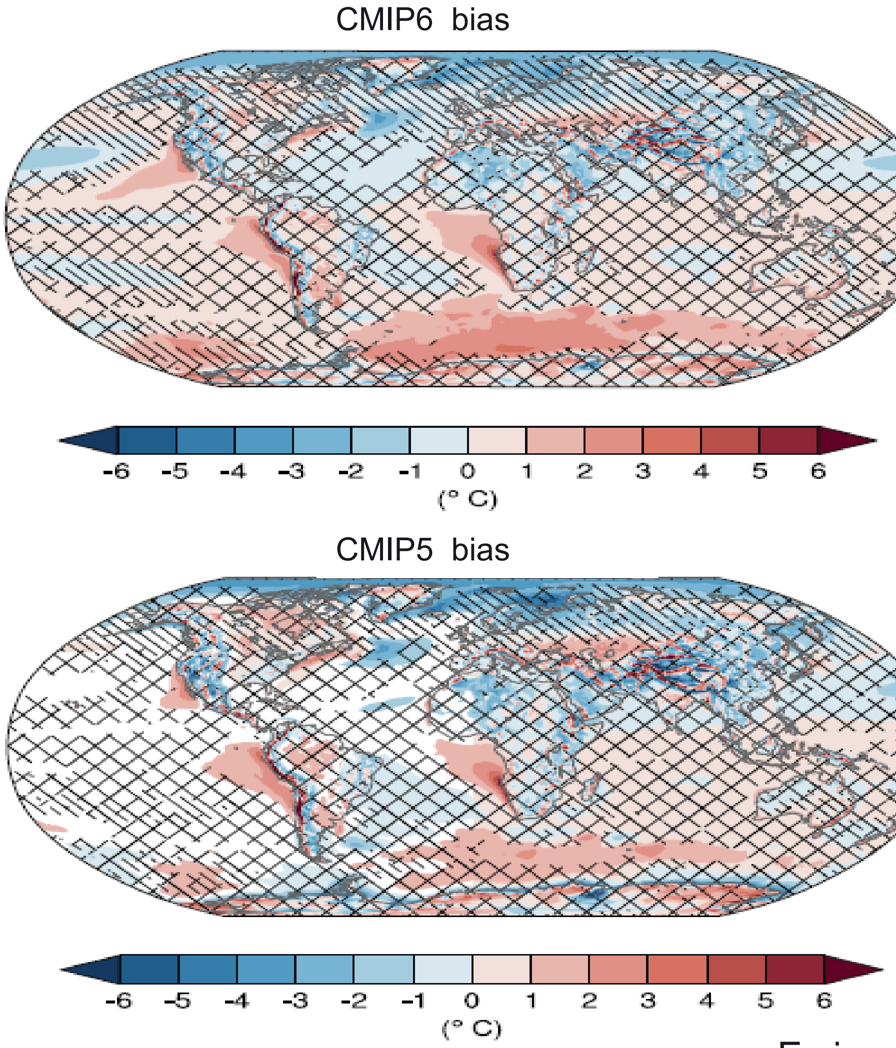
Model evaluation: Spatially resolved

Climatological Planetary albedo



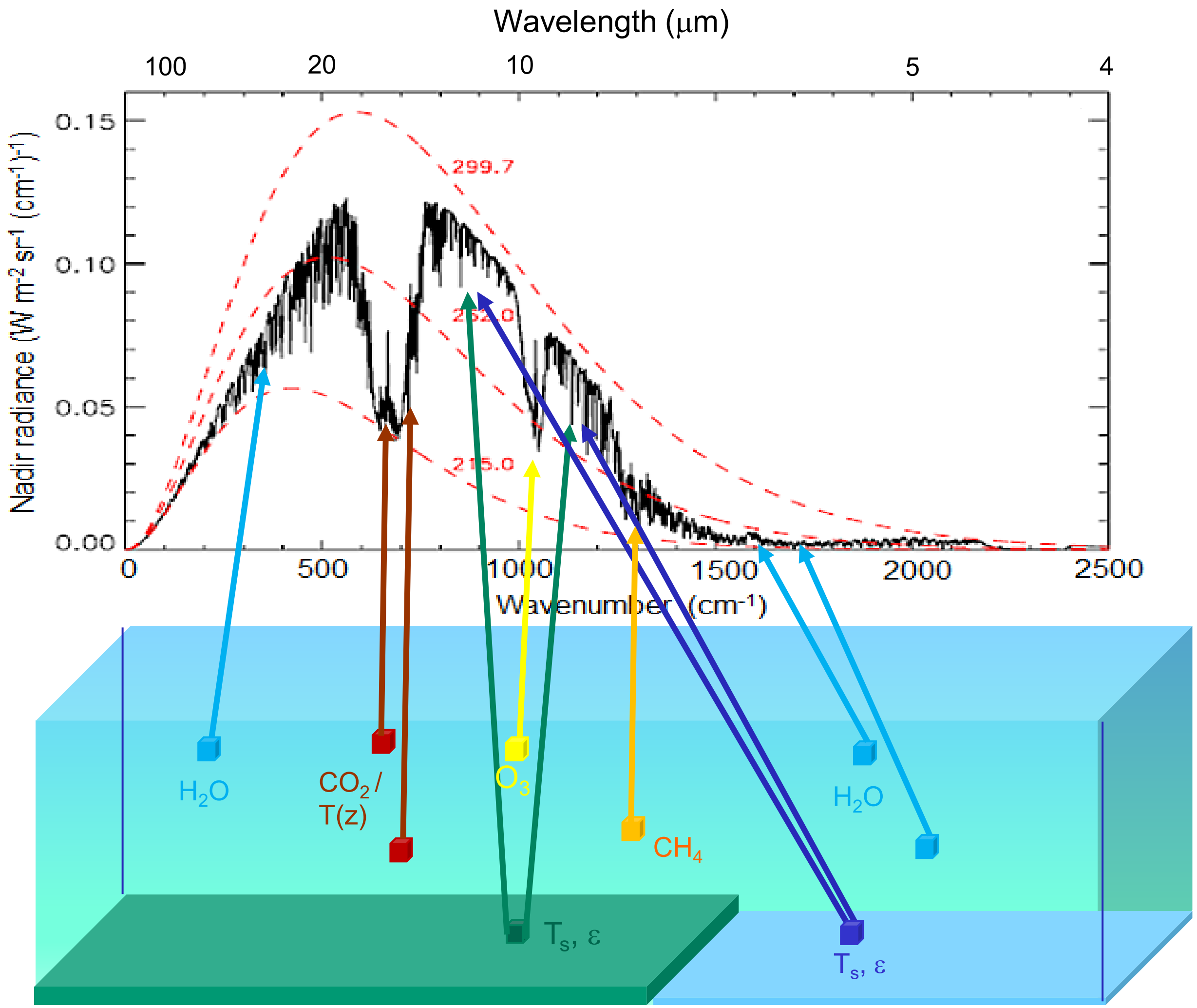
Jian et al., 2020

Multi-model mean near-surface air temperature relative to ERA-5 (using 1995-2014 climatology)

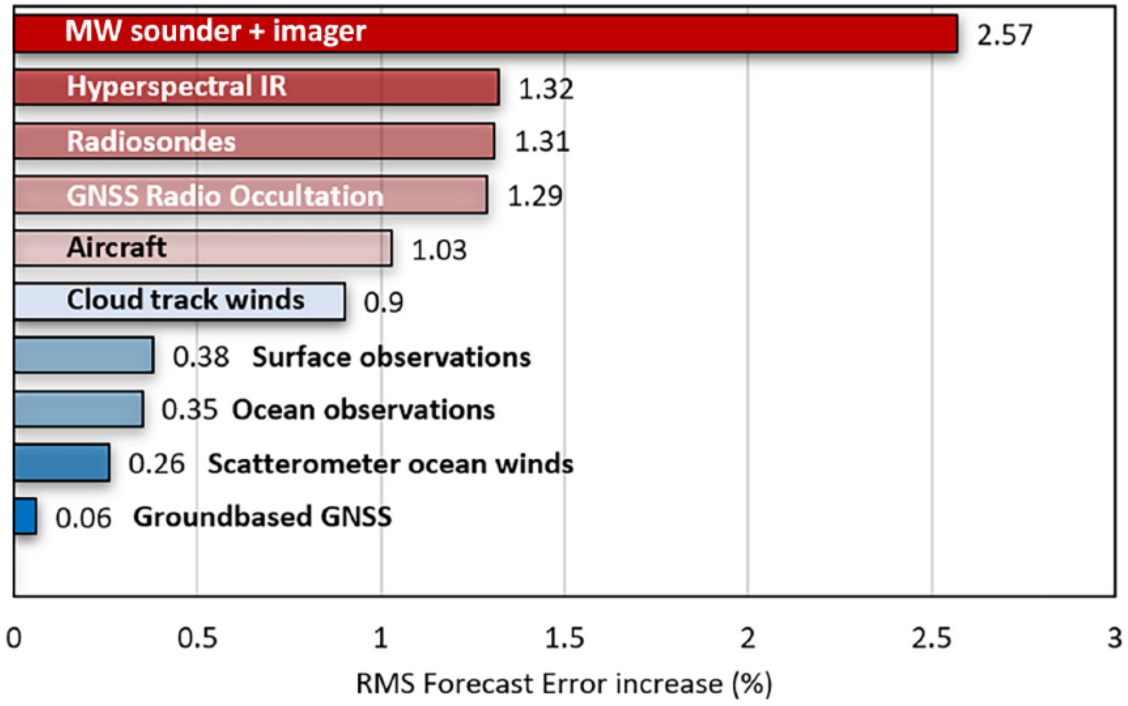


Eyring et al., 2021

Model evaluation: Can we directly exploit the spectral domain?

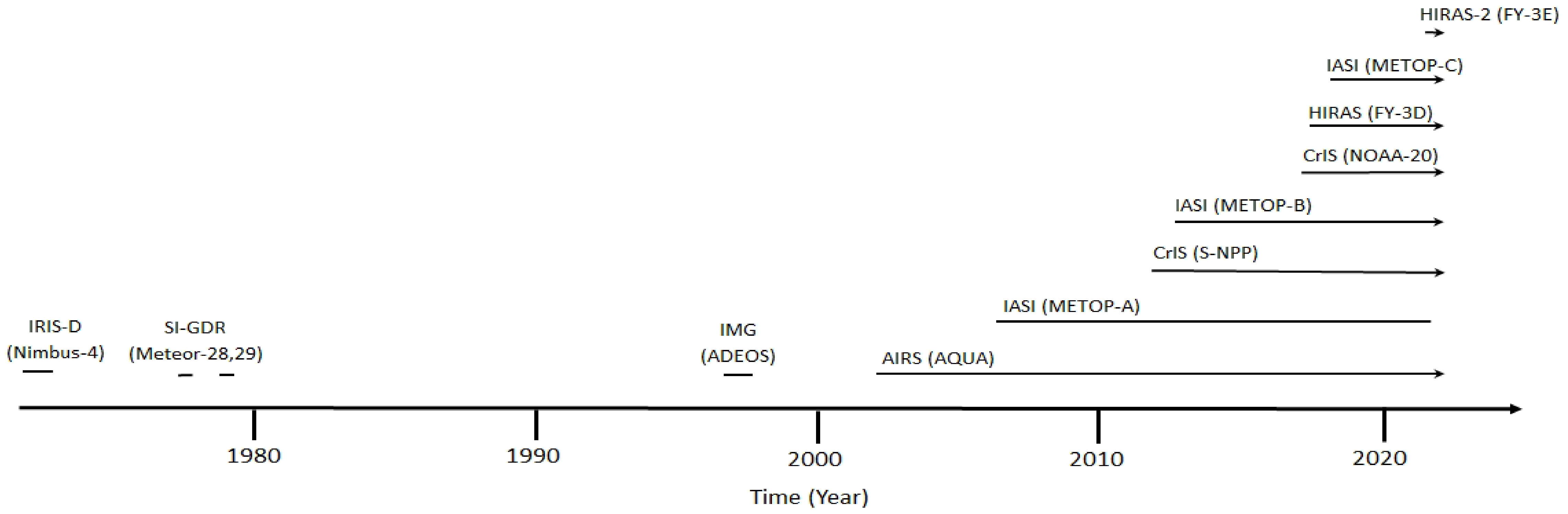


Simulated clear-sky TOA LW nadir radiance spectrum



Percent root mean square increase in forecast errors when different observations types are removed from the Met Office global NWP model (Saunders, 2021)

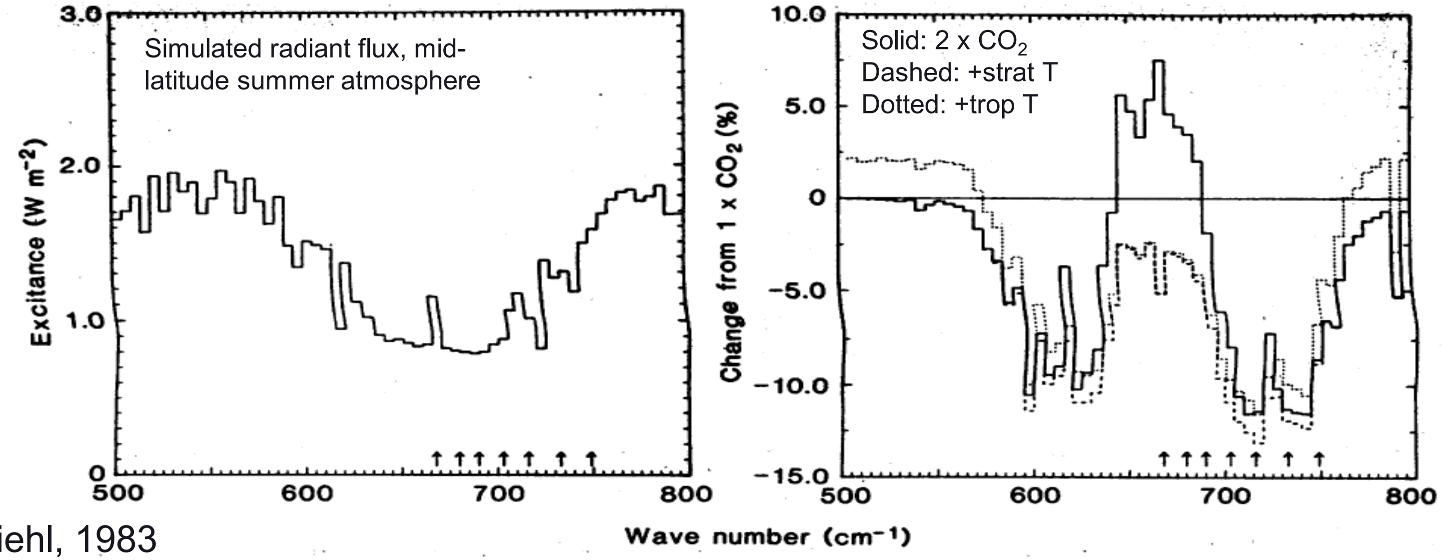
“Hyperspectral” OLR measurements



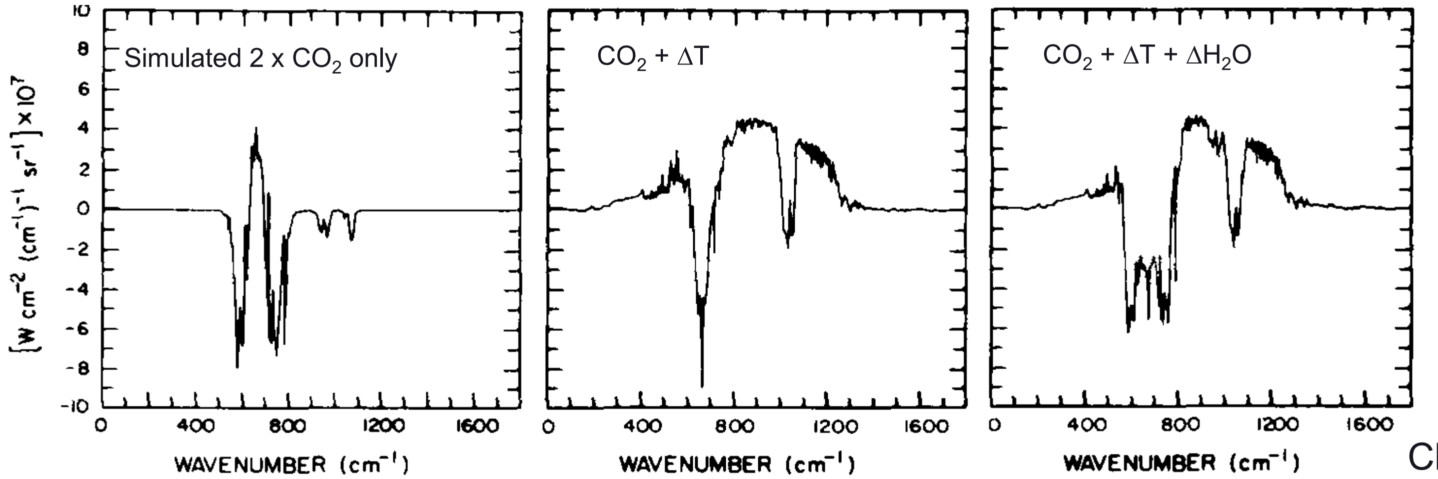
- Hyperspectral satellite measurements of the outgoing longwave radiation have a long heritage but suffer from significant gaps pre-2002
- ‘Golden Age’ from ~2010 onwards

Model evaluation: Can we directly exploit the spectral domain?

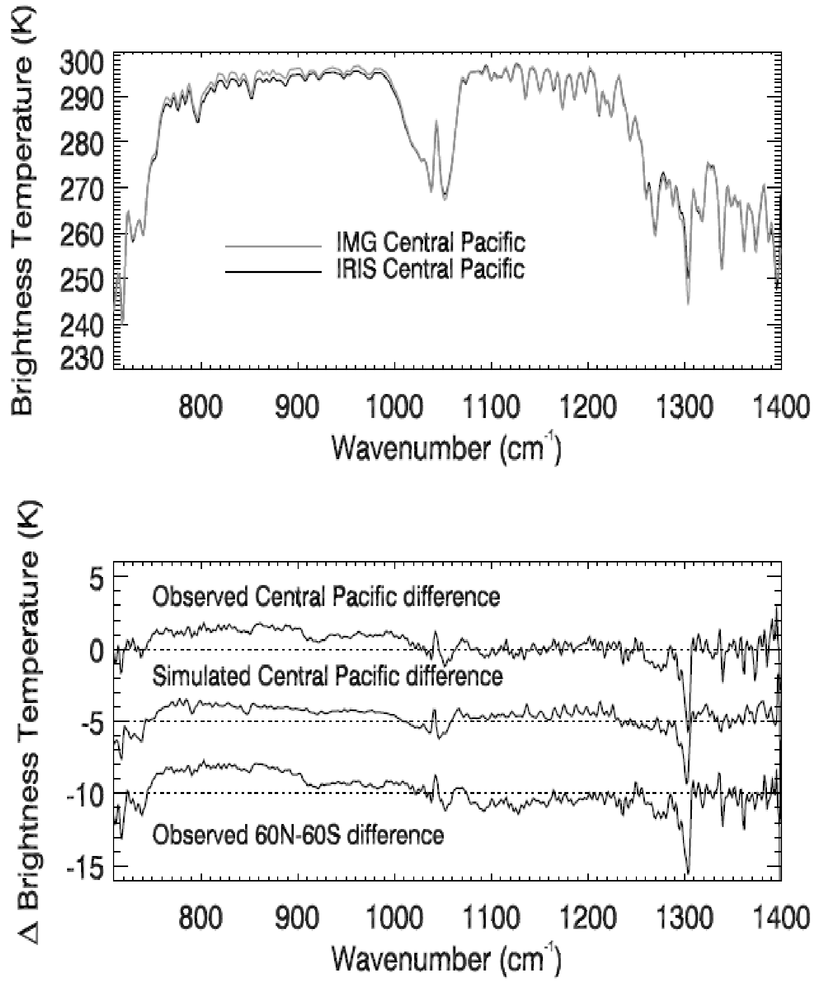
Using spectral radiances measured from space to probe climate forcings and feedbacks is not a novel idea…
….starting from early simulations to opportunistic observational comparisons



Kiehl, 1983



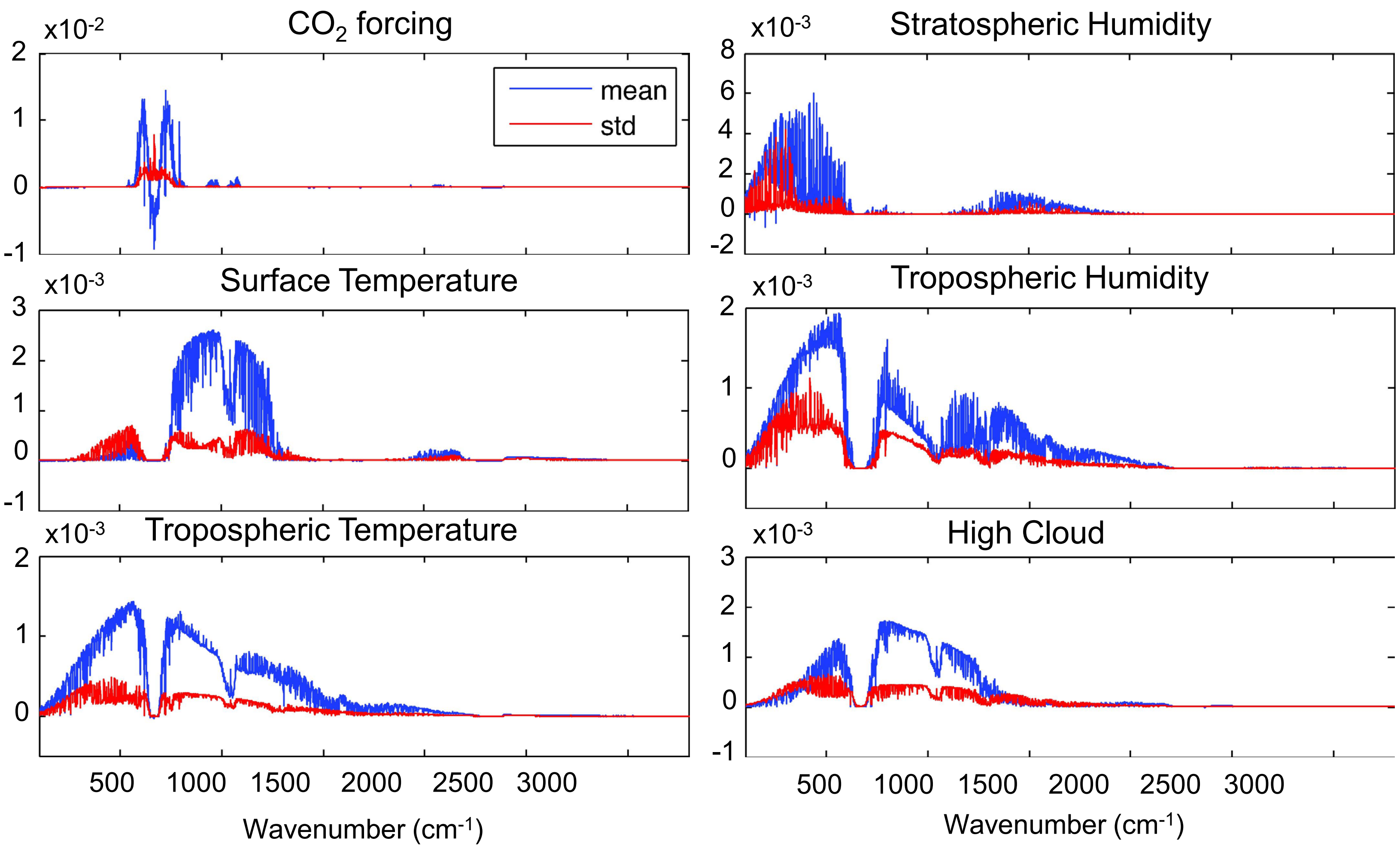
Charlock, 1984



Harries et al., 2001

Model evaluation: Can we directly exploit the spectral domain?

Moving towards more systematic analysis, including the signatures of cloud…



Blue: Global mean normalized spectral nadir radiance change due to given perturbation/ response in $2xCO_2$ experiment (CCCMA model)

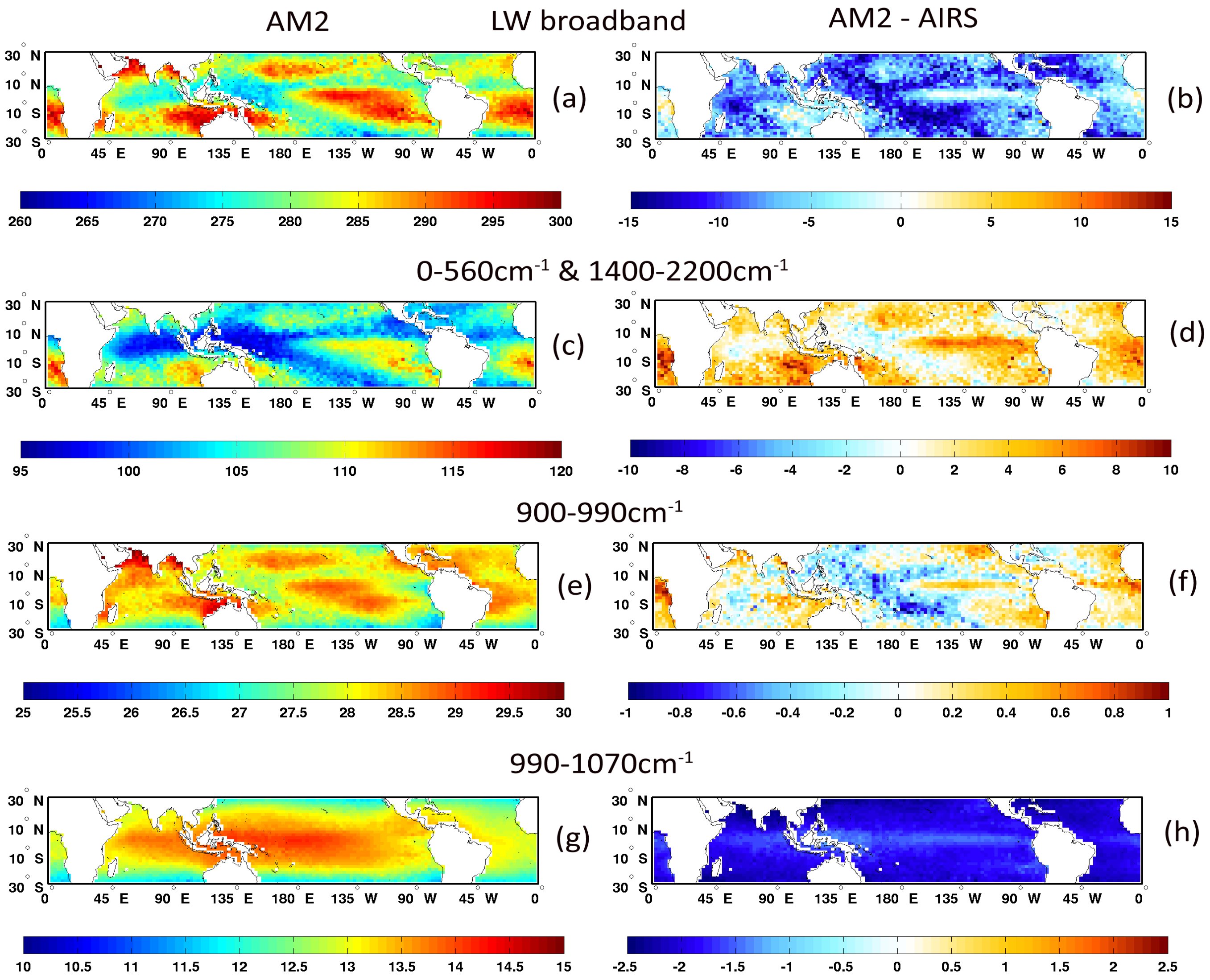
Red: Spatial standard deviation

Simulations are performed using an offline radiative transfer model on monthly mean fields

Adapted from Yi Huang et al., 2010

Model evaluation: Can we directly exploit the spectral domain?

…and, primarily due to the CLARREO initiative, developing and using tools specifically for model evaluation



Comparisons of total and band resolved clear-sky outgoing longwave fluxes from the GFDL Atmospheric GCM (AM2) over the tropical oceans, 2002-2006

Spectral fluxes are derived from AIRS radiance observations at 10 cm^{-1} resolution using scene information and spectral ADMs

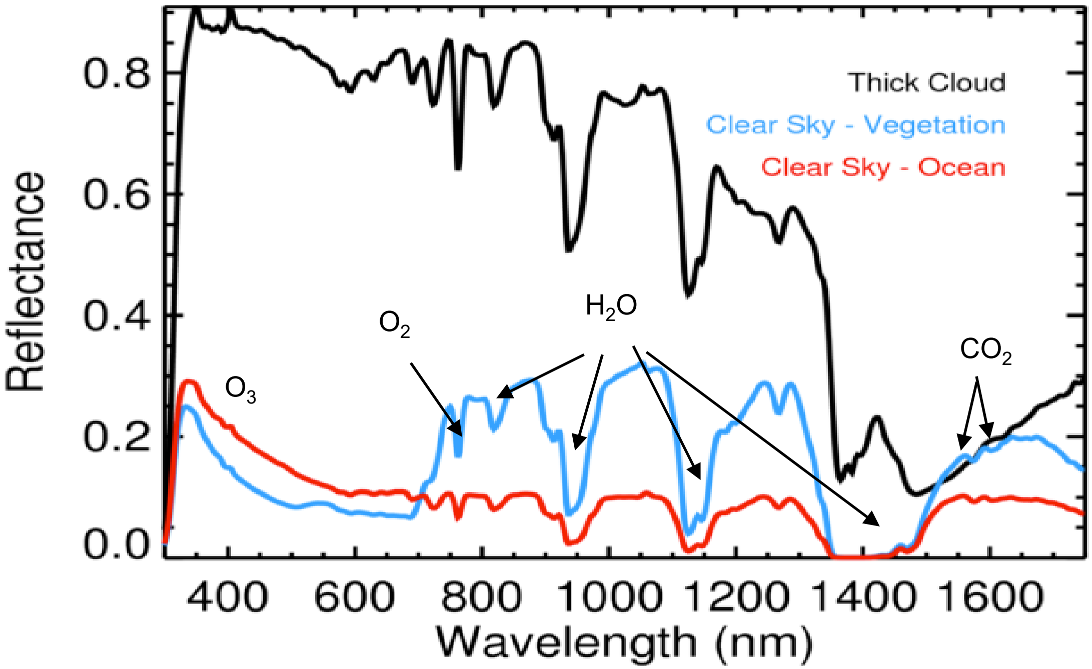
Unmeasured regions of the spectrum are obtained via PC analysis, derived from a basis set of simulated spectral fluxes

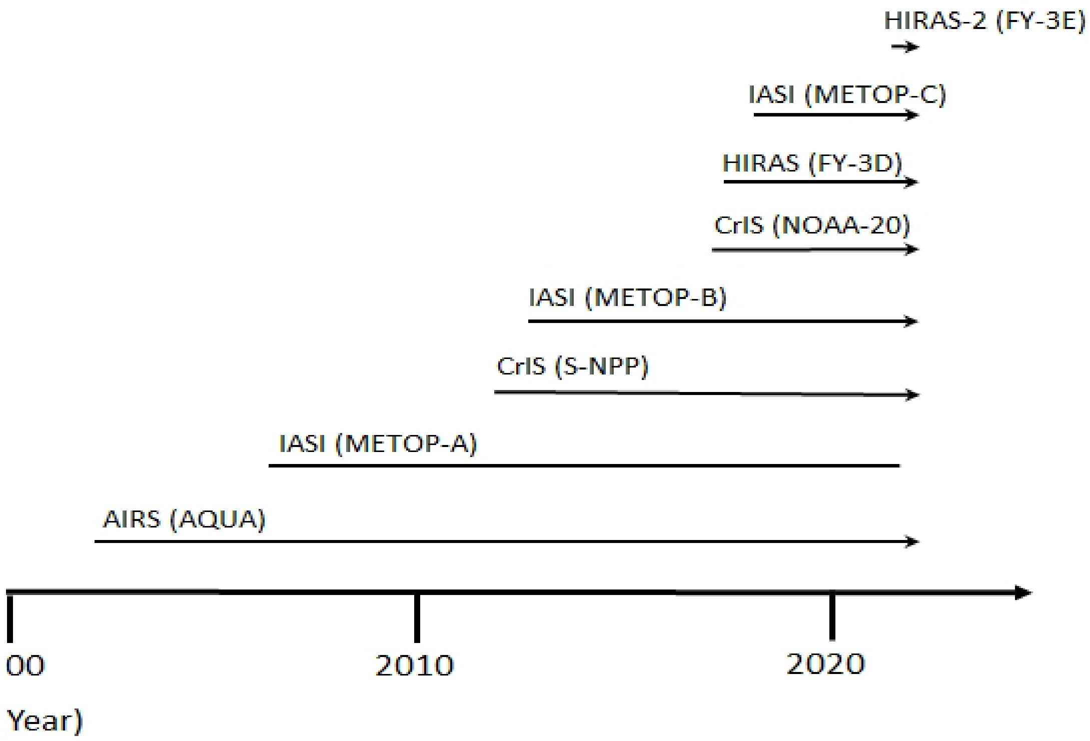
Adapted from X. Huang et al., 2008

Model evaluation: Can we directly exploit the spectral domain?

"Hyperspectral" SW measurements

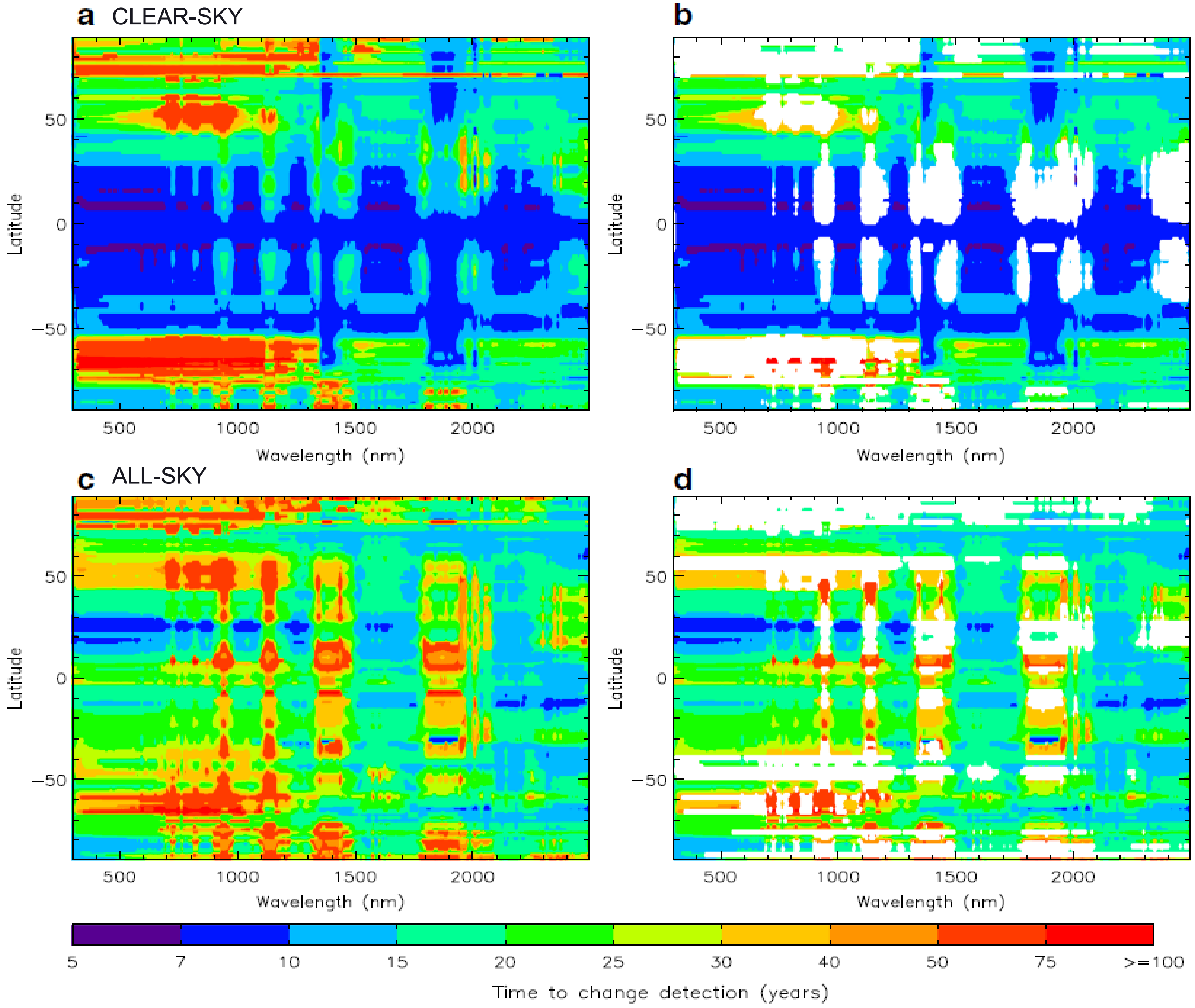
Observed nadir SW reflectance spectra from Sciamachy (adapted from O'Shea et al., 2013)





Model evaluation: Can we directly exploit the spectral domain?

In the SW, questions as to the benefit of spectral resolution have been addressed via bespoke OSSEs



Time when the TOA nadir SW reflectance trend emerges from natural variability as a function of zonal band and wavenumber for CCSM3 under the CMIP3 SRES A2 scenario

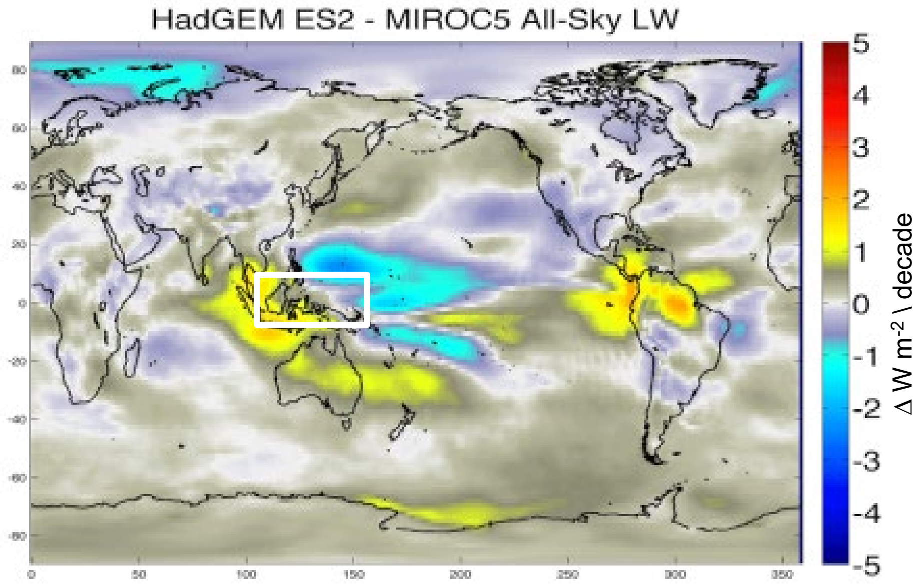
Left and right columns are identical except whited out regions which show where the broad-band signal emerges as quickly or faster than the spectrally resolved case

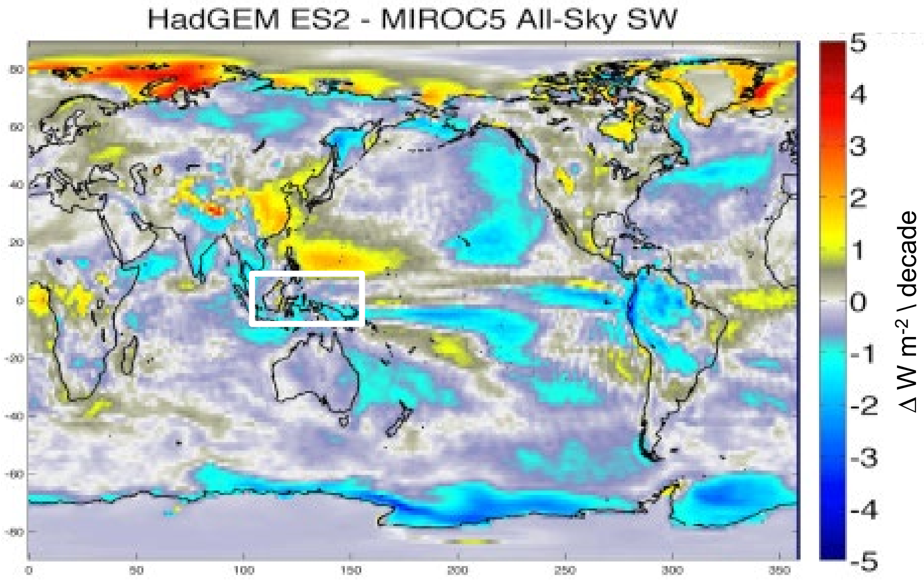
Simulations are performed using an offline radiative transfer model on monthly mean model fields

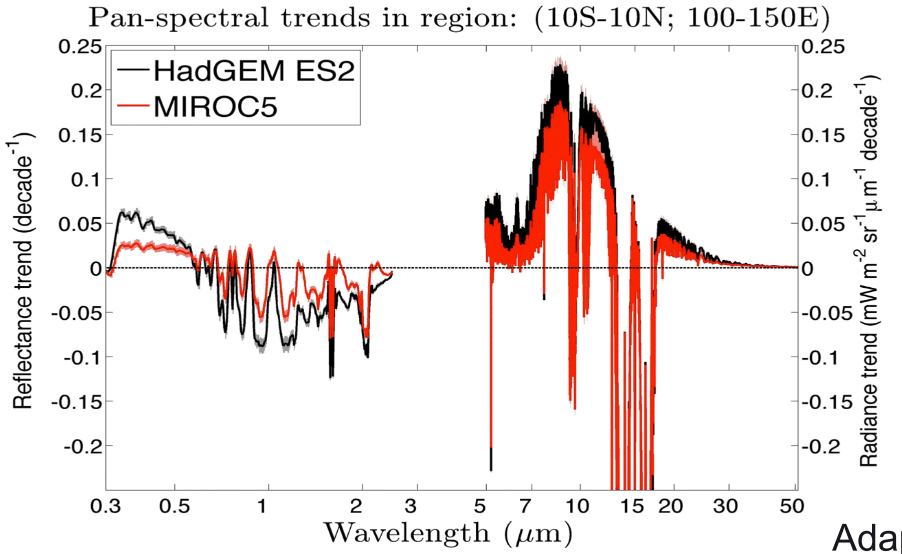
After Feldman et al., 2011

Model evaluation: Can we directly exploit the spectral domain?

Initial investigations into pan-spectral LW and SW signatures have also been performed







Top: All-sky broadband differences in outgoing LW and reflected SW flux decadal trends (2005-2035) between HadGEM2-ES and MIROC5 simulations performed under the AR5 RCP8.5 scenario

Bottom: Spectrally resolved difference in nadir shortwave reflectance and longwave radiance decadal trends over the tropical west Pacific

Adapted from Feldman et al., 2015

Spectral model evaluation: why now?

- Improved confidence in reprocessed, ‘climate quality’ datasets + increasing dataset length
- Enhanced computing power, archiving, potential to investigate:
  - ‘brute force’ spectral flux conversion (e.g. Whitburn et al., 2020)
  - inline radiance simulation capabilities, learning from NWP and building on existing tools, e.g. COSP (Bodas-Salcedo et al., 2011)
- Rapid developments in community evaluation suites: e.g. expansion of ESMValTool (Eyring et al., 2016, 2020)
- Targeted exploitation of upcoming missions, promising to measure spectral radiances with unprecedented accuracy and/or over new spectral regions, including potential to give guidance on product development

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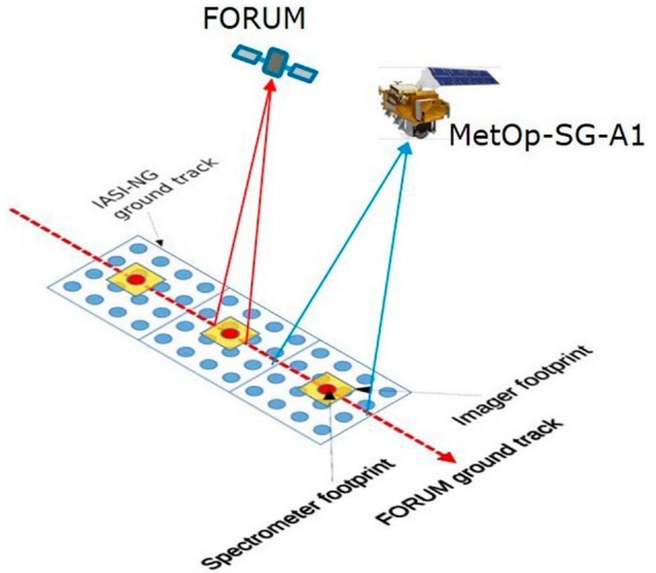
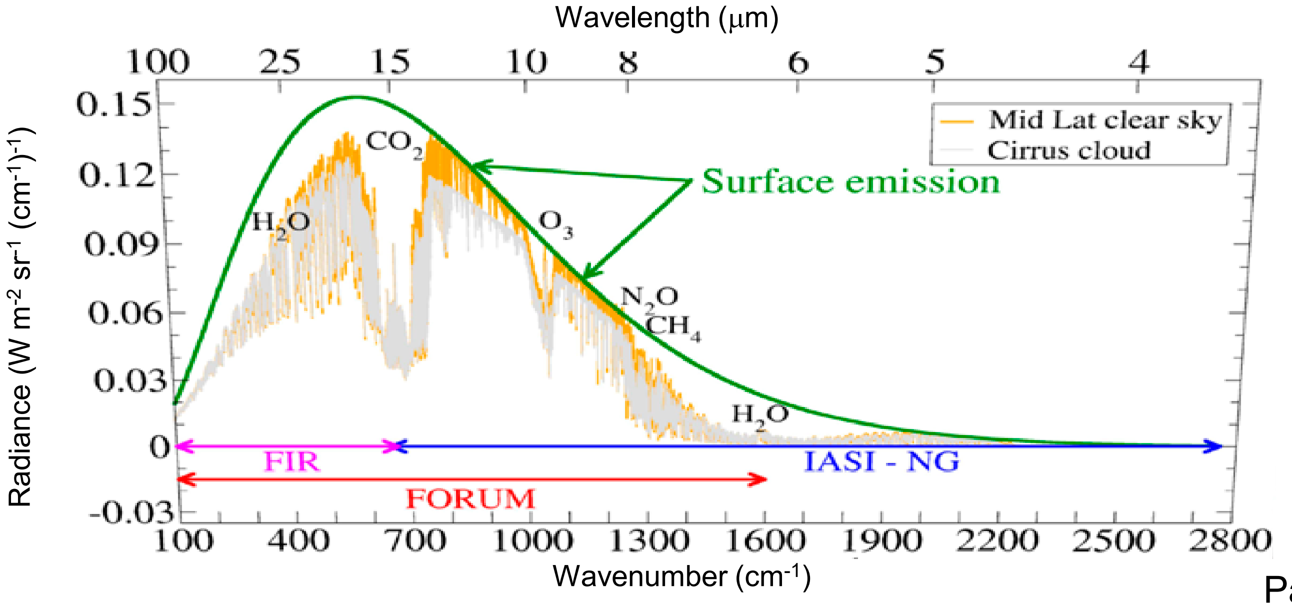
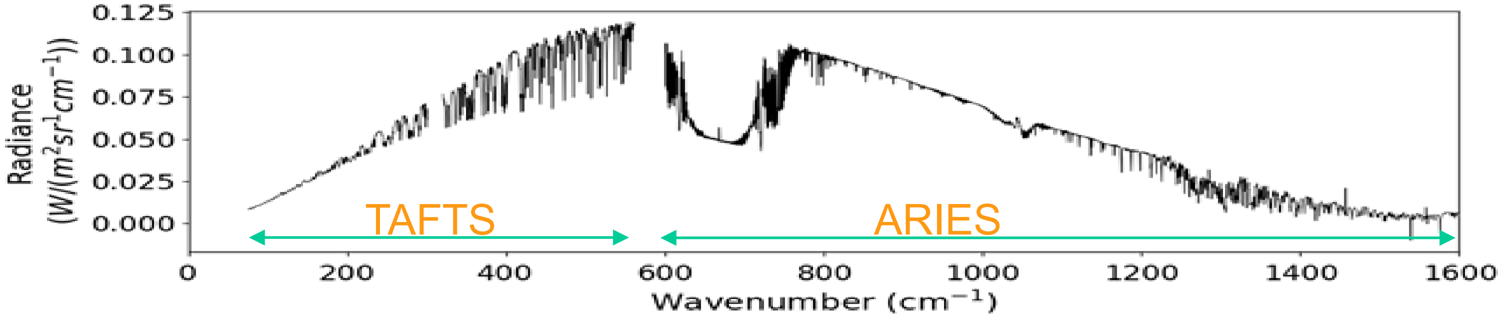
Far-infrared Outgoing Radiation Understanding and Monitoring (FORUM): launch ~2027

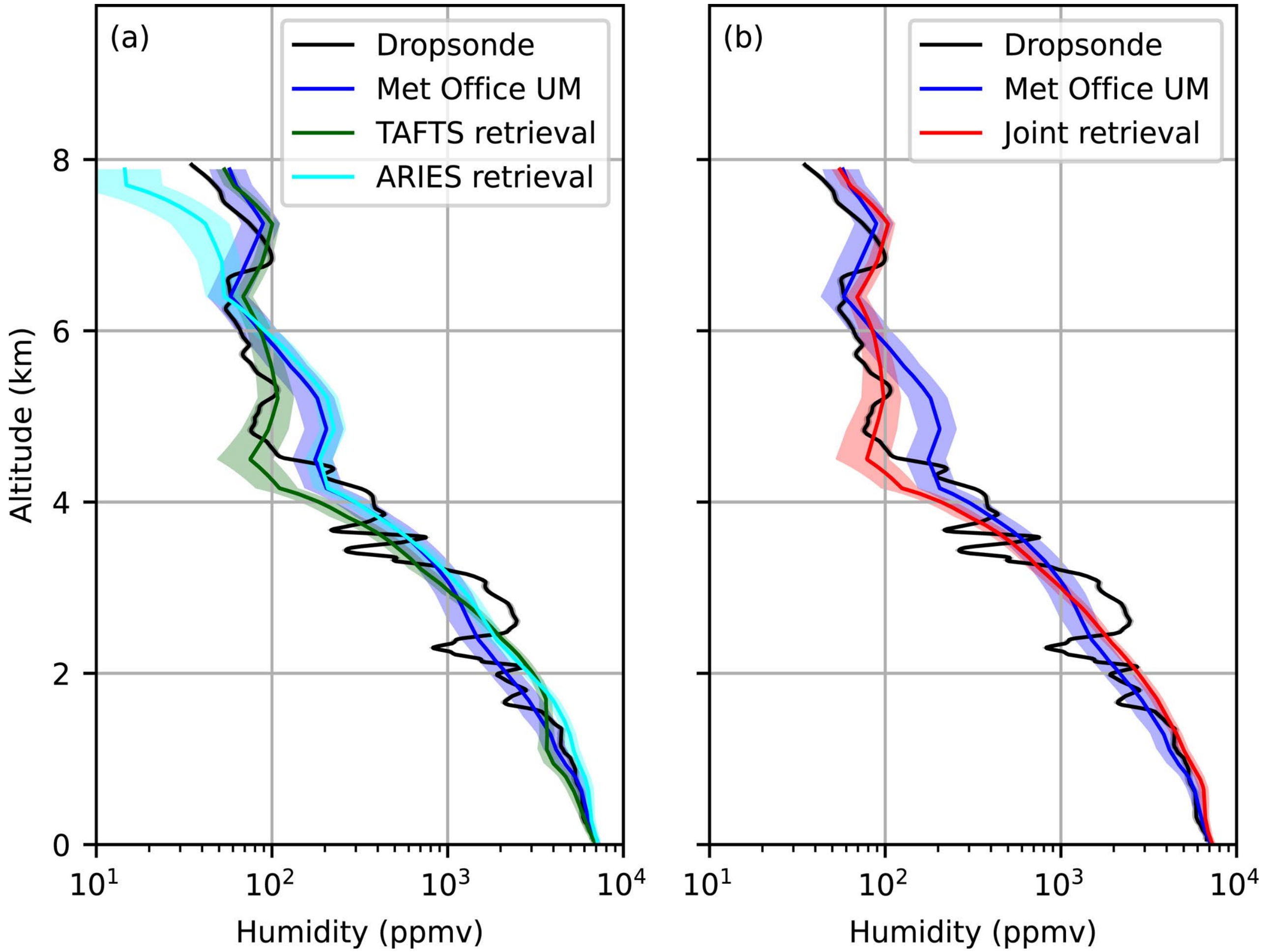


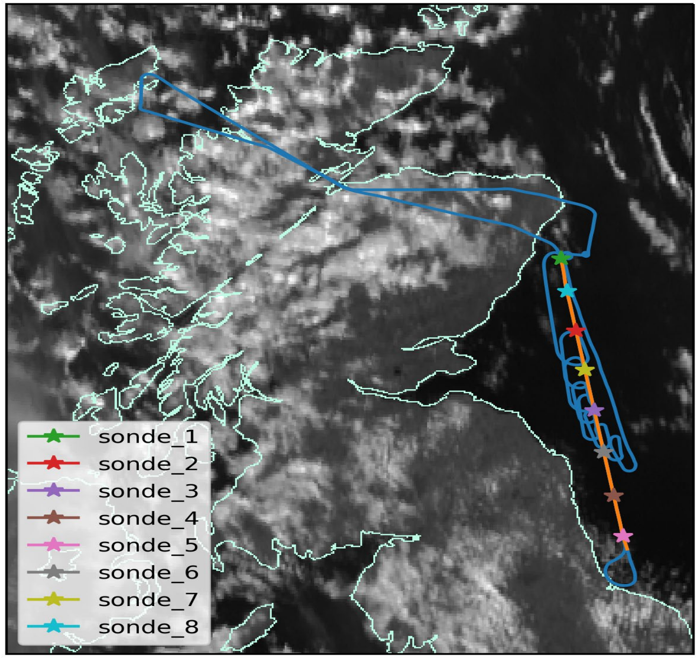


Palchetti et al., 2020

FORUM Science: Water vapour



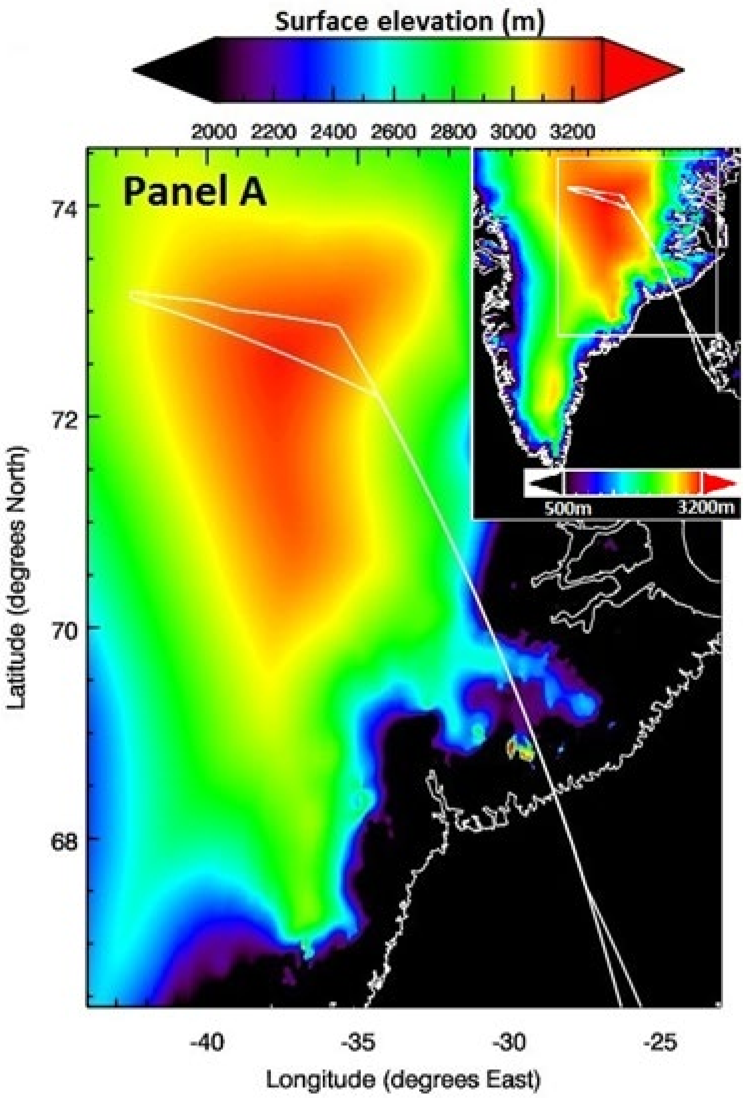


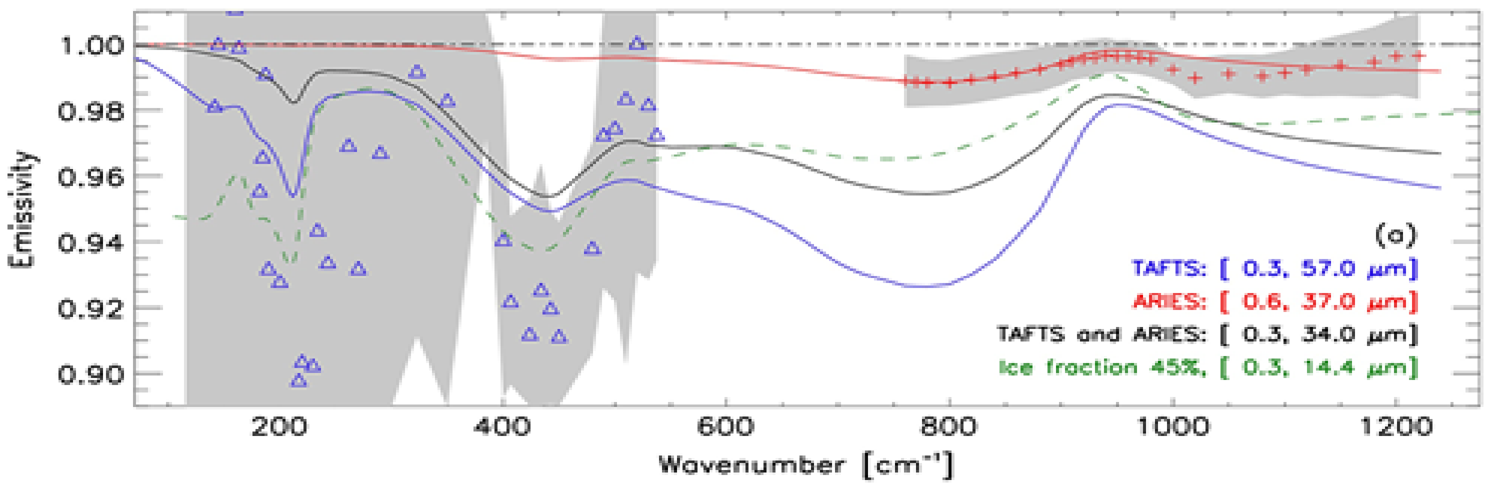


Configuration	DFS
TAFTS only	6.46
ARIES only	3.55
TAFTS & ARIES	6.65

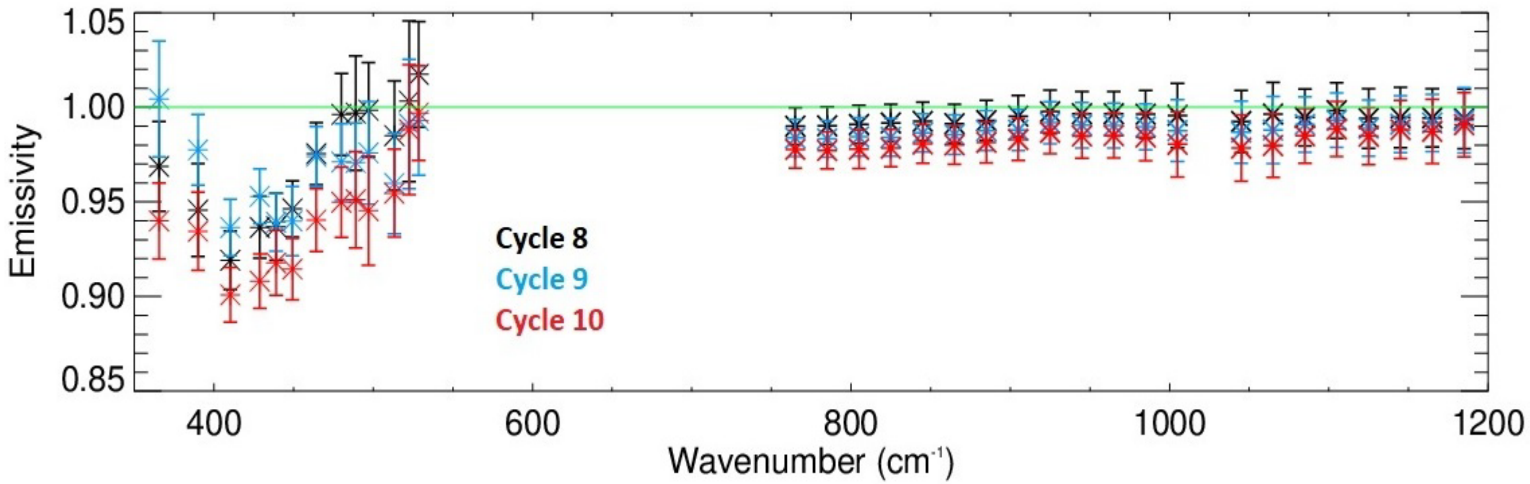
Warwick et al., 2021

FORUM Science: Surface emissivity



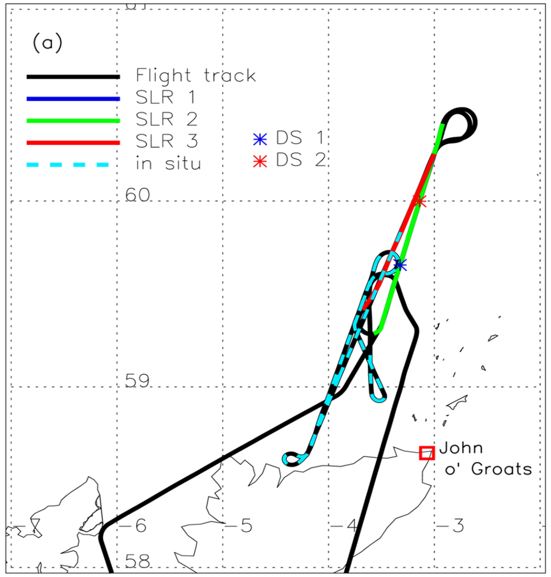


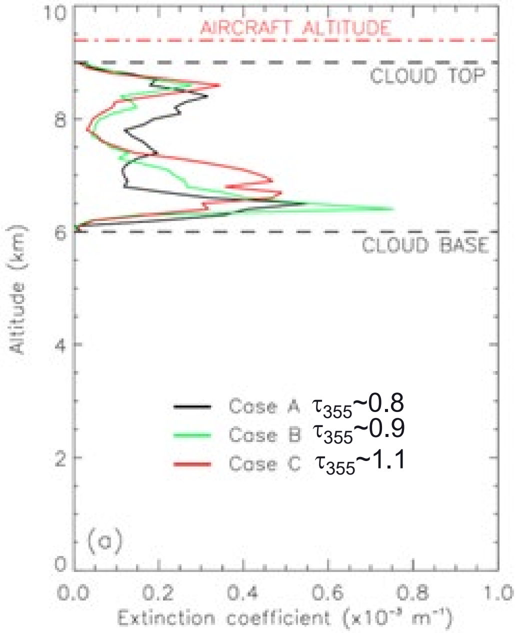
From 330 m: 0.08 mm water vapour below aircraft (Bellisario et al., 2017)



From 9.2 km: 0.4 mm water vapour below aircraft (Murray et al., 2020)

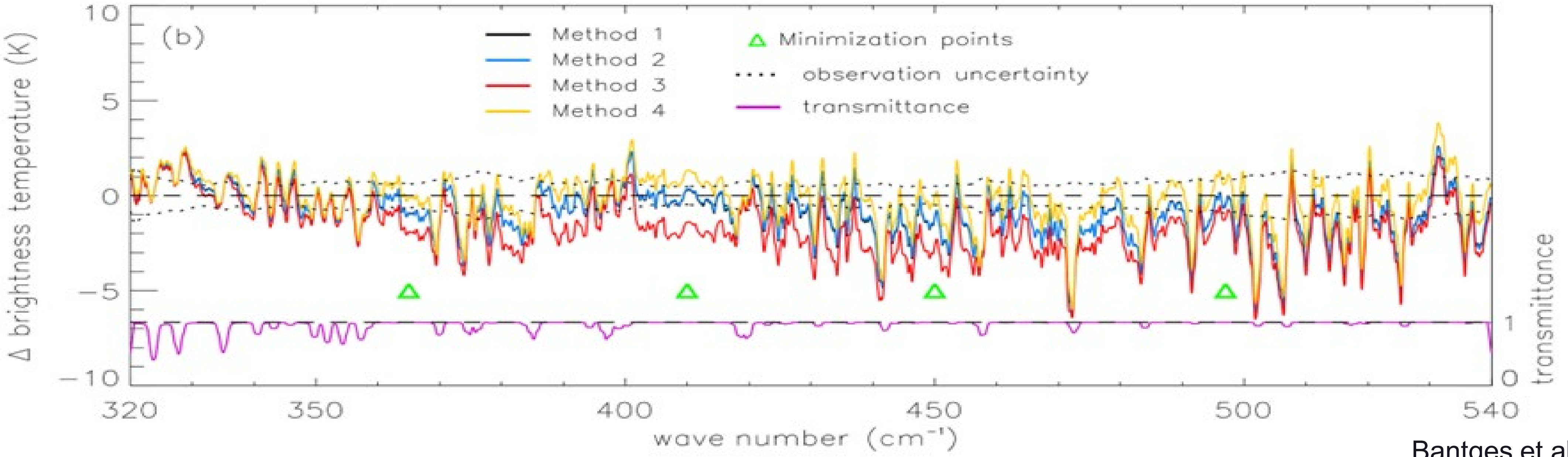
FORUM Science: Cirrus cloud





CASE	110-300 cm^{-1}	320-540 cm^{-1}	600-1400 cm^{-1}	Total
A	-0.09	-1.15	0.17	-1.07
B	-0.02	-2.02	0.22	-1.82
C	0.19	-1.37	0.31	-0.87

Estimated observed – simulated flux difference (W m^{-2}) for different spectral bands after minimizing residuals in four mid-ir channels sensitive to cirrus properties



Bantges et al., 2020

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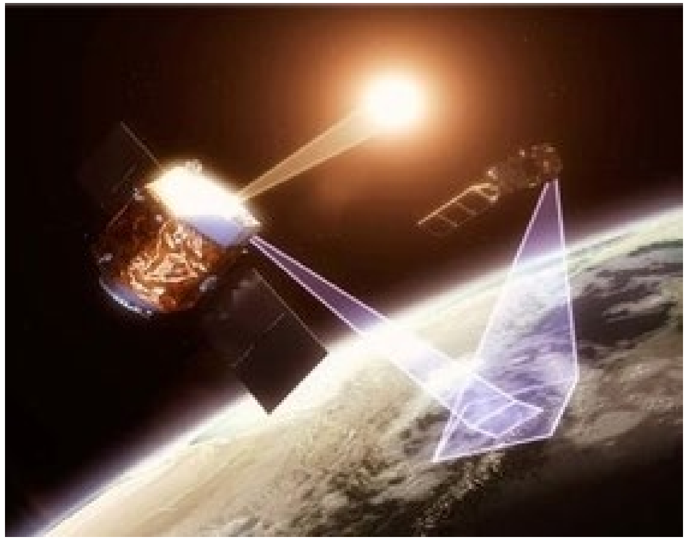
Traceable Radiometry Underpinning Terrestrial- and Helio- Studies (TRUTHS): launch ~2030



Fox and Green, 2020

Level 1 Products	Mission Requirement							
	Spectral Range (nm)	Bandwidth (nm) (Spectral Sampling X0.5)	Uncertainty (%) (k = 2)		SNR (with Respect to Earth Albedo of 0.3)		GIFOV (m)	
			Goal	Threshold				
Earth Spectral Radiance (Climate)	320–2400	8–25 nm	0.3	<1.0	>50		250	
Solar Spectral Irradiance	<320–2400	<1 (<400), <5 (<1000), <10 (<2400)	0.3	<1.0	>300		NA	
Total Solar Irradiance	Total	200–30000	<0.02	<0.05	>500		NA	
					Goal	Threshold	Goal	Threshold
Earth Spectral Radiance (Cal/Val/other)	<380–2400	<8 (< 1000 nm) <16 (>1000 nm)	0.3	<1.0	>300	>80 (<500 nm) >150 (500–1000 nm) >100 (>100 nm)	<50	100 (>500 nm) 250 (<500 nm)
Lunar Spectral Irradiance	<350–2400	<8 (< 1000 nm) <16 (>1000 nm)	0.3	<2.0	>~300		NA	

Summary & Future Challenges

- Simulation and observational studies show that direct use of spectral observations can provide a strong constraint on Earth-System model output, allowing compensating biases to be unveiled and at least partially linked to underlying processes
- Existing records of spectrally resolved LW radiances are approaching multi-decadal length and have been extensively validated: various approaches exist to convert these to spectral flux
- New observations in the LW will fill the far-infrared gap, with unique sensitivity to water vapour, cirrus and surface properties
- New observations in the SW promise to deliver nadir radiances with unprecedented accuracy

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How can we ensure we best exploit these data?

1. Ensure consistency

(a) between model output and observables: e.g. radiance to radiance or flux to flux

(b) in observational sampling: does this preclude use of say monthly mean fields?

(c) between ESM RT schemes and fast codes, which are open source

2. Consider data volume/computational cost: seek to answer targeted questions that the specific observations can be expected to inform upon

3. Define sensible evaluation metrics, likely in conjunction with other observables

4. Facilitate communication between those deriving products and end-users: TRUTHS/FORUM Workshop for climate applications: Spring 2023