Direct Radiative Forcing Due to Aerosol Properties at the Peruvian Antarctic Station And Metropolitan Huancayo Area
We describe the results of the study of aerosol optical depth (AOD) and Direct Radiative Forcing (DRF) in Top Of Atmosphere (TOA), obtained from the measurement and monitoring campaign carried out during the XXI Antarctic Peruvian Expedition in the months of January and February 2013 and in the Metropolitan Huancayo Area in the months of June and July 2019. In the Scientific Peruvian Station at Antarctic “Machu Picchu” our used a SP02-L sun photometer, which is within the instrumental framework of the International Polar Year. This instrument has 4 channels: 412 nm, 500 nm, 675 nm and 862 nm, thus allowing direct radiation spectra measurements. And in the MHA we used the BF5 sensor. This instrument measured Direct, Diffuse and Global Radiation in low wavelength. The results calculated of AOD in polar latitudes varied between 0.0646 to 0.1061, in relation to AOD in MHA, presents the value maximum that is 0.58 (11 of June) and minimum that is 0.19 (12 June). The Angstrom coefficient was determined have values ranging from 0 to 0.07, these values also indicates the presence of big particles. Also to the MHA presents the mean value varied from 0 to 1.8, that indicated the presence the aerosols types biomass burning and industrial. Recorded optical properties used to estimate the direct aerosol radiative forcing (DARF) at the top of the atmosphere. The results indicates that on King George Island site the DARF is between [-2 4] W/m²; also, the direct aerosol radiative forcing in MHA is between [0 20] W/m².

**Keywords:** Aerosol, Radiative Forcing, Antarctic.
INTRODUCTION

As the direct solar radiation passes through the atmosphere, it is attenuated by two main physical processes: scattering (angular redistribution of energy) and absorption (conversion of energy into either heat or photochemical change). Both effects are known to be wavelength dependent (El-Shobokshy & Al-Saedi, 1993). Traditionally, the tool most commonly used for monitoring the aerosol optical depth of the atmosphere has been the sun photometer. Essentially, the instrument which is small in physical dimensions, is sighted at the sun to measure the direct solar irradiance in some selected narrow spectral intervals (Volz, 1959).

Aerosol particles affect the climate system via the following physical mechanisms: First, they scatter and can absorb solar radiation. Second, they can scatter, absorb and emit thermal radiation. Third, aerosol particles act as cloud condensation nuclei (CCN) and ice nuclei (IN). The first two mechanisms are referred to as direct effects and are not subject of this paper but are discussed in detail in e.g., Haywood & Boucher (2000). The last one is referred to as indirect effect. It will be the subject of this review together with other atmospheric properties influenced by aerosols (e.g. semi-direct effect, suppression of convection).

Even though the semi-direct effect is a consequence of the direct effect of absorbing aerosols, it changes cloud properties in response to these aerosols and therefore is part of this review on aerosol-cloud-interactions.

Radiative Forcing (RF) is defined as the change in net irradiance at the tropopause due to an applied perturbation holding all atmospheric variables fixed, once stratospheric temperatures have been allowed to adjust to equilibrium. The concept of RF was first developed for one-dimensional (1-D) radiative convective models (e.g., Intergovernmental Panel on Climate Change - IPCC, 1996) considered the direct radiative forcing from three different anthropogenic aerosol species: sulphate, fossil fuel black carbon (or soot), and biomass-burning aerosols.

IPCC (1996) suggested a range of 20.2 to 20.8 W m$^{-2}$ (“best guess” of 20.4Wm$^{-2}$) for sulphate aerosols, 10.03 to 10.3 W m$^{-2}$ (best guess of 10.1 W m$^{-2}$) for fossil fuel black carbon aerosols, and 20.07 to 20.6 W m$^{-2}$ (best guess of 20.2 W m$^{-2}$) for biomass-burning aerosols.

The present research work estimates the direct radiative forcing of aerosols at the Scientific Peruvian Station Antarctic Machu Picchu and in the Metropolitan Huancayo Area.
METHODS

Site description

The Scientific Peruvian Station at Antarctic “Machu Picchu” (referred as ECAMP, 62°05’30” S, 58°28’16” W and 6 meter above sea level (masl)) is located at King George Island, the largest of the South Shetland Islands, on the northern tip of the Antarctic peninsula (Figure 1). About 90% of King George Island extension is covered by ice (Simoes et al., 1999). The Peruvian station is located very close to the open ocean so the climate regime is characterized by maritime conditions. Brazilian and Polish Antarctic stations are the closest ones. The Peruvian station is only operated during austral summer covering periods from December to March at maximum, depending of logistics aspects. This station is operated by the Peruvian Antarctic Institute and actually is run by the Office of Antarctic Affairs of the Ministry of External Affairs.

The closest station to Peruvian station with continuous meteorological measurements is Comandante Ferraz, the Brazilian Antarctic station that is about only 5 km from the Peruvian one. Temperature records for the period of 1947 to 1995 shows that the mean is –2.8°C, with a minimum of –5.2°C and a maximum of –0.8°C, for year 1959 and 1989, respectively. It showed a warming trend of 0.022°C per year, resulting in a mean air temperature rise of 1.1°C over 49 years. The temperature during summer, the season that covers the aerosol sampling at the Peruvian station, could reach some degrees over 0°C, with a mean of 0.9°C (Ferron et al., 2004). Storms are quite frequent over this region of the Antarctic Peninsula so mean wind speed is above 4 m/s with high variability due to synoptic circulation patterns like the next ones described by Braun et al. (2001):

(a) advection from north to northwest
(b) southerly to southeasterly air mass transport
(c) advection from northwest
(d) advection from west to southwest
Figure 1. Map presenting the location of the Peruvian Antarctic Station “Machu Picchu” and the main geographical references.

The study was also conducted in the MHA located at coordinates 12°4´12.03´´S, 75°12´43.55´´W with altitude of 3300 masl, it is part of the central Andean region of Peru, as seen in Figure 2, located in South America and east of the Pacific Ocean. It is one of the 10 most populous provinces of Peru, whose annual population growth rate is 1.6%, with more than half a million inhabitants (Instituto Nacional de Estadística e Informatica, 2007).

The MHA belongs to the Mantaro Valley, it occupies an area of 319.4 km². Its topography is quite complex with rock formations and altitudes ranging between 3000-5000 masl, this range of altitudes is generally due to the presence of mountains.
Field campaigns for taking sun photometry measurements were carried during Peruvian Antarctic campaign: ANTAR XXI (January and February 2013) and Campaign in the Huancayo province (June and July 2019). The fieldwork at ECAMP and Huancayo has been programmed with the main objective of quantifying the AOD as an indicator of atmospheric pollution and evaluate its variation among the different years of measurements.

The main instrument used was the sun photometer that collects information about the physical and optical properties of aerosols along a vertical path of the atmosphere. This sun-photometer, named herein front as SP02-L, is used to measure solar irradiance at five different wavelengths that nominally are 412, 500, 675, 862 nm with 10 nm of bandpass (Middleton Solar, 2004). A previous model has been used extensively for other research groups by NOAA/USA (Stone, 2002), by the Australian Bureau of Meteorology in its national network (Mitchell & Forgan, 2003) and more recently by groups for doing measurements at Antarctic sites as part of a namely POLAR AOD network (Mazzola et al., 2011). In this improved model it has a 35 mm longer body to give a narrower field of view of 2.5° (1.25° opening angle), a slope angle of 0.7° and a limit angle of 1.8°. The fieldwork at Huancayo
the instrument used was the sun pyranometer, BF5 model; that collects information about
the diffuse and direct radiation along a vertical path of the atmosphere.

For the corresponding measurements of solar radiation in the Province of Huancayo, was
used the BF5 sensor, located at 12°4′0″ S and 75°13′0″ W, in the Metropolitan Huancayo
Area. This records data with a frequency interval every minute, of the following variables:
global radiation and diffuse incident radiation since June 4, 2019. With this information, the
atmospheric clarity index was determined, and the temporal variability was analyzed direct,
diffuse and global solar radiation. The BF5 Sensor is a patented design. It uses a series
of photodiodes with a unique computer-generated hatch pattern to measure incident solar
radiation. A microprocessor calculates the Global and Diffuse components of solar radia-
tion. A built-in heater keeps the BF5 free from dew, ice, and snow down to -20 °C.

Aerosol Optical Depth

The direct solar irradiance measured with this sun-photometer is used to describe the
spectral values of the aerosol optical depth (AOD) associated to each wavelength that are
determined based on the well known law of Lambert-Bougger-Beer.

\[
I(\lambda) = I_0(\lambda)R^{-2}e^{-m\tau(\lambda)} \ldots \ldots \tag{1}
\]

Where \( I(\lambda) \) is the solar intensity recorded at each wavelength \( \lambda \), \( I_0(\lambda) \) is the value of solar
radiation at the top of the atmosphere (TOA), \( R \) is the solar distance expressed as astronomi-
cal units, \( m \) is the air optical mass and \( \tau(\lambda) \) is the total optical depth dependent on wavelength.
This last term can be described as the sum of the different constituents of the atmosphere.

\[
\tau(\lambda) = \tau_a(\lambda) + \tau_R(\lambda) + \tau_o(\lambda) \ldots \ldots \tag{2}
\]

Where \( \tau_a(\lambda) \) is the aerosol optical depth, \( \tau_R(\lambda) \) is the Rayleigh-Scattering optical depth,
and \( \tau_o(\lambda) \) is the ozone optical depth (Liou, 2007).

It should be noted that equations 1 and 2 are used in the estimation of AOD for ECAMP.

For AMH, if the model established by Iqbal (1983) is used, the optical aerosol thickness
can be estimated using the IQC model:

\[
\tau_a = 0.2758 \times 0.38^{-\infty} + 0.35 \times 0.5^{-\infty} \beta \tag{3}
\]
**Angstrom exponent**

Another important optical property of aerosols is the Ångström exponent (Ångström, 1964). It permits to quantify the spectral dependence of the AOD related with size and the vertical profile (Tomasi *et al.*, 1983). Ångström exponent is the slope of the lines that passes through the two values of AOD dependent of $\frac{\lambda_2}{\lambda_1}$ in a logarithmic scale as showed in equation 4 (World Meteorology Organization, 2005).

This indicator is very useful because high values of $\alpha$ indicate the predominance of fine particles and low values of $\alpha$ suggest the opposite. During this study it has been used 500 and 862 nm wavelengths accounting a small difference related to the World Meteorology Organization suggestion of 870 nm.

$$\alpha = - \frac{\log \log \left( \frac{\lambda_2}{\lambda_1} \right)}{\log \log \left( \frac{\lambda_2}{\lambda_1} \right)}$$ (4)

For the calculation of the Angstrom exponent in MHA, it was based on the Iqbal Model, using parameterization techniques as mentioned in his research Flores *et al.* (2014).

**Direct Radiative Forcing**

The attenuation of aerosols during clear sky conditions is known as the ‘direct’ influence of aerosols on climate. This effect results from backscattering and absorption of radiation by the aerosol particles themselves (Charlson *et al.*, 1992; Haywood & Boucher, 2000). Although many monitoring efforts the broad range of estimates due to aerosol direct radiative forcings still remains large and an important source of uncertainty in climate models (Forster *et al.*, 2007). Less data, spatially and temporal, is available at Polar regions. In that sense, as a globally-averaged annual mean, this direct attenuation will produce a cooling sign almost of the same magnitude of the warming caused by the greenhouse gases (Myhre & Shindell, 2013).

The annual mean at the top of the atmosphere direct shortwave aerosol radiative forcing, $DF$, can be roughly estimated using equation 6 and some values suggested by Haywood & Shine (1995).

$$\Delta F = - D S o T_{at} \left( 1 - A_c \right) \omega \beta \tau \left( \frac{1}{\omega} - 1 \right)$$ (5)

Where:
- D is the fractional day length (0.7 and 0.5 to ECAMP and MHA respectively),
- So is the solar constant (1370 Wm-2),
- $T_{at}$ the atmospheric transmission (0.76),
- Ac fractional cloud cover (0.6 and 0.35 to ECAMP and MHA respectively, based on the mean daily record of Cloud_Fraction from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor for King George Island site),
- Rs the surface reflectance (0.65 and 0.20 to ECAMP and MHA respectively, based on the mean daily record of Effective surface reflectivity at 360 nm (%) from Ozone Monitoring Instrument (OMI) sensor),
- $\omega$, the single scattering albedo, 0.8 at 1 and calculate for Iqbal method (1983)
- $\beta$, the upscatter fraction (0.27, based on measurement of medium latitudes),
- $\tau$, the aerosol optical depth,

**RESULTS**

**Aerosol Optical Depth**

Records of AOD at polar latitudes shows the lowest values of the world with higher values at Arctic than Antarctic. Figure 3A shows the complete set of daily records of AOD during Peruvian Antarctic Campaigns at ECAMP developed during austral summers of 2013. During these years AOD (500 nm) varied between 0.0646 to 0.1061, being a typical value for the conditions of atmospheric turbidity at a polar site dominated by maritime conditions, during this season of the year (Tomasi *et al.*, 2007), also are lower than the ones registered at urban cities, from 0.25 to 1.7 (Castro *et al.*, 2001), and much lower that records during biomass burning season where values can have values as high as 2.4 for the same wavelengths (Eck, 2003). Then the Figure 3B, in relation to AOD in MHA, presents the value maximum that is 0.58 (11 of june) and minimum that is 0.19 (12 June). Estevan *et al.* (2019) utilize a CIMEL sunphotometer belonging to the AERONET network have been performed in the Huancayo Observatory, Peru, from March 2015 to August 2017, two and a half years, providing for the first time information about aerosols in the specific area, and obtain the month with the maximum AOD monthly average is September, and in 2016, the absolute maximum value of 0.91 was registered. The mean AOD value for the study period is $0.10 \pm 0.07$ and the alpha mean value is $1.49 \pm 0.36$, indicating presence, of small size aerosols.

Comparing these values with other Antarctic monitoring stations, the ECAMP ones presents a high median for AOD (500 nm) of 0.0781. AOD recorded at Neumayer and Aboa Stations were 0.06 and 0.0551, respectively. These sites are also very close to the coast where the influence of marine aerosols is higher. Continental sites, far from the coast, present
lower values. AOD at Kohne and South Pole stations were values as low as 0.015 were recorded (Tomasi et al., 2007).

The comparison between the ECAMP and the other station offers the evidence of the main and important differences of the optical properties of the aerosols. Polar sites has a relatively very clean atmosphere, but they have a strong influence of particles, very small, mainly of marine source and eventually from anthropogenic sources and to the turbidity conditions that is usually present in summer and fall because the strong prevailing winds that also transport haze and dust (Shaw, 1982).

Figure 3. A. Daily variation of AOD at 500 nm for austral summers of 2013 in ECAMP; B. 2019 in MHA.

Angstrom coefficient

Angstrom coefficient $\alpha$ is useful to compare and characterize the wavelength dependence of AOD and columnar aerosol size distribution (Eck et al., 1999; Cachorro et al., 2001). Smaller values represents bigger particles, for example dust. On the other hand higher values represent smaller particles like smoke and/or burning particles (Shifrin, 1995). One way to
discriminate if the aerosols are mainly composed by particles of medium – small radius, smaller than 1 mm, or higher is to calculate the Ångström for the evaluated days. Values of $\alpha$ that are in the range of 0.12 and 0.4 indicates the presence of particles of big size (Otero et al., 2006), as it is shown in figure 3A from for the Antarctic site. During the year of campaign, the mean value for Angstrom coefficient ($\alpha$) varied from 0 to 0.07 that represents a low variability that can be both to instrumental and atmospheric properties but also indicates the dominance of big particles probably coming from maritime source. Also to the MHA presents the mean value for Angstrom coefficient ($\alpha$) varied from 0 to 1.8, that indicated the presence the aerosols types biomass burning and industrial.

Figure 4. A. Daily Ångström exponent variations during Peruvian Antarctic Campaigns at ECAMP for year 2013 and B. MHA for year 2019.

Aerosol Top Of Atmosphere (TOA) Direct Aerosol Radiative Forcing

The Aerosol TOA Direct aerosol radiative forcing (DARF) is strongly dependent of AOD ($\tau_a$) and of single scattering albedo (SSA, $\omega_0$), that it is a measure of scattering and absorption processes of solar light caused by aerosols becoming a key variable for DARF determination.
Comparing the forcing estimates with AOD values, we find that the radiative forcing is primarily governed by the magnitude of AODs which varied from a low value of 0.04 to high values above 0.065 at 0.5\,\mu m during the field campaigns.

For evaluating and estimating the DARF it was used the median of AOD (at 500\,nm) as it is the most representative value due to this non-parametric distribution. Our estimation for the King George Island site suggests that based on the equation 5 the direct aerosol radiative forcing is between $[-2.4] \, \text{w/m}^2$. The figure 5B shows the variation of the DARF based on the optical properties determined in the MHA, also the direct aerosol radiative forcing is between $[0\, 20] \, \text{w/m}^2$

**Figure 5.** A. Dependence of single scattering albedo ($\omega$) and AOD on the direct aerosol radiative forcing (DARF) for King George Island and B. MHA.

### CONCLUSIONS

Measurements of optical properties of aerosols performed during Peruvian Antarctic campaigns of year 2013 and MHA of year 2019 were analyzed; during these years AOD (500\,nm) varied between 0.0646 to 0.1061, in relation to AOD in MHA, presents the value maximum that is 0.58 (11 of june) and minimum that is 0.19 (12 June).

The Angstrom coefficient was determined by the same years with values ranging from 0 to 0.07 presenting a high variability that can be both to instrumental and atmospheric aspects. These values also indicate the presence of big particles. Also to the MHA presents the mean value for Angstrom coefficient ($\beta$) varied from 0 to 1.8, that indicated the presence the aerosols types biomass burning and industrial.

It was evaluated a first inference about the role of aerosols on the Earth’s energy balance. Recorded optical properties were used to estimate the direct aerosol radiative forcing (DARF) at the top of the atmosphere. The results indicate that focusing on King George Island
site the DARF is between [-2 4] W/m². Also, the direct aerosol radiative forcing in MHA is between [0 20] W/m².

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