Circum-polar Arctic Flux Workshop Report

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Overview

Detailed observations of energetic, hydrological and chemical fluxes at the surface-atmosphere interface are necessary to understand and model coupling within the Arctic climate system. Global and regional models may represent Arctic state variables with relative accuracy, but it has been observed that they consistently fail to represent the observed magnitude and direction of energetic fluxes within the Arctic system (Jones, 2014; Aas et al, in press). Some results of this failure are highly uncertain projections about the future state of the Arctic cryosphere and biosphere (McGuire et al., 2013) and high uncertainty about the fate of cryospheric carbon in the global atmosphere (McGuire et al., 2012; Belshe et al., 2013; Christensen, 2014; Hayes et al. 2014).

To address these poorly constrained processes, coupling between the Arctic atmosphere, land surface and subsurface must be evaluated as an integrated system of energy, moisture and chemical exchange – each with unique observational challenges and process complexities in extreme Arctic environments. For example, closing the terms of the surface energy balance (SEB) requires sustained, high quality observations of key physical parameters (radiation, turbulence, and storage), which are hampered by frost accumulation on sensors and instrument detection limits at extreme low temperatures. In-situ observations of moisture, carbon and other trace gas fluxes in the Arctic are equally challenging and must consider cold-shifted calibrations and conditions unique to frozen ground and permafrost soils (e.g. calibration of soil moisture sensors in permafrost soils). Interpreting seasonal and inter-annual variability in all of these terms requires well-characterized land surface and subsurface properties and processes, including for example, vegetation description, soil carbon quantity and quality, permafrost depth and temperature, and active layer depth interpretation; these require a geographically extensive pan-Arctic approach to sample the vast diversity of landscapes and regional atmospheric forcing regimes. The ability to up-scale surface-based in situ observations enables data to be comparable with global gridded data products, including from satellites, reanalyses, and climate models, but up-scaling requires that representative Arctic landscapes are sampled. Up-scaling is a shared problem across communities and developing common approaches will foster critically needed mutually beneficial information exchange between disparate scientific communities, and is thus of paramount importance.

A host of initiatives, organizations and disciplines share an interest in these topics, yet no one organization has the expertise or mandate to tackle the integrated, pan-Arctic challenge. In recognition of this, it has been proposed to develop an International Arctic Science Committee (IASC) cross-cutting initiative (Atmosphere-Terrestrial-Cryosphere) to bring together the expertise and resources of IASC member science communities. A series of formal and informal discussions[1] and previous terrestrial flux workshops[2] have identified the following topics where progress could be made, based around three themes:

1. **Representativeness:** Why are bottom up and top down estimates of Arctic carbon so different? Are long-term *in-situ* surface energy budgets sites representative of Arctic landscapes?
2. **Flux Synthesis:** What are the environmental variables influencing the Arctic carbon sink strength? What are the key components of the energy balance seasonally and interannually?
3. **Flux Challenges:** What are the challenges in making accurate flux measurements in the arctic?

Below, we discuss each of these issues in terms of how they were presented and discussed at the workshop. We also identify a path forward in terms moving forward on understanding these topics.

<u>Representativeness</u>

An estimated 1700 PgC are frozen in permafrost soils of the Arctic, and current understanding suggests that ~130-160 PgC, primarily as CO_2 could be released over the next century (Schuur et al., 2015). Release of carbon from permafrost is likely to be gradual and occur on century timescales (Schuur et al., 2015). On an annual basis, if this amount of carbon were released at a constant rate, emissions would be far lower than annual fossil fuel emissions (~9 $PgCyr^{-1}$), but comparable to land use change (0.9 PgCyr). However, any strategies to mitigate emissions will need to account for release of carbon from Arctic soils.

Warming of current Arctic terrestrial ecosystems can also be expected to lead to changes in the exchange of greenhouse gases between current terrestrial ecosystems and the atmosphere. For example, northward expansion of woody plants can change carbon storage while also influencing surface energy and moisture budgets. Warming wetlands may lead to increased emissions of CH_4 (e.g.,

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[1] International Arctic Systems for Observing the Atmosphere (IASOA) hosted a brownbag at AGU 2013 Fall meeting; IASOA Atmosphere-surface working group convenes every 6 weeks in an open meeting to make progress on these topics.

[2] Two workshops hosted for a group of ~15 national and international participants in Edmonton in 2009 and Woods Hole in 2008, sponsored by the NSF Arctic Observatory Network (AON) project 'Collaborative Research on Carbon, Water, and Energy Balance of the Arctic Landscape at Flagship Observatories in Alaska and Siberia'

Helbig et al., 2016a). It is important to be able to detect changes in Arctic greenhouse gas emissions, however it is not clear that current observing networks are sensitive enough to detect changes.

Carbon emissions in the Arctic are quantified using two approaches; the “top-down” and “bottom-up” methods. For the former, atmospheric measurements are used along with simple or complex models of atmospheric transport to “invert” concentration signals into estimates of emissions. Bottom-up methods involve scaling trace gas flux measurements from eddy flux towers or flux chambers at multiple sites to Arctic-wide scales. At present, there are inconsistencies between the bottom-up and top-down views of Arctic trace gas fluxes with bottom-up estimates exceeding top-estimates by factors of 2 or 3 for CH_4. Disagreement between top-down and bottom-up approaches indicates an incomplete understanding of the Arctic budget of trace species, and it is therefore worthwhile to understand why the approaches differ.

A key question is whether our flux and concentration observations are representative of Arctic-wide ecosystems. For example, flux observations of CH_4 may be preferentially made in productive locations. Atmospheric concentration measurements may measure well-mixed “background” air far from the sources, thereby obtaining diluted information about the sources of interest. One recommendation is to follow the approach of used in other regions to evaluate the effectiveness of eddy flux networks (e.g. Alaska, Hoffman et al, 2016; Global, Kumar et al., 2016). A tandem approach is also needed for assessing the representativeness of sustained and detailed energy budget estimates across the Arctic, particularly as concerns areas that have experienced relatively high changes in annual snow cover (e.g. Barrow, AK and Ny Alesund, NO) and its subsequent impacts on the net radiation balance and local hydrological conditions. Both the background landscape state and trends in annual snow cover must be well-characterized in order to understand how trends in point measurements of surface energy balance relate to broader signals of Arctic change like rising air temperatures or changes in cloud cover.

An issue closely related to representativeness is how bottom-up information is scaled to represent the entire Arctic, a difficult task. A possible way forward is to combine flux observations with remotely sensed distributions of ecosystems in order to apply site-specific flux information to potentially similar regions where no flux observations exist. A logical first step will be to compile the numerous flux observations collected by various institutions throughout the Arctic. Scaled-up flux observations could then be tested against atmospheric concentration network observations using atmospheric transport models.

Advancements are also needed for top-down approaches. The atmospheric concentration network may not have sufficient spatial density to detect small changes in greenhouse gas emissions, and this should be evaluated using synthetic data experiments. Because of variability in atmospheric transport and inter-annual variability in emissions due to temperature and moisture variability, long time series are essential to detect small trends. Improvements in atmospheric transport models are needed so that concentration measurements are accurately simulated, and the influence of transport from lower latitude sources is well represented.

Flux Syntheses

Long-term net CO_2, CH_4, and energy fluxes at sub-hourly resolution have been measured in the Arctic since the 1990s with the eddy covariance technique providing an important opportunity to explore ecosystem functioning in the Arctic across time-scales from hours to years. The eddy covariance technique requires high-frequency (e.g., 10 Hz) measurements of vertical wind velocity and a scalar of interest (e.g., CO_2 concentrations) to derive vertical net scalar fluxes. Recent developments in CO_2/H_2O and CH_4 gas analyzers and in heated sonic anemometers have improved the performance of high-latitude flux measurements, now allowing long-term, quasi-continuous measurements of turbulent fluxes of energy, H_2O, CO_2, and CH_4 at remote field sites – even with limited power supply (Goodrich *et al.*, 2016; Helbig *et al.*, 2016b). The increasing coverage of flux tower sites across different Arctic ecosystem types bears great potential to better constrain and understand circum-arctic variability in land surface-atmosphere fluxes. In contrast to analysing large-scale integrated flux signals from inversion modelling approaches, spatially-distributed, ecosystem-specific flux measurements can inform us about the local driving mechanisms behind climate sensitivities of net CO_2, CH_4, and energy fluxes (Jung *et al.*, 2017), provide essential information for upscaling ecosystem fluxes to regional and global scales (e.g., Zscheischler *et al.*, 2016), and are used for the evaluation of terrestrial ecosystem models (e.g., Xia *et al.*, 2017)

Flux data from Arctic tower sites are made available through various global and regional flux tower networks, including FLUXNET, AmeriFlux, AsiaFlux, KrasFlux, and the European Flux Database Cluster. Different flux processing procedures and protocols used in these networks result in heterogeneous data structures and organizations. Synthesizing flux observations from readily available datasets requires therefore careful quality control and data harmonization. For example, time series of eddy covariance flux data are usually not complete and larger gaps are typical for northern flux tower sites due to limited power supply and adverse weather conditions (e.g., Goodrich *et al.*, 2016). Reliable and comparable gap-filling methods are therefore required to allow comparisons of long-term CO_2, H_2O, and CH_4 budgets across the multiple flux tower sites (Falge *et al.*, 2001). GOLD files are available for operators to compare their processing software with a standard analysis based on a fixed raw data set. To assist in standardizing data processing, it may be valuable to develop specific Arctic GOLD files based on our "best" Arctic site.

Harmonizing and synthesizing existing flux tower observations from across the Arctic is thus an important first step to improve our understanding of Arctic ecosystem responses to climate change. We identified a number of avenues of possible synthesis, while also noting other ongoing synthesis activities across research groups. We also discussed current datasets that are available for use in synthesis, including those from the European PAGE21 project, as well as those maintained by individual investigators from various sites across Russia, Canada, and Alaska. We also noted that in addition to the terrestrial flux datasets, there is a growing number of flux datasets in both marine and lake environments, which may be interesting to consider as well. We discussed the importance of considering vegetation type and permafrost type within the synthesis and noting how the availability of data corresponds to the representativeness issue described above.

Best Practices

The number of micrometeorological stations in the Arctic sites is a small fraction of the global observational network, but likely to be expanded given the growing scientific interest in the characterization of the greenhouse and energy budget of the Arctic region and its feedback on the global climate system.

Several efforts towards a standardization of the measurements and data processing protocols have been made by the communities of biogeochemists and geophysicists in the last decade through international initiatives and projects such as FLUXNET, ICOS, NEON, etc. Trace gas flux and meteorological measurements in the harsh Arctic conditions have nevertheless specific technical problems, not shared with the generality of other sites worldwide, which need to be addressed in order to allow the inter-comparability of data among the arctic flux network and improve the quality of the flux/meteorological products .

Currently the most relevant and common technical issues include:

i. Ice build-up on sensors. Icing and riming of meteorological instrumentation is a common problem in the Arctic, where temperatures at or below freezing in combination with a sufficiently high atmospheric moisture content are frequently observed. This effect can introduce systematic bias into data from both anemometers and gas analyzers, and thus reduce eddy-covariance data quality. Active heating of affected instrumentation can avoid or at least minimize such effects, but in turn introduce a bias to the observations. Recent research (Kittler et al., 2017) has demonstrated that active heating at sonic anemometers modifies measurements of temperature and sensible heat, but otherwise has little to no effect on flux observations, except at times where heating is switched on or off, respectively. Carbon fluxes were only affected indirectly when applying a density correction for open-path gas analyzers, while closed path measurements remained unchanged. These findings suggest that a frequent (up to continuous) activation of sensor heating may improve the overall quality of carbon flux measurements in the Arctic, but more research will be needed to refine these results.

ii. Data quality flagging protocol. The reliability of flux measurements in the Arctic, particularly at remote and poorly maintained sites, could be strengthened by extending standardized quality assessment protocols for eddy-covariance observations. Additional quality flags could e.g. be introduced to take into account operational limits of instrumentation (e.g. minimum temperatures), activated sensor heating, vertical decoupling between surface and sensor position during very stable stratification in Arctic winter, and so on. Flagging and filtering of disturbed measurements, coupled to a subsequent gap-filling routine, can systematically shift the observed long-term carbon budgets.

iii. Off-grid power supply. Provision of sufficient and stable power supply at remote sites is fundamental to gaps in the flux data, and allow the extension of measurements off-season. However, many of the options commonly used in temperate regions, e.g. solar panels and wind turbines in combination with a battery pack, are highly challenging to implement under Arctic climate conditions because of low light levels in winter, ice-buildup and extremely low temperatures. Alternative options such as fuel cells are also hampered by the harsh climatic conditions, and high costs. It would thus be beneficial for the flux community to collect information on successful implementations of off-grid power supplies (e.g. the AON sites at Imnavait Creek), and thus build up an expertise pool that helps stabilizing power supply also at other sites, including newly implemented ones.

iv. Instrument self-heating. Licor 7500 open-path gas analyzers are popular instruments among the Arctic flux community due to their robustness and low power demand. However, these instruments were found to be affected by heat fluxes emitted from the instrument itself (so-called self-heating effects), causing biased readings of CO_2 molar densities, and ultimately translating into systematic errors in the computed greenhouse gas fluxes. Previous studies (Burba et al., 2008) have devised a correction algorithm for this effect, but its application remains controversial since it is subject to high uncertainties, and tends to overcorrect fluxes. This overcorrection is likely to be associated with the fact that open-path gas analyzers are commonly mounted in inclined positions, so that the heat emitted from the sensor body only affects a small fraction of the measurement path (e.g. Jarvi et al., 2009). Moreover, wind directional effects may change the heat contamination, and it is still under discussion whether this effect is only relevant at cold seasons (e.g. Kittler et al., 2017).

Beyond technical and logistical difficulties there are other challenges, some of more general type others emerging recently, which should be addressed:

i. Representativeness of point measurements (soil temperature, heat flux sensors, albedometers) in often highly heterogeneous flux footprints.

ii. The intermittent nature of methane fluxes (e.g. Schaller et al., 2017) may not be adequately captured by methods based on time averaging of the signals over longer periods assuming stationary conditions such as eddy covariance. As a consequence, pronounced ‘flux outbursts’ that are frequently observed at Arctic observation sites during nighttime may be either removed from the dataset as spikes, or be processed with an incorrect Reynolds decomposition and therefore yielding biased flux values. To adequately address this issue, more information will be needed on where and when these effects can be observed, and what are the mechanisms behind them. Neglect of this problem may exclude a significant portion of emission fluxes from time series of methane fluxes, and thus lead to systematically biased long-term flux budgets.

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