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Probing of the Vertical Structure of the lower Atmosphere over Svalbard (ProVeSAS)

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1. Introduction

Atmospheric measurements in the Arctic are still considered scarce in number and geographical cover. For in situ measurements, this is due to the harsh conditions that need to be faced out and to the low population that is living at these latitudes. Even remote sensing from satellite is limited to the sunny season for some of the atmospheric parameters and detection techniques (e.g. passive remote sensing of aerosol and gases). This shortage is even more evident if one wants to go beyond the ground level measurements and obtain information on the vertical structure of the atmosphere. Existing records of upper-air measurements are insufficient for studying the climate change, as they mainly lack continuity, homogeneity and representativeness of data.

Historically, the vertical profiles of meteorological parameters such as temperature, humidity, wind speed and direction, i.e. meteorological soundings, were the first to be obtained on large scale and they constitute a fundamental input for meteorological forecast models (Ingleby et al. 2018). Before that, it had to be deduced from surface charts, a few scattered balloon and meteorograph ascents and mountain observations. It became very soon a standard for meteorology, considered that a code for the international exchange of radiosonde data was already adopted in 1946. For what concerns other measurements, such as those regarding atmospheric constituents, airborne campaigns remained for long time the only possibility, despite its very high cost. Other techniques that were developed already some decades ago make use of remote sensing, optical and acoustic, to infer some of the properties of the atmosphere through inversion of the measured echoes. Thanks to the technological improvements of the last years that permitted to realize very small and light devices able to measure many atmospheric parameters, new probing techniques are emerging, such as the use of tethered balloon and drones which can host an increasing number of sensing devices.

In this contribution, we review the existing techniques suitable for atmospheric profiling. In Section 2 they are briefly described, defining pros and cons for each of the considered ones. In Section 3 the results obtained by using such techniques in Svalbard and surroundings are reported and summarized, providing references to the relevant literature. This contribution is ideally an extension of Viola et al. (2019) in the SESS report 2018, with the aim to be more specific on studies about the atmospheric vertical column. The techniques illustrated here can be applied for studies described in two chapters of the current issue: ‘Atmospheric Black Carbon at Svalbard’ (Gilardoni et al. 2020), and ‘Multidisciplinary research on biogenically driven new particle formation in Svalbard (Sipilä et al. 2020). Vertical measurements can be useful to understand how local emissions diffuse on the column, or to study the long-range transport of pollution from lower latitudes during the Arctic haze. Ferrero et al. (2016) reported on both these two processes for black carbon in Ny-Ålesund using tethered balloon measurements. Furthermore, in the scientific community is not clear which is the role of black carbon in the formation and evolution of clouds: are they good condensation nuclei or not? Example of studies of new particle formation and ice nuclei on the vertical column can be found in Hoppel et al. (1973), Clarke and Kapustin (2010) and Kontkanen et al. (2016).

2. Overview of existing knowledge

2.1 Existing techniques: history, pros and cons

While there are advantages and disadvantages employing all of the measurement platforms, data can be combined synergistically to build a more comprehensive picture of the lower atmosphere. For example, aircraft measurements that cover a large spatial area can be integrated with the column model provided by a tethered balloon to improve comparisons with simulations. Remote sensing measurements need to be analysed with inverse methods, in order to retrieve actual atmospheric parameters, and hence, direct measurements from unmanned aerial vehicles (UAVs) or balloons are of help in checking the results.

2.1.1 Radiosonde, ozonesonde, dropsonde, driftsonde, controlled balloons

Radiosondes were invented in 1930 by aerologist Pavel Molchanov, as well as the method for using it to study the atmosphere. The next year he was invited by German scientists to join an expedition to the Arctic with the dirigible Graf Zeppelin to operate radiosondes at Polar latitudes. Twelve probes were successfully launched and is surprising that the first observations were conducted in the Arctic. The technological development permitted to obtain miniaturized devices that weigh less than 200 g, instead of the first prototypes weighing about two kilograms, and they can take measurements up to 40 km, drifting for thousand kilometres. Sensors are raised by helium-filled latex balloons that expand gradually, till explosion. Very recently, the use of corn balloons has been introduced in order to reduce the environmental impact. Modern radiosondes can even determine the intensity of radiation, cosmic rays and ozone concentrations. Other supplemental measurements in use today include optical backscattering by particles, electric field, and video imaging of particles and hydrometeors. The same sensors can be adopted by dropsondes, devices designed to be released from aircraft in order to measure atmospheric parameters as the device falls to the surface, slowed by a parachute. They are suitable to be used over remote areas such as the oceans, polar regions, and sparsely inhabited landmasses; they also provide a means to obtain soundings in and around severe weather systems, such as hurricanes. A similar concept is used in the driftsonde system, in this case the sondes are released from a gondola attached to a specially designed balloon platform. An approach that is halfway between radiosonde and tethered balloon is that of the so called controlled meteorological

(CMET) balloons. They can fly for several days in the troposphere with altitude controlled via satellite link (Voss et al. 2013). Altitude control (0-3500 m) is achieved by a dual balloon design (high-pressure inner and low-pressure outer balloon) between which helium is transferred by a pump–valve system.

In general, pros of this kind of measurement techniques are: they provide direct in-situ measurement of many atmospheric parameters; near real-time information are available for the entire globe; 1-2 times per day a snapshot of the global atmosphere (radiosonde); good vertical resolution (about 10 m); they can measure in any meteorological condition. On the other hand, the cons to be considered are: indirect measurement of wind speed and direction; not continuous over long periods; the sensors, as well as the balloons, are lost for each launch (cost and pollution).

2.1.2 Tethered balloons

Alfred Wegener was the first, in 1906, to use tethered balloons (TB) and kites for studying the Polar atmosphere during an expedition in Greenland. Since Wegener, TB have been employed in many locations to study in-situ microphysical parameters of the atmosphere (Morris et al. 1975; Duda et al. 1991; Argentini et al. 1999; Tjernström et al. 2004; Maturilli et al. 2008; Maturilli et al. 2009; Sikand et al. 2010 and 2013; Becker et al. 2018; Egerer et al. 2019), gaseous air pollution (Rankin et al. 2002; Armstrong et al. 1981; Davis et al. 1994; Pisano et al. 1997; Johnson et al. 2008) and aerosol properties (Maletto et al. 2003; Ferrero et al. 2007 and 2012; Hara et al. 2013; Li et al. 2015). A TB system has also been employed in 2007/2008 during the 35th Russian North Pole Ice drifting station (NP-35) to study the dynamics and the structure of the boundary layer (Maturilli et al. 2008). The advantage of in-situ measurements is that they are usually very specific and accurate and do not require a precise understanding of the radiative or acoustic properties of the atmosphere, such as are needed for remote sensing. An important concern of in-situ measurements is insuring the sample is not altered as it is being brought into the measuring device. In general, a TB system is capable of making repeated vertical profiles at high spatial resolution of particle concentrations, meteorological parameters, microphysical and radiative properties of boundary layer clouds. Typical maximum altitudes sounded by a TB system are in the range of 1-2 km.

Pros of TB platforms are: they can stay aloft and collect data for long periods (hours); vertical profiles are possible continuously from ground to about 2 km all the way up and down; profiles are nearly vertical (if wind speed is moderate); the relatively slow ascending/descending speed (typically between 30 and 80 m/min) maximize the spatial resolution and minimize sampling artefacts at the instrument inlets; the cost of operation of a TB is a relatively low if compared with other devices. Cons of a TB include: the payload can't be too heavy; operation is restricted to moderate wind conditions (<10 m/s); operation inside clouds could be subject to icing of the balloon and possibly sudden falls.

2.1.3 Remote sensing: radiometers, SODAR, LIDAR

Remote sensing instruments are by definition not in direct contact with the object, which is to be measured. Hence, by remote sensing instruments, which are ground based or looking downwards from satellites and planes, one can obtain information of (a part of) the atmospheric column without the need of flying in all individual layers. They are further subdivided into “active” and “passive” instruments, depending on whether they emit directly signals (light or sound) or whether they only passively detect natural emissions. Typically, active remote sensing instruments allow for a higher vertical resolution for the price of a more complicated, expensive instruments and the need of a more elaborate data evaluation. Generally, remote sensing instruments got mature in technology. Many environmental quantities like humidity, wind, temperature, trace gas concentration, aerosol and clouds can be measured by dedicated instruments. However, the evaluation of data requires sometimes a complicated physical model or even inverse techniques. An example for easy remote sensing measurement is a wind LIDAR that only requires knowledge of the spectral Doppler shift. Contrary, the derivation of aerosol microphysical properties from remote sensing relies on a scattering theory (for the irregularly shaped aerosol). For this reason, aerosol properties from remote sensing instrument will not have the same precision as in-situ instruments and fully equipped supersites are needed in all climate zones to calibrate the remote sensing instruments by in situ measurements. Microwave radiometers (MWR) measure thermal electromagnetic radiation emitted by atmospheric gases at millimetre-to-centimetre wavelengths. As the atmosphere is semi-transparent in this spectral range, including cloudy sky, they can operate under nearly all weather conditions, continuously and autonomously. They allow to derive important meteorological quantities such as vertical temperature and humidity profile, columnar water vapour amount, or columnar liquid water path with a high temporal resolution in the order of seconds to minutes. First developments of MWR were dedicated to the measurement of radiation of extra-terrestrial origin in the 1930s, but the first application to the study of the atmosphere appeared in the 60s of the same century. Atmospheric LIDAR (acronym for LIght Detection And Ranging) is a class of instruments that uses laser light to study atmospheric properties from the ground up to the top of the atmosphere. Such instruments have been used to study, among other, atmospheric gases, aerosols, clouds, wind and temperature. The basic concepts to study the atmosphere using light were first developed by E.H. Synge in the 1930s to study the density of the upper atmosphere using a searchlight beam. During the first experiments, light scattering patterns observed in the troposphere were not compatible with a pure molecular atmosphere. This incompatibility was attributed to suspended haze particles. After the development of lasers, the LIDAR technique made an enormous step over and by the end of the 1960s, over 20 lasers were already in use by meteorologists in the United States for various applications. SOnic Detection And Ranging (SODAR) is a simple and economically effective device for the ground-based remote sensing of the lower troposphere. The principal physics of acoustic sounding was given by A.M. Obukhov in the 40s of the nineteenth century. The theory of operation is based on the reflection of acoustic pulses at temperature inhomogeneities in the air with subsequent Doppler effect analysis. Minimum height level for the measurements can be as low as 30 m, while the maximum height depends on the atmospheric conditions, during calm days reaching up to 800 m while during windy days not even surpassing 300 m. Using SODARs, a vast amount of knowledge about the structure and dynamics of the atmospheric boundary layer (ABL) can been obtained.

Pros: the observed atmospheric target is not disturbed; operation can be continuous and automatic. Cons: a theory for interpretation of data and retrieving the final information is needed; some kind of instrumentation are sophisticated and hence costly; some observations depend on weather conditions (wind speed, cloudiness); there could be some "blind" layers, for example some hundreds meters above the surface.

2.1.4 Unmanned aerial vehicles

The development of UAVs (or aerial drones or simply drones) technology is rapid and their use is increasing fast. They are being used to collect data in a wide range of scientific disciplines. Their capabilities, with regard to available sensors reliability and performance are increasing rapidly and reduced costs make them more feasible. The main advantages with drones as a measurement platform is that they provide a way to gather data in form of profiles and transects from local to regional scale, bridging point measurements and satellite measurements and allowing for both remote sensing type of sensors as well as in-situ techniques. Compared to manned aircraft, the coverage is usually much more limited but the footprint of the operation is much smaller, and usually emission free, with the exception of the larger long range systems today. Drones have usually less payload capacity than manned aircraft but can to a larger extent be optimized to the payload needs in regard to size and range and be more affordable. Drones also reduce the risk for personnel and can be flown in conditions when manned aircraft could not be used. There are designed drones that can be dropped by weather balloons from up to 40 km altitude and glide back to the starting position, hence securing vertical profiles and reusable payloads, allowing advanced in situ gas and aerosol measurements through the stratosphere and troposphere at an affordable cost. Some of the challenges with using aircraft and drones for atmospheric measurements is that the vehicle is a part of the sensor so care must be taken in integration, calibration and validation of sensors in particular for in-situ measurements. Further, certain types of measurements would require the establishment of a temporal danger area to ensure segregation to other air traffic when flying beyond visual line of sight and above 120 m of the ground. This is a process that could take up to 4 months under current regulations. Initiatives for the developing, fielding, and evaluating of integrated small unmanned aircraft systems for enhanced atmospheric physics measurements exists (Jacob et al. 2018).

2.2 Measurements taken in Svalbard and surroundings: scientific results and knowledge

2.2.1 Radiosonde, ozonesonde, dropsonde, driftsonde, controlled balloon

Routine daily radiosonde launches started in Svalbard during October 1991 from the AWI observatory in Ny-Ålesund. The sondes are launched daily at 11 a.m. UTC while, occasionally and during special programs, multiple launches are made per day. Collected data have been used by many publications as a result of specific campaigns or studies. Treffeisen et al. (2007) used fifteen years of data (1991-2006, 5718 launches in total) to retrieve the key characteristics of the vertical relative humidity evolution in the troposphere over Ny-Ålesund. They found that supersaturation with respect to ice is observed all year round, with a clear seasonal trend, from 19% of occurrence during winter, 12% during spring and 9% during summer. The ice-supersaturation layers were found between 6 and 9 km during winter, while they shift higher during summer. This is in accordance with the results obtained from the SAGE II experiment for sub-visible clouds, indicating that this phenomenon is diffused over the Arctic. A shorter subset (1993-2006) of the above mentioned data was used by Dahlke and Maturilli (2017) to quantify the contribution of the advection to the observed atmospheric warming over Svalbard, showing a strong dependence on the synoptic flow. Analysing FLEXPART back-trajectories, they found that the recent change in the atmospheric circulation favours an increased advection of moist and warm air from the lower latitude Atlantic region. This is valid not only for surface temperatures, but for the entire troposphere. A temperature increase of about 0.45 K per decade over the estimated 2 K for the entire Arctic is attributable to this phenomenon. The difference in tropospheric temperature for airmasses coming from south to that coming from north can reach up to 8 K. Maturilli and Kayser (2017) compiled a homogenized dataset from Ny-Ålesund radiosondes for the period from 1993 to 2014. They found a strong increase in atmospheric temperature and humidity, in particular during winter and below 1 km, as a consequence of a change on the atmospheric circulation[1]. Radiosondes have been launched form the R/V Polarstern, managed by AWI, during cruises around the Arctic and Svalbard in particular. Yamazaki et al. (2015) used observations from radiosondes launched twice per day during the ARK-XXVII/1 and /2 cruises (13 to 29 July 2012) to determine the impact of such additional information on the forecast of an intense Arctic cyclone. They were found to be essential for the prediction, even if the observation were taken far from the actual location of the cyclone, thanks to the reproducibility of the large-scale upper tropospheric circulation pattern. This is not usually possible only relying on the information given by drifting buoys at the surface. Kayser et al. (2017) studied the vertical thermodynamic structure of the troposphere during the Norwegian young sea ICE expedition (N-ICE2015). During the cruise (January to June 2015) radiosondes were launched twice per day. They provided

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[1] The resulting record is available at http://doi.pangaea.de/10.1594/PANGAEA.845373.

statistics of temperature inversion, stability, and boundary layer extent. Radiative cooling is more effective during winter, when also the strongest impact of synoptic cyclones was found. In spring radiative fluxes warm the surface, leading to lifted temperature inversions and a statically unstable boundary layer.

Weekly ozonesonde profiling started in Ny-Ålesund even earlier, during 1988, by the same institution, the launches being always in tandem with the meteorological ones (Schrems 1992). The ozone sensor measures the ozone partial pressure by means of an electrochemical concentration cell, from which the ozone volume mixing ratios can be calculated with a vertical resolution of about 150 m. Wessel et al. (1998) studied the vertical extent of tropospheric ozone minima (detected by continuous surface ozone measurements) increasing the number of launches up to two times per day. During those periods, they determined the following common situations: the depleted layers were restricted to the planetary boundary layer (PBL), where the relative humidity was above 80% and the surface temperature generally decreased by 5–20 K during the event. Usually, temperature inversion coincided with the top of the ozone poor air mass, preventing vertical intrusion from above. The inversion layer height varied between 100 m and 600 m, while a stable stratification was found within the ozone depleted layer. Rex and von der Gathen (2004) analysed data for 10 winters between 1991 and 2003 applying a method (Match) developed to quantify the vertical distribution of the ozone loss. They found that chemical ozone loss indeed occurs in the Arctic and that periods of strong loss were associated with very cold periods and polar stratospheric clouds (PSC) formation. On the contrary, during warm winters, e.g. 1998-1999, no significant loss was detected. Kivi et al. (2007) studied the inter-annual variability and recent trends in Arctic ozone profiles from seven Arctic stations, including Ny-Ålesund, from 1989 to 2003, using a statistical model. Long-term changes have been identified during late winter/spring period for both the stratosphere and troposphere. Negative trends in the lower stratosphere prior to 1997 can be attributed to the combined effect of dynamical changes, the impact of aerosols from the Mt. Pinatubo eruption and winters of relatively large chemical ozone depletion. Since 1996–1997 the observed increase in lower stratospheric ozone can be attributed primarily to dynamical changes. In the free troposphere, a statistically significant increase over the 15 years' period, can likely be attributed to the effects of changes in the Arctic oscillation. Ozone amounts in the stratosphere were found to highly correlate with proxies for the stratospheric circulation, Polar ozone depletion and tropopause height. Petkov et al. (2018) studied the main characteristics of the joint meteorological (temperature and wind speed) and ozone vertical profiles over 1992-2016 (2207 profiles), using a statistical approach. They identified two main subsets, one corresponding to intra-seasonal variations (periods between 30 and 60 days) and another one corresponding to inter-annual variations (period longer than 1 year). Peculiarly, the first two components of the infra-seasonal variations seem to be influenced by phenomena like ozone depletion and solar eclipses. In the inter-annual subset, the three parameters presented harmonics that correspond to large-scale periodic phenomena like

Quasi-Biennial, El Niño-Southern, North Atlantic and Arctic oscillations.

Barstad and Adakudlu (2011) compared model simulations with observations from dropsondes as well as wind and water vapour LIDAR taken by a Falcon aircraft. Five dropsondes were released during the flight of 27 February 2008 in the Hinlopen Strait (which separates Spitsbergen from Nordaustlandet Island) in order to study an episode with significant local disturbances, that caused gap flow and wake formation phenomena. The model simulations have effectively reproduced the observed episodes. Other studies employing dropsondes data are reported in Lüpkes and Schlünzen (1996), Lampert et al. (2012), Kristjánsson et al. (2011), and Tetzlaff et al. (2014). Roberts et al. (2016) analysed observations from five controlled meteorological balloon launches in order to provide insights into tropospheric meteorological conditions around Svalbard. The balloons were launched from the AWIPEV observatory in Ny-Ålesund between 5 and 12 May 2011. One notable flight achieved a suite of 18 continuous soundings that probed the Arctic marine ABL over a period of more than 10 h. They compared acquired data with outputs from two different models, one with moderate and one with high resolution. In one case, the observed stable boundary layer with temperature inversion was reproduced only by the high-resolution model. In another case, presenting strong wind shear, the increasing temperature and humidity profiles were broadly reproduced by both models, but again the high-resolution one captured the wind shear phenomenon[2]. To not forget to cite stratospheric balloons, it is worth to mention the experiments conducted by La Sapienza University (Italy), with launches from Longyearbyen and Ny-Ålesund, mostly devoted to cosmic ray studies, but in some cases aimed at stratospheric solid particles collection (Della Corte et al. 2011).

2.2.2 Tethered balloons

In order to characterize the wind field profile in the Kongsfjorden, Argentini et al. (2003) used a tethersonde system consisting of a 5 m^3 balloon, properly shaped to facilitate orientation upwind, and a winch with 1000 m rope. The payload included dry and wet bulb thermometers, pressure, wind speed and wind direction sensors. Data were sent to the receiving station every 6 seconds. The same TB system described in Maturilli et al. (2008, 2009) is in use since many years by AWI in Ny-Ålesund during multiple campaign periods. In the 2008, a TB system was deployed at Ny-Ålesund (Lawson et al. 2011) for microphysics and radiative measurements in mixed-phase clouds. Measurements at Ny-Ålesund, were compared to those at the South Pole. The stratus clouds at Ny-Ålesund ranged in temperature from 0°C to -10°C and were mostly mixed phase with heavily rimed ice particles. Conversely, mixed-phase clouds at the South Pole contained regions with only water drops at temperatures as cold as -32°C and were often composed of pristine ice

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[2] Information on these and other flights are available at http://www.science.smith.edu/cmet/flight.html.

crystals. Air temperature and specific humidity inversions and low-level jets were studied over two Svalbard fiords, Isfjorden and Kongsfjorden, applying three tethersonde systems (Vihma et al. 2011) in March and April 2009. The same group compared the tethered balloon soundings with simulations of the vertical structure of the atmospheric boundary layer, performed with the mesoscale model Weather Research and Forecasting (WRF) as well as with its polar optimized version Polar WRF model (Kilpelainen et al. 2012). Mayer et al. (2012) compared the performances of a TB system with those of an unmanned aerial system SUMO (Small Unmanned Meteorological Observer) for the observation of the structure and behaviour of the atmospheric boundary layer above the Advent Valley, Svalbard. During a two-week period in early spring 2009, temperature, humidity and wind profiles measured by the SUMO system have been compared with measurements of a small TB system that was operated simultaneously. It is shown that both systems complement each other. Above 200m, the SUMO system outperformed the tethered balloon in terms of flexibility and the ability to penetrate strong inversion layers of the Arctic boundary layer. Below that level, the tethered balloon system provided atmospheric profiles with higher accuracy, mainly due to its ability to operate at very low vertical velocities.

Over 200 aerosol vertical profiles were recorded since spring 2011 in Ny-Ålesund from the Gruvebadet laboratory (Moroni et al. 2015, Ferrero et al. 2016) exploiting a TB system. The first instrumental payload (2011-2012) included two optical particle counters (dry and wet), a black carbon monitor, a total nanoparticle counter, and an ozone monitor. Four main types of profiles were found and their behaviour was related to the main aerosol and atmospheric dynamics occurring at the measuring site. Homogeneous profiles have been observed only for 15% of the cases in spring 2011 while they dominate (37%) in summertime 2012. Aerosol particles were also sampled on filters and characterized by SEM (Scanning Electron Microscopy) analysis (Moroni et al. 2015). The results pointed at a significant role of long-range transport on the aerosol mineralogy in the upper parts of the profiles. The payload has been improved in the 2014 campaign, by including a radio transmitting system and a nephelometer (Mazzola et al. 2016a). Since then, spring aerosol profiles were regularly recorded in Ny-Ålesund in the 2015, 2016, 2017 and 2018, also in the framework of the iAREA campaign (Markowitz et al. 2017). In 2019 the first winter aerosol profiles by TB systems have been measured by the same team and compared with LIDAR profiles (Nakoudi et al. 2019). The TB system and an example of the aerosol absorption coefficient and black carbon concentration measured are shown in Figure 1.

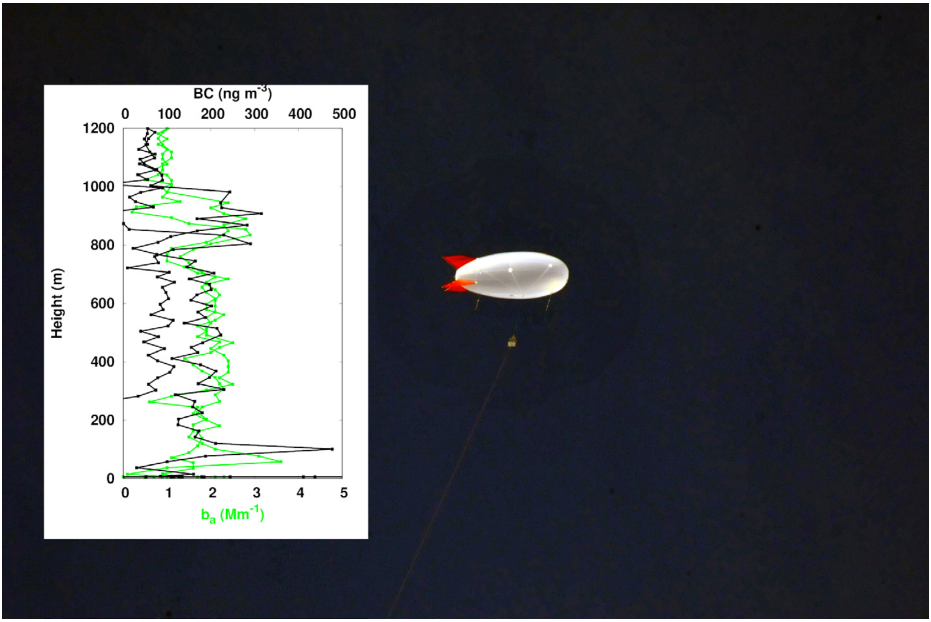

Figure 1: The TB system used by CNR and UniPG during January 2019 in Ny-Ålesund. The payload box and the tether are visible. The graph shows the profiles of aerosol absorption coefficient (b_a) and black carbon (BC) concentration measured on January 22, 2019.

2.2.3 Remote sensing

The remote sensing of temperature is currently done in Ny-Ålesund by microwave radiometers (at the AWIPEV station and at Gruvebadet by NCPOR, India). This evaluation generally requires plane-parallel stratified atmospheric conditions which are only a rough assumption below 2 km altitude in the Kongsfjorden. While the temperature profiles from microwave radiometers below 2 km altitude can be used to judge atmospheric stability (Schulz 2017) and the advection of different air masses in the free troposphere, the humidity profiles of this class of instrument are not very precise. Two radiometers for ozone (GROMOS-C for University of Bern and OZORAM from University of Bremen) and one for water vapour (MIAWARA-C again from University of Bern) are also installed at the AWIPEV station in Ny-Ålesund. Schranz et al. (2017) reported on the diurnal cycle of ozone and its tertiary maximum at an altitude of 70 km. Water vapour data show two and five-day wave activity and a descent rate within the polar vortex.

Remote sensing of clouds by radars has started a few years ago in Ny-Ålesund. A first statistics of cloud occurrences and properties has been published by Nomokonova et al. (2019). They used a combined dataset (14 months) obtained from a ceilometer, a 94 GHz cloud radar, and a microwave radiometer. A cloud occurrence of ~81 % was obtained (45 % multilayer, 36 % single-layer). The dataset has been analysed using the Cloudnet algorithm, obtaining outputs such as cloud target classification and microphysical properties, e.g. ice and liquid water content[3].

Figure 2: The triaxial SODAR and wind LIDAR installed in the proximity of the CCT in Ny-Ålesund.

The remote sensing of wind is currently performed in Ny-Ålesund by SODAR, managed by CNR and in operation since this year at the Amundsen-Nobile Climate Change Tower (CCT, see Mazzola et al. 2016b) and wind LIDAR, active since 2012 at the AWIPEV observatory and since 2017 at CCT (managed by KOPRI). Wind LIDARs gained reliability over the last years but cannot penetrate thick clouds and on overcast days their range is limited. Currently, authors are not aware of publications using this kind of measurements. SODARs were operational temporarily in the past during dedicated campaigns. Figure 2 shows the SODAR and wind LIDAR installed near the CCT at Ny-Ålesund. Beine et al. (2001) reported results for the wind field at different altitudes obtained using a triaxial Doppler SODAR in Ny-Ålesund during the ARTIST campaign, from March to September 1998. Comparing the

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[3] Near real time data and quick-plots can be seen at http://devcloudnet.fmi.fi/.

distributions of wind at 65 and 170 m a.m.s.l., considered to be representative of the lower and upper boundary layer respectively, show that they vary with season as well as with altitude, in particular during the summer months. While Ny-Ålesund receives predominantly katabatic flow from the Kongsvegen glacier, the field is rotated towards East and then North between 300 and 800 m. Other results of the ARTIST campaign are presented in Argentini et al. (2003). Sarchosidis and Klöwer (2016) studied the influence of low-level wind shear on the surface turbulence kinetic energy (TKE) production in Adventdalen during February 2016 using, beside other instruments, a SODAR measuring wind and turbulence up to 1000 m above the ground. Comparing the vertically averaged TKE as obtained from the SODAR with that measured by two sonic anemometers at two surface stations they found that in most situation the TKE is forced by large scale weather. Conversely, some events of high TKE only observed by the SODAR at higher levels, indicate a decoupling of the surface with the above atmosphere. Tjernström (2005) presented results from the Arctic Ocean Experiment 2001 (AOE-2001, 2–21 August), on-board the Swedish icebreaker Oden in the Central Arctic. The cruise started south–east of Svalbard, continued north, north–west and back again to Svalbard. The measuring package included: wind profiler, cloud radar, scanning microwave radiometer, radiosoundings, two SODARs and a tethered balloon for meteorology, turbulence and aerosol measurements. They found that there are often two inversions, one elevated and one at the surface, while occasionally additional inversions occur. The ABL is generally quite shallow, with depth less than 200 m, where aerosols were trapped. Other results from the same campaign are illustrated in Tjernström et al. (2004), while those from similar campaigns in other years are reported in Tjernström et al. (2012, 2014), Brooks et al. (2017).

The remote sensing of atmospheric parameters by means of LIDAR in Ny-Ålesund started in the late 1980s. The stratospheric ozone concentration and temperature have been measured during the dark season. Neuber and Krüger (1990) reported on ozone profiles by a LIDAR and balloon sondes from January until the end of March 1989. The comparison between LIDAR and sonde profiles revealed good agreement, permitting to create an integrated dataset. They detected no ozone depletion during that period, prevented by the extremely cold situation, with a stable vortex insulating the Arctic from middle latitudes. Two ozone pulses were measured during two distinct periods above 20 km, associated with warm air intrusions.

Only a short time later LIDAR measurements of stratospheric aerosol were started. Neuber et al. (1992) reported PSCs profiles for January 1989 and 1990, showing a good correlation with atmospheric temperature. During August 1991, an aerosol layer was detected, presumably due to the Mt. Pinatubo eruption. Since 2000, aerosol measurements by a Raman LIDAR in the tropo- and stratosphere have been performed regularly during all seasons (Schumacher 2001). During night time and clear sky conditions, also measurements of the absolute humidity are possible. Figure 3 shows the laser beam of the KARL LIDAR

Figure 3: The laser beam of the KARL LIDAR from the AWIPEV observatory in Ny-Ålesund, under northern lights.

emerging from the AWIPEV observatory. Gerding et al. (2004) described the measurements obtained between June 2001 and December 2002. During darkness profiling is possible up to 6–7 km, while daylight limits the profiles to maximum 3 km. During specific events, simultaneous observations of humidity and aerosol extinction show distinct differences at the various altitudes. In the boundary layer, aerosols are poorly affected by the humidity, while in the free troposphere, the LIDAR ratio give evidence for water uptake by the particles. Hoffmann et al. (2010) reported on the detection of aerosol plumes coming to Ny-Ålesund from the Kasatochi eruption of 2008. Information on the morphology of the particles were obtained from the measured depolarization ratio at different heights. Di Liberto et al. (2012) used data from an automated small size LIDAR system installed in Ny-Ålesund to estimate the PBL height by means of a gradient method based on abrupt changes in the vertical aerosol profile and monitor its temporal evolution. The results of this method were successfully compared to those obtained by others using radiosondes and a one-dimensional model based on a parameterization of the turbulent kinetic energy, indicating that in favourable cases it may provide reliable results. Lampert et al. (2012) used an inclined LIDAR with very high resolution (0.4 m) for detailed boundary layer studies above the Kongsfjord. On 29 April 2007, a layer of enhanced backscatter by spherical particles was observed in the lowest 25 m above the open water surface, disappearing in the afternoon. On the morning of 1 May 2007, the atmosphere up to Zeppelin showed enhanced values of the backscatter coefficient, while, around noon, the top of the layer decreased from 350 to 250 m as confirmed by radiosonde data. Ritter et al. (2016) analysed LIDAR data for the spring 2014 Arctic haze season, providing typical values and probability distributions for aerosol backscatter, extinction and depolarisation, the LIDAR ratio and the colour ratio along the troposphere. Results showed that the 2014 season was only moderately polluted and no clear temporal evolution over the 4-week dataset was seen, except for the extinction coefficient and the LIDAR ratio, which significantly decreased below 2 km altitude by end April. Between 2 and 5 km the haze season lasted longer. Maturilli and Ebell (2018) presented a 25-year (1992-2017) data record of cloud base height measured by a ceilometer in Ny-Ålesund. This information is essential for interpretation of the surface radiation budget and of meteorological processes. It is also useful as complementary to other advanced technologies that provide information on cloud microphysical properties, such as cloud radar. They found that cloud cover conditions are more frequent in summer and the lowest occurrence is in April[4]. Kulla and Ritter (2019) revised the LIDAR water vapour calibration by co-located radiosonde launches in order to obtain highly resolved profiles. They found that small scale variability of the humidity was a large source of error in the comparison. Averaging over several independent measurements increases the quality of the calibration, up to 5% for individual profiles and 1% for the entire season. The calibrated dataset shows high temporal variability up to 4 km and provides additional, independent information to the radiosonde measurements. While current ceilometers struggle to produce reliable aerosol profiles in the generally clean Arctic conditions, a continuous 24/7 LIDAR operation for aerosol and cloud monitoring is provided by a micro pulse LIDAR (MPL) installed by NIPR at the AWI observatory (Shiobara et al. 2003)[5]. These data have been used by Campell and Shiobara (2008) to study the glaciation of mixed-phase boundary layer clouds. Shibata et al. (2018) analysed 4 years (2014-2018) of aerosol backscattering data showing that monthly averaged concentration of aerosols was largest in the lowest free troposphere at about 1 km in altitude and was an order of magnitude smaller at an about 10 km. At the same time, it was larger from late spring to summer and lower from late summer to fall. Maxima in the monthly averaged non-sphericity and size are not coincident with concentration suggesting a seasonal change in the morphology of the particles. With a synergic use of LIDAR, sun-photometer and radiosonde data, Ritter et al. (2018) studied a strong biomass burning transport episode detected over Ny-Ålesund during July 2015. They obtained size distribution, refractive index and single scattering albedo at different relative humidity, finding predominance of particles in the accumulation mode and hygroscopic growth for RH above 80%.

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[4] Data used for this work are available at https://doi.org/10.1594/PANGAEA.880300.

[5] http://polaris.nipr.ac.jp/~dbase/e/300/e/300_data-MPL-NYA.htm

Up to now, Ny-Ålesund is by far the most important centre for vertically resolved remote sensing in Svalbard, but such activities were performed in the past also at other sites, also during specific campaigns, some of them continuing nowadays. A Raman Lidar was in operation from late 2009 until Sep 2016 in Hornsund. It was used for aerosol and water vapour profiling. Furthermore, a ceilometer is in operation at the Polish station since 2015. Karasiński et al. (2014) reported on the detection of aerosol layers over Hornsund after two volcanic eruptions, those of the Eyjafjallajökull (April–May 2010) and Grímsvötn (May 2011), both located in Iceland. Few days after the eruptions, layers of high aerosol concentration have been observed by multi-wavelength LIDAR, as confirmed by backward trajectories showing their paths passing over the location of volcanoes. Bloch & Karasiński (2014) reported on vertical sounding of a water vapour content in the lower and middle troposphere obtained up to 6 km altitude during winter from 2009 to 2012, obtaining results in good agreement with the results obtained from the AIRS satellite instrument. From 1998 to 2001 a LIDAR was operational in Longyearbyen for research of the upper atmosphere. Höffner et al. (2003) installed a potassium LIDAR near Longyearbyen in order to detect noctilucent clouds (NLCs) and to measure temperature in the lower thermosphere (above 100 km). At the same time a series of meteorological rockets were launched to measure temperature from the lower thermosphere to the stratosphere. They found that during the period between 12 June and 12 August the NLC occurrence is 77%, with a mean peak altitude equal to 83.6 km, without any significant variation with season.

2.2.4 Aircraft, unmanned vehicles

Up to 2015, flight permits were issued on a case by case basis based on applications to the Norwegian Civil Aviation Authority and submitted standard procedures and risk assessments for the planned activity. Norway/Svalbard got a national drone (RPAS) regulation in place in 2016 and a common European (EASA) regulation has been approved and will be adopted into Norwegian law in July 2020. This makes it more predictable to plan for the use of drones in the future but also sets stricter requirements to the operators of drones. The first time drones were used on Svalbard for atmospheric research was in 2008 in connection with the International Polar Year (IPY). As a part of the IPY-THORPEX (Kristjánsson et al. 2011) drones were used to profile the atmospheric boundary layer in February-March out of Longyearbyen. During this experiment the DLR Falcon also had multiple transects in the Svalbard region, with dropsondes and profiling LIDARs to measure wind, turbulence, temperature and humidity profiles. Such profiling up to 1000-3000 meters altitude has been done on single campaign basis since, by several research groups. Basic meteorological observations can be obtained with compact and light instrumentation, hence flown with small and inexpensive drones (Reuder 2009). Most work on Svalbard has been done in a collaboration between University of Bergen and UNIS, and an example of data collected in the Advent valley is presented in Mayer et al. (2012). Drones provide a unique platform for in-situ atmospheric sensing allowing for both vertical and horizontal sampling. This makes drones an interesting platform that support modelling and process studies involving aerosol transport and formation and deposition as well as trace gas chemistry and transport. In 2011 and in 2015 there were larger coordinated campaigns with drones, balloons, ground based and satellite remote sensing with focus on aerosol and black carbon transport and deposition in the Arctic and albedo effects. Drones were operated by AARI, NOAA and Norut (now NORCE). AARI provided meteorological measurements and vertical profiles at different locations over Kongsfjorden. Norut did both meteorological profiles as well as hyperspectral snow reflectance measurements around Ny-Ålesund, Holtedalsfonna and Kongsvegen Glaciers. NOAA flew an advanced aerosol and meteorological instrument package and did profiles from 30 to 3000 meters. Detailed description of drone aerosol instrumentation and results are described in Bates et al. (2013). Snow reflectance measurements are described in Burkhart et al. (2017). Figure 4 shows the team involved in this experiment posing with three drones. In 2018 the University of Braunschweig had an extensive drone campaign investigating aerosol formation and small scale vertical and horizontal variability in the atmospheric boundary layer. This is an ongoing project (RIS 10977) lead by Astrid Lampert.

Figure 4: The CICCI flight teams (NOAA, Norut and AARI) in 2011 on the airstrip of Ny-Ålesund.

3. Unanswered questions

Ny-Ålesund already has a long-lasting competence in aerosol research, both via in-situ and remote sensing techniques via several research institutes. The balloon-borne aerosol measurements (Ferrero et al. 2016) complete and link in an ideal way the ground-based aerosol measurements and the LIDAR observations. Similarly, aerosol in situ measurements on board of UAV will increase the spatial extent of aerosol measurements. However, due to the complexity of aerosol chemical and micro-physical properties and the general missing of a scattering theory for arbitrarily shaped particles such “aerosol closure experiments” (the agreement of aerosol properties derived by different instruments and methods) are difficult and an open task for the near future. Generally, comparing e.g. the various IPCC reports over the last 20 years, our understanding of the radiative impact of aerosol and its contribution to cloud properties has not increases as much as desired. Aerosols still contribute to an unsatisfactory uncertainty in climate models. However, although Ny-Ålesund is a peculiar site with a complicated orography, the suite of aerosol measurements and the used platforms are impressive and quite complete and the main research groups already have a long-lasting cooperation in terms of joint campaigns and publications (e.g. Ritter et al. 2018; Ferrero et al. 2019).

Further, the interaction between aerosol and the boundary layer are a concern for the site of Ny-Ålesund. This is important for the comparison between the different ground-based aerosol in-situ measurements at the site as well as for the comparison between (vertical) remote sensing to either UAV or ground based measurements.

Some important open scientific questions are the aerosol type resolved properties as a function of humidity, the precise pollution pathways into the Arctic, the comparison between aerosol properties on the ground and in the free troposphere, their impact on radiation and cloud microphysics.

4. Recommendations for the future

The joint, international campaigns for atmospheric research, concerning aerosol in particular, in different seasons with different platforms (especially a comparison between balloon- and UAV-borne instruments and LIDAR data) should be continued. For this reason, flight permissions for tethered balloons and UAV, also in dark and cloudy conditions should be facilitated. For the same reason, specific infrastructures devoted to the use of UAVs and tethered balloons should be created. In Ny-Ålesund a facility for UAVs was created in 2015 (coordinated by NORCE). Tethered balloon operations would take advantage from the presence of a dedicated hangar to store the inflated balloons for long periods, with adequate dimension, including the door, and a system (compressor) to recover the helium.

Both these solutions would permit to save a lot of money for buying the gas.

Generally, the link between the various atmospheric measurements in Svalbard and climate modelling on scales from LES (Large Eddy Simulation) to regional modelling could and need to be improved. This would also advance the enormous efforts put into the observational activities by the different countries and institutions. The remote sensing of aerosol could be used to validate aerosol transport into the Arctic. Together with in situ measurements our understanding of life-time, chemical alteration and radiative impact of aerosol could be greatly improved.

Concerning the remote sensing of meteorological quantities, wind LIDARs with a vertical range larger than 2 km become available and have the potential to sound into the free troposphere to give information on the synoptic flow that is no longer influenced by the orography. Lidar-based continuous monitoring of temperature and water vapour (including summer) do not exist yet in Ny-Ålesund. However, at the given rate of technical progress their usage in Arctic conditions may be useful soon. For this reason, a common Ny-Ålesund scientific investment plan for the upcoming years might be discussed within NySMAC.

The efforts on data visibility and sharing, already started by SIOS, should be enforced in order to ameliorate the scientific coordination, to avoid overlapping, and to improve data usage.

5. Data availability

Some of the reported activities regularly contribute to publicly accessible international databases. Table 1 reports the links to these databases, together with referenced publications, the technique used, the site and period of measurements.

On the contrary, most of the collected data are not publicly accessible or easily discovered. They should be requested contacting the corresponding author of the publication.

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Table 1: List of datasets publicly available among those cited in the text. The main reference is reported, as well as sites and available periods.

Reference	Technique	Parameters	Site	Period	Link to database or information
Maturilli and Kayser (2017)	Radiosonde	Meteorology	Ny-Ålesund	1993-2014	http://doi.pangaea.de/10.1594/PANGAEA.845373
Roberts et al. (2016)	Controlled balloon	Meteorology	Ny-Ålesund (surroundings)	May 2011	http://www.science.smith.edu/cmet/flight.html
Nomokonova et al. (2019)	Radar	Cloud microphysics	Ny-Ålesund	June 2016 - July 2017	http://devcloudnet.fmi.fi
Maturilli and Ebell (2018)	Ceilometer	Cloud base height	Ny-Ålesund	1992-2017	https://doi.org/10.1594/PANGAEA.880300
Shiobara et al. (2003)	LIDAR	Aerosol backscattering	Ny-Ålesund	2002-2017	https://mplnet.gsfc.nasa.gov/data?s=Ny_Alesund&v=V2
Mazzola et al. (2016a)	Tethered balloon	Aerosol size distribution and optical properties	Ny-Ålesund	2014-2019	http://mainnode.src.cnr.it/cnr/
Kivi et al. (2011)	Ozonesonde	Ozone concentration	Ny-Ålesund	1990-2013	https://woudc.org/data/stations/?id=089
Ritter et al. (2016), Neuber and Krüger (1990), Kulla and Ritter (2019), Schranz et al. (2017)	LIDAR and radiometers	Aerosol, ozone, temperature, water vapour	Ny-Ålesund	1991-present	http://www.ndaccdemo.org/stations/ny-%C3%A5lesund-norway

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