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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 9th 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.

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

THE FAR INFRARED OBSERVATIONAL GAP AND ASSOCIATED CLIMATE UNCERTAINTIES

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 timescales 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 ~ 0.5-1 W/m^2.

Over 99 % of the thermal radiation emitted by the Earth falls within the spectral range 100 to 2500 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 3333 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 of 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

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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, both in terms of albedo and OLR. The IPCC AR5 report (Stocker et al. 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).

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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 recognised 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 black-body (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.

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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 9th 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 one 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 characterisation of the Earth's OLR spectrum at high spectral resolution (Figure 1). This goal will be achieved by performing spectral measurements that cover the TOA emission spectrum from 100 to 1600 (100-6.25 μm) with a nominal resolution of at least 0.5 cm^{-1} (full width half maximum). The mission will provide a multi-year 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

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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 minute and with the ground tracks located within 300 km of distance, FORUM will complement the MIR spectral measurements performed in the 645-2760 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 2760 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 summarised in Table 1. All-sky spectral OLR fluxes covering the range 100-2760 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 sub-pixel heterogeneities in the observed scene.

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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 x 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 x 0.6 km^2, as seen in Figure 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 and et al. 2016). The flight with the Metop-SG mission requires a sun-synchronous orbit at about 830 km at the same mean local solar time (09:30) at the descending node. The proposed mission lifetime is five to six years in order to perform measurements covering different seasons and to capture inter-annual natural variability.

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 broad-band 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 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 air-borne campaigns. Here below, we summarise 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) prototype is the first example of a 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 1400 cm^{-1} with 0.5 cm^{-1} of spectral resolution, very similar to what required for FORUM. REFIR-

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PAD is based on the Mach-Zehnder interferometric scheme with two input ports and two output ports, which allows alignment errors to be minimised and calibration accuracy to be optimised by looking continuously with the second port at a reference stable black-body 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 (3480 m a.s.l.) and in August-September 2009 from Cerro Toco (Chilean Andes, Atacama desert, 5320 m a.s.l.) within the Radiative Heating in the Under-explored Bands Campaign-II (RHUBC-II), that, together with other dedicated instruments, observed the downwelling radiance from the sub-millimeter 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 (3233 m a.s.l.), providing continuous, unattended operations. These ground-based campaigns have shown the capability to measure the atmospheric downwelling radiation in a very wide spectral band (see Figure 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.

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2006; Bingham et al. 2005; Mlynczak et al. 2005). FIRST is a FTS with a demonstrated spectral coverage of 50 cm^{-1} to 2000 cm^{-1} (200 μm to 5 μm) and a nominal resolution of 0.625 cm^{-1}. Specific technologies demonstrated by FIRST include a broad bandpass beamsplitter, a compact FTS system, and a multi-detector 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, NM (Figure 4). The FIRST instrument flew twice from Fort Sumner, NM on high-altitude balloons, observing the troposphere from a float altitude of approximately 33 km. 4 (left panel) shows a complete infrared spectrum (10 to 1600 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 mid-troposphere in 2006 was cooler and dryer 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, CA 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.

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 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).

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 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 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 – 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 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 (see 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 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 sub-visible 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 for example Figure 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 Figure 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

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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 Maestri et al. (2019a).

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) reanalyses indicate that TCWV is below this humidity level for approximately 20 % of atmospheric profiles poleward of 66.5° during the three year period from 2013-2015.

Tests of the sensitivity of FIR outgoing radiances to surface emissivity have been performed for a polar scenario for 3 different surface elevations. The results shown in Figure 8 indicate 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 MODELLING

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 ν_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 ν_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, (see e.g. Serio et al. 2008; Liuzzi et al. 2014). The FORUM mission is expected to add new information especially in the range 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 ν_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 of the order of the noise affecting modern satellite sensors, such as IASI (see Figure 9). A simultaneous retrieval approach, in which temperature can be retrieved by using e.g. one branch of ν_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.

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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.

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 (Stocker et al. 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 one 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

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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 North-East 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 mid-latitude 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

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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 can not 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.

Recognising 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

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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 (see 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 mid-tropospheric 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

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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.

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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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References

Bantges, R. J., and Coauthors, 2020: A test of the ability of current bulk optical models to represent the radiative properties of cirrus cloud across the mid-and far-infrared. *Atmospheric Chemistry and Physics Discussions*, **2020**, 1–28, doi:10.5194/acp-2019-1181, URL https://www.atmos-chem-phys-discuss.net/acp-2019-1181/.

Baran, A. J., 2009: A review of the light scattering properties of cirrus. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **110 (14)**, 1239–1260.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-19-0322.1.

Baran, A. J., 2012: From the single-scattering properties of ice crystals to climate prediction: a way forward. *Atmos. Res.*, **112**, 45–69.

Baran, A. J., R. Cotton, K. Furtado, S. Havemann, L.-C. Labonnote, F. Marenco, A. Smith, and J.-C. Thelen, 2014a: A self-consistent scattering model for cirrus. ii: The high and low frequencies. *Quarterly Journal of the Royal Meteorological Society*, **140**, 1039–1057, doi:10.1002/qj.2193.

Baran, A. J., P. Hill, K. Furtado, P. Field, and J. Manners, 2014b: A coupled cloud physics–radiation parameterization of the bulk optical properties of cirrus and its impact on the met office unified model global atmosphere 5.0 configuration. *Journal of Climate*, **27**, 7725–7752.

Baranov, Y. I., and W. J. Lafferty, 2012: The water vapour self- and water-nitrogen continuum absorption in the 1000 and 2500 cm^{-1} atmospheric windows. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **370 (1968)**, 2578–2589, doi:10.1098/rsta.2011.0234, URL https://royalsocietypublishing.org/doi/abs/10.1098/rsta.2011.0234, https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2011.0234.

Barkstrom, B. R., 1984: The Earth Radiation Budget Experiment (ERBE). *Bulletin of the American Meteorological Society*, **65 (11)**, 1170–1185, doi:10.1175/1520-0477(1984)065<1170:TERBE>2.0.CO;2, URL https://doi.org/10.1175/1520-0477(1984)065<1170:TERBE>2.0.CO;2, https://doi.org/10.1175/1520-0477(1984)065<1170:TERBE>2.0.CO;2.

Barton, N. P., S. A. Klein, and J. S. Boyle, 2014: On the contribution of longwave radiation to global climate model biases in arctic lower tropospheric stability. *Journal of Climate*, **27**, 7250–7269, doi:doi:10.1175/JCLI-D-14-00126.1.

Baum, B. A., A. J. Heymsfield, P. Yang, and S. T. Bedka, 2005: Bulk scattering properties for the remote sensing of ice clouds. part i: Microphysical data and models. *Journal of Applied*

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-19-0322.1.

Meteorology, **44**, 1885–1895.

Bellisario, C., and Coauthors, 2017: Retrievals of the Far Infrared Surface Emissivity Over the Greenland Plateau Using the Tropospheric Airborne Fourier Transform Spectrometer (TAFTS). *Journal of Geophysical Research: Atmospheres*, **122 (22)**, 12,152–12,166, doi:10.1002/2017JD027328, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017JD027328, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2017JD027328.

Belward, A., and et al., 2016: The global observing system for climate: Implementation needs. GCOS- No. 200, World Meteorological Organization (WMO), URL https://library.wmo.int/index.php?lvl=notice_display&id=19838#.XtEa-6bgphE.

Bianchini, G., and L. Palchetti, 2008: Technical Note: REFIR-PAD level 1 data analysis and performance characterization. *Atmos. Chem. Phys.*, **8 (14)**, 3817–3826, URL http://www.atmos-chem-phys.net/8/3817/2008/.

Bingham, G. E., H. M. Latvakoski, S. J. Wellard, M. G. Mlynczak, D. G. Johnson, W. A. Traub, and K. W. Jucks, 2005: Far-infrared Spectroscopy of the Troposphere (FIRST): sensor calibration performance. *Multispectral and Hyperspectral Remote Sensing Instruments and Applications II*, A. M. Larar, M. Suzuki, and Q. Tong, Eds., SPIE, International Society for Optics and Photonics, Vol. 5655, 190 – 201, doi:10.1117/12.578770, URL https://doi.org/10.1117/12.578770.

Brindley, H., R. Bantges, J. Russell, J. Murray, C. Dancel, C. Belotti, and J. Harries, 2015: Spectral signatures of earth's climate variability over 5 years from IASI. *Journal of Climate*, **28 (4)**, 1649–1660, doi:10.1175/JCLI-D-14-00431.1, URL https://doi.org/10.1175/JCLI-D-14-00431.1, https://doi.org/10.1175/JCLI-D-14-00431.1.

Brindley, H. E., and J. E. Harries, 1998: The impact of far ir absorption on clear sky greenhouse forcing: sensitivity studies at high spectral resolution. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **60**, 151–180.

Calisto, M., D. Folini, M. Wild, and L. Bengtsson, 2014: Cloud radiative forcing intercomparison between fully coupled CMIP5 models and CERES satellite data. *Annales Geophysicae*, **32 (7)**, 793–807, doi:10.5194/angeo-32-793-2014, URL https://www.ann-geophys.net/32/793/2014/.

Canas, T. A., J. E. Murray, and J. E. Harries, 1997: Tropospheric airborne Fourier transform spectrometer (TAFTS). *Satellite Remote Sensing of Clouds and the Atmosphere II*, J. D. Haigh, Ed., SPIE, International Society for Optics and Photonics, Vol. 3220, 91 – 102, doi:10.1117/12.301139, URL https://doi.org/10.1117/12.301139.

Carli, B., A. Barbis, J. E. Harries, and L. Palchetti, 1999: Design of an efficient broadband far-infrared Fourier-transform spectrometer. *Appl. Opt.*, **38**, 3945–3950.

Chen, X. H., X. Huang, and M. Flanner, 2014: Sensitivity of modeled far-IR radiation budgets in polar continents to treatments of snow surface and ice cloud radiative properties. *Geophysical Research Letters*, doi:10.1002/2014GL061216.

Clough, S. A., and M. J. Iacono, 1995: Line-by-line calculation of atmospheric fluxes and cooling rates: 2. application to carbon dioxide, ozone, methane, nitrous oxide and the halocarbons. *Journal of Geophysical Research: Atmospheres*, **100 (D8)**, 16 519–16 535, doi:10.1029/95JD01386, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/95JD01386, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/95JD01386.

Collins, W., and M. Mlynczak, 2001: Prospects for measurement of far infrared tropospheric spectra: Implications for climate modeling. *AGU Fall Meeting Abstracts*.

Cox, C., J. Harries, J. Taylor, P. Green, A. Baran, J. Pickering, A. Last, and J. Murray, 2010: Measurement and simulation of mid-and far-infrared spectra in the presence of cirrus. *Quarterly Journal of the Royal Meteorological Society*, **36**, 718–739, doi:10.1002/qj.596.

Cox, C. J., V. P. Walden, P. M. Rowe, and M. D. Shupe, 2015: Humidity trends imply increased sensitivity to clouds in a warming arctic. *Nature communications*, **6**, doi:10.1038/ncomms10117.

Cox, C. V., J. E. Murray, J. P. Taylor, P. D. Green, J. C. Pickering, J. E. Harries, and A. E. Last, 2007: Clear-sky far-infrared measurements observed with TAFTS during the EAQUATE campaign, september 2004. *Quarterly Journal of the Royal Meteorological Society*, **133 (S3)**, 273–283, doi:10.1002/qj.159, URL https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/qj.159, https://rmets.onlinelibrary.wiley.com/doi/pdf/10.1002/qj.159.

Dessler, A., 2013: Observations of climate feedbacks over 2000-10 and comparisons to climate models. *Journal of Climate*, **26**, 333–342, doi:10.1175/JCLI-D-11-00640.1.

Dessler, A. E., and S. C. Sherwood, 2009: A matter of humidity. *Science*, **323 (5917)**, 1020–1021, doi:10.1126/science.1171264, URL https://science.sciencemag.org/content/323/5917/1020, https://science.sciencemag.org/content/323/5917/1020.full.pdf.

Dolinar, E. K., X. Dong, B. Xi, J. H. Jiang, and H. Su, 2015: Evaluation of CMIP5 simulated clouds and TOA radiation budgets using NASA satellite observations. *Climate Dynamics*, **44 (7)**, 2229–2247, doi:10.1007/s00382-014-2158-9, URL https://doi.org/10.1007/s00382-014-2158-9.

Dong, Y., C. Proistosescu, K. C. Armour, and D. S. Battisti, 2019: Attributing historical and future evolution of radiative feedbacks to regional warming patterns using a green's function approach: The preeminence of the western pacific. *Journal of Climate*, **32 (17)**, 5471–5491, doi:

10.1175/JCLI-D-18-0843.1, URL https://doi.org/10.1175/JCLI-D-18-0843.1, https://doi.org/10.1175/JCLI-D-18-0843.1.

Feldman, D. R., W. D. Collins, R. Pincus, X. Huang, and X. Chen, 2014: Far-infrared surface emissivity and climate. *Proceedings of the National Academy of Sciences*, **111 (46)**, 16 297–16 302, doi:10.1073/pnas.1413640111, URL https://www.pnas.org/content/111/46/16297, https://www.pnas.org/content/111/46/16297.full.pdf.

Ferrare, R. A., and Coauthors, 2004: Characterization of Upper-Troposphere Water Vapor Measurements during AFWEX Using LASE. *Journal of Atmospheric and Oceanic Technology*, **21 (12)**, 1790–1808, doi:10.1175/JTECH-1652.1, URL https://doi.org/10.1175/JTECH-1652.1, https://doi.org/10.1175/JTECH-1652.1.

Forster, P. M. d. F., and K. P. Shine, 2002: Assessing the climate impact of trends in stratospheric water vapor. *Geophysical Research Letters*, **29 (6)**, 10–1–10–4, doi:10.1029/2001GL013909, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2001GL013909, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2001GL013909.

Forster, P. M. F., and J. M. Gregory, 2006: The climate sensitivity and its components diagnosed from Earth Radiation Budget data. *Journal of Climate*, **19 (1)**, 39–52, doi:10.1175/JCLI3611.1, URL https://doi.org/10.1175/JCLI3611.1, https://doi.org/10.1175/JCLI3611.1.

Fox, C., 2015: Far-infrared spectral radiance studies: Application to water vapour and cirrus. Physics phd theses, Physics, doi:https://doi.org/10.25560/25752, URL http://hdl.handle.net/10044/1/25752.

Goody, R., J. Anderson, and G. North, 1998: Testing climate models: An approach. *Bulletin of the American Meteorological Society*, **79 (11)**, 2541–2549, doi:10.1175/1520-0477(1998)

079<2541:TCMAA>2.0.CO;2, URL https://doi.org/10.1175/1520-0477(1998)079<2541:TCMAA>2.0.CO;2, https://doi.org/10.1175/1520-0477(1998)079<2541:TCMAA>2.0.CO;2.

Green, P. D., S. M. Newman, R. J. Beeby, J. E. Murray, J. C. Pickering, and J. E. Harries, 2012: Recent advances in measurement of the water vapour continuum in the far-infrared spectral region. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **370**, 2637–2655, doi:10.1098/rsta.2011.0263, URL http://rsta.royalsocietypublishing.org/content/370/1968/2637.

Hanel, R. A., B. Schlachman, D. Rogers, and D. Vanous, 1971: Nimbus 4 michelson interferometer. *Appl. Opt.*, **10 (6)**, 1376–1382, doi:10.1364/AO.10.001376, URL http://ao.osa.org/abstract.cfm?URI=ao-10-6-1376.

Hang, Y., T. S. L'Ecuyer, D. S. Henderson, A. V. Matus, and Z. Wang, 2019: Reassessing the Effect of Cloud Type on Earth's Energy Balance in the Age of Active Spaceborne Observations. Part II: Atmospheric Heating. *Journal of Climate*, **32 (19)**, 6219–6236, doi:10.1175/JCLI-D-18-0754.1, URL https://doi.org/10.1175/JCLI-D-18-0754.1, https://doi.org/10.1175/JCLI-D-18-0754.1.

Hansen, J., M. Sato, P. Kharecha, and K. von Schuckmann, 2011: Earth's energy imbalance and implications. *Atmospheric Chemistry and Physics*, **11 (24)**, 13 421–13 449, doi:10.5194/acp-11-13421-2011, URL https://www.atmos-chem-phys.net/11/13421/2011/.

Hansen, J., and Coauthors, 2005: Earth's energy imbalance: Confirmation and implications. *Science*, **308 (5727)**, 1431–1435, doi:10.1126/science.1110252, URL https://science.sciencemag.org/content/308/5727/1431, https://science.sciencemag.org/content/308/5727/1431.full.pdf.

Harries, J., and Coauthors, 2008: The far-infrared earth. *Reviews of Geophysics*, **46 (4)**, doi:10.1029/2007RG000233, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/

2007RG000233, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2007RG000233.

Hartmann, D. L., M. E. Ockert-Bell, and M. L. Michelsen, 1992: The Effect of Cloud Type on Earth's Energy Balance: Global Analysis. *Journal of Climate*, **5 (11)**, 1281–1304, doi:10.1175/1520-0442(1992)005<1281:TEOCTO>2.0.CO;2, URL https://doi.org/10.1175/1520-0442(1992)005<1281:TEOCTO>2.0.CO;2, https://doi.org/10.1175/1520-0442(1992)005<1281:TEOCTO>2.0.CO;2.

Haywood, J. M., and Coauthors, 2009: A case study of the radiative forcing of persistent contrails evolving into contrail-induced cirrus. *Journal of Geophysical Research: Atmospheres*, **114 (D24)**, doi:10.1029/2009JD012650, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2009JD012650, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2009JD012650.

Hegglin, M. I., and Coauthors, 2014: Vertical structure of stratospheric water vapour trends derived from merged satellite data. *Nature Geoscience*, **7**, 768–776, doi:10.1038/ngeo2236.

Hilton, F., and Coauthors, 2012: Hyperspectral Earth Observation from IASI: Five Years of Accomplishments. *Bulletin of the American Meteorological Society*, **93 (3)**, 347–370, doi:10.1175/BAMS-D-11-00027.1, URL https://doi.org/10.1175/BAMS-D-11-00027.1, https://doi.org/10.1175/BAMS-D-11-00027.1.

Hong, Y., and G. Liu, 2015: The Characteristics of Ice Cloud Properties Derived from CloudSat and CALIPSO Measurements. *Journal of Climate*, **28 (9)**, 3880–3901, doi:10.1175/JCLI-D-14-00666.1, URL https://doi.org/10.1175/JCLI-D-14-00666.1, https://doi.org/10.1175/JCLI-D-14-00666.1.

Hong, Y., G. Liu, and J.-L. F. Li, 2016: Assessing the Radiative Effects of Global Ice Clouds Based on CloudSat and CALIPSO Measurements. *Journal of Climate*, **29 (21)**, 7651–7674, doi:10.1175/JCLI-D-15-0799.1, URL https://doi.org/10.1175/JCLI-D-15-0799.1, https://journals.ametsoc.org/jcli/article-pdf/29/21/7651/4076204/jcli-d-15-0799_1.pdf.

Hourdin, F., and Coauthors, 2017: The art and science of climate model tuning. *Bulletin of the American Meteorological Society*, **98 (3)**, 589–602, doi:10.1175/BAMS-D-15-00135.1, URL https://doi.org/10.1175/BAMS-D-15-00135.1, https://doi.org/10.1175/BAMS-D-15-00135.1.

Huang, X., X. Chen, M. Flanner, P. Yang, D. Feldman, and C. Kuo, 2018: Improved representation of surface spectral emissivity in a global climate model and its impact on simulated climate. *Journal of Climate*, **31 (9)**, 3711–3727.

Huang, X., X. Chen, D. K. Zhou, and X. Liu, 2016: An observationally based global band-by-band surface emissivity dataset for climate and weather simulations. *Journal of the Atmospheric Sciences*, **73 (9)**, 3541–3555.

Huang, X., J. N. S. Cole, F. He, G. L. Potter, L. Oreopoulos, D. Lee, M. Suarez, and N. G. Loeb, 2013: Longwave band-by-band cloud radiative effect and its application in GCM evaluation. *Journal of Climate*, **26 (2)**, 450–467, doi:10.1175/JCLI-D-12-00112.1, URL https://doi.org/10.1175/JCLI-D-12-00112.1, https://doi.org/10.1175/JCLI-D-12-00112.1.

Huang, X., N. G. Loeb, and W. Yang, 2010: Spectrally resolved fluxes derived from collocated AIRS and CERES measurements and their application in model evaluation: 2. cloudy sky and band-by-band cloud radiative forcing over the tropical oceans. *Journal of Geophysical Research: Atmospheres*, **115 (D21)**, doi:10.1029/2010JD013932, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010JD013932, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2010JD013932.

Huang, X., W. Yang, N. G. Loeb, and V. Ramaswamy, 2008: Spectrally resolved fluxes derived from collocated AIRS and CERES measurements and their application in model evaluation: Clear sky over the tropical oceans. *Journal of Geophysical Research: Atmospheres*, **113 (D9)**, D09 110, doi:10.1029/2007JD009219, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007JD009219, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2007JD009219.

Huang, Y., V. Ramaswamy, X. Huang, Q. Fu, and C. Bardeen, 2007: A strict test in climate modeling with spectrally resolved radiances: GCM simulation versus airs observations. *Geophysical Research Letters*, **34**, doi:10.1029/2007GL031409.

Hurst, D. F., S. J. Oltmans, H. Vömel, K. H. Rosenlof, S. M. Davis, E. A. Ray, E. G. Hall, and A. F. Jordan, 2011: Stratospheric water vapor trends over boulder, colorado: Analysis of the 30 year boulder record. *Journal of Geophysical Research: Atmospheres*, **116 (D2)**, doi:10.1029/2010JD015065, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010JD015065, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2010JD015065.

Iacono, M. J., E. J. Mlawer, S. A. Clough, and J.-J. Morcrette, 2000: Impact of an improved longwave radiation model, RRTM, on the energy budget and thermodynamic properties of the NCAR community climate model, CCM3. *Journal of Geophysical Research: Atmospheres*, **105 (D11)**, 14 873–14 890, doi:10.1029/2000JD900091, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2000JD900091, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2000JD900091.

Jeevanjee, N., and S. Fueglistaler, 2020: Simple spectral models for atmospheric radiative cooling. *Journal of the Atmospheric Sciences*, **77 (2)**, 479–497, doi:10.1175/JAS-D-18-0347.1, URL https://doi.org/10.1175/JAS-D-18-0347.1, https://doi.org/10.1175/JAS-D-18-0347.1.

Kärcher, B., 2017: Cirrus clouds and their response to anthropogenic activities. *Current Climate Change Reports*, **3 (1)**, 45–57, doi:10.1007/s40641-017-0060-3, URL https://doi.org/10.1007/s40641-017-0060-3.

Kempe, V., D. Oertel, R. Schuster, H. Becker-Ross, and H. Jahn, 1980: Absolute IR-spectra from the measurement of Fourier-spectrometers aboard Meteor 25 and 28. *Acta Astronautica*, **7 (12)**, 1403 – 1416, doi:https://doi.org/10.1016/0094-5765(80)90015-6, URL http://www.sciencedirect.com/science/article/pii/0094576580900156.

Kuo, C., D. R. Feldman, X. Huang, M. Flanner, P. Yang, and X. Chen, 2018: Time-Dependent Cryospheric Longwave Surface Emissivity Feedback in the Community Earth System Model. *Journal of Geophysical Research: Atmospheres*, **123 (2)**, 789–813, doi:10.1002/2017JD027595, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017JD027595, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2017JD027595.

Latvakoski, H., M. G. Mlynczak, R. P. Cageao, D. G. Johnson, and D. P. Kratz, 2014: Far-infrared spectroscopy of the troposphere: calibration with a cold background. *Appl. Opt.*, **53 (24)**, 5425–5433, doi:10.1364/AO.53.005425, URL http://ao.osa.org/abstract.cfm?URI=ao-53-24-5425.

Latvakoski, H., M. G. Mlynczak, D. G. Johnson, R. P. Cageao, D. P. Kratz, and K. Johnson, 2013: Far-infrared spectroscopy of the troposphere: instrument description and calibration performance. *Appl. Opt.*, **52 (2)**, 264–273, doi:10.1364/AO.52.000264, URL http://ao.osa.org/abstract.cfm?URI=ao-52-2-264.

L'Ecuyer, T. S., Y. Hang, A. V. Matus, and Z. Wang, 2019: Reassessing the Effect of Cloud Type on Earth's Energy Balance in the Age of Active Spaceborne Observations. Part I: Top of Atmosphere and Surface. *Journal of Climate*, **32 (19)**, 6197–6217, doi:10.1175/JCLI-D-18-0753.1, URL https://doi.org/10.1175/JCLI-D-18-0753.1, https://doi.org/10.1175/JCLI-D-18-0753.1.

Li, J.-L. F., D. E. Waliser, G. Stephens, S. Lee, T. L'Ecuyer, S. Kato, N. Loeb, and H.-Y. Ma, 2013: Characterizing and understanding radiation budget biases in CMIP3/CMIP5 GCMs, contemporary GCM, and reanalysis. *Journal of Geophysical Research: Atmospheres*, **118 (15)**, 8166–8184, doi:10.1002/jgrd.50378, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/jgrd.50378, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/jgrd.50378.

Liuzzi, G., G. Masiello, C. Serio, L. Palchetti, and G. Bianchini, 2014: Validation of H_2O continuum absorption models in the wave number range 180-600 cm^{-1} with atmospheric emitted spectral radiance measured at the Antarctica Dome-C site. *Opt. Express*, **22 (14)**, 16 784–16 801, doi:10.1364/OE.22.016784, URL http://www.opticsexpress.org/abstract.cfm?URI=oe-22-14-16784.

Liuzzi, G., G. Masiello, C. Serio, S. Venafra, and C. Camy-Peyret, 2016: Physical inversion of the full IASI spectra: Assessment of atmospheric parameters retrievals, consistency of spectroscopy and forward modelling. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **182**, 128 – 157, doi:https://doi.org/10.1016/j.jqsrt.2016.05.022, URL http://www.sciencedirect.com/science/article/pii/S0022407316301248.

Lynch, D. K., K. Sassen, D. O. Starr, and G. Stephens, 2002: *Cirrus*. Oxford University Press.

Maestri, T., C. Arosio, R. Rizzi, L. Palchetti, G. Bianchini, and M. Del Guasta, 2019a: Antarctic ice cloud identification and properties using downwelling spectral radiance from 100 to 1,400 cm^{-1}. *Journal of Geophysical Research: Atmospheres*, **124 (8)**, 4761–4781, doi:10.1029/2018JD029205, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018JD029205, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018JD029205.

Maestri, T., W. Cossich, and I. Sbrolli, 2019b: Cloud identification and classification from high spectral resolution data in the far infrared and mid-infrared. *Atmospheric Measure-*

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-19-0322.1.

ment Techniques, **12 (7)**, 3521–3540, doi:10.5194/amt-12-3521-2019, URL https://www.atmos-meas-tech.net/12/3521/2019/.

Mast, J. C., M. G. Mlynczak, R. P. Cageao, D. P. Kratz, H. Latvakoski, D. G. Johnson, D. D. Turner, and E. J. Mlawer, 2017: Measurements of downwelling far-infrared radiance during the RHUBC-II campaign at cerro toco, chile and comparisons with line-by-line radiative transfer calculations. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **198**, 25 – 39, doi:https://doi.org/10.1016/j.jqsrt.2017.04.028, URL http://www.sciencedirect.com/science/article/pii/S0022407316308949.

Matus, A. V., and T. S. L'Ecuyer, 2017: The role of cloud phase in Earth's radiation budget. *Journal of Geophysical Research: Atmospheres*, **122 (5)**, 2559–2578, doi:10.1002/2016JD025951, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016JD025951, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016JD025951.

Merrelli, A., and D. D. Turner, 2012: Comparing information content of upwelling far-infrared and midinfrared radiance spectra for clear atmosphere profiling. *Journal of Atmospheric and Oceanic Technology*, **29 (4)**, 510–526, doi:10.1175/JTECH-D-11-00113.1, URL https://doi.org/10.1175/JTECH-D-11-00113.1, https://doi.org/10.1175/JTECH-D-11-00113.1.

Mlawer, E. J., and Coauthors, 2019: Analysis of water vapor absorption in the far-infrared and submillimeter regions using surface radiometric measurements from extremely dry locations. *Journal of Geophysical Research: Atmospheres*, **124 (14)**, 8134–8160, doi:10.1029/2018JD029508, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018JD029508, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018JD029508.

Mlynczak, M. G., R. P. Cageao, J. C. Mast, D. P. Kratz, H. Latvakoski, and D. G. Johnson, 2016: Observations of downwelling far-infrared emission at Table Mountain California made by the FIRST instrument. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **170**, 90 – 105, doi:https://doi.org/10.1016/j.jqsrt.2015.10.017, URL http://www.sciencedirect.com/science/article/pii/S0022407315300340.

Mlynczak, M. G., D. G. Johnson, G. E. Bingham, K. W. Jucks, W. A. Traub, L. Gordley, and P. Yang, 2005: The far-infrared spectroscopy of the troposphere (FIRST) project. *Enabling Sensor and Platform Technologies for Spaceborne Remote Sensing*, G. J. Komar, J. Wang, and T. Kimura, Eds., SPIE, International Society for Optics and Photonics, Vol. 5659, 81 – 87, doi:10.1117/12.579063, URL https://doi.org/10.1117/12.579063.

Mlynczak, M. G., and Coauthors, 2006: First light from the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument. *Geophysical Research Letters*, **33 (7)**, doi:10.1029/2005GL025114, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2005GL025114, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2005GL025114.

Müller, R., A. Kunz, D. F. Hurst, C. Rolf, M. Krämer, and M. Riese, 2016: The need for accurate long-term measurements of water vapor in the upper troposphere and lower stratosphere with global coverage. *Earth's Future*, **4 (2)**, 25–32, doi:10.1002/2015EF000321, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015EF000321, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2015EF000321.

Oreopoulos, L., N. Cho, D. Lee, and S. Kato, 2016: Radiative effects of global modis cloud regimes. *Journal of Geophysical Research: Atmospheres*, **121 (5)**, 2299–2317, doi:10.1002/2015JD024502, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015JD024502, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2015JD024502.

Palchetti, L., A. Barbis, J. E. Harries, and D. Lastrucci, 1999: Design and mathematical modelling of the space-borne far-infrared Fourier transform spectrometer for REFIR experiment. *Infr. Phys. & Tech.*, **40**, 367–377.

Palchetti, L., G. Bianchini, B. Carli, U. Cortesi, and S. D. Bianco, 2008: Measurement of the water vapour vertical profile and the Earth's outgoing far infrared flux. **8**, 2885–2894, doi: 10.5194/acp-8-2885-2008, URL www.atmos-chem-phys.net/8/2885/2008/.

Palchetti, L., and Coauthors, 2005: The breadboard of the Fourier transform spectrometer for the Radiation Explorer in the Far Infrared (REFIR) atmospheric mission. *Appl. Opt.*, **44**, 2870–2878.

Palchetti, L., and Coauthors, 2006: Technical note: First spectral measurement of the earth's upwelling emission using an uncooled wideband fourier transform spectrometer. *Atmos. Chem. Phys.*, **6**, 5025–5030.

Ridolfi, M., and Coauthors, 2020: FORUM Earth Explorer 9: Characteristics of Level 2 Products and Synergies with IASI-NG. *Remote Sensing*, **12 (9)**, 1496, doi:10.3390/rs12091496, URL https://www.mdpi.com/2072-4292/12/9/1496, https://doi.org/10.3390/rs12091496.

Riese, M., F. Ploeger, A. Rap, B. Vogel, P. Konopka, M. Dameris, and P. Forster, 2012: Impact of uncertainties in atmospheric mixing on simulated UTLS composition and related radiative effects. *Journal of Geophysical Research: Atmospheres*, **117 (D16)**, doi:10.1029/2012JD017751, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2012JD017751, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2012JD017751.

Rizzi, R., and Coauthors, 2002: Feasibility of the spaceborne radiation explorer in the far infrared (REFIR). SPIE, Vol. 4485, 202-209, URL http://link.aip.org/link/?PSI/4485/202/1.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-19-0322.1.

Sassen, K., Z. Wang, and D. Liu, 2008: Global distribution of cirrus clouds from CloudSat/Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) measurements. *Journal of Geophysical Research: Atmospheres*, **113 (D8)**, doi:10.1029/2008JD009972, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008JD009972, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2008JD009972.

Serio, C., G. Masiello, C. Camy-Peyret, and G. Liuzzi, 2019: CO_2 spectroscopy and forward/inverse radiative transfer modelling in the thermal band using IASI spectra. *Journal of Quantitative Spectroscopy and Radiative Transfer*, **222-223**, 65 – 83, doi:https://doi.org/10.1016/j.jqsrt.2018.10.020, URL http://www.sciencedirect.com/science/article/pii/S0022407318304886.

Serio, C., and Coauthors, 2008: Retrieval of foreign-broadened water vapor continuum coefficients from emitted spectral radiance in the H_2O rotational band from 240 to 590 cm^{-1}. *Opt. Express*, **16 (20)**, 15 816–15 833, doi:10.1364/OE.16.015816.

Solomon, S., K. H. Rosenlof, R. W. Portmann, J. S. Daniel, S. M. Davis, T. J. Sanford, and G.-K. Plattner, 2010: Contributions of stratospheric water vapor to decadal changes in the rate of global warming. *Science*, **327**, 1219–1223.

Stephens, G. L., 2005: Cloud Feedbacks in the Climate System: A Critical Review. *Journal of Climate*, **18 (2)**, 237–273, doi:10.1175/JCLI-3243.1, URL https://doi.org/10.1175/JCLI-3243.1, https://journals.ametsoc.org/jcli/article-pdf/18/2/237/3791466/jcli-3243_1.pdf.

Stocker, T., and Coauthors, 2013: *IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* URL https://www.ipcc.ch/report/ar5/wg1/.

Tett, S. F., D. J. Rowlands, M. J. Mineter, and C. Cartis, 2013: Can top-of-atmosphere radiation measurements constrain climate predictions? Part II: Climate sensitivity. *Journal of Climate*, **26**, 9367.

Tobin, D. C., and Coauthors, 1999: Downwelling spectral radiance observations at the sheba ice station: Water vapor continuum measurements from 17 to 26μm. *J. Geophys. Res.*, **104**, 2081–2092.

Trenberth, K. E., J. T. Fasullo, and M. A. Balmaseda, 2014: Earth's Energy Imbalance. *Journal of Climate*, **27 (9)**, 3129–3144, doi:10.1175/JCLI-D-13-00294.1, URL https://doi.org/10.1175/JCLI-D-13-00294.1, https://journals.ametsoc.org/jcli/article-pdf/27/9/3129/4038695/jcli-d-13-00294_1.pdf.

Turner, D. D., and E. J. Mlawer, 2010: The radiative heating in underexplored bands campaigns. *Bulletin of the American Meteorological Society*, **91 (7)**, 911–924, doi:10.1175/2010BAMS2904.1, URL https://doi.org/10.1175/2010BAMS2904.1, https://doi.org/10.1175/2010BAMS2904.1.

Turner, D. D., and Coauthors, 2012: Ground-based high spectral resolution observations of the entire terrestrial spectrum under extremely dry conditions. *Geophys. Res. Lett.*, **39**, doi:{10.1029/2012GL051542}.

Turner, E. C., H.-T. Lee, and S. F. B. Tett, 2015: Using IASI to simulate the total spectrum of outgoing long-wave radiances. *Atmospheric Chemistry and Physics*, **15 (12)**, 6561–6575, doi:10.5194/acp-15-6561-2015, URL https://www.atmos-chem-phys.net/15/6561/2015/.

Vavrus, S., 2004: The impact of cloud feedbacks on arctic climate under greenhouse forcing. *Journal of Climate*, **17 (3)**, 603–615, doi:10.1175/1520-0442(2004)017<0603:TIOCFO>2.0.CO;2, URL https://doi.org/10.1175/1520-0442(2004)017<0603:TIOCFO>2.0.CO;2, https://doi.org/10.1175/1520-0442(2004)017<0603:TIOCFO>2.0.CO;2.

Wellard, S., G. Bingham, H. Latvakoski, M. Mlynczak, D. Johnson, and K. Jucks, 2006: Far infrared spectroscopy of the troposphere (FIRST): flight performance and data processing. *Infrared Spaceborne Remote Sensing XIV*, M. Strojnik, Ed., SPIE, International Society for Optics and Photonics, Vol. 6297, 172 – 182, doi:10.1117/12.683976, URL https://doi.org/10.1117/12.683976.

Wielicki, B. A., and Coauthors, 2013: Achieving climate change absolute accuracy in orbit. *Bulletin of the American Meteorological Society*, **94 (10)**, 1519–1539, doi:10.1175/BAMS-D-12-00149.1, URL https://doi.org/10.1175/BAMS-D-12-00149.1, https://doi.org/10.1175/BAMS-D-12-00149.1.

Wylie, D., D. L. Jackson, W. P. Menzel, and J. J. Bates, 2005: Trends in Global Cloud Cover in Two Decades of HIRS Observations. *Journal of Climate*, **18 (15)**, 3021–3031, doi:10.1175/JCLI3461.1, URL https://doi.org/10.1175/JCLI3461.1, https://doi.org/10.1175/JCLI3461.1.

Yamanouchi, T., and T. P. Charlock, 1995: Comparison of Radiation Budget at the TOA and Surface in the Antarctic from ERBE and Ground Surface Measurements. *Journal of Climate*, **8 (12)**, 3109–3120, URL http://www.jstor.org/stable/26200098.

Yang, P., K.-N. Liou, L. Bi, C. Liu, B. Yi, and B. A. Baum, 2015: On the radiative properties of ice clouds: Light scattering, remote sensing, and radiation parameterization. *Advances in Atmospheric Sciences*, **32 (1)**, 32–63, doi:10.1007/s00376-014-0011-z, URL https://doi.org/10.1007/s00376-014-0011-z.

Yue, J., J. Russell III, Q. Gan, T. Wang, P. Rong, R. Garcia, and M. Mlynczak, 2019: Increasing water vapor in the stratosphere and mesosphere after 2002. *Geophysical Research Letters*, **46 (22)**, 13 452–13 460, doi:10.1029/2019GL084973, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019GL084973, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019GL084973.

Zhang, M. H., and Coauthors, 2005: Comparing clouds and their seasonal variations in 10 atmospheric general circulation models with satellite measurements. *Journal of Geophysical Research: Atmospheres*, **110 (D15)**, doi:10.1029/2004JD005021, URL https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2004JD005021, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2004JD005021.

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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 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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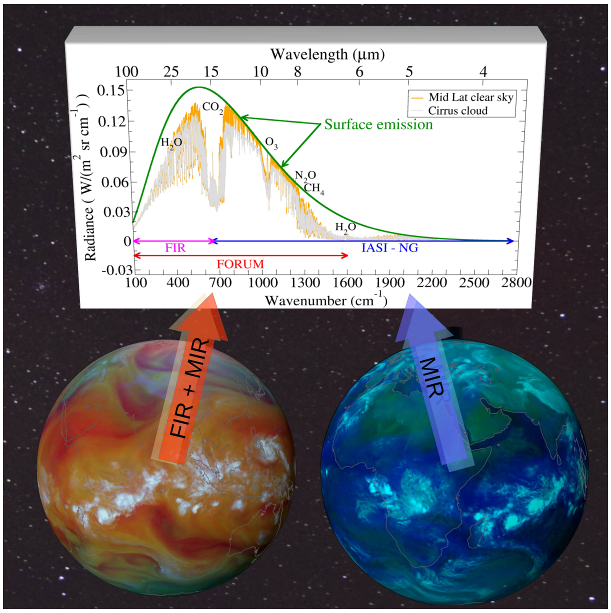

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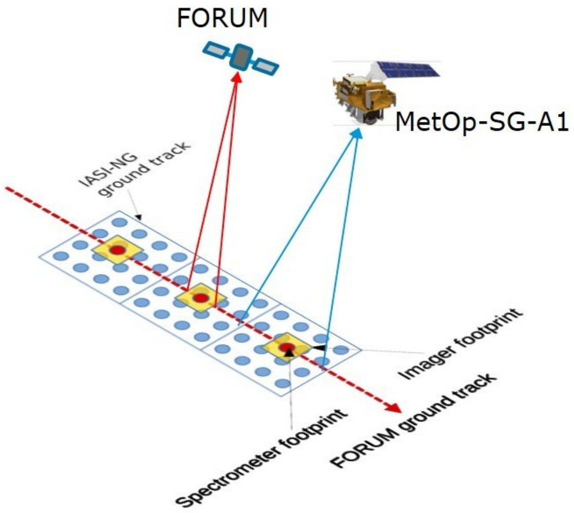

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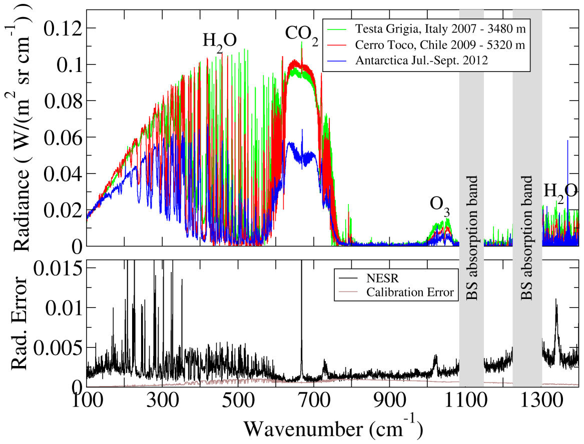


FIG. 3. REFIR-PAD ground-based FIR measurements. NESR is the noise equivalent spectral radiance.

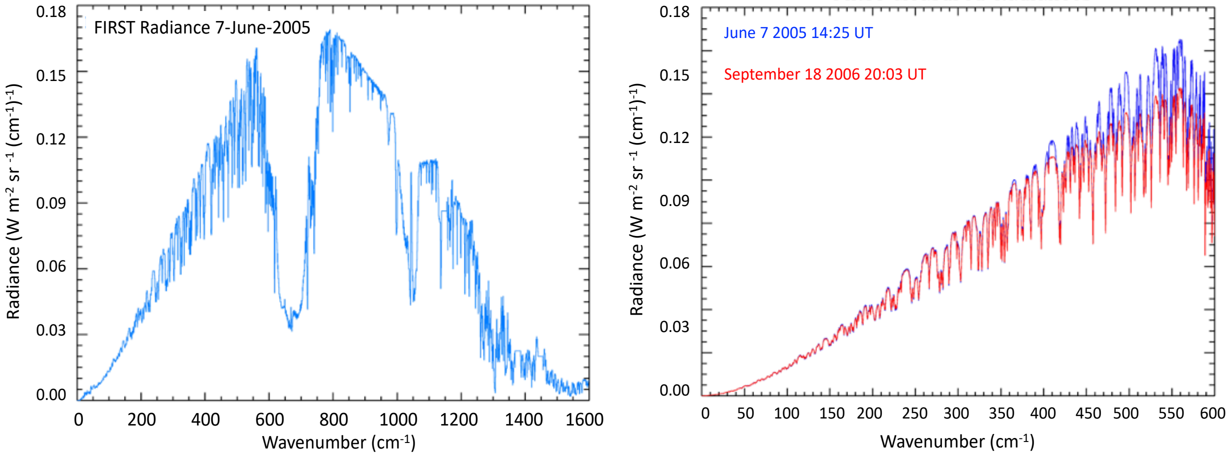


Fig. 4. Complete infrared spectrum (10-1600 cm^{-1}) measured by the FIRST instrument during a high-altitude balloon flight on 7 June 2005 from Ft. Sumner, New Mexico (left panel). Comparison of FIR spectra (10-600 cm^{-1}) measured during high-altitude balloon flights on 7 June 2005 and 18 September 2006 (right panel).

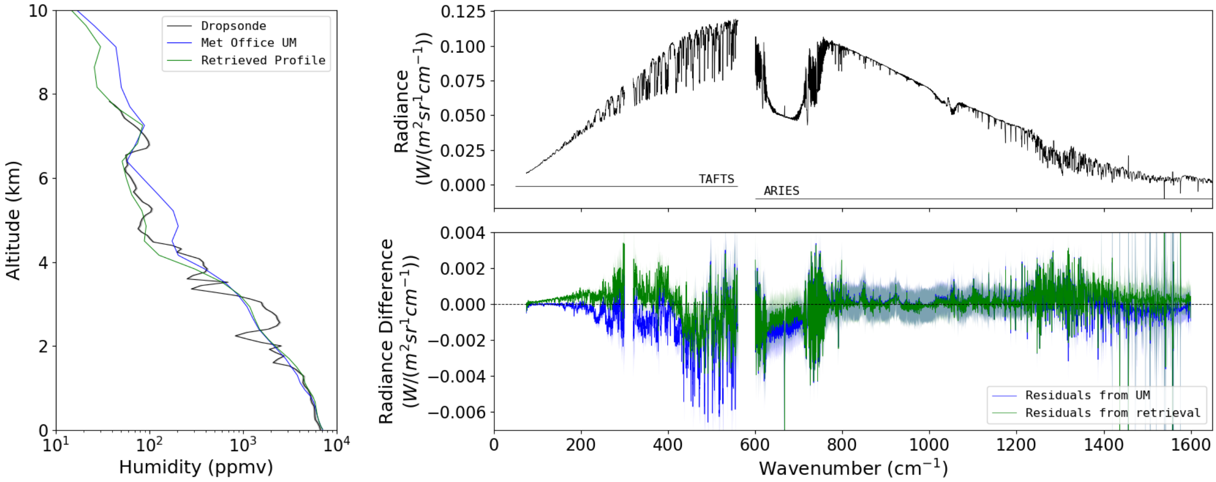
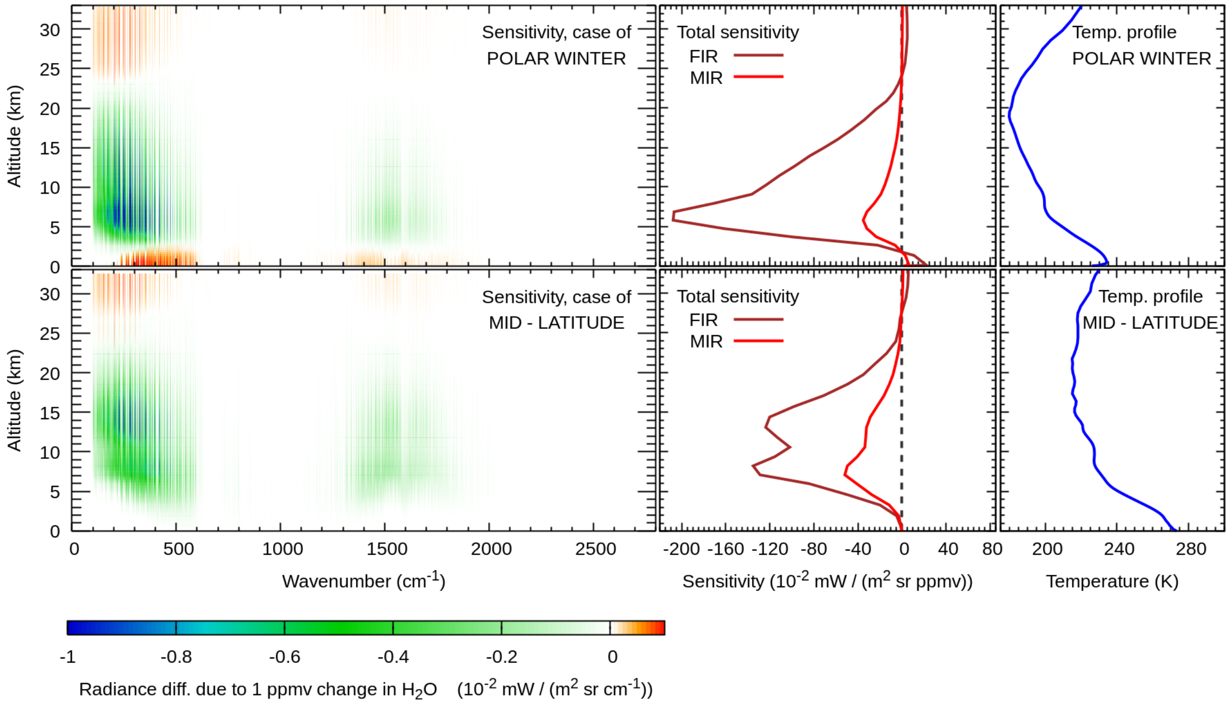


FIG. 5. Top right: Spectral radiances measured by the Tropospheric Airborne Fourier Transform Spectrometer (TAFTS: 80-550 cm^{-1}) and the Airborne Research Interferometer Evaluation System (ARIES: > 600 cm^{-1}), which covers the spectral range required for the FSI, under clear-sky conditions over the 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.



962 FIG. 6. Spectral sensitivity to H_2O vertical distribution assuming the FORUM threshold spectral resolution 963 requirement (0.5 cm^{-1}).

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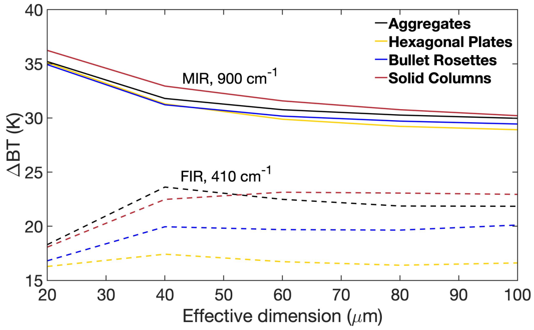

Fig. 7. Brightness temperature differences between clear sky and cirrus clouds as a function of the particle effective dimension. Solid lines account for BT differences at 900 cm^{-1} while dashed lines are for differences at 410 cm^{-1}. Several assumptions on crystal habit are reported in the legend. 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.

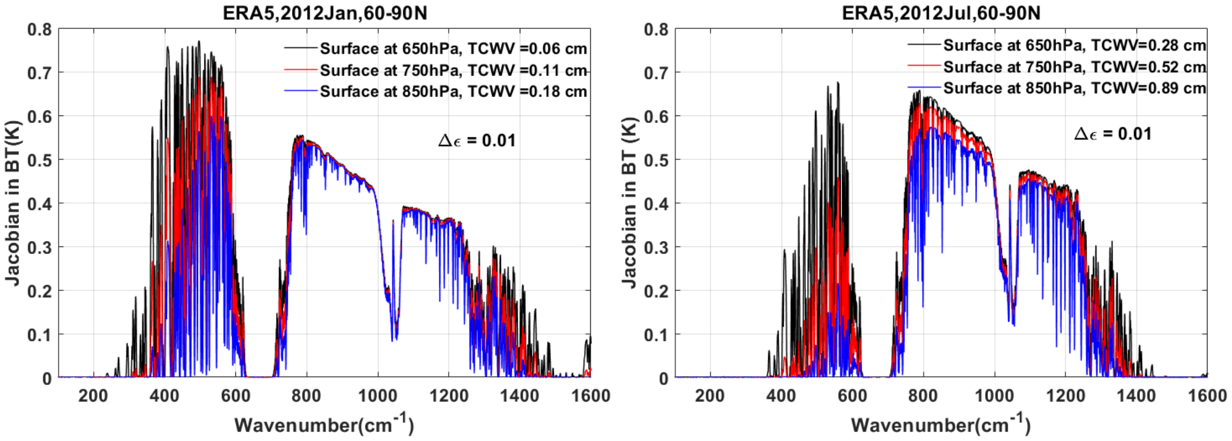

FIG. 8. Sensitivity of BT at TOA to surface emissivity change of 0.01 at different surface elevations. The ERA5 reanalysis profile averaged over the Arctic (60-90N) is used. The left panel is for January 2012 and the right for July 2012. The TCWV for different surface elevations are labeled on each panel.

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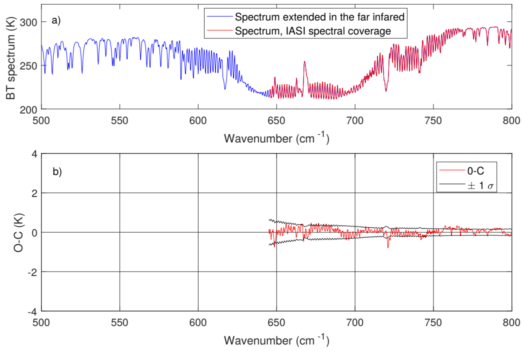

FIG. 9. IASI assessment of spectroscopy accuracy for the core of the ν_2 CO_2 band. Results based on observations (O) minus calculations (C) in panel b for a set of IASI spectra (whose average is shown in panel a) recorded in 2014 over the GRUAN-Manus validation station. The figure is intentionally extended down to 500 cm^{-1} to highlight that portion of the ν_2 CO_2 band which is currently not covered by meteorological satellite missions.