Some issues in near-infrared radiative transfer

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Particular thanks to Jon Elsey (Univ of Reading), Igor Ptashnik (IAO, Tomsk) and Tom Gardiner and Marc Coleman (National Physical Laboratory)

Workshop on Radiation in the Next Generation of Weather Models, ECMWF May 2018

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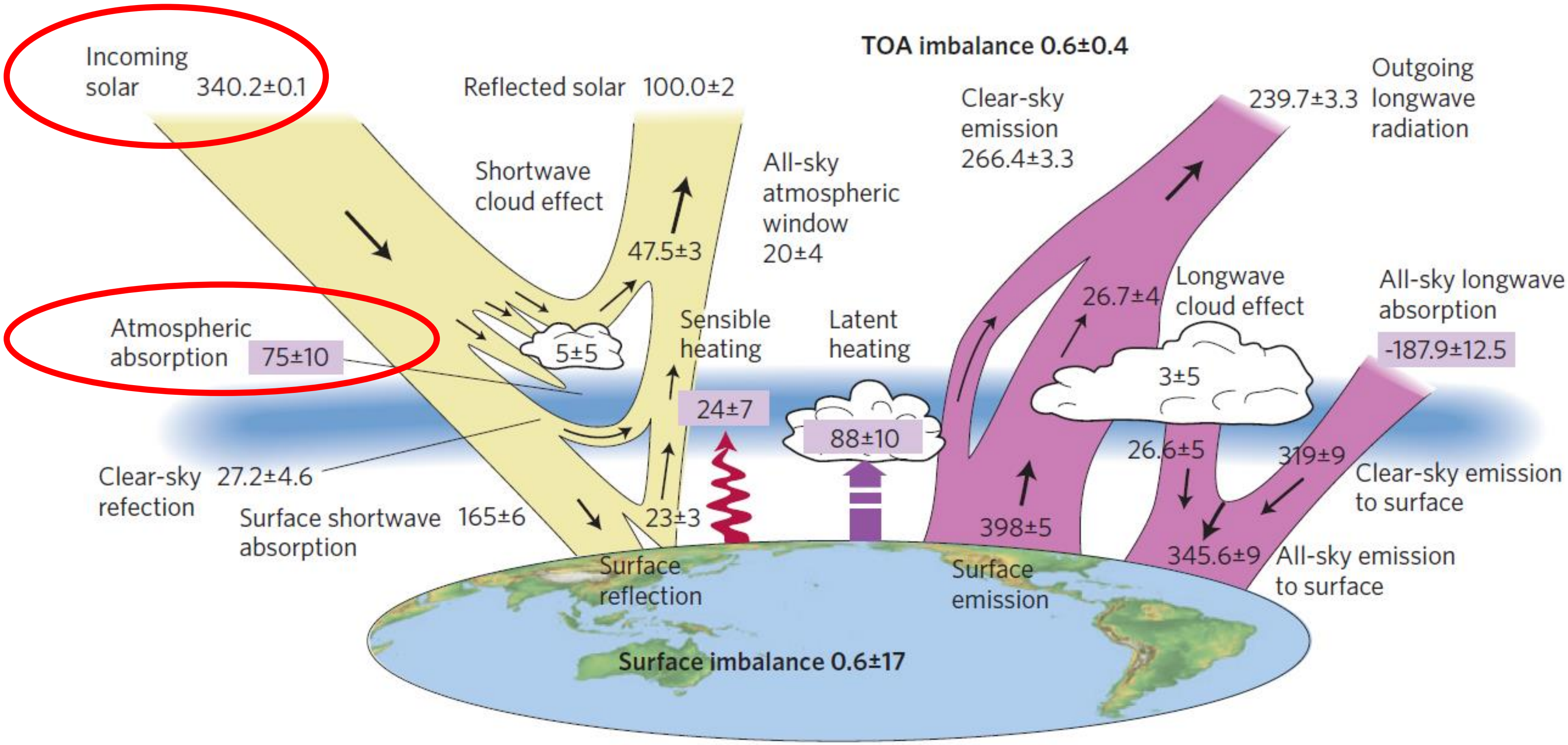
I'll cover three clear/clean sky issues in the near-IR

- The solar spectral irradiance
- The water vapour continuum
- The role of methane near-IR bands

Modern (global and annual averaged) Earth energy budget



Stephens et al. (2012), Nature Geoscience 10.1038/NGEO1580

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A surprising uncertainty!

- The wavelength-integrated total solar irradiance is believed to be known with an uncertainty of less than 0.5% (e.g. Kopp and Lean 2011)
- But how well do we know the spectrally-resolved irradiance?
- Implications for total solar irradiance?
- A controversy largely played out in the solar physics literature

The near-IR Extraterrestrial Solar Spectrum (NIR ESS)

lasp.colorado.edu/lisird/sorce/sorce_ssi/

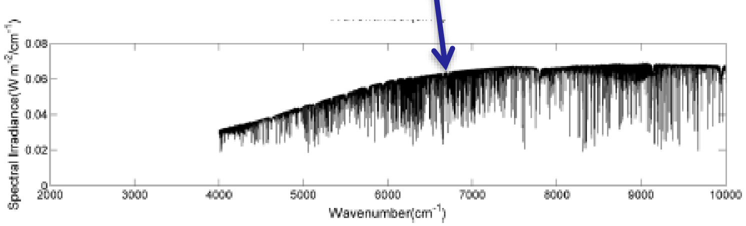

Figure 9. (top) CAVIAR ESS at one astronomical unit (1 AU) from 2000–10,000 cm^{-1} (1–5 μm). (bottom) The merged CAVIAR ESS from 4000–10,000 cm^{-1} (1–2.5 μm). This ESS is a merger of the CAVIAR ESS derived using observations of 18 September 2008 with the ACE-FTS ESS, Kurucz-observed ESS, and Kurucz-modeled ESS.

- ESS are readily available, even if not at the highest spectral resolution (so that many solar lines are not resolved). OK?
- Not really. SORCE SSI is adjusted downwards (by 8%) to agree with ATLAS3 (see soon!) at λ>1.5 μm.
- TSIS launched late 2017. Results pending

Menang et al 2013, JGR
10.1002/jgrd.50425

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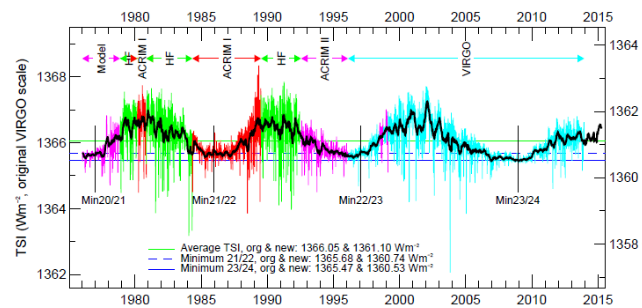
SOLSPEC

- Grating spectrometer, covering (about) 0.17 to 3.1 μm at about 0.5 nm resolution (around 20 cm^{-1})
- First flew on Spacelab I in 1983
- Refurbished and flew on three "ATLAS Space Shuttle missions (1992-1994). **ATLAS3** became a widely-used reference spectrum



- Also flew on European EUREKA mission in 1994 (but called SOSP)
- Then installed on **International Space Station in 2008** with updated electronics and optics

Solar Phys
DOI 10.1007/s11207-013-0461-y

The Solar Irradiance Spectrum at Solar Activity Minimum Between Solar Cycles 23 and 24

G. Thuillier · D. Bolsée · G. Schmidtke · T. Foujols · B. Nikutowski · A.I. Shapiro · R. Brunner · M. Weber · C. Erhardt · M. Hersé · D. Gillotay · W. Peetermans · W. Decuyper · N. Pereira · M. Haberreiter · H. Mandel · W. Schmutz

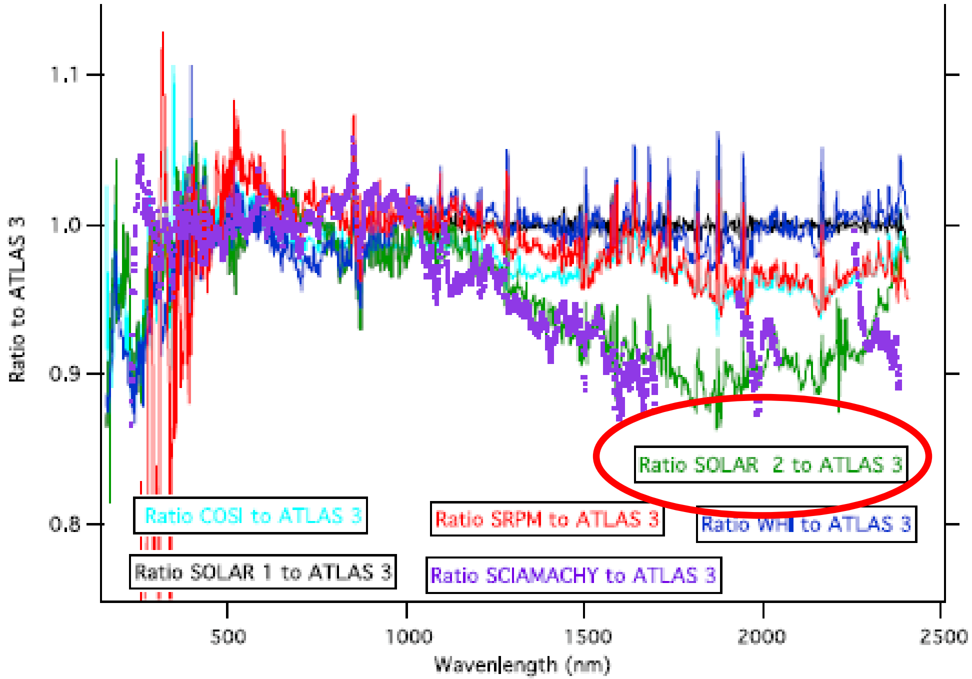


Figure 10 Ratio to ATLAS 3 of the SOLAR 1 and 2 composites, COSI, SRPM, SCIAMACHY, and WHI from 150 to 2400 nm. The main differences are in the IR. We recall that the SOLAR 1 and WHI spectra (using SORCE/SIM) were adjusted to match ATLAS 3 in the IR.

- Thuillier et al. (2014) showed that “new” (2008) NIR ESS measurements were 7% lower than ATLAS-3 at >1.5 μm
- Lower values were consistent with e.g. Sciamachy

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Solar Phys
DOI 10.1007/s11207-014-0474-1

Accurate Determination of the TOA Solar Spectral NIR Irradiance Using a Primary Standard Source and the Bouguer–Langley Technique

D. Bolsée · N. Pereira · W. Decuyper · D. Gillotay · H. Yu · P. Sperfeld · S. Pape · E. Cuevas · A. Redondas · Y. Hernandéz · M. Weber

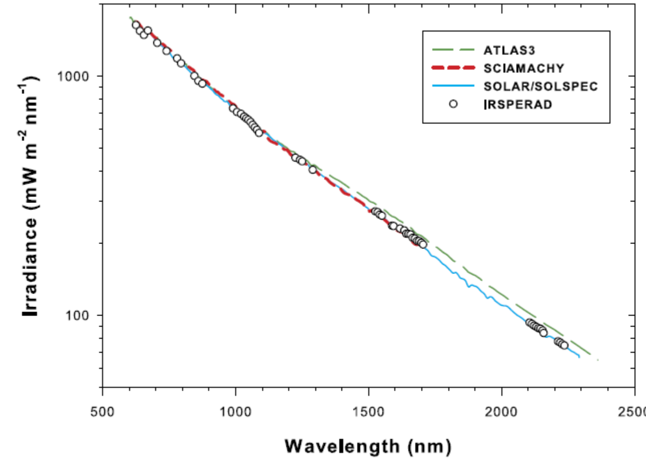
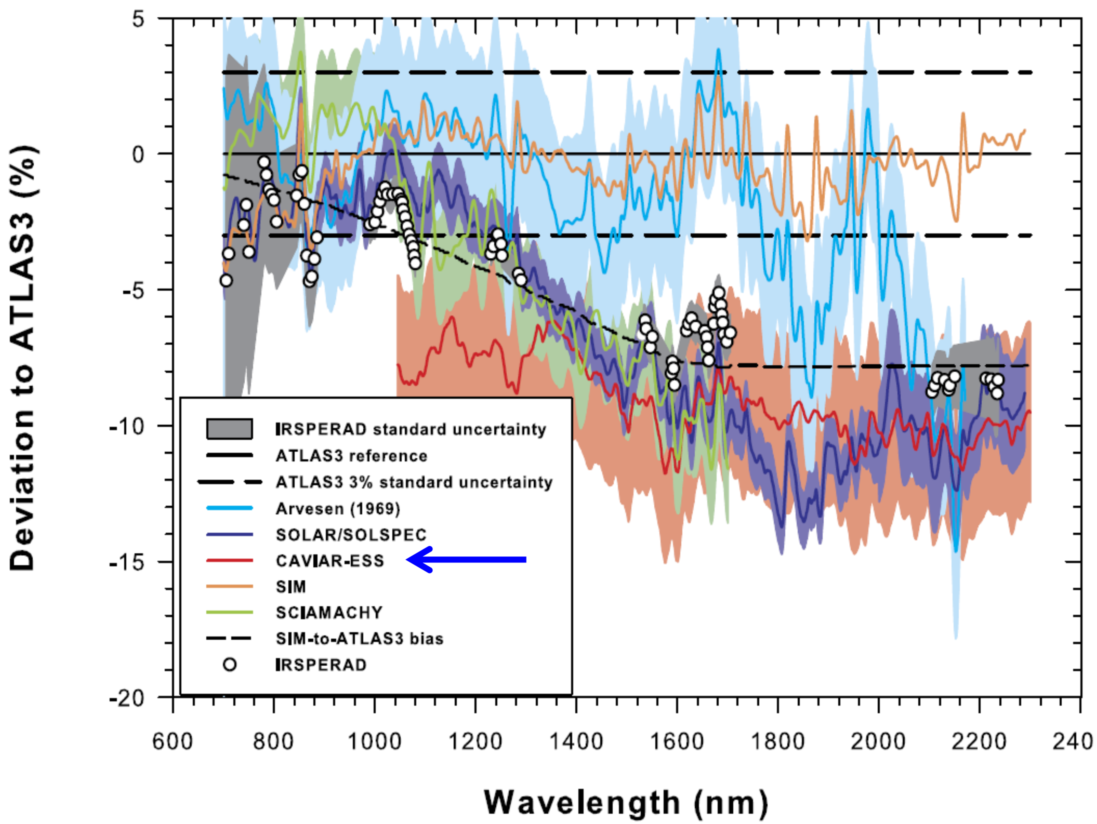


Figure 13 Comparison between different versions of the SOLSPEC instrument (ATLAS3 and SOLAR/SOLSPEC), SCIAMACHY and ground-based measurements performed at Izaña (IRSPERAD). SCIAMACHY, and ATLAS3 are convoluted to 10 nm.



- Bolsée et al. (2014) showed ground-based measurements. Theirs and ours (Menang et al. 2013) were also broadly consistent with the lower values derived by SOLAR2.
- But then ...

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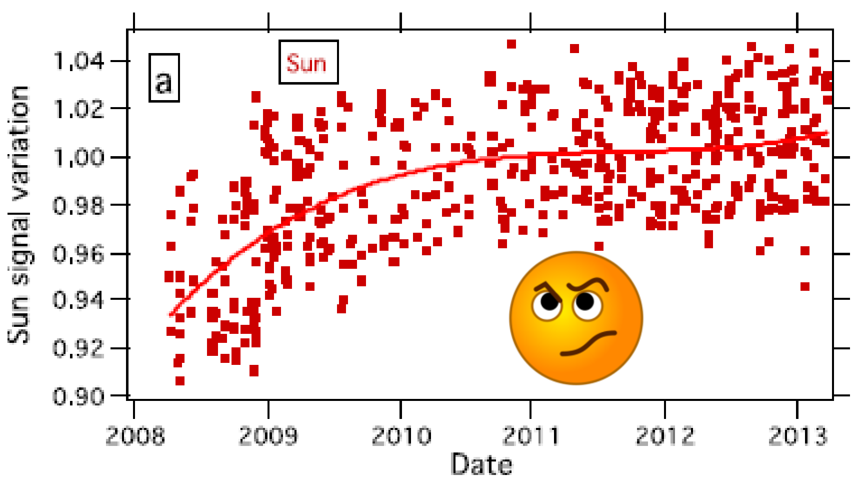
Solar Phys
DOI 10.1007/s11207-015-0704-1

The Infrared Solar Spectrum Measured by the SOLSPEC Spectrometer Onboard the International Space Station

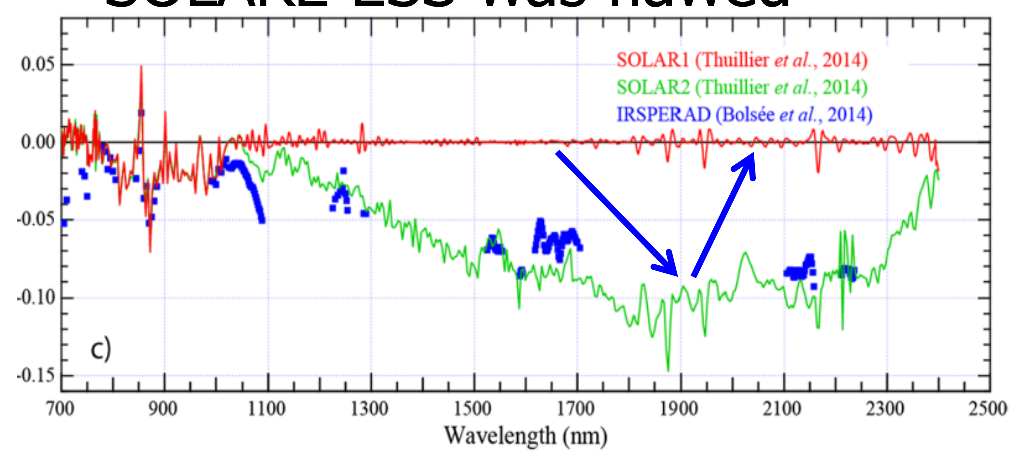
G. Thuillier[1] · J.W. Harder[2] · A. Shapiro[3] · T.N. Woods[2] · J.-M. Perrin[4] · M. Snow[2] · T. Sukhodolov[3] · W. Schmutz[3]

- SOLAR2 was based on ISS "first light" from measurements in April 2008 "to avoid ageing effects"

- Thullier et al. (2015) "Increase of solar signal (with time) ... (has) no clear explanation ... most likely due to some temperature effect and/or outgassing of the instrument"
- They concluded that the ESS was closer to original ATLAS3 (Solar1) spectrum and evidence supporting the lower SOLAR2 ESS was flawed



Thullier et al. (Sol Phys 2015)



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Not every one agreed

Solar Phys
DOI 10.1007/s11207-015-0707-y

CrossMark

Comment on the Article by Thuillier *et al.* "The Infrared Solar Spectrum Measured by the SOLSPEC Spectrometer onboard the International Space Station"

Invited Review

M. Weber[1]

Solar Phys (2016) 291:2473–2477
DOI 10.1007/s11207-016-0914-1

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Comments to the Article by Thuillier *et al.* "The Infrared Solar Spectrum Measured by the SOLSPEC Spectrometer Onboard the International Space Station" on the Interpretation of Ground-based Measurements at the Izaña Site

D. Bolsée[1] · N. Pereira[1] · E. Cuevas[2] · R. García[2] · A. Redondas[2]

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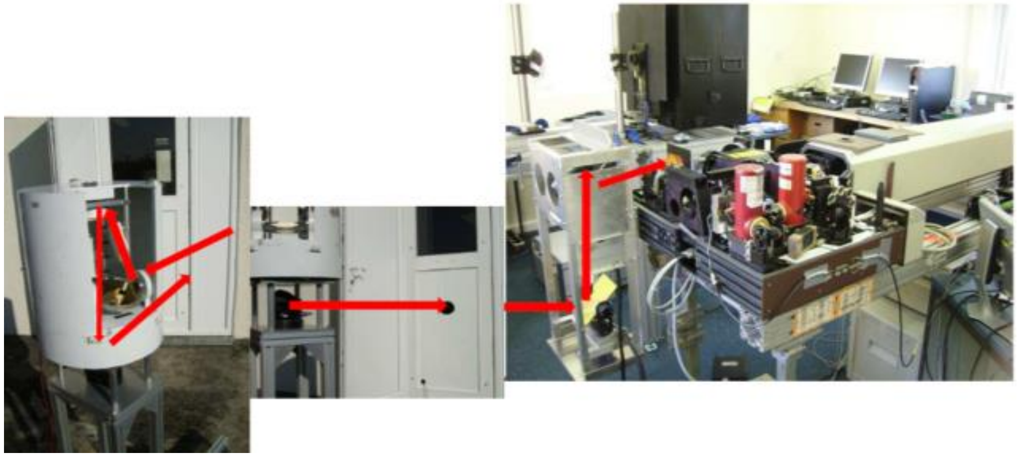
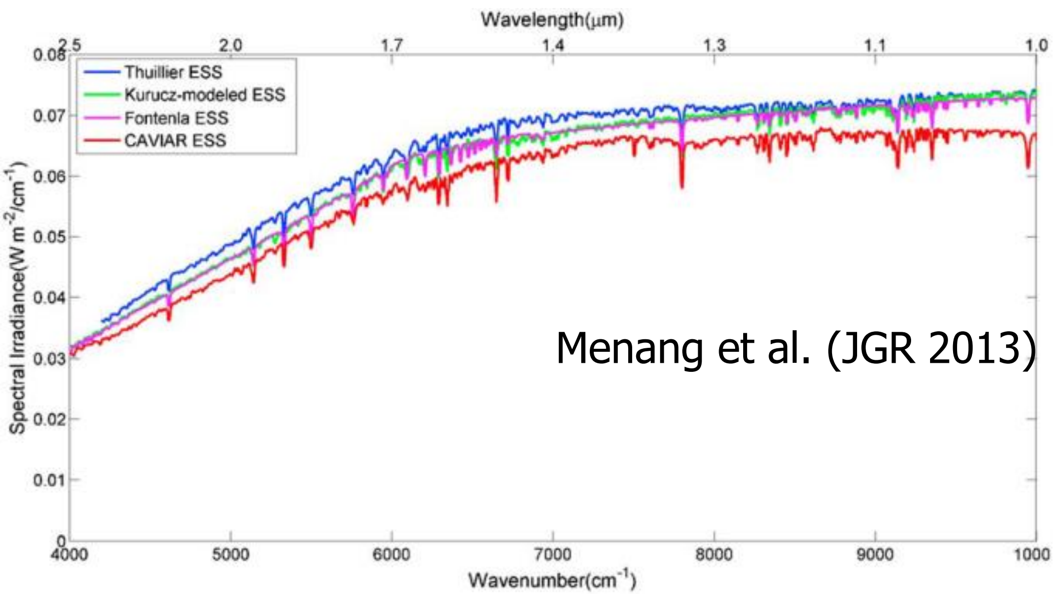
Ground-based sun-pointing FTS measurements

National Physical Laboratory

NPL FTS and sun-tracker





Menang et al. (JGR 2013)

- Calibration traceable to a primary standard cryogenic radiometer
- Field campaign in UK in 2008
- Recent work by Jon Elsey (GRL, 2017) builds on Menang et al. (JGR, 2013) with a more detailed error budget

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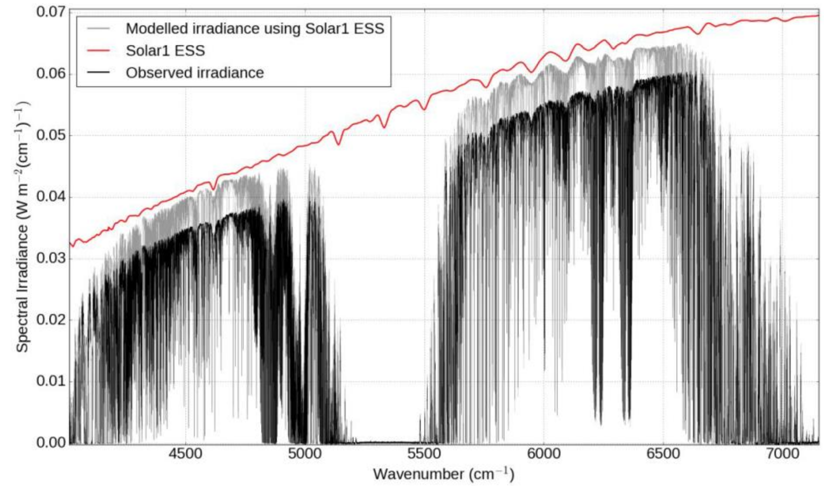
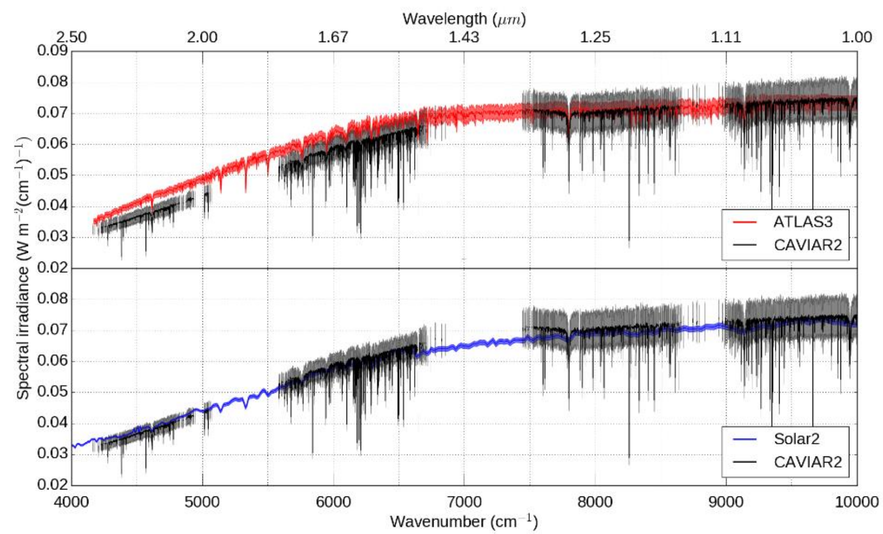
Field campaign results

- Direct modelling of surface spectral irradiance *inconsistent* with observed irradiances using the *higher* SOLSPEC ESS
- Discrepancy is outside known instrumental, spectroscopic or atmospheric state uncertainties
- Updated Langley analysis shows good agreement with the SOLAR2 ESS, and so supports the *lower* value





Elsey et al. 2017 GRL
10.1002/2017GL073902

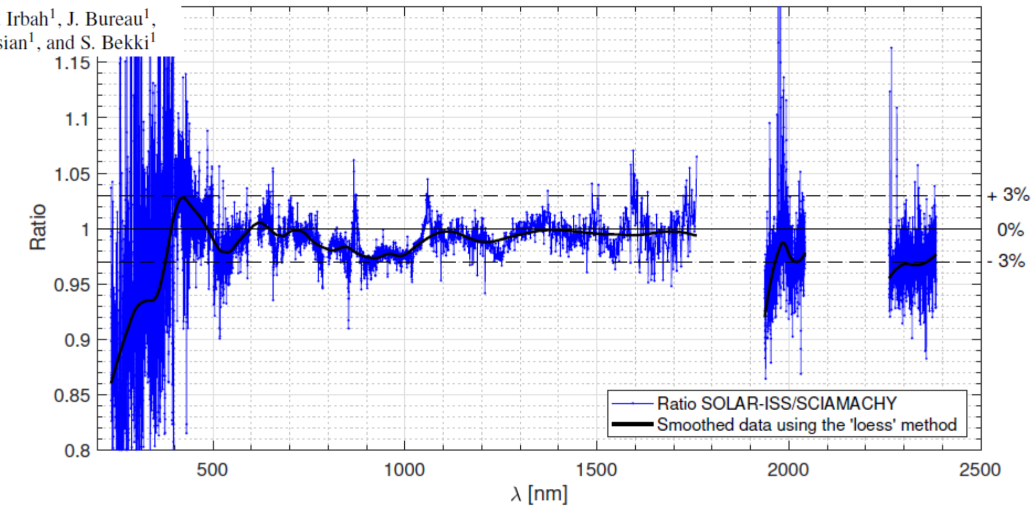
Newer SOLSPEC analysis

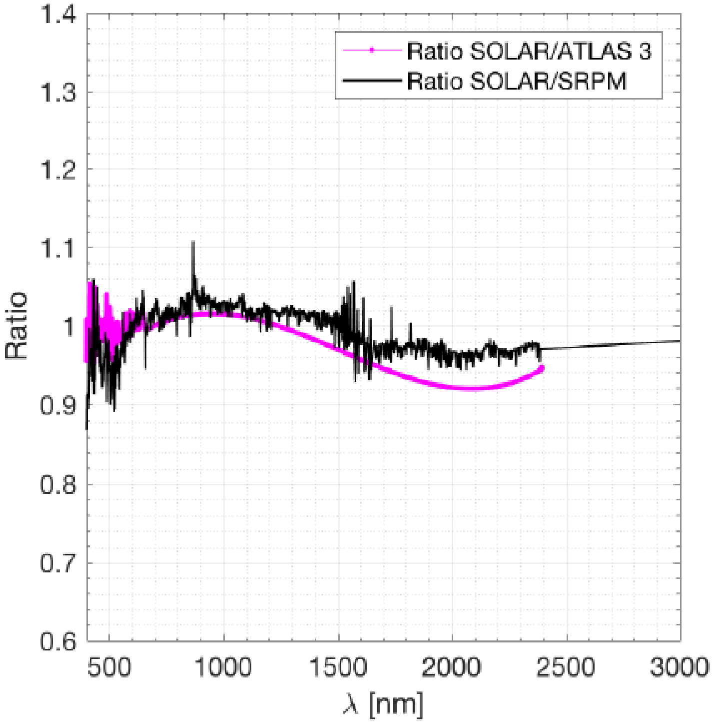
A&A 611, A1 (2018)
DOI: 10.1051/0004-6361/201731316

Astronomy & Astrophysics

SOLAR-ISS: A new reference spectrum based on SOLAR/SOLSPEC observations★

M. Meftah[1], L. Damé[1], D. Bolsée[2], A. Hauchecorne[1], N. Pereira[2], D. Sluse[2], G. Cessateur[2], A. Irbah[1], J. Bureau[1], M. Weber[3], K. Bramstedt[3], T. Hilbig[3], R. Thiéblemont[1], M. Marchand[1], F. Lefèvre[1], A. Sarkissian[1], and S. Bekki[1]





- Newer analysis of Solspec "confirms" ATLAS-3 is an overestimate by 8% in near-IR
- Good agreement with independent SCIAMACHY ESS.

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I'll cover three clear/clean sky issues in the near-IR

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- The role of methane near-IR bands

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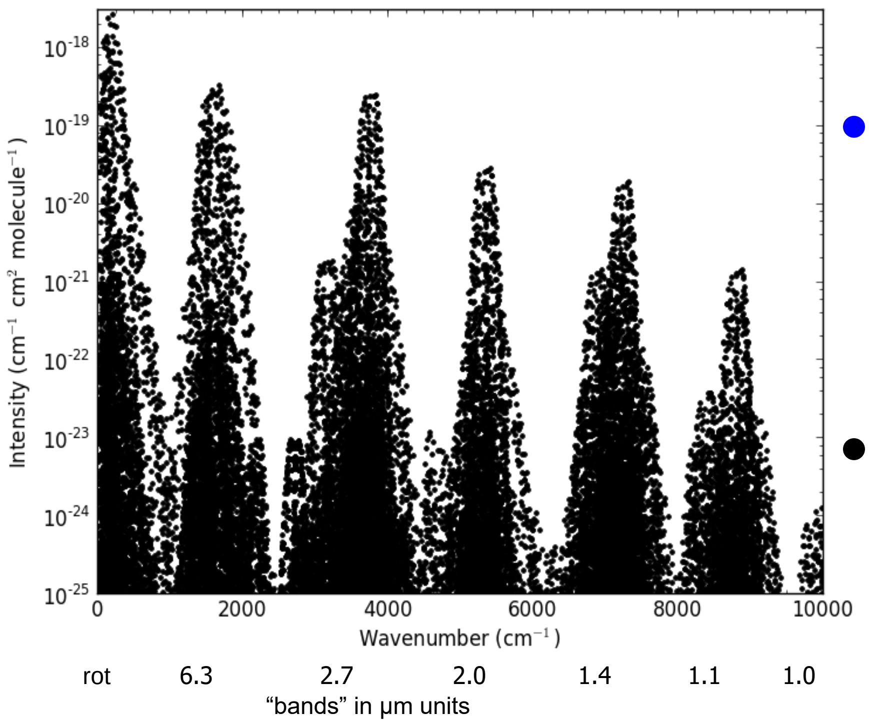
Between the water bands … the water vapour continuum



- Leading importance in the 10 µm window – long history of measurements; *potentially* important in other windows
- No settled scientific cause – not today’s subject
- Very few measurements prior to 2000 in 1.6 and 2.1 µm near-infrared windows. Today there are still just a *few*
- Those that do exist do not agree well near room temperature, and <u>none</u> extend to lower temperatures
- Most models use CKD/MT-CKD self and foreign continuum

Journal of Molecular Spectroscopy 327 (2016) 193–208

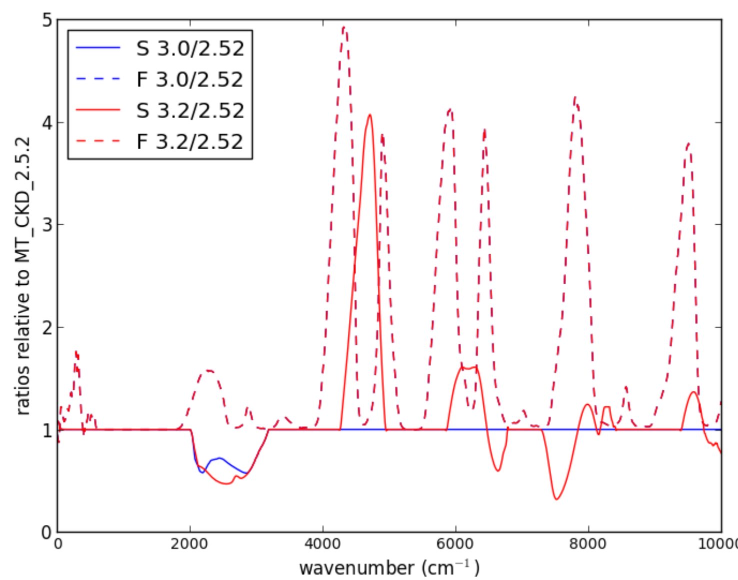
The water vapour continuum in near-infrared windows – Current understanding and prospects for its inclusion in spectroscopic databases

Keith P. Shine [a,*], Alain Campargue [b,c], Didier Mondelain [b,c], Robert A. McPheat [d], Igor V. Ptashnik [e], Damien Weidmann [d]

[a] Department of Meteorology, University of Reading, Earley Gate, Reading RG6 6BB, UK
[b] Univ. Grenoble Alpes, LIPhy, F-38000 Grenoble, France
[c] CNRS, LIPhy, F-38000 Grenoble, France
[d] Space Science and Technology Department, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK
[e] Spectroscopy Division, Zuev Institute of Atmospheric Optics SB RAS, 1 Akademichesky Av., Tomsk 634055, Russia

All comparisons with MT_CKD-2.5

Latest version is 3.2



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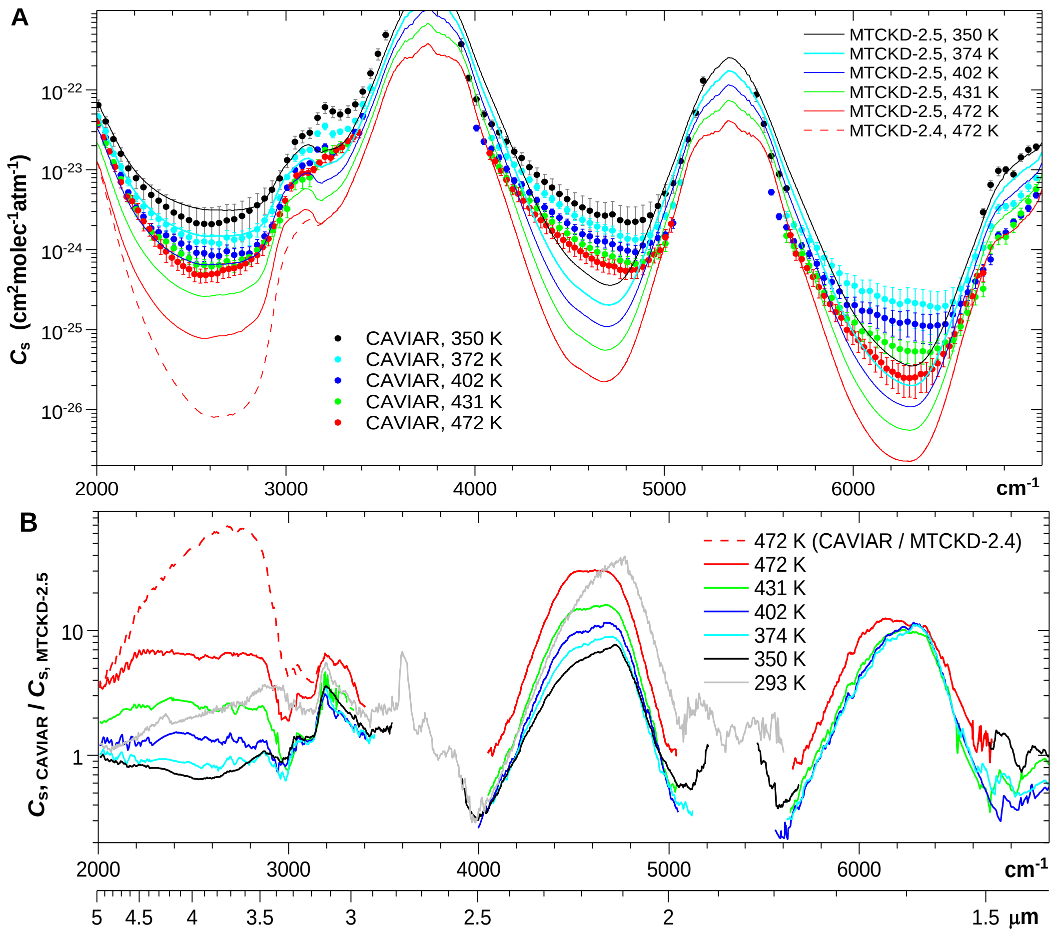
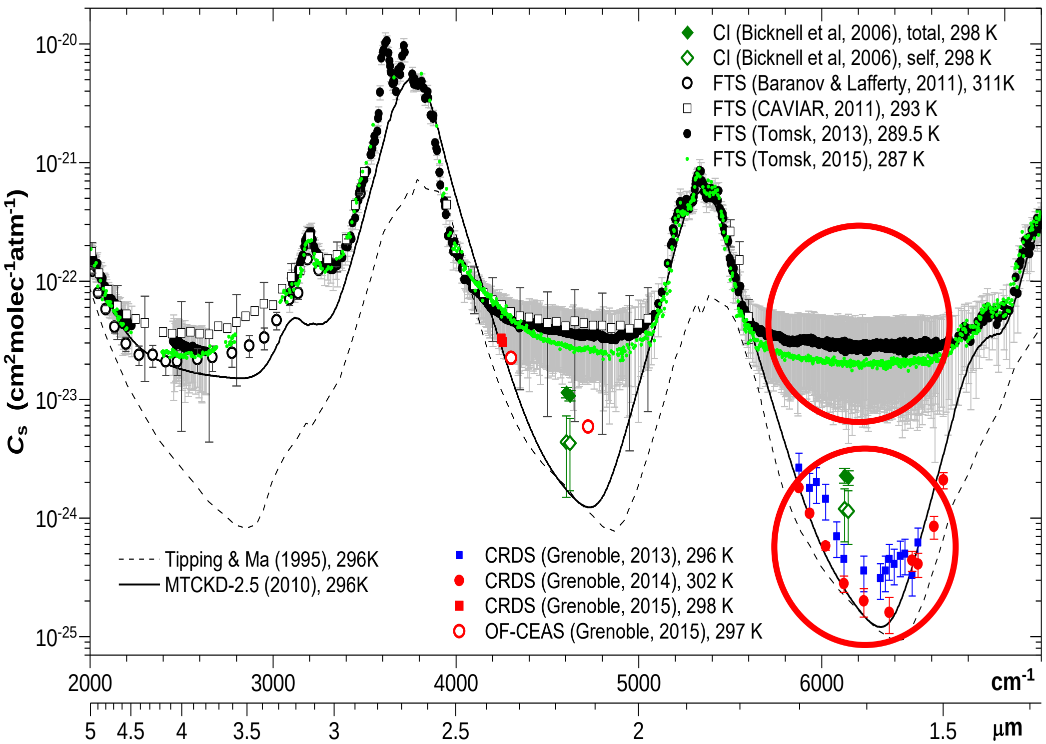
UK CAVIAR (Continuum Absorption at Visible and Infrared wavelengths and its Atmospheric Relevance) project (2006-2011) – indicated that widely-used continuum models are too weak. But most confident lab observations have necessarily been made at high temperature



Shine et al. J Mol Spec 2016

Few measurements near room temperature – main ones are from 3 groups: CAVIAR, Tomsk and Grenoble – and the degree of agreement can be very poor ... especially in the core of the 1.6 μm window at room temperature



Shine et al. J Mol Spec 2016

See also Lechevallier et al. 10.5194/amt-11-2159-2018 (CRDS at 2.0 and 3.3 μm)

and Richard et al. 10.1016/j.jqsrt.2017.06.037 (CRDS at 2.1 and 4.0 μm)

CAVIAR/Tomsk – uses Fourier Transform Spectrometry with large gas cells – large uncertainties at room temperature, but much better at elevated temperatures

CRDS – Cavity Ringdown Spectroscopy with small gas cells. Inherently more precise. Limited wavenumbers

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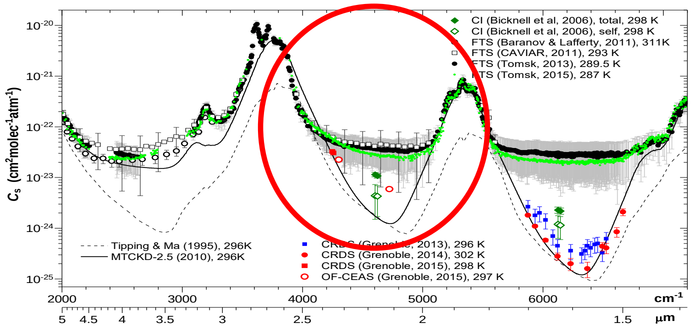
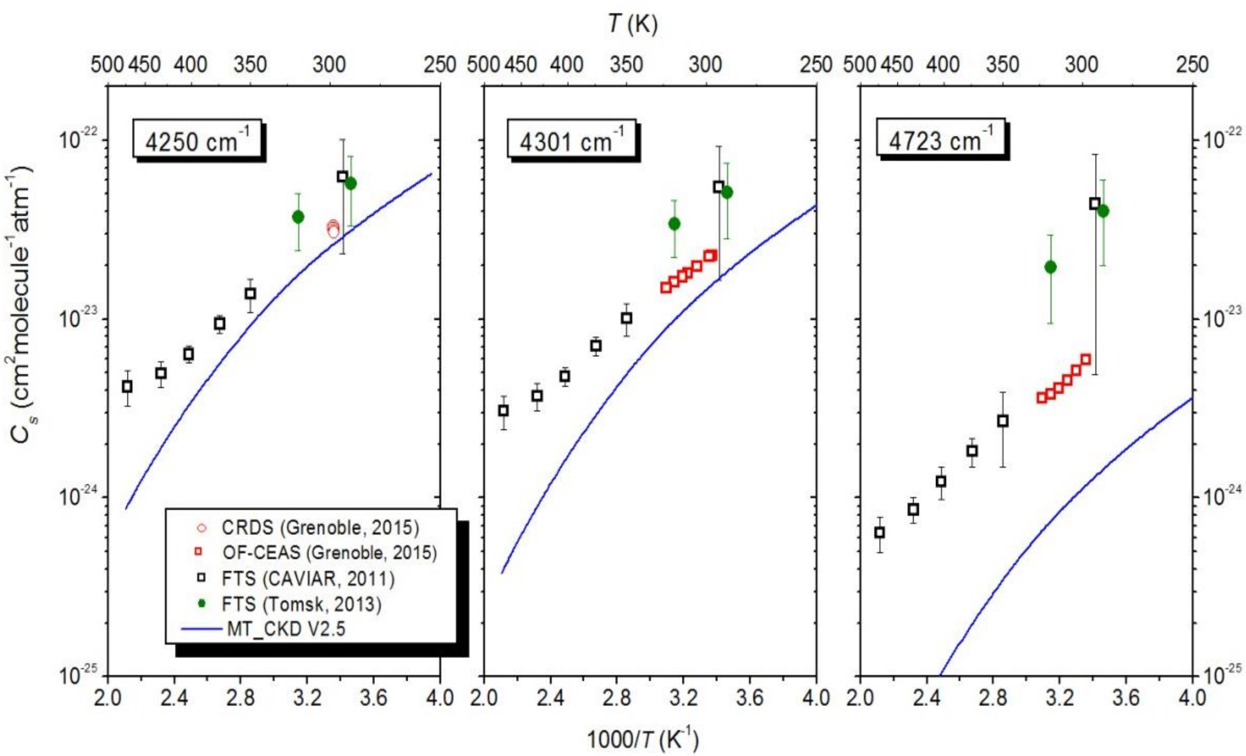


Temperature dependence as a *useful* diagnostic of consistency of measurements.



In 2.1 µm window, high-T CAVIAR FTS data appear strongly consistent with the Grenoble CRDS measurements

Straight line <u>if</u> T dependence is of form exp(D/kT)

Shine et al. J Mol Spec 2016

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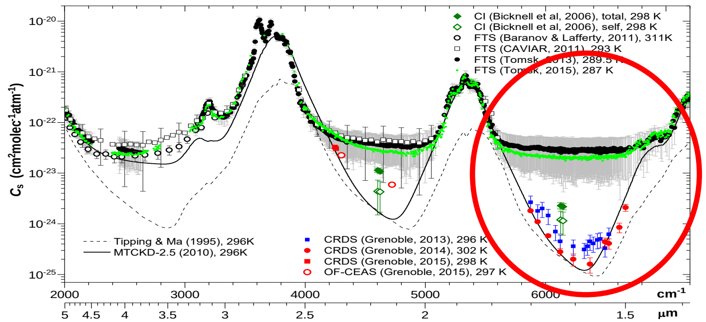
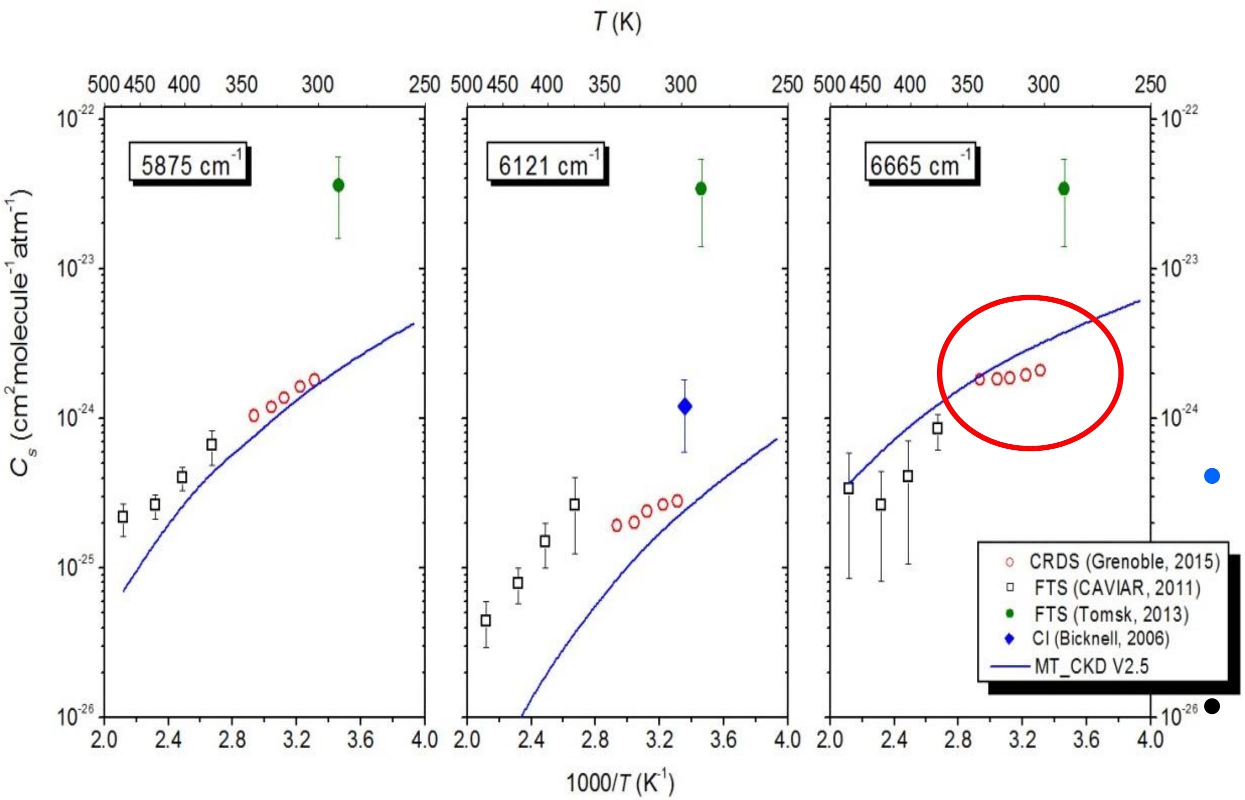
Temperature dependence as a *useful* diagnostic of consistency of measurements.





- In the 1.6 µm window, high-T CAVIAR and CRDS are much less consistent, especially in the centre of the window
- Why are 1.6 and 2.1 µm windows so different?
- CRDS-MT_CKD agreement is really only at room temperature.

Shine et al. J Mol Spec 2016

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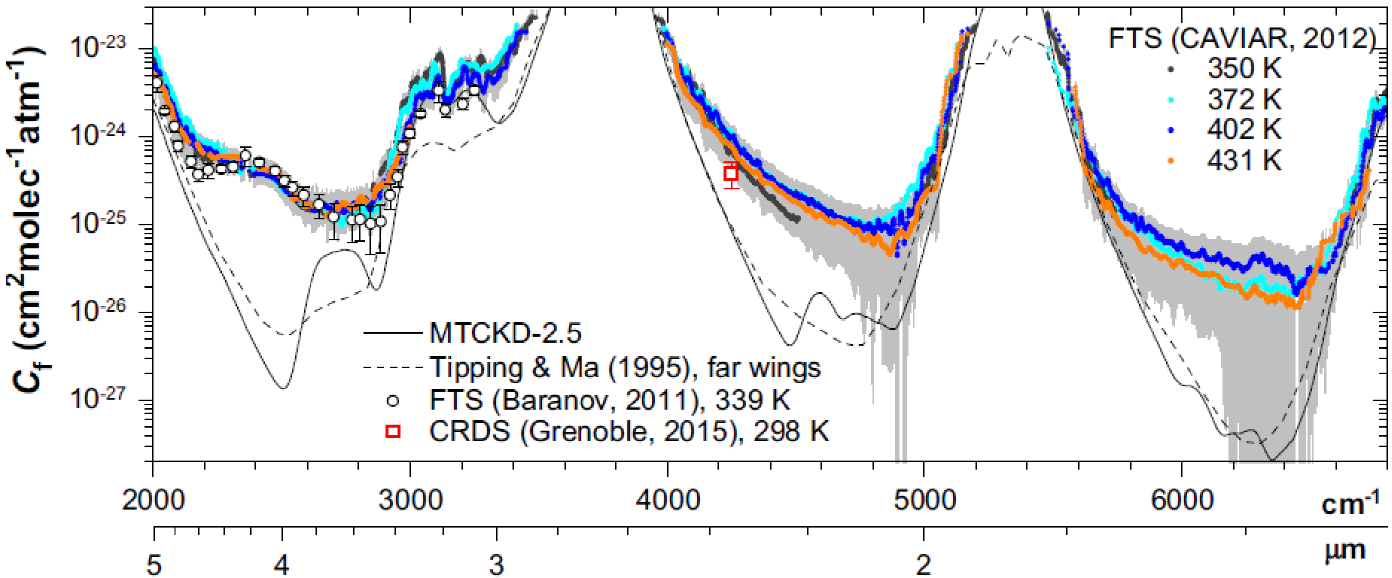
Foreign water vapour continuum



Shine et al. J Mol Spec 2016

- Even fewer measurements in 1.6 and 2.1 µm window – CAVIAR FTS, plus <u>one</u> CRDS measurement
- But expect little temperature dependence and so elevated temperature measurements are more applicable – and constancy exists after self-continuum removed.
- Factor of 2 agreement between FTS and CRDS despite claim by Oyafuso et al. (JQSRT 2017) that CRDS agrees better with MT-CKD.

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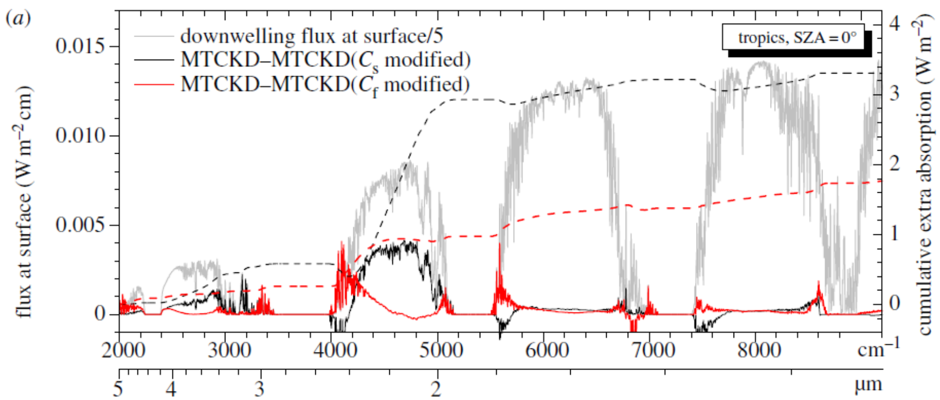
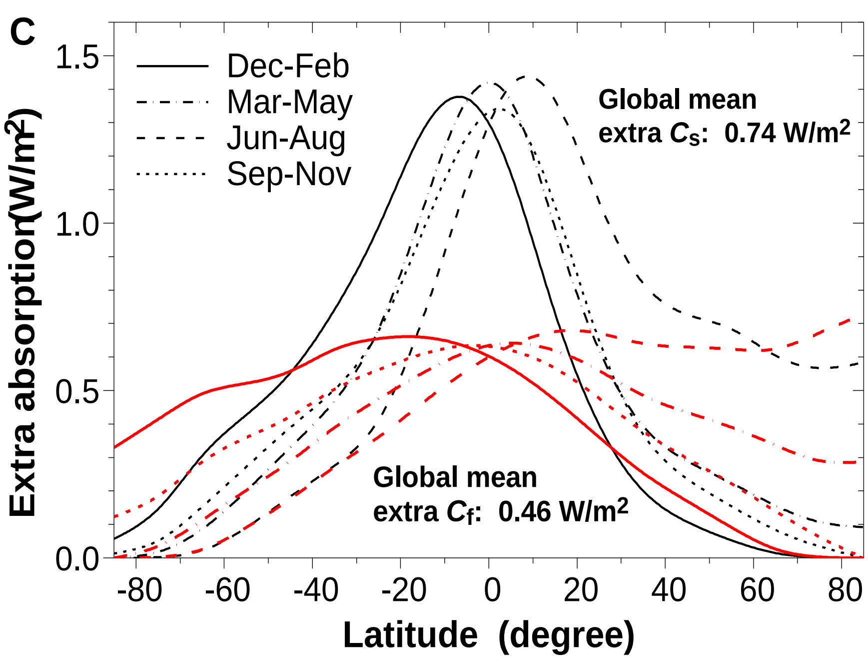
Impact on atmospheric absorption





Ptashnik et al. (Phil Trans Roy Soc, 2012)

Rädel et al. (QJRMS, 2015)

Using the CAVIAR continuum increases the global-mean clear-sky atmospheric shortwave absorption by 2% compared to MT-CKD, mostly from 2.1 µm window

But could be more (e.g. Tomsk 1.6 µm) or could be less (CRDS), if different lab measurements used

In a warming world, this absorption increases by 12% more using CAVIAR continuum than MT-CKD

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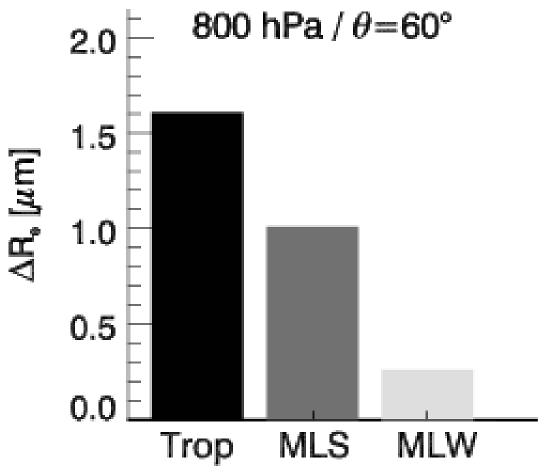
Impact on remote sensing



Shine et al., Surveys in Geophys, 2012

Clouds: If CAVIAR continuum is used, it could systematically reduce the retrieved droplet radius at 4900 cm^{-1} by typically about 1 μm (in 10 μm). Depends on cloud height and location

CO_2 Analysis of TCCON (ground-based FTS) in context of OCO-2 (Oyafuso et al. JQSRT 2017) - could not reconcile variation of retrieved CO_2 with air-mass between summer and winter observations. Concluded "unrealistically large multiplicative factors [~8x in 2.06 μm band and ~150x in 1.6 μm band] for the water vapour continuum were required". Unrealistically?

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The near-IR water vapour continuum: some conclusions

- Significant differences in the room-temperature self-continuum. Generally better agreement at higher temperatures but puzzles about variations between windows
- Too few independent measurements; little overlap in measurement conditions; no lower T measurements; only one set of extensive foreign continuum measurements
- What next? Continued analysis of sun-pointing FTS measurements (Elsey et al. to be presented at HITRAN 2018 and AMS radiation meetings)
- What next? New Reading-RAL project: Advanced Spectroscopy Advanced Spectroscopy for improved characterisation of the near-Infrared water vapour Continuum (ASPIC). Supercontinuum laser sources increase signal and allow increased path length in lab

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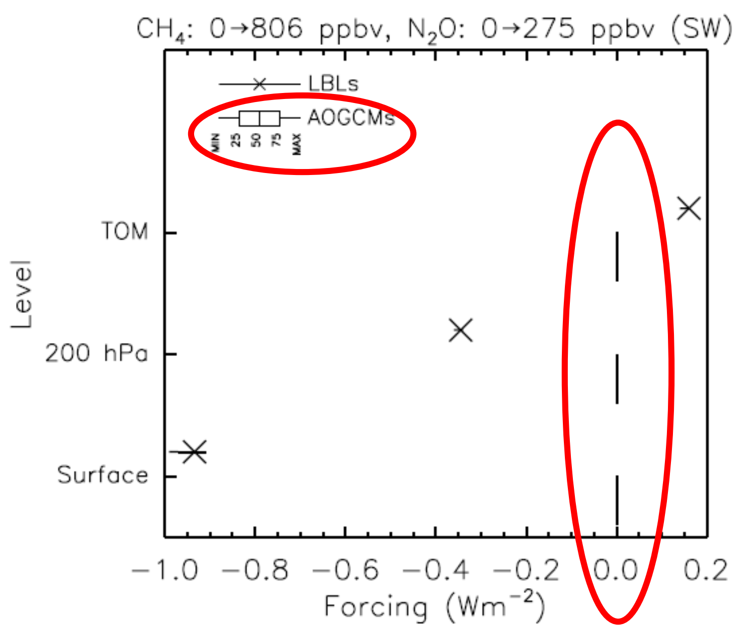
Near-IR bands of CH_4

Radiative forcing by well-mixed greenhouse gases: Estimates from climate models in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4)

W. D. Collins,[1] V. Ramaswamy,[2] M. D. Schwarzkopf,[2] Y. Sun,[3] R. W. Portmann,[4] Q. Fu,[5] S. E. B. Casanova,[6] J.-L. Dufresne,[7] D. W. Fillmore,[8] P. M. D. Forster,[9] V. Y. Galin,[10] L. K. Gohar,[6] W. J. Ingram,[11] D. P. Kratz,[12] M.-P. Lefebvre,[7] J. Li,[13] P. Marquet,[14] V. Oinas,[15] Y. Tsushima,[16] T. Uchiyama,[17] and W. Y. Zhong[18]



Collins et al. (JGR 2006)

Bands are well known but "underrepresented" in GCM radiation schemes.

Collins et al (2006) showed line-by-line codes have positive TOA forcing and negative surface forcing, for an idealised case. GCM codes have zero …

See also Li et al. (JAS, 2010) for impact on GCM simulations

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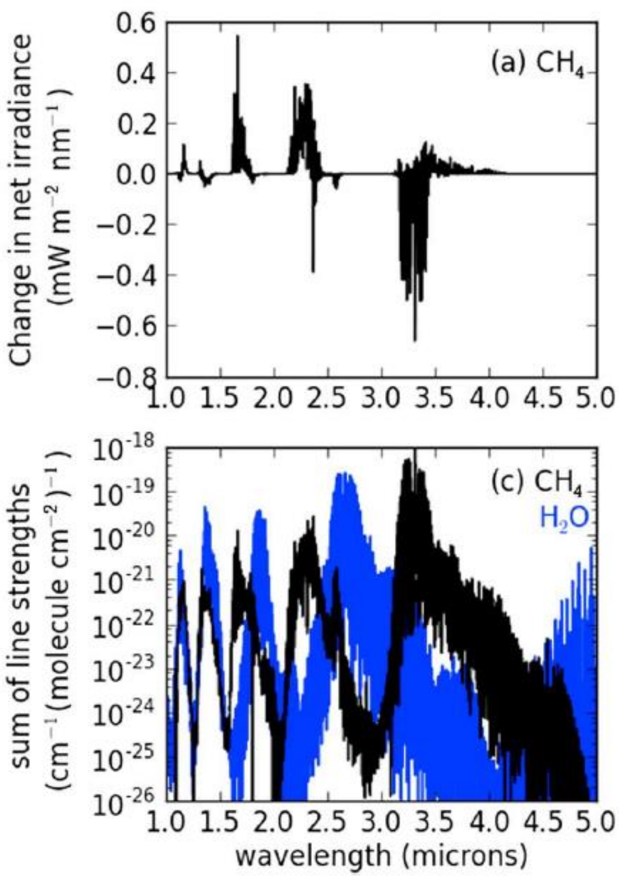
Near-IR bands of CH_4

Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing

M. Etminan[1], G. Myhre[2], E. J. Highwood[1], and K. P. Shine[1]



Etminan et al. (GRL 2016)

- Etminan et al. line-by-line code calculations indicate methane forcing (and GWP etc) is enhanced by about 15% (6% due to direct absorption, 9% due to stratospheric warming) due to near-IR bands
- Deliciously "rich" structure in forcing – even sign of forcing varies spectrally, depending on strength of band and position relative to main water vapour bands
- Strong dependence on cloudiness (and surface albedo) – enhanced absorption of reflected beam changes sign of forcing

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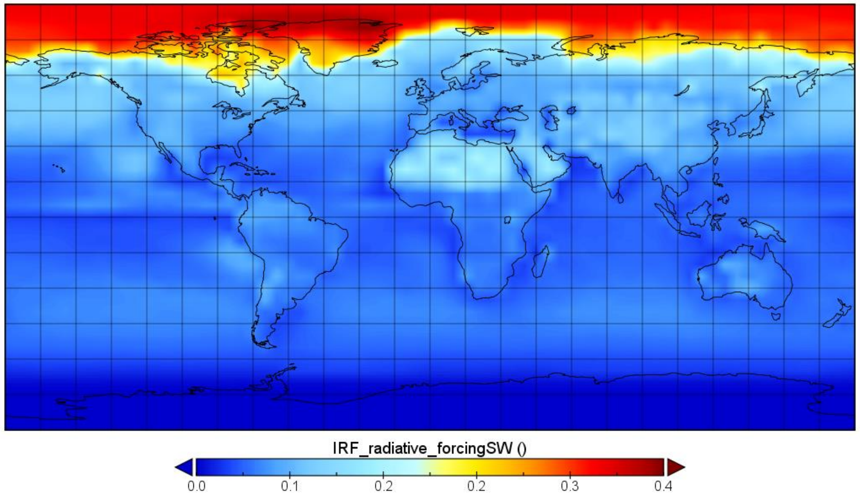
Near-IR bands of CH_4

Some modern GCM codes do include the CH_4 near-IR bands, but those we studied do not generate much forcing from them. Handling of overlap with water vapour?? An issue for codes used for both NWP and climate change.

Awaiting an "independent" and enhanced verification of the Etminan et al. results – will be important for IPCC AR6, if they are to adopt an enhanced methane forcing.



Preliminary: Geographical distribution of SW forcing (W m^{-2}) using high-spectral resolution version of SOCRATES code for May conditions) relative to pre-industrial

Byrom, Checa-Garcia et al, in prep

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Thank you

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