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Towards ground-to-space radiative closure in the mid- to far-infrared

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Abstract. Despite containing up to half of the Earth's thermal emission to space, the far-infrared spectral region (FIR, defined here as 100–667 cm^{-1} or 15–100 µm) has seldom been observed from satellites. This has contributed to substantial uncertainties in the spectroscopy of water vapour, radiative properties of clouds, and surface spectral emissivity; these in turn limit confidence in modelled FIR energy flows. With the advent of the Polar Radiant Energy in the Far-InfraRed Experiment (PREFIRE), a step is taken towards new, systematic, spectral observations of the Earth in the FIR. Launched in 2024, the two PREFIRE CubeSats offer a new perspective of Earth's outgoing longwave energy with moderate spectral resolution. However, the observational uncertainty budget requires further consolidation.

In this study we assess the accuracy of PREFIRE spectral measurements through a 'ground-to-space' closure experiment. Using zenith-viewing observations from the ground-based Far INfrarEd Spectrometer for Surface Emissivity (FINESSE), we gauge the representativity of atmospheric data from in situ sensors and reanalysis. With these data we simulate PREFIRE-observed radiances for an overflight of our field site in eastern Canada. Simulations of the FINESSE radiances are in very good agreement with observations, while those from PREFIRE indicate some bias beyond the calculated uncertainties. We find that atmospheric water vapour specification, uncertain surface properties, and instrument noise dominate the uncertainties. Based on these findings, we highlight proposed techniques for closure experiments using terrestrial and satellite instruments alike. Such experiments will provide a ground-truth for validation of future FIR satellite missions.

1 Introduction

The interaction of thermal infrared radiation with Earth's atmosphere and surface plays a fundamental role in shaping the planet's weather and climate. Spectral observations in the thermal infrared can be used to retrieve atmospheric composition and temperature structure, and to understand the complex physics behind Earth system processes. Satellite observations additionally

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offer a powerful global view of these phenomena, and have been used for decades in the service of meteorology and atmospheric science.

The far-infrared (FIR), defined here as the region from 100–667 cm^{-1} (or 15–100 µm) comprises around half of the globally averaged longwave emission to space (Harries et al., 2008), and as such is a crucial component of the Earth's radiation budget. Water vapour is a key atmospheric absorber in the FIR, contributing to the significant FIR greenhouse effect (e.g. Sinha and Harries, 1995; Brindley and Harries, 1998). Conversely, in very dry and cloudless atmospheric conditions micro-windows 'open' in the FIR. These micro-windows comprise the FIR 'dirty window' region (here defined as 400–600 cm^{-1}), and permit radiation from the surface to escape to space. In this way, surface temperature and emissivity can also affect FIR measurements from space, as well as the top-of-atmosphere energy budget.

Ice clouds exert a strong influence in the FIR, with theoretical studies demonstrating substantial sensitivity of FIR radiances to the size and shape of ice crystals (Yang et al., 2003; Baran, 2007). More recent analyses using ground- and aircraft-based observations have confirmed this sensitivity and suggest that the region could provide uniquely powerful constraints on retrieved cloud properties (Maestri et al., 2014; Panditharatne et al., 2025; Di Natale et al., 2026).

Nevertheless, the scarcity of FIR observations (relative to other spectral regions such as the mid-infrared and microwave) means that significant uncertainties persist in fundamental gas spectroscopy (e.g. Mlawer et al., 2019), underlying ice optical properties and hence cirrus radiative properties (e.g. Wang et al., 2024; Bantges et al., 2020), and surface emissivity (e.g. Chen et al., 2014). These uncertainties can propagate into simulations of the future climate (e.g. Turner et al., 2012; Huang et al., 2018).

Despite its scientific importance, spectrally resolved observations of the FIR from satellites have been impeded by limitations of optical and sensor technology. The only such measurements until recently were from a sparse set of missions in the early satellite era (Hanel et al., 1971; Kempe et al., 1980). However, the launch of the Polar Radiant Energy in the Far-InfraRed Experiment (PREFIRE, L'Ecuyer et al., 2021) in 2024 marks the first step towards filling this FIR observational gap. This mission features two CubeSats launched as part of NASA's Earth Ventures initiative. A relatively low-cost mission, PREFIRE provides moderately resolved spectral radiances stretching into the FIR and aims to contribute to polar science at a time of rapid change in the polar climate. The radiances are used to retrieve temperature, water vapour, surface spectral emissivity, and spectral fluxes in clear-sky polar scenes, but a first step towards being confident in the accuracy of these retrievals is to have confidence in the radiances themselves.

Unbridled by the stringent requirements of a space mission, a limited set of accurate ground- and aircraft-based instruments observing the FIR has been available for some time. These instruments have furthered knowledge of the FIR radiative properties of several components of the Earth system, including water vapour (e.g. Mlawer et al., 2019) and the surface emissivity (Bellisario et al., 2017; Murray et al., 2020). Zenith-pointing observations in clear sky have been used to profile the atmosphere with high accuracy, investigate downwelling radiance, and perform closure tests in the FIR (e.g. Mariani et al., 2012; Belotti et al., 2023; Mosselmans et al., 2026).

With the above in mind, in this work we carry out a radiative closure study in clear sky across the mid- to far-infrared, with a focus on the FIR. We use the FINESSE ground-based spectrometer (Murray et al., 2024) to assess the representativity

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of atmospheric profiles gathered from reanalysis and in situ measurement. The high spectral resolution, accuracy, and known calibration of this spectrometer give us confidence in the accuracy of the atmospheric profiles and of our radiative transfer simulations. We then go on to compare simulations and measurements of satellite radiances from an overpass of the ground measurement site, serving to validate spectral radiance observations from PREFIRE and identify potential instrument biases. As far as we are aware, this work represents the first attempt to perform such an experiment in the far-infrared.

The layout of this paper is as follows. The data sources and methods used in the experiment are presented in Sect. 2. In Sect. 3, we discuss the various challenges to a rigorous radiative closure diagnosis, and present a detailed investigation into the sources of uncertainty in the experiment. We present results of the closure experiment, both on the ground and in space, in Sect. 4 and discuss the findings in Sect. 5.

2 Data sources and methods

2.1 The WHAFFFERS campaign

The W-band, HiSRAMS, AERI, FIRR2, FINESSE and FIRMOS Experiment on Remote Sensing (WHAFFFERS) campaign was a multi-modal field study conducted in Canada, with sites in Ottawa and near Montreal, in January and February of 2025. Observations of the atmosphere and land surface were gathered simultaneously by passive and active instruments across the two sites and from an aircraft. Among the aims of the campaign was to investigate consistencies between radiometric instruments by performing radiative closure experiments. We investigate a closure experiment in this work with a focus on measurements from the research station at the Gault Nature Reserve of McGill University (45.535° N, 73.149° W). This site sits at c.130 m above sea level on the side of a forested hill, surrounded by mostly flat agricultural land at c.30 m above sea level.

Meteorological conditions were anomalously cold and dry in this region of Canada during the campaign which was ideal for study of the far-infrared. The reduced optical depth of the atmospheric column in the FIR water vapour absorption features affords greater sensitivity than normal to higher altitudes and to water vapour spectroscopy when measured from the ground.

2.2 Spectral measurements

2.2.1 FINESSE

The Far-infrared Spectrometer for Surface Emissivity (FINESSE, Murray et al., 2024) is a ground-based radiometer developed at Imperial College, employing a commercial Bruker EM27 Fourier-transform spectrometer. FINESSE was originally configured to measure over the range 400–1600 cm^{-1} with a spectral resolution reaching 0.5 cm^{-1}. It features a custom front-end optics system that enables both the study of surface emissivity and zenith-looking views of the atmosphere. FINESSE has been used to retrieve surface emissivity under laboratory conditions (Warwick et al., 2024) and in the field (Warwick et al., 2025) using measurements from a campaign in Andøya, Norway in 2023. Measurements from this field campaign have also enabled study of the polar atmosphere (Mosselmans et al., 2026). The instrument is equipped with ancillary sensors to measure temperature, pressure, relative humidity, and CO_2 concentration.

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Work has been ongoing since the Norway campaign to improve the FINESSE instrument. Replacing the liquid nitrogen cooling with a Stirling cooler has eliminated the need to interrupt measurements and extended the measurement range slightly further into the FIR, now reaching 380 cm^{-1}. Vibrations induced by the Stirling cooler were removed outside of the required modulated frequency band by doubling the FINESSE scan speed, with each interferometer scan lasting 0.75 s rather than the 1.5 s of the original configuration. Intercomparison with a co-located AERI spectrometer during the WHAFFFERS campaign enabled the diagnosis and removal of a small bias between 1400–1600 cm^{-1}. This bias was caused by internal reflections in the spectrometer assembly and had gone undetected in the Andøya FINESSE measurements.

2.2.2 PREFIRE

The Polar Radiant Energy in the Far-Infrared Experiment mission (PREFIRE, L'Ecuyer et al., 2021) consists of two 6U CubeSats in different near-polar Sun-synchronous orbits, each equipped with a Thermal Infrared Spectrometer (TIRS) instrument; the satellites were launched in May/June 2024. The TIRS is a lightweight grating spectrometer covering a spectral range of 5–54 µm (185–2000 cm^{-1}), with a nominal spectral sampling of ∼0.84 µm (equivalent to ∼5 cm^{-1} at 250 cm^{-1}, or ∼20 cm^{-1} at 500 cm^{-1}). The four order sorting filters used in the TIRS instrument split the measurements into four distinct spectral bands. In order of increasing wavelength, these bands are referred to as MIR-1, MIR-2, FIR-1, and FIR-2.

The TIRS grating separates incoming radiation from eight cross-track 'scenes' onto the uncooled detector array, where each scene has a full complement of detectors for all spectral channels. This results in different sensor noise characteristics for each cross-track view. On the Earth's surface, the scenes are non-contiguous and stretch across a 264 km swath, acting as an eight-toothed 'comb' moving along the satellite track. Each field of view (FOV) has a surface footprint of approx 11.8×34.8 km (cross- × along-track) with cross-track gaps between of approx 24.2 km. There is substantial overlap in the FOVs in the along-track direction, with any point along the orbit observed by up to 7 overlapping footprints. Note that these values will change as the satellites' orbits decay over the mission lifetime. A single spectrum of the TIRS instrument is recorded at each FOV.

In the initial release (R01) of the PREFIRE level 1 radiance product (1B-RAD), the science team have identified discrepancies between the instrument model of the spectral response functions and the true instrument response. The second release (R02) of the L1B data includes an empirical correction factor for the spectral radiance. This correction can be added to the reported spectral radiance to account for these discrepancies, as is done for the analysis in this study. Figure 1 illustrates the effect of this correction on the spectra used in this study. The correction factor is derived using a combination of three distinct reference radiances: IASI collocated spectra convolved to PREFIRE channels, CrIS collocated spectra convolved to PREFIRE channels, and PCRTM modelled clear-sky radiances derived using the PREFIRE Auxiliary Meteorology product (Mattingly et al., 2025) as input. More details on this correction factor will be published in due course.

2.2.3 Selection of spectral data

FINESSE operated on 20 days across the WHAFFFERS campaign, collecting approximately 135 hours of measurements. During the FINESSE observation periods, PREFIRE FOVs with valid spectra passed close to (within ∼25 km of) the site on 7 occasions. A further 19 overpasses were not captured by FINESSE due to either the time of the overpass (in the evening or

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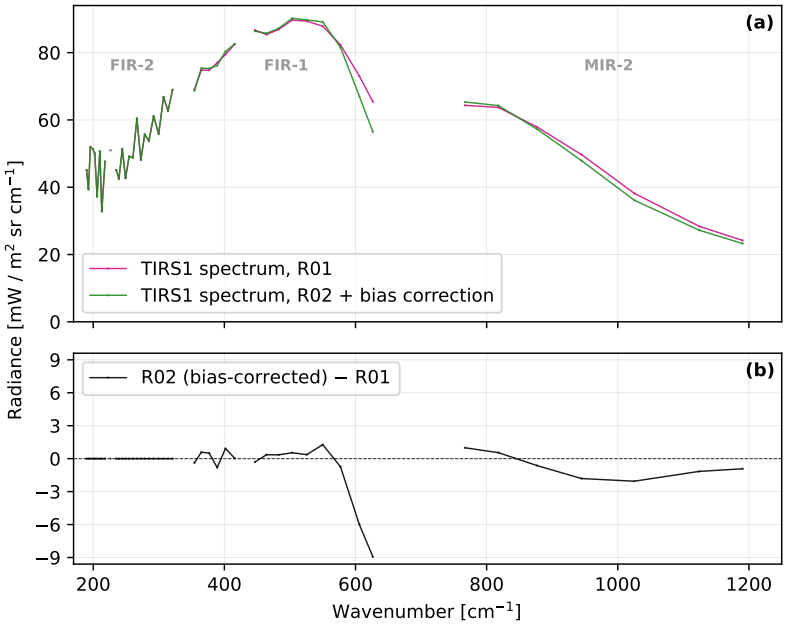

Figure 1. (a): Example PREFIRE TIRS 1 spectra (from across-track scene 6) for the first and second release (R01 and R02) of the Level 1 radiance product. The R02 spectrum includes the new bias correction term. Grey text labels the spectral bands of the TIRS instrument. **(b)**: Spectral differences between the two releases.

at night) or weather conditions (FINESSE cannot operate during precipitation). Of the 7 captured, we focus on the PREFIRE satellite 1 overpass on 28th January 2025 at 20:52 UTC (15:52 local time). This case was the only one of these 7 to have verifiable clear skies throughout the observed scene and a radiosonde release at the time of the overpass.

For this study we average all spectra from a five minute window of the FINESSE measurements, centred on the PREFIRE overpass. FINESSE was continuously recording in zenith view mode and collected 400 interferometer scans in this time. The spectra exhibit good stability over the measurement period, indicating no marked evolution in the atmospheric state. PREFIRE measurements are taken from the Level 1B-RAD product, version R02, with the bias correction factor included. Valid spectra from the overpass whose FOV midpoint was within 0.25° (latitude/longitude) of the Gault station are averaged along-track to yield two spectra for comparison, from the cross-track TIRS 1 scenes 5 and 6. All channels in the MIR-1 PREFIRE band have known calibration issues and so are neglected here.

2.3 Ancillary atmosphere and surface data

To model infrared radiative transfer in clear skies (that is, neglecting the contributions of cloud and aerosol), we require temperature and gas concentrations as functions of pressure or altitude. In the thermal infrared region we study here, encompassing 185–1600 cm^{-1} across both instruments, the dominant absorbing and emitting species are water vapour, carbon dioxide, and ozone, with other trace gases such as methane and nitrous oxide also required to simulate spectral radiance with high accuracy.

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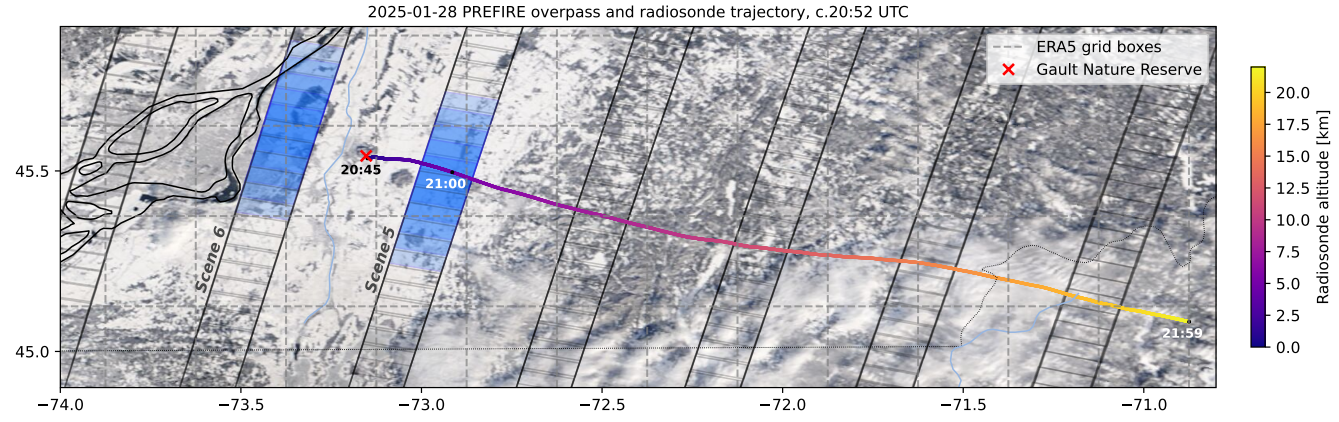

Figure 2. Map showing the layout of measurements for our case study. The red cross marks the the Gault Nature Reserve site, where FINESSE was located. The track of the radiosonde launched from here is shown, with times (UTC) labelled throughout the flight and colours indicating its altitude. Solid boxes across the image indicate the PREFIRE FOV polygons from the overpass, with significant overlap in the along-track direction (approx. north-east–south-west). FOVs selected for averaging in the scenes 5 and 6 are shaded blue. Grey dashed lines indicate the ERA5 grid boxes for reference. The background image is from MODIS Terra observations, approx 6 hours before the PREFIRE overpass (Credit: NASA).

The spectral emissivity and radiating temperature of the surface are needed in addition to simulate infrared radiation upwelling to space.

For this study, we make use of a range of atmospheric data sources. Firstly we use ERA5 hourly profiles of temperature, specific humidity, and ozone concentration as a function of pressure on 137 atmospheric model levels, at a horizontal resolution of 0.25° (Hersbach et al., 2020). We also use the corresponding ERA5 estimates of the surface skin temperature (T_{sfc}).

Secondly, radiosondes launched periodically during the WHAFFFERS campaign also measured profiles of temperature and humidity. The radiosonde model used during WHAFFFERS was the InterMet Systems iMet-4 radiosonde. In the literature, we found limited prior studies using this model (see e.g. Ghysels et al., 2024; Liu et al., 2024) or brand (Hurst et al., 2011; Flores et al., 2013); its performance has not been independently and systematically reviewed. Figure 2 shows the track of the radiosonde launched at 20:45 UTC on 28th January 2025, with the PREFIRE observation footprints from the c.20:52 UTC overpass overlaid. Temperature, relative humidity, altitude, and pressure measured by the radiosonde are available at 5 m vertical intervals.

Finally, during the WHAFFFERS campaign, near-surface meteorological data were recorded continuously at the Gault Nature Reserve at a weather station within 50 m of FINESSE. Measurements of relevance to our study are from eight Vaisala HMP155A probes at different heights up to 10 m above ground, with temperature and relative humidity readings taken every minute. Analysis of these data over several measurement days indicated that probes at 1.5 m and 3.5 m above ground level were consistently biased and so their readings have been discarded.

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The emissivity of the surface ($\varepsilon_{\mathrm{sfc}}$) is taken from the dataset compiled by Huang et al. (2016) which provides modelled estimates of spectral emissivity at nadir-view for a variety of surface types and is the only dataset to offer this into the far-infrared. The 'medium snow' surface type (with median grain size 600 µm) is used in this study; fine and coarse snow as well as ice surface types are also available.

Concentrations of CO_2, CH_4, and CO are taken from the CAMS global greenhouse gas forecasts (Agustí-Panareda et al., 2019). For N_2O and SF_6, we take mixing ratios from NOAA's Global Monitoring Laboratory (NOAA), while for CFC-11, CFC-12 and CCl_4 concentrations are estimated by extrapolating the average 5-year trend of Atmospheric Histories (Bullister and Warner, 2017). Mixing ratios of the latter five greenhouse gases are assumed constant with height.

The different sources of atmospheric data are combined to generate profiles specifically for downwelling (FINESSE) and upwelling (PREFIRE) radiance simulations. To probe the impact of the characterisation of the atmosphere on the associated radiances, in each case we create two sets of temperature and humidity profiles. The 'ERA5' set is based purely on the closest ERA5 profile in space and time (45.5° N, 73.25° W, 21:00 UTC), while the 'in-situ' set is based primarily on the available in situ measurements. Table 1 provides a summary of the inputs to each set and the associated nomenclature we use to refer to each simulation. Apart from atmospheric temperature and humidity, all components described above are specified identically for the ERA5 and in-situ simulations. The same surface and atmosphere is used to simulate both TIRS scenes 5 and 6.

The only difference between the ERA5-DW and ERA5-UW profile is the choice of the lower boundary. For the former, we take the observation level as 130 m above sea level, consistent with FINESSE's altitude on a hillside at the Gault site. For the latter we use the entire ERA5 vertical profile (which has a surface altitude of 30 m). There are more substantial differences between the in-situ-DW and in-situ-UW cases. For the former we replace the radiosonde profile between 130–140 m with values from the weather station tower. For the latter, we do not use the weather station measurements and instead supplement the radiosonde values with co-located ERA5 data between 130 m and the surface. Similarly, in both cases, at altitudes above the maximum extent of radiosonde measurements we add the ERA5 data. The radiosonde data used in the in-situ profiles is smoothed from its native 5 m resolution before simulation.

Temperature and water vapour mixing ratio profiles for the ERA5 and in-situ cases are shown in Fig. 3. The insets highlight the near-surface conditions crucial for simulating FINESSE measurements. The profiles of temperature are broadly similar, with some differences reaching up to 5 K in parts of the free troposphere. The near-surface temperatures measured by the radiosonde immediately after launch are around 0.5–1 K warmer than the corresponding ERA5 values, behaviour which is not seen in the weather station observations. This does lead to a distinct feature in the in-situ-UW profile where the ERA5 and radiosonde profiles are joined, but sensitivity studies confirmed this has negligible impact on simulated upwelling radiances at the top of the atmosphere. The two water vapour profiles are more different; while both show a moist layer of similar extent at c.500 hPa, water vapour varies significantly below that. Overall, the in-situ profiles indicate a drier atmosphere.

2.4 Radiative transfer modelling

Simulated radiances at the top of atmosphere and at the surface are generated using the Line-by-Line Radiative Transfer Model (LBLRTM, Clough et al., 2005). Its high accuracy has led to it becoming a standard benchmark for spectrally resolved radiative

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Table 1. Data sources used to specify temperature and water vapour concentration across altitude regimes (left-hand column) for the different atmospheric profiles simulated. Simulated surface properties are also shown for PREFIRE observations. The marking "—" indicates that no simulation of this level was performed in this case. Specification of other gases is identical across the four profiles and is detailed in the text.

Instrument	FINESSE		PREFIRE	
Profile shorthand	ERA5-DW	In-situ-DW	ERA5-UW	In-situ-UW
>21.8 km	ERA5	ERA5	ERA5	ERA5
140 m–21.8 km		Radiosonde (smoothed)		Radiosonde (smoothed)
130–140 m		Weather station		
<130 m	—	—		ERA5
Surface	—	—	T_{sfc}: ERA5; ε_{sfc}: Huang et al. (2016)	

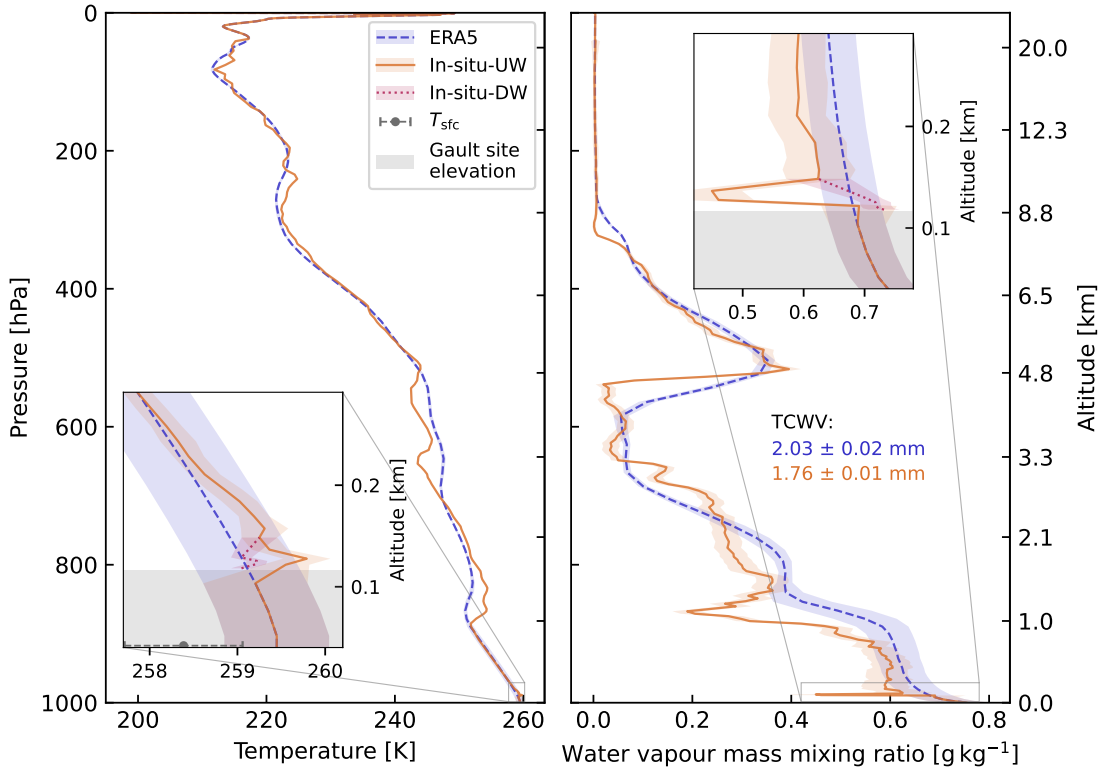

Figure 3. Profiles of temperature (left) and water vapour (right) for the cases simulated, with coloured shading showing the respective uncertainties. The ERA5-DW and -UW profiles use the same data. The dotted line indicates where the in-situ-DW profile differs from the in-situ-UW profile; above this, the two in-situ profile specifications are identical. Grey shading in the inset plots indicates the elevation of the Gault site; data below this is neglected for downwelling (DW) simulations. The skin temperature from ERA5, used in both upwelling simulations, is shown in the temperature inset plot. Colour-coded text shows the total column water vapour (TCWV) for ERA5-UW and in-situ-UW profiles (right).

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closure experiments (e.g. Delamere et al., 2010; Sussmann et al., 2016; Mlawer et al., 2019) and for evaluation of other radiative transfer codes (e.g. Oreopoulos et al., 2012; Hogan and Matricardi, 2020). For this work, we use LBLRTM v12.17, including spectral lines from AER Line File v3.8.1, and the MT_CKD v4.3 water vapour continuum model (Mlawer et al., 2023).

We input the profiles described in Sect. 2.3 to LBLRTM, simulating the effects of the first 30 molecules listed in the HITRAN database. For those gases not mentioned above, we use the LBLRTM 'mid-latitude winter' default values.

To simulate the PREFIRE and FINESSE measurements, instrument characteristics must be applied to the very high resolution radiances calculated by LBLRTM. For PREFIRE, the radiance from each channel of the grating spectrometer is calculated by integrating the LBLRTM output with the normalised channel spectral response function (v13, PREFIRE team, 2025). To simulate FINESSE radiances, spectra are converted to interferograms and truncated to mimic the effects of an ideal Fourier-transform spectrometer with FINESSE's maximum optical path difference. After converting the truncated interferograms back to spectra, they are convolved with a spectrally dependent instrument line shape as described by Murray et al. (2024), which simulates asymmetries in FINESSE's optical path.

3 Uncertainties and challenges in closure analysis

3.1 Spatial collocation

In the discussion of the experimental setup thus far we have assumed that all data sources and instruments describe or measure the same atmospheric column. Since this is not the case, we examine here the effect of imperfect horizontal collocation in our measurements.

We use ERA5 fields to estimate the spatial variability in the scene meteorology at scales larger than the ERA5 horizontal scale of 0.25°. In the absence of horizontal wind, the radiosonde would sample only the atmospheric column immediately above FINESSE. In reality, the wind advects the radiosonde some 185 km east of the Gault reserve over its flight. We construct a profile which 'follows' the radiosonde trajectory and samples from the spatially and temporally closest ERA5 grid cells (termed 'ERA-following-sonde' as shorthand), assuming that the ERA5 fields are representative of the true spatial variability of the scene meteorology. The radiances from this profile are simulated as described in section 2 and compared to those using the standard ERA5 profile; this comparison is shown in Fig. 4a and b. This offset is included as an uncertainty for the in-situ simulations.

As demonstrated in Fig. 2, the PREFIRE FOVs 5 and 6 lie either side of the Gault site, and so do not pass directly over FINESSE. To assess the impact this has, we simulate the radiances from the ERA5 grid points contained in the PREFIRE footprints. The comparison between these and radiances simulated from the closest grid point to the Gault site is shown in Fig. 4. The average of these offsets, weighted by the number of FOV midpoints falling in each box, is included as an uncertainty source for the PREFIRE simulations.

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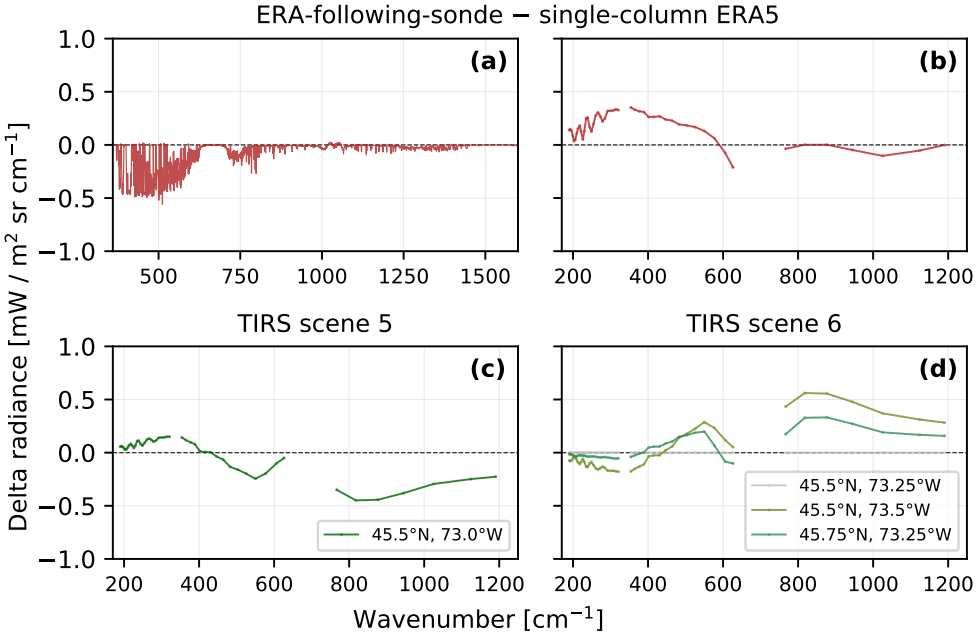

Figure 4. Top row: differences in simulated FINESSE **(a)** and PREFIRE **(b)** radiances when using a profile of ERA5 data 'following' the radiosonde track, compared to a single ERA5 column at the Gault site. Bottom row: differences in simulated PREFIRE radiances for TIRS scene 5 **(c)** and 6 **(d)** simulated using various ERA5 grid points located within the instrument FOV, compared to that closest to the Gault site (45.5° N, 73.25° W).

3.2 Instrument performance

Uncertainties in FINESSE radiances are well-characterised and fully described by Murray et al. (2024). Briefly, the noise-equivalent spectral radiance (NESR) is a random error resulting from spectrally uncorrelated detector noise and can be reduced through averaging, while other uncertainties arise from the calibration process. For the measurement conditions of our study, these are both shown in Fig. 5a.

Uncertainties in the PREFIRE radiances are quantified as noise-equivalent radiances, shown in Fig. 5b. Some elements of the detector array are known to have high noise or responsivity faults and we have masked their readings. This leads to some gaps in the FIR spectra. Channels in the FIR-2 band are flagged as having 'uncategorised calibration' due to uncharacterised instrument issues. Uncertainty in PREFIRE calibration (i.e. absolute radiometric accuracy) is not known. Information on PREFIRE observational issues identified prior to launch is detailed by Drouin et al. (2025), and post-launch in section 4 of the PREFIRE radiance product R01 user guide (Hokanson Wagner et al., 2025).

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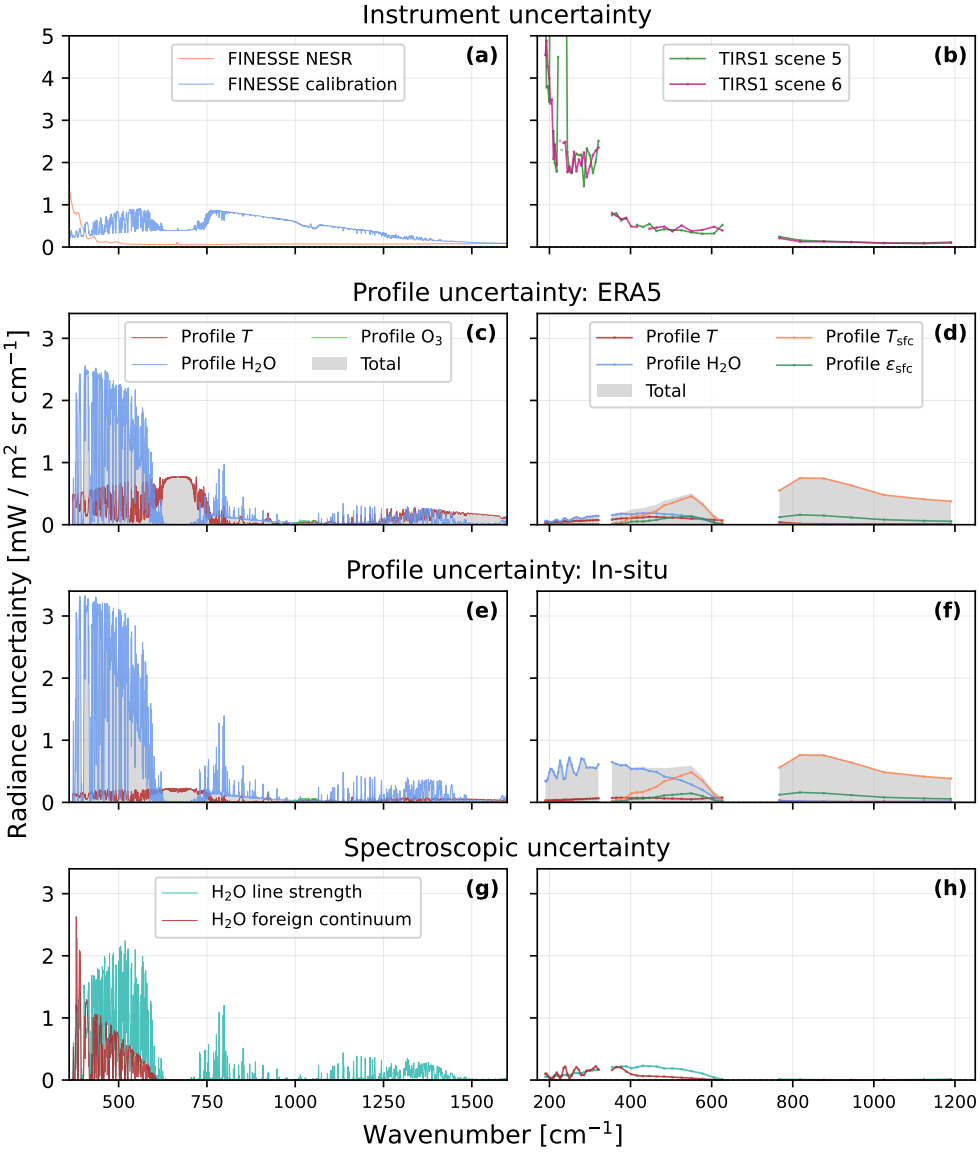

Figure 5. Estimates for several sources of uncertainty considered in the closure experiment. The left column **(a, c, e, g)** is for FINESSE, the right **(b, d, f, h)** for PREFIRE. **(a, b)**: uncertainty in measured radiances due to instrument noise and calibration. **(c–f)**: uncertainty in simulated radiances due to uncertainty in the various labelled profile quantities; the legends in **(c)** and **(d)** apply also for **(e)** and **(f)** respectively. **(g, h)**: uncertainty in simulated radiances following from uncertain H_2O spectroscopic parameters; the legend in **(g)** applies to both plots. Note the different y-scale used in **(a, b)** compared to other rows.

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3.3 Constraining atmospheric and surface states

Quantification of the uncertainty in the input atmosphere and surface profiles varies by data source. For ERA5 data, we represent the uncertainty in reanalysis quantities using the standard deviation of the accompanying 10-member ensemble. Uncertainties in readings from the radiosonde and weather station are calculated using information from the respective manufacturers' data sheets (InterMet Systems, 2022; Vaisala, 2025). 'Calibration uncertainty' or 'repeatability in calibration' figures are treated as systematic uncertainties and 'accuracy' or 'combined uncertainty' figures as random uncertainties. Surface emissivity uncertainty is estimated as the spectrally averaged spread in the fine, medium, and coarse snow types in the dataset. These uncertainties encompass temperature, humidity, ozone concentration, surface temperature, and surface emissivity; uncertainty in other quantities supplied to the radiative transfer code is considered negligible. Uncertainty estimates for temperature, water vapour mixing ratio, and T_{sfc} are shown in Fig. 3.

For a simulated total state vector $\boldsymbol{x}$, the uncertainties described above may be represented as a pair of vectors $(\boldsymbol{\sigma}, \boldsymbol{s})$ of random and systematic errors respectively. These vectors have components (σ_i, s_i) for the level i where s_i may be zero if there is no systematic uncertainty considered. We tackle random and systematic uncertainties separately to calculate a sample set of realistic errors in the total state vector, represented $\delta_m \boldsymbol{x}$ (the m subscript labelling the samples). For random errors, we construct a covariance matrix such that they are correlated between nearby atmospheric levels. This matrix $\mathbf{C}$ has terms defined by

$$C_{ij} = \sigma_i \sigma_j \exp\left(-\frac{|z_i - z_j|}{h}\right), \tag{1}$$

with z_i the altitude of level i and h some vertical scale height (Rodgers, 2000; Feldman et al., 2008). Sample random profile errors $\delta_m \boldsymbol{x}_{\mathrm{rand}}$ are randomly sampled from a multivariate normal distribution with mean $\boldsymbol{\sigma}$ and covariance $\mathbf{C}$. Conversely, systematic errors are modelled as fully vertically correlated. In practice, this means that sample systematic profile errors $\delta_m \boldsymbol{x}_{\mathrm{sys}} = z_m \times \boldsymbol{s}$, with z_m sampled from a standard normal distribution. These random and systematic sources are then added for each sample: $\delta_m \boldsymbol{x} = \delta_m \boldsymbol{x}_{\mathrm{sys}} + \delta_m \boldsymbol{x}_{\mathrm{rand}}$.

Using LBLRTM, the Jacobian $\mathbf{J}$ is then evaluated as $J_{ij} = \frac{\partial y_i}{\partial x_j}$ for a spectral point i and some state variable x_j at layer j. The instrument response is applied to the output high-resolution Jacobians as described in Sect. 2.2. Sample profile uncertainties $\delta_m \boldsymbol{x}$ are propagated to sample spectral uncertainties $\delta_m \boldsymbol{y}$ using $\delta_m \boldsymbol{y} = \mathbf{J}\, \delta_m \boldsymbol{x}$. The overall spectral uncertainty $\delta \boldsymbol{y}$ is calculated as the standard deviation of the $\delta_m \boldsymbol{y}$, using 5000 samples. This is repeated for each variable considered. For FINESSE these variables are temperature, and water vapour and ozone concentrations. We found that PREFIRE had little sensitivity to ozone concentration uncertainty, so we consider temperature, water vapour concentration, surface temperature and emissivity.

The in-situ profiles have a significant error contribution from systematic uncertainties which dominates over random uncertainties; as such these profiles have little sensitivity to the choice of h. We found some sensitivity to the choice of h for the ERA5 profile uncertainty, having only random errors. For a similar quantity to h in the literature, Rodgers (2000, Ch 2) use the atmospheric scale height and Ridolfi et al. (2022) use a 5 km correlation in retrieval covariances, Warwick et al. (2022) find a vertical correlation length of 0.8 km for temperature and water vapour in the Met Office UM, and from measurements Fischer et al. (2013) suggest a non-convective water vapour correlation of 0.23 km. Investigating across this range, we found

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that radiance uncertainties due to water vapour errors varied by a factor of 3; we choose a value of $h = 1.5$ km for temperature and water vapour in this work, representing a slightly conservative middle ground. The resulting uncertainties in simulated radiances are shown in Fig. 5c–f.

3.4 Water vapour spectroscopy

Since we use a relatively fine vertical resolution and perform line-by-line calculations, the most significant uncertainties in the radiative transfer forward modelling come from either the input spectroscopic data or in the assumptions used to model spectroscopic phenomena such as spectral line mixing. We neglect investigation of line mixing uncertainty and instead focus on the uncertainty from water vapour spectroscopy as the dominant and most variable absorber in this case. In particular, we consider uncertainties in H_2O line strengths and in the absorption coefficients of the FIR components of the H_2O foreign continuum, similar to Mosselmans et al. (2026). We found that uncertainties in the line positions had a negligible effect on the simulated spectra. We also neglect any uncertainties in absorption coefficients for other parts of the water vapour continuum, as (a) foreign continuum absorption is substantially smaller at larger wavenumbers, and (b) the self-continuum absorption will be small anyway in this case due to the very dry atmosphere.

Water vapour line strengths are perturbed according to the assigned uncertainty code in the AER Line File, while foreign-continuum absorption coefficients are perturbed by the uncertainty values assigned by Mlawer et al. (2019). LBLRTM is then re-run using this perturbed spectroscopy. The resulting difference of this compared to a simulation with unperturbed spectroscopy is taken as the spectral uncertainty due to spectroscopic uncertainties. These uncertainties are presented in Fig. 5g and h.

In our results, we combine the spatial collocation, instrument, forward-modelled profile, and spectroscopic uncertainties in quadrature to form a total uncertainty for each of the four simulations.

4 Results

To assess radiative closure, we subtract the spectra measured by the FINESSE and PREFIRE TIRS instruments from the spectra simulated as described in sections 2.3 and 2.4. This difference is termed a 'residual', representing the offset of measurements from simulations. These residuals are compared to the bounds given by the total uncertainties calculated in Sect. 3.

We begin by discussing residuals for the FINESSE instrument, shown in Fig. 6. In these cases, a positive residual indicates more emission by the overlying atmosphere in the simulation than was recorded in reality. For the viewing geometry here, this typically means either too much gas and/or too warm an atmospheric temperature; the inverse is true for negative residuals.

In both FINESSE cases, the residuals are generally close to zero throughout and mostly within the bounds of the uncertainty, indicating good agreement between observations and simulations. A large negative spike around 597.6 cm^{-1} is attributed to deficiencies in the LBLRTM line coupling modelling used for CO_2 and has been noted in other studies (e.g. Delamere et al., 2010; Mosselmans et al., 2026). We expect that the negative spike at 392 cm^{-1} is related to the higher instrument noise at the edge of the FINESSE detection capability. A large positive spike at 667 cm^{-1} is caused by the absorption and emission of the

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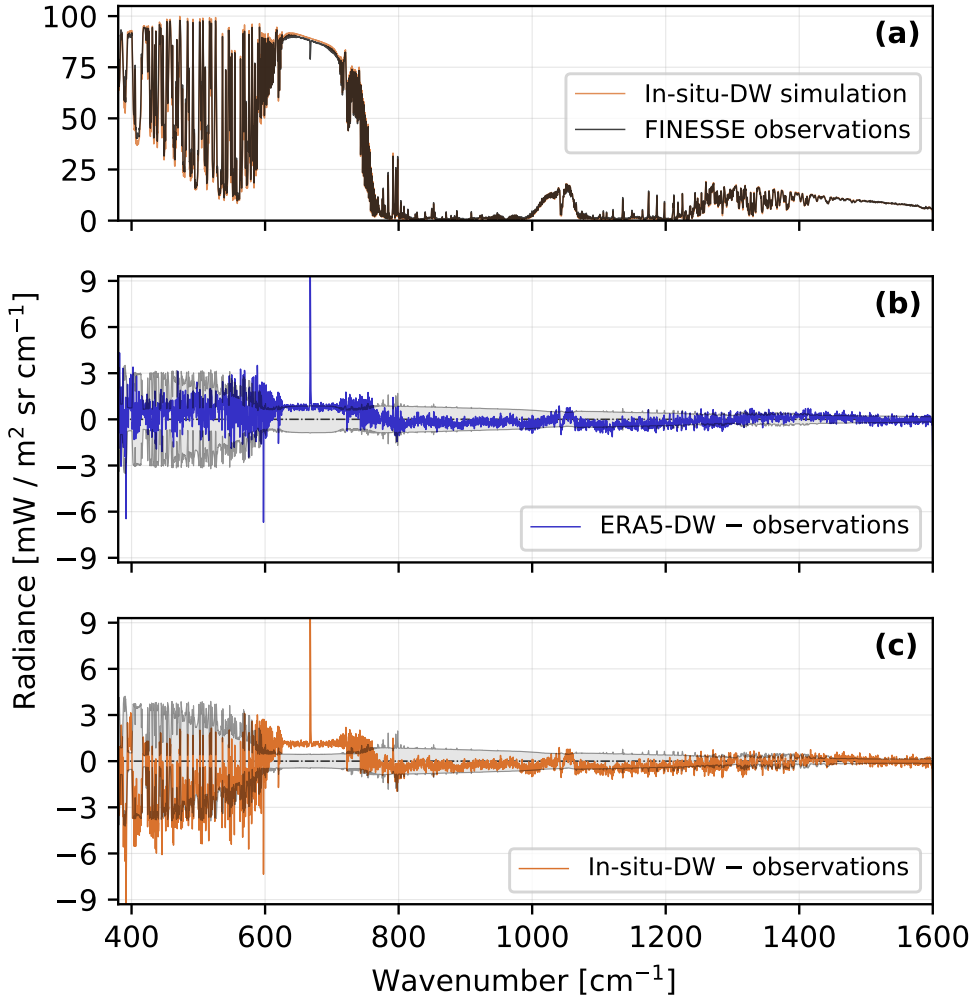

Figure 6. **(a)** FINESSE observations (black) and the in-situ-DW simulation for comparison. **(b)**: residuals for the ERA5-DW simulation compared to observations. The grey shading and line indicate the total uncertainty limits described in Sect. 3. **(c)**: as in **(b)**, but for the in-situ-DW simulation.

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CO_2 molecule; at this frequency it is so strong that only the cold air inside the instrument is sensed. Nearby wavenumbers are also quite opaque, so the positive bias of this feature in both ERA5 and in-situ profiles indicates that near-surface atmospheric temperatures are too warm in the simulated profiles.

In the mid-infrared (for FINESSE, 667–1600 cm^{-1}) outside of the influence of CO_2, the FINESSE residuals in both cases are very small and close to zero, without notable excursions from the uncertainty bounds. There is little downwelling radiance in the region, but the small residuals point towards a reasonably good specification of methane (1200–1400 cm^{-1}) and water vapour (1300–1600 cm^{-1}). Within the infrared window, agreement around the ozone absorption band (1000–1100 cm^{-1}) implies an accurate specification of ozone concentrations and upper-atmospheric temperatures. A very small negative bias within the uncertainty bounds is noted throughout the atmospheric window; this could be caused by emission from aerosols or trace species which are not simulated.

In the far-infrared, the ERA5-DW residuals are almost entirely within the uncertainty bounds. The slight positive bias in this region strongly affected by water vapour would suggest the simulated profile having slightly too warm or moist conditions, especially near the surface. Having too high a simulated near-surface temperature would be consistent with the positive residual in the (620–720 cm^{-1}) CO_2 spectral feature. We note an unexplained deviation beyond the uncertainty limits around 395 cm^{-1} but this is likely due to instrument noise, again being on the edge of the detection range.

The in-situ-DW residuals in the FIR have a negative bias, with the residual for many wavenumbers lying below the lower uncertainty bound for this case. We conclude from the spectral range of this bias, the profile in Fig. 3, and the near-surface warm bias of the simulated atmosphere diagnosed from the CO_2 emission feature, that this FIR negative bias is caused by the radiosonde recording less total water vapour than is present in the atmosphere.

The PREFIRE residuals in Fig. 7 are separated by cross-track TIRS scene to account for the different sensor characteristics, viewing angle, and FOV geographies. Here, a positive residual may indicate the simulation has too warm or emissive a surface or atmospheric layer, or too transparent an atmosphere (transmitting more radiation from warmer levels below and from the surface than in reality). In spectral regions common to both instruments, the PREFIRE residuals generally have a slightly larger magnitude, and much greater spectral variation, compared to FINESSE residuals degraded to PREFIRE spectral resolution (not shown). The effect of the large instrument noise in the FIR-2 band (185–330 cm^{-1}) is clear, with significant scatter even after averaging over five spectra.

The features of the residuals in the MIR-2 band show little difference between the ERA5-UW and in-situ-UW simulations; this is to be expected, as the simulations have identical specification of surface temperature, surface emissivity, and ozone concentrations. These are the main factors controlling radiances in this region under these conditions. The MIR-2 residuals exhibit a similar pattern in both cross-track scenes, with a slight spectral zig-zagging. In all comparisons residuals are positive in this region indicating too much modelled radiation from the surface, indicating either too warm or too emissive a surface in the simulations.

Turning to the far-infrared bands, the difference between the ERA5-UW and in-situ-UW simulations becomes somewhat clearer. For both scenes in the dirty window (FIR-1 band), the ERA5-UW residuals lie slightly closer to zero than those for in-situ-UW. This matches the findings of too dry an atmosphere from the radiosonde readings; the in-situ-UW simulated

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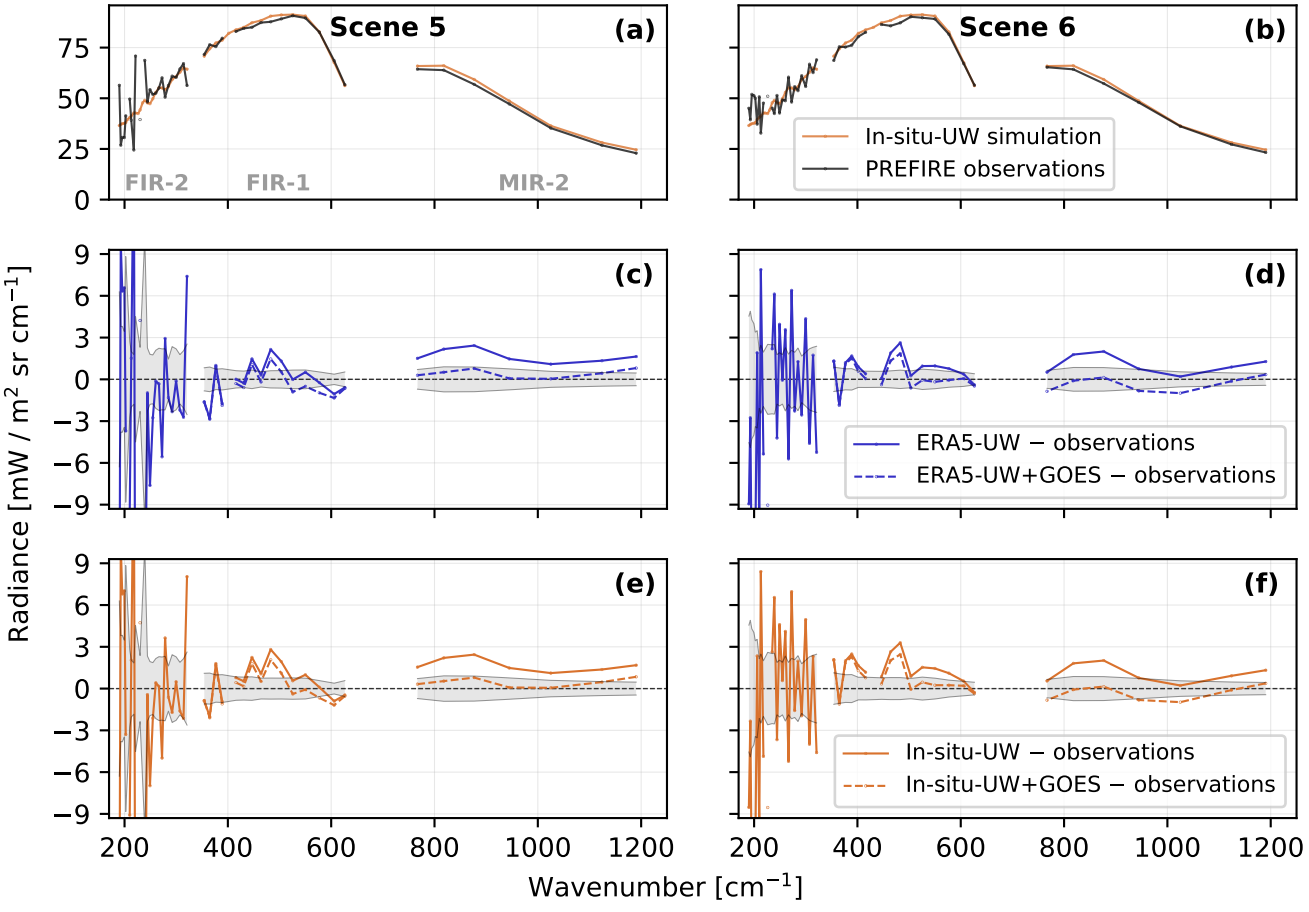

Figure 7. (a, b) PREFIRE observations (black) and the in-situ-UW simulation for comparison. **(c, d)**: residuals for the ERA5-UW simulation compared to observations. Additional dashed lines indicate residuals for a simulation using land surface temperature observations from the ABI on GOES-16. The grey shading and line indicate the uncertainty limits described in Sect. 3. **(e, f)**: as **(c, d)**, but for the in-situ-UW simulation. The left column **(a, c, e)** shows the TIRS scene 5 radiances, and **(b, d, f)** shows TIRS scene 6. The grey text in **(a)** labels the spectral bands of the TIRS instrument.

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atmosphere is more transparent in this spectral range and so permits more thermal radiation to escape to space from the (near-)surface than is observed. A slight positive bias in the residuals in scene 6 could also point to issues with the surface specification. In the FIR-2 band (170–340 cm^{-1}), the number of points lying outside of the uncertainty bounds suggests that the total radiance uncertainty of the instrument is underestimated at present; the instrument noise makes further quantitative deductions difficult.

4.1 Use of GOES ABI surface temperature

The findings of a consistent positive bias of simulations relative to PREFIRE observations in the infrared window region prompts a re-evaluation of the simulated surface properties. Surface emissivities in the mid-infrared are sufficiently well-constrained and constant across surface types to preclude this being the sole cause of the residuals seen, so we explore modifications of the emitting skin temperature.

To find an alternative source of this T_{sfc}, we turn to observations from geostationary platforms. Specifically, from the GOES-16 satellite we take the Advanced Baseline Imager's (ABI) full-disk land surface temperature retrieval (ABI-L2-LST). This is sampled at 21:00 UTC, just seven minutes after the PREFIRE overpass, and has a 10 km resolution at nadir. For each PREFIRE scene, we take an average of the ABI retrieved land surface temperature readings within the TIRS FOV polygons weighted by area and overlap fraction. The resulting temperatures ($256.8 \pm 0.7\,\mathrm{K}$ and $256.7 \pm 0.6\,\mathrm{K}$ for scenes 5 and 6 respectively) then replace the ERA5 T_{sfc} in otherwise identical simulations.

The resulting residuals from the simulations with modified T_{sfc} are shown as dashed lines in Fig. 7. In the MIR-2 band, the inclusion of the ABI T_{sfc} significantly improves the residuals, with most channels' residuals now lying within the uncertainty bands. In the FIR-1 band an improvement is clear for both simulations in scene 6, while any improvement in scene 5 is marginal.

5 Discussion

Given the excellent agreement of the ERA5-DW simulation with observations by the FINESSE instrument, we infer that this profile represents a robust knowledge of the overlying atmosphere. The corresponding simulation for PREFIRE, when using the observed ABI T_{sfc}, also lies close to the observations, but slightly more spectral points lie outside the uncertainty limits than would be expected, especially in the FIR-2 band. We believe that these anomalous residuals are mostly a result of instrument effects. In the MIR-2 and FIR-1 bands, where residuals show a similar pattern for the two scenes, the similarity hints at a common cause warranting further investigation, such as calibration error remaining even after the radiance bias correction. In the FIR-2 band, the cause is likely detector noise, which is perhaps underestimated at present. We note that the current PREFIRE L1B products mark all FIR-2 band channels with a flag indicating the quality is unknown and that there may be calibration biases. It is worth highlighting that for both FINESSE and PREFIRE, the largest uncertainties are found in the far-infrared.

The detailed analysis of uncertainties in Sect. 3 allows us to identify the main sources of uncertainty in the experiment. For FINESSE, specification of water vapour profiles is a large source of uncertainty in both simulations, especially in the FIR.

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This is slightly larger in the in-situ case, where we have treated systematic errors in the radiosonde measurements as fully vertically correlated. The residuals shown in the in-situ-DW case, however, lead us to question the veracity of the radiosonde measurements. Several studies have noted dry biases in radiosonde measurements, particularly in dry conditions (Vömel et al., 2007; Rowe et al., 2008; Miloshevich et al., 2009; Dzambo et al., 2016). Our results suggest a similar dry bias for the iMet-4 radiosonde as used in the WHAFFFERS campaign, which has not yet been thoroughly investigated.

Given the radiosonde residual bias in the FIR and the good performance of the ERA5-DW profile, we investigate a bias correction method. The total moisture content of the column measured by radiosondes over the entire WHAFFFERS campaign was calculated and compared to values calculated from ERA5 following each radiosonde track (as in Sect. 3.1). Of the ten launches without issue, seven featured very low column water vapour < 3 mm. Across these seven cases, the radiosonde measurements exhibit a consistent dry bias of about 9 % relative to ERA5 (i.e. $CWV_{\mathrm{sonde}} \approx 0.91 \times CWV_{\mathrm{ERA5}}$). Remedying this bias by a scalar adjustment of the radiosonde-measured water column and re-running the experiment much improves agreement with the bias-adjusted in-situ-DW case, even outperforming the ERA5-DW case in the FIR (not shown). We thus conclude that it is likely that the radiosonde has dry humidity bias in these conditions. However, we also cannot rule out the possibility that this radiosonde bias is caused by campaign-specific errors in the launch process.

We recommend that for closure experiments, radiosondes be used in tandem with either a trusted bias correction algorithm or an auxiliary source of information. This information could come from reanalysis, as in our brief investigation, but ideally it would be from collocated measurements, such as retrievals from microwave sensors. We argue further that passive remote sensing in spectral regions different to those measured by the closure-targeting instrument is crucial to ensure independence of observations from simulations. Uncertainties in the FIR spectroscopy of water vapour also have a sizeable impact on modelling FINESSE radiances. Further closure or laboratory studies may be able to address this.

The appearance of some residuals beyond uncertainty for FINESSE between 390–400 cm^{-1} in both simulations was investigated by comparing the simulated and measured radiances to 160 spectra acquired over a 60 minute window, each one an average of 20 scans. The many individual spectra showed a large spread in which the residual signal was not an outlier (not shown). The fact that residuals lie beyond the uncertainty limits could indicate that the FINESSE NESR is under-reported in this region, and/or that the extension of FINESSE to 380 cm^{-1} requires further validation.

Finally for FINESSE, characterising the air temperature very near the instrument is key. There are some significant residuals for wavenumbers with strong sensitivity to the surface layers, especially in the CO_2 emission features (c. 600–750 cm^{-1}). Readings from FINESSE's auxiliary temperature sensor were anomalous in this field campaign and so not used; ensuring valid measurements from this sensor could enhance the robustness of future closure tests with FINESSE.

PREFIRE closure diagnosis in the FIR, particularly in the FIR-2 band, is largely hindered by instrument noise. Further evaluation of persistent biases could be possible using substantial averaging. In similar conditions to this study, this noise would no longer be a dominant uncertainty source in the FIR-1 band after averaging over 10 spectra, or 150 spectra in the FIR-2 band, for PREFIRE satellite 1. Satellite 2 has a higher instrument noise which would require approximately twice as many spectra. A study using a set-up like ours employing an averaging approach would hence require a long-term ground-based spectrometer data record (possibly over 12 months to build up the clear sky statistics required, though latitude dependent),

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and may not be able to use radiosonde data for the quantity of overflights needed. Uncertainty in the radiosonde water vapour specification is comparable to instrument noise around 350–500 cm^{-1} and would become a leading uncertainty source with more averaging of spectra, reinforcing the need for precise water vapour measurements in FIR closure studies.

In the MIR, the dominant uncertainty for PREFIRE is due to the temperature of the underlying surface, with its emissivity also playing an important role. The importance of the surface temperature in this setup is further reinforced by the finding of a drastic improvement, in this instance, of taking this figure from the GOES ABI rather than ERA5. Due to the large area of the measured swath, a ground-based temperature or emissivity measurement would likely only be representative for a very homogeneous surface. Another possibility is to remotely sense the surface temperature with a drone-mounted instrument in the region around the ground station; this platform could then additionally sample the nearby variation in the humidity field. Radiances observed by a low-flying aircraft could also be used to retrieve surface temperature and emissivity separately, as demonstrated by Bellisario et al. (2017).

There is also further opportunity for satellite-to-satellite validation of PREFIRE, in the MIR spectral region, using geostationary satellites. They offer coverage over a large swath with much shorter repeat times than polar-orbiting missions. The Infrared Sounder on the Meteosat Third Generation (MTG-IRS) will provide spectrally resolved mid-infrared radiances from a geostationary platform. This could yield plentiful opportunities to perform radiance comparisons under a range of conditions for the PREFIRE MIR channels. Here a key issue to resolve would be the impact of viewing geometry.

Finally, we note that the simulations performed for this study have already proven useful in validating improvements in the second release of the PREFIRE L1B radiance product (though direct comparison of simulations to the first release is not shown in this paper), and can continue to be used as a benchmark for future revisions.

6 Conclusions

In this paper, we have performed a ‘ground-to-space’ radiative closure study using the FINESSE instrument and an overpass of the PREFIRE satellite 1. To our knowledge, this is the first attempt at this type of experiment in the far-infrared. Thorough consideration of the various sources of uncertainty confirmed the validity of this approach and illustrated the main challenges in this experiment.

The ground-based FINESSE instrument demonstrated excellent closure, in particular when simulations used atmospheric data from the ERA5 reanalysis. Simulations based on in situ data did not agree as well with the FINESSE observations. This is a contrasting result to that found with FINESSE by Mosselmans et al. (2026), but may reflect the use of a different radiosonde brand in our study. The radiance results, and additional comparisons between ERA5 profiles and radiosonde launches throughout the WHAFFFERS campaign, led us to conclude that there is likely a dry bias in humidity measurements from the iMet-4 radiosonde in the very dry conditions of the campaign. The largest source of uncertainty in the comparison between simulated and observed radiances was in the specification of atmospheric water vapour profile, followed by the spectroscopy of water vapour. Many other authors note that precisely determining water vapour spectroscopy from field studies is limited by uncertainties in atmospheric water vapour content, and so we encourage further laboratory study and for future field studies targeting

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the region to be designed with accurate, precise, and independent determination of water vapour at their core. These techniques will also help to calibrate and validate observations from the upcoming Far-infrared Outgoing Radiation Understanding and Monitoring (FORUM) satellite mission, scheduled to launch in 2028 (Palchetti et al., 2020).

The agreement of PREFIRE observations of upwelling radiances at the top-of-the-atmosphere with simulations varied by spectral region. In the mid-infrared and FIR dirty window, the agreement is only slightly weaker than obtained for the downwelling FINESSE measurements, though PREFIRE residual points are more scattered. In the furthest infrared band (185–330 cm^{-1}) agreement was somewhat poorer, largely due to a high radiometric noise in the PREFIRE TIRS instrument which may be underestimated at present. We also noted that inaccurate specification of water vapour by the radiosonde, diagnosed by FINESSE, degraded the PREFIRE residuals in the FIR dirty window, reinforcing the importance of water vapour profiling for these experiments. In these dry conditions, the infrared window and the FIR dirty window are both sensitive to the surface, and so uncertainty in our results was dominated by specification of surface temperature and emissivity in these spectral regions. We found that the use of independent satellite-observed surface temperature was able to remedy a bias in that from ERA5. However, it appears there remain some small systematic errors. Rigorous quantification of these errors will require further targeted comparisons over a longer time period and a wider range of conditions. We note that the approach developed here, and the database of simulated radiances with associated uncertainties will be useful for validating further efforts by the PREFIRE team to correct biases in the measured radiances. We discussed potential options for reducing the surface uncertainty, including the use of other field or satellite measurements.

PREFIRE, and the upcoming FORUM mission, open a new measurement window from space. They are designed to exploit the information content within the far-infrared to provide new insights into water vapour distributions, the radiative effects of clouds and, where conditions permit, surface properties. However, the community must be prepared with the right set of experimental designs and auxiliary measurement capabilities to comprehensively validate the new observations and hence maximise their scientific impact. Our study provides a stepping stone towards this goal.

Data availability. At time of submission, measurement data used in this study from the WHAFFFERS campaign are not yet available in an open archive, but can be accessed upon request to the authors.

Author contributions. BP and HB conceived the study. BP carried out the investigation and wrote the first draft of the manuscript, with supervision from HB and RH. JM, SM, SP, LW, YH, and BR-B took field measurements on the WHAFFFERS campaign. TL provided PREFIRE expertise and data curation. SM, SP, LW, and BR-B provided input to the radiative transfer modelling methodology. HO, DS, HB, and YH assisted with funding acquisition and project administration for the WHAFFFERS campaign. All authors assisted with editing the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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