

# Response of mixed-phase cloud microphysics to aerosol perturbations at the contrasting sites of Limassol, Cyprus, and Punta Arenas, Chile

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**Abstract:** Based on combined lidar-radar observations, two mixed-phase cloud cases from Limassol and Punta Arenas are studied. While the mixed-phase cloud observed over Limassol was embedded in a dust plume, the case over Punta Arenas was associated with continental and marine aerosols. Good agreement between the number concentrations of ice crystals (ICNC) and ice-nucleating particles (INPC) can be found in both cases, indicating the crucial role of INPs in ice formation. Abundant dust INPs at Limassol result in a large ICNC of  $1\text{--}10\text{ L}^{-1}$ . In contrast, much lower INPC was found at Punta Arenas, contributed by continental aerosols, resulting in two orders of magnitude lower ICNC ( $10^{-2}\text{--}10^{-1}\text{ L}^{-1}$ ).

## 1. Introduction

Mixed-phase clouds cover approximately 1/3 of the Earth's surface and play an essential role in the radiation budget of the atmosphere. Primary ice formation in mixed-phase takes place at  $0\text{--}38^\circ\text{C}$  with the aid of aerosol acting as ice-nucleating particle (INP), which is so-called heterogeneous nucleation [1]. The aerosol conditions, including the type, amount, vertical distribution, and ice-nucleation efficiency, significantly vary from region to region, which thus differ in the microphysical properties of ice crystals. In general, dust particles are considered a good type of INP, while marine aerosols show a much weaker ability for ice nucleation. Therefore, it is of great interest to understand the role of contrasting aerosol in ice properties.

With multi-year ground-based remote-sensing, Radenz et al. [2] have shown that clean Punta Arenas shows the lower fractions of ice-containing clouds by 0.1-0.4 absolute difference at temperatures ranging from  $-24^\circ\text{C}$  to  $-8^\circ\text{C}$  compared to dust-influenced Limassol, Cyprus and polluted Leipzig, Germany. This study will provide two case studies from Punta Arenas (53.2S, 70.9W) and Limassol (34.67N, 33.04E), respectively, to disentangle how the different aerosol conditions result in the different ice microphysics. The study goes thus a step ahead of the statistical analysis presented by [2].

## 2. Instruments and Method

In this study, we employed the observational datasets collected by the mobile Leipzig Aerosol and Cloud Remote Observations System (LACROS) from the Leibniz Institute for Tropospheric Research (TROPOS) [3]. The instruments of a MIRA-35 35-GHz cloud radar and a portable Polly<sup>XT</sup> multi-wavelength Raman polarization lidar were involved in observing the mixed-phase clouds. The case at Limassol was observed during the Cyprus Clouds, Aerosol, and Rain Experiment (CyCARE) from October 2016 to March 2018 [4]. The case at Punta Arenas was recorded during the Dynamics, Aerosol, Clouds, And Precipitation Observations in the Pristine Environment of the Southern Ocean (DACAPO-PESO) field campaign from November 2018 to November 2021 [2].

With the method from Bühl et al. [5], we can obtain the ice crystal number concentration (ICNC) with the combination of lidar and radar observations. The ratio of lidar-derived particle extinction to radar reflectivity was employed to retrieve the ice mean diameter and the ICNC was then derived by using the measured extinction coefficient. Note that we obtained the lidar particle extinction with the Fernald method starting from a reference height at sub-cloud regions by using a fixed lidar of 20 sr. The reference values of particle backscatter below clouds were taken from the Raman retrievals for

the nearby cloud-free period. In addition, we also employed the Polarization Lidar PHOtometer Networking (POLIPHON) method to obtain the dust-related INP concentration (INPC) out of the aerosol properties in the cloud surroundings [4].

### 3. Observational Results

Figure 1 shows that two dust layers were transported to Limassol on 30 April 2017. Two mixed-phase clouds appeared within the aloft dust layer, showing the cloud top temperatures of  $-26.7^{\circ}\text{C}$  and  $-20.6^{\circ}\text{C}$ , respectively. Optical and microphysical properties of the first ice virga around 1900 UTC are shown in Figure 2.

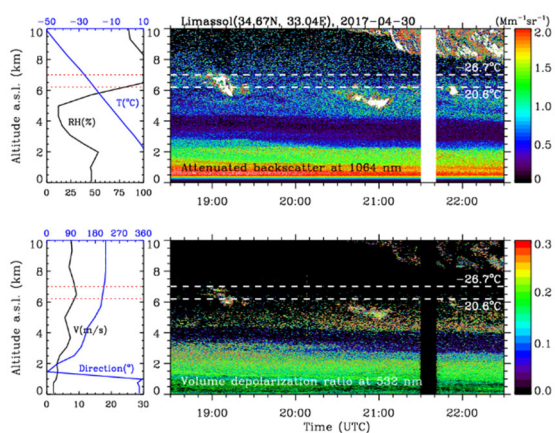


Figure 1. Lidar-derived attenuated backscatter at 1064 nm and volume depolarization ratio at 532nm on 30 April at Limassol. The meteorological parameters are provided by GDAS1 analysis.

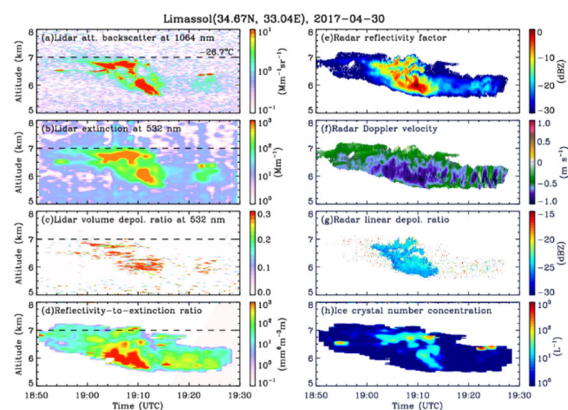


Figure 2. Optical and microphysical properties of the first ice virga in Figure 1 retrieved with the combination of lidar and radar. The plate-like shape is assumed for ice crystals (see Table A2 in [5])

In Figure 3, we show the comparison of INPC and ICNC profiles. The average ICNC for the period from 1902-1926 UTC ranges from 1-10

$\text{L}^{-1}$  and generally agrees well with the dust-related INPC derived with the parameterization from DeMott et al. [6]. This indicates that dust particles play a role in primary ice formation.

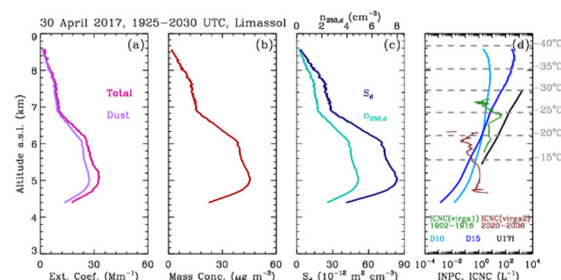


Figure 3. Lidar-derived INP-relevant parameters and the number concentrations of INP and ice crystals for the Limassol case.

In Figure 4, a well-defined mixed-phase cloud was observed at Punta Arenas at altitudes of 3.2-4.7 km on 28 November 2018. The cloud top temperature was  $-14.8^{\circ}\text{C}$ . Supercooled liquid top and ice virga below were evidently seen. The optical and microphysical properties of the ice virga derived from lidar and radar observations are shown in Figure 5.

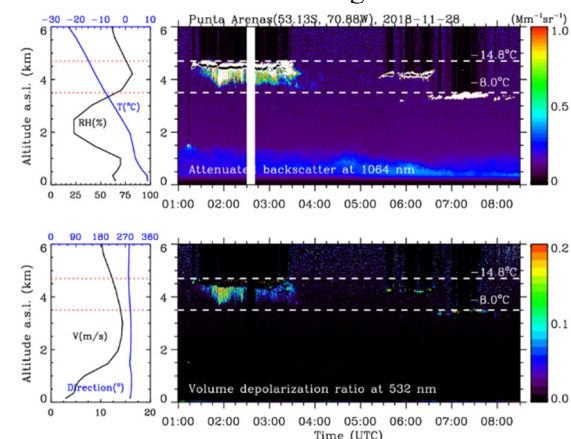


Figure 4. Same as Figure 1 but for 28 November 2018 at Punta Arenas.

In Figure 6, very different INPC can be found by assuming a contribution fraction of 4% by continental aerosols and 96% by marine aerosols. The continental aerosol is the main contributor to the total INP supply; the INPC value (derived with the parameterization from DeMott et al. [7]) is consistent with the ICNC value within one order of magnitude. This suggests the primary ice formation was dominated by a small amount of continental aerosols in the region. However, it is interesting to find that the ICNC values ( $10^{-2}$ - $10^{-1} \text{L}^{-1}$ ) are generally two-order-of-magnitudes smaller than those in the dust-influenced mixed-phase cloud

at Limassol, meaning that INP supply may directly determine the number of ice crystals formed in the mixed-phase clouds.

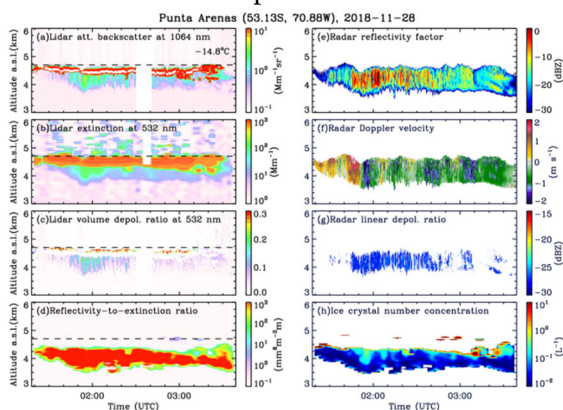


Figure 5. Same as Figure 2 but for the ice virga in Figure 4.

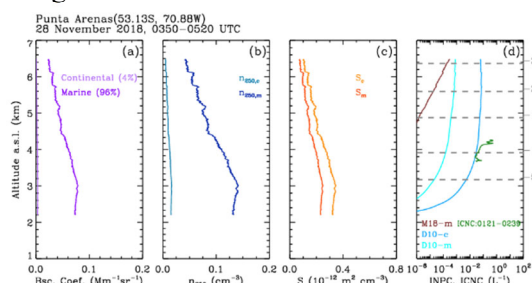


Figure 6. Same as Figure 3 but for the Punta Arenas case.

#### 4. Summary

With the case studies at Limassol and Punta Arenas, significant differences in INPC and ICNC values can be found. Given abundant dust INP supply, ICNC values ranging from  $1 \text{ L}^{-1}$  to  $10 \text{ L}^{-1}$  are obtained in the Limassol case. At Punta Arenas, the continental aerosol INPs are dominant even with an assumed contribution fraction as small as 4% to the total aerosol loading, resulting in the ICNC values of  $10^{-2}$ - $10^{-1} \text{ L}^{-1}$ . In addition, a general closure between INPC and ICNC is found within one order of magnitude. In consequence, two orders of magnitude fewer INPC quantitatively cause two orders of magnitude fewer ICNC at Punta Arenas, accordingly. In the future, more cases from both sites covering a similar temperature range will be examined to challenge the contributions drawn from the preliminary results presented here.

#### 5. References

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