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FORUM

Unique Far-Infrared Satellite Observations to Better Understand How Earth Radiates Energy to Space

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

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

Over 99% of the thermal radiation emitted by the Earth falls within the spectral range 100–2,500 cm^{-1} (100–4 μm) and is commonly called the outgoing longwave radiation (OLR). Part of this spectral region, from 100 to 667 cm^{-1} (100–15 μm) is known as the far infrared (FIR), which, based on model calculations, accounts for at least half of the Earth's energy emitted to space (Collins and Mlynczak 2001; Harries et al. 2008). However, up to now, our scientific understanding of how the FIR contributes to the Earth's OLR has mostly been inferred either from model simulations or from spectral measurements in the middle infrared (MIR) from 667 to 3,333 cm^{-1} (15–3 μm) combined with radiative transfer calculations (Huang et al. 2008; Turner et al. 2015). Indeed there is a lack of extensive spectral measurements covering the FIR region because the FIR technology is much less mature than the MIR technology. Nevertheless, even without comprehensive FIR measurements, multiple studies have indicated that the spectral signatures of the OLR in that spectral region are particularly sensitive to water vapor in the upper troposphere (UT) and to the presence of ice clouds (e.g., Harries et al. 2008, and references therein).

The importance of water vapor as greenhouse gas is well known. Simulations have shown that an increase on the order of 10% in tropospheric water vapor exerts a radiative effect which is equivalent to a doubling of CO_2, and up to 55% of this effect occurs within the FIR (Brindley and Harries 1998). Any estimate of its radiative impact is, of course, dependent on the quality of the underlying spectroscopy and knowledge of its vertical distribution.

A number of measurement campaigns have substantially improved our knowledge of water vapor spectroscopy within the FIR (Mlawer et al. 2019; Fox 2015; Green et al. 2012; Turner et al. 2012; Tobin et al. 1999). In contrast, despite attention spanning more than two decades, uncertainties in UT water vapor amounts are still significant because all current measurement techniques have shortcomings within this altitude range (Müller et al. 2016; Ferrare et al. 2004). Similarly, estimates of water vapor trends and variability within the lower stratosphere are also poorly constrained and suffer large uncertainties (Hurst et al. 2011; Hegglin et al. 2014; Yue et al. 2019). Improving our knowledge of the global water vapor distribution in the upper troposphere–lower stratosphere (UTLS) region is essential given its key role in influencing surface temperature trends (Dessler 2013; Solomon et al. 2010; Forster and Shine 2002; Dessler and Sherwood 2009). Improved water vapor records in this region would also have strong benefits for elucidating climate–chemistry interactions and have the potential to enhance the quality of numerical weather prediction (NWP) (Hilton et al. 2012).

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

Recently, Cox et al. (2015) and Feldman et al. (2014) have suggested that the FIR part of the OLR spectrum may have a more important role than previously recognized in modulating high-latitude climate response and future change. The underestimation of polar climate change (Barton et al. 2014) is thought to be due to deficiencies in our understanding of the polar radiative energy balance. In polar regions, this balance is highly sensitive to both ice-albedo feedback and longwave surface emission (Yamanouchi and Charlock 1995; Vavrus 2004). Because of the very cold surface temperatures typical of these regions, a large part of the emitted surface longwave energy is in the FIR. Moreover, the very low water vapor content, with columns of H_2O that can be as low as 0.1 mm, makes the atmosphere in the FIR much more transparent than at other latitudes (Turner and Mlawer 2010). Typically, climate models have assumed that the surface emissivity in the FIR is that of an ideal blackbody (i.e., spectrally invariant unit emissivity). However, there is growing awareness that this assumption is unphysical (Chen et al. 2014) and that may result in marked radiative biases in polar regions (Kuo et al. 2018). Given the FIR enhanced atmospheric transparency in polar regions, the surface emissivity in the FIR can be directly measured with remote sensing measurements from airborne platforms (Bellisario et al. 2017).

Finally, broadband, spectrally integrated measurements of the OLR emitted by the Earth have been made by a variety of satellite sensors for almost four decades (Barkstrom 1984). These observations can reduce uncertainty in climate predictions by helping to constrain climate models (e.g., Forster and Gregory 2006; Tett et al. 2013). However, the integrated broadband OLR measurements are unable to identify changes in the spectral distribution of the OLR and compensation effects can, and do, occur. Many theoretical studies have indicated that specific perturbations to the climatic state will exhibit distinct signatures in the OLR spectrum (Huang et al. 2010; Goody et al. 1998). More recent work, exploiting both spectrally resolved and broadband observations, suggests that the FIR plays an important role in controlling global-scale OLR variability (Brindley et al. 2015). New spectral observations, including the MIR and the FIR, will allow us to quantify, for the first time, the degree to which spectral compensation effects may be masking OLR signatures associated with specific geophysical parameters. Moreover, the information contained within the collected spectra will also allow us to better constrain the physical processes, including forcing and feedbacks, driving these OLR signals.

The FORUM mission

The need for a complete picture of the processes governing OLR and their subsequent effects on the Earth's climate will be addressed by the FORUM mission (https://www.forum-ee9.eu), which has been selected to be the ninth ESA Earth Explorer (EE9) mission. Growing international interest in the role of the FIR in climate is also reflected by the selection of the NASA Earth Venture CubeSat mission PREFIRE (Polar Radiant Energy in the Far-Infrared Experiment). With the overriding aim of better understanding key drivers of Arctic climate, PREFIRE will nominally launch in 2022 and will measure IR spectra between 4 and 50 μm at a relatively coarse (0.84 μm) resolution for 1 year and focused on polar regions only.

Complementary to this effort, but expanding on its reach in terms of temporal coverage, measurement accuracy and spectral resolution, the main goal of the FORUM mission is to deliver an improved understanding of the climate system, informing climate policy decisions by supplying a complete global characterization of the Earth's OLR spectrum at high spectral resolution (Fig. 1). This

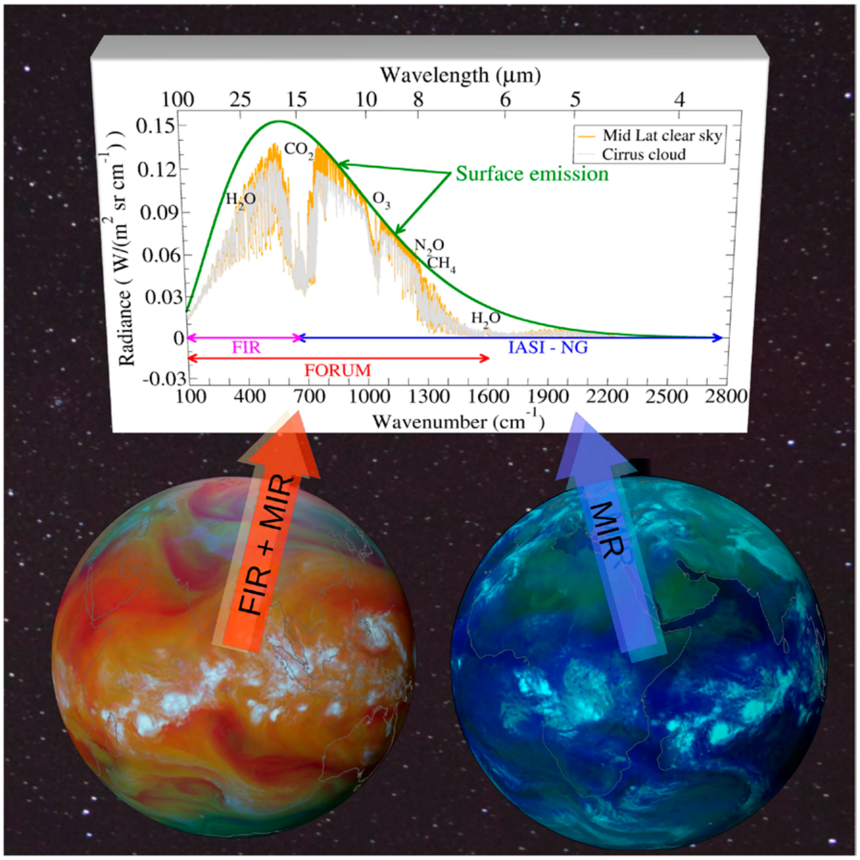

Fig. 1. (top) Spectrum of the outgoing radiance expected at TOA for clear sky (orange line) under a midlatitude standard scenario and in presence of a cirrus cloud (gray line) compared to the ground surface emission (green line). The spectral ranges covered by FORUM and IASI-NG and the FIR range are also shown. (bottom) The Earth globes in false colors show a pictorial view of what can be seen (left) using three channels spanning the FIR and MIR regions compared with (right) using only two channels in the MIR.

goal will be achieved by performing spectral measurements that cover the top-of-the-atmosphere (TOA) emission spectrum from 100 to 1,600 (100–6.25 μm) with a nominal resolution of at least 0.5 cm^{-1} (full width half maximum). The mission will provide a multiyear dataset benchmarked against international standards with an absolute accuracy of at least 0.1 K at 3σ in TOA brightness temperature. Previous space missions that sampled part of the FIR were exploratory in nature and had neither the necessary lifetime nor the accuracy to provide a quantitative assessment of the relevance of the FIR region for climate change applications (Hanel et al. 1971; Kempe et al. 1980).

By flying in "loose formation" with the Meteorological Operational Satellite–Second Generation (MetOp-SG), at a time difference less than 1 min and with the ground tracks located within 300 km of distance, FORUM will complement the MIR spectral measurements performed in the 645–2,760 cm^{-1} range by the Infrared Atmospheric Sounding Instrument New Generation (IASI-NG). With this synergy, the mission will supply unique high spectral resolution observations of the Earth's entire emission spectrum from 100 to 2,760 cm^{-1} (100–3.62 μm), which can be used to provide a stringent test of our understanding of, and ability to model, the links between key underlying physical processes driving climate change, their spectral signatures, and the ERB.

While the delivery of a climate quality radiance dataset spanning the FIR represents a major scientific outcome in its own right, additional mission objectives include the generation of the geophysical products summarized in Table 1. All-sky spectral OLR fluxes covering the range 100–2,760 cm^{-1} will also be delivered by directly exploiting the synergy with IASI-NG and using forward modeling of the measured atmospheric state for the radiance-to-flux conversion.

Measurement concept and level of maturity

The FORUM measurement concept requires two instruments:

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

The observing mode has to be as close as possible to nadir-viewing with a single ground footprint of about 15 km in diameter for the FSI and a 36 × 36 km^2 field of regard for the FEI for documenting the FSI footprint and the surrounding area with a finer spatial resolution of 0.6 × 0.6 km^2, as seen in Fig. 2. The along–track sampling is less than 100 km, comparable to the spatial resolution recommended by the Global Climate Observing System for the TOA OLR (Belward et al. 2016). The flight with the MetOp-SG mission requires a sun-synchronous

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

Geophysical product	Uncertainty
Vertical profiles of water vapor concentration with 2-km resolution	15% in the lower/midtroposphere, 1 ppmv in the upper troposphere
Vertical profiles of temperature with 2-km resolution	1 K throughout the troposphere
Cloud-top height, cloud-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 of 300–600 cm^{-1} with 50-cm^{-1} spectral grid	<0.01
Surface temperatures in clear-sky conditions	<0.5 K

orbit at about 830 km at the same mean local solar time (0930) at the descending node. The proposed mission lifetime is 5–6 years in order to perform measurements covering different seasons and to capture interannual natural variability.

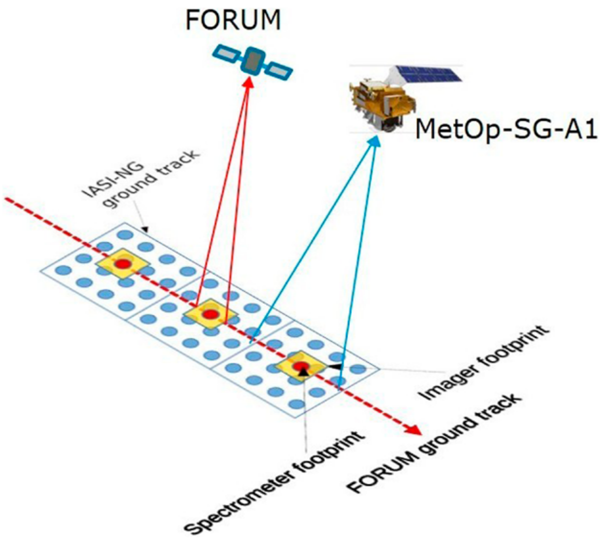

Fig. 2. Satellite ground tracks and footprints: FORUM FSI footprints (red), FEI (yellow), and IASI-NG footprints (blue).

Whereas the FEI is a standard single-spectral-band thermal infrared imager, the core FSI is a challenging instrument. The proposed solution is based on a Fourier transform spectrometer (FTS) designed to cover the full spectral range required by FORUM. Recent technology advances using uncooled detectors and broadband beam splitters have allowed the design of a small satellite to cover the FIR spectral range from a space platform. The first feasibility study of this instrument, named REFIR (Radiation Explorer in the Far-Infrared), was funded by the European Union in 1998 (Rizzi et al. 2002; Palchetti et al. 1999). Since then, the technical and scientific maturity required for space application have been achieved by continuous development of FIR prototypes and through knowledge gained from numerous ground-based and airborne campaigns. Below, we summarize the instrumentation and field campaigns that improved the level of maturity supporting the development of the FORUM mission.

The REFIR-PAD (REFIR–Prototype for Applications and Development) is the first example of an FTS in which technology developments have allowed uncooled operations over a wideband spectral region (Palchetti et al. 2005; Bianchini and Palchetti 2008), from 100 to 1,400 cm^{-1} with 0.5 cm^{-1} of spectral resolution, very similar to what is required for FORUM. REFIR-PAD is based on the Mach–Zehnder interferometric scheme with two input ports and two output ports, which allows alignment errors to be minimized and calibration accuracy to be optimized by looking continuously with the second port at a reference stable blackbody source (Carli et al. 1999). The capability of this instrument configuration, which was selected as baseline for the FSI, to provide a full spectral characterization of the atmospheric emission has been assessed in several field campaigns. In July 2005, the instrument took part in a stratospheric balloon flight, obtaining the first spectrally resolved measurement of the Earth's upwelling emission using an uncooled system (Palchetti et al. 2006, 2008). Following that the instrument was adapted to operate from high-altitude ground-based sites to take measurements of the downwelling radiation, where the atmosphere is highly transparent to perform sounding in the FIR. In March 2007 and 2011, it was operated from Testa Grigia, in the Italian–Swiss Alps (3,480 m MSL) and in August–September 2009 from Cerro Toco (Chilean Andes, Atacama Desert, 5,320 m MSL) within the Radiative Heating in the Underexplored Bands Campaign-II (RHUBC-II), that, together with other dedicated instruments, observed the downwelling radiance from the submillimeter to the MIR, enabling the first complete infrared spectrum of downwelling radiation (Turner et al. 2012). Finally, since 2011, REFIR-PAD has been operating permanently in Antarctica at Concordia Station, Dome C (3,233 m MSL), providing continuous, unattended operations (Palchetti et al. 2015). These ground-based campaigns have shown the capability to measure the atmospheric downwelling radiation in a very wide spectral band (see Fig. 3), contributing in such a way to update the water vapor spectroscopy in the FIR region (Liuzzi et al. 2014; Mlawer et al. 2019), which was used for studies performed to increase the science readiness level of FORUM.

Another FORUM precursor is the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument that was developed through NASA's Instrument Incubator Program beginning in 2001 to demonstrate technologies needed to measure the FIR with a space-based instrument (Wellard et al. 2006; Bingham et al. 2005; Mlynczak et al. 2005). FIRST is a FTS with a demonstrated spectral coverage of 50–2,000 cm^{-1} (200–5 μm) and a nominal resolution of 0.625 cm^{-1}. Specific technologies demonstrated by FIRST include a broad bandpass beam splitter, a compact FTS system, and a multidetector focal plane array. FIRST measured the entire infrared spectrum from a space-like environment during demonstration flights on 30-km-altitude balloon platforms in June 2005 (Mlynczak et al. 2006), and again in September 2006 from Fort Sumner, New Mexico (Fig. 4). The FIRST instrument flew twice from Fort Sumner on high-altitude balloons, observing the troposphere from a float altitude of approximately 33 km. The left panel of Fig. 4 shows a complete infrared spectrum (10–1,600 cm^{-1}) measured by FIRST on 7 June 2005. The right panel shows a comparison of the FIR spectra measured in June 2005 and again on 18 September 2006. The midtroposphere in 2006 was cooler and drier than during the 2005 flight, and accounts for the lower radiance values observed in the FIR between 400 and 600 cm^{-1}. FIRST radiances in the MIR were shown to be consistent with those measured by the Atmospheric Infrared Sounder (AIRS) satellite instrument during a coincident overpass. Subsequent to the technology demonstrations, FIRST participated in the RHUBC-II campaign, whose data were used to recommend changes to the water vapor continuum absorption in the FIR (Mast et al. 2017), which have since been adopted (Mlawer et al. 2019). FIRST underwent a substantial recalibration after the RHUBC-II campaign (Latvakoski et al. 2014, 2013) and conducted a ground-based measurement campaign at Table Mountain, California, in 2012. The results from the Table Mountain deployment of the FIRST instrument affirmed the need for high radiometric accuracy FIR measurements, such as those to be made by FORUM, for understanding climate change (Mlynczak et al. 2016). The FIRST project contributed to the awareness of the criticality of FIR measurements in the framework of climate change, which are now part of the overall strategy of a climate observing system known as the NASA Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission (Wielicki et al. 2013), and will be addressed by the FORUM mission.

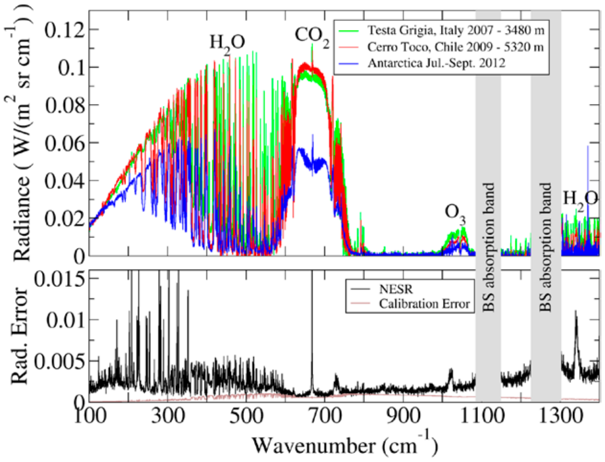

Fig. 3. REFIR-PAD ground-based FIR measurements. NESR is the noise equivalent spectral radiance.

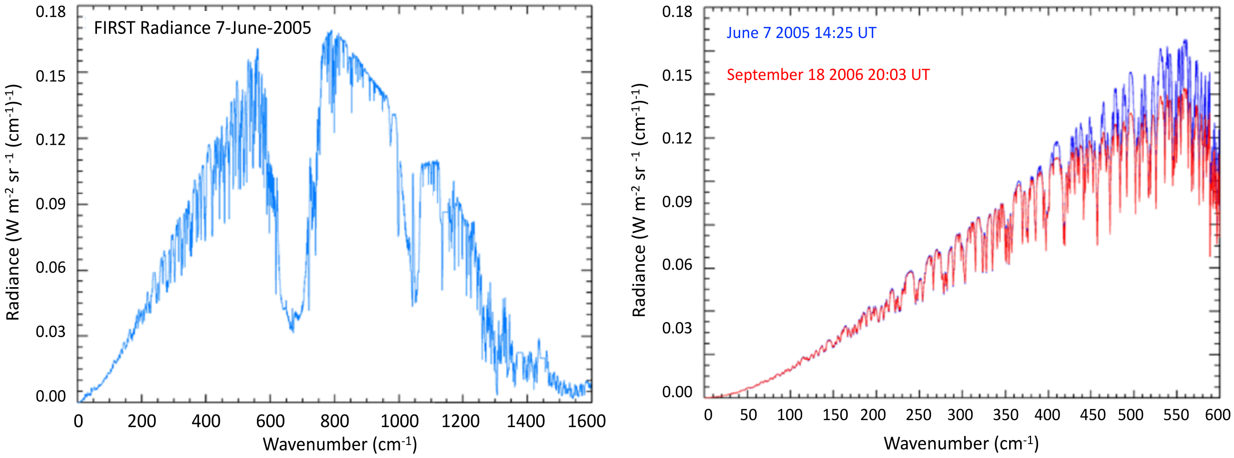

Fig. 4. (left) Complete infrared spectrum (10–1,600 cm^{-1}) measured by the FIRST instrument during a high-altitude balloon flight on 7 Jun 2005 from Ft. Sumner, New Mexico. (right) Comparison of FIR spectra (10–600 cm^{-1}) measured during high-altitude balloon flights on 7 Jun 2005 and 18 Sep 2006.

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

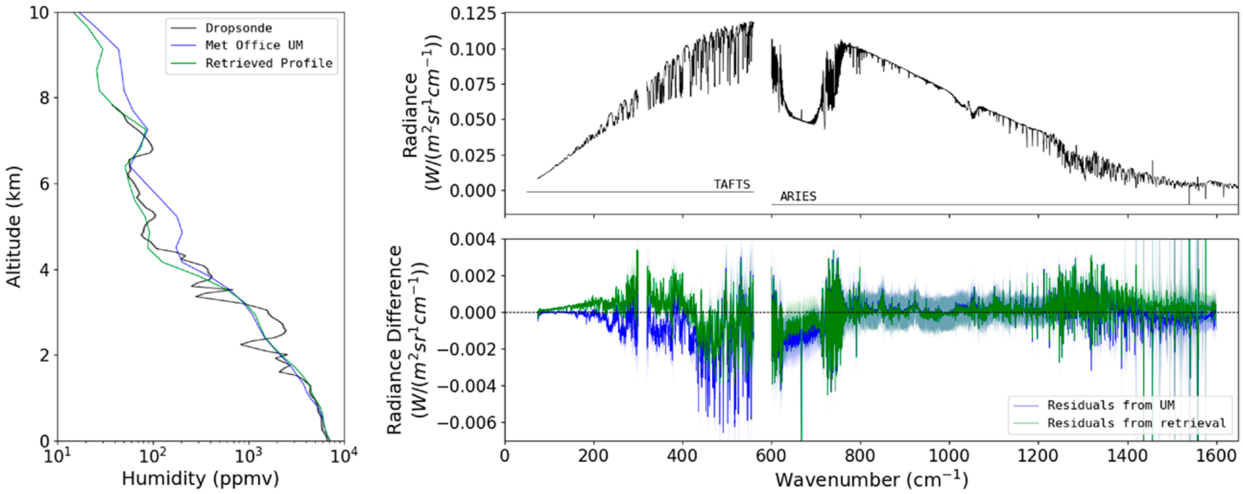

Fig. 5. (top right) Spectral radiances measured by TAFTS (80–550 cm^{-1}) and ARIES (>600 cm^{-1}), which covers the spectral range required for the FSI, under clear-sky conditions over the North Sea during the PiknMix-F campaign. (left) Humidity profiles observed by dropsonde at the time of the radiance measurements, forecast by the Met Office Global NWP model (UM) for the time and location of the flight, and retrieved using the observed radiances with the Met Office forecast as the initial guess. (bottom right) Radiance residuals between the observed radiances and those simulated using the Met Office forecast and after retrieving the atmospheric state. The addition of TAFTS radiances markedly improves the retrieval between 4 and 6 km.

Sensitivity to water vapor vertical distribution. Figure 6 illustrates the sensitivity of the upwelling spectral radiance to changes in the H_2O volume mixing ratio (VMR). The top panels refer to an Antarctic Polar Winter atmosphere, the bottom panels to a midlatitude 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 H_2O 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 (667–2,800 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 Fig. 6. This is clearly indicating that the FIR region is between 3 and 5 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 Fig. 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 cooling of the atmosphere and a negative climate feedback. Conversely, in the height ranges where the temperature decreases with altitude, an increase of water vapor causes a decrease of the TOA radiance, therefore a net warming (Riese et al. 2012).

Cirrus cloud parameters. Owing to the low emitting temperatures and unique optical properties that are a consequence of the spectral variations of the imaginary part of the refractive index of ice, cirrus clouds have a significant impact on the Earth FIR spectrum. Many studies have evaluated the OLR sensitivity to particle microphysics (particle shape and size distribution) and cloud geometrical properties (e.g., Harries et al. 2008; Maestri et al. 2019b). It has been noted that radiance sensitivity in the FIR with respect to particle effective dimension (equivalent to diameter for the case of spherical particles), cloud geometrical and optical

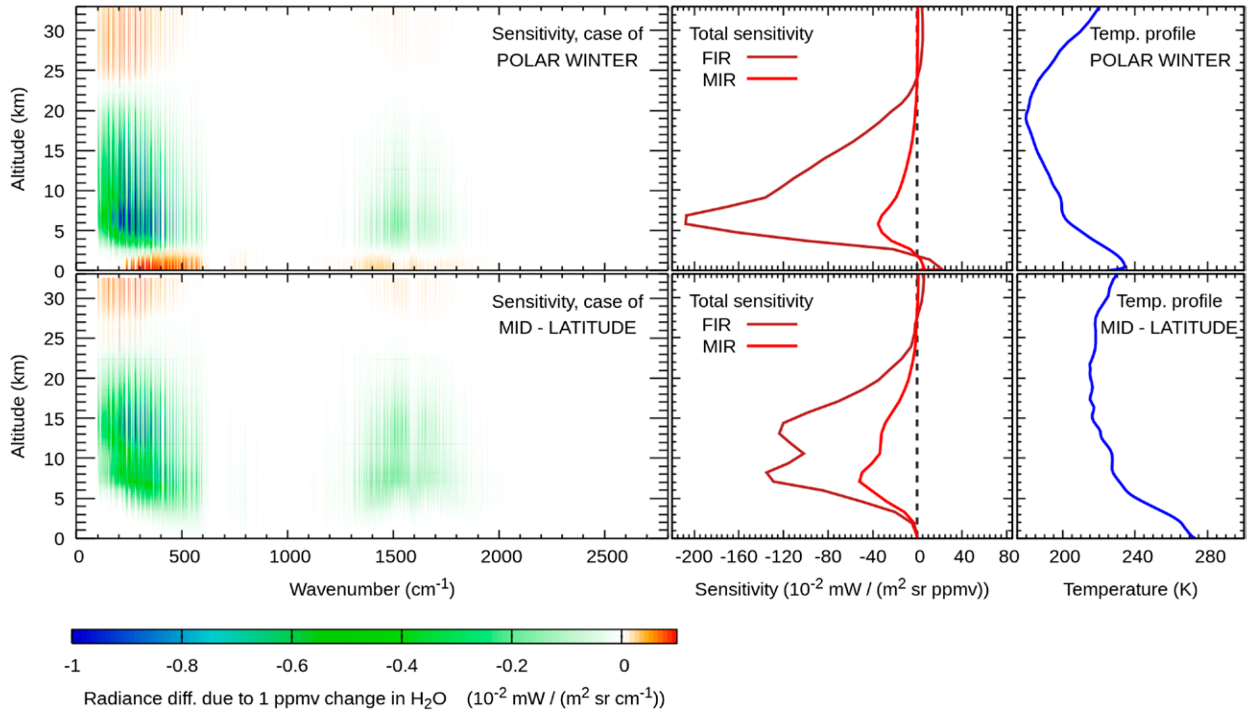

Fig. 6. Spectral sensitivity to H_2O vertical distribution assuming the FORUM threshold spectral resolution requirement (0.5 cm^{-1}).

depth, and ice water path (IWP) is very large. In particular, the information from the FIR is critical to disentangle different processes, such as the presence of a subvisible cirrus cloud, the variation of surface properties or of water vapor concentration, which, otherwise, could not be unequivocally identified by relying on MIR radiances only (see, e.g., Fig. 2 in Maestri et al. 2019b). Moreover, the FIR radiance sensitivity to crystal habits is relevant, mainly around 410 cm^{-1}, where the imaginary part of the refractive index of ice has a local minimum, making scattering significant. In Fig. 7 the brightness temperature (BT) differences, with respect to clear sky when a cirrus cloud with optical depth (OD) equal to 1.4 at 0.555 μm is considered, are shown for two wavenumbers (410 and 900 cm^{-1}) and for several assumptions on crystal shape. The results show that BT differences in the MIR range within 1 K, almost insensitive to the assumed habit, independently of the crystal size. On the contrary, BT differences in the FIR span over more than 3 K for small crystals (less than 40 μm) and 8 K for medium and large crystal sizes. Similar results are obtained (not shown here) for cirrus clouds with smaller and larger opacity (i.e., OD = 0.5 and OD = 5). This suggests that the analysis of combined observations in the FIR and MIR part of the spectrum, acquired with a brightness temperature accuracy of 0.1 K as required for the FSI measurements, might be sufficient to allow an identification of the crystal habits, as recently shown in Maestri et al. (2019a).

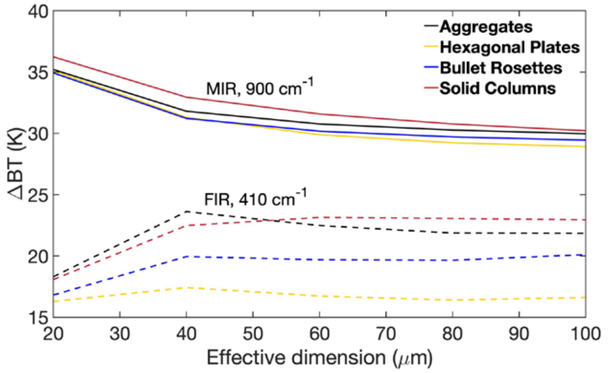

Fig. 7. Brightness temperature differences between clear sky and cirrus clouds as a function of the particle effective dimension. Solid lines account for BT differences at 900 cm^{-1} while dashed lines are for differences at 410 cm^{-1}. Several assumptions on crystal habit are reported in the legend. A tropical atmosphere is considered here. Cloud OD is 1.4 (at 0.555 μm), cloud-top height is 14 km, and geometrical thickness is 1 km.

Surface emissivity at high latitudes. As the atmosphere becomes drier, in the absence of cloud or aerosol, the OLR at the TOA contains an increasing contribution from surface emission. Substantial surface to TOA transmission is expected across much of the FIR when the total column water vapor (TCWV) is less than about 1 mm. These conditions are relatively common over the Arctic and Antarctica: ERA-Interim (ERA-I) indicate that TCWV is below this humidity level for approximately 20% of atmospheric profiles poleward of 66.5° during the 3-yr period from 2013 to 2015.

Tests of the sensitivity of FIR outgoing radiances to surface emissivity have been performed for a polar scenario for three different surface elevations. The results shown in Fig. 8 indicate

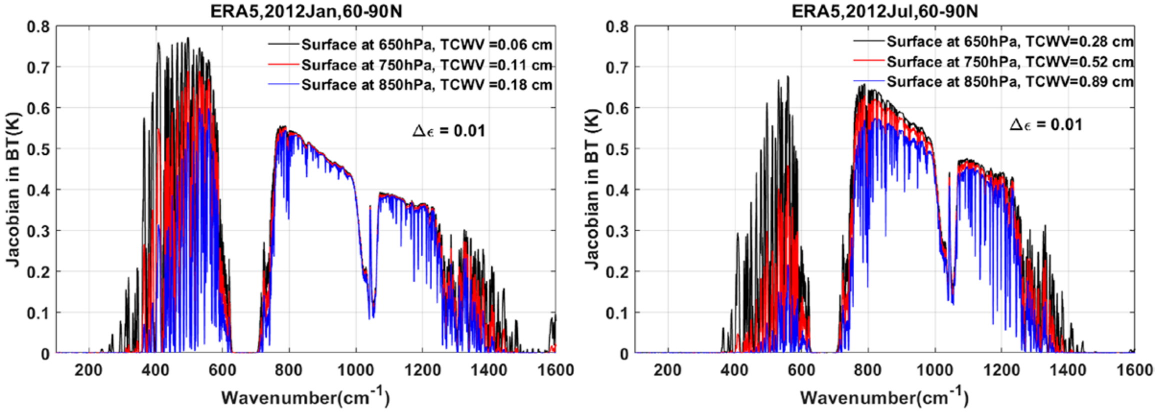

Fig. 8. Sensitivity of BT at TOA to surface emissivity change of 0.01 at different surface elevations. The ERA5 profile averaged over the Arctic (60°–90°N) is used. (left) January and (right) July 2012. The TCWV for different surface elevations are labeled in each panel.

that under these conditions a satellite observation with an accuracy of 0.1 K in brightness temperature, as required to the FSI measurement, will have sufficient sensitivity to estimate the emissivity of frozen surfaces within the FIR to an accuracy better than 0.01. These estimates are consistent with retrievals made from aircraft measurements over the Greenland plateau (Bellisario et al. 2017). Based on theoretical calculations of hemispherical emissivity, this level of accuracy should also permit the effect of fine and coarse snow grain sizes to be distinguished (Huang et al. 2018).

Expected improvements in modeling

FIR spectroscopy of molecular species. FORUM measurements will allow a complete evaluation of the current spectroscopy of both the FIR water vapor rotation band and the υ_2 absorption band of CO_2 at 667 cm^{-1} (15 μm). Current satellite missions in the infrared for meteorological and climate studies only sense the OLR spectrum down to 645 cm^{-1}, covering only the high-frequency branch of the υ_2 CO_2 band and missing the intense absorption/emission of H_2O below 500 cm^{-1}.

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

A validation/consistency experiment of the CO_2 spectroscopy covering the whole υ_2 absorption band is still missing. The recent work by Liuzzi et al. (2016) and Serio et al. (2019) has covered the CO_2 band only down to 640 cm^{-1} showing that CO_2 spectroscopy uncertainty is on the order of the noise affecting modern satellite sensors, such as IASI (see Fig. 9). A simultaneous retrieval approach, in which temperature can be retrieved by using e.g., one branch of υ_2 band while the CO_2 mixing ratio is retrieved using the other branch, will give an unique opportunity to check the quality and consistency of the spectroscopic parameters over the full 15-μm CO_2 absorption band, which still remains fundamental for temperature sounding from satellite.

The FORUM mission will therefore be of paramount significance to improve the quality and accuracy of temperature and water vapor retrievals from modern satellite infrared sounding instruments.

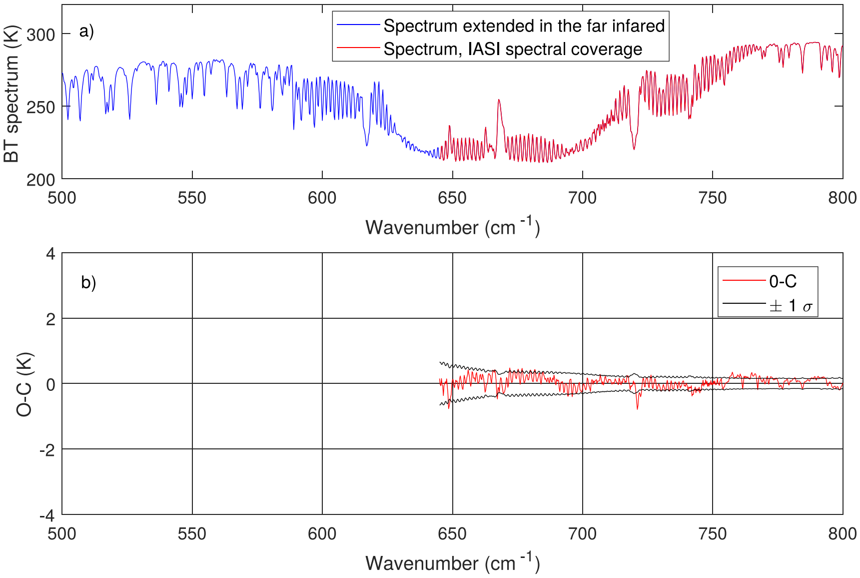

Fig. 9. (a) IASI assessment of spectroscopy accuracy for the core of the υ_2 CO_2 band. (b) Results based on observations (O) minus calculations (C) in for a set of IASI spectra [whose average is shown in (a)] recorded in 2014 over the Global Climate Observing System Reference Upper-Air Network (GRUAN) Manus validation station. The figure is intentionally extended down to 500 cm^{-1} to highlight that portion of the υ_2 CO_2 band that is currently not covered by meteorological satellite missions.

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

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

Two recent studies by Hong and Liu (2015) and Hong et al. (2016), based on 1 year of data from the two active instruments (lidar and radar) of the A-Train constellation, and the associated ice water content profile products, have extended this understanding by investigating the variation of the CRE as a function of cloud opacity (given by their IWP in g m^{-2} or OD at 532 nm). These studies have shown the importance of very thin ice cloud (IWP < 20 g m^{-2} or OD < 0.6) in the global CRE, due to their high occurrence (more than 50% of the total ice clouds detected). Moreover, the authors have highlighted the significant uncertainties attached to their computation due to the poor understanding of the ice cloud microphysics. These numbers highlight the importance of a good representation, in terms of occurrence, localization, and microphysical properties of high clouds in numerical model and for climate studies.

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

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

Snow emissivity modeling. The TCWV at high latitudes is much smaller than that at midlatitude and tropics. As a result, in polar regions the "dirty" FIR window between 245 and 600 cm^{-1} (16.7–29 μm) is not opaque and the surface emission can reach the TOA. This fact affords an opportunity of inferring spectrally-dependent surface emissivity from the FORUM measurements, across both the main MIR atmospheric window and FIR dirty window. Recent studies have underlined the importance of surface spectral emissivity in the modeling of longwave coupling between surface and atmosphere in the high latitudes (Chen et al. 2014; Huang et al. 2018). However, since there have been no extensive measurements of FIR surface emissivity, these studies had to make use of calculated values based on first principles (Huang et al. 2016). FORUM measurements will change this predicament and provide observation-based surface spectral emissivities in the FIR for polar regions. Moreover, surface optical properties in the visible, near-IR, MIR, and microwave regions have been routine products from different satellite observations, such as IASI, AIRS, and the Moderate-Resolution Imaging Spectroradiometer (MODIS). FORUM measurements will fill the spectrum gap by providing such surface optical properties in the FIR.

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

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

Recognizing the intrinsic value of spectral information, several authors have attempted to estimate spectrally resolved radiances and fluxes spanning the full infrared by developing physical or statistical relationships between MIR observations and the unmeasured FIR spectrum (e.g., Huang et al. 2008, 2010; Turner et al. 2015). These approaches have already seen the development of spectral ADMs in order to perform the radiance to flux conversion and the resulting fluxes are now being used to evaluate climate model performance (e.g., Huang et al. 2013). Results illustrate how a good agreement in broadband fluxes can mask much larger discrepancies within individual spectral bands, with substantial differences seen in the FIR. We anticipate that FORUM will enable a significant advance in this field since there will no longer be a need to infer the unmeasured FIR radiances from the MIR observations. We also speculate that the FORUM/IASI-NG measurements could be exploited to develop new, observationally based relationships between MIR and FIR radiances that could be used, in conjunction with existing MIR sounder data, to retrospectively create a much longer and more extensive spectral OLR record extending back to the early 2000s.

Expected improvements in evaluation of climate models

There are several primary achievements where we expect FORUM data to substantively improve our projections of the Earth's climate. First, FORUM data will enable the scientific community to finally achieve a complete picture of the radiative impact of the atmosphere's most important greenhouse gas: water vapor. This will address unresolved issues with modeled water-vapor absorption at low latitudes (e.g., Baranov and Lafferty 2012). This absorption has been shown to influence the general circulation (Jeevanjee and Fueglistaler 2020) and greatly impact modeled projections of surface temperature and midtropospheric water vapor (Iacono et al. 2000). FORUM will characterize H_2O distribution globally by spanning cold and dry conditions, where this absorption is well understood, and the warm and moist conditions, where it is not.

FORUM observations will also provide an exacting test for how models achieve their OLR. Models are tuned to agree with observed OLR, but the tuning choices (Hourdin et al. 2017) are reflected differentially in the spectral properties of OLR (Huang et al. 2013, 2007). To date, only the MIR has been used to test modeled clouds and water vapor, but FORUM will provide direct, rather than inferred, observational constraints on how these quantities modulate most of the OLR, thereby revealing how well models achieve their OLR computation with realistic distributions of water vapor, cloud type, amount, and microphysics, or through error compensation.

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

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

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

The unprecedented radiometric accuracy of the FORUM instrument assures that any differences between observations and models are statistically significant, thus enabling a substantive improvement in our knowledge of radiative transfer in the far infrared and the associated impacts on climate.

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

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