# POLSTRACC

## A HALO mission to investigate the Polar Stratosphere in a Changing Climate

**Aircraft Campaign Preparation Document**

**“White Book” (Version 2.4)**

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**Project Coordination:**

**Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research**

**Consortium Members:**

**KIT, DLR, FZJ, Universities of Mainz, Frankfurt, Heidelberg, and Wuppertal, and Associated Partners**

www.polstracc.kit.edu

# PREFACE

The HALO mission POLSTRACC (The Polar Stratosphere in a Changing Climate) was selected by the WLA after the first Call for Proposals as one out of six missions to demonstrate the capabilities of the new German research aircraft HALO for performing complex atmospheric research studies. After some iterations of the HALO campaign plan the POLSTRACC mission window has finally been fixed in 2013 for winter 2015/2016.

POLSTRACC aims at providing new scientific knowledge on the Arctic lowermost stratosphere and upper troposphere in a changing climate, specifically one to two decades after the era of intensive arctic campaigns that were dedicated to the investigation of ozone loss processes. This implies the study of chemical, microphysical and dynamical processes under the present load of halogens and state of climate variables in the mid 2010s in contrast to what was present 10 to 20 years ago. For this purpose a large suite of established and novel in-situ and remote sensing techniques will be deployed on HALO to measure key chemical species, tracers, as well as aerosol, cloud particles and meteorological parameters.

The consortium is headed by Karlsruhe Institute of Technology (KIT), Institute of Meteorology and Climate Research, and includes DLR, Research Centre Jülich, and Universities Mainz, Frankfurt, Heidelberg, and Wuppertal.

According to the mission objectives of POLSTRACC, target regions for measurement flights are the Arctic and northern middle latitudes northward of about 50° to study mixing processes between the polar vortex or vortex-influenced air and the mid-latitudes with a clear focus on the Arctic region to study the polar vortex itself. Therefore the POLSTRACC mission needs to be undertaken during a Northern winter, preferentially covering the Arctic winter from the onset of the polar stratospheric vortex in December to the final stage in mid-March.

In the very first proposal of POLSTRACC in early 2005 it was hoped to realize the first deployment still in the framework of the IPY activities. Later on, after first delays in the adaptation and qualification of the HALO aircraft, the RECONCILE proposal was approved by the EC in 2008. RECONCILE (coordinated by Forschungszentrum Jülich) contained, similarly to POLSTRACC, a major campaign activity in the Arctic, but by taking use of the Geophysica aircraft instead of the HALO aircraft. In view of the partly overlapping scientific objectives of POLSTRACC and RECONCILE the project coordinators of both projects had agreed in 2008 to combine forces in order to utilize the synergies offered by the different instrumentation and the different airplanes. Part of this coordinated approach was to coordinate the missions of the Geophysica and HALO aircraft in the winter 2009/2010. Unfortunately, this goal could not be met due to major delays in the certification process of the HALO aircraft and related instrumentation.

As a consequence the science plan of POLSTRACC, as originally set up and later adapted to a joint campaign with RECONCILE was redesigned. The updated science concept now considers recent findings from the RECONCILE campaign and particularly the record Arctic ozone loss that happened in winter 2011, which both have been taken into account for the updated POLSTRACC white book.

We are convinced that POLSTRACC will have the potential of providing new and essential scientific results even after a successful RECONCILE campaign. We deduce this from the following facts:

- POLSTRACC will make use of HALO which provides a much larger range and payload capacity than Geophysica. This will allow to cover larger areas from outside of the vortex to deep inside the vortex and to map the vortex boundary.

- POLSTRACC will largely benefit from a combination of in-situ instruments and new or upgraded remote sensing instruments, in particular the upgraded DLR LIDAR and the new imaging FTS GLORIA-AB. This will allow embedding the precise but localised in-situ measurements into the 2-D or 3-D distributions provided by the remote sensing measurements. The 3-D view will provide unprecedented views in three dimensions on structures and filaments of vortex air interacting with its surrounding.

- POLSTRACC will benefit from a more complete set of atmospheric parameters to be measured.

- POLSTRACC is suited to tackle scientific topics in the Arctic that were not covered by RECONCILE, such as processes linked to cold cirrus clouds and outflow of vortex air at the bottom of the vortex. The cloud and tracer mapping capabilities of the LIDAR instruments and of GLORIA-AB will provide a broader view to the rather detailed process-dedicated in-situ measurements. This will be backed by numerous drop sondes making use of the newly developed KIT sonde.

- In view of the currently planned HALO missions POLSTRACC will very likely be able to study the coldest cirrus clouds, offering a valuable complement to the cirrus-dedicated HALO missions CIRRUS-ML and ACCRIDICON.

POLSTRACC is the only planned HALO mission that is focusing on chemical and dynamical processes at high northern latitudes and thus allows comparisons with similar campaigns in the nineties. POLSTRACC will cooperate closely with the ROMIC project GW-LCYCLE that aims at studying gravity waves from the source region up to the mesopause with a suite of ground-based stations, aircraft campaigns and modeling. The POLSTRACC payload will be used for dedicated flights contributing to GW-LCYCLE. In addition to the 50+ flight hours of POLSTRACC 30 flight hours will be devoted to GW-LCYCLE science.

POLSTRACC will also be closely linked to a part of the SALSA project which continues the successful TACTS mission with the goal to study the seasonality of transport processes through the subtropical jet. The POLSTRACC payload will also be used for this winter-spring component of SALSA with up to 30 flight hours.

In summary, the combination of the scientific tasks of POLSTRACC, GW-LCYCLE, and SALSA-1 into one joint mission with the same payload needing the flight certification just once offers a huge synergy both from a logistical and a scientific viewpoint.

# OVERVIEW

# 1 THE SCIENTIFIC OBJECTIVES OF POLSTRACC

POLSTRACC is a mission to investigate the role of the Arctic upper troposphere and lower stratosphere (UTLS) in a changing climate. The Arctic is the region that experiences the largest changes in Earth's climate, with a rapid decline of Arctic sea ice, a strong warming of the surface atmosphere and changes in the chemistry and dynamics of the UTLS. In the Arctic stratosphere, large depletion of Arctic stratospheric ozone has been observed in recent cold winters (**Manney et al., 2011**), with still large uncertainties how this will respond to future climate change (**Sinnhuber et al. 2011**). Changes in the trace gas composition and cirrus cloud occurrence in the UTLS have a large impact on radiative forcing and surface climate (**Riese et al., 2012**).

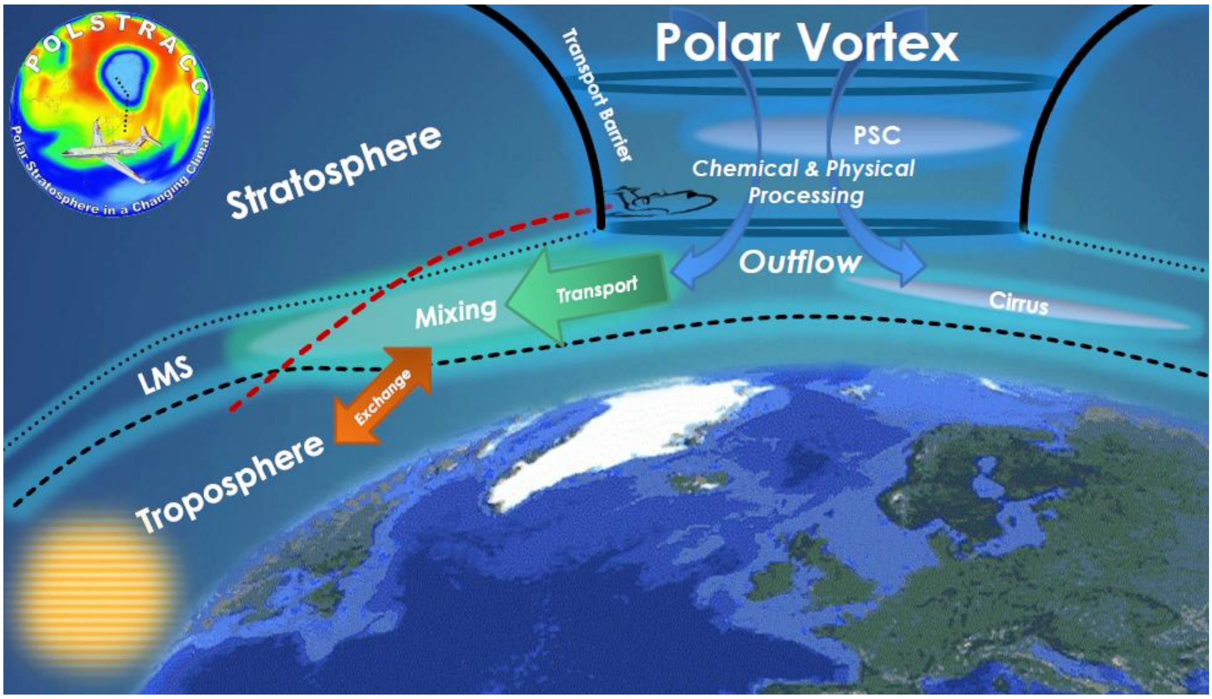


Figure 1: POLSTRACC will help improving our understanding on the evolution of the Arctic polar stratosphere in a changing climate. A special focus will be set on the lowermost stratosphere (LMS) region at high latitudes, where processed air from the polar vortex outflow can be transported rapidly towards lower latitudes and affect local chemistry and radiative budgets.

Inside the polar winter vortex, aged stratospheric air is processed chemically and physically by catalytic ozone depletion, vertical redistribution of nitric acid and water vapour by condensation and sedimentation of polar stratospheric cloud (PSC) particles as well as specific photochemical and heterogeneous chemical processes. In spring the Arctic polar vortex breaks up, processed ozone-poor air is transported to lower latitudes and mixes with the ambient stratospheric air, affecting the local chemistry and radiative forcing.

Due to the diabatic descent of air inside the polar vortex, processed air is introduced via the lower vortex boundary into the Arctic LMS. During the entire Arctic winter period, rapid transport processes can occur inside the LMS, transporting processed vortex air towards lower latitudes (**Werner et al., 2010**). While the polar vortex is largely isolated from exchange processes with ambient air due to a strong transport barrier associated with the polar night jet, mixing processes occur when the vortex dissipates during minor and major warming episodes and when air originating from the vortex outflow is transported to mid-latitudes in the LMS.

The LMS is furthermore of special interest, since it is the interface between the stratosphere and the tropopause, where exchange processes occur via Rossby wave breaking, warm conveyor belts, tropopause folds and gravity waves. Cold temperatures result in the formation of cirrus clouds which are thought to be capable of significantly affecting the radiative forcing at high latitudes and furthermore are capable of dehydration and denitrification via condensation and sedimentation of ice particles associated with $HNO_3$ uptake similar to PSCs (e.g. **Kärcher, 2005; Voigt et al., 2006; Krämer et al., 2008**). Furthermore there might be a significant potential of chlorine activation on Arctic cirrus clouds as a consequence of trends towards colder stratospheric temperatures in the future.

Significant achievements have been established in understanding of the manifold processes involved in stratospheric ozone destruction in the last decades (**WMO, 2011**). However, the impact of climate change on the evolution, strength, stability and persistence of the polar vortex challenge predictions for the evolution of the ozone layer and the UTLS region in the future. The speed and extent of the expected recovery of the ozone layer will not only depend on the future decline of man-made halogen compounds in the stratosphere following the Montreal protocol and its amendments, but also on the development of the stratospheric temperatures, the global circulation as well as the stratospheric water and bromine content.

Aiming on improving our understanding of the role of the Arctic stratosphere in the atmospheric system and improving future projections of the development of the ozone layer, the key objectives of POLSTRACC are:

- Investigating the structure, dynamics and chemical composition of the UTLS at high latitudes with a special focus on the LMS. Studies on the outflow of the polar vortex and its influence on the composition of the LMS at high and middle latitudes

- Improving the understanding of catalytic processes involved in polar ozone loss with a focus on chlorine and bromine chemistry in the LMS

- Improving the knowledge on polar stratospheric cloud (PSC) composition, de-/re-nitrification by sedimentation of $HNO_3$-containing particles and the role of gravity waves or orographic waves on PSC occurrence

- Investigating Arctic cirrus clouds, their influence on the radiative forcing and their potential for denitrification, dehydration and chlorine activation

Thereby, the goal of POLSTRACC is to improve simulations of the future evolution of the ozone layer, atmospheric composition changes and surface climate in the next decades. While previous high-altitude aircraft campaigns mainly concentrated on the stratosphere and the tropopause region (e.g. SOLVE/THESEO and RECONCILE; see **Newman at al., 2002; von Hobe et al., 2013**), the POLSTRACC mission sets a special focus on processes related to the Arctic LMS and its connections to the UT and mid-latitude UTLS in the winter and spring season. POLSTRACC employs an innovative combination of remote sensing and in-situ instruments aboard the German High Altitude and LOng Range Research Aircraft (HALO), allowing spatially highly resolved and accurate measurements of the structure, chemical composition and dynamics of the UTLS region.

The POLSTRACC measurements will be complemented by chemistry transport modelling activities for accurate flight planning and for studies of chemical processes and radiative budgets on large and fine scales. Climate chemistry models will provide long term projections of the ozone layer development. Combining field measurements, satellite observations provided by associated partners and model simulations, POLSTRACC will help improving our understanding on the role of the polar stratosphere and UTLS region in the atmospheric system in the future.

The key scientific themes to be addressed by POLSTRACC as mentioned above are grouped into the four major scientific work packages outlined below. The POLSTRACC objectives are complemented by the objectives of GW-LCYCLE and SALSA, which are discussed in dedicated sections in the same context.

## 1.1 Structure, composition and dynamics of the Arctic winter LMS

The LMS is the lowest part of the stratosphere between the tropopause and the 380 K isentrope and can be seen as the interface region between the stratosphere and the troposphere. It is an important region for the radiation budget of the atmosphere and directly affects surface temperatures (**Forster and Shine, 2002 Solomon et al., 2010**). The composition of the LMS is directly affected by airmasses originating in the extratropical tropopause, the tropical tropopause region and tropical transition layer as well as the polar vortex and the unperturbed stratospheric background.

This interaction occurs from the micro to the global scale, allowing for direct interaction and mixing of air with different origin. While tropospheric air can enter the LMS via transport across the extratropical and tropical tropopause, stratospheric air from higher altitudes enters this region via large scale downwelling in the frame of the Brewer-Dobson circulation (**Holton, 1995**). The composition of the LMS and the tropopause region is therefore controlled not only by Stratosphere-Troposphere Exchange (STE) processes but also by interaction of stratospheric air masses of different origin, which both affect the chemical and radiative properties of this important region for the climate system (**Rosenlof 1997; Tuck et al., 1999; Hoor, 2005; Boenisch, 2009; Haynes et al., 2001**).

The Arctic winter LMS can be regarded as a composition of three different types of airmasses (**Werner et al., 2010**), (i) tropospheric air entering the LMS via transport across the tropopause, (ii) extra-vortex stratospheric air descending from potential temperatures > 400 K and (iii) chemically processed vortex air subsiding from potential temperatures > 400 K. Tropospheric influence on the LMS region is believed to happen mainly in a so-called mixing-zone with an extension of about 20-30 K above the local tropopause (**Hoor et al., 2002**).

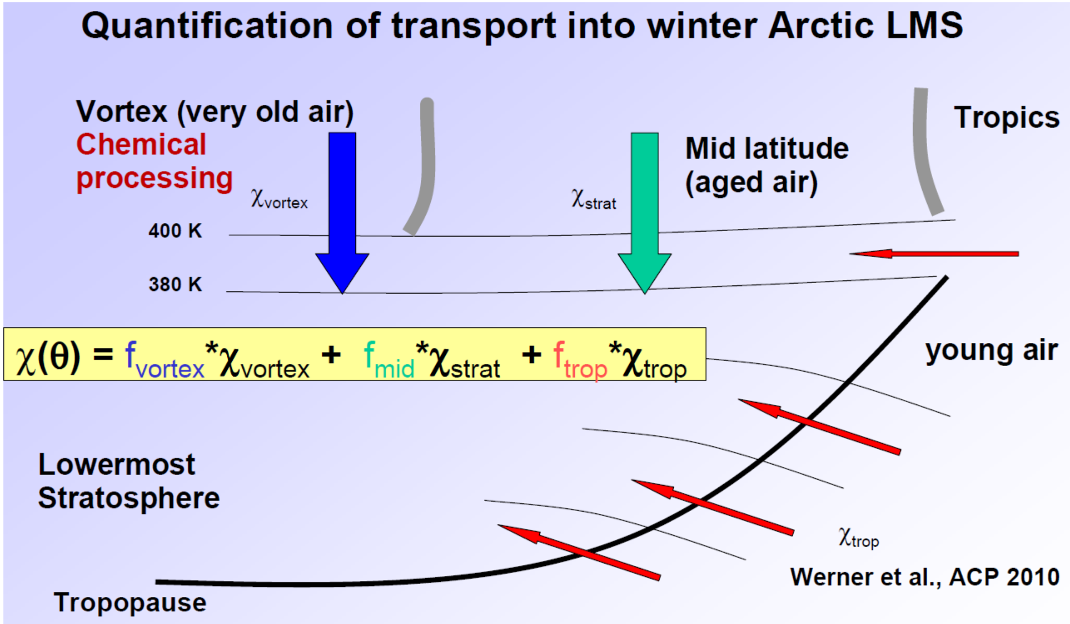


Figure 2: Schematic representation of processes affecting the composition of the LMS region. In Arctic winter processed air from the polar vortex enters the LMS region and can be transported towards lower latitudes, affecting the local chemistry and radiative forcing.

Inside the intact polar vortex, airmasses above about the 400k isentrope are mostly well isolated from the ambient stratosphere by a strong isentropic transport barrier and are chemically and physically processed. However, during periods of enhanced dynamic activity when the vortex may be disturbed, observations and simulations have shown that mixing of vortex and extra-vortex air resulting from the dissipation of the polar vortex contributes to ozone loss in the mid- and high-latitudes (i.e. **WMO, 2011**), even at altitudes higher than the 400k isentrope. At altitudes below the 400 K isentrope the absence of a mixing barrier allows fast transport into the mid-latitudes (**Chen et al., 1994; Werner et al. 2010**) and potential interaction with air from the tropics. Therefore, processed air of the aged vortex in the LMS region can be transported to lower latitudes and mixed with other airmasses during the entire winter/spring period. The high radiative sensitivity of the UTLS region to changes in the chemical composition was investigated by **Riese et al. (2012)**. The authors found that especially changes in the contributions of water vapour and ozone in UTLS at middle and high latitudes have a significant impact on the radiative forcing and the surface temperature.

**Werner et al. (2010)** quantified transport into the LMS in Arctic winter 2002/03 by in-situ tracer measurements above northern Europe. They found that in spring 2003 the LMS region at mid- and high latitudes above Europe was significantly influenced by the polar vortex. Their observations show a considerable fraction of vortex air at an equivalent latitude as low as 40° N. Their findings were mainly based on limited balloon profiles, posing the question whether the influence of vortex air is comparable on other regions and in other winters. As the polar vortex of the northern hemisphere is episodically disturbed by gravity waves, the question of the influence of the polar vortex on the high- and mid-latitude LMS is also linked to the influence of gravity waves onto the Arctic LMS region.

POLSTRACC aims on improving the understanding of the Arctic winter/spring LMS and its influence on the ambient atmosphere by addressing the following questions:

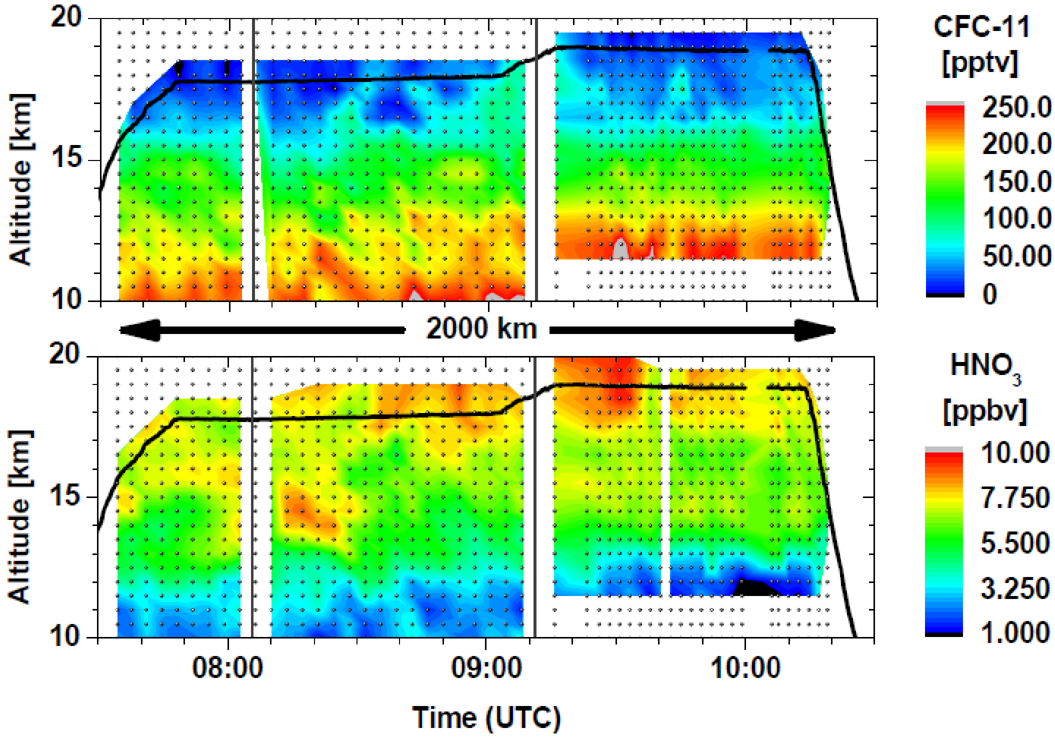


Figure 3: Vertical cross-sections of the stratospheric tracers CFC-11 and $HNO_3$ retrieved from MIPAS-STR infrared limb-observations during the RECONCILE/PREMIER-EX-Flight above northern Scandinavia on 10 March 2010. The observations show dynamical structures and patterns from vertical $HNO_3$ redistribution inside the late dissipating polar vortex reaching down into the LMS.

- What is the chemical composition of the vortex outflow and how does it affect the composition of the extra-vortex Arctic LMS?
- What are the fractions of tropospheric air, extra-vortex stratospheric air and vortex air inside the Arctic LMS at different stages of the polar winter?
- How fast and how frequent is vortex air transported towards lower latitudes and how strong is the impact on the chemical composition and radiative forcing? How strong is the interaction with tropical air?
- What are the typical spatial and temporal scales of atmospheric structures and filaments where exchange between stratospheric and tropospheric air occur?

POLSTRACC combines the capability of HALO of covering long horizontal distances with a comprehensive payload of high-resolution remote-sensing instruments and accurate in-situ measurement techniques, allowing for vortex-scale observations of one-, two- and three-dimensional tracer distributions. Utilizing innovative concepts for the characterisation of different airmasses in this vertical region (**Ray et al.; 1999**, **Ehalt et al., 2007; Bönisch et al., 2009; Werner et al., 2010, Jurkat et al., 2014**), POLSTRACC will provide improved understanding of the role of the high- and mid-latitude LMS in the northern winter/spring season.

## 1.2 Chemical processes affecting ozone in the Arctic winter UTLS

In Arctic winters stratospheric ozone is depleted through catalytic cycles involving chlorine- and bromine-containing radical species (**Solomon et al., 1999; WMO, 2011; references therein**). These radical species arise from chlorofluorocarbons (CFCs, i.e. Freon 11 ($CCl_3F$) and Freon 12 ($CCl_2F_2$)) and other man-made and natural halogen-containing species which are introduced into the stratosphere via the Brewer-Dobson circulation and are decomposed slowly by photolysis in the ultraviolet light. While the resulting chlorine species during the most time of the year are trapped in the reservoir species HCl and $ClONO_2$, highly reactive chlorine radical species are released when temperatures fall below the activation temperature for chlorine $T_{ACl}$ (**Drdla and Müller, 2010**).

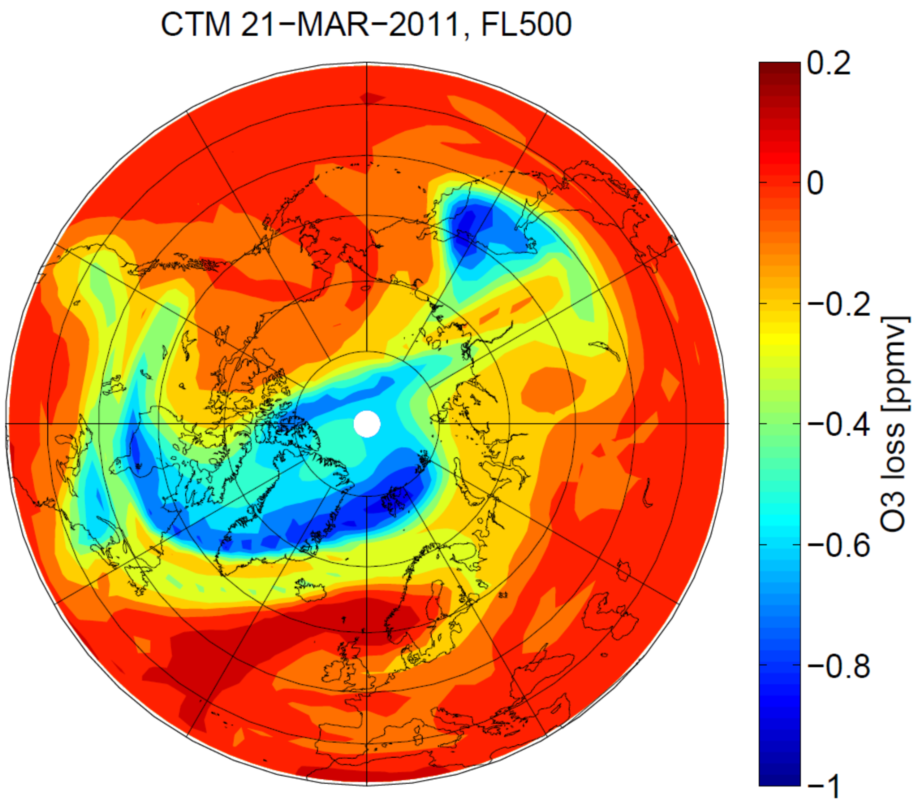


Figure 4: Chemical ozone loss on 21 March 2011 at Flight Level 500 (50000ft, 15.2km pressure altitude) as calculated by the Chemical Transport Model (CTM), based on **Sinnhuber et al. (2011)**. A well-defined vortex exists at this altitude and substantial ozone depletion, corresponding to a maximum loss of more than 50%, can occur at this altitude in cold winters such as March 2011.

Bromine is assumed to be transported into the stratosphere in the form of the longer-lived bromine species methyl bromide ($CH_3Br$), Halon-1211 ($CBrClF_2$) and Halon-1301 ($CBrF_3$) and also via very short lived bromine species such as $CHBr_3$, $CH_2BrCl$, $CHBrCl_2$ and $CH_2BrCH_2Br$ (**Salawitch et al. 2005; Aschmann and Sinnhuber, 2013; references therein**).

The radical species BrO resulting from decomposition of these species takes place in rapid catalytic ozone depletion, with the associated reservoir species $BrONO_2$ being quickly photolysed in the sunlight (**Soller et al, 2002**). Ozone depletion following the ClO-dimer cycle and the synergistic interaction of chlorine and bromine persists into spring, until the reactive chlorine species are deactivated into their reservoir species. Fast deactivation of the reactive chlorine species into the reservoir species $ClONO_2$ occurs via the reaction with $NO_2$ arising from $HNO_3$-photolysis. However, depending on the extent and duration of PSC occurrence, the availability of $HNO_3$ may be limited in certain stratospheric altitude regions through the denitrification process (i.e. irreversible vertical redistribution of $HNO_3$ through the condensation and sedimentation of $HNO_3$-containing particles), leading to extended ozone depletion in Arctic spring.

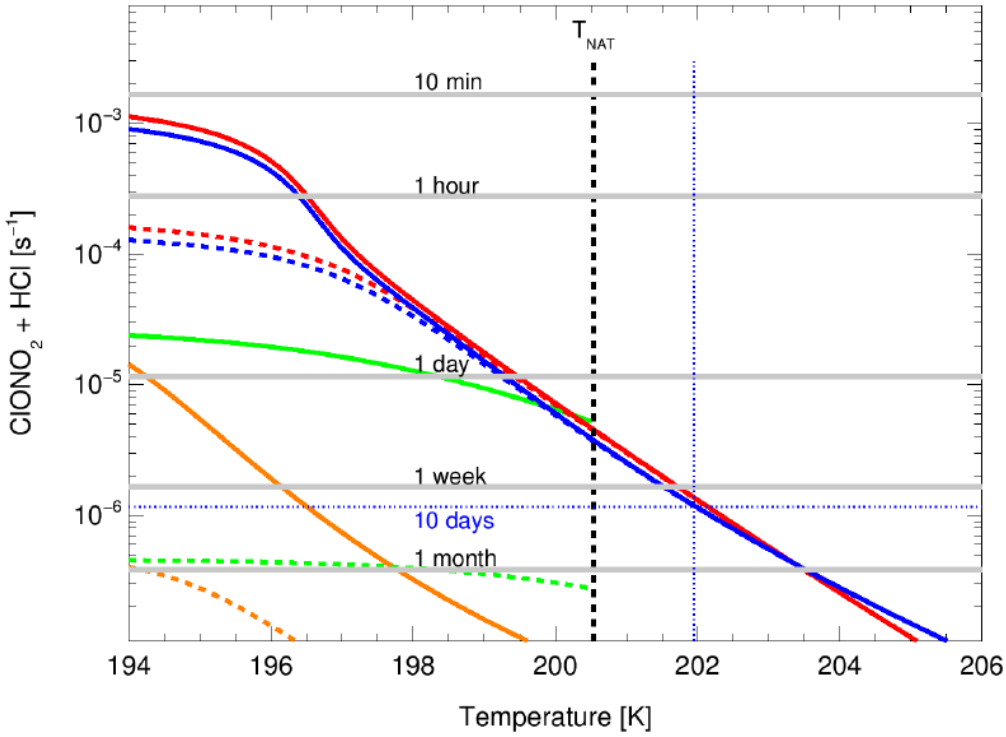


Figure 5: Estimated chlorine activation at the pressure level of 150 hPa (about 13 km altitude) assuming typical mixing ratios of $H_2O$, $HNO_3$, $ClONO_2$ and HCl ($T_{NAT}$=existence temperature of nitric acid trihydrate). The knowledge about the chlorine budget and the role of chlorine activation and ozone depletion in the Arctic LMS region is limited (e.g. **Thornton et al., 2005**).

In contrast to higher stratospheric altitudes, only limited field observations of chlorine- and bromine-containing species in the Arctic LMS are available, allowing to derive the extent of Arctic winter ozone depletion in this region (e.g. **Lelieveld et al., 1999; Thornton et al., 2003; Salawitch et al., 2005**).

Therefore, POLSTRACC will address the following issues:

- What is the distribution and the variability of chlorine species in the Arctic LMS?
- How large is the extent of chlorine activation in the Arctic LMS?
- How significant is ozone depletion through chlorine and bromine in this vertical region and what are the consequences for column ozone?
- What is the branching ratio of the reaction of ClO and BrO?

The POLSTRACC mission will involve in situ and remote sensing observations of chlorine and bromine radical and reservoir species, allowing to measure the extend of chlorine and bromine activation in the lower UTLS region and to constrain the rates of reactions involved in ozone depletion. Furthermore, the role of cirrus clouds in chlorine activation in the Arctic LMS (compare **Bormann et al., 1996**) will be investigated if favourable meteorological conditions are available. The observations will be used to improve parameterisations of chemical ozone depletion in model simulations.

Furthermore, POLSTRACC will provide observations helping to quantify the budget of ozone relevant CFCs and their hydrogenated derivatives (HCFCs) in high latitude regions, as the content of active chlorine in the Arctic UTLS depends on the abundance and photolysis of these species.

## 1.3 Polar Stratospheric Clouds and Denitrification

Polar Stratospheric clouds play an important role in the chemistry of the Arctic winter stratosphere (**Peter and Grooß, 2012; references therein**). The cloud particles provide sites for heterogeneous reactions, including the activation of ozone-destroying chlorine and bromine species (**Solomon, 1999 and references therein**). Certain polar stratospheric cloud particles are known to consist of nitric acid trihydrate (NAT) (**Voigt et al., 2000; Höpfner et al., 2006**) and irreversibly redistribute $HNO_3$ towards lower stratospheric altitudes and can thereby delay the deactivation of ozone-destroying compounds.

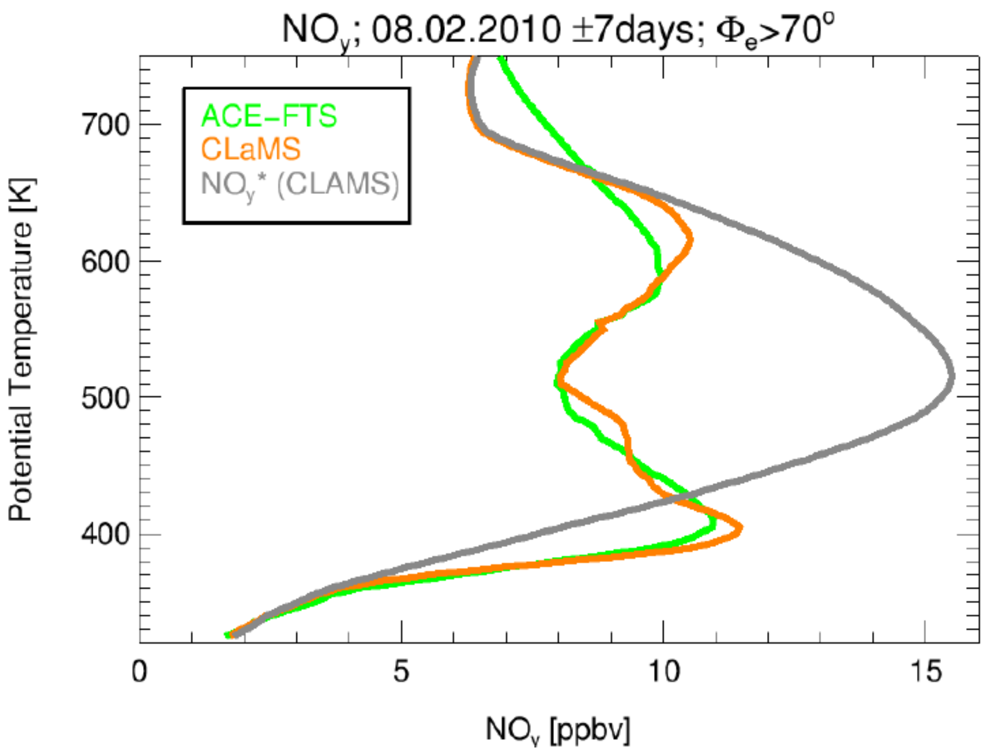


Figure 6: Measured and modelled vertical $NO_y$ redistribution inside the polar vortex in early 2010. Enhanced $NO_y$ mixing ratios are found inside the LMS region below the 400 K isentrope as a consequence of nitrification through the sedimentation of $HNO_3$-containing PSC particles. Quantitative understanding of the process of vertical $HNO_3$ redistribution by condensation, sedimentation and evaporation of $HNO_3$-containing particles is still lacking.

Quantitative understanding is still lacking regarding the nucleation, sedimentation and physical properties of $HNO_3$-containing particles involved in denitrification (**Grooß et al., 2014; Molleker et al., 2014; Woiwode et al. 2014**) and it is still not clear whether other hydrates of $HNO_3$ than NAT are also involved. Furthermore it is not clear, how deep denitrification and associated nitrification can penetrate into the LMS region, which is critically dependent on the availability of cold temperatures and on the settling behaviour of the particles. Nitrified airmasses resulting from the evaporation of PSC particles were observed by airborne remote sensing instruments (i.e. **Ungermann et al. , 2012; Woiwode et al., 2012; Kalicinsky et al., 2013**) at stratospheric altitudes as low as 14 km, posing the question on the influence of nitrification on the $NO_y$ budget (i.e. reactive nitrogen species) in the LMS.

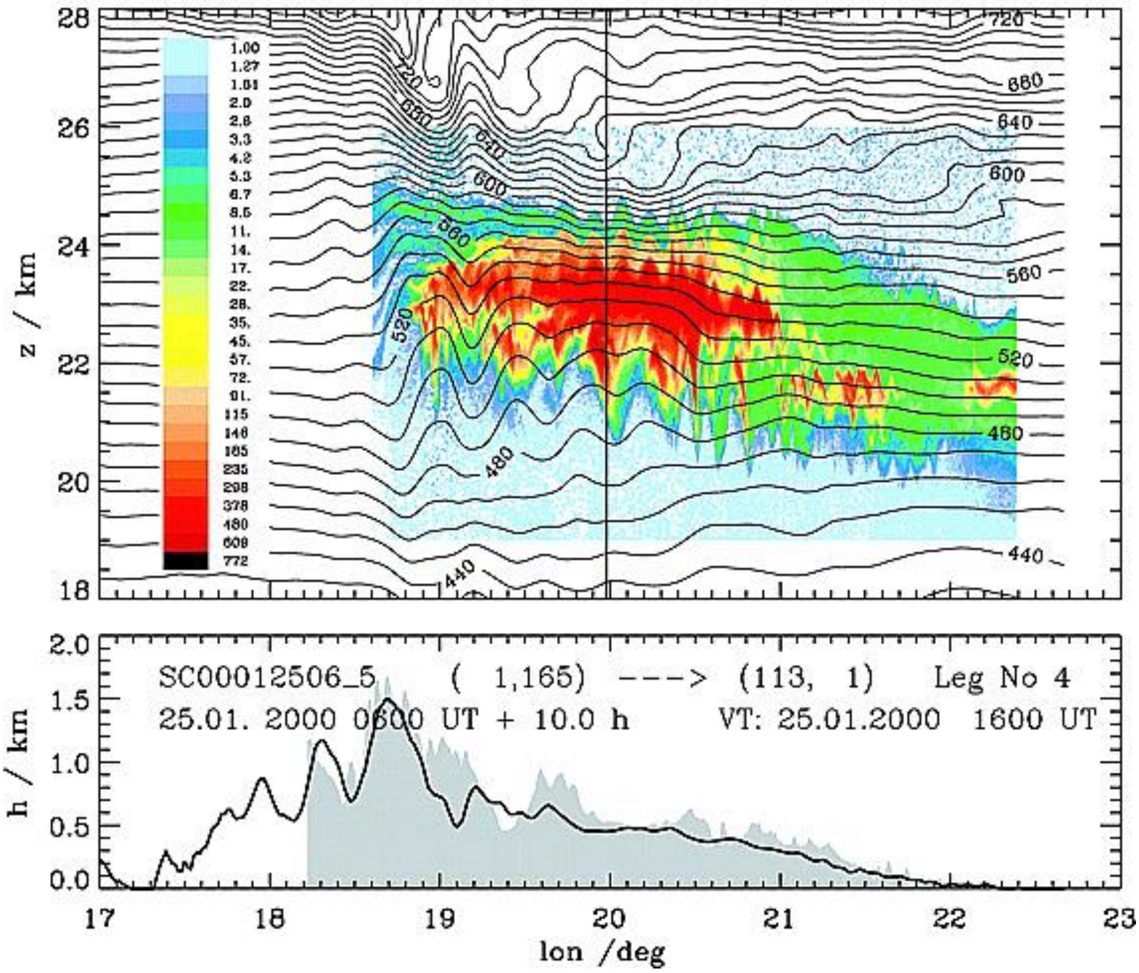


Figure 7: Backscatter ratio $\gamma$ at 1064 nm derived from lidar observations aboard the DLR Falcon on 25 January 2000 above northern Scandinavia (upper panel). Superimposed: MM5 potential temperature (10 K interval) along flight track. Elevation of the topography below the flight leg (lower panel). The POSTRACC and GW-LCycle flights will employ lidar and IR-limb observations to study the extent, formation and composition of PSCs and vertical redistribution of $HNO_3$. Adapted from **Dörnbrack et al. (2002)**.

Lidar offers the opportunity to measure orographic induced PSCs (**Dörnbrack et al, 2002**) and synoptic scale PSCs (**Flentje et al., 2002**). This technique allows for classification of the PSCs and for estimates of the particle size distribution. Furthermore, infrared limb observations allow to classify different types of PSCs and to derive number density profiles (**Höpfner et al., 2006**). During POLSTRACC, the combination of WALES and GLORIA offers the opportunity to study the patterns, formation and composition of PSCs as well as the vertical and horizontal $HNO_3$ redistribution in much more detail than before. Observations by the space-borne lidar system CALIPSO will provide a broader context to the POLSTRACC observations.

POLSTRACC will involve airborne remote sensing and in-situ observations in combination with chemistry transport simulations to address the following issues:

- What are the optical and physical characteristics of aerosols and particles in PSCs
- How far do PSCs reach down into the Arctic UTLS and what are the consequences for the chemistry of the LMS?
- What are the characteristics of $HNO_3$-containing particles involved in denitrification and how does vertical $HNO_3$-redistribution affect the composition of the LMS?
- How can the representation of denitrification (i.e. particle nucleation and sedimentation) be improved in simulations?

The formation of PSCs can be strongly linked to the occurrence of lee waves, which are a frequently observed downstream of Greenland and Scandinavia and are capable of inducing the nucleation of solid ice and NAT particles. POLSTRACC will be carried out in cooperation with the GW-LCYCLE (Investigation of the life cycle of gravity waves) project, investigating dynamical coupling processes through gravity waves from the troposphere into the stratosphere and mesosphere. The combination of the scientific objectives and mission scenarios of both projects along with a suite of ground-based observations and model simulations will help to improve our understanding of PSC formation and vertical redistribution of $HNO_3$, the role of gravity waves and the effects on the chemistry and composition of the LMS region.

## 1.4 The Role of Cirrus Clouds in the Arctic UTLS

Cirrus clouds form in the upper troposphere/lower stratosphere region at altitudes above 5 km and temperatures below 235 K. On the global average high clouds cover ~40% of the Earth with slightly lower coverage in the Arctic region (**Wylie et al., 2005**). The role of Arctic cirrus clouds on atmospheric chemistry of the Arctic region is poorly known, in fact cirrus observations from aircraft in the Arctic tropopause region are limited to date (**Spang et al., 2014, Lübke et al., 2013, Kärcher, 2005; references therein**). Arctic cirrus clouds can form in mountain waves, outflow linked to storm tracks, jet streams or high pressure systems; still, the relative contribution of the individual meteorological situations to Arctic cirrus cloud occurrence is unknown.

Cirrus clouds modify chemical composition of the UTLS region through uptake of water vapour and trace species (e.g. nitric acid, chlorinated and brominated compounds), sedimentation and sublimation, thereby transporting of trace species to lower altitudes. In-situ measurements by **Schiller et al. (1999)** show that the sedimentation of large ice crystals in

Arctic cirrus clouds can result in significant dehydration. Nitric acid is trapped in the growing cirrus ice crystals, potentially leading to local denitrification in the Arctic tropopause region (**Kärcher and Voigt, 2006, Krämer et al., 2006, Voigt et al., 2006**). This effect could be enhanced in the late polar winter, when denitrification due to PSCs leads to high nitric acid concentrations in the Arctic lower stratosphere. The uptake of nitric acid in cirrus clouds is has been modelled and compared to a suite of laboratory and in-situ measurements under different meteorological conditions (**Ziereis et al., 2004; Kärcher and Voigt, 2006; Krämer et al., 2008**). Saturation effects may occur at higher nitric acid levels (**Kärcher et al., 2009**), which still demand critical validation with observations. Measurements in Arctic cirrus are rare and may not cover the total possible IWC range.

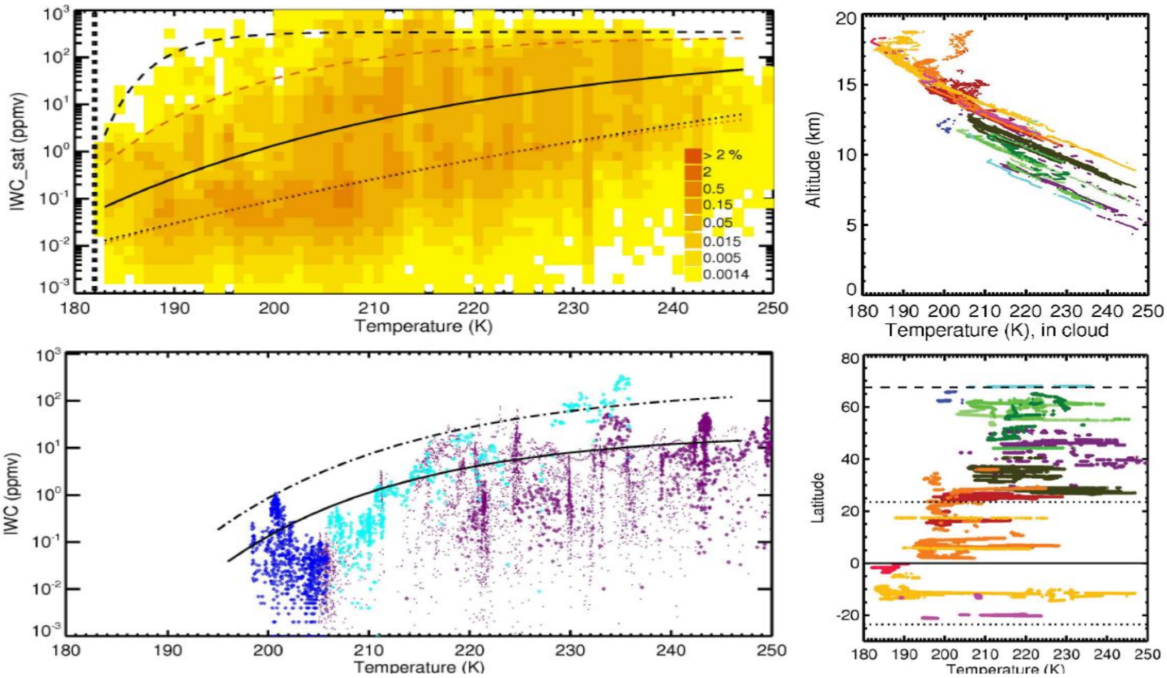


Figure 8: Ice water content (IWC) in globally measured (upper panel) and in Arctic (lower panel) cirrus clouds, altitude and temperature range of in-situ cirrus observations and latitudinal coverage of in-situ cirrus observations **(from Lübke et al., 2013)**. In situ cirrus observations in the Arctic are rare.

Ice clouds have been detected in the vertical range between the local tropopause and hygropause at Arctic latitudes (i.e. **Kärcher and Solomon, 1999**). Airborne measurements and trajectory analyses indicate a significant potential for cirrus cloud formation up to about 3 km above the local tropopause in the Arctic (**Pfister et al., 2003).** Recently, **Spang et al. (2014)** demonstrated by means of satellite observations in combination with model simulations the potential for the occurrence of cirrus clouds in the Northern hemispheric lowermost stratosphere and tropopause region due to quasi-horizontal transport of water vapour from the sub-tropics.

Cirrus cloud particles provide sites for chlorine activation, potentially leading to ozone loss in the Arctic UTLS region, first suggested by **Bormann et al. (1996)**. Observations show enhanced active chlorine in the form of ClO near the Arctic winter tropopause (**Thornton et al., 2003)** traced back to chlorine activation on Arctic cirrus clouds. Models find contradictory results concerning the efficiency of chlorine activation on cirrus (**Solomon et al., 1997;**

**Lelieveld et al., 1999, Bregman, 2002**) and its impact on the ozone distribution in the UTLS region is still under debate (**von Hobe et al., 2013**).

POLSTRACC will involve vortex-scale high spatial resolution remote sensing measurements and in situ instruments in combination with drop sondes to detect the distribution and properties of cirrus clouds.

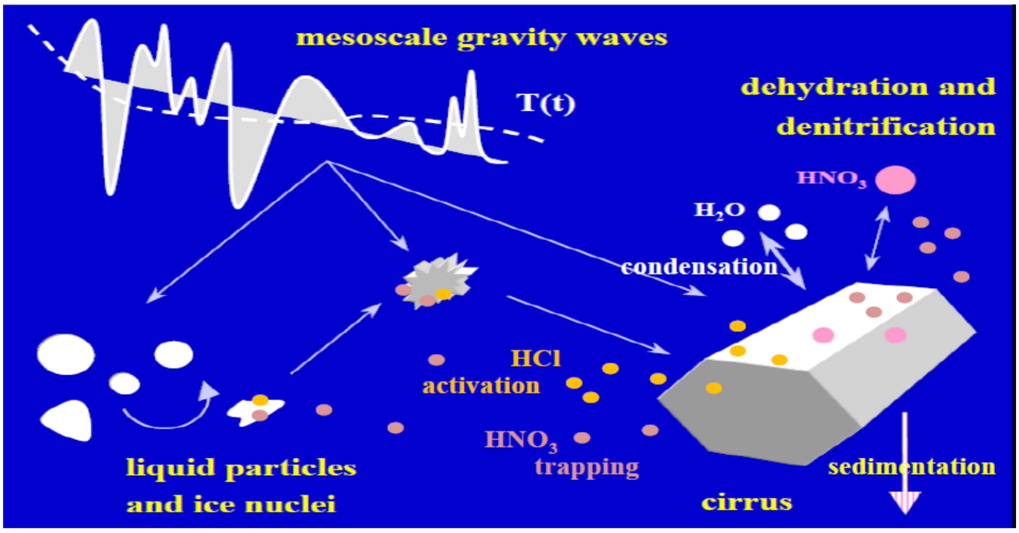


Figure 9: Role of cirrus clouds for atmospheric chemistry, modified from **Kärcher (2003)**.

Dedicated in-situ and remote sensing measurements will allow to study the abundances of gas-phase and particulate $H_2O$ as well as reactive nitrogen and chlorine species inside and near cirrus clouds. Observations of gravity waves and mountain waves in cooperation with GW-LCYCLE will help to link these events to cirrus occurrence and will give new insight on the effects of the trace gas distributions of condensable species.

The POLSTRACC observations will help to address the following questions:

- To which extent are cirrus clouds capable of dehydration and associated denitrification?
- Can we confirm saturation effects in trapping of $HNO_3$ by Arctic cirrus clouds?
- Can cirrus cloud occurrence be attributed to isentropic transport of water vapour in the Artic LMS?
- Can we relate $HNO_{3,ice}$ trapped in ice crystals to different ice crystal growth rates?
- Can we detect a removal of gaseous HCl by cirrus or cold Arctic aerosol?

The combination of the long range remote sensing and in-situ observations with high-resolution chemistry model simulations will help to improve our understanding of chemical and microphysical processes in cirrus affecting the Arctic UTLS.

## 1.5 Gravity Wave Life Cycle Experiment (GW-LCYCLE)

The Gravity Wave Life Cycle Experiment will study dynamical coupling processes by gravity waves from the troposphere into the mesosphere. GW-LCYLCE aims at improving gravity wave parameterizations for use in climate models. Therefore, the goal of GW-LCYCLE is to investigate the full lifecycle of gravity waves, including gravity wave excitation, propagation and dissipation. GW-LCYCLE will employ observations aboard the research aircrafts HALO and FALCON, ground-based observations, correlative satellite observations and numerical modelling. GW-LCYCLE is a coordinated initiative of German research institutions with close collaboration to the DFG research group „Multiscale Dynamics of Gravity Waves" (MS-GWAVES).

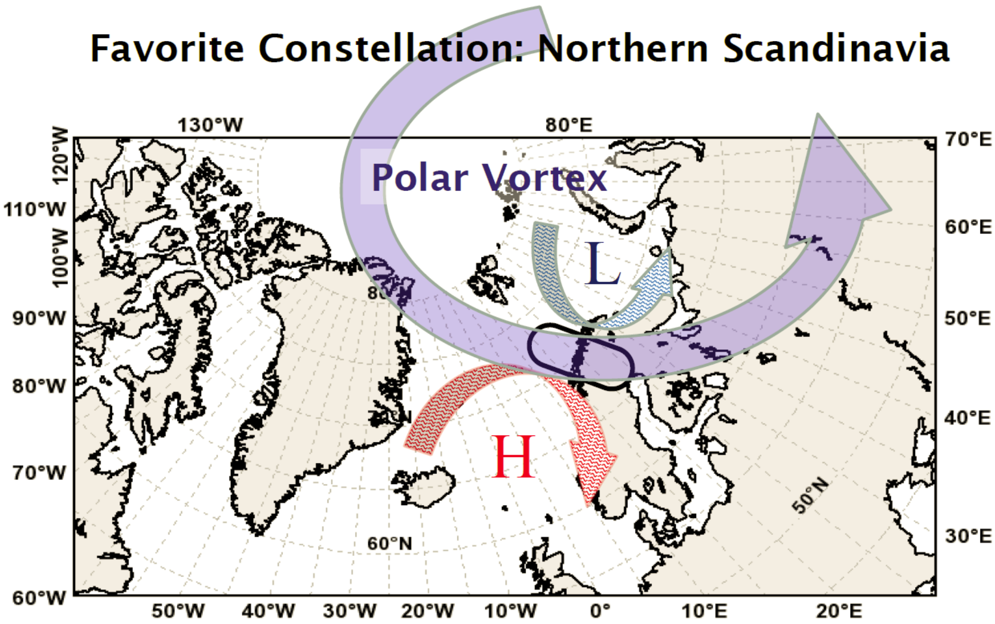


Figure 10: Preferential meteorological situation for gravity wave excitation above northern Scandinavia, which is in the focus of the GW-LCYCLE observations.

The most active season for gravity wave formation in Arctic winter is typically between December and February. Therefore, the most intensive phase for gravity wave observations of the aircraft campaign will be from January to February and, depending on the meteorological situation, also in the December. During the phase from January to February, both HALO and FALCON will be available for coordinated flights from Kiruna. The advantage of coordinated flights using the two aircrafts is that a gravity wave scenarios can be probed by in situ instruments (T, tracers, wind) at different levels at the same time, e.g. above and below the tropopause. The downward looking wind lidar aboard FALCON, the upward looking WALES lidar (backscatter, $O_3$, and $H_2O$) and the GLORIA limb observations (T, $O_3$, $H_2O$, tracers, cloud-parameters) will provide 2-dimensional vertical cross-sections of key parameters suitable to study gravity waves.

In particular, the GLORIA observations enable 3-dimensional tomographic observations to study the vertical and horizontal wavelengths of gravity waves as well as their phase velocities. Complementary ground based observations including radiosondes, lidar and radar, observations of mesospheric OH from the FALCON as well as satellite-borne observations will provide additional information required to study the full life cycle of gravity waves.

Numerical modelling by the Weather Research and Forecast Model (WRF) will be utilized to provide forecasts, nowcasts and idealized representations of gravity the wave scenarios to be probed by the observations. Furthermore, the combination of forward and backward ray tracing will be used to identify sources of gravity wave excitation. The synergistic analysis of the observations and model results will be used to improve gravity wave parameterizations for climate models.

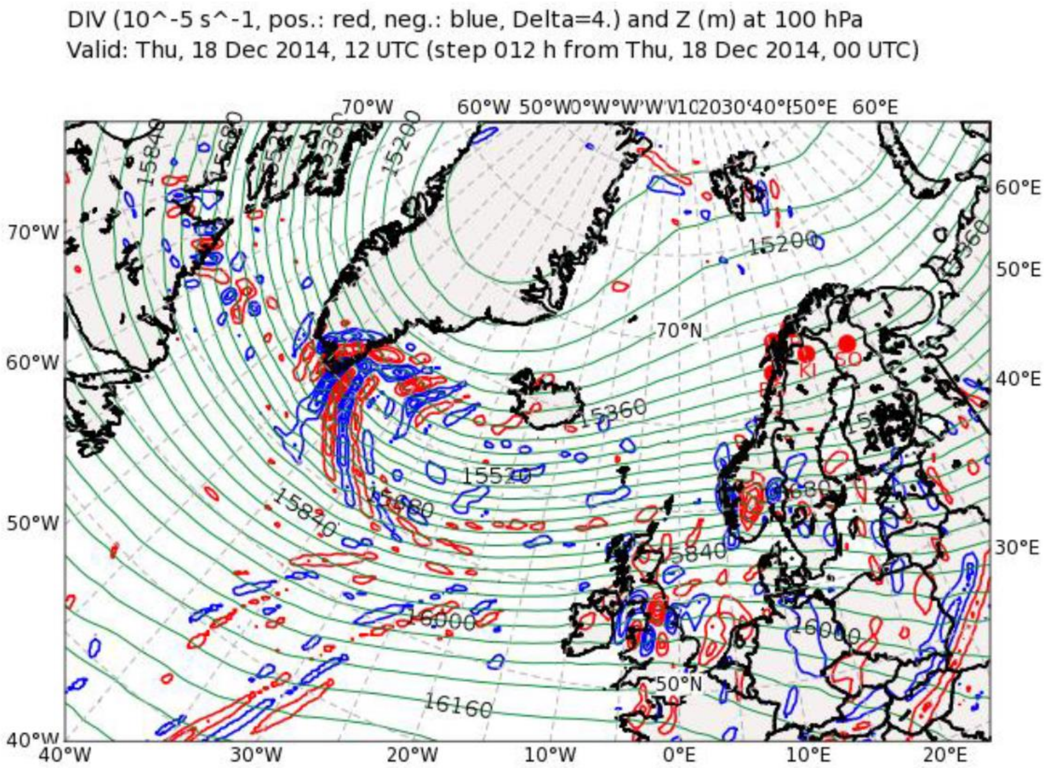


Figure 11: Gravity wave scenario at the southern tip of Greenland, which would be accessible to HALO.

The combined flight scenarios of HALO and FALCON will focus on gravity observations above Scandinavia, since the Scandinavian mountains are one of the most important source regions for gravity waves in the northern hemisphere and since in this region the best coverage of coordinated ground-based observations is available. The long range capabilities of HALO will furthermore enable to probe more distant gravity wave scenarios, e.g. induced above Greenland or Island, and to observe the development of wave patterns above the northern Atlantic.

## 1.6 Seasonality of Air mass transport and origin in the Lowermost Stratosphere (SALSA)

The UTLS represents a nexus for troposphere stratosphere coupling as well as for chemistry-climate coupling (e.g. **Shepherd 2007**). Greenhouse gases such as water vapour and ozone exhibit strong gradients across the tropopause (e.g. **Pan et al. 2004**). Additionally, the cold tropopause temperatures cause radiative forcing to be very sensitive to the distribution of greenhouse gases in the UTLS (e.g. **Forster and Shine 1997; Riese et al., 2012**). The tropical UTLS and its chemical composition therefore set the boundary condition for stratospheric trace gases that have their origin in the troposphere (e.g. water vapour, halocarbons). Likewise, most stratosphere-to-troposphere transport (STT) takes place through the extratropical tropopause, which sets the boundary condition for tropospheric trace gases with stratospheric origin (e.g. ozone, hydrogen chloride) and plays a role for the understanding of upper tropospheric oxidation capacity and chemical burden. A quantitative description of the time-scales and seasonalities of the stratosphere-troposphere exchange (STE) is one of the most challenging tasks in understanding of transport across the tropopause.

The overall scientific rationale of SALSA (Seasonality of Air mass transport and origin in the Lowermost Stratosphere using the HALO Aircraft) is to improve the understanding of UTLS transport and chemistry through a better knowledge of the seasonality of trace gas distributions. As different trace gases have different source/sink characteristics and different lifetimes, they can be used to distinguish different transport pathways and different transport timescales. A detailed discussion on this is given in the SALSA Whitebook. Many of the studies proposed in the SALSA Whitebook depend on a complete seasonal cycle of trace gas distributions in the LMS. These are in particular important for the derivation of mass budgets (which transport pathway contributes to which extend to the chemical composition of the LMS?) and for the investigation of long-term changes in dynamics (e.g. through changes in the seasonality of the $N_2O$-$O_3$ correlation). The winter season is also part of the studies to investigate the seasonality of the tropopause inversion layer (TIL) (**Birner at al., 2006**) and the extratropical tropopause layer (ExTL) (**Fischer et al., 2000**), as well as the halogen and nitrogen oxide budget of the UTLS region.

For some science aspects of the SALSA mission the winter season will be of particular importance or present a particular challenge. The reason is that – as outlined in the SALSA Whitebook and section 1.1 – the LMS is influenced by (1) stratospheric air from above, (2) young tropical airmasses which have passed the tropopause in the tropics or partly in the subtropics and (3) extratropical tropospheric air. The balance between these two latter pathways and the descent from above controls the amount of water vapour and its seasonality in the LMS (see e.g. **Randel and Jensen, 2013, Krebsbach et al., 2006**). During the winter season the input from above (aged stratospheric air) is in addition modified by the strong descent in the polar vortex, which modulates the chemical composition of descending air. The mass balance for the winter LMS thus has an additional term, namely the winter polar vortex (see e.g. **Werner et al., 2010**). In regions, where the polar winter LMS is influenced significantly by the additional influx of strongly descended polar vortex air, particular issues are:

- **Investigation of correlations in order to study where stratosphere-troposphere-transport occurs.** Due to the influx of air from above, which has descended in the polar vortex, the slope of correlations is expected to change over the course of the winter. This could be used to differentiate the contribution from polar vortex air and from mid-latitude air descending from above into the LMS.

- **How far into the LMS does troposphere-stratosphere-transport occur?** The winter season is characterised by strong descent in the polar winter vortex which extends into the LMS. This will also modify the way that tropospheric air can be mixed into the LMS. Using tracers with different lifetimes we can investigate the depth to which tropospheric air penetrates into the LMS and the associated timescales. This will be used to investigate if the influx of tropospheric air influences the LMS during winter in high latitudes in a different way than during other seasons.

- **What are the age spectra in the UTLS?** Age spectra can be derived from observations of tracers with different lifetimes using specific assumptions (**Schoeberl et al., 2005, Ehhalt et al., 2007**), in particular about their lifetimes. Here again, the portion of the age spectrum, which took the long transport pathways via the upper branch of the Brewer-Dobson circulation, is modified during winter as part of the descending air from higher up in the stratosphere due to the strong descent rates in the polar vortex. It will be tested if these age spectra are different from those derived during other seasons.

# 2 THE POLSTRACC CAMPAIGN

## 2.1 Platform

The scientific objectives of POLSTRACC require a carrier that is able to accommodate a comprehensive suite of instruments, to fly over long distance and to get into the lowermost stratosphere at high and middle latitudes in winter and spring. HALO with its large payload capacity and its capability to access long range (up to about 10.000 km) and rather high altitudes of up to 15.5 km (as demonstrated during the TACTS/ ESMVAL and ML-CIRRUS missions) appears almost ideally suited to meet the requirements of the POLSTRACC mission. Research flights will be carried out between December 2015 to March 2016 and cover the formation of the polar-vortex, the mid-winter vortex and late dissipating vortex (vortex break-down period).

Figure 12: HALO research aircraft

To extend the scientific scope of POLSTRACC, co-operations with ground-based observation stations, balloon sounding activities (ozone soundings and radiosondes) as well as satellite-borne projects (i.e. CALIPSO, **Pitts et al., 2011**; MLS, **Santee et al., 2011;** ACE-FTS, **Bernath et al., 2005**) will be exploited. Utilizing the scientific data and findings accumulated by the POLSTRACC framework, chemistry transport and climate chemistry model studies will be carried out to analyse critical chemical, physical and dynamical processes and to improve long-term projections for the evolution the Arctic stratosphere within the climate system.

## 2.2 Campaign location and season

The observations shall cover the core region of the polar vortex, the vortex edge as well as the vicinity of the polar vortex to study chemical and physical processes inside the polar vortex and its interaction with the ambient stratosphere and troposphere. The most suitable and well established airport for this task is at Kiruna in northern Sweden (67° 49′ N/ 20° 20′ E). The Kiruna airport provides reliable access with HALO to the polar vortex allows flying deeply into the polar vortex (even if dislocated from the campaign base Kiruna) and providing extended cuts and cross-sections of the polar vortex.


Figure 13: The POLSTRACC field campaign will be housed in the hangar Arena Arctica at Kiruna Airport (Sweden), providing a modern technical infrastructure, meeting rooms and logistics, and allowing long-haul flights through the polar vortex..

It provides a comprehensive infrastructure known to most involved scientific groups, is easily accessible via scheduled flights from Stockholm and is located close to Kiruna city, where housing, shops and all kinds of facilities are available. Since in winter there is very few air traffic at and around Kiruna airport, research flights can be carried out as soon as the pre-flight operations are ready and no long waiting times due to traffic have to be taken into account. Due to the almost empty airspace north and west of Kiruna flight safety restrictions are comparably low although the sparsity of alternates need to be taken into account when flying over the high Arctic. Furthermore, the airport is well prepared for winter conditions, i.e. the runway can be quickly prepared after snow fall or under icy conditions.

The modern hangar Arena Arctica (5.000 square meters) offers all requirements necessary for aircraft housing and maintenance, instrument integration, flight planning and monitoring, as well as logistic infrastructure. The campaign operations centre will also be housed in the hangar were comfortable bureaus and meeting rooms and internet access are available.

To follow up the dynamical and chemical evolution of the whole winter, two or three campaign phases would be ideal which however would block HALO for a long time. Instead, thanks to the long range of HALO essential phases of the Arctic winter and spring season can be covered by a combination of local flights from Oberpfaffenhofen in December and possibly early January followed by one or two intensive measurement campaign(s) from Kiruna airport in February and March. HALO will allow covering a much more extended area (preferably vortex-wide) than was possible in earlier Arctic aircraft campaigns.

## 2.3 Instrumentation

POLSTRACC utilizes an innovative combination of in-situ and remote sensing instrumentation providing highly resolved and accurate observations of the polar UTLS region. As already demonstrated during TACTS/ESMVAL with a subset of the instruments, this combination exploits the synergy of local but highly specific and precise in-situ observations with 2D- and 3D-distributions of atmospheric parameters derived from the remote sensing instruments. Observations will be done with respect to physical conditions (pressure, temperature, wind), chemical composition (trace gas composition), clouds (PSCs, cirrus clouds and aerosol) and dynamic processes (using combinations of these parameters).

| Instrument | Target Parameter | Technique | Institution |
|---|---|---|---|
| GLORIA | $N_2O$, $CH_4$, $H_2O$, HDO, $SF_6$, CFCs, $O_3$, $ClONO_2$ | IFTS | IMK-ASF, KIT IEK-7, FZJ |
| Mini-DOAS | $O_3$, $NO_2$, $CH_2O$, $O_4$, BrO, OClO, IO, OIO | UV/VIS/NIR Spectrometer | University of Heidelberg |
| WALES | Aerosol, $H_2O$, $O_3$ | Lidar | DLR-IPA |
| AIMS | HCl, $HNO_3$, $ClONO_2$, $SO_2$ | Mass Spectrometer | DLR-IPA |
| BAHAMAS | Meteorologic and Avionic Data | BAsic Measurement And Sensor System | DLR-FX |
| FAIRO | $O_3$ | UV Photometer/ Chemiluminescence | IMK-ASF, KIT |
| FISH | Total/Gas-phase $H_2O$ | Lyman-Alpha Hygrometer | IEK-7, FZJ |
| GhOST-MS | $CH_3Br$, $CHBr_3$, $CHCl_3$, $CH_3I$, CFCs, $SF_6$ | GC-MS | University of Frankfurt |
| HAGAR-V | $SF_6$, $CH_4$, $H_2$, $N_2O$, CFCs, NMHCs, $CO_2$ | GC-MS | University of Wuppertal |
| HAI | Total/Gas-phase $H_2O$ | TDL (incl. Open-Path) | PTB |
| IPA-NOy | NO, $NO_y$ | Chemiluminescence | DLR-IPA |
| Dropsonde | p, T, Humidity, Wind | Drop Sonde System | DLR-IPA |
| TRIHOP | CO, $N_2O$, $CH_4$ and $CO_2$ | Laser Spectrometer | University of Mainz |
| SHARC | Gas-phase $H_2O$ | TDL | DLR-FX |

Table 1: Designated HALO payload for the POLSTRACC campaign.

The remote sensing instruments will include passive IR limb observations using the new imaging technique, UV-VIS differential optical absorption spectroscopy and a new multi-wavelength LIDAR system. The in situ instruments include various different techniques including mass spectrometers, different spectroscopic techniques and drop sondes, allowing highly accurate and high frequent observations of trace gases including minor species and physical parameters.

Most of the instruments have flown already on HALO in a similar configuration during TACTS/ESMVAL. The most prominent and important complements compared to TACTS/ESMVAL will be the deployment of DLR's multi-wavelength LIDAR, the GC/Mass Spectrometer system HAGAR-V (University of Wuppertal) and the drop sondes. The individual instruments are introduced briefly in the following:

## Remote Sensing instruments

### GLORIA

The imaging Fourier transform spectrometer GLORIA will provide two and three-dimensional vertically and horizontally highly resolved distributions of trace gases, temperature and cloud parameters around and below flight altitude (**Friedl-Vallon et al., 2014; Riese et al., 2014**). The instrument is operated in two different observation modes: The "chemistry mode" is optimized to spectrally highly resolved observations, allowing the retrieval of a comprehensive set of minor species (i.e. $ClONO_2$, (H)CFCs, potentially ClO and $BrONO_2$). The fast and spectrally less resolved "dynamics mode" is optimized to high spatial resolution observations of more abundant species (e.g. $O_3$, $HNO_3$, CFC-12) in order to investigate dynamic structures on fine-scale also with tomographic approaches.

### Mini DOAS

The Mini-DOAS (**Prados-Roman et al., 2011**) provides slant columns and vertical cross-sections of a comprehensive set of species and cloud parameters, including highly reactive trace species with extremely low mixing ratios (e.g. BrO, OClO, IO and OIO).

### WALES

The multi-wavelength LIDAR system provides observations of the traces $O_3$ and $H_2O$ and cloud parameters (e.g. backscatter, depolarization, aerosol optical path depth). The LIDAR system will be mounted in upward viewing mode, thereby extending the vertical range of the POLSTRACC observations up to 25 km and above, which is especially important for studies of PSCs.

## In Situ Instruments

### AIMS

The mass spectrometer AIMS (**Voigt et al., 2014; Jurkat et al., 2014**) provides accurate observations of the important chlorine reservoirs HCl and $ClONO_2$ as well as $HNO_3$, $SO_2$ and further species, allowing to study chemical and physical processes associated to PSCs and cirrus clouds. The trace gases are ionized using $SF_5^-$ ions and the resultant educt ions are detected with a quadrupole mass spectrometer. The instrument is calibrated in flight to enhance accuracy. It has been developed in 2011 and since then deployed during several HALO (TACTS, ESMVal, ML-CIRRUS) and Falcon (CONCERT, ACCESS) missions.

### BAHAMAS

The HALO BAsic HALO Measurement And Sensor System (BAHAMAS) records meteorologic data (e.g. wind and water vapour) and avionic data (aircraft speed, altitude, geolocation and attitude) with high accuracy and provides a comprehensive user infrastructure (e.g. video server and network).

### FAIRO

The Fast and Accurate In-situ Ozone instrument (FAIRO) employs a fast and precise chemiluminescence detector and an accurate dual-beam UV photometer for highly accurate ozone observations with high time resolution.

### FISH

The Fast In-situ Stratospheric Hygrometer (FISH) detects water vapour based on the Lyman-alpha photofragment fluorescence technique (**Zöger et al., 1999**). It has been deployed for almost two decades for high-precision measurements of water vapour in the UTLS on various platforms and has been validated with several in situ instruments and within laboratory studies.

### GhOST-MS

The GC/MS-system GhOST-MS measures a large set of chemical tracers with different lifetimes (e.g. $CH_3I$, $CH_3Br$, $CHBr_3$, CFCs) with lifetimes from several days to many years. The GhOST-MS-measurements allow to study transport processes on different timescales and have a high time-resolution in the order of a minutes depending of the observed species.

### HAGAR-V

The modular gas-chromatograph/mass spectrometer system HAGAR-V measures a comprehensive set of airmass tracers with atmospheric lifetimes ranging from days to many years. It consists of three modules: (i) two GC-ECD channels measuring $SF_6$, $CH_4$, $H_2$, $N_2O$, CFC-11, CFC-12 and Halon-1211, (ii) a dual channel GC/MS measuring several short-lived non-methane hydrocarbons (NMHCs) and (iii) a non-dispersive IR detector measuring $CO_2$ at high time resolution and with high accuracy. HAGAR-IV is a successor of the very successful HAGAR system that has been deployed for many years aboard the Geophyisca (e.g. **Werner et al., 2010**).

### IPA-NOy

The IPA-$NO_y$ instrument is a two channel instrument for the simultaneous detection of nitrogen oxide (NO) and the sum of all reactive nitrogen species ($NO_y$). It is based on the chemiluminescence detection of NO in combination with a gold converter technique for $NO_y$

measurements. Its time resolution is one second. This instrument was successfully operated during several missions, e.g. POLSTAR (**Ziereis et al., 2000**) and INCA (**Ziereis et al., 2004**). The instrument was also deployed during recent HALO missions (TACTS, ESMVAL, ML-CIRRUS, and ACRIDICON).

### Dropsonde

The dropsonde system by DLR-IPA provide vertical profiles of pressure, temperature, humidity and wind.

### TRIHOP

The laser spectrometer system TRIHOP is based on the TRISTAR instrument from the Max Planck Institute for Chemistry in Mainz operated during the SPURT project. It constitutes of three quantum cascade lasers, which will be used to simultaneously measure CO, $N_2O$, $CH_4$ and $CO_2$ with a time resolution of 10 seconds. The instrument has been successfully used during the TACTS / ESMVal mission in 2012.

## 2.4 Synergies from combining POLSTRACC, GW-LCYCLE and SALSA-1 to one joint campaign using the same payload

The POLSTRACC mission will be complemented by airborne observations in the framework of the GW-LCYLCE (BMBF ROMIC-framework) and SALSA (DFG-SPP) projects that will be linked to POLSTRACC by sharing the same HALO payload. The using of a shared payload, the same campaign base and the same infrastructure reduces the efforts in context of payload/aircraft certification, campaign logistics and flight operations drastically. The combination of the projects into one joint and focused campaign furthermore extends the available datasets of the individual projects and therefore broadens their scientific scopes, enabling to study the links between the processes that are investigated primarily by the individual projects.

During the campaign phase, flight planning will be performed on site utilizing up-to-date meteorological analyses and forecasts provided by ECMWF (European Centre for Medium-Range Weather Forecasts) and involving a suite of modelling tools for identifying promising scientific targets. Flight scenarios will be planned flexibly in order to cover as many aspects of the three projects at the same time as possible.

Extended flights (e.g. early winter flights in December into the vortex and extended survey flights in the main campaign phase) will cover wide ranges of latitudes and provide the possibility to study links between chemical and physical processes in the polar vortex and the seasonality of the UTLS. Further details on SALSA, GW-LCYCLE and their links to POLSTRACC are given in the sections 1.5 and 1.6.

## 2.5 Campaign strategy

POLSTRACC aims at covering the complete Arctic winter/spring cycle from December 2015 until end of March 2016. The POLSTRACC field campaign will comprise flights from Oberpfaffenhofen (Germany) into the early vortex in December 2015 and the winter campaign based in Kiruna (Sweden), covering the evolution of the polar vortex during winter and spring. Flights associated to the SALSA and GW-LCYCLE projects will complement the POLSTRACC flights and vice versa, extending the temporal and geographical coverage of the available observations for the scientific benefit of all three projects.


Figure 14: Planned strategy for the POLSTRACC campaign.

The whole winter/spring period will be analysed and investigated by accompanying model simulations, providing the basis for flight planning and identification of promising targets. The POLSTRACC observations will be accompanied by ground-based activities (i.e. LIDAR-observations and balloon soundings).

Co-operations with satellite-borne projects such as CALIPSO and MLS are being exploited. During the whole campaign, quick-look and science meetings will provide the basis for identification of promising geophysical situations, cooperation and exchange of first results.

## 2.6 Overview of mission planning

The flight templates given in the following section are focused on the POLSTRACC needs but take into account also the requests from the GW-LCYCLE and SALSA projects. It is not planned to label flights with the individual projects names beforehand but to design the flights such that the best scientific output is expected for all three projects. Anyhow, some flights might be configured primarily or even exclusively for one of the three projects.

Currently, we calculate with the following flight hour budgets:

- 10 hrs for mission preparation (handling quality, EMV, flight performance, instrument test) in November 2015
- 60 hrs for POLSTRACC science
- 30 hrs for GW-LCYCLE science
- 30 hrs for SALSA science

In total we request therefore 120 flight hours for science flights.

**a) Early campaign phase, December 2015. Base: Oberpfaffenhofen, 20-30 flight hrs.**

20 hrs are planned in early winter (before Christmas 2015) for two long-haul flights from the Oberpfaffenhofen airbase: (1) a POLSTRACC/SALSA survey flight into the early vortex and (2) a SALSA flight towards South-West to cross the subtropical jet. Depending on the meteorological situation the flights can be planned such that also GW-LCYCLE science can be addressed in flight (1) and POLSTRACC science can also be addressed in flight (2).

A third flight (7-10 hrs) might be undertaken if a suitable gravity wave situation over Scandinavia should appear in December 2015. This flight would be dedicated to GW-LCYCLE at the cost of the flight hours available in January to March 2016.

**b) Intensive campaign phases in the January to March 2016 time frame. Base: Arena Arctica (Kiruna/Sweden), 70-80 flight hrs (incl. transfer to/from Kiruna).**

The intensive campaign phase will be based in Kiruna, Sweden, at 68°N and will allow extensive flights inside and in the vicinity of the polar vortex. The activities in Kiruna will be split into two phases from the begin of January to the begin of February 2016 (Kiruna 1) and from the end of February to the mid of March 2016 (Kiruna 2).

During the intensive campaign phase scientific flights will be planned according to the actual meteorological situation. Templates for typical flight patterns are given in the following section. Typical flight durations will be between 7 and 10 hrs, yielding about 7-11 local flights from Kiruna, i.e. 1-2 flights per week on average. Transfer flights will be also used for scientific purposes and might be expanded depending on the actual situation.

**c) Closing campaign phase in March 2016. Base: Oberpfaffenhofen, 7-10 flight hrs.**

This local flight from Oberpfaffenhofen is foreseen to serve the spring component of the SALSA project. The flight route will depend on the location of the subtropical and polar jets. Most likely this will be a long-haul flight towards South or South-West. Alternatively, this flight can be combined with an extended transfer flight from Kiruna back to Oberpfaffenhofen at the end of the intensive campaign phase.

## 2.7 Flight Templates

### 2.7.1 Survey Flight

This type of flight is performed to cover extended sections of the polar vortex during the entire Arctic winter in order to study the following goals:

- dynamics of the polar vortex
- vortex edge and core as well as the vicinity of the polar vortex
- chemical and physical processes on vortex scale (chlorine (de)activation, bromine chemistry, de-/renitrification, dehydration, cirrus clouds and PSCs)

Primary characteristics of survey flights are long distances and high altitudes to allow optimal vertical and horizontal coverage along with deep penetration of the polar vortex at different stages of the Arctic winter with in situ observations. Dives may be included to record vertical in situ profiles (see also profile template in next section). In the following, templates for survey flights are shown. Drop sondes may be released during the survey flights. Thereby, drop sonde release above the central Arctic, Greenland and the northern Atlantic may be desirable, since observations in these regions are rare.

**Early Winter Survey Flight (Oberpfaffenhofen-Oberpfaffenhofen): Vortex Formation**
Early survey flights will be carried out from Oberpaffenhofen in December 2015 and possibly early January 2016 to study the formation and consolidation of the polar vortex.

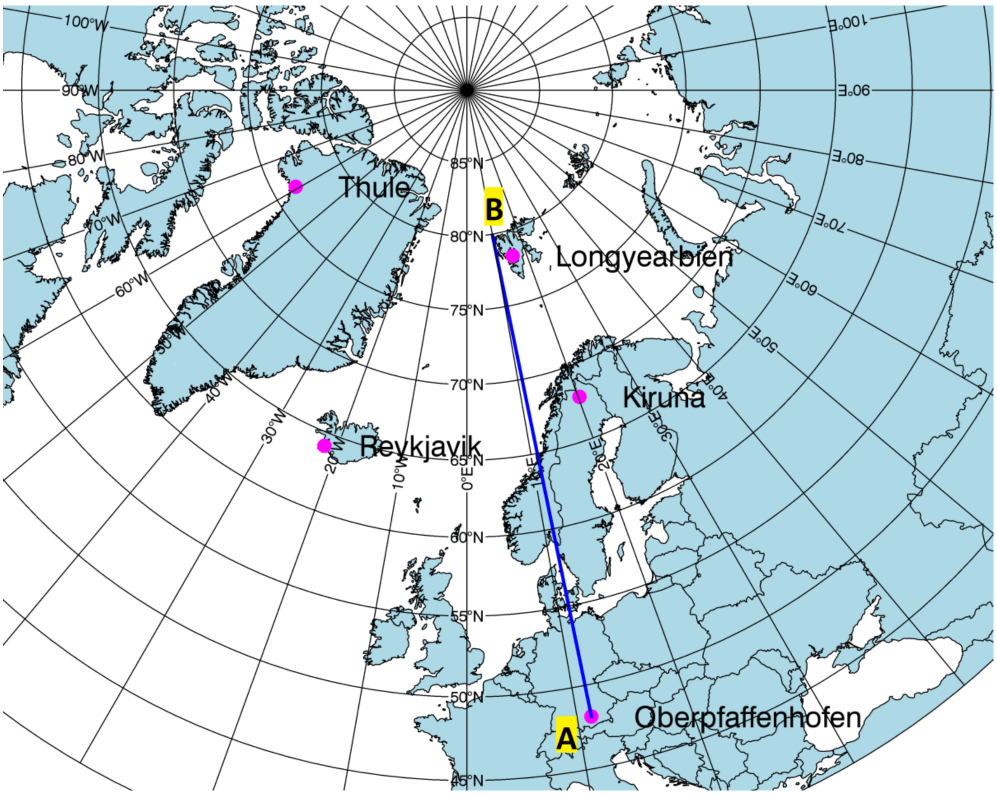


Figure 15 Template for survey flight from Oberpfaffenhofen (40°N/11°E) into the early polar vortex (turning point: 80°N/10°W) and back (~4400 NM) in December 2015. Template for vertical profile: see next Figure.

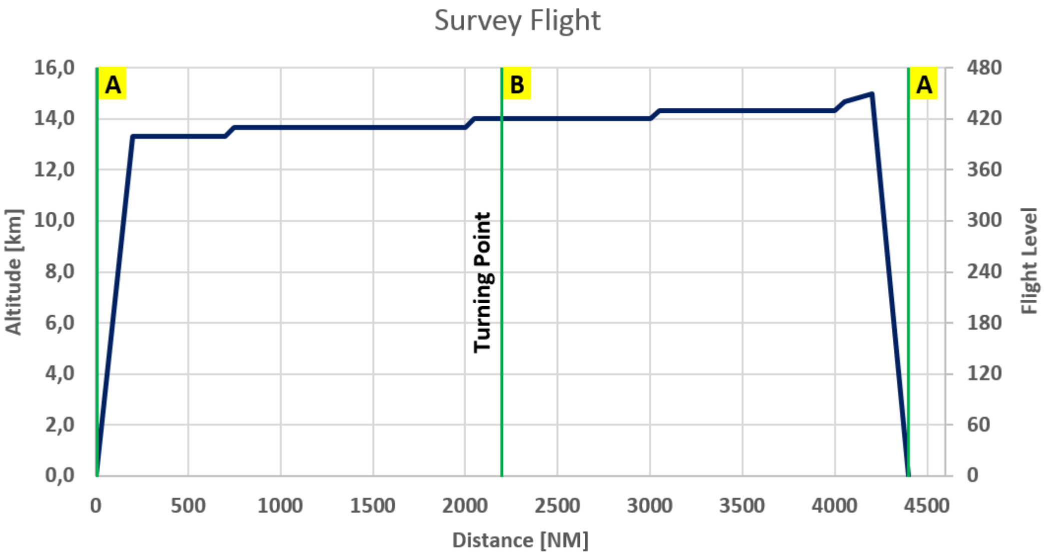


Figure 16: Vertical profile template for survey flights, designated for long range and high ceiling altitudes.

As the descent of airmasses due to diabatic cooling is in an early stage at this time of the winter, especially for this flight scenario high ceiling altitudes are essential. A dive could be foreseen on the way back depending on the vortex situation, but is not mandatory. Long range is the primary goal.

**Mid-/Late Winter Survey Flight (Kiruna-Kiruna): Vortex Cuts and Vortex Vicinity**
Extended survey flights will be carried out from Kiruna to allow cuts of the polar vortex and the vortex vicinity during the mid- and late winter periods. The location of the section and the range will depend on the actual vortex situation. The same holds for a possible dive on the way back to Kiruna.

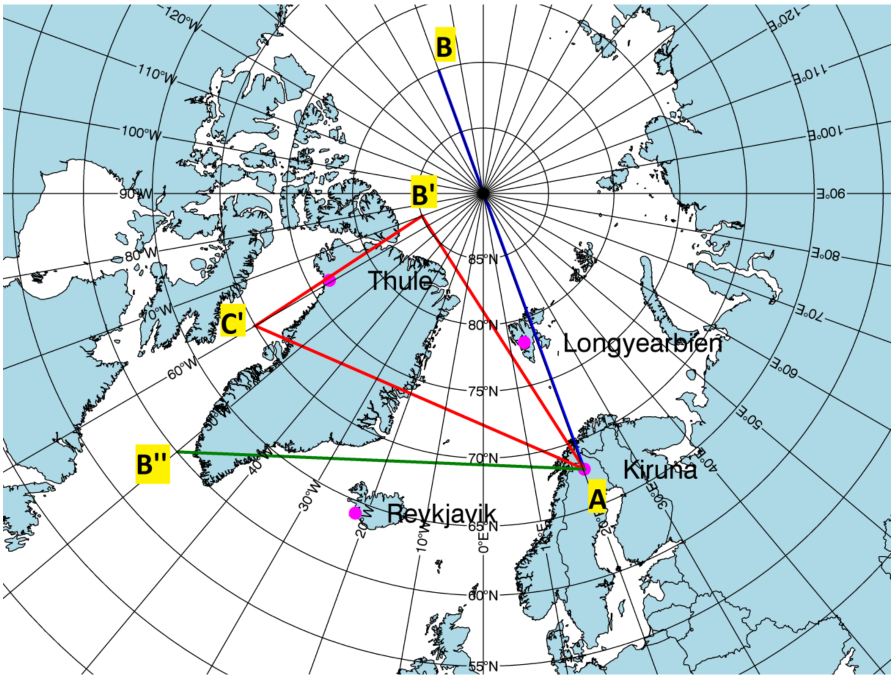


Figure 17: Templates for survey flights from Kiruna (68°N/20°E) into the polar vortex and back between January and March 2016 (blue: Kiruna – 80°N/160°W - Kiruna (~4450 NM); red: Kiruna – 85°N/70°W – 70°N/60°W – Kiruna (~4500 NM); green: Kiruna – 60°N/50°W - Kiruna (~4150 NM)). Template for vertical profile: see previous Figure.

### 2.7.2 In Situ Profiling / Remote Sensing Validation flight

In scientifically promising regions of the polar vortex (identified by meteorological forecasting and chemistry forecasts; e.g. chlorine/bromine activation, cirrus clouds, vortex filaments and mixing regions) vertical profiles from in situ observations are an important tool to study chemical and dynamical processes associated with the polar vortex. Furthermore, in situ observations are useful for the cross-comparison with remote sensing observations. Therefore, this type of flight contains dives at designated flight sections to allow recording of vertical in situ profiles. In the following, a template for an in situ profiling / remote sensing validation flight is shown.

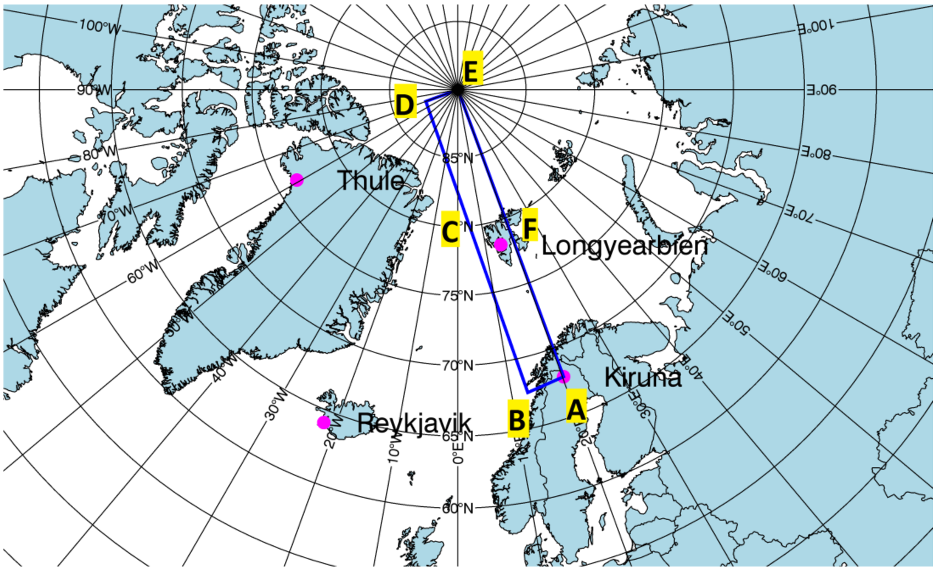


Figure 18: Template for in-situ profiling/remote sensing validation flight from Kiruna (68°N/20°E) into the polar vortex and back (Kiruna – 67.5°N/13°W – 87.5°N/70°W – 90°N/0°E – Kiruna; ~3500 NM). The flight is performed clock-wise, with the remote sensing instruments GLORIA and mini-DOAS pointing to the centre of the flight pattern. A dive is included between the points C and D. The remote sensing observations between E and F match the in situ profiles associated to the dive. Template for vertical profile: see next Figure.

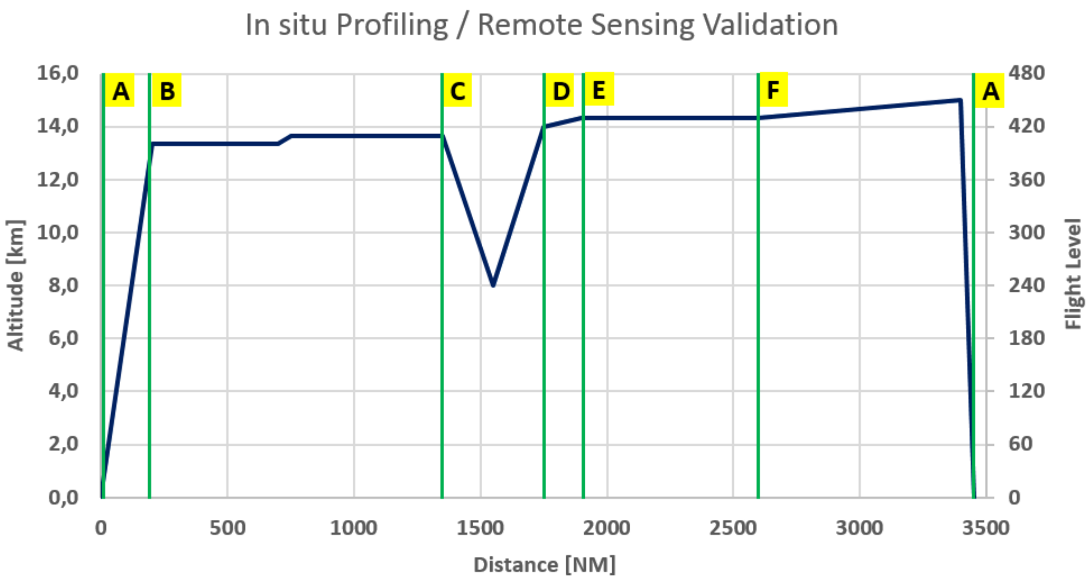


Figure 19 Vertical profile template for in-situ profiling/remote sensing validation flights, including a dive inside the polar vortex, match between in situ and remote sensing observations and self-match of the remote sensing observations (B-D versus E-A).

### 2.7.3 Specific Flight Patterns

Adapted flight patterns will be employed to address specific scientific goals (e.g. tomography, lee wave observations, cirrus cloud / PSC sampling, drop sonde operations, in situ self-match observations around sunrise/sunset). Selected flight templates are given below.

**Tomographic Flight Pattern including Drop Sonde Release**

The following flight template may be employed to investigate a lee-wave scenario induced by (north-)westerly winds at the east coast of Greenland. Prior to the hexagon pattern dedicated to the tomographic observations by GLORIA, drop sondes may be released, which are then transported by the wind towards the region sampled tomographically by GLORIA for cross-comparison and validation. Once the clock-wise hexagon is finished, a dive is carried out, transecting the hexagon pattern for in situ profiles to cross-compare with the GLORIA observations.

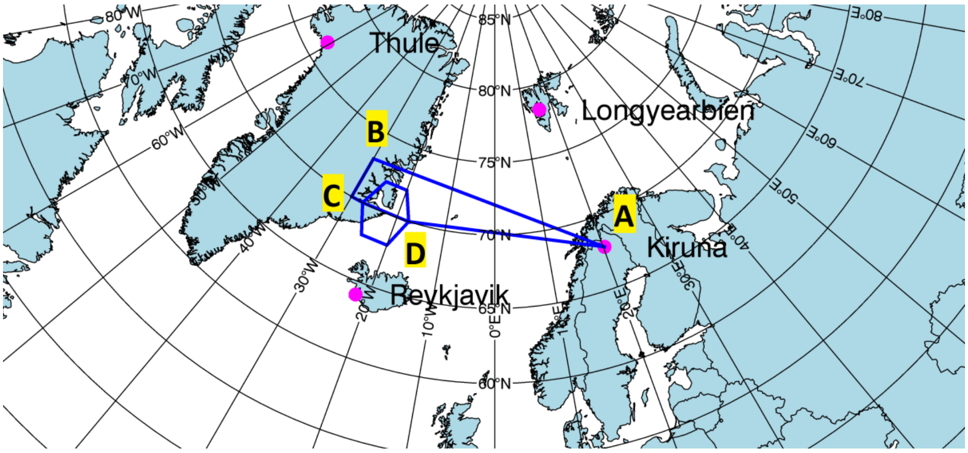


Figure 20: Template for tomographic flight from Kiruna (68°N/20°E) into the polar vortex and back (Kiruna – 73°N/30°W – 70°N/30°W – Hexagon centred at 70°N/22.5°W (clockwise flight pattern, max. extension 300 NM) – Kiruna; ~3500 NM). Drop sondes may be released between B and C. Template for vertical profile: see next Figure.

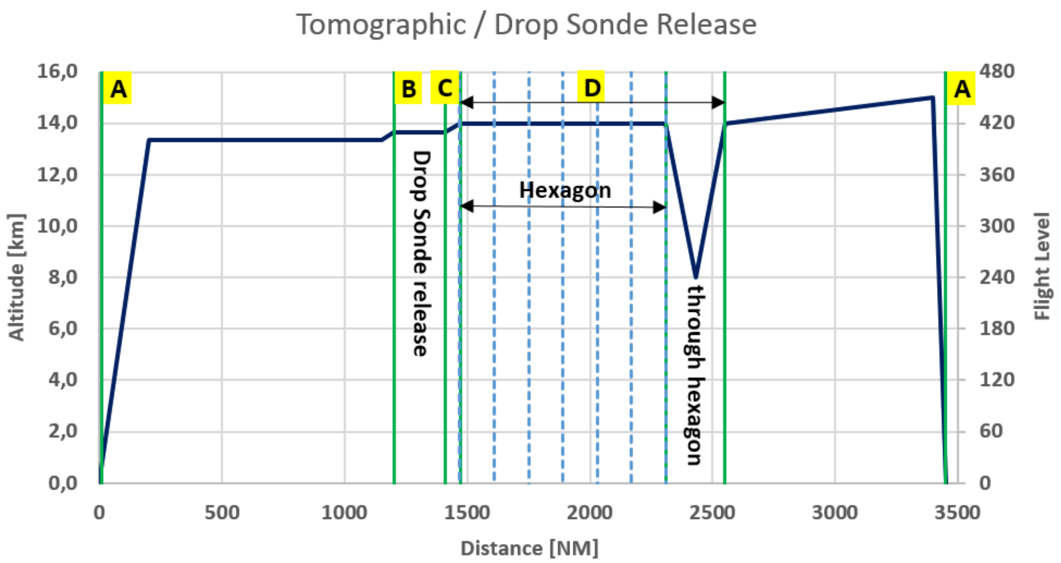


Figure 21: Vertical profile template for a tomographic flight pattern including optional the release of drop sondes. After the drop sonde release, a clockwise hexagonal pattern is performed, followed by a dive transecting the hexagon.

**Staggered Flight Patterns: Lee Wave, Cirrus Cloud and PSC Observations**

For lee wave, cirrus cloud and PSC observations staggered flight patterns at specific vertical levels/regions may be employed for probing temperature and tracer distributions, different cloud layers, de/rehydration layers and de/renitrification layers subsequently with in situ observations. The following flight pattern considers a lee-wave flight scenario above the Scandinavian mountains (north-westerly winds)

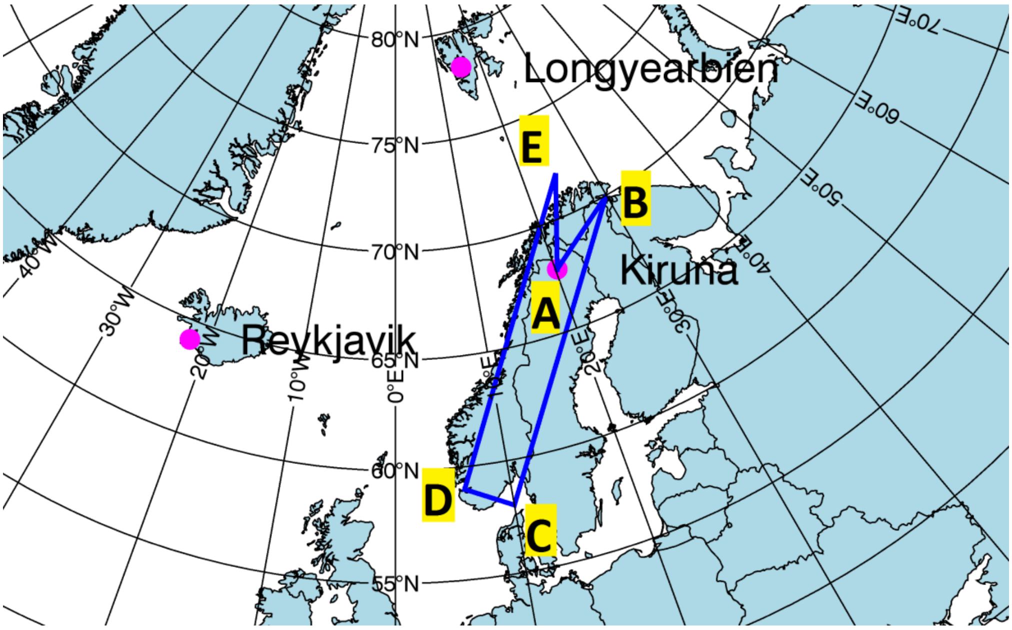


Figure 22: Template for staggered flight from Kiruna (68°N/20°E) probing a lee-wave-induced cirrus cloud and PSC scenario above the Scandinavian mountains (Kiruna – 70°N/30°E – 58°N/10°E – 59°N/6°E – 72°N/25°E – Kiruna; ~2800 NM). Drop sondes may be released between D and E. Template for vertical profile: see next Figure.

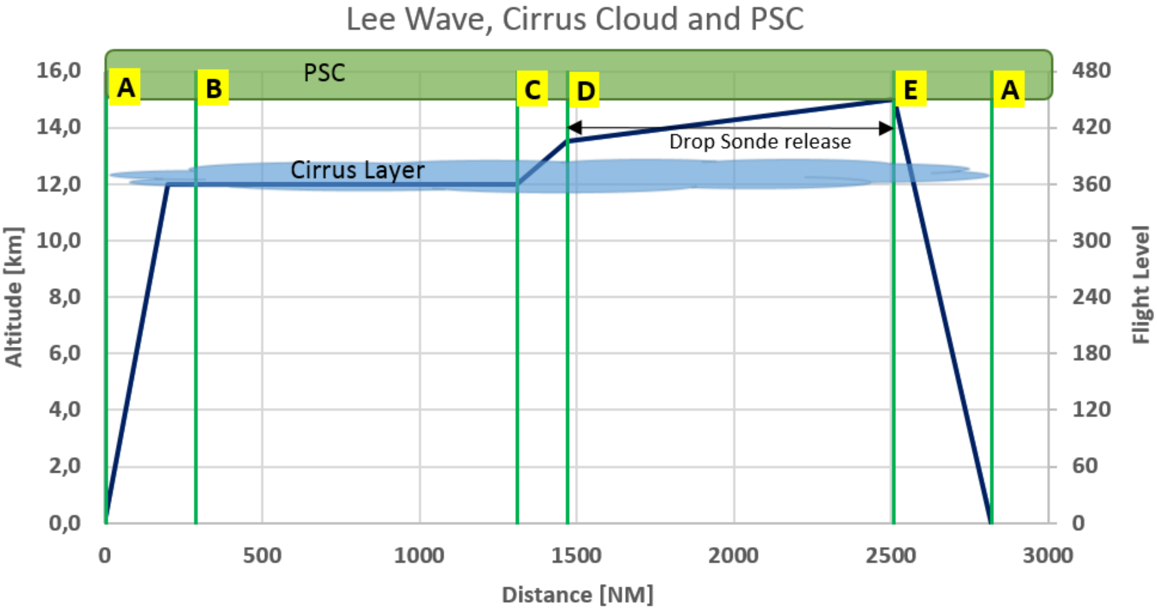


Figure 23: Vertical profile template for a flight probing a lee-wave-induced cirrus cloud and PSC scenario. The flight pattern is designated for extended cloud observations by in situ instruments, multiple self-match conditions between remote sensing and in situ / remote sensing observations and optimal vertical coverage. Further “steps” at specific altitudes may be included (e.g. below/inside cirrus clouds).

The shown scenario is optimised for the following aspects:

- Ascent and descent in situ profiles in region of interest and matched twice by remote sensing observations at different flight stages
- Constant section at ~12 km altitude inside/below cirrus clouds (B-C) and below PSCs. ➔in situ observations inside/below cirrus clouds, WALES observations of clouds above, GLORIA and mini-DOAS observations inside, below and above cirrus clouds)
- Ascending flight section at ~13.5 to 14.5 km above cirrus clouds and below (or at lower edge of) PSCs (D-E). ➔ Match of GLORIA/mini-DOAS observations with WALES, in situ and GLORIA/mini-DOAS observations at 12 km-leg. In situ observations of layers below (inside) PSC. Remote sensing observations of PSCs.
- Drop sonde measurements in regions sampled previously by remote sensing observations.

## 2.8 Synergistic Observations and Co-operations

Apart from combining POLSTRACC with GW-LCYCLE and SALSA-1, additional ground-based and space-borne observing systems will be considered both for mission planning and for the scientific studies. The potential of synergistic observations and the POLSTRACC airborne observations will be exploited. The setup of two aircrafts (HALO and FALCON) allows studying the effect of gravity waves on the distribution and transport of tracers simultaneously at different altitudes by measurements of corresponding species on different platforms.

Ground-based and space-borne LIDAR observations (CALIPSO, **Pitts et al., 2011 and references therein**) will provide additional information on PSC and cirrus cloud coverage as well as their composition. They will furthermore allow for inter-comparisons and cross-validations with the airborne observations. CALIPSO observations will also be utilised for quick-look analyses and in the context of flight planning. Matches between the HALO flight track and CALIPSO observations will performed in order to provide a broader context to the airborne observations and to allow comprehensive cross-validation.

Regarding the analysis of the chemical composition of the UTLS region, satellite-borne observations (e.g. MLS, **Santee et al., 2011;** ACE-FTS, **Bernath et al., 2005**) will complement and widen the focus of the POLSTRACC observations. Radiosondes and ozone soundings (MATCH-Campaign) will add valuable information on the evolution of the polar vortex 2015/16, especially during the periods between the HALO flights.

One important goal of the POLSTRACC mission is to establish manifold international co-operations in order to enhance the scientific output and to promote scientific exchange

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## 2.9 Modelling Activities

Modelling activities will complement the POLSTRACC campaign for flight planning and for post-flight data analysis to address the scientific questions along with the observations. Specific models involved in POLSTRACC will be the Chemical Lagrangian Model of the

Stratosphere (CLaMS) developed by the research centre Jülich, and the chemistry climate model EMAC run by KIT.

The chemistry transport model CLaMS is based on a Lagrangian formulation of tracer transport (**McKenna et al., 2002; Konopka et al., 2004**) and can be driven by ECMWF forecasts and reanalyses. CLaMS considers an ensemble of air parcels on a time-dependent irregular grid that is transported employing 3-D-trajectories. The model provides global and high resolution (up to 20 km / few 100m – horizontal/vertical resolution) and covers both the troposphere and the stratosphere. The setup of CLaMS also includes a denitrification scheme including an implementation of nucleation, growth and sedimentation of NAT particles that are transported on Lagrangian trajectories (**Grooß et al., 2014; references therein**). Furthermore, CLaMS is capable of including the radiation code introduced by **Edwards and Slingo (1996)**, allowing to study radiative forcing in the UTLS region. CLaMS will be used for flight planning and forecasting, for the analysis of transport and mixing processes, studies of PSCs and denitrification and analysis of the radiative budget.

The chemistry climate model EMAC is based on the climate model ECHAM5 and the Modular Earth Submodel System (MESSy) (**Jöckel et al. 2006; Roecker et al., 2006**). EMAC is a global model, covering the atmosphere from the surface up to about 80km altitude. Typical resolutions are in the order of 100 to 300 km horizontally and about 1 km vertically. EMAC can be used as a free running climate model or nudged with meteorological analyses or reanalyses (e.g., ECMWF operational or ECMWF ERA-Interim) to allow for direct point-by-point comparisons with observations. EMAC simulations at KIT throughout the POLSTRACC campaign will complement the CLaMS activities by providing a large-scale and long-term context and for investigating the climate-impact of the investigated processes.

Further modelling activities in the POLSTRACC framework and co-operations are planned. For example, high-resolution simulations of the UTLS on regional scale by the chemistry transport model ICON-ART (performed by KIT) might complement the large-scale and global simulations by CLaMS and EMAC.

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