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## Middle-Atmosphere Temperature Monitoring Addressed with a Constellation of CubeSats dedicated to Climate issues

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### ► To cite this version:

Philippe Keckhut, Alain Hauchecorne, Mustapha Meftah, Sergey Khaykin, Chantal Claud, et al.. Middle-Atmosphere Temperature Monitoring Addressed with a Constellation of CubeSats dedicated to Climate issues. *Journal of Atmospheric and Oceanic Technology*, 2021, 38 (3), pp.685-693. 10.1175/JTECH-D-20-0046.1 . insu-03136030v1

**HAL Id: insu-03136030**

**<https://insu.hal.science/insu-03136030v1>**

Submitted on 10 Dec 2021 (v1), last revised 6 Jan 2023 (v2)

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1 **Middle-Atmosphere Temperature Monitoring**

2 **Addressed with a Constellation of Cube-Sats dedicated to Climate issues**

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## ABSTRACT

11 While meteorological numerical models extend upward to the mesopause, mesospheric observa-  
12 tions are required for leading simulations and numerical weather forecasts and climate projections.  
13 This work reviews some of the challenges about temperature observation requirements and the  
14 limiting factors of the actual measurements associated with atmospheric tides. A new strategy is  
15 described here using the limb scattering technique based on previous experiments in space. Such  
16 observations can be placed on board cube-satellites. Technical issues are the large dynamic range  
17 (4 magnitudes) required for the measurements, the accuracy of the limb pointing and the level of  
18 stray light. The technique described here will expect accuracy of 1-2 K with a vertical resolution of  
19 1-2 km. A constellation of 100 platforms could provide temperature observations with space (100  
20 km) and time resolution (3 hours) recommended by the World Organization Meteorology, while  
21 tidal issues could be resolved with a minimum of 3-5 platforms with specific orbit maintained to  
22 avoid drifts.

## 23 **1. Introduction**

24 The middle atmosphere (MA) is under the conjugated influence of climate changes, due to  
25 anthropogenic activities and natural variability. This region exhibits variability on time and space  
26 with scales ranging from thousands of kilometers to tens of meters and extending in the different  
27 atmospheric layers from troposphere up to the lower thermosphere. The MA extends from the  
28 tropopause (10-15 km) to the turbopause (100-105 km) comprising the stratosphere and mesosphere  
29 (Blanc et al. 2017). The stratosphere (12-50 km) was extensively studied because of the ozone  
30 hole discovery (Farman et al. 1985) and the associated cooling due to the strong temperature-ozone  
31 dependence in the upper stratosphere. The increase of GHGs (Green House Gases) induces a  
32 global warming at the surface and in the troposphere but also a global cooling in the MA due to the  
33 thermal infrared radiation emitted by GHGs escaping directly to the space because of the low optical  
34 thickness of the atmosphere above. However, full interactive numerical models including the MA  
35 have only appeared since the 1990s (Rind et al. 1990). The Coupled Model Inter-comparison  
36 Project reveals that models that do not represent the MA present biases in the representation of  
37 stratospheric climate and variability (Charlton-Perez et al. 2013). For this reason, the European  
38 Center for Medium range Weather Forecast (ECMWF) extends meteorological analyses up to the  
39 mesopause (80 km). However, comparisons between meteorological analyses and ground-based  
40 instrument reveal large biases (Le Pichon et al. 2015; Wright and Hindley 2018) that are due  
41 to a critical lack of observations above the stratopause and deficiencies in the parametrization  
42 of radiation as well as gravity wave effects in assimilating models. Limb missions, providing  
43 atmospheric observations with a high vertical resolution, will all stop soon their operations (Fussen  
44 et al. 2019). Apart from ISS/SAGE-III launched in 2016, only few limb scattering missions are  
45 planned in the future while they are not specifically dedicated to temperature retrieval. Long-term

46 temperature evolutions in the mesosphere (Beig et al. 2003) also suffer from the lack of dedicated  
47 observations (section 2). However limb viewing observations allows temperature retrieval with a  
48 good vertical resolution and can be deployed on small satellites (section 3). An issue is related to  
49 the fact that temperature observations exhibit strong interferences with tides as described in section  
50 4. The concept of constellation of several cubesats as described in section 5 could be an interesting  
51 approach to provide unbiased mesospheric temperature fields for models. Section 6 will provide  
52 conclusions about such perspectives.

## 53 **2. Middle Atmosphere Temperature Variability**

54 Systematic global temperature observations from space were initiated since October 1978 with the  
55 SSU (Stratospheric Sounding Unit) onboard the successive NOAA operational satellites (Gelman  
56 and Nagatani 1977) while assimilation of SSU data begins in December 1978 in ERA5. After  
57 adjustments with rockets (Gelman et al. 1986) continuous temperature series were derived by the  
58 U.S. National Centers for Environmental Prediction (NCEP), and decadal temperature trends were  
59 estimated (Hood et al. 1993; Lambeth and Callis 1994) with large uncertainties due to adjustment  
60 uncertainties between the successive satellites (Wild et al. 1995). The updated temperature series  
61 by two different groups show that derived trends exhibit larger differences between both of them  
62 than with temperature series provided by numerical models (Thompson et al. 2012) and finally  
63 provide a better agreement on zonal series (Maycock et al. 2018). A new generation of stratospheric  
64 temperature sounders were obtained with the Advanced Microwave Sounding Unit (AMSU) on  
65 board successive NOAA satellites and have also been flown more recently on NASA/Aqua and  
66 EUMETSAT/Metop satellites. The overlap periods reveal bias and drifts (Keckhut et al. 2015)  
67 in agreement with tidal models indicating that most of the observed drifts are likely due to the  
68 atmospheric tides. Atmospheric tides are caused by a combined effect of ozone and water vapor

69 photodissociation (Haefele et al. 2008) and insolation absorption by these same species, inducing  
70 waves with periods of 24 hours and associated harmonics on dynamical parameters (temperature,  
71 wind and pressure) that propagate in the whole atmosphere(Chapman and Lindzen 1970). The  
72 difficulties about time continuity on both SSU and AMSU series are mainly due to the combined  
73 effects of satellite orbit, atmospheric tides, and differences in weighting functions (Figure 1). With  
74 temperatures from the AQUA/AMSU instrument having an orbit maintained, more accurate trends  
75 can be obtained (Funatsu et al. 2016; Khaykin et al. 2017a). While trend analyses are very sensitive  
76 to time and space sampling (Funatsu et al. 2011), observations need to continue over periods longer  
77 than one solar cycle. However, tide characteristics may also change in response to climate change  
78 inducing additional apparent trends (Morel et al. 2004). AMSU has a finer vertical resolution than  
79 SSU but sounds not as high as SSU (Zou and Qian 2016). Mesospheric temperature was first  
80 investigated by rocketsondes operated systematically since the 1960s up to the end of the 1980s.  
81 Since then, observations have been performed with lidars within the NDSC network (Kurylo 1991)  
82 at several sites from tropics to poles. In the upper mesosphere temperature data are also obtained  
83 from airglow OH spectrometers (Bittner et al. 2002). In addition, few other research instruments  
84 have provided multi-years temperature data, and trends have been derived by several groups (Beig  
85 et al. 2003). These observations are consolidated and coordinated through the ARISE project  
86 (Blanc et al. 2017). No operational satellites are dedicated to provide systematic mesospheric  
87 temperatures. Some research satellites like the HALOE experiment aboard UARS provide multi-  
88 year observations using the solar occultation technique (Remsberg et al. 2002) with a good vertical  
89 resolution. However, no successive similar instruments were planned to be launched soon to  
90 ensure the continuity. At that time, only two research satellites provide continuing temperature  
91 series in the mesosphere: MLS (Microwave Limb Sounder) on board AURA/NASA and SABER  
92 (Sounding of the Atmosphere using Broadband Emission Radiometry) on board TIMED/NASA

93 (Thermosphere Ionosphere Mesosphere Energetics Dynamics). Large bias with ground-based  
94 observations are reported (Wing et al. 2018), and no similar follow-up missions are planned.  
95 Microwave instruments like MLS do not exhibit a good vertical resolution with typical values of 8  
96 km at 30 km growing with altitude up to 14 km at 80 km, and are then not sensitive enough to reveal  
97 disturbances like mesospheric inversions. Instruments like SABER provides more information in  
98 the mesosphere/thermosphere region with a constant vertical resolution of around 2 km. In the  
99 MA, short scale processes like gravity waves are fundamental to understand atmospheric evolution  
100 like sudden stratospheric Warmings (Hauchecorne et al. 2019a; Noguchi et al. 2020) and cannot be  
101 vertically resolved by operational sensors (Figure 1). Comparison with numerical weather model  
102 shows that under 10 days part of the observed variability is not included in meteorological analyses  
103 (Le Pichon et al. 2015). The variability in the mesosphere is also due to gravity waves breaking  
104 leading to mesospheric inversions of several tens of degrees within a vertical layer of 10-20 km  
105 (Hauchecorne et al. 1987). Such structures are already observed from space (Leblanc et al. 1995)  
106 and modelled (Hauchecorne and Maillard 1990) and were detected also by GOMOS (Hauchecorne  
107 et al. 2019a). The role of the mesospheric and upper stratospheric circulations appear to be critical  
108 on the onset and development of SSWs (Charlton-Perez et al. 2013).

109 The observation requirements are compiled by World Meteorological Organization (WMO)  
110 through the Observing Systems Capability Analysis and Review Tool (OSCAR: [www.wmo-](http://www.wmo-sat.info/oscar)  
111 [sat.info/oscar](http://www.wmo-sat.info/oscar)). The target resolutions correspond to 50-100 km and 3-6 hours time-resolution  
112 with an accuracy of 1-2 K.

### 113 **3. Limb viewing measurements from small satellites**

114 The scattering of sunlight is only due to atmospheric molecules above the aerosol stratospheric  
115 layer (25-30 km) and when no high-altitude polar clouds are present (Polar Stratospheric or

116 Mesospheric Clouds). Since Lord Rayleigh, the scattering is known to have a better higher  
117 efficiency for the shorter wavelengths revealing a blue scattering (Figure 2). This scattering is  
118 directly proportional to the atmospheric density.

119 Thus, similarly to the lidar technique (Hauchecorne and Chanin 1980), temperature can be  
120 retrieved by downward integration of the hydrostatic equation assuming the atmosphere follows  
121 the perfect gas law. The initialization is performed at the top of the profile assuming that the  
122 temperature is close to the climatology. The associated uncertainty is decreasing rapidly with  
123 altitude because the density itself increases sharply and the error becomes rapidly negligible  
124 providing an unbiased absolute temperature profile in the whole MA. This method has been first  
125 applied from space on bright limb using the Solar Mesosphere Explorer (Clancy et al. 1994).  
126 The similar retrieval was applied on space experiments that were not initially planned to provide  
127 temperatures like WINDII on UARS (Shepherd et al. 2001), OSIRIS on Odin (Sheese et al.  
128 2012) and more recently with GOMOS on ENVISAT (Hauchecorne et al. 2019b) but having a  
129 limb viewing geometry. The temperature retrievals were validated by ground-based instruments  
130 showing very accurate unprecedented observations in the mesosphere with agreement better than 2K  
131 with a vertical resolution of 2km. While existing instrument in space shows great capabilities, the  
132 development of a dedicated instrument appears to be feasible as it could be integrated on a small  
133 platform. Similar strategy have already be proposed for Earth radiative balance (Meftah et al.  
134 2020) for other essential climate variable. Such an instrument requires to observe the bright limb,  
135 and make the image of the Limb (Figure 3) on a CCD sensor. The main difficulties consist in:

- 136 • tracking the limb with a good accuracy,
- 137 • being sensitive to a large dynamic signal while density is decreasing by two magnitudes from  
138 30-80 km and



- fully eliminating parasitic lights from Earth surface and internal glint.

To achieve an accuracy of 1 K, a pointing reliability better than 250 meters is required as the mean temperature gradient in the mesosphere corresponds to 4K/km. For the pointing, if we consider a satellite cruise altitude of 600 km and a tangent altitude at 65 km above the surface, the distance to the limb is 2678 km. An accuracy of 200 meters corresponds to 70 microradians (or 15 arcsec). With GOMOS such accuracy was ensured with an efficient star tracker (Bertaux et al. 2010), while the occultation method requires to track a star through the different atmospheric layers during the satellite course. Similar device is required for temperature observations but with lower capability requirements as we only need to retrieve 200 m resolution (15 arcsec) in one exposure time. While the room is limited in a Cube-Sat, if the pointing efficiency is not as good as expected, the altitude can be also derived directly from the image of the horizon observed on the full multi-point detector. Such concept avoids to scan the limb in order to retrieve the density profile with a mechanic system and provide an altitude reference in detecting the Earth horizon. The main challenge with such a detector consists in providing enough sensitivity with a small noise level, over a signal range covering more than 4 magnitudes (Figure 4). Simulations of expected limb radiances have been performed for several bands and Figure 4 exhibits the two bands selected. It shows that whatever the wavelength, the signals should cover four orders of magnitude. The blue part of the spectrum is optimum as it is not affected by any absorbing component. Since the temperature retrieval requires a pure molecular scattering, the red part of the spectrum, more sensitive to the particulate scattering, will be used to detect the presence of aerosol and cloud particles. Even though the MA is mostly free of particulates, moderate volcanic eruptions or intense biomass burning events can inject considerable amounts of aerosols into the stratosphere (Khaykin et al. 2017b, 2020). Additionally, high-altitude tropical cirrus clouds, polar winter stratospheric clouds

162 as well as mesospheric noctilucent clouds or meteorite showers can also contaminate molecular  
163 scattering. The detection of aerosol and clouds using limb scattering technique will be the subject  
164 of a different study. Multi-point detectors exhibit different characteristics in term of sensitivity  
165 response and noise level as observed on GOMOS detector (Keckhut et al. 2010). Altitude retrieval  
166 will require an accurate inter-pixel calibration (0,5) as performed on GOMOS for spectrum retrieval  
167 (Kyrola et al. 2010). The calibration issue will be the task of the coming tests with the instrument  
168 prototype.

169 Another important issue is related to the noise induced by the external stray light reaching the  
170 detector. It appears that some light outside the nominal field of view of the instrument was observed  
171 on the GOMOS instrument (Figure 5) analyses on Envisat (Kyrola et al. 2010). Such noise reduce  
172 the altitude range. Part of the light can be scattered by some platform hardware into the baffle and  
173 optics. The other part is coming from the sun-illuminated nadir. Noise can be estimated directly  
174 from signals coming from altitudes above 100 km, however capability will be increased if the  
175 noise effects could be reduced by the design of the instrument. The dynamic and level of noise  
176 will allow to select the correct 2D multi-pixel detector. If no active thermal control on board is  
177 planned, power consumption will fit with a 3U (6W) or 6U (15W) standard orbit average power  
178 available. An accurate characterization of the dark current with temperature and data processing  
179 need to be performed at ground. All the components of similar limb measurements have already  
180 operated in space through instruments mentioned above. So the technical challenge consists today  
181 in performing similar measurements on a small platform with reduced room, electrical power,  
182 and weight. To achieve the 3 main technical issues described in section 3, nano-satellite pointing  
183 devices qualified for nanosat are not numerous but one has already shown promising capabilities  
184 (Mason et al. 2017) that need to be investigated further for our application. The dynamic of the  
185 signal can be covered by a CCD sensor while design, simulations and tests will be conducted

186 to reduce stray light issues on a small platform. Observation geometry as well as illumination  
187 conditions will not change during temperature observations that should reduce large evolution of  
188 the noise from successive observations. At that time a prototype with a flexible setup is under  
189 study and coming measurement campaigns in a high altitude observatory will allow for a better  
190 assessment of the noise and adjustment of the final design including the potential inclusion of  
191 foldable baffle.

#### 192 **4. Tidal issues**

193 Atmospheric tidal theory has been proposed by Chapman and Lindzen (1970) predicting a  
194 zonally-invariant migrating mode (Sun-synchronous) and a zonally-variant non-migrating tide.  
195 The atmospheric tides are primarily induced by the daytime heating of stratospheric ozone layer  
196 and convective latent heat release in the upper troposphere, whereas the ozone and water vapor are  
197 themselves subject to a strong diurnal cycle due to the photodissociation effect (Haefele et al. 2008).  
198 Perturbations of dynamical parameters like temperature and wind propagate vertically throughout  
199 the different atmospheric layers up to the thermosphere, and their amplitudes grow with decreasing  
200 pressure due to energy conservation.

201 Until recently, only few observations of tides in the stratosphere were available. Tidal studies  
202 in this layer have thus been restricted almost exclusively to rocket soundings. Rocket-borne  
203 temperature measurements had sparse diurnal coverage and were also prone to errors induced by  
204 radiation from exposed components of the rocketsonde (Finger and H.M. 1967; Hoxit and Henry  
205 1973). Atmospheric tides from temperature satellite measurements have been obtained from  
206 different space instruments (Raju et al. 2010): LIMS (Limb Infrared Monitor of the Stratosphere)  
207 instrument aboard the Nimbus7 (Hitchman and Leovy 1985), ISAMS (Improved Stratospheric  
208 and Mesospheric Sounder) and MLS (Microwave Limb Sounder) instruments aboard the Upper

209 Atmosphere Research Satellite (Dudhia et al. 1993; Keckhut et al. 1996), and more recently from  
210 CRISTA mission (Ward et al. 1999; Oberheide and Gusev 2002). However, satellite radiometers  
211 need systematic validations and periodic calibrations by ground references and observations are  
212 impeded with low horizontal and vertical resolutions and a viewing window that limits the local time  
213 of observations. The analyses of daily-scale atmospheric fluctuations associated for example with  
214 planetary waves are potentially contaminated by the non-migrating diurnal tides. The distortion  
215 in the analysis of planetary waves due to the tidal contamination was found to be of the same  
216 magnitude to the impact of noise in the data averaging over space and time (Zhang et al. 2006).  
217 The diurnal solar tide is one of the most prominent features in the middle atmosphere. While  
218 the tidal effect on large-scale stratospheric dynamics is small, its representation in a model is  
219 important for data assimilation in order to avoid introducing biases associated with the local time  
220 of the measurements (Swinbank and O'Neill 1994; Swinbank et al. 1999). This issue is much more  
221 critic in the mesosphere where the tidal amplitude is nearly a magnitude larger. Data processing  
222 from a single satellite requires large assumption about tidal characteristics (Huang et al. 2010). The  
223 tide is also modulated by ozone, water vapor density and by the dynamic (McLandress 2002), thus  
224 is sensitive to inter-annual changes like the QBO and SAO. Numerical simulations reveal a high  
225 sensitivity and expect tides characteristics to vary with climate changes (Morel et al. 2004). Thus  
226 simultaneous tidal estimates are required for assimilation or comparisons of any measurements  
227 performed at different time of the day. One shortcoming of the satellite mesospheric temperature  
228 data is that they are biased by the presence of migrating tides depending on the local times at which  
229 the daily zonal mean temperatures are obtained. No single satellite is able to provide a full diurnal  
230 coverage above a given location. At best if we consider a long period, the orbit changes allow to  
231 sample different parts of the diurnal cycle permitting the derivation of mean tidal information in  
232 comparing with temperatures at fix given times given by operational NOAA satellites. This is the

233 case for UARS/MLS (Keckhut et al. 1996) and SABER that obtained a full 24-hour coverage in  
234 respectively 36 and 60 days. However tidal retrievals are biased by the daily variability (Forbes and  
235 Wu, 2006). For WINDII only daytime observations are obtained and the diurnal tide parameters  
236 (amplitudes and phases) cannot be determined without some assumptions about phase information.  
237 This issue is a strong limitation for waves with period greater than 2 days, because of aliasing effects  
238 with this tidal periods. In the mesosphere, ERA interim model, which provides data every 6 hours,  
239 allow us to derive a diurnal cycle in assuming no semi-diurnal component and only a diurnal  
240 one (Figure 6). This calculation average over one month reveals at 60 km a large difference with  
241 latitudes but also unexpected large differences along the longitudes because of the strong presence  
242 of non-migrating tides. Complementary analyses with superDARN radar reveal a large variability  
243 of tides in wind with time and even over a single latitude (Hibbins et al. 2019).

## 244 **5. Small-satellite strategy, stable orbit and constellations**

245 The orbit needs to be selected to see an illuminated limb. In the summer hemisphere, above 30  
246 km, a large portion of the diurnal cycle is concerned (more than 15 hours at  $45^\circ$  in latitude) while in  
247 the winter hemisphere a reduced portion is available (less than 10 hours at  $45^\circ$  in latitude). If most  
248 of the variability induced by migrating atmospheric tides can be modelled by a diurnal and a semi-  
249 diurnal components, 5 unknown variables need to be considered (amplitude and phase for both  
250 waves and the mean). Temperature time evolution induced by tides are provided by the Global Wave  
251 Scale Model (Hagan 1999). If we consider a noise of 2K at 65 km at mid-latitudes with 5 different  
252 solar times and 30 observations (corresponding to 1 month daily measurements), the retrieval of the  
253 tidal evolution is perfectly reproduced (deviations smaller than 5% over the full cycle) as shown in  
254 figure 7. If the satellite has two solar time observations for respectively ascending and descending  
255 orbits, then only 3 satellites are necessary to retrieve atmospheric tides. During winter, the night is

256 too long to provide a sufficient coverage to retrieve the full characteristics of tidal waves (Figure 7).  
257 Figure 7 clearly shows how crucial are the observations at around 19:00 to retrieve the amplitude  
258 of tides as this portion of the cycle exhibits the largest differences between December and August  
259 tidal behaviors. So, the 3 solar-time observations are enough to retrieve the daylight portion of  
260 the temperature daytime evolution. However, orbits of the different satellites need to be decided  
261 accurately to remove tide effects if only 3 platforms are in space. One of the important issues to  
262 time continuity, consists in maintaining the orbit stable in time while a drift would induce change  
263 of the time of measurements. Due to the atmospheric tides inducing several-degrees temperature  
264 oscillations in the middle atmosphere, the drift about the revisiting time over a given location, will  
265 induce a temperature drift that could be interpreted either as anthropogenic trend or instrumental  
266 drift. As discussed in section 2, tides have been already observed with operational instruments  
267 like SSU (Wild et al. 1995) and AMSU (Keckhut et al. 2015) and were a severe limitation for  
268 trend estimates, unless the instruments have been installed on platforms with stable orbits (Funatsu  
269 et al. 2016). Small thrusters have been developed for Cube-Sats and can be used to maintain the  
270 time of measurements. If many satellites are in space simultaneously the maintenance of the orbit  
271 is not required in theory. However, while it is miniaturized and recommended for de-orbitation  
272 and collision avoidance such a device will present a plus-value for trend retrieval using a reduced  
273 number of platforms.

274 However, such temporal sampling should be considered as a minimum requirement to address  
275 tidal issues as only migrating time were considered. Very few is known about non-migrating tides  
276 and it is difficult to plan specific operations. WMO requirements will certainly allow a better  
277 representation of the induced regional effects. In order to achieve the required resolution provided  
278 by OSCAR/WMO during daytime with Low Earth Orbit (LEO) satellites, 4 orbital planes with a  
279 3-hours offset between them are needed, for example at 7:30, 10:30, 13:30 and 16:30 local time

280 (Thompson et al. 2012). To achieve the horizontal resolution of 100 km for each orbit plane, 400  
281 longitudes are needed at the equator. With up to 16 orbits per day for a LEO satellite, 25 platforms  
282 are needed on each orbit plane, corresponding to a total of 100 platforms.

283 Due to the agility of CubeSats, an international collaborative heterogeneous constellation can be  
284 envisioned to detect and study global dynamical structures in the MLT region using deep learning  
285 approaches as already suggested (Kaufmann et al. 2018; Meftah et al. 2020). Heterogeneity can  
286 come from limb scattering platforms like the one introduced here with additional capabilities  
287 or other limb-viewing instruments not primarily designed for temperature retrieval like ALTIUS  
288 (Fussen et al. 2019) or OMPS-LP on JSPS, or even measurements based on other techniques that  
289 provide observations on the dynamics in the MA (Baron et al. 2018; Fussen et al. 2019).

## 290 **6. Conclusions and recommendations**

291 Previous studies have revealed difficulties to derive temperature trends in the upper strato-  
292 sphere with successive operational instruments with different orbits and/or having experienced  
293 orbit drifting in time due to tidal effects. Tidal issue is also limiting the assimilation processes  
294 in meteorological analyses. Moreover in mesosphere, where tidal amplitudes are much larger,  
295 temperature is only probed by few research satellites and requires a better observation strategy.  
296 To insure a good time temperature coverage of the upper stratosphere and mesosphere to avoid  
297 interferences with tides, several orbits are required, ideally more than 5 as shown by simulations  
298 described in section 5. Ideally, process studies would require around 100 platforms. This can  
299 not insure with traditional space platforms. While climate variables are linked together and is  
300 required to quantify and understand the Earth imbalance, different constellations will be merged  
301 together with artificial intelligence methods. Temperature observations should be performed with  
302 a noise smaller than 1-2 Kelvin, and a systematic bias even smaller by 2 magnitudes. Previous

303 temperature retrievals from limb scattering appear to be one of the best technologies to provide  
304 accurate temperatures with a simple concept that can fit a small satellite platform, adequate for a  
305 constellation configuration of several cube-satellites. The design will need a viewing angle better  
306 than 70 micro-radians to insure a vertical resolution around 1 kilometer as required by WMO.  
307 The final goal is a constellation of several satellites that view a region of interest from different  
308 perspectives. Such a constellation will be a perfect complement to ground observations deployed  
309 within the ARISE European infrastructure (Blanc et al. 2017) in construction.

310 *Data availability statement.* Atmospheric tide characteristics (amplitude and phase of the diurnal  
311 and semi-diurnal components) from the GSWM simulations are provided by Maura Hagan and can  
312 be downloaded freely on <http://www.hao.ucar.edu/modeling/gswm/gswm.html>. ERA Interim data  
313 used for estimating tidal changes can be obtained from [https://apps.ecmwf.int/datasets/data/interim-](https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=ml/)  
314 [full-daily/levtype=ml/](https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=ml/).

315 *Acknowledgments.* Authors thank Adrian Simmons (ECMWF) for its support and useful discus-  
316 sions about the temperature requirements for ECMWF analyses. Authors thank also Jean-Francois  
317 Mahfouf (Meteo-France), Amal Chandran (Nanyang Technological University) Loren Chang (Na-  
318 tional Central University) and Pierre Tabary (CNES) for discussions about Nanosat opportunities  
319 in the domain of Earth observation. Authors thank the constructive comments of the 3 referees.

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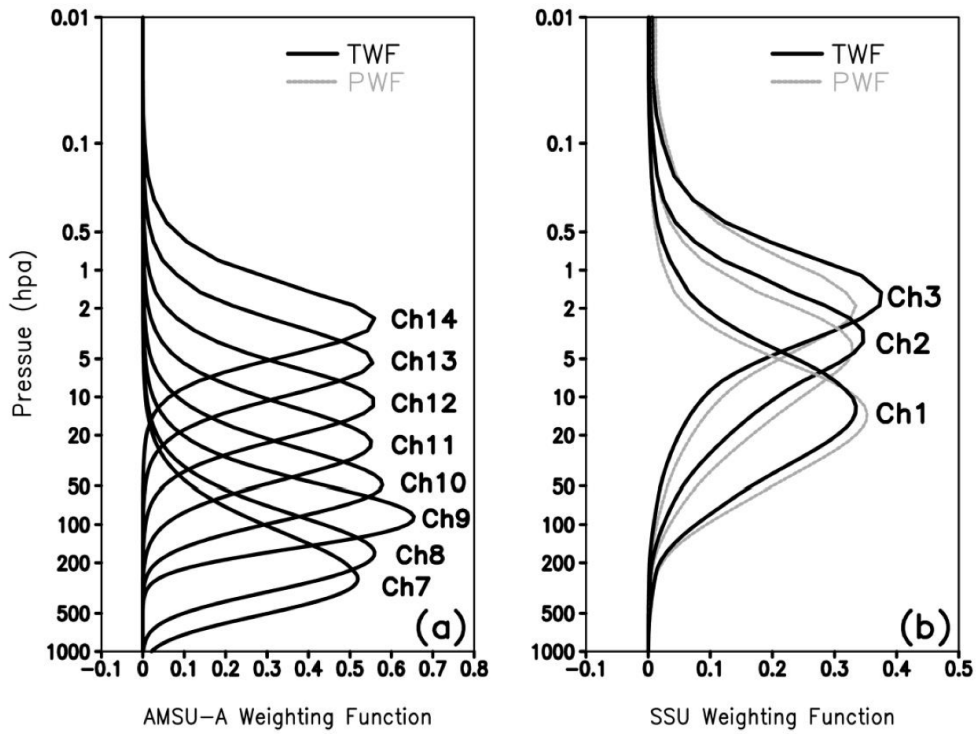
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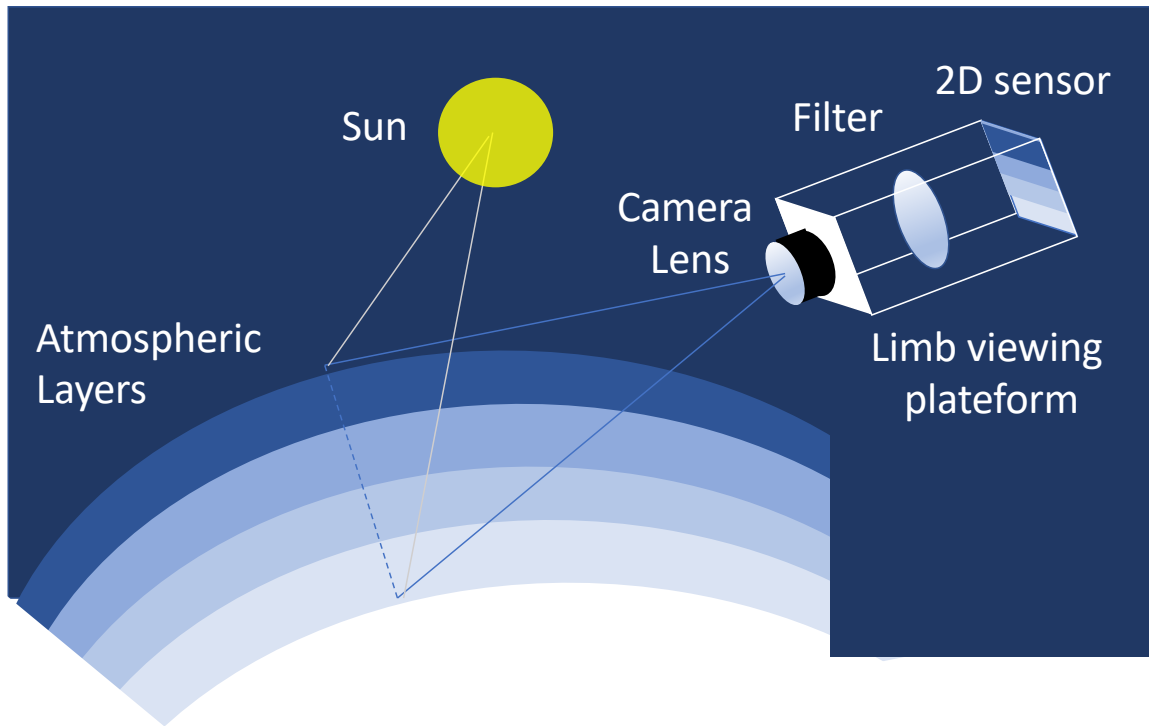
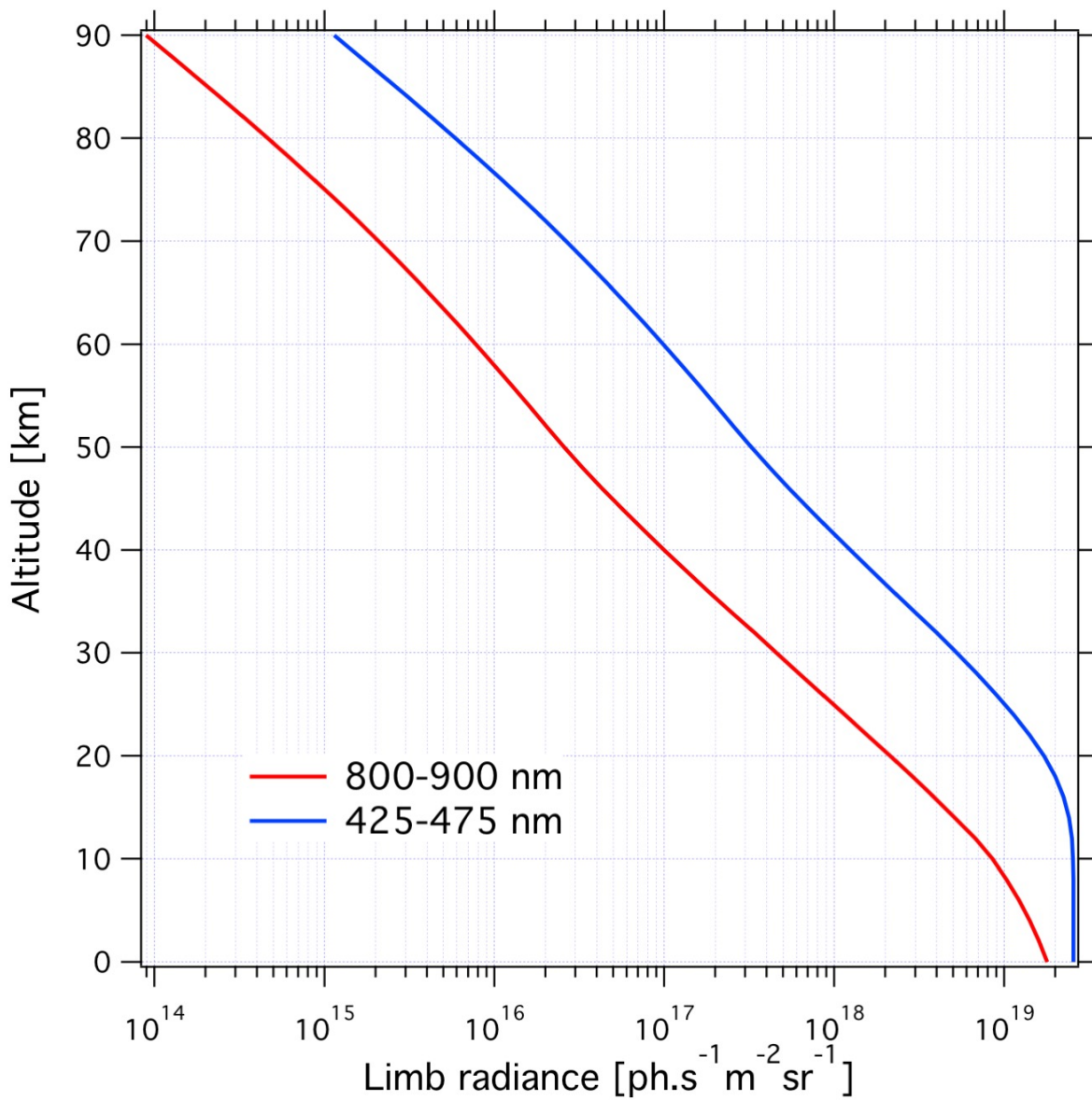
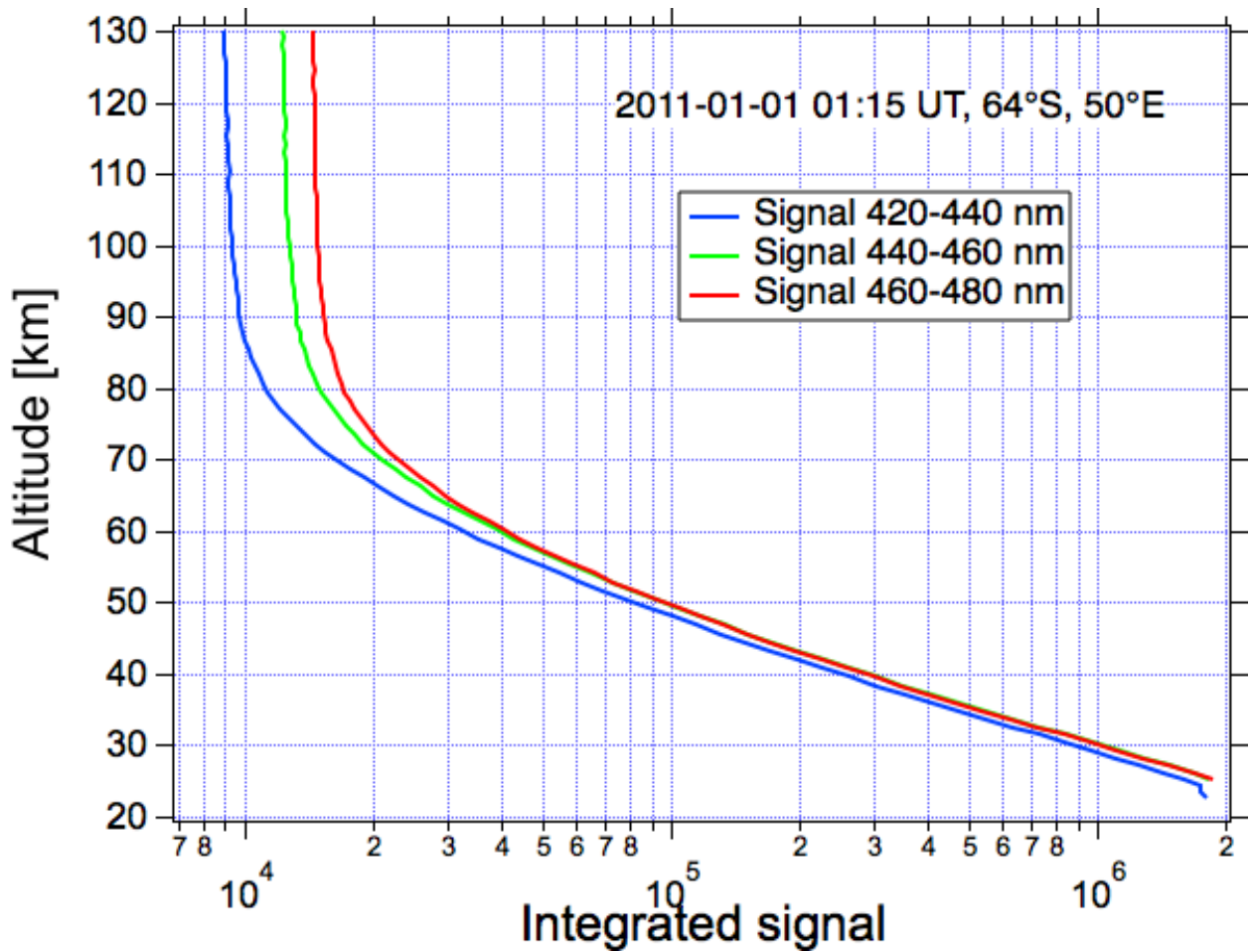


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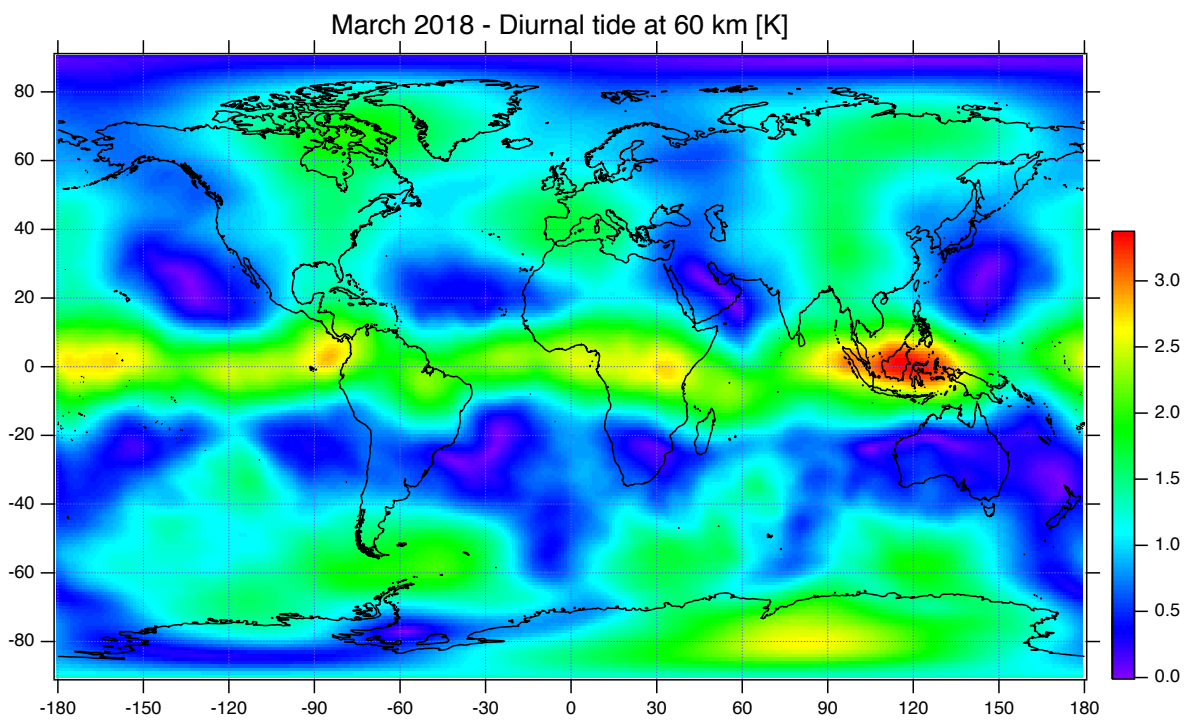
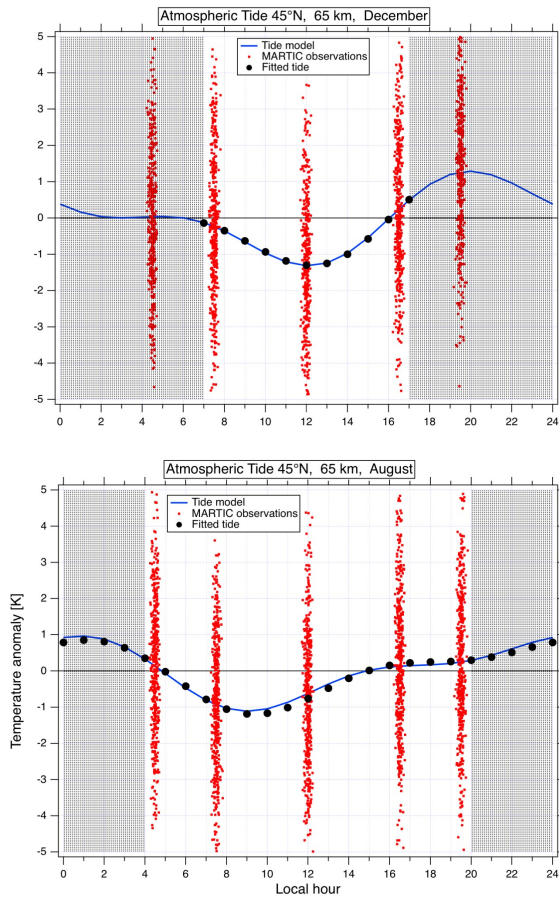


FIG. 6. Diurnal cycle derived from 6 hours ERA interim output average at 60 km over the month of March 2018.



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