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:

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Project description:

For an improved understanding of ice and mixed-phase clouds (**MPCs**), measurements of ice nucleating particle (**INP**) concentrations are performed on a regular basis at the High Altitude Research Station Jungfraujoch (**JFJ**). Continuous measurements of INP concentrations in an environment relevant for clouds containing ice are rare, because a fully automated instrument to measure INP concentrations in real-time and continuously does not exist (DeMott et al., 2010). We perform measurements with the Horizontal Ice Nucleation Chamber, **HINC** (Kanji and Abbatt, 2009) several times a year in different seasons (winter, spring and summer) at JFJ to extend the existing INP measurements from our group (see activity report 2014, Chou et al., 2011 and Boose et al., 2016). Although JFJ is situated most of the year in free tropospheric conditions, air from the boundary layer may reach the station in spring and summer, especially during daytime (e.g. Lugauer et al., 1998; Zellweger et al., 2003; Collaud-Coen et al., 2011; Griffiths et al., 2014). As such, we want to investigate if there exists an annual cycle of INP concentrations in the free troposphere due to injections of boundary layer air, Saharan dust or air masses from marine environments. We address the question if the influence from boundary layer air is related to phenological periods, like the influence from biological aerosols. Furthermore, we want to compare their influence on INP concentrations to Sahara dust, as the JFJ is regularly affected by Sahara dust events (**SDE**) in spring which influence the INP concentrations significantly (Chou et al., 2011). Last but not least, our project aims to investigate the influence of meteorological conditions on the INP concentration.

Activities 2015 (INP, HINC)

The main achievements in 2015 were the performances of three field campaigns with HINC during winter, spring and summer. With the addition of three more seasons of INP measurements to the existing measurements done at the JFJ in prior years, not only could we compare INP concentrations between different seasons, but also had the chance to sample during interesting special events with higher INP concentrations compared to the campaign average value.

In winter 2015 for example, measurements of INP in the condensation mode (see Figure 1) show two interesting events: an increase in INP from 1-10 std l^{-1} to > 50 INP std l^{-1} was observed during the 2nd and 6th of February. The latter was caused by a SDE, which could be identified with nephelometer data (Nicolas Bukowiecki, PSI), size distribution data (Erik Herrmann, PSI), FLEXPART back trajectories (Stephan Henne, EMPA) and chemical analysis of cloud water samples (Assaf Zipori, Hebrew University of Jerusalem). During the 2nd February the station was not under the influence of Sahara dust, and the cloud water sample analysis revealed influence of marine air, supported by FLEXPART back trajectories. The influence of marine aerosol on ice nucleation is recently discussed (e.g. Wilson et al., 2015), causing the question if the ocean is a possible source for INP.

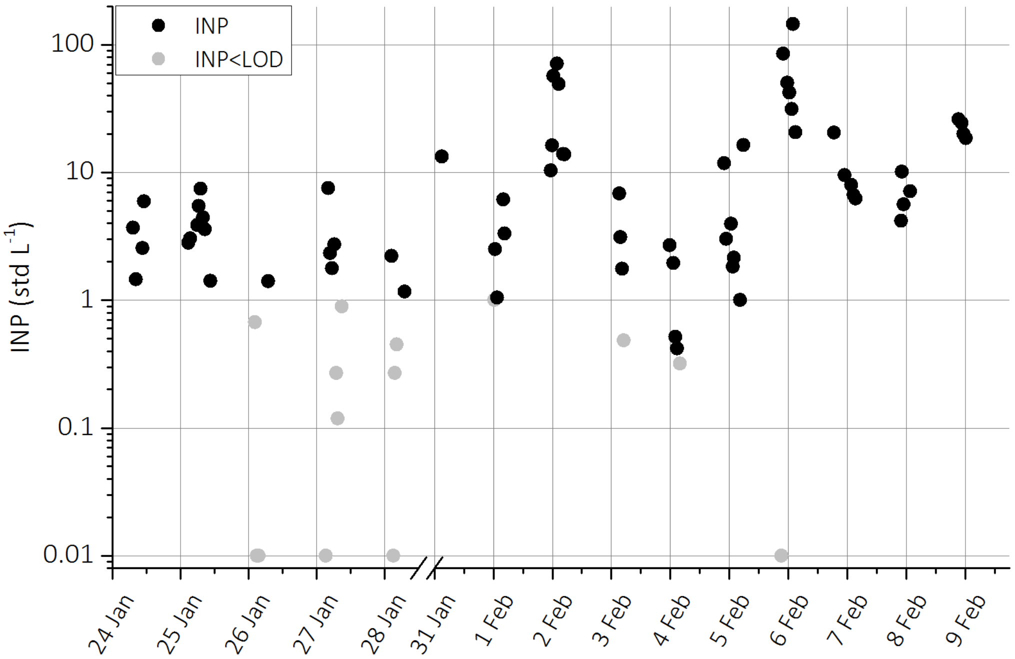

Figure 1. INP concentrations in winter 2015, measured with HINC (T=-31°C; RH_w = 104%).

INP climatology is shown in Figure 2 for measurements in the condensation and deposition mode. Campaign and special event averages such as SDE or marine influenced air masses are also shown. Campaign averages are shown both for excluding (marker) and including (grey box) INP measurements which were below the limit of detection (**LOD**) of HINC. What we demonstrate here is that for periods when INP concentrations are low (i.e. close to the LOD of HINC), if we completely exclude and report only measurements above the LOD, we could be significantly overestimating the INP concentrations at JFJ. This is typically true for the deposition mode, where the grey shaded area is larger. In the condensation mode, the effect of excluding data points below the LOD is not significant indicated by tiny grey shaded areas.

INP concentrations below water saturation range from 0.1 and 10 std l^{-1}, with lower concentrations in winter. The highest average concentration of > 50 INP std l^{-1} was measured during a SDE in spring 2015. Above water saturation, INP concentrations in winter are between 1-10 std l^{-1}, and reach higher concentration during special events in this season. In spring and summer INP concentrations are higher as well.

To assess the influence of boundary layer air and Sahara dust, which both can cause higher INP concentrations, for the period of INP measurements we analysed the NOy/CO ratio (Zellweger et al., 2003) and the particle concentrations above 90 nm (Herrmann et al., 2015) to assess time periods when we had influence from the boundary layer leading to disturbed free tropospheric conditions.

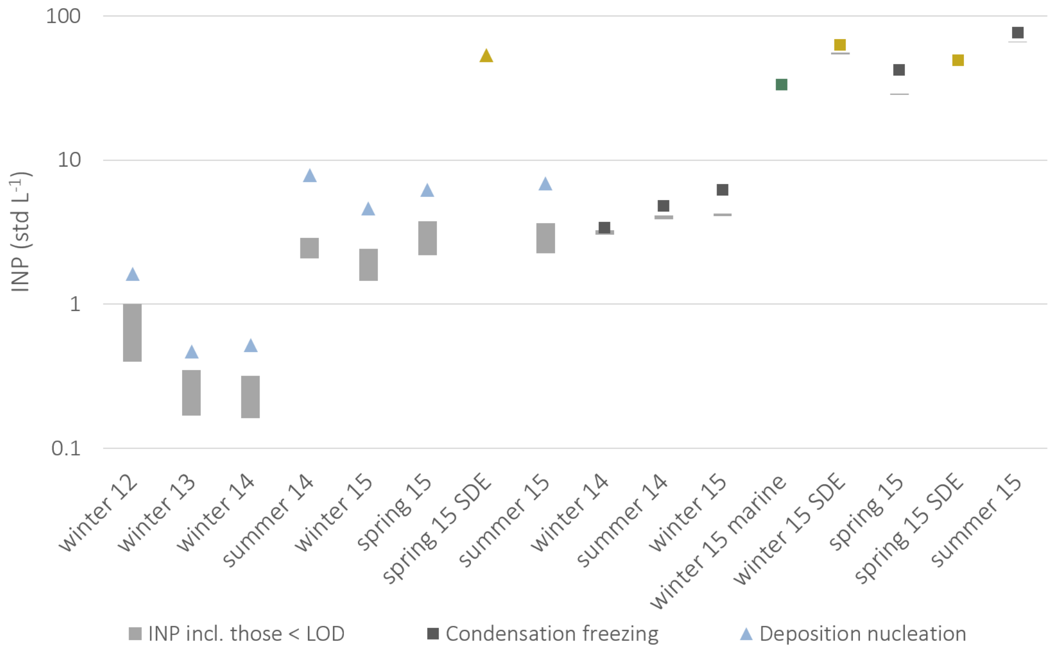

Figure 2. INP measurements at JFJ performed with PINC (up to winter 2014) and HINC (from summer 2014 onwards) for deposition nucleation at T ~ -31°C; RH_w ~ 92%; and for condensation freezing ~ 104% RH_w. Data points are averaged values for one field campaign.

The distinction reveals, that INP concentrations are generally lower in the free troposphere in both freezing modes, ranging between 1-10 std l^{-1} (Figure 3). The free tropospheric INP concentrations during spring and summer 2015 are lower as well, indicating that the high INP concentrations were measured during times with boundary layer influence. Additionally to this, FLEXPART back trajectories revealed that the station could have been under the influence of Sahara dust, without the declaration of a SDE. This could be the reason why the average free tropospheric INP concentration in spring 2015 was higher than the other campaign averages.

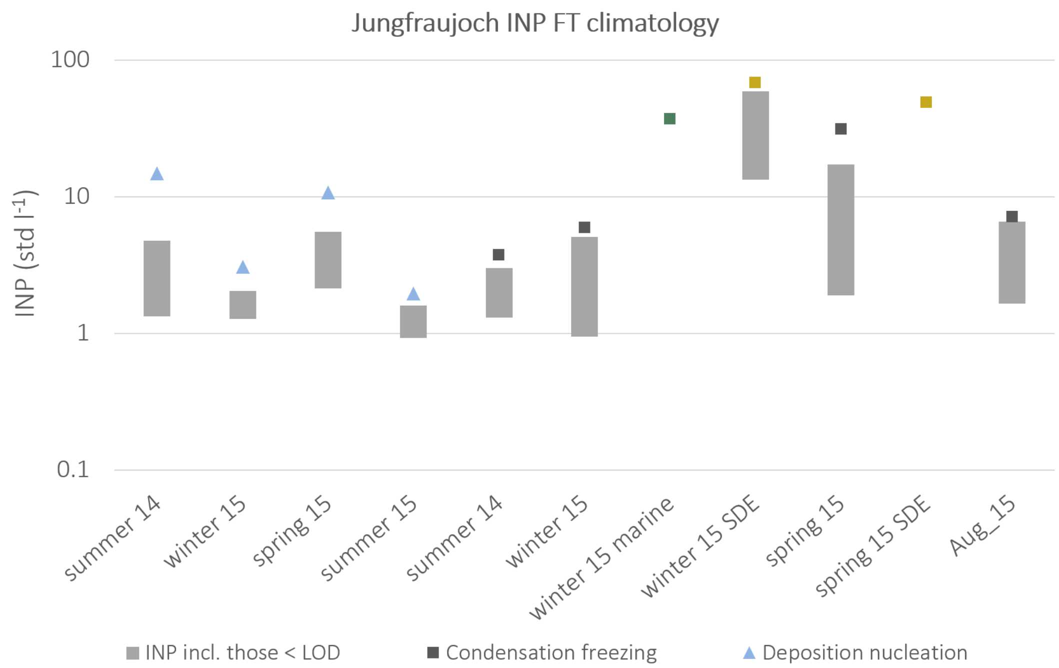

Figure 3. INP measurements at JFJ for only free tropospheric conditions. Measurements were performed with HINC (T=-31°C; deposition nucleation = 94% RH_w; condensation freezing = 104% RH_w); data points are averaged values for one field campaign.

Cloud Microphysics Measurements with HOLIMO

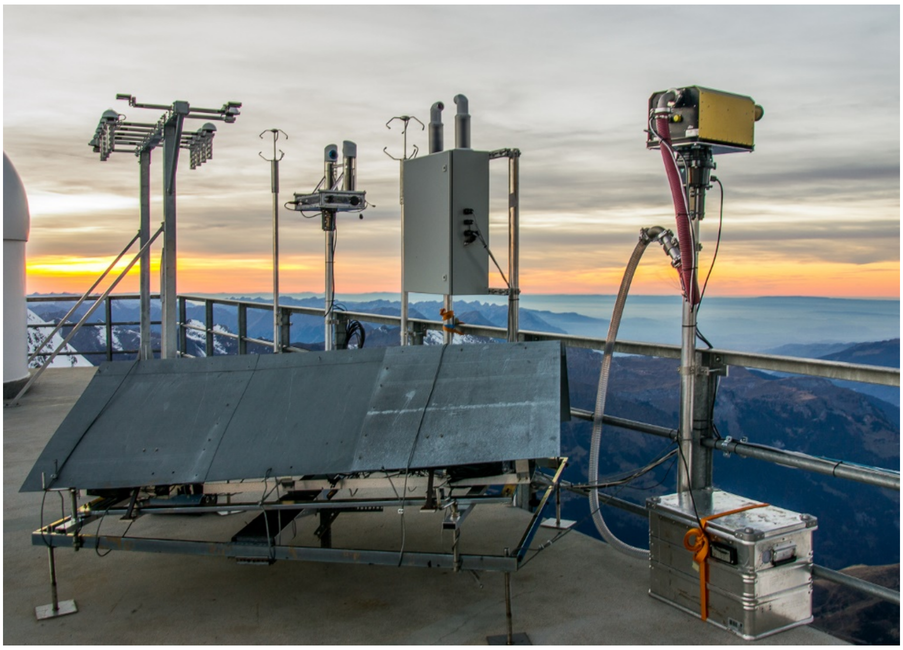

Figure 4. Instruments set-up during the inter-comparison campaign at the JFJ during November 2015. Side-by-side a Fog Monitor (from the right), HOLIMO 3M and HOLIMO 3G are employed, together with two 3D sonic anemometer.

During 2015, the newly designed holographic imager HOLIMO 3M (see activity report 2014) was deployed at the JFJ for the first time. Between January and March, HOLIMO 3M continued measuring the micro-physical properties of the clouds arriving at the JFJ. In addition, the new developed measurements platform HOLOGondel was deployed at the cable car Eggishorn in the Valais valley. The main component of the HOLOGondel platform is a digital holographic imager HOLIMO 3G, very similar to HOLIMO 3M. The data from both field locations will be analysed to find cloud cases were the same air mass was sampled at the Eggishorn and at the JFJ, which will contribute to a better understanding of the spatial and temporal evolution of orographic MPCs by targeting the same air mass at two different locations.

For an inter-comparison campaign, both holographic imagers (HOLIMO 3M and 3G) and a Fog Monitor, which is a single-particle scattering spectrometer, where employed at the JFJ at the same time (Figure 4). By comparing these simultaneously obtained measurements at the same location, the concentration calculation and variation due to instrument design will be quantified. With this inter-comparison and a size calibration data during post-analysis, the measurement uncertainty can be specified and a more precise calculation of cloud parameters can be achieved.

Data Analysis: Obtaining long time-series of cloud data with a holographic imager requires demanding data analysis both computationally and time wise. The holographic imager produces up to eight terabytes of raw data per day. The reconstruction of the raw holograms is computer-intensive. Furthermore it is complicated to reliably extract cloud particle features from reconstructed images to get the cloud data finally. In all of these steps, the data analysis was improved in 2015.

First, the data storage was centralized on a network storage system. The reconstruction of holograms into images is done on the Euler Cluster, which is one of ETH's high-performance computer cluster. The parallelization on multiple nodes speeds-up the time needed for reconstruction by up to factor of 10. During the past years, a software package, called

HOLOSuite, has been developed to extract the cloud data out of the reconstructed data. The HOLOSuite software is shared between multiple research groups and approximately 15 people use his software to analyse holographic data. In December 2015 a workshop was organized to bring this community together to share the knowledge and to discuss further developments. In the future, the HOLOSuite software will be organized with a version control system to share new development faster and avoid parallel programming of the same feature. With all this improvement, less time and effort is needed to synthesize the cloud properties data from the raw data.

Results: We continued the analysis of the in-situ observation of orographic clouds at JFJ. Phase resolved measurements of the size distributions, concentrations, and cloud water contents were obtained by HOLIMO. MPCs consisting of a mixture of supercooled liquid droplets and ice crystals were observed in high frequency at the JFJ. Although MPCs are thermodynamically unstable, they were observed over long periods (up to 7 hours). This can be explained by orographic lifting. Updraft velocities, high enough to exceed saturation with respect to liquid water, cause the simultaneous growth of water droplets and ice crystals.

The finding that the two main wind directions at the JFJ lead to distinctly different cloud properties supports the explanation of stabilization of the mixed-phase cloud due to orographic lifting. A larger frequency of mixed-phase clouds is observed during north-westerly wind cases which are associated with a steeper ascent than south-easterly wind cases (Figure 5).

Unfortunately, information on the updraft velocities are missing as the measurements at the JFJ are much too influenced by the local topography. Therefore, the updraft velocity measurements do not represent the condition inside the cloud. Simulation with the regional climate model COSMO were performed, to get more information on the origin of air masses reaching JFJ and what factors influence the formation and glaciation of MPCs. The simulation confirmed that the updraft speeds during the MPCs cases were higher, but also synoptical changes have a strong influence on the cloud phase arriving on the JFJ.

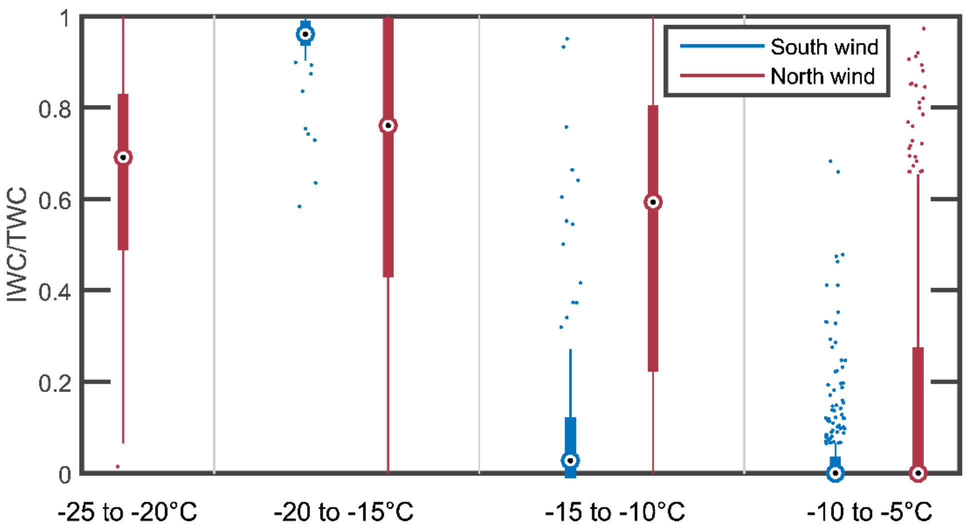

Figure 5. Boxplot of ice fraction (ice water content (IWC) divided by total water content (TWC)) at different temperature intervals grouped by the main wind direction.

In addition, high ice crystal concentrations up to 1 cm^{-3} were observed (Lloyd et al., 2015, see refereed articles section). As the measured INP concentrations were at least two orders of magnitude lower, these high ice crystal concentrations cannot be explained by primary ice nucleation, but indicate that an ice multiplication process is active. It is unlikely that the high ice crystal concentrations were produced through the Hallett–Mossop process as the cloud was most often not in the active temperature range for this process, but was caused more likely by the snow covered surrounding of the JFJ station. Either by hoar frost crystals generated where the cloud touches the terrain or blowing snow which is re-suspended from the ground at higher wind speeds (Lloyd et al., 2015).

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Paul Connolly, Gary Lloyd, Tom Choularton (University of Manchester)
Assaf Zipori (Hebrew University of Jerusalem)

Scientific publications and public outreach 2015:

Refereed journal articles and their internet access

Lloyd, G., T.W. Choularton, K.N. Bower, M.W. Gallagher, P.J. Connolly, M. Flynn, R. Farrington, J. Crosier, O. Schlenczek, J. Fugal, and J. Henneberger, The origins of ice crystals measured in mixed-phase clouds at the high-alpine site Jungfraujoch, Atmospheric Chemistry and Physics, **15**, 12953–12969, doi: 10.5194/acp-15-12953-2015, 2015.
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Grazioli, J., G. Lloyd, L. Panziera, C.R. Hoyle, P.J. Connolly, J. Henneberger, and A. Berne, Polarimetric radar and in situ observations of riming and snowfall microphysics during CLACE 2014, Atmospheric Chemistry and Physics, **15**, 13787-13802, doi: 10.5194/acp-15-13787-2015, 2015.
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Conference papers (names in bold are GAW project participants)

L. Lacher*, U. Lohmann and **Z. A. Kanji**, Field measurements of ice nucleating particles on the High Altitude Research Station Jungfraujoch, Goldschmidt Conference, Prague, Czech Republic, August 16-21, 2015 (*Oral*).

Y. Boose*, F. Mahrt, M. I. Garcia, S. Rodriguez, C. Linke, M. Schnaiter, S. Nickovic, U. Lohmann, **Z. A. Kanji** and B. Sierau, Ice nucleating particle properties in the Saharan air layer close to the dust source, American Geophysical Union, San Francisco, CA, USA, December 14-18, 2015 (*Oral*).

Z. A. Kanji, **J. Henneberger**, Y. Boose, **L. Lacher** and U. Lohmann, Field Measurements of Atmospheric Ice Nucleating Particles and Ice Crystal Numbers, Gordon Research Conferences, Atmospheric Chemistry, Waterville, NH, USA, August 2-7, 2015 (*Poster*).

Z. A. Kanji, Y. Boose, **L. Lacher** and U. Lohmann, Climatology of Ice Nucleating Particles at the High Altitude Station Jungfraujoch, PACIFICHEM, Chemistry of Atmospheric Aerosols, Honolulu, HI, USA, December 15-20, 2015 (*Oral*).

J. Henneberger, O. Henneberg, G. Lloyd, J. P. Fugal and U. Lohmann, In-situ measurements of orographic mixed-phase clouds in a High Alpine Environment using Digital in-line Holography, European Geophysical Union, Vienna, Austria, April 12-17, 2015 (*Oral)*.

Magazine and Newspapers articles

Online Magazine interview, Nautilus, August 5, 2015.

Radio and television

Radio Interview, Radio Télévision Suisse, January 22, 2015.

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