Application of IASOA circumpolar observations in studies of atmospheric transports into and out of the Arctic for the Year of Polar Prediction

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Executive Summary

The International Arctic Systems for Observing the Atmosphere (IASOA) is an International Polar Year legacy consortium that focuses on coordinating measurements of the Arctic atmosphere collected at ten observatories in the U.S., Canada, Russia, Norway, Finland, and Greenland. The IASOA data portal and collaboratory process support thematic expert groups that work towards common goals for utilizing interoperable data products across the observatories. In addition to detailed surface observations and upper-air radiosonde program, some of the IASOA observatories collect information on the vertical profiles of moisture, cloud boundaries, cloud water/ice contents, and aerosols using radars, lidars ceilometers and radiometers. Collectively the IASOA network provides a unique source of information that can be utilized in order to provide the best possible empirical estimates of the horizontal atmospheric transports of momentum, heat, moisture, cloud water, cloud ice, and aerosols into and out of the Arctic Ocean region. These can be used in turn to support the evaluation of atmospheric reanalyses, weather and climate models, and satellite remote sensing products, and subsequently studies on the interaction between the Arctic and lower latitudes including the role of mid- and low-latitude forcing on the Arctic amplification of climate warming and the effects of Arctic changes on mid-latitude weather and climate. In addition, the IASOA data are valuable for the evaluation of gridded products (reanalyses, models, and satellite data) with respect to Earth surface variables, such as snow depth, soil moisture, surface temperature, radiative fluxes, albedo, as well as turbulent fluxes of sensible heat, latent heat, CO_2, and CH_4. Evaluation of surface fluxes is a vital to complement the evaluation of horizontal transports. These together will yield a comprehensive assessment of the quality of available gridded products in representing atmospheric budgets of heat, moisture, greenhouse gases, and aerosols in the Arctic. The IASOA thematic study will be a unique approach as Arctic transport studies have so far been addressed without full utilization of direct observations; it is expected that this activity will directly support the objectives of global initiatives such as the WMO Year of Polar Prediction (YOPP).

1. Introduction

During recent decades, climate warming in the Arctic has been 2-4 times faster than the global mean. This phenomenon is called as the Arctic amplification. The air temperature increase has been both a reason for and a consequence of recent rapid changes in the Arctic sea ice and snow cover. Since the early 1980s, Arctic sea ice extent has decreased by roughly 50% in summer and autumn, and an equal relative decrease has been observed in winter sea ice thickness. In May and June, the rate of decrease in Northern Hemisphere terrestrial snow cover has been even faster. Arctic amplification is partly due to local processes in the Arctic, related to the surface albedo, clouds, water vapor, aerosols, the shape of the temperature profile, and the small heat capacity of the shallow atmospheric boundary layer (e.g., Vihma et al., 2014). In addition, heat transport in the ocean and heat and moisture transports in the atmosphere strongly contribute to Arctic amplification. The Arctic near-surface warming has been mostly driven by changes in local sea ice cover and sea surface temperatures (SST), but the majority of warming aloft is explained by SST changes at lower latitudes and related changes in the temperature of air-masses originating from the south (Screen et al., 2012). In addition, a few studies have suggested strong effects of the tropics on the Arctic (e.g., Ding et al., 2014). In addition to climate trends, weather events in the Arctic may be strongly affected by forcing from lower latitudes. During recent decades, extreme weather events have been common in the Arctic but, in general, little attention has been paid to the attribution of individual weather events in the Arctic.

Concurrent with Arctic amplification, changes have been observed in the occurrence, duration, and strength of extreme weather events at lower latitudes. High extremes in air temperature and precipitation have become increasingly common (Donat et al., 2013). Summer events have included heat waves and droughts in the USA and central/southern Europe and Russia, as well as rains and floods in central/northern Europe and East Asia. However, despite the average net global warming, the occurrence of cold winter months has increased in recent decades over land areas from 20° to 50°N (Cohen et al., 2014). Throughout mid-latitudes, recent weather extremes have often been associated with the persistence of particular circulation patterns (Hoskins and Woollings, 2015). An intriguing question is whether extreme weather events have been related to climate change in the Arctic (Vihma, 2014; Overland et al., 2015). Probably the most evident effect of Artic warming on mid-latitude weather is that cold-air outbreaks from the Arctic are, on average, not as cold as they used to be (Serreze et al., 2011). Despite this body of work, currently, the science of Arctic-midlatitude linkages is still largely hypothetical and the numerous physical mechanisms potentially responsible for teleconnections between the Arctic and lower latitudes remain poorly known. Some possibilities include changes in cyclone activity and tracks, in latitude, speed and meridional amplitude of the Polar front jet stream, as well as the effects of planetary waves and their resonance with surface thermal and orographic forcing.

All the above calls for better quantitative understanding on the atmospheric transports of heat, momentum, potential energy, moisture, other greenhouse gases, clouds, and aerosols from lower latitudes to the Arctic and vice versa. As the possible Arctic effects on mid-latitudes may be regional, seasonal, and episodic (Overland et al., 2015), extensive, multi-decadal circumpolar observations are necessary to support meaningful analysis and particular attention is needed on the vertical profiles of the transports. For moisture transport it is not enough to estimate the latent heat transported to the Arctic but also the cloud formation and enhanced downward longwave radiation that the transport will produce in the Arctic. Seasonal aspects of the transports and the effects of the meridional structure of recent climate warming are particularly important. The decrease in the north-south temperature gradient within mid-latitudes has been strongest in summer (Coumou et al., 2015) but simultaneously a new frontal zone has appeared across the southern coasts of the Arctic Ocean, where in summer the continents have warmed much faster than the ocean (Crawford and Serreze, 2015). The effects of these changes on summer weather need to be investigated.

The prospects for better understanding and quantifying Arctic transports depend on optimized usage and further enhancement of atmospheric observations from the circumpolar Arctic land surfaces as well as the Arctic Ocean. Present observations available include basic variables (atmospheric pressure, air temperature, humidity as well as wind speed and direction) from standard weather stations but these only yield near-surface data. Vertical profiles of air temperature, moisture, and wind are available from about 40 circumpolar radiosonde sounding stations north of 65°N (e.g. Nygård et al., 2014), and more detailed observations are made at the ten observatories of the International Arctic Systems for Observing the Atmosphere (IASOA). When utilized together with near-surface, radiosonde, and satellite observations as well as atmospheric reanalyses, the IASOA observations have a potential to bring a significant added value for investigations of atmospheric transports in and out of the Arctic Ocean region by providing a picket fence of observations that are roughly distributed in the coastal regions that bound the Arctic Ocean.

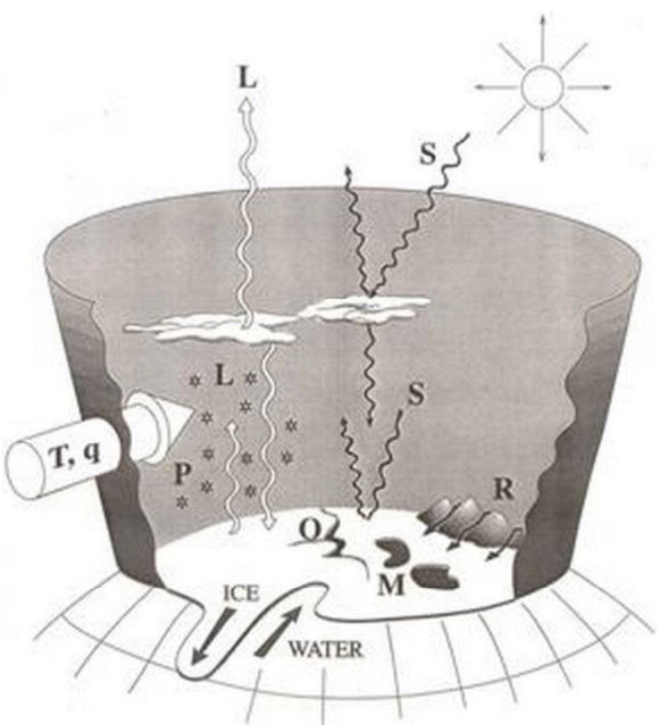

Figure 1. Schematic illustration of processes in the Arctic atmosphere. Figure by N. Untersteiner. First used in "SHEBA, a research program on the Surface Heat Budget of the Arctic Ocean", NSF Arctic System Science Report No. 3, August 1993.

R=Runoff (freshwater)
L=Longwave radiation
S=Shortwave radiation
O= Ocean heat
M = Melt (snow and ice)
P = Precipitation
T = Temperature (heat transfer)
q = moisture

2. The Circum-Arctic Atmospheric Observatories

Over the last decade the environmental agencies and research institutions involved with operating a number of atmospheric observatories that encircle the Arctic Ocean have voluntarily developed a consortium to promote comprehensive networked observing of the important components of the atmospheric system (Figure 2). The IASOA consortium has been described by Uttal et al. (2015). To date the focus has been on developing cross-network inventories, filling observing gaps, providing data access, developing standardized observing practices and compiling climatologies of individual components of the atmospheric system. The IASOA consortium now enters its second decade with the intent to support a system science approach to global observing initiatives. In doing this the challenge will be to not only maintain and expand high-quality, long-term, observing programs, but also to develop products and protocols that will allow full usage and integration of the surface observational datasets. A critical component of this effort is maintenance of a data portal. Table 1 shows a current inventory of observations that are accessible through the IASOA portal at http://www.esrl.noaa.gov/psd/iasoa/dataataglance.

Figure 2: The member IASOA observatories as of November 2015. The red circle marks Cape Baranova, which is expected to soon become an official IASOA station.

The IASOA sites also provide valuable data for satellite validation. The satellite and surface-based observing communities are inter-reliant users of each other's data products because these observations complement each other in two ways. Surface-based observations are essential for assessing the validity of many satellite products. In turn, satellite products provide a spatial context for in situ point observations. The former is most important for IASOA design and implementation, as it benefits the satellite user community. The latter is most important for balancing the limitations of the fixed (and mostly coastal) locations of the IASOA observatories.

There are several observatory design considerations for the use of surface-based observations for satellite product validation. First, meteorological satellite sensors measure upwelling radiation, whether emitted or reflected, passive or active. Therefore, everything that affects the radiation between the satellite and the feature of interest (e.g., clouds) would ideally be measured from the surface and fully characterized. Second, satellite sensors measure over an area. Surface measurements should be characteristic of that area, either by being made in a homogeneous area or by being distributed over an area representative of a satellite field-of-view (FOV). For a single satellite FOV (375 m^2 to 100 km^2, depending on the sensor and product), homogeneity is an important consideration. The third design consideration is temporal sampling. Generally this is not an issue for satellite validation since most surface-based measurements are made much more frequently than satellite overpasses.

Table 1. IASOA data inventory – The IASOA portal is populated with links to archives by a process of harvesting metadata files. Each metadata file describes a unique data set; therefore the blue bars show the total number of data sets in each measurement category for each station and white bars show the distribution of data sets for subcategories; for instance Barrow has 77 unique data sets describing atmospheric state (meteorological parameters), 50 of which are upper air measurements and 27 of which are surface measurements.

Category	Alert	Barrow	Cherskii	Eureka	Ny-Alesund	Pallas-Sodankyla	Summit	Tiksi	Villum
Atmospheric State	**8**	**77**	**4**	**11**	**19**	**8**	**13**	**14**	**5**
Upper Air State	3	50	2	4	10	4	8	3	2
Surface Meteorology	5	27	2	7	9	4	5	11	3
Cloud Properties	**2**	**117**	**0**	**12**	**3**	**1**	**15**	**3**	**0**
Macrophysical	2	66		7	3	1	8	2	
Microphysical		48		4			4		
Optical and Radiative Properties		3		1			3	1	
Radiometric	**13**	**53**	**2**	**14**	**2**	**3**	**22**	**13**	**0**
Longwave Broadband	6	8	1	4	1		1	4	
Shortwave Broadband	7	13	1	5	1	3	1	9	
Longwave Spectral		7		3			3		
Shortwave Narrowband		7							
Microwave		4		1			1		
Shortwave Spectral		14		1			16		
Surface Properties	**3**	**89**	**6**	**5**	**0**	**0**	**0**	**11**	**0**
Surface Flux	2		1	4				4	
Surface/Subsurface State	1	89	5	1				7	
Cryosphere	**1**	**31**	**2**	**1**	**0**	**0**	**1**	**2**	**0**
Frozen Ground/Permafrost		30	1						
Snow	1	1	1	1			1	2	
Aerosol	**10**	**22**	**0**	**6**	**7**	**11**	**7**	**9**	**0**
Greenhouse Gas	**35**	**91**	**1**	**13**	**23**	**15**	**54**	**14**	**0**
Ozone	**8**	**10**	**0**	**12**	**13**	**12**	**10**	**6**	**0**
Reactive Gas	**25**	**24**	**0**	**23**	**38**	**45**	**19**	**2**	**0**

From a satellite perspective, the ideal observatory would measure the atmosphere (temperature, humidity, and winds at many vertical levels, cloud properties, aerosols, some chemical species, surface radiation), cryosphere (snow cover, depth, and water equivalent, sea and lake ice cover and thickness, permafrost active layer and soil temperatures, glacier/ice sheet properties), and land (land cover, surface temperature, soil moisture). Prioritization of these measurements depends on the application. Geophysical parameters that are most difficult to estimate from space provide one perspective on user needs. These include, but are not limited to, low-level temperature inversion strength and depth, snow grain size and snow water equivalent, cloud optical depth and the frequency of mixed-phase clouds, sea and lake ice thickness, the depth of snow on ice, and surface radiation. Point measurements of atmospheric properties are generally sufficient; surface properties would ideally be measured in multiple locations over an area.

The current IASOA sites are all based on land, but many border the Arctic Ocean and are, therefore, influenced by open water and sea ice depending on the time of year. These sites already provide valuable data on the atmospheric state and cloud properties over the sites, but the detail of characterization depends on the particular instruments deployed at the site. In general, IASOA sites measure basic surface meteorology; some also launch routine radiosondes for vertical profiling. Many sites also measure broadband solar and infrared radiative fluxes, which is challenging in Arctic conditions (Long and Shi, 2008; Matsui et al., 2012). Despite the difficulties, high-quality broadband measurements can yield valuable information regarding clouds (Long and Ackerman, 2000; Long and Turner, 2008). A few of the IASOA sites are considered “super sites” (Barrow, Eureka, Summit) and deploy additional sophisticated instrumentation, including cloud radar, cloud lidar, microwave radiometers and spectral radiometers (in the visible, near-infrared, and infrared). These sites provide much more detailed information of boundary-layer processes and cloud macrophysical and microphysical properties, and, therefore, are an extremely valuable and under-utilized resource for satellite validation (e.g., Turner 2005; Shupe et al., 2006; Shupe et al., 2008; Shupe et al., 2011; Shupe 2011; Cox et al., 2014a; Cox et al., 2014b).

The combined perspectives of the satellite community, the modeling community and diverse stakeholders interested in atmospheric indices all should inform the bottom-up design of the observing assets at the IASOA observatories and the way in which data products are developed from those assets. IASOA has developed the organizational potential to host and recommend experts to the forums in which these needs can be iteratively addressed.

3. Developing Useable Observation-based Products and Analysis Tools

Observers and modelers have long struggled to build meaningful linkages through ingesting observations into reanalyses, observation-model validation/comparison exercises, developing model parameterizations based upon observational data, and through running model-based observing system simulations. In general, these efforts continue to be hampered by different “world views” manifested by large differences in observation versus time and space resolutions and differences in what is actually observed (e.g., radar reflectivities) and what is modeled (e.g., cloud hydrometeor sizes and composition). Another problem is presented by the requirement for “product” data sets such as derivations of quantities that require careful quality control, editing, calibration, interpolation, error flagging and retrieval of parameters from raw data sets, and often requires integration of data from multiple sensors. Consequently, a major challenge in the utilization of the IASOA data sets will be coordinating the development of standardized observing products across the network. Examples of possible products include separate components of the energy-surface flux balance, radar-lidar based cloud microphysical profiles, black carbon absorption coefficients from filter samples, and development of a net moisture and energy horizontal flux product from the IASOA network of upper air observations.

Another line of effort that has been initiated to address the challenges of time-space matching is the development of an IASOA tool set for extracting data from large gridded data in the vicinity of the IASOA observatories. At present, a test tool has been developed for extracting model output from the following archives at the NOAA Earth Systems Research Laboratory including the NCEP/NCAR Reanalysis monthly means, the NCEP/DOE AMIP-II Reanalysis monthly means and the North American Regional Reanalysis (NARR). http://www.esrl.noaa.gov/psd/data /timeseries/arctic/. Additionally, the National Snow Ice and Data Center has developed a utility to interactively subset MODIS satellite data for the IASOA Observatory sites for certain Version 5 (V005) MODIS products. The products available are: MOD09A1, MOD10A1, MOD11A2, MCD43A1, MCD43A2, and MCD43A4. http://nsidc.org/cgi-bin/mist/mist_search.pl.

4. Usage and added value of IASOA observations in studies of atmospheric transports

High-resolution circumpolar estimates of atmospheric transports of momentum, heat, moisture, cloud water, cloud ice, and aerosols into and out of the Arctic require gridded products, such as atmospheric reanalyses, weather or climate model output, or satellite observations. All these products include errors and uncertainties. We expect that IASOA data will be particularly useful for validation of these gridded products, allowing quantification of the errors and uncertainties. In addition, direct calculations on atmospheric transports can be made for the locations of the IASOA observatories.

In the Arctic, atmospheric reanalyses and short-term numerical weather prediction results are reasonably accurate for synoptic-scale patterns of atmospheric pressure and, above the boundary layer, wind and air temperature, but large errors are present in all variables close to the Earth surface (Jakobson et al., 2012) and in moisture variables at all altitudes (Jakobson and Vihma, 2010). Both global and regional climate models include considerable uncertainties in basically all variables in the Arctic (e.g. Tjernström et al., 2008; Hawkins and Sutton, 2009). Satellite remote sensing in the Arctic is hampered by the darkness during the polar night, extensive cloud cover during summer, and challenges in distinguishing between signals originating from the atmosphere and snow/ice surface.

The latter issue is a problem particularly for remote sensing of atmospheric moisture, cloud water, and cloud ice.

Reliable estimates of transports in various atmospheric layers are only possible if the vertical profiles of wind components and the transported quantity are accurate. IASOA data provide possibilities to evaluate reanalyses, weather and climate models, and satellite remote sensing products with respect to the vertical profiles of air temperature, humidity, wind speed and direction, cloud water and ice content, and aerosols. Accordingly, also the vertical profiles of transports of momentum, heat, moisture, cloud water, cloud ice, and aerosols can be evaluated at the locations of the IASOA observatories, yielding estimates of the biases and uncertainties of circumpolar transports calculated on the basis of the gridded products. The vertical profiles of wind, temperature, and humidity are observed also in radiosonde sounding stations, but profiles of cloud water and ice content as well as aerosols and only observed at IASOA stations (Table 1). The evaluation results will provide guidance for the selection of the best method of calculating the transports of various quantities. If the errors are small for a certain quantity, the transport can be reasonably well estimated on the basis of the gridded products, whereas in the case of large errors for another quantity, one should consider if a correction can be applied or if it is better to estimate the transports solely on the basis of observed vertical profiles data with interpolation between the measurement sites.

After transports based on gridded products are evaluated and optimal methods to obtain most accurate transports are selected, these best available transport estimates can be calculated. This allows for an advance in studies on regional processes and interactions between the Arctic and lower latitudes. It is remarkable that the work carried out in the field has so far hardly utilized observations on transports. Observations have mostly been used as a source of information on the changes in the Arctic (e.g observations on sea ice, snow and air temperatures in the Arctic) and on the effects of Arctic changes on mid-latitudes (e.g. observations on precipitation and near-surface air temperature in mid-latitudes), but the estimates of the transports and teleconnections have been mostly based on reanalyses and model products (see Vihma (2014) and Cohen et al. (2014) for reviews). Due to the station locations (Figure 2), IASOA data are particularly suitable in investigating the effects of the new frontal zone that has appeared across the southern coasts of the Arctic Ocean (Section 1). In addition to exact comparison of gridded products and IASOA observations on the same variables, interesting comparisons between related variables can be made; an example is given in Figure 3.

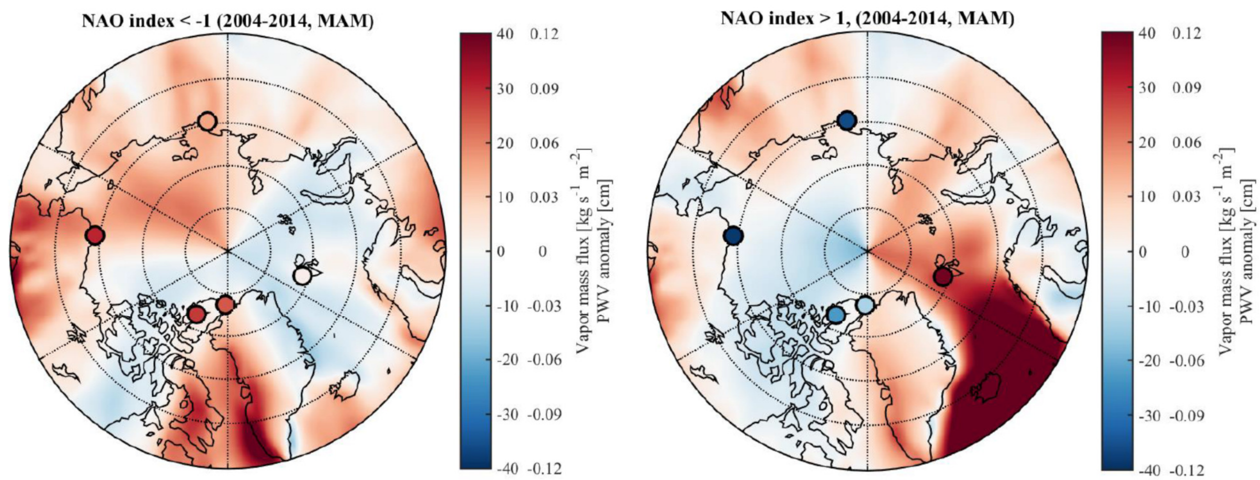

Figure 3. An example of comparison between reanalysis products and IASOA observations. The water vapor mass flux based on ERA-Interim is plotted for circumpolar high-latitudes and the observed precipitable water vapor anomaly is plotted for the sites of five IASOA observatories. The fields differ a lot between springs (MAM) of strongly negative (left) and positive (right) NAO index.

In addition to atmospheric transports, the IASOA data are valuable to evaluate reanalyses, weather and climate models, and satellite remote sensing products with respect to Earth surface variables, such as snow depth, soil moisture, surface temperature, shortwave and longwave radiative fluxes, albedo, as well as turbulent fluxes of sensible heat, latent heat, CO_2, and CH_4. Evaluation of surface fluxes is a vital activity complementing the evaluation of horizontal transports. These together will yield comprehensive understanding on the quality of available gridded products in representing budgets of heat, moisture, greenhouse gases, and aerosols in the Arctic.

The activities described above strongly contribute to the WMO Polar Prediction Project and its Year of Polar Prediction (YOPP). The preparatory and YOPP work will include (a) development of interoperable, error-corrected climatology of long-term meteorological observations and other key data (e.g. surface energy balance data products), (b) exploration of impact of Arctic observations on forecast models, (c) identification of specific regimes for forecast improvements (e.g. strong surface inversions) and most sensitive locations, and (d) coordinated experiments for enhanced observations across the IASOA network during YOPP (e.g. four daily radiosonde soundings). Much of the work will be carried out in the recently established IASOA Regional Processes Working Group.

5. Linkages between IASOA and other regional and global observing initiatives

The IASOA consortium serves as a key building block for an international Arctic network for atmospheric observations. In this capacity, it serves as a contributing task to the Sustaining Arctic Observing Networks (SAON) process. IASOA can be viewed as a regional network that draws together a host of global networks, including the Global Atmosphwere Watch (GAW), the Baseline Surface Radiation Network (BSRN), the Global Cryosphere Watch (GCW), the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN), the Total Carbon Column

Observing Network (TCCON), the Aerosol Robotic Network (AERONET) and more. Each of these global networks has a specific topical focus and has made great strides towards establishing common observing practices for key parameters and developing global archives for data. IASOA builds upon the value of these existing global networks by providing the impetus to move from common observational practices to value-added, interoperable data products for the Arctic region. For some programs, notably GAW and GCW, IASOA will provide critical input on best practices for conducting these observations in the Arctic.

IASOA also provides an organizational nexus for coordinating with other regional efforts with overlapping interests. For example, IASOA has begun to network through Europe's International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT) program to develop synergies between terrestrial and atmospheric observations of Arctic carbon. IASOA shares common objectives with the Pan Eurasian Experiment (PEEX) program through their common interest in observing atmospheric composition of importance to Arctic air pollution.

6. Future perspectives

Presently IASOA is a well-functioning consortium with a unique network of observatories around the Arctic Ocean and a value-added capacity to establish topical Collaboratories to accelerate research in key areas. Analyses of the measurements have yielded advance in understanding the properties of Arctic clouds and aerosols, the atmosphere-surface exchanges of heat, energy, and gases, and the role of black carbon, ozone and methane, in the Arctic climate system. Further, a major role of IASOA observatories has been to provide ground-truth for satellite remote sensing. Broadening the focus of IASOA from local observations to regional processes, particularly to transports of heat, momentum, and atmospheric constituents in and out of the circumpolar Arctic will be a major step forward. A large part of it is reachable with the present observations, but there are several paths to make further advance.

First is the continuation of filling measurement gaps at individual stations of high-resolution vertical profiles of wind, air temperature and humidity, cloud water and ice contents and aerosols. In particular, using information from the three stations (Barrow, Eureka, Summit), which already have comprehensive suites of radars, lidars and spectral radiometers that allow calculation of profiles cloud water/ice and aerosols, it will be assessed if it would substantially enhance the Arctic observing network to add this capacity to additional stations. Second, additional stations are needed to fill data gaps, which may be critical with respect to information on atmospheric transports into and out of the Arctic. For instance a recent significant advance is the development of Cape Baranova Station in Severnaya Zemlya, which is expected to become an official IASOA station when data transfer protocols are established (Figure 2). Thirdly, work is being initiated to increase the number of distributed measurements around stations to assess horizontal variability of the Arctic land surface, which appears to be significant. Finally, the IASOA observatories are sites where active utilization of recent advances in measurement technology, including Unmanned Aerial Systems (UAS), is being deployed.

To maximize the added value of IASOA observatories, the priority of actions in developing the network have to be considered taking into account the expected advances in (a) satellite remote sensing of the atmosphere and Earth surface, (b) other in-situ observations, such as standard weather stations and radiosonde sounding stations, and (c) numerical models and data assimilation systems. For example, if we expect a strong advance in satellite remote sensing of precipitation and soil moisture, the value of IASOS stations is maximized by investing more on observations on soil moisture, terrestrial ecosystems, snow cover, evapotranspiration, precipitation, air moisture, cloud water and ice contents, as well as the related atmospheric transports. This will yield better understanding in the level of the Arctic freshwater cycle, which is an actual research topic (Prowse et al., 2015).

Finally, there is potential to better integrate IASOA observations with research on Arctic ecosystems. A lot of changes have been observed in Arctic biomes and ecosystem types, many of them being driven by changes in climate and hydrological conditions. Changes in biomes and ecosystems in turn affect fluxes of carbon/methane, heat and water (Wrona et al., 2015, submitted), which calls for integration of IASOA observations and terrestrial ecosystem research. In addition, there is potential for more inter-disciplinary science via analyzing the effects of the atmospheric transports on hydrology, glaciology, physical oceanography, as well as marine ecosystem research. This can be achieved via close integration with observation networks in the above-mentioned fields.

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