Name of research institute or organization:

Institute for Atmospheric and Climate Sciences, ETH Zurich

Title of project:

Field measurements of aerosols acting as ice nucleating particles and their influence on mixed-phase clouds

Part of this programme:

GAW CH +

Project leader and team:

Dr. Zamin A. Kanji (Project Leader)
Dr. Jan Henneberger, Larissa Lacher
Dr. Yvonne Boose (not funded by GAWCH+)

Project description:

Primary ice nucleation of ice in clouds is still not completely understood, and continuous measurements of aerosols acting as ice nucleating particles (**INPs**) in an environment, where ice and mixed-phase clouds (**MPCs**) occur, are rare. We measure INP concentration at the High Altitude Research Station Jungfraujoch (**JFJ**) with the Horizontal Ice Nucleation Chamber (**HINC**; Kanji and Abbatt, 2009). The measurement campaigns are performed for several consecutive days to weeks in a row, during different seasons, and extend the existing INP measurements conducted previously by our group. The research station provides mostly free tropospheric conditions and can be influenced by diurnal boundary layer injections, which are more prevalent in the warm season (Lugauer et al., 1998; Zellweger et al., 2003; Collard Coen et al., 2011; Griffiths et al., 2014, Herrmann et al., 2015). By measuring in different seasons we want to investigate the influence of boundary layer injections on the INP concentration. In addition, special air masses enriched in INPs can reach Jungfraujoch, like dust events originating in the Sahara (Collaud Coen et al., 2004; Chou et al., 2011) whose influence on INP concentration we want to quantify. By excluding the influence from these special air mass events and the boundary layer, we want to investigate the seasonal variation in INP concentrations in the free troposphere. This would allow us to arrive at a representative INP concentration for background conditions in the free troposphere.

Activities 2016 (INP Measurements with HINC)

In 2016, three field campaigns were performed at JFJ with HINC, resulting in a total of seven field campaigns within this project since it began in August 2014. The field campaigns took place in winter, spring and summer 2016 (see Fig. 1), each lasting for several weeks. In winter 2016, INP concentrations were on average 23.3 $stdL^{-1}$, with highest INP concentrations during air masses arriving with anthropogenic influence (16th January), influence of Saharan dust (25th - 30th January; 28th February) and an air mass of marine origin (6th March). Identifications of INP measured within these air masses are based on source emission sensitivities (FLEXPART; Stohl et al., 2005, Sturm et al., 2013, Pandey Deolal et al., 2014) and cloud water sample analysis (data courtesy A. Zipori, see list of partners below). The identification of the anthropogenic event is further strengthened by NO_y/CO trace gas ratios (data courtesy M. Steinbacher) and aerosol size distributions (data courtesy E. Herrmann). The Saharan dust events are identified by a negative single scattering exponent (Collaud Coen et al., 2004; data courtesy N. Buckowieki) and also supported by aerosol size distributions. In spring 2016, average INP concentrations were an order of magnitude higher with a value of 440.6 $stdL^{-1}$, with no identification of special air masses. In summer 2016, INP concentrations were on average 54.6 $stdL^{-1}$, and two Saharan dust events (9th August and 12th August) were detected.

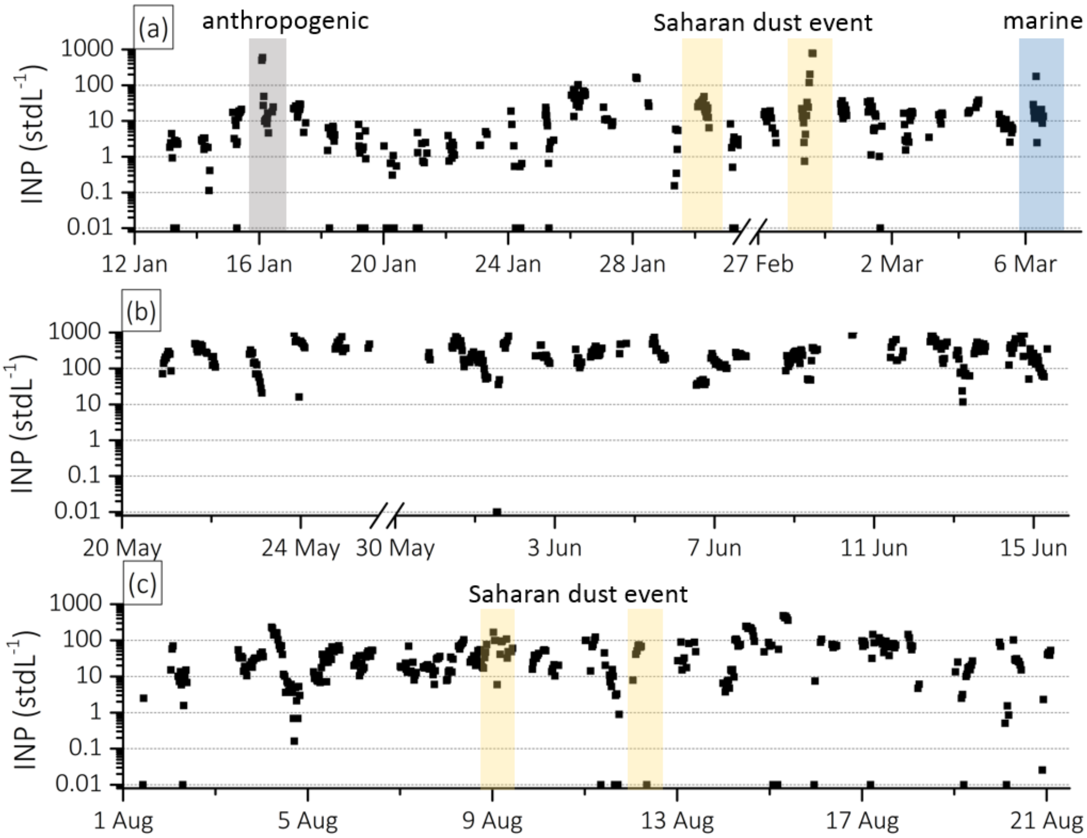

Figure 1. INP concentrations in winter (a), spring (b) and summer (c) 2016, measured with HINC at T=-31°C; RH_w = 104%.

In order to explain the variability in INP concentrations during different seasons, the influence of boundary layer injections needs to be considered in contrast to free tropospheric conditions. For that, the concentration of particles with d > 90 nm, a particle size which originates only in the boundary layer, was used (Herrmann et al., 2015). Free tropospheric INP concentrations, excluding special air masses, are generally lower with average concentrations usually < 10 INP $stdL^{-1}$, and show no seasonal variation (see Fig. 2). Exceptions are spring and summer 2016. The higher free tropospheric INP concentration in summer 2016 could be explained by a generally higher Saharan dust influence: two dust events were detected at JFJ, based on the single scattering albedo exponent criteria, but it is possible that the station was under influence of dust particles however, not with enough optical thickness to satisfy the 4 hours criteria of the negative exponent of the single scattering albedo. In spring 2016 no dust events based on the single scattering albedo criteria were detected. Another possible source of INPs are particles of biological origin, like pollen and pollen fragments or bacteria emitted from vegetative sources (Desprès et al., 2012). These particles can be transported in the updrafts to JFJ.

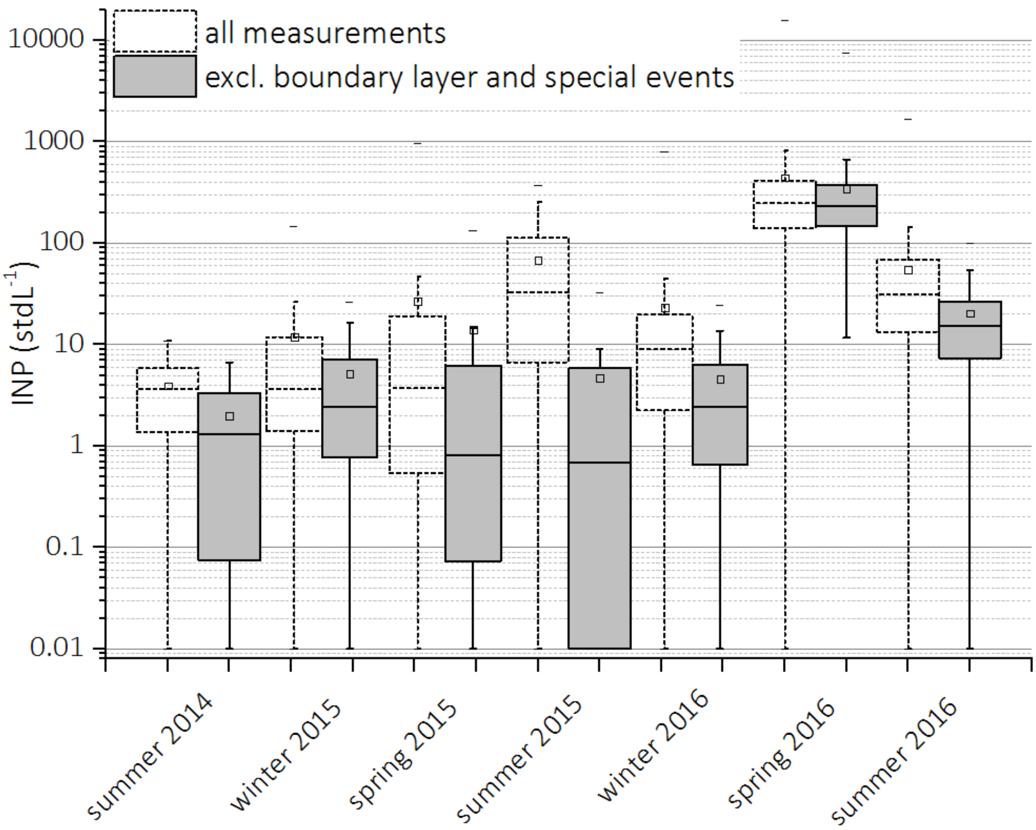

Figure 2. INP concentrations at T=-31°C; RH_{water} = 104% including all measurements (dashed) and free tropospheric conditions (bold) excluding boundary layer injections and special events (bold).

<u>Cloud Microphysics Measurements with HOLIMO</u>

During the past winter season, we continued the observation of the microphysical properties of orographic clouds at JFJ. Phase resolved measurements of the size distribution, concentration, and cloud water content were obtained by the holographic imager HOLIMO.

MPCs, consisting of a mixture of supercooled liquid droplets and ice crystals, are thermodynamically unstable. Once ice crystals form in a cloud of supercooled water droplets, they rapidly grow to precipitation size because their environment is supersaturated with respect to ice. In a MPC, once the relative humidity drops below saturation with respect to water, ice crystals will grow at the expense of their neighboring evaporating cloud droplets. This process is known as the Wegener-Bergeron-Findeisen process and can result in a glaciated cloud. Observations of frontal clouds over Canada show that only 20% of them are mixed-phase clouds irrespective of the temperature (Korolev et al., 2003 in Figure 3).

MPCs at the JFJ are also rare if the air masses approach the JFJ from the SE with a shallow ascent (Figure 3), but occur in over 75% of the time in NW wind cases with strong uplifts for temperature below -10°C. The frequency of occurrence of MPCs increases with decreasing temperature and peaks with more than 90% at the coldest temperatures we measured between −20 and −25°C.

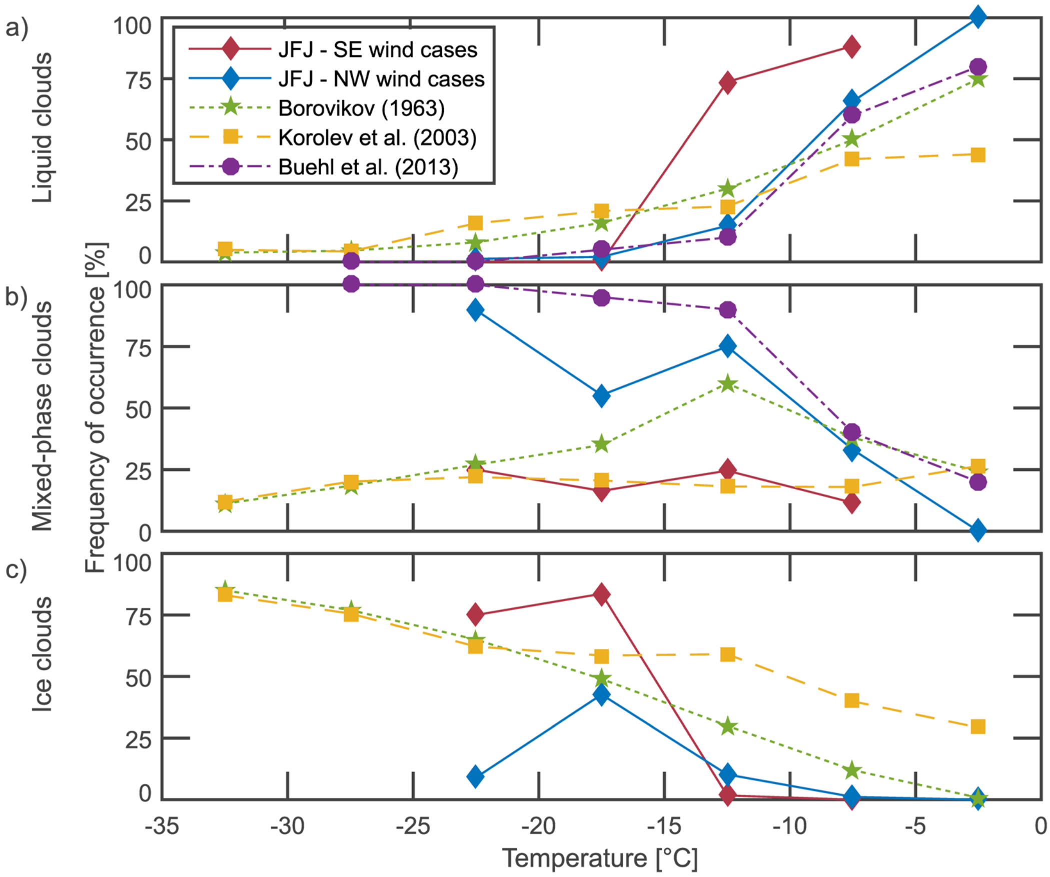

Figure 3. Percentage of (a) liquid water, (b) mixed-phase, and (c) ice clouds between −35 and 0°C as composed from three different studies: Frontal clouds over Canada (updated from Korolev et al., 2003), various clouds over Israel (Borovikov et al., 1963) and Leipzig (Bühl et al., 2013), and orographic clouds obtained at Jungfraujoch (published in Lohmann et al., 2016).

Secondary ice production mechanisms that could have operated between the primary ice nucleation events and when the cloud arrived at JFJ include the Hallett-Mossop process and surface-based processes. Surface-based processes probably caused or at least contributed to the observed ice crystals at the warmest sub-zero temperatures, especially to the higher INP concentrations during NW cases, such as hoar frost crystals generated where the cloud encounters the snow surface (Farrington et al., 2015) and at higher wind speeds also blowing snow (Lloyd et al., 2015). According to our holographic measurements and images, fragments of snow flakes are rare during all conditions. Most importantly, the difference between NW and SE wind cases arises because of the presence of the liquid phase during NW cases, which surface-based sources of ice crystals cannot explain.

To quantify the influence of the updraft velocity on the cloud properties at the JFJ, we simulate the periods of the measurement campaigns using the regional model COSMO. We stratified the frequency of occurrence of vertical velocity in COSMO for all observed cloud cases into no clouds, liquid or MPCs and ice clouds up to the altitude of JFJ (see Fig. 4). For NW wind cases, the simulated vertical velocities range between 0 and 4 ms^{-1} and thus are considerably higher than for SE wind cases, where wind speeds between -1.3 and 0.5 ms^{-1} were simulated.

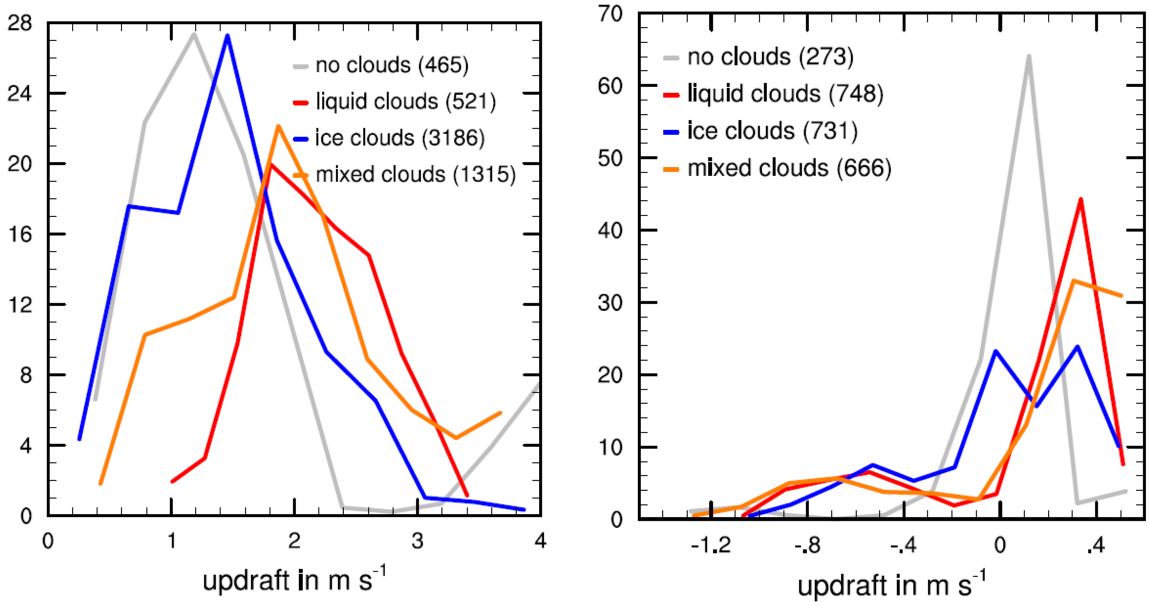

Figure 4. The Histogram of the frequency of occurrence of vertical wind velocity (ms^{-1}) for cloud-free, liquid, mixed-phase, and ice clouds aggregated at all altitudes between the surface (between 2897 and 3226 m) and 3550 m as obtained from simulations with the COSMO model for all observed (left) NW wind cases and (right) SE wind cases (published in Lohmann et al., 2016).

These results show that MPCs are frequently found in the Swiss Alps, when the updraft velocities are high enough to exceed saturation with respect to liquid water allowing simultaneous growth of supercooled liquid droplets and ice crystals. Most of the time, the observed ice crystal numbers were not sufficiently high to convert these MPCs into a fully glaciated cloud.

For orographic cloud, two different regimes can be distinguished depending on the steepness of the orography: First, there is a microphysics regime associated with weak updrafts and small supersaturations as also observed over Leipzig and in the Arctic. Here ice particles grow by diffusion due to the Wegener-Bergeron-Findeisen process, and the physical and chemical properties of the aerosol particles matter more for the cloud evolution. Second, there is a dynamics regime where strong updrafts stabilize the MPC by activation of more and smaller aerosol particles and growth of existing cloud droplets. The associated stronger turbulence might also enhance growth of ice crystals by aggregation and secondary ice production due to collisional breakup and uplift of ice particles from the surface

Our findings imply that cloudy regions with stronger updrafts are more prone to prolonged MPC conditions and aircraft icing. For climate modelling, more persistent MPCs than glaciated clouds mean that the optical depth of these clouds is higher and that the climate sensitivity in a 2 x CO_2 climate will be larger because the negative cloud phase feedback (conversion from ice to liquid due to the higher temperatures) is smaller (Tan et al., 2016).

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Key words:

Ice Nucleating Particles, Ice Crystals, HINC, HOLIMO, Mixed-Phase Clouds, Aerosols, Ice Nucleation

Internet data bases:

BACCHUS INP database (http://www.bacchus-env.eu/in/index.php)
In this database maintained by my group at ETH, one can find the INP concentration time series taken at JFJ by ETHZ and other groups during various campaigns and monitoring activities

Collaborating partners/networks:

Erik Hermann, Urs Baltensperger, Nicolas Bukowiecki (Paul Scherrer Institute)
Martin Steinbacher, Stephan Henne (EMPA)
Assaf Zipori, Daniel Rosenfeld (Hebrew University of Jerusalem)
Tom Choularton, Gary Lloyd (University of Manchester)
Jacob Fugal (MPI-Mainz)

Scientific publications and public outreach 2016:

Refereed journal articles and their internet access

Boose, Y., Z.A. Kanji, M. Kohn, B. Sierau, A. Zipori, I. Crawford, G. Lloyd, N. Bukowiecki, E. Herrmann, P. Kupiszewski, M. Steinbacher, U. Lohmann, Ice Nucleating Particle Measurements at 241 K during Winter Months at 3580 m MSL in the Swiss Alps, Journal of the Atmospheric Sciences, **73**, 5, 2203-2228, doi:10.1175/JAS-D-15-0236.1, 2016. http://journals.ametsoc.org/doi/abs/10.1175/JAS-D-15-0236.1

Lohmann, U., J. Henneberger, O. Henneberg, J.P. Fugal, J. Bühl, Z.A. Kanji, Persistence of orographic mixed-phase clouds, Geophysical Research Letters, **43**, 10512–10519, doi:10.1002/2016GL071036, 2016. http://onlinelibrary.wiley.com/doi/10.1002/2016GL071036/full

Conference papers

Henneberger, J., O. Henneberg, A. Beck, and U. Lohmann, Observation of orographic clouds at the high alpine site Jungfraujoch, Switzerland, International Conference on Clouds and Precipitation (ICCP) 2016, Manchester, UK, July 25-29, 2016.

Lacher L., U. Lohmann, Z.A. Kanji, Ice nucleating particles on the High Alpine Research Station Jungfraujoch: 5 years of measurements, European Geophysical Union, 4th Workshop on Microphysics of Ice Clouds, Vienna, Austria, April 23-28, 2016.

Lacher L., U. Lohmann, Z.A. Kanji, Free tropospheric INP concentrations at the High Altitude Research Station Jungfraujoch, International Conference on Clouds and Precipitation (ICCP) 2016, Manchester, UK, July 25-29, 2016.

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