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1 **FORUM: unique far-infrared satellite observations to better understand**
2 **how Earth radiates energy to space**

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ABSTRACT

47 The Outgoing Longwave Radiation (OLR) emitted to space is a fundamental component of
48 the Earth's energy budget. There are numerous, entangled physical processes that contribute
49 to OLR and that are responsible for driving, and responding to, climate change. Spectrally-
50 resolved observations can disentangle these processes, but technical limitations have precluded
51 accurate space-based spectral measurements covering the far-infrared (FIR) from 100 to 667 cm^{-1}
52 (wavelengths between 15 and 100 μm). The Earth's FIR spectrum is thus essentially unmeasured
53 even though at least half of the OLR arises from this spectral range. The region is strongly
54 influenced by upper tropospheric/lower stratospheric water vapor, temperature lapse rate, ice cloud
55 distribution and microphysics, all critical parameters in the climate system that are highly variable
56 and still poorly observed and understood. To cover this uncharted territory in Earth observations,
57 the Far-infrared Outgoing Radiation Understanding and Monitoring (FORUM) mission has recently
58 been selected as ESA's 9th Earth Explorer mission for launch in 2026. The primary goal of FORUM
59 is to measure, with high absolute accuracy, the FIR component of the spectrally-resolved OLR for
60 the first time with high spectral resolution and radiometric accuracy. The mission will provide a
61 benchmark dataset of global observations which will significantly enhance our understanding of
62 key forcing and feedback processes of the Earth's atmosphere to enable more stringent evaluation
63 of climate models. This paper describes the motivation for the mission, highlighting the scientific
64 advances that are expected from the new measurements.

65 *Capsule summary.* The Far-infrared Outgoing Radiation Understanding and Monitoring mission
66 will observe the Earth's emitted outgoing radiation spectrum across the far-infrared with high
67 spectral resolution and accuracy from space for the first time.

68 **THE FAR INFRARED OBSERVATIONAL GAP AND ASSOCIATED CLIMATE UNCER-** 69 **TAINTIES**

70 The Earth's climate is regulated by the energy absorbed from the Sun and the loss of energy to
71 space through both the reflection of the solar radiation itself and the emission of infrared radiation.
72 The sum of these phenomena is called the Earth Radiation Budget (ERB). The study of the ERB is
73 of fundamental importance for understanding the climate for many reasons. First, global climate is
74 directly linked to the Earth's average temperature, which in turn is determined by the ERB (Dong
75 et al. 2019). Then the equator to pole gradient of the ERB, due to the fact that the solar insolation
76 is stronger at the equator than at the poles, is the driver of the general circulation in the atmosphere
77 and the oceans, which transports heat from the equator to the poles. In a climate in equilibrium,
78 the ERB terms are in balance. However, numerous model and observationally based studies have
79 highlighted the Earth's current energy imbalance, arising as a result of anthropogenic activities and
80 the differing response timescales of the atmosphere, land and ocean (e.g. Trenberth et al. 2014;
81 Hansen et al. 2011, 2005), with estimates of the variability in the imbalance over the last decade
82 ranging from $\sim 0.5-1 \text{ W/m}^2$.

83 Over 99 % of the thermal radiation emitted by the Earth falls within the spectral range 100
84 to 2500 cm^{-1} ($100-4 \mu\text{m}$) and is commonly called the Outgoing Longwave Radiation (OLR).
85 Part of this spectral region, from 100 to 667 cm^{-1} ($100-15 \mu\text{m}$) is known as the far-infrared
86 (FIR), which, based on model calculations, accounts for at least half of the Earth's energy emitted
87 to space (Collins and Mlynczak 2001; Harries et al. 2008). However, up to now, our scientific

88 understanding of how the FIR contributes to the Earth's OLR has mostly been inferred either from
89 model simulations or from spectral measurements in the middle infrared (MIR) from 667 to 3333
90 cm^{-1} (15-3 μm) combined with radiative transfer calculations (Huang et al. 2008; Turner et al.
91 2015). Indeed there is a lack of extensive spectral measurements covering the FIR region because
92 the FIR technology is much less mature than the MIR technology. Nevertheless, even without
93 comprehensive FIR measurements, multiple studies have indicated that the spectral signatures of
94 the OLR in that spectral region are particularly sensitive to water vapor in the upper troposphere
95 (UT) and to the presence of ice clouds (e.g. Harries et al. 2008, and references therein).

96 The importance of water vapor as greenhouse gas is well known. Simulations have shown that
97 an increase of the order of 10 % in tropospheric water vapor exerts a radiative effect which is
98 equivalent to a doubling of CO_2 , and up to 55 % of this effect occurs within the FIR (Brindley
99 and Harries 1998). Any estimate of its radiative impact is, of course, dependent on the quality of
100 the underlying spectroscopy and knowledge of its vertical distribution. A number of measurement
101 campaigns have substantially improved our knowledge of water vapor spectroscopy within the
102 FIR (Mlawer et al. 2019; Fox 2015; Green et al. 2012; Turner et al. 2012; Tobin et al. 1999).
103 In contrast, despite attention spanning more than two decades, uncertainties in UT water vapor
104 amounts are still significant because all current measurement techniques have shortcomings within
105 this altitude range (Müller et al. 2016; Ferrare et al. 2004). Similarly, estimates of water vapor
106 trends and variability within the lower stratosphere are also poorly constrained and suffer large
107 uncertainties (Hurst et al. 2011; Hegglin et al. 2014; Yue et al. 2019). Improving our knowledge of
108 the global water vapor distribution in the upper troposphere - lower stratosphere (UTLS) region is
109 essential given its key role in influencing surface temperature trends (Dessler 2013; Solomon et al.
110 2010; Forster and Shine 2002; Dessler and Sherwood 2009). Improved water vapor records in this

111 region would also have strong benefits for elucidating climate-chemistry interactions and have the
112 potential to enhance the quality of numerical weather prediction (NWP) (Hilton et al. 2012).

113 Clouds strongly impact the ERB, both in terms of albedo and OLR. The IPCC AR5 report
114 (Stocker et al. 2013) states that the insufficient knowledge of clouds, their radiative properties
115 and their associated impact on the radiation budget, is the major source of discrepancy between
116 predictions of future climate by different state-of-the-art models. The net effect of clouds on the
117 climate system is complex as they can both reflect incoming solar radiation (cooling effect) and
118 absorb outgoing longwave radiation (heating effect). Cirrus clouds are particularly important as
119 they are widespread (Wylie et al. 2005; Sassen et al. 2008), typically occur within the critical UT
120 region (Lynch et al. 2002), are influenced by anthropogenic activity (Haywood et al. 2009; Kärcher
121 2017) and are formed of ice crystals of a large variety of sizes and shapes (Baum et al. 2005).
122 Unlike the spherical droplets typical of liquid water clouds, the highly complex shapes of ice
123 crystals observed in cirrus clouds makes modeling their radiative impact particularly challenging
124 (Baran et al. 2014b). Efforts to simulate the radiative impact of cirrus clouds have primarily focused
125 on the visible and MIR spectral regions where the abundance of data has enabled the development,
126 iteration and validation of ice particle single scattering models (Baran 2012; Yang et al. 2015).
127 However, to date, there have been very few spectral observations of cirrus clouds spanning the FIR,
128 precluding a rigorous test of how well these models are able to capture the radiative signature of
129 cirrus within this spectral region (Baran et al. 2014a). This is a major shortcoming given that the
130 typical emitting temperatures of cirrus clouds mean that the majority of their emission to space
131 falls within the FIR. The limited radiative measurements of cirrus spanning the FIR and MIR that
132 do exist indicate that current optical models are unable to match the observed signals consistently
133 across the full infrared spectrum (Cox et al. 2010; Fox 2015).

134 Recently Cox et al. (2015) and Feldman et al. (2014) have suggested that the FIR part of the
135 OLR spectrum may have a more important role than previously recognised in modulating high-
136 latitude climate response and future change. The underestimation of polar climate change (Barton
137 et al. 2014) is thought to be due to deficiencies in our understanding of the polar radiative energy
138 balance. In polar regions, this balance is highly sensitive to both ice-albedo feedback and longwave
139 surface emission (Yamanouchi and Charlock 1995; Vavrus 2004). Because of the very cold surface
140 temperatures typical of these regions, a large part of the emitted surface longwave energy is in
141 the FIR. Moreover, the very low water vapor content, with columns of H₂O that can be as low as
142 0.1 mm, makes the atmosphere in the FIR much more transparent than at other latitudes (Turner
143 and Mlawer 2010). Typically climate models have assumed that the surface emissivity in the
144 FIR is that of an ideal black-body (i.e., spectrally invariant unit emissivity). However, there is
145 growing awareness that this assumption is unphysical (Chen et al. 2014) and that may result in
146 marked radiative biases in polar regions (Kuo et al. 2018). Given the FIR enhanced atmospheric
147 transparency in polar regions, the surface emissivity in the FIR can be directly measured with
148 remote sensing measurements from airborne platforms (Bellisario et al. 2017).

149 Finally, broadband, spectrally integrated, measurements of the OLR emitted by the Earth have
150 been made by a variety of satellite sensors for almost four decades (Barkstrom 1984). These
151 observations can reduce uncertainty in climate predictions by helping to constrain climate models
152 (e.g. Forster and Gregory 2006; Tett et al. 2013). However, the integrated broadband OLR mea-
153 surements are unable to identify changes in the spectral distribution of the OLR and compensation
154 effects can, and do, occur. Many theoretical studies have indicated that specific perturbations to the
155 climatic state will exhibit distinct signatures in the OLR spectrum (Huang et al. 2010; Goody et al.
156 1998). More recent work, exploiting both spectrally resolved and broadband observations, suggests
157 that the FIR plays an important role in controlling global scale OLR variability (Brindley et al.

158 2015). New spectral observations, including the MIR and the FIR, will allow us to quantify, for
159 the first time, the degree to which spectral compensation effects may be masking OLR signatures
160 associated with specific geophysical parameters. Moreover, the information contained within the
161 collected spectra will also allow us to better constrain the physical processes, including forcing and
162 feedbacks, driving these OLR signals.

163 **THE FORUM MISSION**

164 The need for a complete picture of the processes governing OLR, and their subsequent effects on
165 the Earth's climate will be addressed by the FORUM mission (<https://www.forum-ee9.eu>), which
166 has been selected to be the 9th ESA Earth Explorer (EE9) mission. Growing international interest in
167 the role of the FIR in climate is also reflected by the selection of the NASA Earth Venture CubeSat
168 mission PREFIRE (Polar Radiant Energy in the Far InfraRed Experiment). With the overriding
169 aim of better understanding key drivers of Arctic climate, PREFIRE will nominally launch in 2022
170 and will measure IR spectra between 4 and 50 μm at a relatively coarse (0.84 μm) resolution for
171 one year and focused on Polar regions only.

172 Complementary to this effort, but expanding on its reach in terms of temporal coverage, mea-
173 surement accuracy and spectral resolution, the main goal of the FORUM mission is to deliver an
174 improved understanding of the climate system, informing climate policy decisions by supplying a
175 complete global characterisation of the Earth's OLR spectrum at high spectral resolution (Figure
176 1). This goal will be achieved by performing spectral measurements that cover the TOA emission
177 spectrum from 100 to 1600 (100-6.25 μm) with a nominal resolution of at least 0.5 cm^{-1} (full
178 width half maximum). The mission will provide a multi-year dataset benchmarked against interna-
179 tional standards with an absolute accuracy of at least 0.1 K at 3σ in TOA brightness temperature.
180 Previous space missions that sampled part of the FIR were exploratory in nature and had neither

181 the necessary lifetime nor the accuracy to provide a quantitative assessment of the relevance of the
182 FIR region for climate change applications (Hanel et al. 1971; Kempe et al. 1980).

183 By flying in "loose formation" with the Meteorological Operational Satellite - Second Generation
184 (Metop-SG), at a time difference less than 1 minute and with the ground tracks located within 300
185 km of distance, FORUM will complement the MIR spectral measurements performed in the 645-
186 2760 cm^{-1} range by the Infrared Atmospheric Sounding Instrument New Generation (IASI-NG).
187 With this synergy, the mission will supply unique high spectral resolution observations of the
188 Earth's entire emission spectrum from 100 to 2760 cm^{-1} (100-3.62 μm), which can be used
189 to provide a stringent test of our understanding of, and ability to model, the links between key
190 underlying physical processes driving climate change, their spectral signatures and the ERB.

191 While the delivery of a climate quality radiance dataset spanning the FIR represents a major
192 scientific outcome in its own right, additional mission objectives include the generation of the
193 geophysical products summarised in Table 1. All-sky spectral OLR fluxes covering the range
194 100-2760 cm^{-1} will also be delivered by directly exploiting the synergy with IASI-NG and using
195 forward modeling of the measured atmospheric state for the radiance-to-flux conversion.

196 **MEASUREMENT CONCEPT AND LEVEL OF MATURITY**

197 The FORUM measurement concept requires two instruments:

- 198 • a sounder, named FORUM Sounding Instrument (FSI), as the primary instrument, measuring
199 the spectrum of the Earth's emitted energy across the required spectral range, and
- 200 • a standard imager co-aligned with the FSI, named FORUM Embedded Imager (FEI), operating
201 in the thermal infrared atmospheric window at 10.5 μm to identify clouds and sub-pixel
202 heterogeneities in the observed scene.

203 The observing mode has to be as close as possible to nadir-viewing with a single ground footprint
204 of about 15 km in diameter for the FSI and a 36 x 36 km² field of regard for the FEI for documenting
205 the FSI footprint and the surrounding area with a finer spatial resolution of 0.6 x 0.6 km², as seen
206 in Figure 2. The along-track sampling is less than 100 km, comparable to the spatial resolution
207 recommended by the Global Climate Observing System for the TOA OLR (Belward and et al.
208 2016). The flight with the Metop-SG mission requires a sun-synchronous orbit at about 830 km
209 at the same mean local solar time (09:30) at the descending node. The proposed mission lifetime
210 is five to six years in order to perform measurements covering different seasons and to capture
211 inter-annual natural variability.

212 Whereas the FEI is a standard single-spectral-band thermal infrared imager, the core FSI is a
213 challenging instrument. The proposed solution is based on a Fourier Transform Spectrometer
214 (FTS) designed to cover the full spectral range required by FORUM. Recent technology advances
215 using uncooled detectors and broad-band beam-splitters have allowed the design of a small satellite
216 to cover the FIR spectral range from a space platform. The first feasibility study of this instrument,
217 named REFIR (Radiation Explorer in the Far-InfraRed), was funded by European Union in 1998
218 (Rizzi et al. 2002; Palchetti et al. 1999). Since then, the technical and scientific maturity required
219 for space application have been achieved by continuous development of FIR prototypes and through
220 knowledge gained from numerous ground-based and air-borne campaigns. Here below, we sum-
221 marise the instrumentation and field campaigns that improved the level of maturity supporting the
222 development of the FORUM mission.

223 The REFIR-PAD (REFIR-Prototype for Applications and Development) prototype is the first
224 example of a FTS in which technology developments have allowed uncooled operations over a
225 wideband spectral region (Palchetti et al. 2005; Bianchini and Palchetti 2008), from 100 to 1400
226 cm⁻¹ with 0.5 cm⁻¹ of spectral resolution, very similar to what required for FORUM. REFIR-

227 PAD is based on the Mach-Zehnder interferometric scheme with two input ports and two output
228 ports, which allows alignment errors to be minimised and calibration accuracy to be optimised
229 by looking continuously with the second port at a reference stable black-body source (Carli et al.
230 1999). The capability of this instrument configuration, which was selected as baseline for the FSI,
231 to provide a full spectral characterization of the atmospheric emission has been assessed in several
232 field campaigns. In July 2005, the instrument took part in a stratospheric balloon flight, obtaining
233 the first spectrally-resolved measurement of the Earth's upwelling emission using an uncooled
234 system (Palchetti et al. 2006, 2008). Following that the instrument was adapted to operate from
235 high-altitude ground-based sites to take measurements of the downwelling radiation, where the
236 atmosphere is highly transparent to perform sounding in the FIR. In March 2007 and 2011, it was
237 operated from Testa Grigia, in the Italian-Swiss Alps (3480 m a.s.l.) and in August-September 2009
238 from Cerro Toco (Chilean Andes, Atacama desert, 5320 m a.s.l.) within the Radiative Heating in the
239 Under-explored Bands Campaign-II (RHUBC-II), that, together with other dedicated instruments,
240 observed the downwelling radiance from the sub-millimeter to the MIR, enabling the first complete
241 infrared spectrum of downwelling radiation (Turner et al. 2012). Finally, since 2011, REFIR-
242 PAD has been operating permanently in Antarctica at Concordia Station, Dome C (3233 m a.s.l.),
243 providing continuous, unattended operations. These ground-based campaigns have shown the
244 capability to measure the atmospheric downwelling radiation in a very wide spectral band (see
245 Figure 3), contributing in such a way to update the water vapor spectroscopy in the FIR region
246 (Liuzzi et al. 2014; Mlawer et al. 2019), which was used for studies performed to increase the
247 science readiness level of FORUM.

248 Another FORUM precursor is the Far-Infrared Spectroscopy of the Troposphere (FIRST) in-
249 strument that was developed through NASA's Instrument Incubator Program beginning in 2001 to
250 demonstrate technologies needed to measure the FIR with a space-based instrument (Wellard et al.

251 2006; Bingham et al. 2005; Mlynczak et al. 2005). FIRST is a FTS with a demonstrated spectral
252 coverage of 50 cm^{-1} to 2000 cm^{-1} ($200 \mu\text{m}$ to $5 \mu\text{m}$) and a nominal resolution of 0.625 cm^{-1} .
253 Specific technologies demonstrated by FIRST include a broad bandpass beamsplitter, a compact
254 FTS system, and a multi-detector focal plane array. FIRST measured the entire infrared spectrum
255 from a space-like environment during demonstration flights on 30 km altitude balloon platforms in
256 June 2005 (Mlynczak et al. 2006), and again in September, 2006 from Fort Sumner, NM (Figure
257 4). The FIRST instrument flew twice from Fort Sumner, NM on high-altitude balloons, observing
258 the troposphere from a float altitude of approximately 33 km. 4 (left panel) shows a complete
259 infrared spectrum (10 to 1600 cm^{-1}) measured by FIRST on 7 June 2005. The right panel shows
260 a comparison of the FIR spectra measured in June 2005 and again on 18 September 2006. The
261 mid-troposphere in 2006 was cooler and dryer than during the 2005 flight, and accounts for the
262 lower radiance values observed in the FIR between 400 and 600 cm^{-1} . FIRST radiances in the MIR
263 were shown to be consistent with those measured by the Atmospheric Infrared Sounder (AIRS)
264 satellite instrument during a coincident overpass. Subsequent to the technology demonstrations,
265 FIRST participated in the RHUBC-II campaign, whose data were used to recommend changes to
266 the water vapor continuum absorption in the FIR (Mast et al. 2017) which have since been adopted
267 (Mlawer et al. 2019). FIRST underwent a substantial recalibration after the RHUBC-II campaign
268 (Latvakoski et al. 2014, 2013) and conducted a ground-based measurement campaign at Table
269 Mountain, CA in 2012. The results from the Table Mountain deployment of the FIRST instrument
270 affirmed the need for high radiometric accuracy FIR measurements, such as those to be made by
271 FORUM, for understanding climate change (Mlynczak et al. 2016). The FIRST project contributed
272 to the awareness of the criticality of FIR measurements in the framework of climate change, which
273 are now part of the overall strategy of a climate observing system known as the NASA Climate

274 Absolute Radiance and Refractivity Observatory (CLARREO) mission (Wielicki et al. 2013), and
275 will be addressed by the FORUM mission.

276 Still the only instrument capable of making hyperspectral radiance observations across the
277 FIR from aircraft, the Tropospheric Airborne Fourier Transform Spectrometer (TAFTS) (Canas
278 et al. 1997) is a Martin-Puplett polarizing interferometer with a spectral range of $80\text{--}600\text{ cm}^{-1}$
279 ($125\text{--}12.5\text{ }\mu\text{m}$). The TAFTS configuration is a four-port system composed of two input and
280 two output ports. A single input port is directed to either a nadir or zenith view with each
281 view having dedicated blackbody calibration targets. The two output ports each comprise a pair of
282 cryogenically cooled detectors which are used to obtain "longwave" ($80\text{--}300\text{ cm}^{-1}$) and "shortwave"
283 ($330\text{--}600\text{ cm}^{-1}$) spectral radiances at a nominal resolution of 0.12 cm^{-1} . The cooled detectors
284 allow fast acquisition of sufficient precision/calibration compatible with the rapid scene variations
285 associated with aircraft based measurements. TAFTS has been successfully operated on a variety
286 of different aircrafts during a number of measurement campaigns. Particular highlights include
287 flights aimed at evaluating the FIR radiative impact of water vapor variability in clear-sky (Cox et al.
288 2007), the radiative signature of cirrus across the MIR and FIR (Cox et al. 2010), the assessment
289 of water vapor FIR continuum spectroscopy (Green et al., 2012) and the first retrieval of FIR
290 surface emissivity from airborne observations (Bellisario et al. 2017). More recent work in direct
291 support of FORUM preparation has exploited contemporaneous TAFTS and MIR hyperspectral
292 measurements, covering the broad band required by the FSI (see an example in 5), to explore the
293 benefit that FIR radiances may provide for water vapor retrievals and the ability of current ice
294 bulk-scattering databases to capture observed cirrus radiances across the infrared.

SPECTRAL SENSITIVITY OF THE OLR TO CLIMATE VARIABLES

In this section the spectral response of the OLR to variations of climate variables, which have signatures in the longwave region, is discussed. The objective of this section is to provide quantitative evidence of the better sensitivity of the FIR portion of the OLR spectrum which will be sounded by FORUM. A first assessment of the quality of the parameters that can be retrieved from FORUM spectral measurements is also presented in Ridolfi et al. (2020).

Sensitivity to water vapor vertical distribution

Figure 6 illustrates the sensitivity of the upwelling spectral radiance to changes in the H₂O volume mixing ratio (VMR). The top panels refer to an Antarctic Polar Winter atmosphere, the bottom ones to a Mid-Latitude atmosphere. The color maps on the left show the changes in the TOA spectral radiance as a function of the wavenumber, resulting from an increase by 1 ppmv of the H₂O VMR, chosen as the accuracy required to the FORUM mission, in a 1 km-thick layer, stepping from 0 to 30 km. These changes can be integrated across the FIR (100 – 667 cm⁻¹) and the MIR (667 – 2800 cm⁻¹) spectral regions to get a proxy of the global sensitivity of these two regions to the water vapor vertical distribution. The results of this integration are shown in the center panels of Figure 6. This is clearly indicating that the FIR region is between three to five times more sensitive than the MIR to changes in the upper tropospheric water content. Also vertical profiles of heating rates show a peak in the UT and for the FIR spectral range (Clough and Iacono 1995; Turner and Mlawer 2010). The information content for water vapor profile retrievals is therefore expected to increase when FIR channels are combined with MIR channels (Merrelli and Turner 2012). Finally, the right panels of Figure 6 show the corresponding temperature profiles. In the vertical ranges where temperature increases with altitude, an increase of the water vapor causes an increase of the TOA radiance (shown with reddish colors on the left panels), thus a more effective

318 cooling of the atmosphere and a negative climate feedback. Conversely, in the height ranges where
319 the temperature decreases with altitude, an increase of water vapor causes a decrease of the TOA
320 radiance, therefore a net warming (Riese et al. 2012).

321 *Cirrus cloud parameters*

322 Owing to the low emitting temperatures and unique optical properties, that are a consequence
323 of the spectral variations of the imaginary part of the refractive index of ice, cirrus clouds have a
324 significant impact on the Earth FIR spectrum. Many studies have evaluated the OLR sensitivity to
325 particle microphysics (particle shape and size distribution) and cloud geometrical properties (see
326 e.g. Harries et al. 2008; Maestri et al. 2019b). It has been noted that radiance sensitivity in the
327 FIR with respect to particle effective dimension (equivalent to diameter for the case of spherical
328 particles), cloud geometrical and optical depth and ice water path (IWP) is very large. In particular,
329 the information from the FIR is critical to disentangle different processes, such as the presence
330 of a sub-visible cirrus cloud, the variation of surface properties or of water vapor concentration,
331 which, otherwise, could not be unequivocally identified by relying on MIR radiances only (see
332 for example Figure 2 in Maestri et al. 2019b). Moreover, the FIR radiance sensitivity to crystal
333 habits is relevant, mainly around 410 cm^{-1} where the imaginary part of the refractive index of ice
334 has a local minimum, making scattering significant. In Figure 7 the brightness temperature (BT)
335 differences, with respect to clear sky when a cirrus cloud with optical depth (OD) equal to 1.4
336 at $0.555 \mu\text{m}$ is considered, are shown for two wavenumbers (410 and 900 cm^{-1}) and for several
337 assumptions on crystal shape. The results show that BT differences in the MIR range within 1
338 K, almost insensitive to the assumed habit, independently of the crystal size. On the contrary,
339 BT differences in the FIR span over more than 3 K for small crystals (less than $40 \mu\text{m}$) and 8
340 K for medium and large crystal sizes. Similar results are obtained (not shown here) for cirrus

341 clouds with smaller and larger opacity, (i.e. $OD = 0.5$ and $OD = 5$). This suggests that the analysis
342 of combined observations in the FIR and MIR part of the spectrum, acquired with a brightness
343 temperature accuracy of 0.1 K as required for the FSI measurements, might be sufficient to allow
344 an identification of the crystal habits, as recently shown Maestri et al. (2019a).

345 *Surface emissivity at high latitudes*

346 As the atmosphere becomes drier, in the absence of cloud or aerosol, the OLR at the TOA contains
347 an increasing contribution from surface emission. Substantial surface to TOA transmission is
348 expected across much of the FIR when the total column water vapor (TCWV) is less than about
349 1 mm. These conditions are relatively common over the Arctic and Antarctica: ERA-Interim
350 (ERA-I) reanalyses indicate that TCWV is below this humidity level for approximately 20 % of
351 atmospheric profiles poleward of 66.5° during the three year period from 2013-2015.

352 Tests of the sensitivity of FIR outgoing radiances to surface emissivity have been performed
353 for a polar scenario for 3 different surface elevations. The results shown in Figure 8 indicate that
354 under these conditions a satellite observation with an accuracy of 0.1 K in brightness temperature,
355 as required to the FSI measurement, will have sufficient sensitivity to estimate the emissivity of
356 frozen surfaces within the FIR to an accuracy better than 0.01. These estimates are consistent with
357 retrievals made from aircraft measurements over the Greenland plateau (Bellisario et al. 2017).
358 Based on theoretical calculations of hemispherical emissivity, this level of accuracy should also
359 permit the effect of fine and coarse snow grain sizes to be distinguished (Huang et al. 2018).

360 **EXPECTED IMPROVEMENTS IN MODELLING**

361 *FIR spectroscopy of molecular species*

362 FORUM measurements will allow a complete evaluation of the current spectroscopy of both
363 the FIR water vapor rotation band and the ν_2 absorption band of CO_2 at 667 cm^{-1} ($15 \mu\text{m}$).
364 Current satellite missions in the infrared for meteorological and climate studies only sense the
365 OLR spectrum down to 645 cm^{-1} , covering only the high frequency branch of the $\nu_2 \text{ CO}_2$ band
366 and missing the intense absorption/emission of H_2O below 500 cm^{-1} .

367 FIR H_2O spectroscopy, which also includes the contribution of the so-called "self and foreign
368 continuum absorption", has been largely explored in the past few years only with field campaigns
369 based on the existing ground-based prototypes described before, (see e.g. Serio et al. 2008; Liuzzi
370 et al. 2014). The FORUM mission is expected to add new information especially in the range 100
371 to 400 cm^{-1} , which is very difficult to sense from ground-based locations even by performing
372 measurements in very dry sites, such as high mountains and Arctic-Antarctic stations.

373 A validation/consistency experiment of the CO_2 spectroscopy covering the whole ν_2 absorption
374 band is still missing. The recent work by Liuzzi et al. (2016) and Serio et al. (2019) has covered
375 the CO_2 band only down to 640 cm^{-1} showing that CO_2 spectroscopy uncertainty is of the order of
376 the noise affecting modern satellite sensors, such as IASI (see Figure 9). A simultaneous retrieval
377 approach, in which temperature can be retrieved by using e.g. one branch of ν_2 band while the
378 CO_2 mixing ratio is retrieved using the other branch, will give an unique opportunity to check the
379 quality and consistency of the spectroscopic parameters over the full $15 \mu\text{m}$ CO_2 absorption band,
380 which still remains fundamental for temperature sounding from satellite.

381 The FORUM mission will therefore be of paramount significance to improve the quality and
382 accuracy of temperature and water vapor retrievals from modern satellite infrared sounding instru-
383 ments.

384 *Cirrus cloud modeling*

385 It is now well established that clouds and more specifically high clouds represent one of the
386 largest modeling uncertainties in estimating the ERB (Stocker et al. 2013). This is mainly due
387 to the inability of models to correctly represent the diversity of their geographical and vertical
388 distribution and their complex particle microphysics (Baran 2009, 2012; Calisto et al. 2014; Zhang
389 et al. 2005).

390 Understanding the cloud radiative effect (CRE) of high clouds has been the subject of numerous
391 studies in recent decades. While there is no longer evidence that the global CRE of high clouds
392 is warming (Hartmann et al. 1992; Matus and L'Ecuyer 2017; Stephens 2005), the average value
393 of this warming and its zonal and vertical distribution remains highly uncertain (Hang et al. 2019;
394 L'Ecuyer et al. 2019; Oreopoulos et al. 2016).

395 Two recent studies by Hong and Liu (2015) and Hong et al. (2016), based on one year of data from
396 the two active instruments (LIDAR and RADAR) of the A-Train constellation, and the associated
397 ice water content profile products, have extended this understanding by investigating the variation
398 of the CRE as a function of cloud opacity (given by their IWP in g/m^2 or OD at 532 nm). These
399 studies have shown the importance of very thin ice cloud (IWP < 20 g/m^2 or OD < 0.6) in the global
400 CRE, due to their high occurrence (more than 50% of the total ice clouds detected). Moreover, the
401 authors have highlighted the significant uncertainties attached to their computation due to the poor
402 understanding of the ice cloud microphysics. These numbers highlight the importance of a good

403 representation, in terms of occurrence, localization, and microphysical properties of high clouds
404 in numerical model and for climate studies.

405 Similarly, a recent airborne campaign, carried out on 13 March 2015, off the North-East coast
406 of Scotland and focused on straight and level run made above an optically thin cirrus cloud, has
407 put into question the ability of currently available microphysical models to consistently reproduce
408 high spectral resolution measurements on the whole infrared spectrum. Indeed, these models
409 have been able to reproduce the measured signal in the MIR (residual noise < instrumental noise)
410 satisfactorily, but have been unable to do so in the FIR. This result highlighted one of the weaknesses
411 of the current particle ice microphysical models, namely their spectral inconsistency linked either
412 to a poor knowledge of the ice refractive index and in particular its temperature dependence in the
413 FIR or to an inaccurate representation of the size and shape distribution (Bantges et al. 2020).

414 These findings demonstrate the undeniable contribution of an instrument such as FORUM to
415 improve the modeling of spectrally resolved optical properties of ice particles.

416 *Snow emissivity modeling*

417 The TCWV at high latitudes is much smaller than that at mid-latitude and tropics. As a
418 result, in Polar regions the "dirty" FIR window between 245 and 600 cm^{-1} (16.7-29 μm) is
419 not opaque and the surface emission can reach the TOA. This fact affords an opportunity of
420 inferring spectrally-dependent surface emissivity from the FORUM measurements, across both
421 the main MIR atmospheric window and FIR dirty window. Recent studies have underlined the
422 importance of surface spectral emissivity in the modeling of longwave coupling between surface
423 and atmosphere in the high latitudes (Chen et al. 2014; Huang et al. 2018). However, since there
424 have been no extensive measurements of FIR surface emissivity, these studies had to make use
425 of calculated values based on first principles (Huang et al. 2016). FORUM measurements will

426 change this predicament and provide observation-based surface spectral emissivities in the FIR for
427 polar regions. Moreover, surface optical properties in the visible, near-IR, MIR, and microwave
428 regions have been routine products from different satellite observations, such as IASI, AIRS and
429 the Moderate-Resolution Imaging Spectroradiometer (MODIS). FORUM measurements will fill
430 the spectrum gap by providing such surface optical properties in the FIR.

431 *TOA spectral fluxes*

432 FORUM and IASI-NG observations will quantify the variability of the full outgoing longwave
433 spectrum over a range of temporal and spatial scales. As seen from the previous sections, the
434 information content of the measurements will also allow us to identify key atmospheric factors
435 driving these energetic signatures. This combination promises to be a powerful new tool for the
436 evaluation of TOA radiation fields in climate models, avoiding compensation effects that can not
437 be disentangled with readily available broadband flux observations, such as from the Clouds and
438 the Earth's Radiant Energy Systems (CERES) instrument (e.g. Dolinar et al. 2015; Li et al. 2013).

439 For the purpose of evaluating climate models and for ease of use by the community, FORUM
440 will provide level 2 spectral and broadband flux products. We are currently investigating two
441 potential approaches for generating these fluxes: (1) employing spectral Angular Distribution
442 Models (ADMs) based on an underlying scene classification or (2) forward modeling of the angular
443 radiance distribution directly using the surface, atmospheric profile and, where appropriate, cloud
444 property information retrieved from the FORUM and IASI-NG observations.

445 Recognising the intrinsic value of spectral information, several authors have attempted to estimate
446 spectrally resolved radiances and fluxes spanning the full infrared by developing physical or
447 statistical relationships between MIR observations and the unmeasured FIR spectrum (e.g. Huang
448 et al. 2008, 2010; Turner et al. 2015). These approaches have already seen the development

449 of spectral ADMs in order to perform the radiance to flux conversion and the resulting fluxes
450 are now being used to evaluate climate model performance (e.g. Huang et al. 2013). Results
451 illustrate how a good agreement in broadband fluxes can mask much larger discrepancies within
452 individual spectral bands, with substantial differences seen in the FIR. We anticipate that FORUM
453 will enable a significant advance in this field since there will no longer be a need to infer the
454 unmeasured FIR radiances from the MIR observations. We also speculate that the FORUM/IASI-
455 NG measurements could be exploited to develop new, observationally based relationships between
456 MIR and FIR radiances that could be used, in conjunction with existing MIR sounder data, to
457 retrospectively create a much longer and more extensive spectral OLR record extending back to
458 the early 2000s.

459 **EXPECTED IMPROVEMENTS IN EVALUATION OF CLIMATE MODELS**

460 There are several primary achievements where we expect FORUM data to substantively improve
461 our projections of the Earth's climate. First, FORUM data will enable the scientific community
462 to finally achieve a complete picture of the radiative impact of the atmosphere's most important
463 greenhouse gas: water vapor. This will address unresolved issues with modeled water-vapor ab-
464 sorption at low-latitudes (see e.g. Baranov and Lafferty 2012). This absorption has been shown
465 to influence the general circulation (Jeevanjee and Fueglistaler 2020) and greatly impact modeled
466 projections of surface temperature and mid-tropospheric water vapor (Iacono et al. 2000). FO-
467 RUM will characterize H₂O distribution globally by spanning cold and dry conditions, where this
468 absorption is well-understood, and the warm and moist conditions, where it is not.

469 FORUM observations will also provide an exacting test for how models achieve their OLR.
470 Models are tuned to agree with observed OLR, but the tuning choices (Hourdin et al. 2017) are
471 reflected differentially in the spectral properties of OLR (Huang et al. 2013, 2007). To date, only

472 the MIR has been used to test modeled clouds and water vapor, but FORUM will provide direct,
473 rather than inferred, observational constraints on how these quantities modulate most of the OLR,
474 thereby revealing how well models achieve their OLR computation with realistic distributions of
475 water vapor, cloud type, amount, and microphysics, or through error compensation.

476 Finally, at high-latitudes, FORUM will be able to see through the partially-transparent FIR
477 and completely characterize the longwave radiative environment, including its atmospheric and
478 surface contributions. This will quantify the relative contributions of surface emission and cloud
479 longwave scattering, both of which have been mentioned for explaining persistent model biases of
480 high-latitude surface temperature (Huang et al. 2018; Kuo et al. 2018).

481 While we have described in this work the most likely climate model advances that will arise as
482 a result of FORUM observations, it must be emphasized that the mission is true to the spirit of
483 the ESA EE9 program that is supporting it: the FORUM mission is exploratory in nature. Our
484 expectation of science that can be achieved with FORUM data arises from the new possibility
485 to piece together the many processes that modulate FIR radiation from the limited FIR data we
486 currently have. The lack of comprehensive data means that the scientific understanding of the
487 radiative processes that impact the FIR is highly immature. It is quite unlikely that current climate
488 models are fully accounting for the many processes controlling the hundreds of watts per square
489 meter that are emitted in the FIR, since spectra have not been measured comprehensively.

490 Fundamental features of how the Earth's climate system emits energy to space are still incom-
491 pletely understood and modeled. The greenhouse effect from water vapor, its modulation by clouds,
492 and the role of surface properties in controlling most of the Earth's infrared energy, have only been
493 measured in part. We therefore urge a larger scientific community to be prepared for unanticipated
494 surprises in not just the Earth's radiation field, but also to consider and adapt to the implications of
495 these surprises for atmospheric circulation, that emerge from the FORUM data.

496 The unprecedented radiometric accuracy of the FORUM instrument assures that any differences
497 between observations and models are statistically significant, thus enabling a substantive improve-
498 ment in our knowledge of radiative transfer in the far infrared and the associated impacts on
499 climate

500 We therefore look forward to working with the larger scientific community to use FORUM data
501 to explore the far-infrared frontier.

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901 TABLE 1. FORUM geophysical products with expected uncertainties. The total error includes both random
 902 and accuracy components.

Geophysical product	Uncertainty
Vertical profiles of water vapor concentration with 2 km of resolution	15 % in the lower/mid troposphere, 1 ppmv in the upper troposphere
Vertical profiles of temperature with 2 km of resolution	1 K throughout the troposphere
Cloud Top/Base Height (CTH,CBH)	1 km
Ice water path (IWP)	20 g/m ²
Effective diameter of ice particles	20%
Spectral emissivity of frozen surfaces in polar regions wavenumber range 300 to 600 cm ⁻¹ with 50 cm ⁻¹ spectral grid	< 0.01
Surface temperatures in clear sky conditions	< 0.5 K

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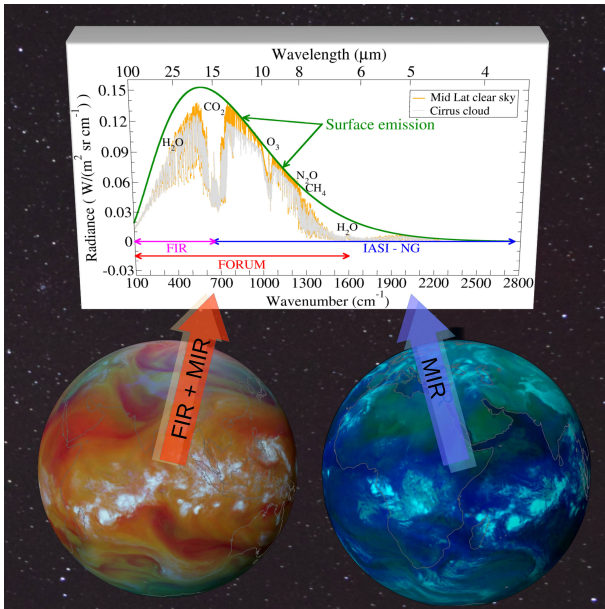
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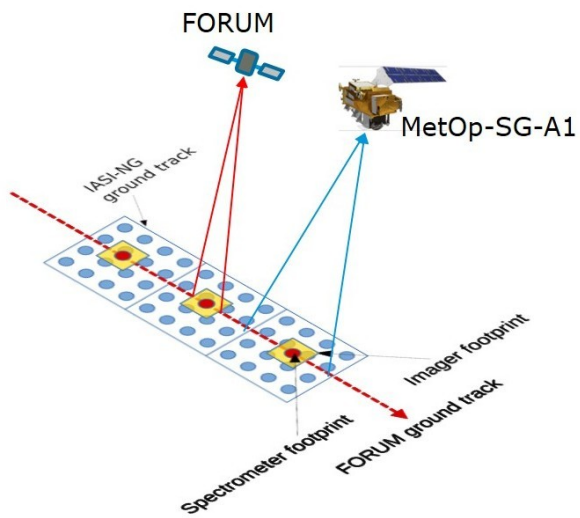
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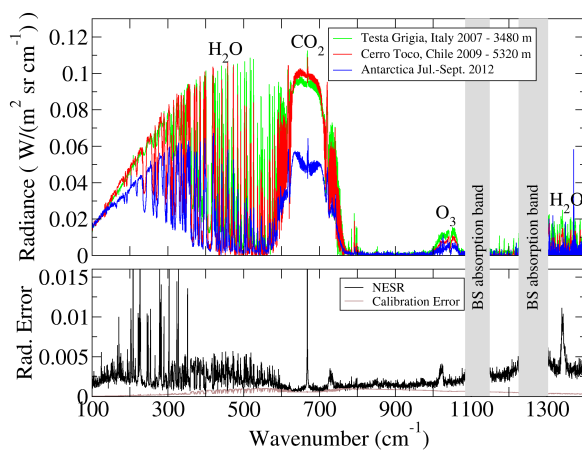
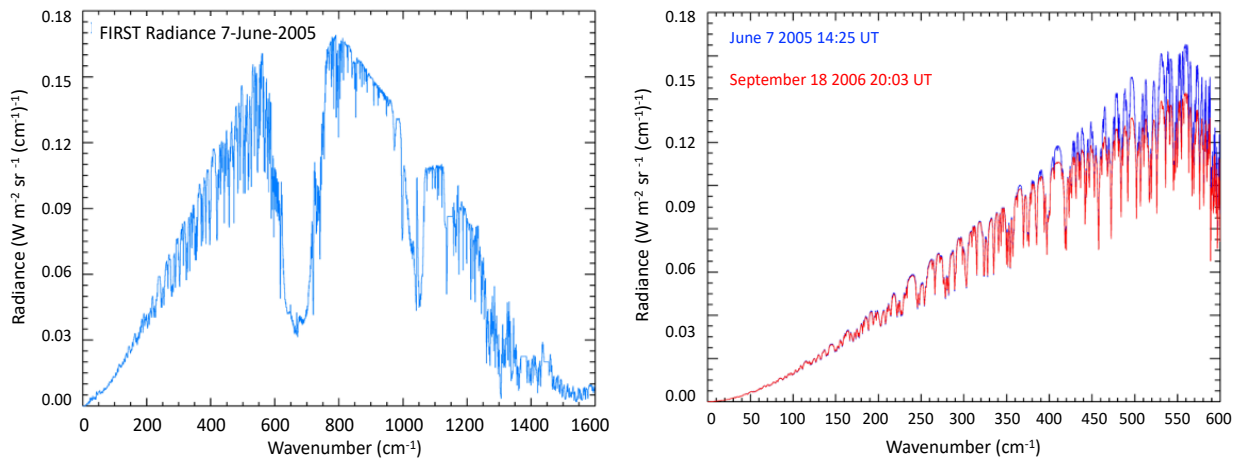
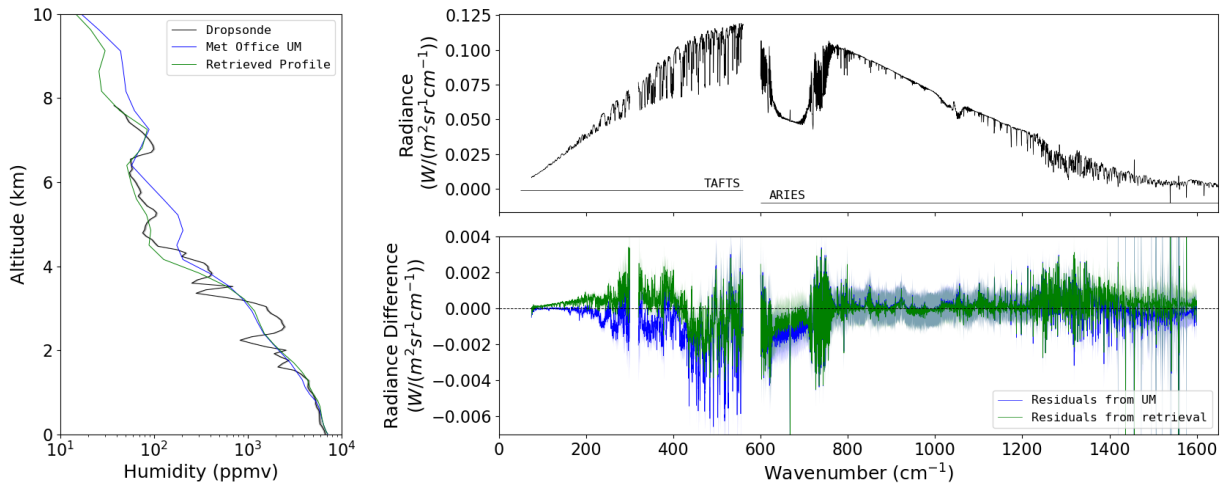


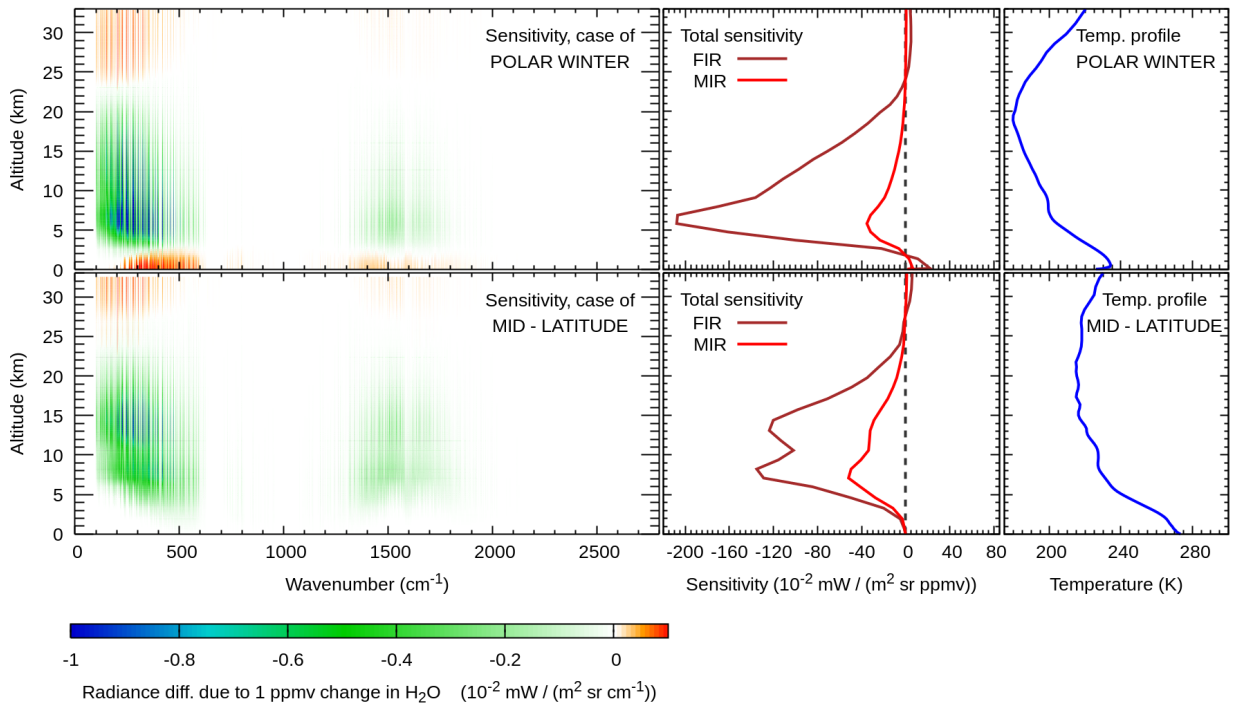
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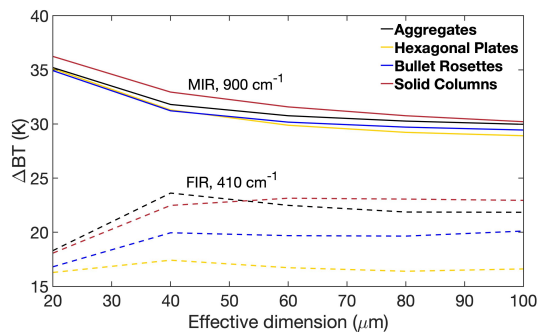
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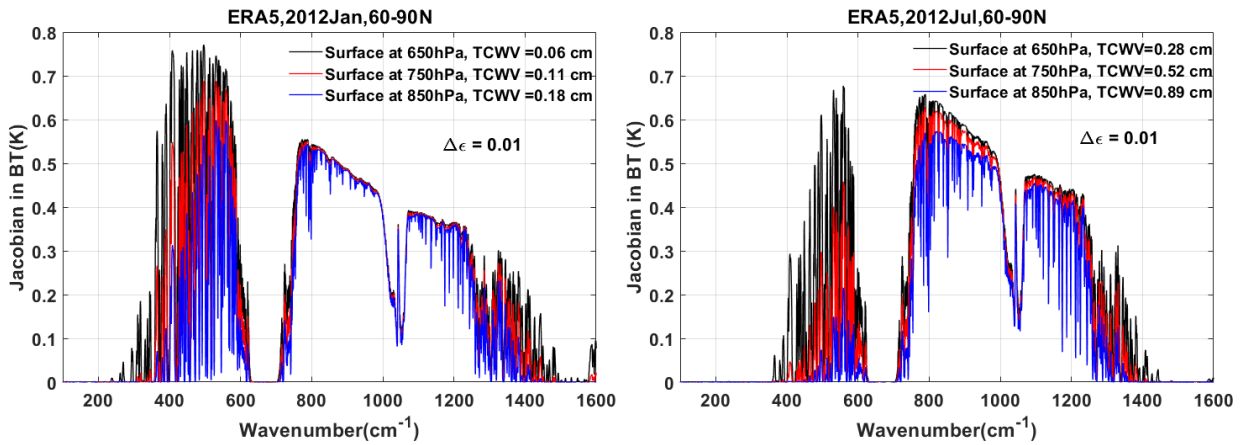
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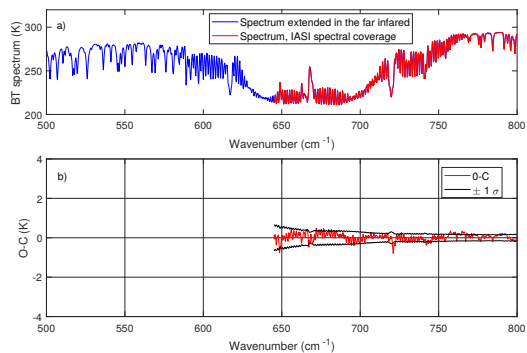
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