INTERNATIONAL ARCTIC SYSTEMS FOR OBSERVING THE ATMOSPHERE

An International Polar Year Legacy Consortium

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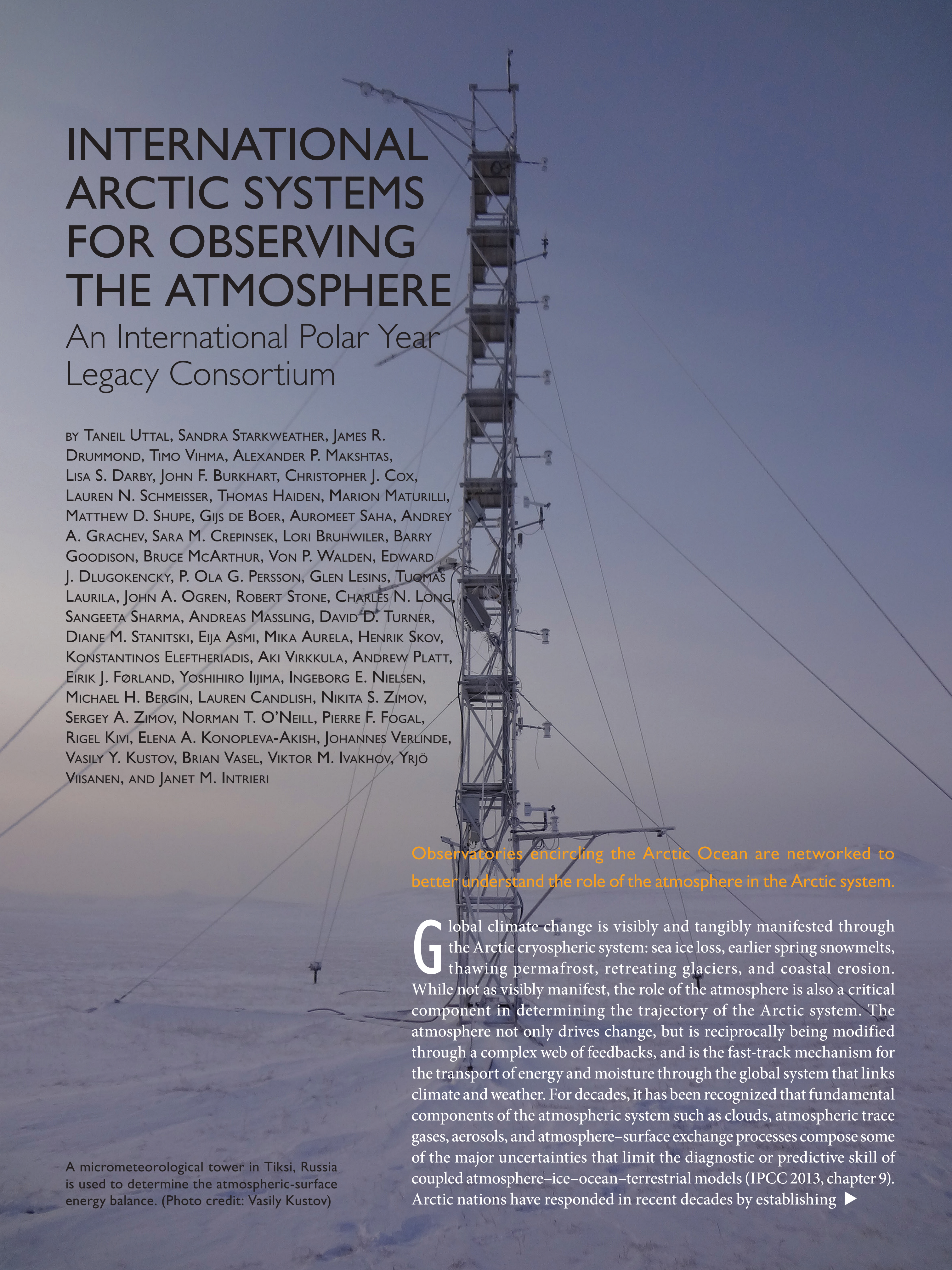

A micrometeorological tower in Tiksi, Russia is used to determine the atmospheric-surface energy balance. (Photo credit: Vasily Kustov)

Observatories encircling the Arctic Ocean are networked to better understand the role of the atmosphere in the Arctic system.

Global climate change is visibly and tangibly manifested through the Arctic cryospheric system: sea ice loss, earlier spring snowmelts, thawing permafrost, retreating glaciers, and coastal erosion. While not as visibly manifest, the role of the atmosphere is also a critical component in determining the trajectory of the Arctic system. The atmosphere not only drives change, but is reciprocally being modified through a complex web of feedbacks, and is the fast-track mechanism for the transport of energy and moisture through the global system that links climate and weather. For decades, it has been recognized that fundamental components of the atmospheric system such as clouds, atmospheric trace gases, aerosols, and atmosphere–surface exchange processes compose some of the major uncertainties that limit the diagnostic or predictive skill of coupled atmosphere–ice–ocean–terrestrial models (IPCC 2013, chapter 9). Arctic nations have responded in recent decades by establishing ▶

long-term Arctic observatories with the objective of sustained monitoring and process-oriented interrogation of the Arctic atmosphere. However, it is clear that these independent endeavors and substantial investments in year-round, high-latitude observing infrastructure cannot independently produce a comprehensive perspective of the Arctic atmosphere because of 1) the regional diversity of various Arctic physical subsystems and the 2) operational constraints imposed by geopolitical boundaries. Accordingly, the International Arctic Systems for Observing the Atmosphere (www.iasoa.org) is a consortium of researchers and operators who are focused on using pan-Arctic observations collaboratively to improve our understanding of the Arctic atmosphere by answering the following questions:

- What are the impacts of short-lived climate forcers such as black carbon, ozone, and methane on the Arctic climate system?
- What are the processes that control the formation, longevity, and microphysical/macrophysical properties of Arctic clouds including the effects of, and sensitivities to, aerosols?
- How do atmosphere–surface exchanges of heat, energy, and gases drive changes in the Arctic cryosphere (permafrost, snow cover, glaciers, and sea ice) and ecosystems?
- What are the two-way linkages between the Arctic and global weather and climate?

THE ORIGINS OF IASOA. The concept for the International Arctic Systems for Observing the Atmosphere (IASOA) was first developed during the International Polar Year (IPY) to address the requirement for intentional and international collaboration that would result in a pan-Arctic, networked observing system. The IPY was an International Year of Science (Krupnik et al. 2011) focused on Arctic and Antarctic physical science, social science, and educational activities. The IPY actually spanned a 2-yr period between March 2007 and March 2009 to ensure that full coverage of complete annual cycles would be obtained for both poles and was the fourth in a series of similarly themed polar years conducted in 1882–83, 1932–33, and 1957–58. In preparation for the IPY, an International Programme Office (IPO) released

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a call for expressions of intent (EoIs) and organized resulting submissions into clusters. IASOA resulted from a cluster of proposed efforts from 20+ individual EoIs, submitted by seven of the eight Arctic countries, including Canada, Russia, United States, Finland, Denmark, Norway, and Sweden. The common theme linking the IASOA EoIs was improving ground-based, atmospheric observational capacity and coverage in the data-sparse Arctic. The IASOA IPY cluster originally developed the following statement of requirements:

> To adequately monitor and understand Arctic climate and processes, a necessary component is the development and uninterrupted support of a system of strategically located, long-term Atmospheric Observatories. In addition to the routine measurements made at meteorological stations and more densely distributed networks, the Observatories are/will be designed to make intensive measurements at the surface and through the depth of the atmosphere. Measured quantities can include (but are not limited to) solar radiation, aerosol physical and chemical properties, air chemistry, trace gases, cloud properties, water vapor, ozone, temperatures, winds, surface albedo and stratospheric properties. IASOA will coordinate intensive measurements of the Arctic atmosphere over Canada, Russia, the U.S., Finland, Greenland, Norway and Sweden. The focus of the program is to combine information so that it can be determined WHY, not just HOW the atmosphere is affecting Arctic climate change. The activities and partnerships initiated during the IPY are expected to continue for decades.

The original member observatories in the IASOA consortium were Barrow (Alaska), Eureka and Alert (both in Nunavut, Canada), Summit (Greenland), Ny-Ålesund (Norway), Pallas and Sodankylä (Finland), Tiksi and Cherskii (Russia), and Abisko[1] (Sweden). All of the stations implemented major upgrades during (Darby et al. 2011) and since the IPY; the Tiksi location in particular was identified by IASOA as a location where it would be particularly advantageous to rebuild measurement capacity (Uttal et al. 2013) to close a geographical gap in the eastern Arctic. Also, during the IPY, various traditional avenues were pursued to foster collaborations between observatory researchers with special sessions and side meetings at international venues such as American and European Geophysical Union conferences and through a website originally supported by Norway, Canada, and the United States.

STRATEGIC DEVELOPMENT. The official end of the IPY was marked by the IPY2012 From Knowledge to Action meeting in Montreal, Quebec, Canada (www.ipy2012montreal.ca). IASOA was emerging from the IPY with not only significantly enhanced measurement capabilities, but also a promising vision of promoting collaborative science based on the premise that no one nation could independently monitor (because of the enormous expenses associated with operating Arctic stations) or understand (because of the regional diversity spread over geopolitical boundaries) the complexities of the Arctic atmosphere. Despite the compelling concept of a collaborative network of Arctic observatories, it was unclear which aspects of IASOA's potential contributions should be prioritized, or how IASOA's vision could be implemented on voluntary efforts and shared intentions alone. An important initial exercise was to assess IASOA's potential legacy work in relation to other efforts in the Arctic constellation of national and international organizations that were already focused on enabling Arctic science, typically by creating inventories, developing science plans, identifying driving science questions, supporting assessments, and conducting surveys of societal needs. In other words, an inaugural step was to focus on exactly what IASOA would do as a body, and how it would do it without duplicating the efforts of other Arctic science organizations. Relevant organizations included the International Arctic Science Committee–Atmosphere Working Group (IASC-AWG; www.iasc.info), the Sustaining Arctic Observing Networks (SAON; www.arcticobserving.org), and the Arctic Council's Arctic Monitoring and Assessment Program (AMAP; Table 1).

A newly formed IASOA steering committee (www.esrl.noaa.gov/psd/iasoa/steering_committee) met for the first time at the Montreal conference. It was agreed that

> "The mission of IASOA is to advance and coordinate research objectives from independent pan-Arctic atmospheric observatories through (1) strategically developing comprehensive observational capacity, (2) facilitating data access and usability through a single gateway, and (3) mobilizing contributions to synergistic science and socially-relevant services derived from IASOA assets and expertise."

This mission statement is the foundation for the observatories–data–science approach described in this article.

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[1] The Swedish Abisko Scientific Research Station was an original IASOA station that did not continue participation.

THE OBSERVATORIES. IASOA defines an observatory as a facility or collection of collocated facilities that is staffed throughout the year, is intended to operate into the foreseeable future, and has a significant observing capacity above and beyond standard meteorological measurements. Currently IASOA has 10 member observatories (Fig. 1). While the IASOA observatories have overlapping scientific

Table 1. Summary of the enabling and integrating objectives of IASOA compared to IASC-AWG, SAON, and AMAP. The extensive IASOA cross cut is enabled by a focus on 1) Arctic, 2) atmospheric, and 3) surface-based observations, as well as 4) the long term.

	Pan-Arctic collaborative activities	IASOA	IASC–AWG	SAON	AMAP
Enabling science	Science planning	×	×	×*	×
	Developing inventories of activities and data	×		×	
	Advancing access to observational data	×		×	
	Coordinating observations and experiments	×	×		
Integrating science	Producing pan-Arctic data products	×		×**	
	Advancing topical network science	×		×**	×
	Advancing Arctic system science	×			×
	Producing decision-relevant assessments and services	×*			×

* Included in future plans.
** Not a focus of SAON as a whole, but included in some SAON contributing projects.

Fig. 1. Locations of the IASOA observatories

objectives, each has a unique history based on mixed and evolving scientific and nonscientific purposes. The governance structure of each observatory has also developed uniquely; some are centrally managed through sponsoring environmental agencies with missions to support long-term observing (e.g., Barrow, Alert, Pallas), others are the result of an international consortium of institutions (e.g., Ny-Ålesund and Tiksi), and yet others are reliant on the success of competitive, multiyear academic grant funding to define their evolving objectives (e.g., Eureka and Summit). This has implications for how observatory scientists conduct research, how they participate in IASOA, and how they share data.

The observatories also have a wide range of observational capabilities with some stations focused on conducting long-term measurements that support global observing networks, for instance the Global Atmosphere Watch (GAW; www.wmo.int/gaw), the Network for the Detection of Atmospheric Composition Change (NDACC; www.ndsc.ncep.noaa.gov), the Baseline Surface Radiation Network (BSRN; www.ndsc.ncep.noaa.gov), the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN; www.wmo.int/pages/prog/gcos/index.php?name=GRUAN), and the Aerosol Robotic Network (AERONET; http://aeronet.gsfc.nasa.gov). Other "supersite" observatories have a mission to collect advanced, collocated data to understand the processes driving the atmospheric system (cloud microphysics, aerosol direct and indirect effects, interaction between atmospheric gases, radiant energy transfers, and atmospheric coupling with the underlying surface). These observatories deploy technologically advanced passive and active sensors such as radars, lidars, and spectral radiometers.

Aside from the variety of governance models and observing assets, the observatories also represent a vast diversity of Arctic subregions with different climatologies, geographies, and biomes so that each IASOA observatory effectively gathers information on a unique Arctic regional system subtype. A summary of the salient features of the observatories is presented in Table 2.

DATA. IASOA's vision for integrated data sharing predates the National Science Foundation Advisory Committee for Geosciences Strategic Plan (NSF GEO Advisory Committee 2012), but directly addresses their recommendation: "While many countries have their own capabilities, to provide a complete global data set there is a need to develop an intelligently integrated and consistent system for observing with transparency relative to aspects such as calibration, algorithms, and data utilization." At the inaugural meeting of the IASOA science committee in 2012, discovery and access to data were identified as essential. Consequently, IASOA has developed an innovative and dynamically generated data portal (www.esrl.noaa.gov/psd/iasoa/dataataglance) that provides direct access to original datasets and data products from across the IASOA network. The mechanics of the data portal are discussed with some detail in the Inbox article in this issue (Starkweather and Uttal 2016).

SCIENCE WORKING GROUPS. To further capitalize on new measurement infrastructure developed during the IPY and an increasingly functional data portal, IASOA began accelerating the collaborative research process (Wulf 1993) by initiating a number of thematic working groups in 2013 (Table 3). This section describes the current direction of three active working groups (those dealing with aerosols, radiation, and surface–atmosphere exchanges) and the scientific impetus for developing three additional working groups (investigating regional predictions, trace gases, and clouds) in the near future.

Aerosol Working Group. In recent years, considerable international attention and policy development have been directed toward the abatement of black carbon in the atmosphere as a result of questions about the negative climate and health impacts of black carbon in the Arctic (e.g., Quinn et al. 2011). Black carbon affects Arctic climate through the direct absorption of incoming solar radiation, aerosol indirect effects on cloud radiative forcing, and modification of surface albedo when deposited on snow (Quinn et al. 2008). Work is being done on many fronts related to the Arctic black carbon topic, including the development of emissions inventories, analyses of transport trajectories and sources, modeling of black carbon in the atmosphere (Eckhardt et al. 2015), and measurements in the snow (Grenfell et al. 2009), in order to better understand the black carbon climatology and resulting climatic implications (Sharma et al. 2006; Hegg et al. 2009; Doherty et al. 2010).

Seven IASOA observatories (Alert, Barrow, Pallas, Summit, Tiksi, Station Nord, and Ny-Ålesund) monitor aerosol optical properties including concentrations of absorbing equivalent black carbon (EBC; Petzold et al. 2013). Despite the unique and exciting analysis opportunities afforded to scientists by an Arctic-wide EBC measurement network, comparing data across stations requires caution because diverse

Table 2. Detailed information for the IASOA observatories. Note that this table includes one additional candidate observatory (Cape Baranova). Candidate observatories are considered for acceptance during annual meetings of the IASOA steering committee. While all the stations have upper-air measurement programs, those that are designated as weather stations are additionally part of national meteorological observing programs contributing to the WMO. Dates without asterisks show when measurements (usually weather) were first taken at site. Dates with asterisks indicate when significant higher order measurement capabilities were initiated bringing stations to observatory status.

Observatory	Lat, lon	Elevation (m MSL)	Year(s) established	Network affiliations (ID)	Biome/ geography	Website	Institutions providing support	Weather station	Primary scientific focus areas and measurement programs
Barrow	71.3°N, 156.6°W	8–20	1949 1974* 1998*	GAW, NDACC, Global Climate Observing System (GCOS; www.wmo.int/pages/prog/gcos/index.php?name=GRUAN) Reference Upper Air Network (GRUAN), BSRN, AERONET, ARM, NOAA baseline	Tundra/coast	www.esrl.noaa.gov/gmd/obop/brw; www.arm.gov/sites/nsa	National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Energy (DOE), National Science Foundation (NSF)	Yes	The scientific focus of NOAA efforts includes research on atmospheric constituents that drive climate change, stratospheric ozone depletion, and baseline air quality; DOE Atmospheric Radiation Measurement (ARM) supports process studies of clouds, aerosols, radiation, and surface–atmosphere exchanges (Verlinde et al. 2016)
Oliktok Point	70.5°N, 149.9°W	5	2013	ARM (mobile)	Tundra/coast	www.arm.gov/sites/amf/oli/	DOE	No	DOE ARM supports process studies of clouds, aerosols, radiation, and surface–atmosphere exchanges; in addition, this facility supports profiling the atmosphere in restricted airspace through unmanned aircraft and tethered balloon systems
Eureka	80.1°N, 86.6°W	0–620	1947 1993* 2005*	NDACC, AERONET, Total Carbon Column Observing Network (TCCON), BSRN	Tundra/ archipelago	www.candac.ca	Canadian Natural Sciences and Engineering Research Council (NSERC), Environment Canada (EC), Canadian Space Agency (CSA)	Yes	The scientific focus is on air quality, climate change, and stratospheric ozone; measurements are made by spectrometers, radiometers, radars, and lidars as well as an instrumented 10-m micrometeorological tower; observations of atmospheric conditions are made for the whole atmosphere from the surface to ~100-km altitude throughout the year (Fogal et al. 2013)
Alert	82.5°N, 62.5°W	8–210	1950 1986*	GAW, NDACC, BSRN	Tundra/coast	www.ec.gc.ca	EC Canadian armed forces (in-kind support)	Yes	The primary focus of the GAW station at Alert is on measurements for improving understanding of the atmosphere, pollutants, influence of emission sources and their interactions with the oceans and biospheres. Measurements currently

									being made at Alert include greenhouse gases, aerosols related to climate change, persistent organic pollutants (POPs) and gaseous and particulate mercury under the Northern Contaminants Program
Summit Station	72.6°N, 38.4°W	3250	1997 2010*	GAW, NDACC, AON, NOAA Baseline	Ice sheet/ interior	www.summitcamp.org; www.geosummit.org; www.esrl.noaa.gov/gmd/obop/sum	NOAA DOE NSF	No	The scientific focus of NOAA efforts includes research on atmospheric constituents that drive climate change, stratospheric ozone depletion, and baseline air quality; NSF supports fundamental science that can be uniquely addressed at Summit Station including process studies of clouds, aerosols, radiation, and surface–atmosphere exchanges (Shupe et al. 2013)
Villum Research Station, Station Nord	81.4°N, 16.7°W	24	1970 1990* 2014*	GAW, AMAP, European Monitoring and Evaluation Programme (EMEP), Gridded Model Output Statistics (GMOS)	Tundra/coast	www.au.dk/villumresearchstation	Danish National Environmental Research Institute (NERI), Department of Environmental Science, Aarhus University	No	The scientific focus is on both long-term measurements of the composition of trace gases, and of aerosol physical and chemical properties; process studies are carried out in campaigns
Ny-Ålesund Zeppelin Station	78.9°N, 11.9°E 78.9°N, 11.9°E	0–30 473	1969 1992* 1975 1988*	BSRN, GRUAN, NDACC, TCCON GAW; Aerosols, Clouds, and Trace gases Research Infrastructure Network (ACTRIS); EMEP; AMAP	Tundra/ archipelago Alpine/ archipelago	nysmac.npolar.no	Norwegian Polar Institute (NPI), Norwegian Institute for Air Research (NILU), Alfred Wegener Institute (AWI), Japanese National Institute for Polar Research (NIPR), Italian National Research Council (CNR), Korean Polar Research Institute (KOPRI), and others from various nations	Yes No	The Ny-Ålesund research complex is composed of a number of individual research stations with atmospheric observation programs (Neuber et al. 2008) that are supported by a number of different institutions; scientific foci include examining the effects of long-range transport, as well as surface–atmosphere exchanges; atmospheric observations include long-term monitoring of meteorological parameters, radiation, aerosols, atmospheric trace gases, and atmospheric chemistry; measurements are made by in situ, ground-based, balloon-borne, tower-mounted and remote sensing instrumentation

Continued.

Table 2. Continued.

Observatory	Lat, lon	Elevation (m MSL)	Year(s) established	Network affiliations (ID)	Biome/ geography	Website	Institutions providing support	Weather station	Primary scientific focus areas and measurement programs
Pallas	68.0°N, 24.1°E	565	1991	GAW, NDACC, AERONET, GRUAN, ICOS, TCCON, Global Energy and Water Cycle Experiment (GEWEX), ACTRIS, AMAP, EMEP	Forest (boreal)/ interior	fmiarc.fmi.fi/index.php	Finnish Meteorological Institute (FMI)	No	At Pallas the scientific focus is on clean air atmospheric composition of aerosols and trace gases and air quality.
Sodankylä	67.4°N, 26.6°E	179	1908					Yes	At Sodankylä, the scientific focus is on tropospheric and stratospheric observations, radiation and remote sensing calibration–validation (CAL/VAL) activities. (Hatakka et al. 2003)
Tiksi	71.6°N, 128.9°E	1–30	1932 2009*	GAW, AERONET, BSRN	Tundra/coast	www.esrl.noaa.gov/psd/arctic/observatories/tiksi	Russian Federal Services for Hydrometeorological and Environmental Monitoring (Roshydromet), FMI, NOAA, NSF, Japanese Agency for Marine-Earth Science and Technology	Yes	At Tiksi the scientific focus is on surface–atmosphere exchanges including studies of clouds, aerosol and radiation, and greenhouse gases (GHGs); advantage is taken of the long history of meteorological measurements to conduct multidecadal climatology studies within the context of the surrounding East Siberian region and linkages to the shore fast ice in the adjacent Sogo Bay
Cherskii	68.7°N, 161.4°E	16	1989	NDACC	Forest (taiga)/ interior	www.pleistocenepark.ru/en	Pacific Institute of Geography of the Far East Branch of the Russian Academy of Sciences (FED RAS)	No	The science focus is on carbon cycles, methane fluxes, paleoclimate, and the changing ecosystem; it is collocated with Pleistocene Park, an experimental wildlife preserve (Zimov 2005)
Ice Base Cape Baranova (candidate station)	79.3°N, 101.7°E	24	1986–91 2013*	To be determined	Glacier/ tundra/coast	www.aari.ru	Roshydromet, FMI	No	The scientific focus is on process studies of aerosols, radiation, and surface–atmosphere exchanges; research activities include radiosoundings, lidar, radiometers, intensive aerosol and greenhouse gases measurements, surface radiation measurements, surface meteorology and turbulent flux measurements; the site provides additional opportunities for profiling the atmosphere with unmanned aircraft

filter-based instruments have been deployed. Multi-instrument comparison requires a process of disentangling differences in instrument-reported values in order to get comparable data from each instrument across the network. Because of the large uncertainty still surrounding the correction schemes for these instruments, absolute EBC values are being teased out from instrument light attenuation measurements; here, normalized comparisons are possible (Fig. 2). Most EBC observations from IASOA stations demonstrate the expected high EBC loading relative to the annual average in spring and winter, indicative of the well-documented phenomenon of "Arctic haze" (Shaw 1995; Quinn et al. 2008). Exceptions to this seasonal variability pattern include Summit (3250 m MSL), which follows the pattern suggested by Scheuer

Table 3. IASOA began the process of convening open collaborative working groups in 2013. Each group's focus is influenced by the interest of its investigators. Three groups (Aerosols, Radiation, and Atmosphere–Surface Exchanges) have actively convened; three groups (Regional Prediction, Trace Gases, and Clouds) are in the process of forming.

Working group	Status	Focus	Collaboration
Aerosols	Convened since May 2013	Developing consistent error correction schemes for historical aethalometer data from six observatories	20 collaborators from seven sites
		Synthesizing a pan-Arctic climatology of aerosol optical properties from IASOA observatories	
Radiation	Convened since May 2013	Developing a cross-site framework for long-term albedo trends	22 collaborators from six sites
		Developing a cross-site framework for cloud radiative forcing analysis	
		Developing a cross-site framework for longwave radiation trends and processes	
		Exploring statistical relationships between radiation anomalies and Arctic system change	
		Developing value-added data products from broadband radiation measurements	
Atmosphere–surface exchange	Convened since Mar 2014	Developing intercomparable data products for radiative, turbulent, conductive heat, and trace gas fluxes from IASOA and other contributing Arctic sites	24 collaborators from nine or more sites
		Developing consistent methods for characterization of high-latitude sites and means to address scale issues	
		Sharing best practices for high-latitude flux observations	
Regional processes	Planned for 2015	Organizing IASOA activities for the Year of Polar Prediction	To be determined (TBD)
		Identifying key data products to develop from sometimes heterogeneous, long-term meteorological observations	
		Promoting the use of IASOA data in global and regional reanalysis and prediction models	
		Conducting circumpolar analyses of linkages between the Arctic and lower latitudes	
Trace gas	Planned for 2015–16	Bounding and describing the regional and interannual variability in key trace gas observations around the Arctic	TBD
		Studying key processes that control uptake and deposition of trace gases in Arctic environment	
		Serving as an organizational nexus for campaigns that study the vertical distribution of key trace gases and deposition processes	
Clouds	Planned for 2015–16	Bounding and describing macro- and microphysical cloud properties in high latitudes	TBD
		Bounding and understanding the impacts of clouds on Arctic system change	

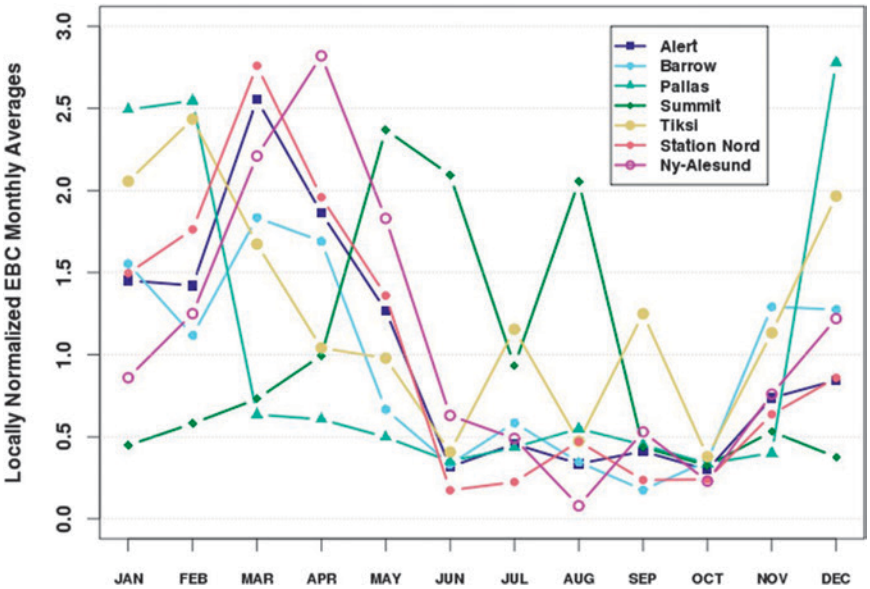

Fig. 2. EBC monthly averages from the year 2012 normalized by the station's local annual average of that same year, showing the annual variability in EBC at seven stations within the IASOA network. In the absence of an accepted correction scheme, these indicate locally normalized EBC monthly averages that indicate a diverse network-wide seasonal variability, but do not indicate EBC loading relative to other stations. Data from Barrow, Alert, Pallas, Tiksi, and Ny-Alesund are from an aethalometer model AE31 (7 wavelength), Summit data are from an aethalometer model AE16 (880 nm), and Station Nord data are from a MAAP (670 nm). Normalizing the data by local annual averages minimizes any differences between these instruments and allows a direct comparison of annual EBC cycles.

et al. (2003) of aerosol loading in the free atmosphere reaching a peak in summer, and Tiksi, which demonstrates high winter EBC loadings because of its proximity to biomass burning and industrial smelting sources (Hirdman et al. 2010). The diverse seasonal variability at each station shows that a network-based collaboration provides necessary insight into the complex spatial distribution of EBC, which is controlled by seasonally driven long-range transport and by regional sources. The Aerosol Working Group is developing standardized EBC and aerosol optical properties data products that will be submitted to the World Data Center for Aerosols (WDCA) hosted at EBAS (http://ebas.nilu.no).

Aerosol optical depth (AOD) is a measure of turbidity due to various aerosols (e.g., pollutants, smoke, dust, sea salts, and volcanic emissions) being distributed through the atmosphere. Derived from photometric observations during clear, sunlit periods, spectral AOD retrievals are used to quantify aerosol abundance and type. NASA's AERONET program operates sun photometers at several Arctic stations including four IASOA stations (Ny-Ålesund, Barrow, Alert, and Tiksi). Considerable work has gone into developing AOD climatologies under Polar-AOD, another project initiated during IPY (Tomasi et al. 2012). Stone et al. (2014) provide in-depth analyses of long-term AOD observations made at Ny-Ålesund, Barrow and Alert in terms of aerosol types, annual cycles, and interannual variations attributed to changing emissions and atmospheric flow patterns. Recently, Saha et al. (2014) analyzed Arctic AOD data to produce Fig. 3, which illustrates the seasonal and regional complexity of aerosol optical properties with a general decrease in AOD from west to east across the western Arctic and a general pattern of maximum AOD during spring attributed to a buildup of Arctic haze. The IASOA Aerosol Working Group will be able to use the AOD measurements to link the in situ, surface-based information on aerosol optical properties to larger-scale circulation and emission questions.

Radiation Working Group. Accurate quantification of the components that contribute to the surface radiation budget is essential for understanding net surface–atmosphere exchange processes, cloud radiative forcing, and linkages to other components of the Arctic system such as sea ice (DeWeaver 2008) and snow cover. Five of the IASOA observatories (Barrow, Alert, Eureka, Ny-Ålesund, and Tiksi) are World Meteorological Organization (WMO) BSRN sites, with Summit being a candidate site. The BSRN (Ohmura et al. 1998) monitors the surface radiation budget (SRB) as a part of GCOS. The IASOA Radiation Working Group interfaces with the BSRN Cold Climate Issues Working Group to improve Arctic radiometer data quality through standardized field operations and mitigation of rime, frost, and accumulation of snow, intermittent operator maintenance, and extreme temperatures that can result in instrument biases. Also, a recommendation from the IASOA Radiation Working Group resulted

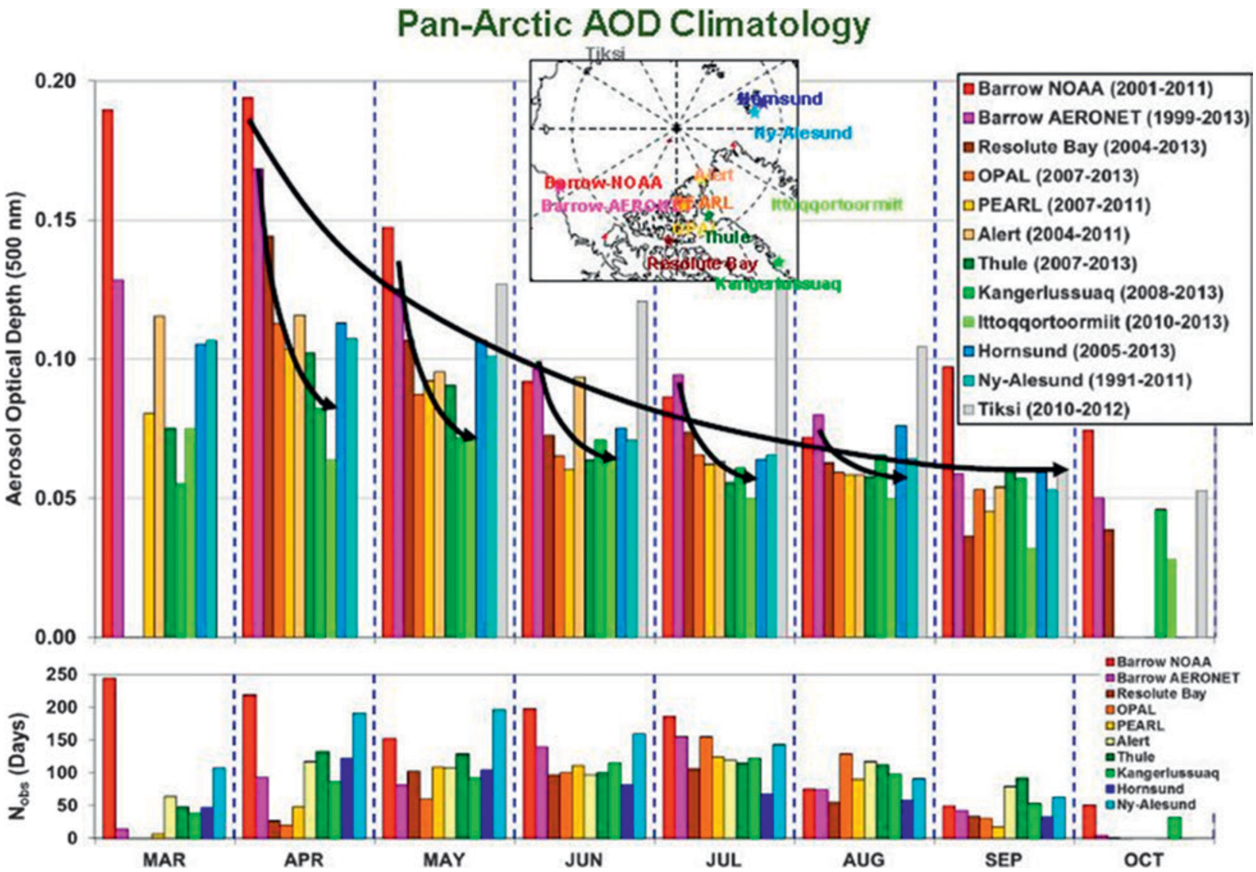

Fig. 3. AOD monthly climatologies at high-Arctic stations simultaneously showing the spring-to-summer decrease, as well as a west-to-east decrease in AOD on a pan-Arctic scale.

in installation of new instrumentation (Fig. 4) at the Summit observatory to provide baseline comparisons with a longer-term radiation site

Based on a Ny-Ålesund surface radiation climatology (Maturilli et al. 2015), the IASOA Radiation Working Group has begun developing a pan-Arctic radiation climatology. The Ny-Ålesund study identified albedo as an indicator of the snowmelt and snow onset dates that were showing climatological trends toward longer snow-free summers, with implications for ecosystems and regional climate. An expanded analysis (Fig. 5) shows the regionally diverse range in the timing of the transition from snow-covered to snow-free conditions for Ny-Ålesund, Alert, Barrow, and Tiksi, as inferred from albedo measurements. Factors such as snow accumulation, temperature, and cloudiness influence the timing of snowmelt in spring (Stone et al. 2002; Stanitski and Stone 2014; Cox et al. 2014), which in turn modulates the annual surface radiation budget.

Although an IASOA Cloud Working Group is being developed, it is clear that there will be areas of overlap between working groups with opportunities to integrate experts on key topics; for example, the

Fig. 4. An early initiative of the IASOA Radiation Working Group was to support the installation of radiometers (calibrated in 2014) at Summit Station to conduct an in situ intercomparison of BSRN-candidate radiometers that were installed in 2004. (Copyrighted photo courtesy of R. Albee.)

Radiation Working Group has begun examining cloud representation in models (Fig. 6). Clouds, and particularly mixed-phase and high-latitude clouds,

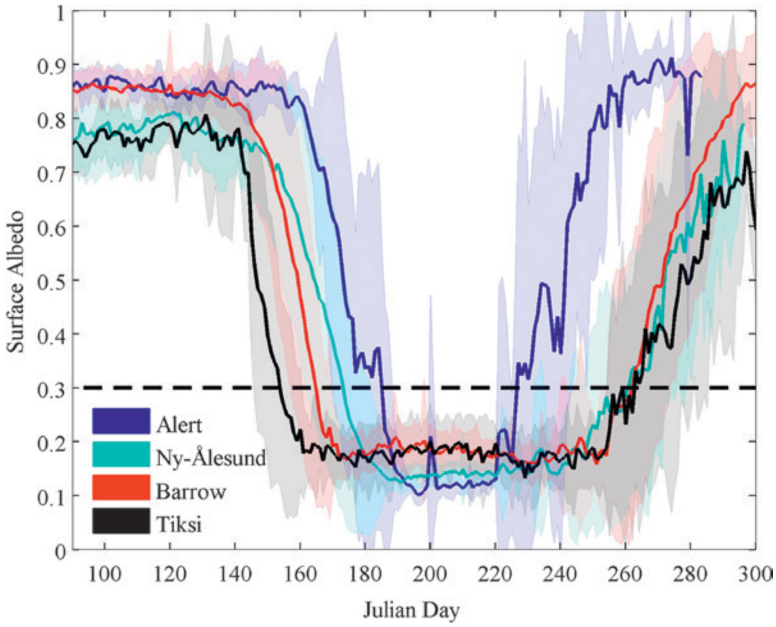

FIG. 5. Daily mean surface albedo derived from upward- and downward-facing broadband shortwave radiometers from the BSRN stations at Alert (2005–11; blue), Ny-Ålesund (1993–2014; cyan), Barrow (1985–2014; red), and Tiksi (1997–2003 and 2011–14; black). Shaded regions represent plus or minus one standard deviation of all years in the record. Horizontal dashed black line is the surface albedo threshold (0.3) used to identify snow-free days. The period when albedo begins dropping from ~0.8 to ~0.2 is the period when the surface transitions from snow to snow-free conditions.

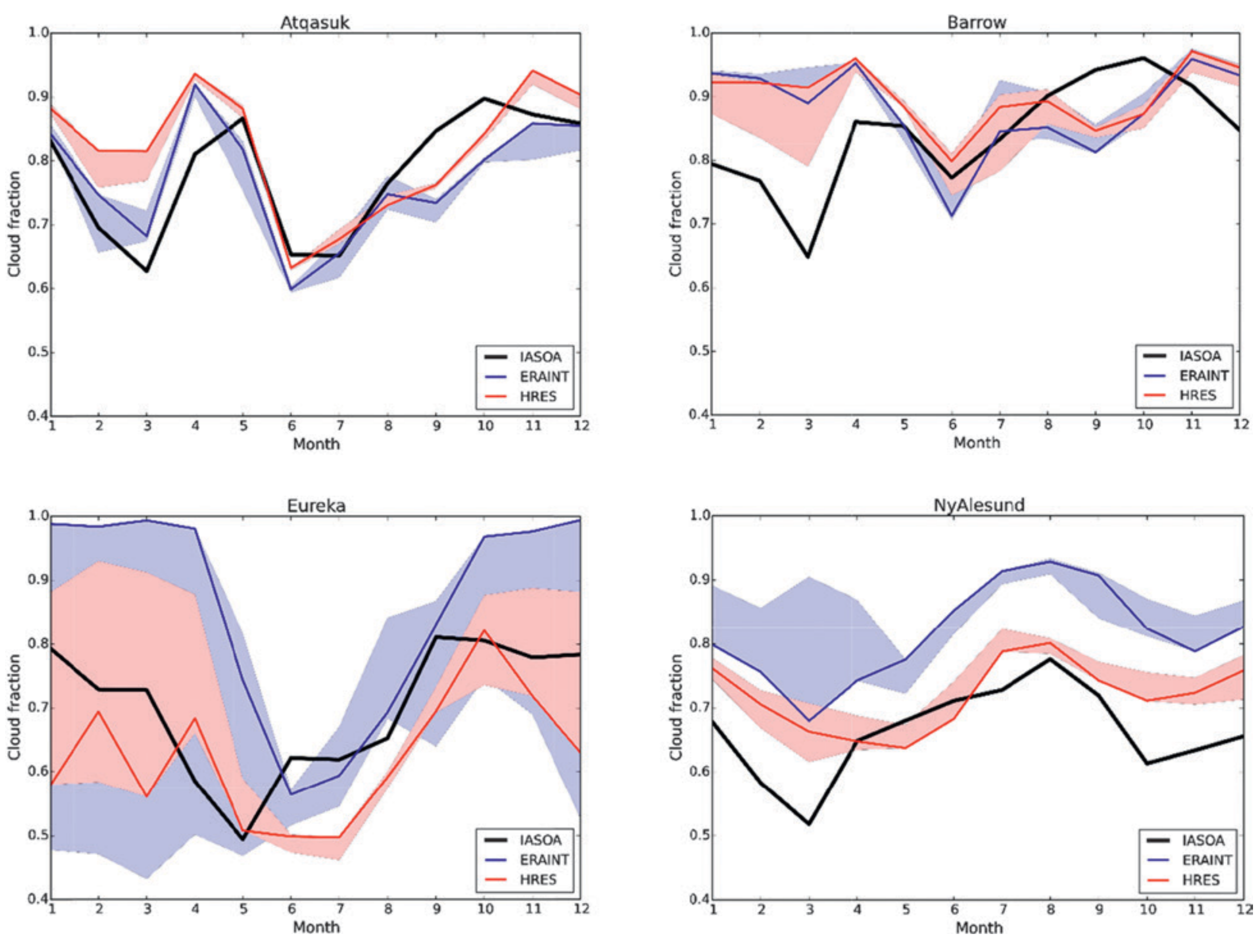

FIG. 6. Reasonable agreement is shown between monthly mean (2005–09) cloud fraction for European Centre for Medium-Range Weather Forecasts (ECMWF) ERAINT (blue) and HRES (red) models with observations (black) at a Department of Energy (DOE) site at Atqasuk, Alaska (50 km inland), while there are substantial differences at the coastal IASOA sites Barrow, Eureka, and Ny-Alesund. Shading indicates the range of cloud fraction values spanned by the four nearest grid points in the analysis.

induce some of the largest uncertainties in numerical modeling (Chaudhuri et al. 2014; de Boer et al. 2012). Some of the challenges with simulation of Arctic clouds have come from obstacles involved with validating the model performance through the comparison of grid-box-average cloud properties to temporal averages derived at observatories using upward-looking sensors (e.g., Cox et al. 2014). While some of the observatories are adding scanning instrument capabilities that allow for data products that compare more favorably with gridbox averages, and while continued advancement of instrument simulators should provide a more direct comparison with the models, caution must still be exercised when making comparisons between models and observatories at coastal sites (e.g., Barrow), sites that are situated within extreme topography (e.g., Eureka), and on islands (e.g., Ny-Ålesund). At these locations, sharp cloud gradients may exist either in reality or as an artifact in the model products. These recognized issues with cloud studies are being specifically considered within the context of the special circumstances of the Arctic environment by the IASOA Radiation Working Group and will also inform the IASOA Cloud Working Group.

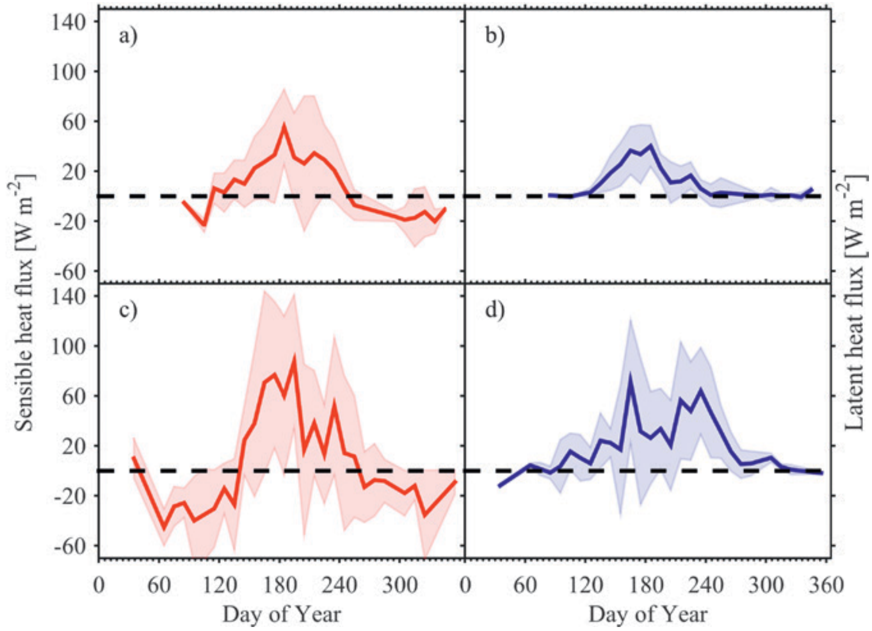

Fig. 7. Time series of (a) sensible heat flux (Eureka, 2014), (b) latent heat flux (Eureka, 2014), (c) sensible heat flux (Tiksi, 2014), and (d) latent heat flux (Tiksi, 2014). Solid lines are 10-day-averaged data. Shaded regions represent plus or minus one standard deviation.

Atmosphere–Surface Exchanges Working Group. Observational evidence suggests the transfer of energy from the atmosphere to the surface is an important factor driving the fluctuations of the Arctic pack ice, seasonal land snow cover, and the warming of the surrounding land areas and permafrost layers (Serreze et al. 2009; Lesins et al. 2009; Döscher et al. 2014). To better understand the atmosphere–surface exchange mechanisms, improve models, and diagnose Arctic climate variability, continuous accurate measurements are required of all components of the total surface energy budget. Seven of the IASOA stations (Barrow, Alert, Eureka, Summit, Ny-Ålesund, Pallas/Sodankylä, and Tiksi) take measurements from micrometeorological towers that allow calculation of the turbulent fluxes of sensible heat, latent heat (water vapor), momentum, and CO_2 from a number of covariance (e.g., Grachev et al. 2007) and bulk flux schemes (e.g., Andreas et al. 2010). The IASOA Atmosphere–Surface Exchanges Working Group is working to standardize methods across observatories to create a consistent product that can be archived with the global FluxNet (www.fluxnet.ornl.gov) program.

Examples of the annual cycles of covariance turbulent fluxes for Tiksi and Eureka (Fig. 7) show that nonsummer sensible heat fluxes are generally downward (heating the surface) and summer fluxes generally cool the surface. Moisture fluxes show a loss to the atmosphere in summer, and are very small during nonsummer seasons. Because soil moisture is generally high in early summer just after the snowmelt at both locations (~yeardays 160–180), the greater moisture loss at Eureka compared to Tiksi suggests that the summer atmosphere in Eureka is drier and/or that the underlying surface is wetter. The IASOA Atmosphere–Surface Exchanges Working Group is developing strategies, in collaboration with terrestrial ecologists and permafrost scientists, to characterize surface and subsurface properties in the vicinity of the micrometeorological towers in order to understand sources of variability and determine the relative magnitude of local versus regional influences.

Figure 8 shows the annual cycle composite for radiative and turbulent heat components of the surface–atmospheric flux as well as the permafrost temperature structure at the Alert observatory. This single-station analysis forms the basis for the Atmosphere–Surface Exchanges Working Group to pursue similar intercomparable analyses at the other IASOA stations and for longer multiyear time periods. This type of in-depth, multisensor observation of annual cycles, their interannual variability, and comparisons between stations is expected to lead to an improved process-level understanding of atmospheric coupling with the Arctic surface.

Regional Processes and Transports Working Group. Arctic regional processes (on weather and climate scales) have been identified as an important focal area and consequently, a Regional Processes and Transports Working Group is currently being organized. In addition to the needed predictive model improvements in cloud processes and atmosphere–surface coupling representation, there is also still a need for more basic information on vertical profiles of temperature, humidity, and wind in the Arctic atmosphere, as demonstrated by the large errors found in reanalyses (Jakobson et al. 2012), by the considerable uncertainty in the vertical profiles of Arctic warming and heat transport from lower latitudes to the Arctic (Graversen et al. 2008; Screen and Simmonds 2010) and the continued struggles with model representation of the atmospheric boundary layer.

A desirable criteria met by a majority of IASOA observatories is collocation with a multidecadal, ongoing program of standard meteorological measurements. Most of the IASOA observatories have observer-supported meteorological records that span decades. These climatologies are essential for site characterization, for suggesting processes that require further investigation, and providing historical context for short data records collected by more sophisticated sensors. Such data become particularly important for the upcoming WMO-supported Polar Prediction Project (www.polarprediction.net),

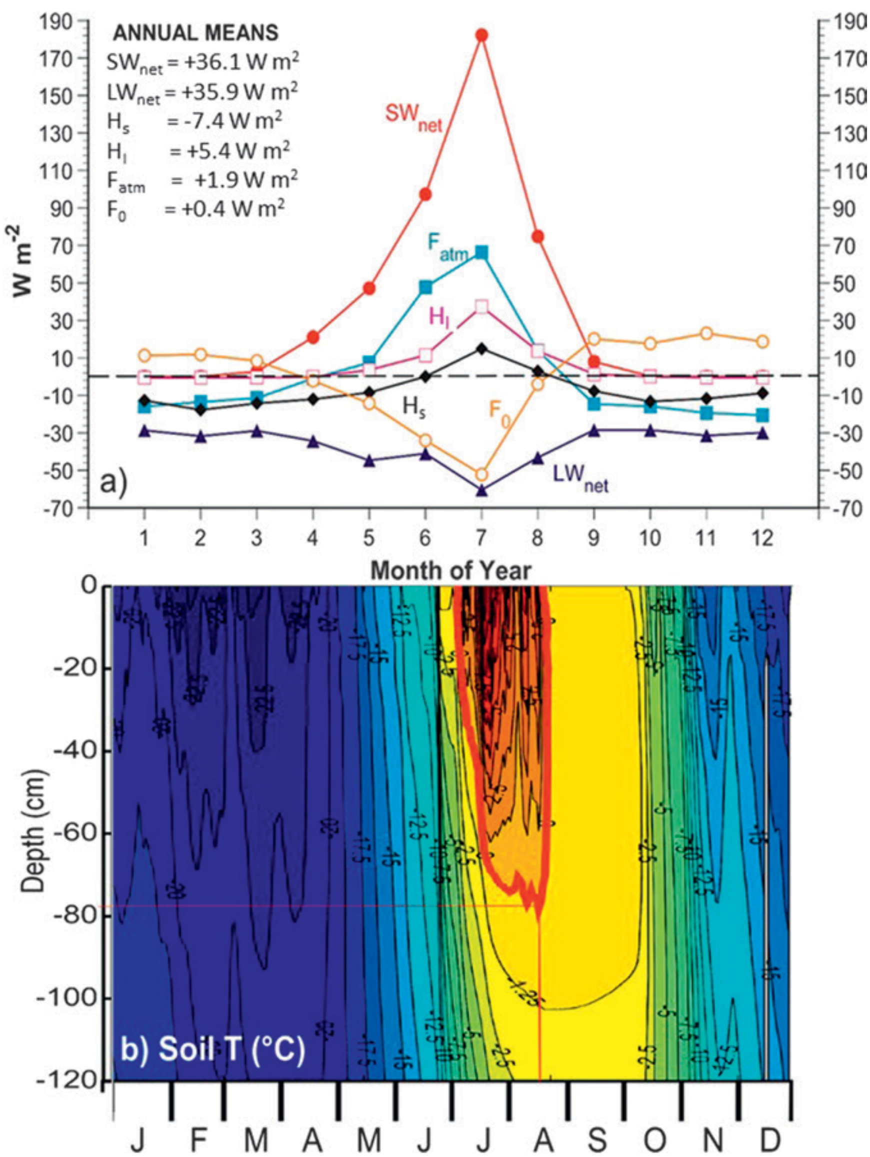

Fig. 8. (a) Monthly mean values of the radiation (SW_{net} = shortwave, LW_{net} = longwave) and turbulent (H_l = latent heat, H_s = sensible heat) fluxes for 2004–07 and the conductive heat flux (F_0) for 2005–07. Here, $F_{atm} = SW_{net} + LW_{net} + H_l + H_s$. Annual means of the terms are given in the top left. (b) Temperatures in the upper 120 cm of the soil at Alert for 2006. The thick red line is the 0°C isotherm.

which will sponsor the Year of Polar Prediction (YOPP) that will comprise coordinated international modeling and observational efforts to improve model predictive skill in the Arctic region from 2017 to 2019.

The IASOA observatories have some of the longest aerological sounding measurements in the Arctic region but various authors have commented on the difficulty of comparing these observations across measurements programs so that they can be used reliably to evaluate trends (Gaffen 1994; Seidel et al. 2009). Figure 9 shows height-resolved annual temperature trends (°C yr^{-1}) based on quality controlled upper-air datasets produced using a consistent methodology (Maystrova et al. 1986) for the period 1950–2013 for Barrow, Alert, Eureka, Tiksi, Cherskii, and Sodankylä. All stations show a warming trend at lower levels with cooling in the upper levels. However, there are significant differences between observatories as to the depth of the warming layer, with Cherskii and Tiksi showing lower-level warming below the 800- and 700-hPa pressure levels, respectively, while Sodankylä, Eureka, Alert, and Barrow have increasingly deeper warming layers (up to 500, 325, and 300 hPa, respectively). In general, the trends show interesting variations as a function of height and observatory location, varying from −0.06° to +0.05°C yr^{-1}. Analyses based on IASOA and other circum-Arctic upper-air data also include studies on humidity inversions (Nygård et al. 2014).

The possibilities for using reanalyses to quantify the warming structure in the Arctic have been evaluated (Chung et al. 2013) and Perlwitz et al. (2015) used model experiments to suggest that Arctic sea ice loss is the largest contributor to near-surface, Arctic tropospheric warming; homogenized data from the IASOA network of upper-air stations can provide an observational constraint on such model experiments. Future efforts for an IASOA Regional Processes and Transports Working Group will include efforts to further harmonize original, high-resolution sounding data, additional comparisons with various reanalysis products, and designing increased temporal resolution (four and six times per day) launch campaigns for the YOPP. All 10 of the IASOA stations have rawinsonde launch programs but only 3 of the stations (Barrow, Ny-Ålesund, and Soldankylä), are GRUAN stations; a likely objective for the regional processes group will be to investigate requirements so that more of the IASOA sites will be eligible for the GRUAN network. This further utilization of circumpolar IASOA upper-air observations together with model products supports analyses of two-way interactions between the Arctic and the midlatitudes.

Trace Gases Working Group. Characterization and improved process understanding of Arctic trace gases (particularly methane and ozone) have been identified as important focal areas; a Trace Gases Working Group to address this area is currently

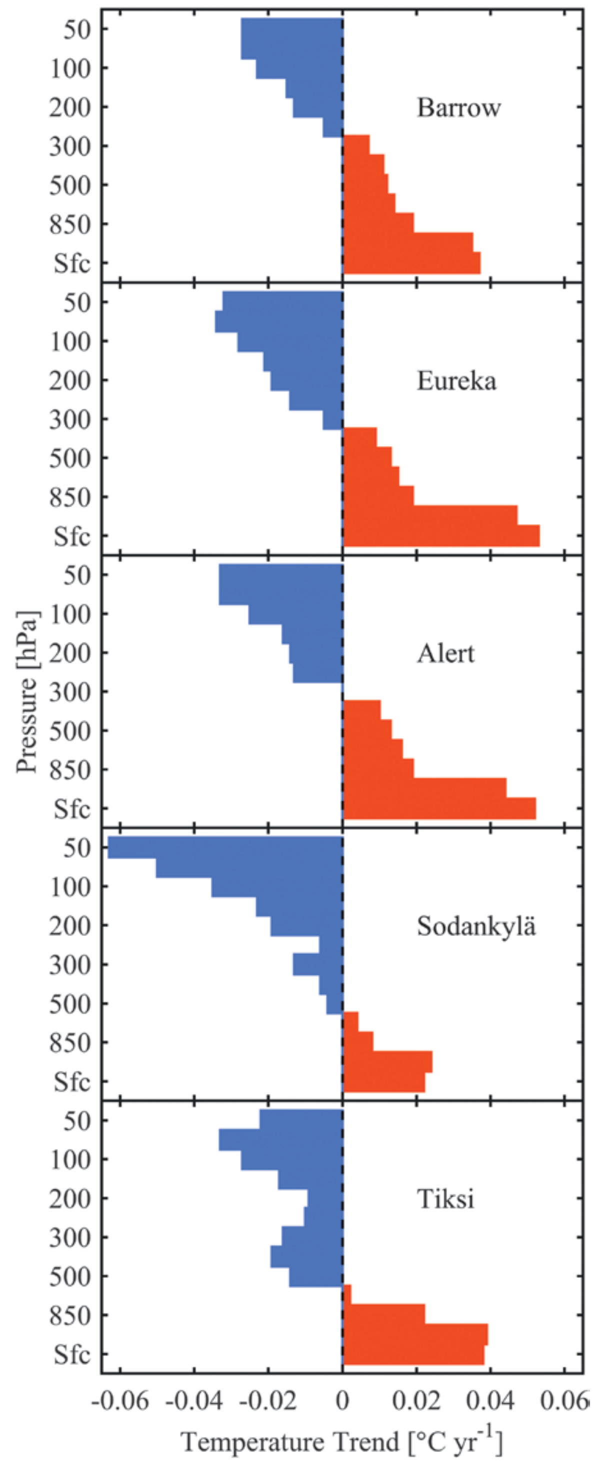

Fig. 9. Temperature trends (°C yr^{-1}) from sounding data for Barrow, Eureka, Alert, Sodankylä, and Tiksi.

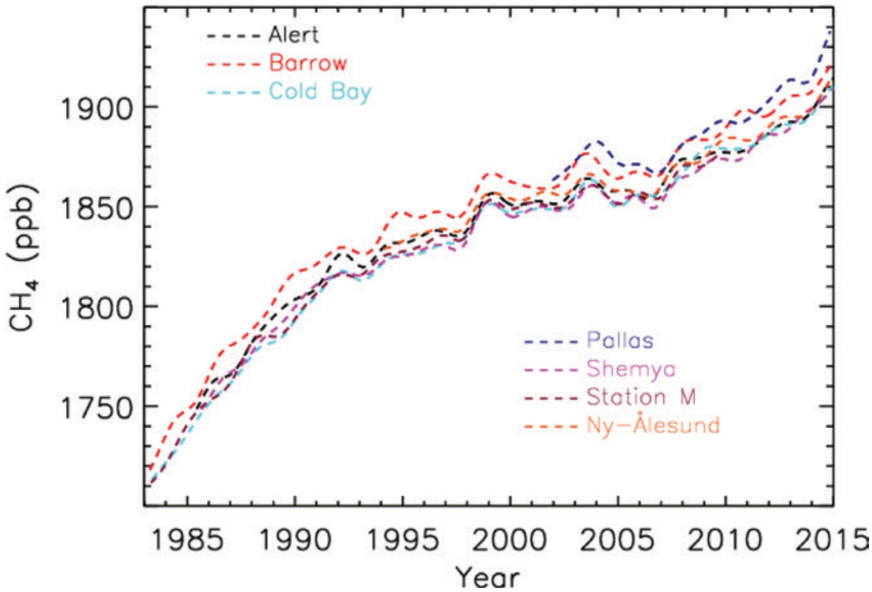

Fig. 10. Deseasonalized atmospheric CH_4 determined from weekly discrete air samples. Note that northward transport of changes in emissions at the mid- and tropical latitudes is thought to make the largest contribution to the upward trend since 2007. Observations from Cold Bay, Alaska, and Station M are not part of the IASOA network, but contribute to GAW.

being organized. Globally, CO_2 and CH_4 are responsible for 82% of increased direct radiative forcing since 1750 by long-lived greenhouse gases (Hofmann et al. 2006). Increased radiative forcing by CO_2 has been measured at two Northern Hemisphere sites and found to be consistent with radiative transfer models (Feldman et al. 2015). Natural emissions of these gases are of particular interest in the Arctic where there are large vulnerable reservoirs of carbon in the soil and possibly clathrates that can be released into the atmosphere as CO_2 and CH_4 by thawing and decomposition, potentially acting as a positive feedback on global climate. Atmospheric CH_4, CO_2, and their stable isotopic composition are measured at seven of the IASOA observatories (Alert, Ny-Ålesund, Summit, Tiksi, Barrow, Cherskii, and Pallas). After a hiatus in growth of its atmospheric burden from 1999 to 2006 (Fig. 10), CH_4 began increasing in 2007 (Dlugokencky et al. 2009). Renewed growth in globally averaged CH_4 since 2007 is attributed to a combination of increased tropical natural emissions and emissions from fossil fuel production, agriculture, and waste (Bruhwiler et al. 2014; Bergamaschi et al. 2013). The increase in annual mean from 2013 to 2014 for CH_4 zonally averaged over 53°–90°N was 11.9 ± 2.0 ppb, which is comparable to the global CH_4 increase (9.4 ± 1.4 ppb). Although interannual variability in Arctic emissions are captured in the Arctic observations, large sustained increases in Arctic CH_4 emissions have not been observed.

For CH_4, changes in Arctic CH_4 emissions can be detected with good sensitivity by looking at the difference between zonal averages for high latitudes (northern minus southern). The measurements at IASOA sites constrain estimates of emissions over large scales made with inverse models. The smoothed decadal trends show consistent concentrations across sites, with small differences (e.g., Pallas) accounted for by latitudinal gradients and local emissions sources. The current distribution of sites is adequate for determining the large-scale Arctic-wide changes in emissions of CH_4, but significantly greater density of quasi-continuous measurements is necessary to better understand the processes responsible for emissions and how they are affected by changing climate. A valuable feature of the IASOA observatories is the intensive and sustained process observations (e.g., turbulent fluxes), at many sites collocated with cryospheric and ecosystem studies. Combining continuous CH_4 surface measurements with flux measurements and ecosystem characterization will improve our understanding of the Arctic ecosystem response to the changing climate (Christensen 2014).

Tropospheric ozone, and particularly its regionally diverse interactions with the Arctic ecosystem, make it another trace gas of interest for IASOA science. For example, surface ozone depletion events were first observed at Alert (Barrie et al. 1988; Bottenheim et al. 1990) and Barrow (Oltmans et al. 1989) and were linked to atmospheric halogen chemistry (bromine) processes. Recent research (Oltmans et al. 2012) indicates that the ozone depletion events are related to increased open-ocean area as the Arctic icepack retreats; the resulting open ocean provides a source for the ozone-destroying halogens. A side product of this reaction of particular concern is the conversion of mercury from a nonreactive to a toxic reactive form that precipitates into the terrestrial and ocean systems; ozone measurements are thus important as an indicator of mercury chemistry. Surface ozone measurements are made at five of the IASOA observatories (Alert, Barrow, Pallas and Sodankylä, Summit, and Tiksi). Comparisons between Barrow and Tiksi relate the timing of the ozone depletion events to a combination of offshore and onshore air flows and the timing of the sea ice retreat (Patrick et al. 2012). Figure 11 shows a comparison of the monthly averages of ozone at Barrow, Alert, Tiksi, and Summit for 2011. The maximum variability and lowest ozone occurs in Barrow in March–April; for Tiksi and Alert, the ozone depletion period is shifted forward into April–May. Summit, which is a noncoastal site, has generally higher ozone values year-round (40–60 ppb as opposed to 5–50 ppb) than the other three sites; this is an expected result as Summit is the farthest removed from local open-water bromine sources.

Cloud Working Group. Characterization and improved process understanding of Arctic clouds has been identified as an important focal area; a Cloud Working Group to address this area is currently being organized. In recent years, significant advancement has been made in understanding Arctic mixed-phase clouds, cloud–radiation–turbulence interactions, and the influence of aerosol–cloud–radiation interactions on the surface energy budgets (Shupe et al. 2013; Morrison et al. 2012; Vavrus 2004; Verlinde et al. 2007; Cox et al. 2015); however, the topic is complex and significant challenges remain. The radars, lidars, and radiometers at four of the IASOA observatories (Barrow, Oliktok Point, Eureka, and Summit) are powerful tools for determining cloud properties and for obtaining process measurements that are helpful in improving our understanding of Arctic cloud life cycles. For instance, multisensor analysis can be used to develop detailed cloud and precipitation masks (Fig. 12); these can then be used to provide information not only on cloud heights and temporal occurrence, but also the partitioning of liquid and ice within mixed-phase clouds (Fig. 13). This partitioning

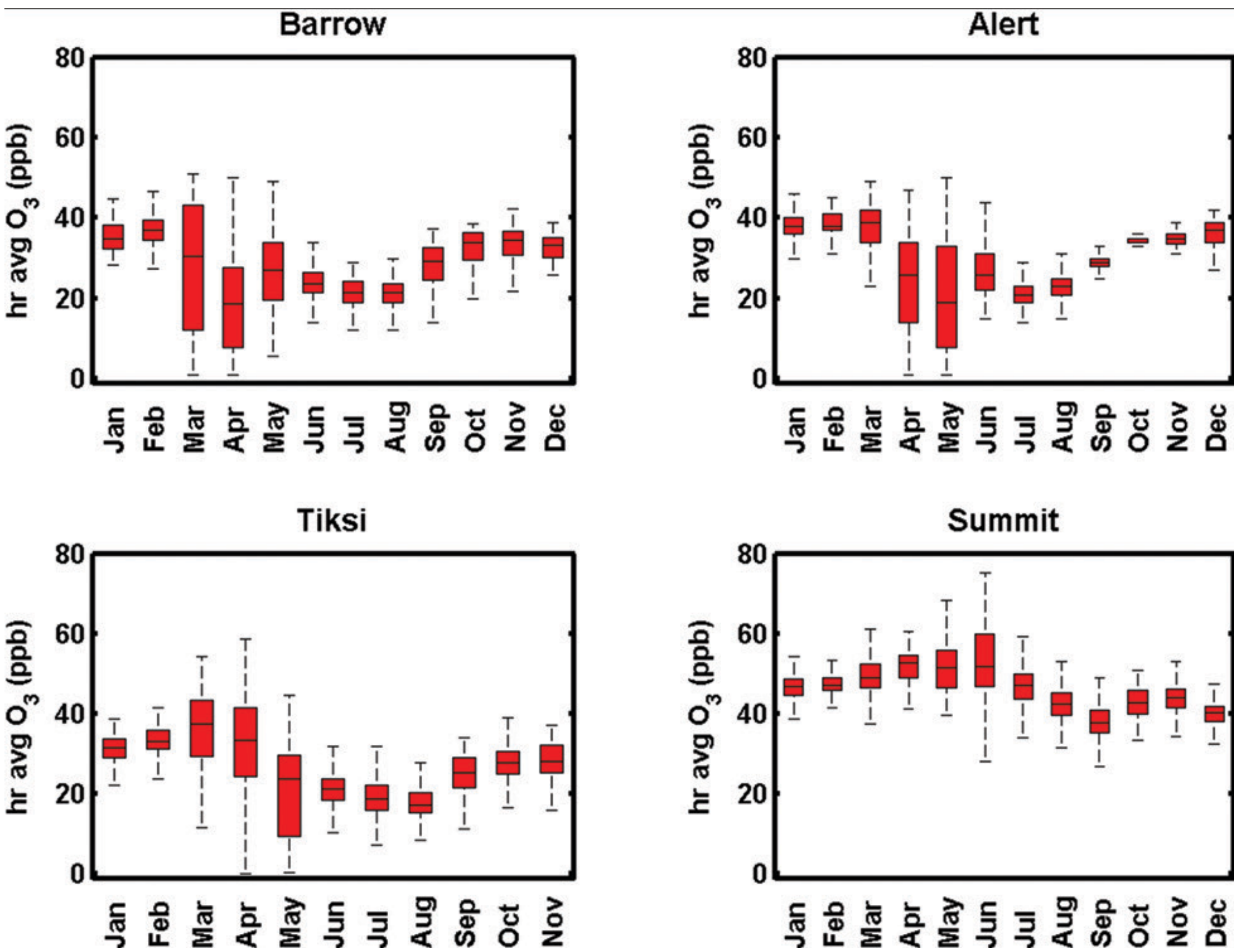

Fig. 11. Monthly averages and variability of the surface ozone detected with in situ samplers at Barrow, Alert, Tiksi, and Summit during 2011.

has been demonstrated to play a critical role in the duration of mixed-phase cloud lifetime, as ice precipitation intensity acts as a sink for moisture within the cloud layer (Morrison et al. 2012). This information, along with collocated measurements of surface radiative flux and atmospheric thermodynamics, is critical for quantifying the influence of clouds on the Arctic surface energy budget (Zuidema et al. 2005; Shupe and Intrieri 2004; Curry and Ebert 1992; Intrieri et al. 2002; Dong et al. 2010; Miller et al. 2015).

For climate models and global reanalyses where a single parameterization must meet the needs of a variety of sites, the pan-Arctic nature of the IASOA observatories offers a true test that extends beyond the measurements from any one site. Therefore, a major challenge for the IASOA Cloud Working Group will be providing the information required for the development of cloud microphysical parameterizations that are representative of the entire Arctic region (Vihma et al. 2014).

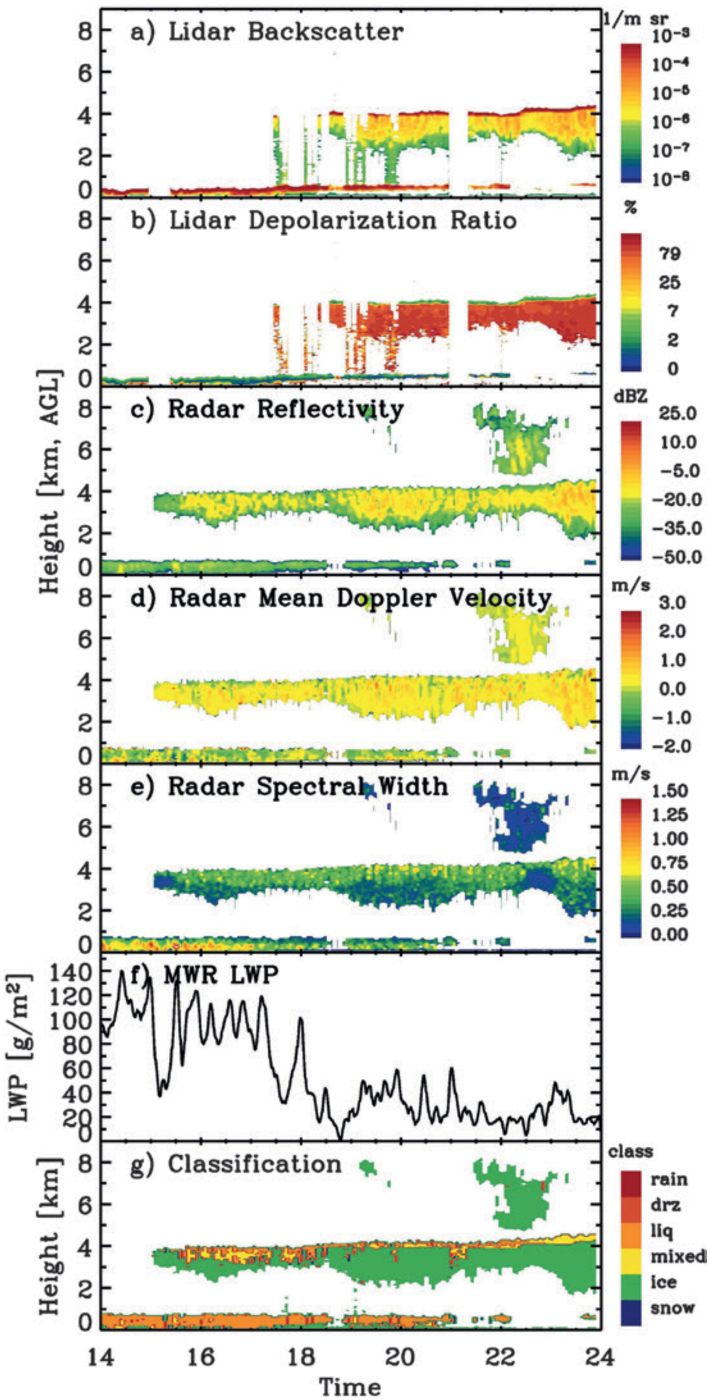

Fig. 12. (a)–(f) Examples of combining data from vertically pointing active and passive remote sensors to create a cloud and (g) precipitation classification mask for a 24 h × 8 km time–height cross section on 10 Sep 2006 at Eureka. [Adapted from Shupe (2011).]

NEXT FOR IASOA. IASOA moves forward into the future based upon several integrating approaches. The first is the geographical expansion of several globally coordinated, standardized networks of observational data that are focused on a specific aspect of the atmosphere through programs supported by the World Weather Watch and similar global networking programs. Within this context, the IASOA observatories can be considered to be *a regionally specific network of networks with a self-given charge to expand global observations northward* (AON 2010). Second, the IASOA consortium is promoting coordinated investments in value-added, often high-technology, observational capacities that can advance our understanding of not just how the Arctic system is changing but also why the system is changing *by collecting data sufficient for determining processes*. This is especially important in the changing Arctic environment where the physical processes of interest may not be static (Jeffries et al. 2013); a recent term that summarizes this concept is that of "emergent processes," which appear to be resulting from the increasing nonlinearity of the Arctic system. Third, it is recognized that the Arctic region requires *continuous, multidecadal measurement programs* in anticipation of both semirandom events (such as ozone depletions) and emerging trends (such as changes in cloudiness) since it is impossible to go back in time to collect observations that were not made and, which in hindsight, may be critical. This may be particularly important in planning for the mitigation of extreme events such as volcanic eruptions, sudden upticks in methane release, or man-made disasters such as oil spills. Finally, the IASOA consortium acknowledges that there is a growing need in the increasingly busy Arctic for *use-inspired science that feeds into services* to support transportation, safety, energy development, environmental stewardship, and anticipation/mitigation of the impacts of climate change on resident Arctic communities and global weather. A future emphasis on services will require identification and prioritization of the measurements needed, not only from a scientific, but also from a stakeholders' point of view (Murray et al. 2012).

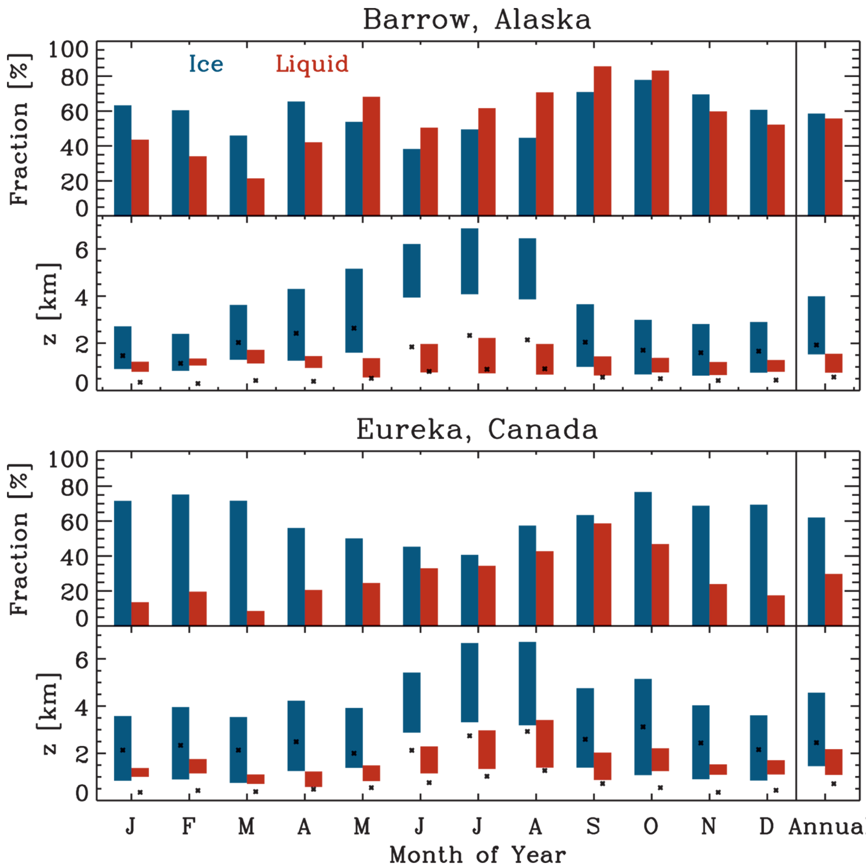

Fig. 13. (top) Monthly mean occurrence fraction and (bottom) cloud boundary statistics for cloud ice (blue) and cloud liquid (red) layers for Barrow and Eureka. Bottom panels show low base height (bottom of bar), high top height (top of bar), and total thickness (symbol). Annual mean values are provided on the far right side. [Adapted from Shupe (2011).]

Data that were collected during the first IPY in 1882–83 by a similar meteorological network were not analyzed for over 122 years (Wood and Overland 2006). The IASOA consortium has mobilized in response to the lesson learned from this history. Although recent data availability is beginning to result in multiobservatory analyses (e.g., Eckhardt et al. 2015; Berchet et al. 2015; Stone et al. 2014) that were not coordinated by IASOA, it cannot be assumed that full utilization of the networked observatory data will happen spontaneously. It is for this reason that one decade after its inception, IASOA is supporting a pan-Arctic, international collaboration that is furthering a network-based science approach to understanding the Arctic atmosphere system.

In addition to studies that focus on a particular aspect of the Arctic atmosphere, there is an ambitious intention of eventually integrating between the traditional atmospheric discipline boundaries of aerosols, radiation, atmosphere–surface exchanges, regional processes, trace gases, and clouds to create a system-science understanding of the Arctic atmosphere (Fig. 14).

Furthermore, although IASOA observations and science are conducted largely within the circumscribed boundaries of the Arctic atmosphere, the IASOA constituency is keenly aware of the tremendous opportunities and potential of an even more holistic Arctic system-science picture that involves interacting with colleagues from the cryospheric, terrestrial, and oceanographic communities. Collaborative opportunities are being discovered and built between IASOA and organizations such as the World Meteorological Organization's (WMO) Global Cryosphere Watch (GCW; globalcryospherewatch.org) and the European Union (EU)-led International Network for Terrestrial Research and Monitoring in the Arctic (INTERACT; www.eu-interact.org). Given the current Arctic research focus on the state and fate of Arctic Ocean sea ice, IASOA research efforts must certainly be coordinated in the future to address the coupled atmosphere–ocean system, specifically investigating the role of atmospheric forcing on interannual sea ice variability and predictability

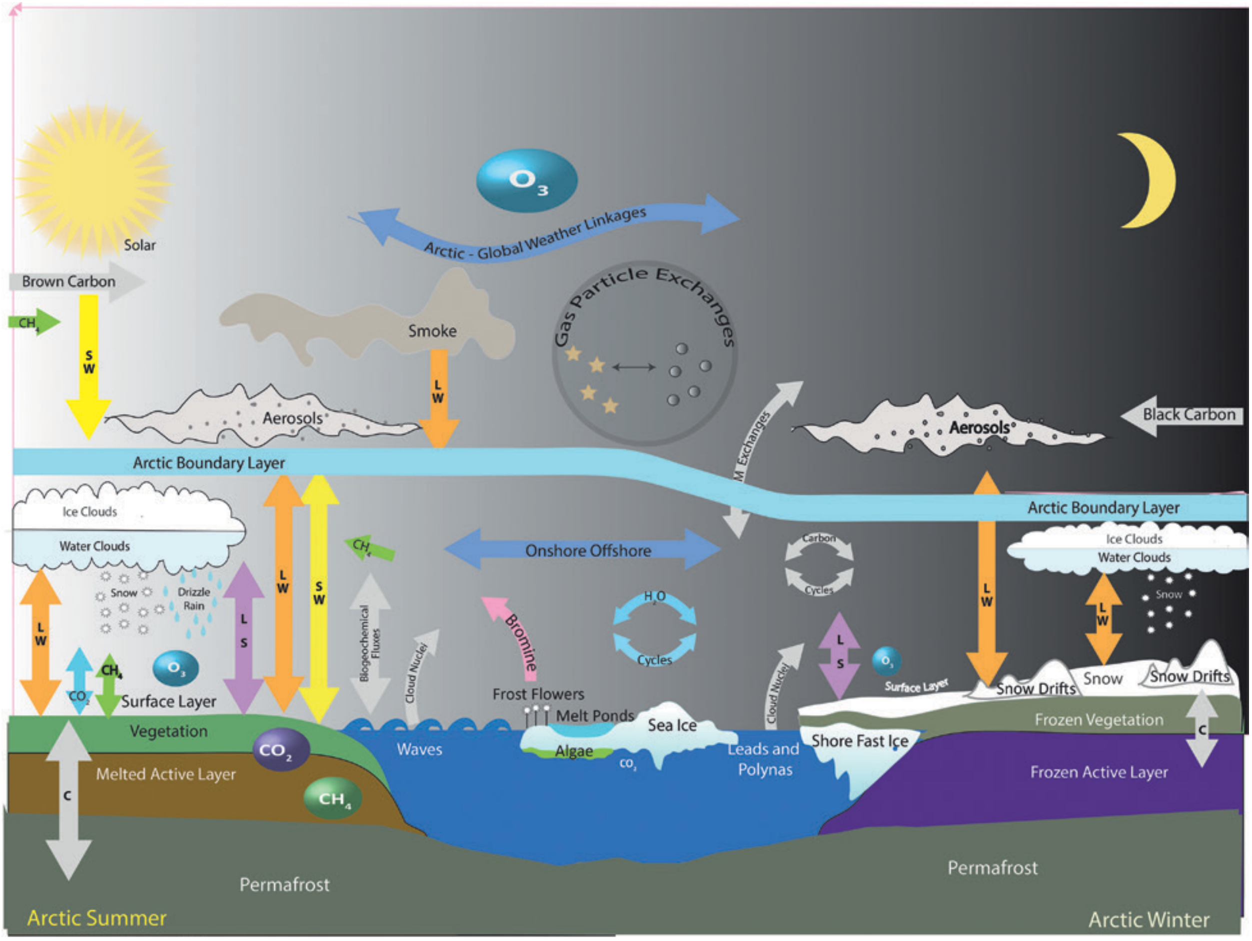

Fig. 14. Schematic of parameters and processes that are measured at the IASOA observatories (in the atmospheric regions over land) and/or impacted by or have impacts on the atmosphere (over ocean regions). The figure represents Arctic "day" elements on the left and Arctic "night" elements on the right. "SW" = shortwave radiation, "LW" = LW radiation, "C" = soil fluxes, and "L S" = latent and sensible heat fluxes.

(e.g., Makshtas et al. 2012; Nedashkovsky et al. 2009; Semiletov et al. 2004). Within this context, IASOA provides a linkage between land and ocean processes by providing a picket fence of measurements around the Arctic Ocean.

Finally, because IASOA is designed to scale up Arctic perspectives in many ways—single types of measurements between stations (e.g., Fig. 11), multiple coordinated atmospheric measurements at a single station (e.g., Fig. 8), variability between Arctic subregions, and atmospheric linkages with other components of the Arctic system—the IASOA consortium is also particularly well positioned to contribute to campaign programs such as the Pan Eurasian Experiment (PEEX; www.atm.helsinki.fi/peex) and the Year of Polar Prediction (YOPP).

The IASOA collaboration is built upon voluntary in-kind contributions of the many institutions and organizations investing in Arctic atmospheric observations and the efforts of scores of Arctic researchers that result from annual expenditures of many millions of dollars, euros, rubles, and kroner, as well as contributions from many non-Arctic countries. These expenditures are significantly leveraged by a relatively small investment (currently made by the U.S. National Oceanic and Atmospheric Administration and in the past by the U.S. National Science Foundation) to support an implementation scientist to manage development of the data portal and facilitation of the working groups (Starkweather and Uttal 2016) as well as continued development of the IASOA website (www.iasoa.org).

In concluding this article, special note must be made of the operators that live and work at the IASOA observatories in the frequently dark, freezing, and hazardous conditions for assignment periods that vary from days to decades. Without this small and dedicated group of individuals the measurement programs would be unsustainable. It is to their credit that each of the trillions of data points they have collected may now contribute to a critical understanding of Arctic mysteries that are of consequence for the entire planet. The resulting heritage of information increases in significance as data collection efforts are expanded, sustained, and utilized by a world in which the Arctic is emerging politically, economically, and climatologically as an increasingly significant player.

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