Millimetre and submillimetre atmospheric performance at Dome C combining radiosoundings and ATM synthetic spectra

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ABSTRACT

The reliability of astronomical observations at millimetre and submillimetre wavelengths closely depends on a low vertical content of water vapour as well as on high atmospheric emission stability. Although Concordia station at Dome C (Antarctica) enjoys good observing conditions in this atmospheric spectral windows, as shown by preliminary site-testing campaigns at different bands and in, not always, time overlapped periods, a dedicated instrument able to continuously determine atmospheric performance for a wide spectral range is not yet planned. In the absence of such measurements, in this paper we suggest a semi-empirical approach to perform an analysis of atmospheric transmission and emission at Dome C to compare the performance for seven photometric bands ranging from 100 GHz to 2 THz. Radiosoundings data provided by the Routine Meteorological Observations Research Project at Concordia station are corrected by temperature and humidity errors and dry biases and then employed to feed Atmospheric Transmission at Microwaves (ATM) code to generate synthetic spectra in the wide spectral range from 100 GHz to 2 THz. This approach is attempted for the 2005–2007 data set in order to check its feasibility. To quantify the atmospheric contribution in millimetre and submillimetre observations we are considering several photometric bands, largely explored by ground-based telescopes, in which atmospheric quantities are integrated. The observational capabilities of this site at all the selected spectral bands are analysed considering monthly averaged transmissions joined to the corresponding fluctuations. Transmission and precipitable water vapour statistics at Dome C derived by our semi-empirical approach are consistent with previous works. It is evident the decreasing of the performance at high frequencies. We propose to introduce a new parameter to compare the quality of a site at different spectral bands, in terms of high transmission and emission stability, the site photometric quality ratio. The effect of the instrument filter bandwidth is involved on the estimate of the optical depth performed by the water vapour content knowledge.

Key words: atmospheric effects – site testing – cosmology: observations – submillimetre: general.

1 INTRODUCTION

Astronomy and astrophysics in the 100–1000 GHz band allow the study of a large variety of processes, in the local and distant Universe, which involve cool matter absorbing and re-radiating efficiently at these frequencies, in environments often unaccessed through observations at visible wavelengths. In fact, many key topics in modern astronomy and cosmology, such as galaxy formation and evolution, the amount and role of dark matter and dark energy in the Universe, star formation, protoplanetary discs or the properties of cold debris at the outskirts of the Solar system, are related to radiative phenomena in this band. The field has undergone a huge development in the last two decades, thanks to the development of sensitive detectors, large cameras, polarization sensitive devices and spectroscopically capable instrumentation. Some key achievements range from the measurement of the intensity and polarization power spectra of the cosmic microwave background (CMB) at millimetre (mm) wavelengths, to the discovery and the characterization of the optically elusive submillimetre (submm) galaxy population.

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[Submillimetre Common-User Bolometer Array (SCUBA), Balloon-borne Large Aperture Submillimeter Telescope (BLAST)], and the recent galaxy cluster surveys through subarcminute resolution observations of the Sunyaev–Zel’dovich effect [Atacama Cosmology Telescope (ACT), South Pole Telescope (SPT)].

Ground-based observations in the mm/submm band are usually plagued by the transparency of the atmosphere (and its stability over time), mainly because of the presence of large, time-dependent pressure-broadened features in the emission (and absorption) spectrum of the water vapour. Of course, this issue is strongly mitigated when operating stratospheric balloon-borne or airborne detectors, and completely averted when moving detectors on spacecrafts. BOOMERanG, BLAST, SOFIA, Planck and Herschel have proven the effectiveness of mm and submm observations from the stratosphere and from space, providing ground breaking advancements in their respective fields at the time of their operation.

Anyway, the practical limitations on the telescope size, the weight and the accessibility of instrumentation still make substantially unfeasible the deployment of large (10-m class) telescopes on balloons, aircrafts or satellites. As a matter of fact, the ground-based solution appears presently the only viable way to routinely perform high angular resolution observations of compact objects and/or small spatial and spectral features in cool diffuse media at submm wavelengths.

As a consequence, the last few years have witnessed increasing efforts in the design and construction of large telescopes in places of the planet which provide the potentially most attractive atmospheric features for mm and submm astronomy. The community has realized the need to perform a thorough characterization of astronomical sites in terms of atmospheric opacity and stability across the whole mm/submm spectral region, both for observation planning and for transparency monitoring during the observing sessions.

At a time where bolometric detectors can easily approach the photon noise limit, and large cameras with hundreds or thousands of such detectors already allow to break this limitation, it is straightforward to realize that an improper characterization of the atmospheric properties may become the strongest restriction to the effective science return from ground-based instruments of the present (ACT, SPT) and next generation (CCAT) [Cornell Caltech Atacama Telescope].

In order to continuously monitor the atmospheric transmission several approaches are possible: tippers or tau-meters, hygrometers, GPS, water vapour radiometers, radiosoundings and spectrometers. The first approaches allow a continuous data recording by simple instruments but with the drawback of single frequency observations, needing a synthetic atmospheric model to infer transmission at other frequencies.

Dome C is considered one of the best sites in the world to perform observations in a wide range of the electromagnetic spectrum allowing also to explore terahertz windows (Minier et al. 2008; Tremblin et al. 2011). Anyway a wide frequency coverage transmission measurements campaign at Dome C, employing the direct spectroscopic information derived by an interferometric experiment, was never carried out.

The goal of this paper is to compensate the lack of those data by estimating the atmospheric performance with a semi-empirical approach. We test this method using the available data set of radiosounding measurements recorded by the Routine Meteorological Observations (RMO) Research Project (http://www.climantartide.it) at Concordia station in the period from 2005 May to 2007 January, carefully corrected for the main lag errors and dry biases. The profiles of air temperature, pressure and relative humidity allow us to generate synthetic spectra, ranging from 100 GHz to 2 THz, with the ATM code (Pardo, Cernicharo & Serabyn 2001a).

The paper is organized as follows. Atmospheric synthetic spectra, as derived by ATM code, are described in Section 2.

In Section 3 estimates of atmospheric transmission and emission corresponding to largely explored ground-based telescope bands between 150 and 1500 GHz are analysed. The effect of the filter bandwidths on the estimate of opacity is for the first time included in the relation showing a contribution up to a 30 per cent overestimate on the opacity in the case of the highest frequency band.

A parameter to rank the observational conditions for each of the selected spectral bands is introduced as the ratio between average transmission and the corresponding fluctuations.

Finally, a discussion on the analysis and the conclusions are summarized in Section 4.

A detailed description of the correction procedure used to analyse the raw radiosounding data and determine the vertical profiles of the main thermodynamic parameters is reported in Appendix A.

2 SYNTHETIC SPECTRA PRODUCTION

At present, for the site of Dome C we can rely only on the atmospheric monitoring performed at a few individual frequencies, with no simultaneous measurements in different regions of the spectrum. In order to compensate for the lack of a continuous and spectrally wide atmospheric monitoring at Dome C, we predict the performance in the mm/submm bands in the period from 2005 May to 2007 January by means of a semi-empirical approach.

A set of raw radiosounding data was recorded for the present study, consisting of an overall number of 469 radiosounding measurements taken routinely at Dome C, at 12:00 UTC from 2005 May 2 to 2007 January 31 ranging from a minimum of 15 in 2005 May to a maximum of 30 in 2006 November.

In general, each radiosonde measurement consists of values of air pressure \( P \), air temperature \( T \) and relative humidity \( R_H \), taken at more than 800 standard and additional levels in the altitude range from surface to 10 km above mean sea level (amsl). Data provided by the radiosonde sensors are affected by lag and instrumental errors as well as by various dry biases. They were all corrected following the procedure described in Appendix A.

The time patterns of the daily precipitable water vapour (pwv) values are shown in Fig. 1. Two main features are evident in Fig. 1, showing that the majority of pwv values are lower than 0.3 mm during the austral autumn months, although presenting largely dispersed patterns (of 50 per cent or more), and, hence, low stability.

As shown by Tomasi et al. (2011a), a limited contribution is given to the overall value of atmospheric pwv by the amount of water vapour present in the upper troposphere and low stratosphere (UTLS) region from 8 to 12 km amsl, while negligible fractions of pwv ranging mainly between 0.003 and 0.005 mm throughout the year are present in the stratosphere from 12 to 50 km above Dome C (Tomasi et al. 2011b).

To verify the reliability of the present estimates of pwv, a comparison is made in Fig. 2 among the present daily values of pwv and those correspondingly determined by Tomasi et al. (2011a) (indicated as W) using a more advanced correction procedure from surface level to 12 km amsl. The comparison showed that a close relationship exists between the present results and those of Tomasi et al. (2011a), defined by a regression line with nearly null intercept and slope coefficient of +0.9425, having regression coefficient better than +0.99, and providing a standard error of estimate

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Figure 1. Daily values of pwv estimated from the 12:00 UTC radiosounding measurements performed at Dome C over the period from 2005 May to 2007 January are shown in the upper left-hand panel. Monthly averages of pwv are overplotted as red dots. In the right-hand panel the corresponding pwv versus cumulative frequency is plotted. The bottom panel shows the monthly pwv fluctuations quantified as the daily values standard deviation, $\sigma_{pwv}$.

Equation: $pwv = 9.466 \times 10^{-3} + 0.9425 \ W$

$R = +0.993$

$SEE = +0.04 \ mm$

Figure 2. Daily values of precipitable water vapour (pwv) obtained through the present analysis from surface level to 8 km amsl, and plotted versus $W$, the corresponding values of precipitable water derived by Tomasi et al. (2011a) over the altitude range from surface level to 12 km amsl. The data are best-fitted by a regression line with intercept equal to 9.466$\times$10$^{-3}$ and slope coefficient equal to 0.9425, which was obtained with regression coefficient $R = +0.993$, and provided a standard error of estimate $SEE = 0.04 \ mm$. These findings clearly indicate that the present evaluations of pwv, as obtained over the altitude range from surface level to 8 km amsl, are fully suitable for the purposes of our study, especially considering the intrinsic uncertainty of the simulation model.

Figure 3. Atmospheric transmission spectra as modelled by atm program for each radiosounding. Photometric bands in Table 1 (grey) match the main transmission windows.

We have estimated synthetic spectra in emission and in opacity by means of the atm code in the wide spectral range from 100 GHz to 2 THz. Each spectrum is derived considering the corrected radiosounding data. The transmission corresponding to each radiosounding data set, estimated from optical depth spectra as $T = e^{-\tau}$, is shown in Fig. 3.

In the period under consideration, the inferred pwv values show an average close to 0.3 mm with a mean dispersion of about 150 $\mu$m (see Fig. 1). The same amount of pwv variation can contribute with a different weight to the total optical depth. As example in Fig. 4 we represent the optical depth fluctuations derived by atm, quantified as the maximum dispersion, due to fluctuations of pwv of the order of 150 $\mu$m around three different pwv values (0.15, 0.5 and 1.0 mm).
3 MULTIBAND ANALYSIS

A quantitative analysis is performed considering seven photometric bands centred at the frequencies of several astrophysical and cosmological experiments: SPT, ACT, Millimetre and Infrared Testagrigia Observatory (MITO) and B-mode Radiation Interferometer (BRAIN) for low frequency (LF) atmospheric windows; SCUBA and SCUBA-2 and Two Hundred Micron Photometer (THUMPER) for submm bands (high frequency, HF). The central frequency of each band, as well as the bandwidth, quantified with the full width at half-maximum (FWHM), are listed in Table 1 (see also Fig. 3). The band profiles are assumed to be top-hat assuming in this way the maximum rejection to off-band contributions.

To assess the constraints on astronomical observations arising from the atmosphere emission above Dome C, we give an estimate of the noise equivalent power (NEP) and the noise equivalent flux density (NEFD) for all the seven bands. In fact in such a wide spectral region both the quantities are normally employed: the power density, mainly for the low-frequency bands, while the flux density, for the high-frequency region. The quoted NEP is the root of the sum of NEP$_\text{atm}^2$, the term considering the atmospheric emission fluctuations, and NEP$_\text{tele}^2$, i.e. the instrumental contribution to the photon noise. The atmospheric emissivity spectra are generated by ATM. The telescope is assumed a 10 m in diameter Al-mirror with a surface emissivity of the order 3 per cent at 150 GHz and depending on the frequency as $\sqrt{\nu}$. The throughput of the telescope is assumed diffraction limited at each band. Focal plane optical efficiencies are taken as unitary for all the bands as well as telescope main beam efficiency. The dominant sky sources (CMB and dust) are not included, the instrument detector noise is assumed lower than the background noise and the spill over emission is neglected. In order to quantify the maximum variation of these quantities we plot in Fig. 5 NEP and NEFD values for all the bands, for the extreme conditions occurred during the austral summers and winters at Dome C in the 2005–2007 period.

3.1 Dome C statistics comparison

To validate the proposed semi-empirical approach, we compare the derived atmospheric performance with the results available in literature.

Fig. 6 shows Dome C atmospheric transmission as a function of the cumulative time frequency derived by radiosounding data and ATM model for the bands listed in Table 1 (the corresponding quartiles are reported in Table 2). Transmission statistics at Dome C performed by Valenziano & Dall’Oglio (1999), Minier et al. (2008), Yang et al. (2010), Tremblin et al. (2011) and Battistelli et al. (2012) are compared with our analysis.

Low-frequency atmospheric windows show high transparency during the whole period confirming that high-quality mm observations can be performed from this site for most of the time. For instance the 150 GHz 50 per cent quartile transmission is about
the Microwave Humidity Sounder (MHS) sounding on the National transmission at Dome C of about 60 per cent estimating pwv with a portable photometer in 1997 January.

Valenziano & Dall’Oglio (1999) by pwv measurements performed about 95 per cent (see the cyan line in Fig. 6) as already derived by considering their integrated in-band result.

During the summer campaign in 2009 December–2010 January, even the 95 per cent value recently measured by Battistelli et al. (2012) is likely to degrade the quality of a scientific observation. In addition it is not possible to identify the month with the best term of high transmission) occur when the atmospheric fluctuations are large than others months (red dots in Fig. 7). Referring to the atmospheric window centred at 200 µm, when the transmission has the maximum value, the large fluctuations at short time-scales are likely to degrade the quality of a scientific observation.

We note that during the austral winter the atmospheric transmission in all the considered bands is generally higher, as expected. (T) shows values close to the unity in mm bands and decreases towards THz windows, while relative dispersions σT (rms values) of in-band transmissions, ranging from 2005 May until 2007 January and splitting between austral summer (from October to February) and winter months (from March to September) are shown in Fig. 7.

Monthly averaged transmission fluctuation is a good proxy of emission stability due to the fact that transmission and emission fluctuations are linearly correlated. In addition we assume that the estimated monthly averaged fluctuations, quantified in terms of the standard deviation, could be an underestimate of atmospheric stability because they derive from a daily data sampling, the time interval between two consecutive radiosoundings.

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In addition it is not possible to identify the month with the best atmospheric performance as one can see from the gap between two consecutive years atmospheric transmission and fluctuations (red and blue dots in Fig. 7).

450 and 350 µm bands transmission show a reduction of few per cent ranging from winter to summer months, while fluctuations are not sensitive to seasonal effects.

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Dome C median transmission for the 350 µm atmospheric window is about 50 per cent (see the bottom panel in Fig. 6), as derived by Tremblin et al. (2011) using the MOLIERE model and 200 µm optical depth measurements.

They found also that the Dome C 200 µm window opens with a transmission of 10 per cent for less than 25 per cent of the time while Yang et al. (2010) found that the transmission at 200 µm is about 13 per cent for 25 per cent of the time in 2008.

The 200 µm transmission as a function of the cumulative frequency is the black solid line in the bottom panel of Fig. 6: the 25 per cent quartile transmission value is above 10 per cent.

Pwv quartiles since 2005 May until 2007 January (see the right-hand panel in Fig. 1) have been compared with Dome C water vapour estimates performed in previous works in Table 3.

Table 3. Pwv quartiles comparison.

| Period               | 25 per cent | 50 per cent | 75 per cent | References |
|----------------------|-------------|-------------|-------------|------------|
| 1997 January         | 0.38        | 0.52        | 0.68        | 1          |
| 2005 May–2007 January| 0.20        | 0.30        | 0.45        | 2          |
| 2008                 | 0.15        | 0.24        | ...         | 3          |
| 2008–2010            | 0.21        | 0.27        | 0.35        | 4          |
| 2009 December–2010 January | 0.49 | 0.75 | 1.1 | 5 |

Notes. References: 1 – Valenziano & Dall’Oglio (1999); 2 – this work; 3– Yang et al. (2010); 4 – Tremblin et al. (2011); 5 – Battistelli et al. (2012).

3.2 High transmission and emission stability

Following an observational approach, we report the statistics of integrated in-band quantities, like emission and transmission. Both monthly averages ⟨T⟩ and relative dispersions σT (rms values) of in-band transmissions, ranging from 2005 May until 2007 January and splitting between austral summer (from October to February) and winter months (from March to September) are shown in Fig. 7.

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450 and 350 µm bands transmission show a reduction of few per cent ranging from winter to summer months, while fluctuations are not sensitive to seasonal effects.
All the considered bands are characterized by high stability in October (see the black or orange dots in the middle panel of Fig. 7) with the exception of the 200 µm window, showing high stability especially during summer months like January or February, when atmospheric transparency is not suitable to perform astrophysical observations.

To quantify the real capability of the observational site we need to study the atmospheric performance, mainly the stability, strongly affected by the weak reproducibility of weather conditions at long time-scales. In order to highlight this issue we introduce a specific parameter, the site photometric quality ratio (SPQR),

$$SPQR = \frac{\langle T \rangle}{\sigma_T}$$

relating monthly averaged transmission to its fluctuations, sampled on a daily time-scale, for all the considered atmospheric windows. SPQR amplitude provides information about atmospheric performance and it allows us to determine if high transmission combined with high transmission (i.e. emission) stability conditions are both satisfied for each band. Even if we are not able to identify the desired SPQR threshold, this factor could represent a useful tool to compare several bands performance or sites. In the right-hand panel of Fig. 7 monthly values of the SPQR are shown in different colours. The differences between the two years are more evident in SPQR, anyway a decrement of the SPQR towards THz regime occurs in austral winter as well as in summer periods. Seasonal averaged values of the SPQR in Table 4 suggest the good quality of atmospheric conditions in the low-frequency bands, notably during the austral winter. While SPQR appears useful for comparison among different bands at Dome C it could also be employed for comparison among different sites. It is worth reminding that it is difficult to quantify for SPQR a threshold value to discriminate the goodness of a site.

Two outcomes can be gathered from this analysis. If we believe in the transmission values, as derived by this semi-empirical approach, a continuous atmospheric sampling is mandatory at least at high frequency to contrast the low transmission stability. Otherwise if we consider the data derived in this work not reliable enough for an accurate estimate of atmospheric properties, we need direct observational techniques. In either case continuous atmospheric transparency measurements in all the spectral range of interest are necessary.

### 3.3 Effect of broad-band filter on optical depth estimate

The average of the optical depth over a band, $\tau_{\nu_0}(\Delta \nu)$, is larger than its central value $\tau_{\nu_0}$ so the opacity is overestimated by broad-band instruments like tippers, as remarked as example by Calisse et al. (2004). The determination of this effect is not unique because several pwv values could give the same in-band integrated opacity. Low-frequency instruments are less sensitive to this degeneracy even for large values of the bandwidth due to the flatness of the corresponding atmospheric windows. On the other hand a submm broad-band instrument overestimates the opacity (underestimates the transmission) and this difference depends on the filter shape as well as on the atmospheric conditions. Little variations of atmospheric conditions give rise to a dispersion of this overestimate because of the relative shapes of the atmospheric window and the corresponding filter. For each band in Table 1 we have included the effect in the relation between the integrated zenith opacity $\tau_{\nu_0}(\Delta \nu)$

| $\nu_0$ (GHz) | Summer | Winter |
|---------------|--------|--------|
| 150           | 272    | 335    |
| 220           | 127    | 152    |
| 270           | 79     | 94     |
| 350           | 36     | 42     |
| 660           | 6      | 7      |
| 870           | 5      | 6      |
| 1500          | 1      | 2      |
from Table 3, while low-frequency windows are less sensitive to this effect, as expected (10 per cent at 150 GHz).

The uncertainty related to the optical depth value due to the intrinsic scatter of the $\tau_{\nu}$ versus pwv relation can be approximated by a linear trend as a function of the instrumental bandwidth:

$$\sigma_{\tau_{\nu}}(\Delta \nu) = c_0 + c_1 \Delta \nu.$$  \hspace{1cm} (3)

The optical depth uncertainty turns out to be 0.002 at 150 GHz and rise up to 0.3 at 200 $\mu$m, assuming the dispersion independent on pwv value (see Fig. 8). As a consequence the percentage uncertainty on optical depth estimate is about 15 per cent all over the considered atmospheric windows assuming the best pwv quartile and it remains above 10 per cent even assuming the 75 per cent quartile in Table 3.

The six parameters corresponding to the seven bands are listed in Table 5. Equation (2) is useful to infer the atmospheric opacity at the preferred frequency, with a specific bandwidth, when the pwv content is known, but it is important to remind that this relation is appropriate only in the environs of Dome C.

In Tremblin et al. (2011) the opacity is related to the atmospheric pwv by means of the MOLIERE model. The resulting linear regression of the pwv as a function of the 200 $\mu$m opacity and the corresponding best-fitting parameters in Table 5, neglecting $a_1$ and $b_1$, gives less than 5 per cent difference in transmission for low pwv values. Such a gap could be easily included in the atmospheric performance variations observed at Dome C over the years. Also the difference in transmission evaluated for 220 GHz best-fitting parameters in Table 5 and $\tau_{\nu}(225$ GHz)$–$pwv linear fit in Valenziano & Dall’Oglio (1999) is lower than 4 per cent.

### 4 CONCLUSIONS

The quality of cosmological and astrophysical measurements performed from ground-based observational sites in the mm and submm wavelength regions are strongly dictated by the atmospheric performance.

The simultaneous measurement of atmospheric transparency and transmission fluctuations, i.e. emission stability, is a necessary condition to determine the true capabilities of the site of interest.

We try to monitor the atmosphere across a wide spectral range, mm and submm, with a semi-empirical approach. The transmission at Dome C is inferred by generating ATM synthetic spectra as derived by radiosounding data in the period from 2005 May to 2007 January. Excellent performance is evident in the low-frequency bands while large emission fluctuations are present in the high-frequency bands. In fact even if the median winter transmission is large in all the considered atmospheric windows, daily atmospheric emission fluctuations are not negligible and become remarkable in the submm range. In addition, large time-scales fluctuations of the atmospheric performance have been detected during two consecutive years.

The ratio between monthly averaged transmission and the corresponding fluctuations, defined SPQR, turns out to be an efficient estimator to rank the photometric performance of the atmosphere, in terms of stability, above Dome C, as well as any observational site. It allows us to verify when high transmission as well as low sky noise requirements are satisfied for the atmospheric window of interest. The SPQR threshold for each band is not easily defined: it is depending on the detectors architecture and on the adopted observational strategy.

We attempted to validate the proposed semi-empirical approach comparing pwv and transmission quartiles with other site-testing
campaigns performed at Dome C during the last years also at different wavelengths.

In the usual linearly dependent opacity–pwv relation, we include the effect due to the bandwidth of the monitor instrument.

Anyway only direct and frequent measurements of atmospheric transmission in a wide spectral range can provide a perfect knowledge of atmospheric influence on astronomical observations. If the opacity measurements are done in a narrow (a few MHz) spectral coverage, it is impossible to distinguish between clear sky opacity, hydrometeors contributions and systematic errors. A wide frequency coverage (several hundreds of GHz) is necessary to make sure we are in clear sky conditions and no instrumental offset is affecting our measurement and our analysis. In this way it is also possible to determine the dry and the wet continuum terms, see Pardo, Serabyn, & Cernicharo (2001b).

A large spectral sampling can be achieved at the price of a bit complex instrument. The possibility to monitor the atmosphere towards different positions in the sky, also avoids bias due to a spatial model assuming the multi layers approximation.

A dedicated spectrometer, like the one proposed for Dome C (De Petris et al. 2005) and in operation at Testa Grigia station (3500 m asl, Alps, Italy) in a spectrally limited version (100/360 GHz), CASPER 2 (Decina et al. 2010; De Petris et al., in preparation), is a viable solution.

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APPENDIX A: CORRECTION OF THE radiosonde DATA AND CALCULATIONS OF PRECIPITABLE WATER VAPOUR

The meteorological data were obtained at Dome C using two Vaisala radiosonde models: (i) the RS92 model for 430 measurement days, i.e. for 94 per cent of the overall days, and (ii) the RS80-A model for 29 radiosonde launches only. Each triplet of signals giving the measurements of $P$, $T$ and RH at a certain level was sent by the transmitter onboard the radiosonde to the ground station every 2 s. Considering that the radiosonde ascent rate was in general 5–6 m s$^{-1}$, the triplets of signals were recorded in altitude steps of 10–12 m.

The main characteristics of the three sensors (Barocap, Thermocap and Humicap) mounted on the two radiosonde models are available in table 1 of Tomasi et al. (2006), where their measurement range, resolution, accuracy, repeatability in calibration and reproducibility in sounding are given.

The measurements of $P$, $T$ and RH provided by the radiosonde sensors were all corrected following the procedure defined by Tomasi et al. (2006), which consists of numerous steps adopted to minimize the errors due to

(i) the not correct calibration of the Barocap sensors;
(ii) the effects caused by solar and infrared radiation heating, heat conduction and ventilation on the Thermocap sensors;
(iii) log errors, ground-check errors and dry biases of the Humicap sensors due to basic calibration model, chemical contamination, temperature dependence and sensor aging, corrected according to Wang et al. (2002).

This procedure substantially differs from that defined by Tomasi et al. (2011a) only in the parts regarding the correction of solar heating dry biases for both A- and H-Humicap sensors: (1) those of the A-Humicap sensor were corrected by Tomasi et al. (2006) using the algorithm of Turner et al. (2003), while Tomasi et al. (2011a) preferred to use the algorithm derived more recently by Cady-Pereira et al. (2008) and (2) those of the H-Humicap sensor were corrected by Tomasi et al. (2006) using the average correction factors proposed by Miloshevich et al. (2006) as a function of solar zenith angle, while Tomasi et al. (2011a) employed the pair of day-time and night-time correction algorithms of Miloshevich et al. (2009). A large part of the few per cent discrepancies found in the comparison shown in Fig. 3 between the present values of pwv and those determined by Tomasi et al. (2011a) arise from the use of these different algorithms in correcting the instrumental and solar heating dry biases affecting the field measurements of RH.
Using the correction procedures previously described, the daily vertical profiles of pressure $P(z)$, temperature $T(z)$ and RH($z$) were determined at fixed levels above the surface level, in regular steps of 25 m from 3.25 to 4 km, 50 m from 4 to 5 km and 100 m from 5 to 8 km amsl.

In order to calculate the values of absolute humidity $q(z)$ at the same fixed levels, the following procedure was adopted, consisting of the three steps: (i) calculation at each level of the saturation vapour pressure $E(T)$ in the pure phase over a plane surface of pure water, using the well-known Bolton (1980) formula; (ii) calculation at each level of the water vapour partial pressure $e(z)$ as the product $E(T)\, RH(z)$; (iii) calculation at each level of absolute humidity $q(z)$ measured in g m$^{-3}$ in terms of the well-known equation of state of water vapour, and, hence, as the ratio between $e(z)$ (in hPa) and the product $R_w \, T(z)$ (in K), in which the water vapour gas constant $R_w = 0.4615 \mathrm{J} \, \mathrm{g}^{-1} \, \mathrm{K}^{-1}$ is put in place of the constant $R_a = 0.287 \mathrm{J} \, \mathrm{g}^{-1} \, \mathrm{K}^{-1}$ used in the equation of state for dry air.

For all the 469 daily vertical profiles of $q(z)$ obtained using the above procedure, the values of pwv were then calculated by integrating each vertical profile of $q(z)$ from the surface level to 8 km amsl (i.e. up to 4.767 km above the ground level).

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