Atmos. Meas. Tech., 6, 2865–2877, 2013
www.atmos-meas-tech.net/6/2865/2013/
doi:10.5194/amt-6-2865-2013

Atmospheric Measurement Techniques
Open Access

Maïdo observatory: a new high-altitude station facility at Reunion Island (21° S, 55° E) for long-term atmospheric remote sensing and in situ measurements

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Received: 26 June 2013 – Published in Atmos. Meas. Tech. Discuss.: 15 July 2013
Revised: 11 September 2013 – Accepted: 26 September 2013 – Published: 29 October 2013

Abstract. Since the nineties, atmospheric measurement systems have been deployed at Reunion Island, mainly for monitoring the atmospheric composition in the framework of NDSC/NDACC (Network for the Detection of *Stratospheric* Change/Network for the Detection of Atmospheric Composition Change). The location of Reunion Island presents a great interest because there are very few multi-instrumented stations in the tropics and particularly in the southern hemisphere. In 2012, a new observatory was commissioned in Maïdo at 2200 m above sea level: it hosts various instruments for atmospheric measurements, including lidar systems, spectro-radiometers and in situ gas and aerosol measurements.

This new high-altitude Maïdo station provides an opportunity:

1. to improve the performance of the optical instruments above the marine boundary layer, and to open new perspectives on upper troposphere and lower stratosphere studies;
2. to develop in situ measurements of the atmospheric composition for climate change surveys, in a reference site in the tropical/subtropical region of the southern hemisphere;
3. to offer trans-national access to host experiments or measurement campaigns for focused process studies.

Published by Copernicus Publications on behalf of the European Geosciences Union.

1 Introduction

Since the beginning of the 20th century, the increase of anthropogenic atmospheric emissions has induced an evolution of the atmosphere which must be understood and surveyed, in order to improve climate projections. Global observing networks allow the study of dynamical and physico-chemical processes in all their complexity and comprehensiveness: NDACC (Network for the Detection of Atmospheric Composition Change, http://www.ndacc.org) mainly focuses on the monitoring of the stratosphere and troposphere (Kurylo and Solomon, 1990) and GAW (Global Atmosphere Watch) on climate change (Wuebbles et al., 1999)

Strategies for atmospheric monitoring are largely based on modeling and global satellite data but we still need local observations for assimilation, validation and to study processes with a good accuracy and vertical resolution. The TTL (Tropical Transition Layer), located between 14 and 18.5 km and bounded by subtropical jet streams, is the place where exchanges of air masses between the troposphere and the stratosphere occur (Fueglistaler et al., 2009). It is also the place where the understanding of water vapor variability is crucial and has to be based on data within a reference network for upper air climate observations such as GRUAN (GCOS Reference Upper-Air Network, Immler et al., 2010).

First atmospheric instruments, mainly based on the lidar technology, have been deployed at the coastal site of Saint Denis of Reunion Island (21° S, 55° E) since 1994 (Baray et al., 2006). Since 2012, the new observatory located at Maïdo mount at 2200 m above sea level (a.s.l.) has hosted these remote sensing instruments and constitutes the ideal place to perform studies of water vapor near the TTL.

Being near the free troposphere during the night, the Maïdo observatory is also a good place to perform large-scale representative in situ measurements of greenhouse gases and aerosols. Aerosols have a direct radiative effect, but also indirect and semi-direct effects in interaction with clouds. For these fields, the Maïdo observatory has implemented two inlets to measure interstitial aerosols and the condensed matter included within cloud droplets. A set of measurement instruments for greenhouse gases, aerosol size distributions, cloud condensation nuclei counters and aerosol chemical filters were implemented in 2013. The objectives are two-fold: these measurements are an interesting observation point of the free lower troposphere characterizing the region of the southwest Indian Ocean. These measurements also have a very strong interest in observing networks as WDCA and WDCGG from the Global Atmospheric Watch (GAW) or as the European network ICOS and the French network ICARE. Second, due to the presence of clouds formed on the slopes of humid forests, the site of the Maïdo observatory is well located to study the aerosol-clouds interactions and the in-cloud formation of the condensed secondary organic matter.

The purpose of this paper is to give a technical description of this facility, and of the instrumentation that is and will be deployed, and to highlight the scientific themes that will be documented with Maïdo data.

2 Atmospheric observations and Maïdo Facility

2.1 Location and atmospheric processes

Reunion Island (21° S, 55° E) is a volcanic island located in the southwestern part of the Indian Ocean. It is particularly well located to study stratospheric tropical waves and large-scale dynamics of air masses. Due to its location, Reunion Island is seasonally exposed to biomass burning plumes, which can significantly affect the free tropospheric concentrations of ozone (Clain et al., 2009) and other pollutants like carbon monoxide and several volatile organic compounds (Duflot et al., 2010; Vigouroux et al., 2012). Moreover, it is affected by the dynamical influence of the subtropical jet stream and the tropical convection which are key processes for the understanding of the TTL.

Reunion Island is affected by southeasterly trade winds near the ground, and westerlies in the free troposphere. The eastern/western parts of the island are respectively wet and dry. Clouds develop daily on the summits of the island, with a well-established diurnal cycle (formation in the late morning, dissipation at the beginning of the night). Maïdo mount is a summit on the western part of the island. During the night and at the beginning of the morning, air masses at the Maïdo mount are separated from local and regional sources of pollution, due to the strengthening of the large-scale subtropical subsidence at night. The number of clear sky nights is then very important, in comparison with the coastal site of Saint Denis, where the lidars were operated from 1994 to 2011.

A recent numerical study allowed identification of processes of pollution transport and dispersion, including vortices in the wake of the island, causing counterflow circulation and trapping of polluted air masses near the northwestern coast and protecting the observatory from volcanic plumes in case of eruption (Lesouëf et al., 2011).

For these reasons, all lidars and in situ measurements, which were deployed at the coastal site of Saint Denis (80 m above sea level), are now performed at the Maïdo facility, improving the conditions of acquisition and quality of data. Passive spectrometers measuring total columns (SAOZ, CIMEL) are still performing at Saint Denis. Fourier-transform Infrared (FTIR) solar absorption measurements will be performed at both sites with two instruments, mainly in the framework of TCCON (Total Carbon Column Observing Network, http://www.tccon.caltech.edu) at Saint Denis and NDACC at Maïdo. UHF radar and ozone sondes are performed from Gillot, the Meteo-France station near the airport (8 m above sea level). The location of these three sites is shown in Fig. 1. This observation strategy is optimally taking into account the advantages/disadvantages of each site and measurement technique. The list of instruments currently

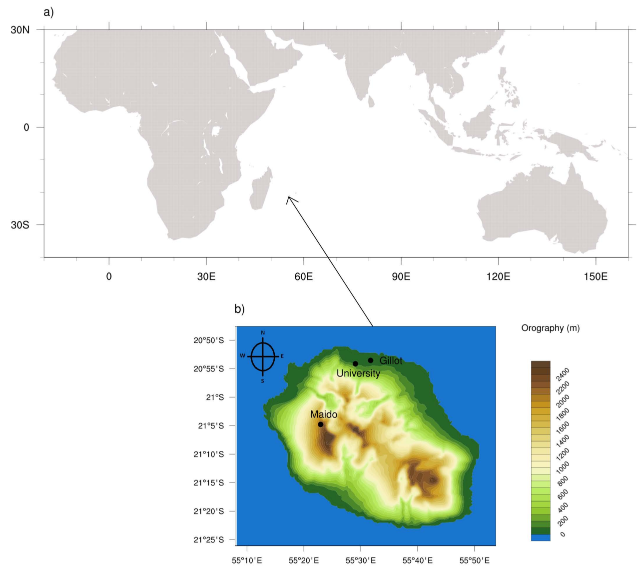

Fig. 1. Maps showing the locations of Reunion Island in the Indian Ocean **(a)** and of the different measurement sites, Maïdo facility, Gillot, and University in Reunion Island **(b)**.

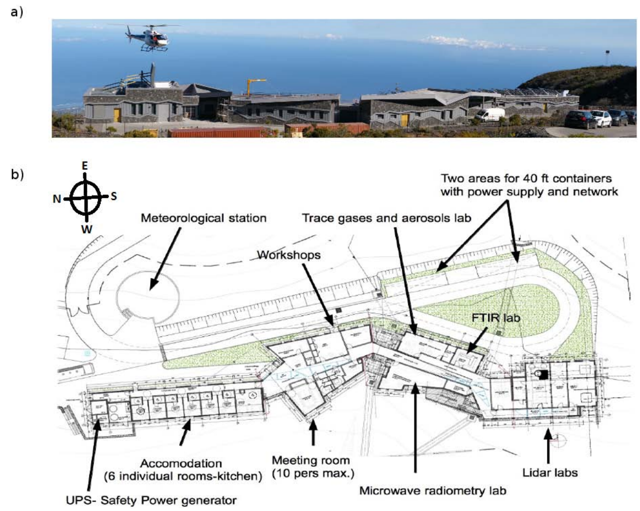

Fig. 2. The Maïdo building: **(a)** photo and **(b)** map.

deployed at the Maïdo station, and those we plan to deploy in the next two years are given respectively in Tables 1 and 2.

2.2 Calendar and evolution

Atmospheric observations began at Reunion Island in 1992 and have been developed gradually. In collaboration with the Service d'Aéronomie (SA/CNRS) and the Institut Pierre Simon Laplace (IPSL), measurements of ozone, temperature and humidity profiles by radio soundings started in 1992, followed by a SAOZ UV-visible spectrometer in 1993. lidar experiments began in 1993 with a Rayleigh–Mie temperature and aerosol system, followed by Raman and differential absorption measurements of ozone. FTIR measurements were performed since 2002, in a collaboration with the Belgian institute for Space Aeronomy (BIRA-IASB, Belgisch Instituut voor Ruimte Aëronomie – Institut d'Aéronomie Spatiale de Belgique). The idea of a high-altitude station to improve lidar measurements was first proposed in 1989, before the beginning of atmospheric measurements at Reunion Island. But it took a long time to resolve political, financial and administrative problems and the first drawings were produced only in 2007; the road and building works began mid-2010. The facility was commissioned in June 2012 and the inauguration ceremony was organised on the 24 October 2012. The total cost of the infrastructure project (design studies, the observatory, a 9 km-high voltage power line and a dedicated road) amounts to EUR 9 million, including EUR 4.7 million for the building, and EUR 4.3 million for the studies and the other infrastructures. In addition EUR 2.8 million were obtained for upgrade of existing instruments and development of new ones.

2.3 Technical presentation of the Maïdo Facility

The total surface of the plot of land is 6600 m^2 including the road access, scientific container areas, parking, building, electrical substation, and outsides. The surface of the building is 600 m^2 including, 173 m^2 for the lidar space, 129 m^2 for other scientific rooms (FTIR, Micro Wave Radiometer, in situ measurements), 300 m^2 for bedrooms, meeting room, and storage and ancillaries (water plant, power supply, secondary diesel power supply unit). A total of 164 m^2 of scientific areas are available on the roof (Fig. 2), enabling the installation of measurement heads above the scientific labs. Two specific experimental container areas for 12 m sea containers (40 feet) are equipped with water, electricity and local area network, enabling an easy plug in of experiments for campaigns. The access road is sized for big container trucks. During the design studies, most rooms have been designed taking into account the properties of the instruments and some space has been reserved for future instruments. Two dedicated radio links and optical fibers are connecting the station to phone and data link networks.

3 Stratospheric and UTLS studies using Remote Sensing measurements

3.1 Processes and atmospheric composition of subtropical UTLS and stratosphere

The understanding of dynamical and physico-chemical processes in the subtropical southern troposphere and stratosphere is an historical theme documented by studies performed with Reunion Island data since the beginning of atmospheric measurements in the nineties. Several early studies based on radio sounding and ozone lidar measurements that characterized the effects of biomass burning on

Table 1. List of instruments currently deployed at the Maïdo observatory. Data are available at https://opar.univ-reunion.fr/?lang=en.

Instrument	Parameter – range	Begin of operation at Maïdo (other site)	Mode of operation	Network	Laboratories involved
Rayleigh–Mie–Raman lidar	T – 10–90 km H_2O – 2–17 km	2012 (1994–2011 at St Denis)	routine	NDACC	LATMOS/LACy
DIAL lidar	O_3 – 6–17 km	2013 (1998–2011 at St Denis)	routine	NDACC	LACy
DIAL lidar	O_3 – 15–45 km	2013 (2000–2006 at St Denis)	routine	NDACC	LACy/LATMOS
Doppler lidar	Wind – 5–50 km	2013	campaign		LATMOS
FTIR	Many molecules	2013	routine	NDACC	BIRA-IASB
Microwave radiometer	H_2O – 15–75 km	2013	campaign		Météo-France/GAME
Lightning sensor	Lightning location	2013 (2010–2013 at Gillot airport)	continuously	WWLLN	LACy
CPC 3775	Particle counter	2013	continuously	GAW	CNRM/LACy – LaMP
Chemical filters	Aerosol chemistry	2013	continuously	GAW	LSCE/LACy
GPS ground-based receiver	H_2O – total column	2013	continuously	IGS	LACy

tropospheric ozone (Baldy et al., 1996), stratosphere-to-troposphere exchanges (Baray et al., 1998) and isentropic meridian filamentations in the stratosphere (Portafaix et al., 2003). Cirrus clouds and their link with ozone (Roumeau et al., 2000) and water vapour (Hoareau et al., 2012) have also been documented. The deployment of FTIR instruments allowed the study of biomass burning tracers having a long lifetime in the troposphere such as carbon monoxide (Duflot et al., 2010) or other shorter-lived species (Vigouroux et al., 2012). Climatological and long-term trends aspects developed in Clain et al. (2009) emphasize the geophysical interest of Reunion Island location in relation to these processes and justify the interest of networks such as NDACC for Reunion Island observations. However, in order to progress in these themes, we need to improve the quality and quantity of the remote sensing observations. As described in Sect. 2.1, the Maïdo site will allow us to take advantage of a more transparent and less cloudy sky to fulfill this objective. The new instrumental configuration, coupled with satellite data (MEGHA-TROPIQUES, IASI, COSMIC/FORMOSAT…) and different types of modeling will allow us to document stratosphere to troposphere exchanges using simultaneous water vapour and ozone lidar profiles, but also troposphere to stratosphere intrusions and influence of tropical cyclones on the TTL, the transition area bounded by the subtropical jet streams and presenting dynamical, chemical and radiative characteristics of the stratosphere and troposphere (Flueglistaler et al., 2009).

In the stratosphere, understanding and quantifying chemical or dynamical variability is central to validate predictive models. In this context, the tropics play an essential role although this region historically suffers from a lack of ground-based measurements with high vertical resolution. Recent papers (e.g. Randel and Thompson, 2011) exhibit significant negative ozone trends in the tropical stratosphere (between -2 and -4 % per decade over 17–21 km), from combined satellite and sounding data for the period 1985–2009. These results could be linked with modifications in the Brewer Dobson circulation. Thus, stratospheric measurements performed at Maïdo tropical site will allow us to investigate and understand the transport in the lower tropical stratosphere and better characterize ozone variability and long-term trends in this region.

3.2 Active remote sensing measurements

Active remote sensing activity at Maïdo is mainly composed of lidar instrumentation. Four main lidar systems are deployed at the Maïdo Facility, one for temperature-water vapor, one for tropospheric ozone, one for stratospheric ozone, and one for stratospheric wind. In addition, a mobile system devoted to tropospheric aerosols can be deployed at Maïdo or at Saint Denis.

The first lidar at Reunion Island was a Rayleigh–Mie, operating since 1994. This system was based on a Nd:YAG laser emitting at 532 nm, and a reception system composed by a mosaic of 4 parabolic mirrors, with a diameter of 500 mm each and optical fibers at their focus points to collect the backscattered light. This system was successively upgraded in 1998 with DIAL channels to produce tropospheric ozone profiles (Baray et al., 1999) and Raman channels in 2002 to produce water vapor profiles (Hoareau et al., 2012). The actual Raman water vapor lidar system is an upgrade of the receiving optics of the existing Rayleigh–Mie lidar system in operation since 1994. It is principally dedicated to water vapor measurements in the UTLS but also to the measurements of the stratospheric temperature using Rayleigh scattering. The light source of this lidar consists in two Quanta Ray Nd:Yag lasers. The system is designed to work at 532 or 355 nm. Pulses of both lasers can be synchronized, and coupled through polarization cubes. The backscattered signal is collected by a 1.2 m diameter telescope that was previously used at Biscarrosse (France) for Rayleigh and Raman measurements (Hauchecorne et al., 1991) and that was refurbished in 2011. A narrow field of view of 1 mrad can be used to reduce as much as possible sky background and detector noise. Contrary to the lidar system used at Reunion Island University before 2012, the current system uses a set of lenses and mirrors instead of optical fibers to transfer backscattered signals to the optical ensemble, in order to avoid a systematic bias in water vapor measurements due to fluorescence in fiber-optic cables. Regarding the photon detector, we use, in a first step, new Hamamatsu R7400-03g or

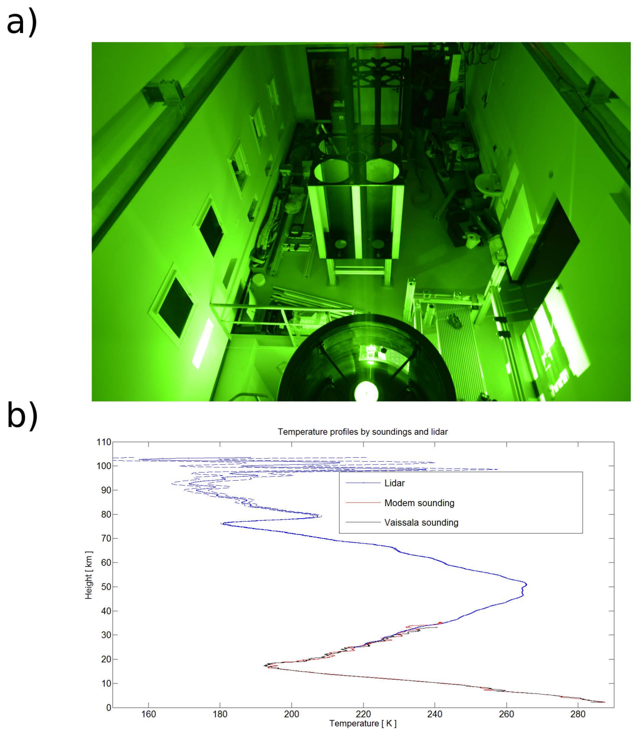

Fig. 3. (a) Photo showing the optical reception of the three lidar systems: water vapor and temperature at the foreground, tropospheric ozone at the middle and stratospheric ozone at the background. The lasers are in the room on the left and the spectrometers in the room on the right. **(b)** Temperature profiles on 2 April 2013 with M10 Modem radiosonde and lidar at Maïdo. Vertical ranges for lidar, Modem and Vaisala Soundings are respectively 24–90 km, 2–35 km and 2–33 km above sea level.

20g (depending on the wavelengths) mini-PMTs and data acquisition consists in the use of LICEL PR 10–160 transient recorders in photo-counting. Coaxial geometry for emission and reception provides parallax effects to be avoided, extends measurement down to the ground and facilitates the alignment. We defined and built an integrated and removable support for a calibration lamp to complement the calibration with total water vapor column measurements from a co-located GPS instrument to use the hybrid technique (Leblanc and Mc Dermid, 2008). Both possible emitted wavelengths combined with a set of permanently installed detection boxes working both in the visible and in the UV enable different operating modes that have been tested and compared, on the same instrument. An example of a profile of temperature reaching a 90 km altitude, combining lidar and simultaneous radiosonde measurements on 2 April 2013, is shown in Fig. 3.

The tropospheric ozone DIAL lidar system is another upgrade of the existing Rayleigh–Mie lidar system. The emission part of this system consists of a wavelength pair (289 and 316 nm) obtained by Raman shifting of the fourth harmonic of the Nd:Yag laser in a high pressure deuterium cell. The energy at 266 nm is 40 mJ pulse^{-1}. The laser frequency is 30 Hz and the beam diameter 10 mm. The length and diameter in/out of the Raman cell are respectively 1500, 20 and 55 mm. The beam is expanded in a divergence optimizer system located after the Raman cell. The output diameter and divergence of the emitted beam are 30 mm and 0.25 mrad (Baray et al., 1999). Regarding the reception system, we use the 4 telescope mosaic used before. The signal collected is transmitted with 1.5 mm diameter optical fibers. The spectral separation of 289 and 316 nm beams is obtained with a spectrometer formed by a Czerny–Turner holographic grating. The altitude of the Maïdo Mount being 2200 m a.s.l., the transfer of the tropospheric ozone DIAL system from the university (80 m a.s.l.) to this location is positive concerning the upper limit of the profile, but it will also increase the lower limit from 3–4 to 5–6 km, i.e. over the lower limit of the free troposphere corresponding to the trade wind inversion. In order to compensate this, we add a smaller 200 mm diameter telescope, with a commutation from one mode to the other by switching the optical fibers at the entrance of the spectrometer.

Another DIAL lidar system allowing upper tropospheric and stratospheric ozone measurements has been operational at Reunion Island since June 2000. The geophysical objectives associated with this instrument are (1) the long-term monitoring of stratospheric ozone, (2) the study of the stratospheric ozone budget in the tropical region, (3) the study of tropical stratospheric dynamics and its variability. This DIAL system is similar in principle to the tropospheric ozone lidar presented before, but to observe the stratosphere, it is necessary to use another pair of emitted wavelengths. The design of this lidar is similar to another stratospheric ozone DIAL lidar implemented at the Observatoire de Haute-Provence in France (Godin-Bekmann et al., 2003)

Laser sources are a tripled Nd:Yag laser (Spectra-Physics Lab 150) and a XeCl excimer laser (Lumonics PM 844). The Nd:Yag provides the non-absorbed beam at 355 nm with a pulse rate of 30 Hz and a power of 5 W, and the excimer provides the absorbed beam at 308 nm with a pulse rate of 40 Hz and a power > 9 W. An afocal optical system is used to reduce the divergence of the beam to 0.5 mrad.

The receiving optical part is composed of 4 parabolic mirrors (diameter: 500 mm). The backscattered signal is collected by 4 optical fibers located at the focal point of each mirror. The spectrometer used for the separation of the wavelengths is a Jobin Yvon holographic grating (3600 lines mm^{-1}, resolution 3 Å mm^{-1}, efficiency > 25 %). After the separation by the holographic grating, the two Rayleigh beams at 308 and 355 nm are separated again at the output of the spectrometer by a lens system in the proportion 8 % and 92 %, respectively, in order to adapt the signal to the non-saturation range of the photon-counting system. The optical signals are detected by 6 Hamamatsu R7400 non-cooled photomultipliers (PM). A mechanical chopper is used to cadence the laser shots and cut the high

Table 2. List of instruments planned to be deployed at the Maïdo observatory.

Instrument	Parameter	Begin of operation	Mode of operation	Network	Laboratories involved
CRDS	CO_2, CO, CH_4, H_2O – ground	End of 2013	continuously	GAW, ICOS	LSCE
O_3 analyser	O_3 – ground	End of 2013	continuously	GAW	LACy
CCNC	CCN – ground	End of 2013	continuously	GAW	LaMP/LACy
DMPS	Aerosol granulometry – ground	End of 2013	continuously	GAW	LaMP/LACy
NO_x analyser	NO_x – ground	2014	continuously	GAW	LaMP

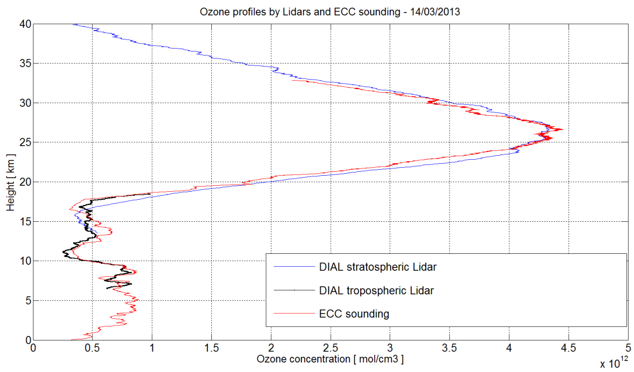

Fig. 4. Ozone profiles on 14 March 2013 by stratospheric DIAL (blue) and tropospheric DIAL (black) at Maïdo, and ozone sonde (red) near the airport.

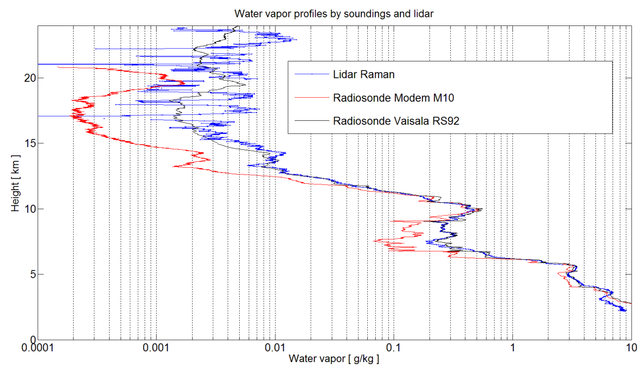

Fig. 5. Raman water vapor profile obtained at Maïdo observatory on 8 April 2013 (integration time: 1 h), intercompared with simultaneous M10 Modem and RS92 Vaisala radiosondes. The lidar profile has been calibrated with the RS92 sonde.

energy signal originating from the lower altitude range. This chopper consists of a steel blade rotating at 24 000 rpm in primary vacuum.

The current configuration provides the simultaneous acquisition of 6 channels: 2 channels at 355 nm corresponding to the lower and upper parts of the profile, 2 channels at 308 nm (lower and upper parts) and 2 Raman channels at 332 and 387 nm. In addition to the mechanical gating, the 2 upper Rayleigh channels are equipped with an electronic gating in order to protect the PM tubes from the signals corresponding to altitudes below 17 km.

The system worked from 2000 to 2006 at the Saint Denis site of Reunion Island University and was included in the NDACC network. It was moved to the Maïdo facility after the update of the electronic system (now LICEL TR and PR transient recorders) and of the XeCl excimer laser. This new configuration allows us to obtain ozone profiles in the 12–45 km altitude range. An intercomparison campaign of all the NDACC lidar systems (water vapor, temperature, ozone) with the mobile system of NASA-GSFC (McGee et al., 1995) is planned for October 2013.

First ozone profiles obtained with DIAL lidar at Maïdo and ozonesondes at the airport are given in Fig. 4. The temporal and spatial differences are 2 h and 30 km. The agreement between the three profiles is satisfactory, taking into account the ranges of each profile, 6–16 km for the tropospheric DIAL, 13–38 km for the stratospheric DIAL and 0–34 km for the ozonesonde. Water vapor profiles obtained with the Raman system cover from the ground to the lower stratosphere and demonstrate the capacity of this instrument to document UTLS water vapor studies (Fig. 5).

A Doppler lidar giving the wind profile from 5 to 50 km is currently deployed at the Maïdo facility for the validation of the Doppler wind space lidar ADM-AEOLUS and for studies on the dynamics of the stratosphere and the UTLS. The second harmonic of a monomode Nd:Yag laser is sent alternatively in the west and south directions at 45° from the zenith. The two components of the horizontal wind are obtained from the measurement of the Doppler shift of the return signal spectrally filtered by a double-edge Fabry-Pérot etalon (Souprayen et al., 1999).

Finally, the mobile lidar Leosphere ALS450, devoted to tropospheric aerosols and used previously for Marion Dufresne campaigns (Duflot et al., 2011), can be deployed at Maïdo in order to provide additional lidar profiles at the 355 nm wavelength to document tropospheric aerosol and cirrus issues, complementary to ozone and water vapor issues.

3.3 Passive remote sensing measurements

Passive remote sensing activity at Maïdo mainly consists of FTIR solar absorption measurements at high spectral resolution (of order $0.003\,cm^{-1}$). First measurement campaigns have been performed at the Saint Denis site of Reunion Island University in 2002, 2004, and 2007 by the Belgian Institute for Space Aeronomy (BIRA-IASB) in collaboration with the Free University of Brussels (ULB), and routine measurements started in 2009. The experiment provides total and partial columns of ozone and water vapour and several more tropospheric and stratospheric trace gases and is part of the NDACC. The experiment configuration, the characteristics of the data and the data analysis procedures are described in Senten et al. (2008). It is worth mentioning that the FTIR technique has the particular capability of measuring total column amounts of individual isotopologues of atmospheric species, e.g., of HDO. The FTIR experiment is operated using BARCOS, a system developed at BIRA-IASB for automatic operation with the possibility of remote control from the institute in Brussels (Neefs et al., 2007).

In the early campaigns and up to the end of 2011, the FTIR observations were carried out with a mobile Bruker 120M spectrometer at the University of Reunion in St Denis. In September 2011, we installed a Bruker 125HR spectrometer next to the Bruker 120M. This spectrometer is no longer transportable, but of higher quality and stability. It is the latest version of the Bruker spectrometer series dedicated to atmospheric measurements; it is also the instrument that is the actual standard for TCCON (Total Carbon Column Observing Network) observations. After a few months (September to December 2011) during which we operated the Bruker 125HR and Bruker 120M in parallel at St Denis, for verifying the consistency of the data, we removed the Bruker 120M, and continued the observations with only the Bruker 125HR. The instrument switched between TCCON observations in the near infrared (4000 to $8000\,cm^{-1}$ or 1.25 to 2.5 µm) and NDACC observations in the 2200 to $4500\,cm^{-1}$ (2.2 to 4.5 µm) spectral range using an InSb detector and CaF_2 optics.

In February 2013, a second Bruker 125HR spectrometer was installed at Maïdo, primarily dedicated to NDACC measurements in the mid-infrared (InSb and HgCdTe detectors with KBr optics), covering the spectral range 600 to $4500\,cm^{-1}$ (2.2 to 16 µm). Since then, the FTIR observations at Saint Denis have primarily been dedicated to TCCON observations for making high-precision measurements of the concentration of greenhouse gases. Both experiments, at Maïdo and Saint Denis, are operated with an updated version of BARCOS. Also the suntracking at Maïdo has been updated according to the method developed by Gisi et al. (2011), to be more precise. It is planned to implement a similar update of the suntracking at Saint Denis in August 2013. Photos of the Maïdo FTIR instrument and first spectra obtained at Maïdo are given in Fig. 6. The scientific objectives are in line with the NDACC and TCCON objectives, respectively. In addition to the continuous monitoring of the atmospheric chemical composition and transport processes, our intention is also to participate to dedicated ob-

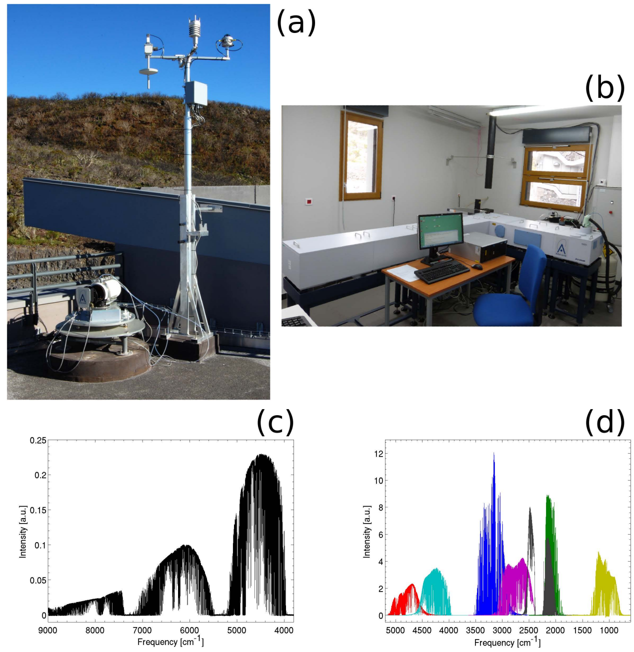

Fig. 6. (a) The sun tracker and meteorological station of the FTIR instrument. **(b)** The high-resolution Bruker IFS 125/HR infrared spectrometer in the room underneath the solar tracker. **(c)** A near-infrared spectrum collected according to the TCCON specifications on 18 April 2013. **(d)** Several mid-infrared spectra, collected using different NDACC optical filters and two different detectors (InSb and HgCdTe). These spectra were recorded on 28 May 2013.

servations campaigns. The FTIR instrument at Saint Denis is also equipped with all necessary optics and detectors for making NDACC-type observations. We intend to perform a 1 yr campaign (probably in 2014) during which we will perform NDACC-type observations simultaneously at Saint Denis and Maïdo, to study the processes in the 2 km-thick layer between both stations. Hereto, we will make use of the FTIR data, model simulations and the in situ surface data at both stations.

Moreover, a Trimble NetR9 Global Navigation Satellite System (GNSS) reference receiver coupled to a Zephyr Geodetic 2 Antenna has been set up since March 2013. Using the latest generation of Trimble receiver technology, this reference receiver offers 440 channels for unmatched GNSS multi-constellation tracking performance at 1 Hz frequency. The choice of this additional instrument for water vapor monitoring comes from many reasons. First, the high acquisition frequency will provide the opportunity to document the temporal variability of water vapor above the Maïdo observatory with a very high resolution. Secondly, the accuracy in GPS integrated water vapor (IWV) has been assessed by many authors, using intercomparisons with radiosondes, microwave radiometers, sun photometers, lidars, and very long baseline interferometry (Foelsche and Kirchengast, 2001; Niell et al., 2001; Bock et al., 2004). The agreement between these techniques is about 1–2 kg m^{-2} and leads to make the GPS as a reference for total columns. In addition, being independent from solar radiations, this GPS will be devoted to the nighttime Raman water vapor lidar system calibration. Indeed, lidar calibration by comparison with other collocated sensors has become the standard (Ferrare et al., 1995; Turner et al., 2002; Whiteman et al., 2006).

The basic GPS atmospheric product is the tropospheric delay of the GPS signal that has traveled between a GPS satellite and a ground-based receiver. The standard procedure for GPS data analysis assumes that the delay in any direction can be mapped from the delay at zenith to which a horizontal gradient is added. Three sets of parameters are then estimated during the analysis: zenithal tropospheric delays (ZTDs), gradients, and postfit residuals, which are the difference between the modeled atmosphere and the measurements. The dry-atmosphere component is removed from the ZTD, and the remainder is converted into Integrated Water Vapor, using surface pressure and temperature and empirical formulas (Emardson and Derks, 1999).

The next objective for this GPS station at Maïdo is to be part of the IGS global system of satellite tracking stations and data center, where high-quality GPS data products are stored on line in near-real-time to meet the objectives of a wide range of scientific and engineering applications and studies (http://igscb.jpl.nasa.gov/network/netindex.html).

A station of the World Wide Lightning Location Network (WWLLN – http://www.wwlln.net/) is also installed at Maïdo. The WWLLN is a real-time lightning detection network with global coverage operated by the University of Washington. The WWLLN uses the "time of group arrival" of very low-frequency radiation (3–30 kHz) to locate lightning strokes (Dowden et al., 2002; Rodger et al., 2006). This network detects both cloud-to-ground and intra-cloud lightning. As cloud-to-ground flashes have higher peak current, their detection efficiency is about twice the intra-cloud one. Currently, the network is composed of 54 sensors detecting sferic (impulsive signal from lightning discharges) activity. The VLF receiver station consists of a short (1.5 m) whip antenna, a GPS receiver, a VLF receiver, and an Internet-connected processing computer. This network permitted the analysis of the lightning activity in the southwest Indian Ocean (Bovalo et al., 2012), the lightning activity associated to transient luminous events (Soula et al., 2011), and the study of potential of lightning activity to be indicative of tropical cyclone intensity change.

Finally, the ground-based microwave radiometer DODO (Fig. 7a) funded by Reunion Island University (France) and developed at the Laboratoire d'Aérologie, Toulouse (France) and Technical Division of INSU, Meudon (France) was installed in April 2013 at the Maïdo station facility. The instrument detects the 6_{16}–5_{23} water vapor transition line at 22.235 GHz by means of a corrugated horn 80 cm long and 6° HWHM (half-width at half-maximum) angular resolution. After 2 frequency downscalings, the radio frequency (RF)

a)

b)

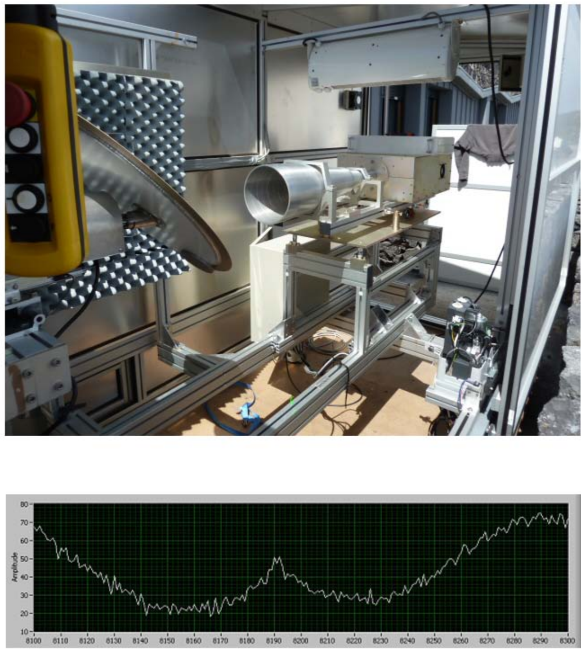

Fig. 7. (a) Photo showing the DODO radiometer installed at the Maïdo Observatory in March 2013. **(b)** Calibrated spectra (Kelvin) obtained on 12 April 2013 at the Maïdo station facility after an integration time of 20 h focusing on the center of the spectrometer (H_2O line center is located at the channel number 8192).

signal enters a FFT (Fast Fourier Transform) spectrometer centered at 500 MHz over a bandwidth from 0 to 1 GHz with a spectral resolution of 64 kHz. Based upon the same measurement principle as described in Motte et al. (2008), the radiometer, operating in a single side band (SSB) mode, can measure a spectrum in a balancing mode between low (20°–30°) elevation angles and zenith angle every 15 min. The instrument is automated and currently installed inside a dedicated shelter of $3 \times 1.5 \times 2.1$ m^3. Liquid nitrogen calibration has to be performed on a monthly basis. The receiver noise temperature is about 165 K. A typical calibrated spectrum obtained after 20 h integration is shown on Fig. 7b. Some points are worth mentioning. The radiometer tuning is not optimized. Some of the undulations present on the spectra will certainly be reduced by translating the rotating mirror when making measurements to cancel out coherent signal induced by reflections on any obstacles (for instance, the mirror). Once these tunings provide a calibrated spectrum with reduced undulations, vertical profiles will be obtained using the analysis tool Microwave ODIN Line Estimation and Retrieval (MOLIERE) originally developed for the space mission ODIN (Urban et al., 2003). It is based on the Optimal Estimation Method (Rodgers, 2000) to retrieve vertical profiles and has been successfully adapted to the ground-based H_2O instruments: (1) MobRa, stratospheric H_2O measured at 22 GHz (Motte et al., 2008), and

(2) HAMSTRAD, tropospheric H_2O measured at 183 GHz (Ricaud et al., 2013). Theoretical calculations (Motte, 2008) show that the DODO radiometer will be able to measure vertical profiles of H_2O from ~ 15 to ~ 75 km with a resolution of 7–12 km. This instrument provides an opportunity for external teams to perform measurements with this or other radiometric instruments for intercomparisons.

4 In situ measurements of tropospheric gases and aerosol composition

4.1 Low layer atmospheric composition study

We have described in Sect. 3 the remote sensing instrumentation and the scientific interest of Maïdo measurements for the tropical UTLS. But the site also provides a unique platform for studying in situ properties of atmospheric gases and aerosols. Indeed, in situ measurements of atmospheric gas and aerosol properties are rather scarce in the southern hemisphere, and even more rare over oceanic regions. The only other long-term monitoring station in this region of the world is, to our knowledge, the Amsterdam Island observatory, which is located further south towards the Antarctic region. The Maïdo observatory is located at an altitude that will allow for the characterization of the composition of the free troposphere under the southern oceanic influence, when nighttime samples are selected. The Maïdo observatory will thus offer a unique opportunity to sample atmospheric gases and aerosols representative at a large scale of the marine unperturbed environment in the southern atmosphere under moderate temperatures. In a context where large uncertainties in the organic content of marine aerosols, and its possible link to the biological activity of the sea water, are still large, the Maïdo observatory will be an ideal environment to provide contrasted conditions compared to the Atlantic ocean. The site is also favorable to the study of the volcanic ash (gas and aerosol phase), thanks to the presence of the Piton de la Fournaise active volcano (Tulet and Villeneuve, 2011). Furthermore, specific studies can be performed under cloudy conditions to understand gas-aerosol-cloud interactions for various, but rarely studied types of air mass types previously mentioned, in the form of intensive campaigns. Hence the Maïdo facility is a TNA (TransNational Access) European site in the framework of the European project ACTRIS.

4.2 Gas measurements

Ambient in situ measurements of trace gases (reactive gases and greenhouse gases) are being deployed at the Maïdo facility to provide qualified data to global networks (GAW and NOAA GMD aerosol monitoring programs). A main advantage of the Maïdo facility aerology for ambient measurements is its capacity to represent synoptic scales of the free troposphere at night and local scales during the diurnal development of the planetary boundary layer with sea breeze and orographic lifting.

Greenhouse gases will be continuously measured at the Maïdo observatory, as part of the French monitoring program SNO-ICOS-France. The measurement system has been designed in accordance with the technical requirements and recommendations established by ICOS working groups. One can distinguish three parts: the air inlet system, the calibration scale, and the analyzer. We are using a CRDS (cavity ring down spectroscopy) analyzer commercialized by Picarro (Crosson, 2008), which detects CO_2, CH_4, CO and H_2O (G2401 model). The optical cavity equipped with high reflectivity mirrors enables an optical path of about 12 km with a measurement cell of 10 cm^3, and is internally regulated both in temperature and pressure. A precise determination of each trace gas is performed every five seconds. The analyzer is automatically calibrated every three weeks by using a suite of four standard gases, which have been themselves calibrated at LSCE against WMO reference scales. In addition to the calibration scale, spanning the typical variability observed in the atmosphere, two more standard gases are connected to the analyzer. These two target gases are used for quality control purposes, and are used respectively about twice per day and once per month. The measurement precisions determined from measurements performed at Saint Denis (standard deviation of the one-minute averaged raw data of the calibration gases measurements) are 0.03 ppm, 0.3 ppb and 1.0 ppb respectively for CO_2, CH_4 and CO. The data will be transferred once per day to the ICOS atmospheric thematic centre which is in charge of the data processing. After the validation phase the data set will be available for distribution to the World Data Center for Greenhouse Gases (WDCGG).

From 2008 to 2012, a UV photometric analyser (Thermo Scientific model 49i) has provided ambient measurements of concentrations of ozone in Bourg-Murat (nearby the center of the island at 1600 m a.s.l.). This device will be installed at the Maïdo facility before October 2013 to provide ambient measurements at the ground level and to complete the vertical profile performed by the tropospheric ozone lidar. The Model 49i uses a dual-cell photometer, the concept adopted by the National Institute of Standards and Technology as the principle technology for the national ozone standard. It measures amounts of ozone in the air from mole fractions of 0.05 ppb to 200 ppm with a response time of 20 s and a precision of 1 ppb. It is certified by air pollution monitoring networks (e.g. US Environmental Protection Agency , ATMO France).

In addition, the instrument Environnement SA AC31M for the measurement of NO_x ($NO + NO_2$) is currently testing at the laboratory LaMP (Clermont Ferrand, France) and inter-comparing at the Puy de Dome station (http://wwwobs.univ-bpclermont.fr/SO/mesures/instru.php) with another NOx instrument (Thermo environmental Instrument TEI), validated by the ACTRIS consortium (http://www.actris.net). In common with other commercially available instruments, the Nitrogen Oxides analyzer uses an ozone

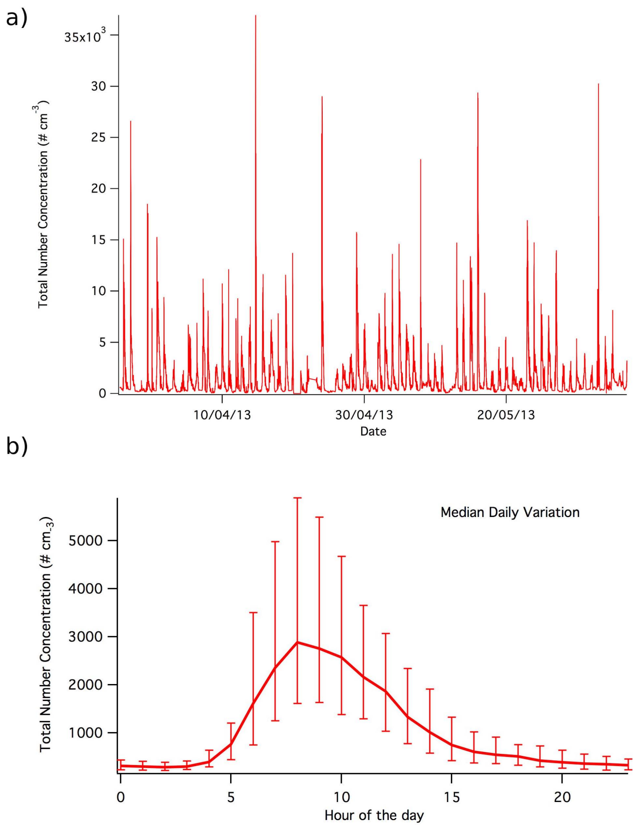

Fig. 8. First aerosol total number concentration observed at Maïdo facility: **(a)** 2 months time series (April and May 2013). **(b)** Median daily variation averaged over the whole measurement period.

chemiluminescence technique. The instrument does not measure nitrogen dioxide (NO_2) directly. Instead the instrument measures nitric oxide (NO) and total oxides of nitrogen (NO_x), which is assumed to consist of NO and NO_2 only. Chemiluminescence is used to measure NO concentration by detecting the UV light emitted during the reaction within the analyser between NO and internally generated ozone (O_3), producing NO_2* in an excited state, which then decays to its normal state by the emission of a photon. The photons emitted are then measured using a photo-multiplier tube. NO_x is measured by passing the sample of ambient air through a catalyst at around 300 °C which converts all NO_2 to NO, leaving ambient NO unaffected. The NO is then measured to give total NO_x concentration. The Environnement SA AC31M is a dual chamber analyser with separate paths for measuring NO_x and NO simultaneously. Its deployment at Maïdo is planned for the beginning of 2014.

4.3 Aerosols measurement

Because of the frequency with which the station is in clouds, it was necessary to build specific inlets dedicated to sampling aerosols under cloudy conditions. A whole air inlet (WAI) which upper size cut is at least 30 microns for the average wind speed measured at the site permits the sampling of a large fraction of cloud droplets with their subsequent evaporation along the sampling duct. The sampling duct is driving the residual aerosol over a distance of 4 m vertically below the sampling head. Residual aerosols can then be analyzed for their physico-chemical characteristics. Sub and super-micron aerosols are directly measured at the end of the vertical duct for their chemical composition, using a PM_{10} size cut and two filter holders for subsequent IC and EC/OC analysis. The sampling of aerosols is performed on a weekly basis, only selecting nighttime periods in order to exclude possible daytime local contamination of the filters. Hence, the chemical composition of the aerosol is representative of the marine free troposphere. Size distributions will be monitored using a DMPS system, mainly composed of a Ni-63 neutralizer, a TSI-type DMA, and a TSI 3772 condensation particle counter (CPC). The sheath air of the system operates in a closed loop, the flow rate of which is maintained constantly using a blower and pressure difference sensors. The aerosol flow rate, temperature and relative humidity are continuously monitored following the recommendation of Wiedensholer et al. (2012). Quality control of the size distribution is performed with a zero CPC counting and total concentration checks on a weekly basis. In parallel, size-selected aerosols are also characterized for their CCN properties using the mini-CCN (Roberts and Nenes, 2005), coupled to the size-selecting DMA of the SMPS. The CCN chamber is operated at a constant temperature roughly corresponding to a 0.25 % supersaturation (Asmi et al., 2012). Inversion and charge correction procedures are described in Asmi et al. (2012). Calibrations of the CCNC supersaturation is performed using ammonium sulfate on a weekly basis according to the ACTRIS recommendations. The first aerosol total number concentrations observed at Maïdo are given in Fig. 8. The measurements display a daily cycle with very low nighttime values (about 300 cm^{-3}) and daytime relatively high concentrations (about 10 000 cm^{-3}). This daily cycle is in accordance with air masses' behavior predicted by modeling studies (Lesouef et al., 2011).

In addition, chemical composition of bulk (PM_{10}) aerosol is currently monitoring using filter sampling. Collection is performed between 22:00 and 05:00 local time in order to capture only free tropospheric aerosols without local (Reunion Island) contamination. Aerosol number concentration measurements performed in parallel are used to ensure that collections were performed within free tropospheric conditions. Filter samples are collected on a weekly basis for the quantitative determination of the particulate mass (gravimetry), the major ion species (Cl^-, ${NO_3}^-$, ${SO_4}^{2-}$, Na+, ${NH_4}^+$, K^+, Mg^{2+}, Ca^{2+}), light organics (oxalate, methanesulfonate), light absorption (at 370 and 880 nm), elemental and organic carbon (EC, OC). This large data set will be further compared against similar observations performed in the southern Indian Ocean at Amsterdam and Crozet Islands (Sciare et al., 2009) and in South Africa (Cape Point station). Marine (biogenic) emissions will be studied on a seasonal perspective. Influence of long-range transport and possible contribution of African biomass burning will also be evaluated based on specific tracers and air masses back-trajectories.

To complete the set of basic aerosol measurements, it would be useful to add optical aerosol properties measurement. Hence, we plan to collaborate in the future with the laboratory LGGE (Grenoble) to analyze optical properties of sub- and super-micron aerosols using a 7lamda aethalometer and Ecotech nephelometer.

5 Conclusion and perspective

The Maïdo facility, open since 2012, is devoted to the long-term atmospheric survey in the southern edge of the tropical band. Because of the altitude of the site, its location on the western coast of the island and the technical evolution of the instruments, the observatory represents a significant improvement in remote sensing measurements since the beginning of atmospheric observations in 1992 (Baray et al., 2006). It will provide valuable data for satellite validation and it will become a reference site in the southern subtropics for the global networks for the survey of the atmosphere such as NDACC. It will be possible to exploit original data coupling ozone, water vapor, and aerosols to document processes in the UTLS and TTL. Located in the free troposphere during the night, in situ measurements will also characterise the baseline atmospheric composition in the framework of climate change, and participate to the Global Atmosphere Watch (GAW) program. In addition, the facility has been over-dimensioned in order to offer the possibility to host experiments or measurement campaigns for external teams.

Acknowledgements. The project to build an altitude station at Maïdo has been imagined and initiated by Gérard Mégie, Jean Leveau and Serge Baldy, and politically strongly supported by Jean-Marie Flaud. The UMS 3365 of OSU-Reunion and the Maïdo facility have been supported by Reunion Island Council, the French Ministry of Research and European Community for building and equipment funding. They are now supported by CNRS and Reunion Island University for the operational phase. The research laboratory LACy (UMR8105) is supported by the CNRS, Météo-France and Reunion Island University. Water vapor and aerosols instrumentations are supported by French national SOERE programs, respectively ROSEA and ORAURE. Doppler lidar instrumentation is supported by the French agency CNES. The FTIR instruments have been acquired with Belgian LOTTO funding, and supported by the Belgian Science Policy via Belgian national research programs, by the ESA PRODEX program, and through short-term EU R&D projects. We acknowledge Gérard Ancellet and Hassan Bencherif for their work on tropospheric ozone and temperature lidars of Reunion Island when the instruments were deploying at Saint Denis, Corinne Vigouroux, Nicolas Kumps and Bavo Langerock for their work on FTIR instrument and data processing, Mickael Ribeiro, David Picard and Christophe Bernard for deploying aerosols inlets, and Serge Deconihout for deploying the 1200 telescope. We acknowledge also the technical and administrative staffs of UMS3365-OSU Réunion and LACy, with a special attention to Martial Barblu, Meriem Braham, Rémy Decoupes, Eric Golubic, Patrick Hernandez, Louis Mottet, Dominique Perrot, Joyce Poinen, Stéphane Richard, and Padmapriya Tirougnanasambandame.

Edited by: D. Griffith

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