ANNUAL AND LATITUDINAL VARIATIONS OF ENERGY FLUXES AND SURFACE ENERGY BUDGET AT TWO ARCTIC TERRESTRIAL SITES

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Keywords: Arctic, Carbon dioxide, Radiative fluxes, Surface energy budget, Turbulent fluxes.

INTRODUCTION

The Arctic region is experiencing unprecedented changes associated with increasing average temperatures (faster than the pace of the globally-averaged increase) and significant decreases in both the areal extent and thickness of the Arctic pack ice. Observational evidence suggests that atmospheric energy fluxes are a major contributor to the decrease of the Arctic pack ice, seasonal land snow cover and the warming of the surrounding land areas and permafrost layers (e.g., Stone *et al*., 2002; Persson, 2012). In this cross-disciplinary synthesis study, multi-year measurements of hourly averaged surface fluxes (turbulent, radiative, and soil ground heat), surface meteorology, and basic surface/snow/permafrost parameters made at near-coastal climate observatories located around the Arctic Ocean are used to examine the annual cycle of the fluxes and its coupling to atmospheric and surface processes. The unique turbulent fluxes collected at Eureka (Canadian territory of Nunavut) and Tiksi (Russia, East Siberia) located at two quite different latitudes (80.0°N and 71.6°N respectively) are analysed. Turbulent fluxes and mean meteorological data are measured continuously and reported hourly at various levels on 10-m (Eureka) and 20-m (Tiksi) flux towers. Tower-based eddy covariance and solar radiation measurements provide a long-term near continuous temporal record of hourly average mass and energy fluxes respectively. We compare annual cycles of the surface fluxes including solar radiation and other ancillary data to describe the seasons in the Arctic.

OBSERVED VARIATIONS OF SURFACE FLUXES AND SURFACE METEOROLOGY

We first analysed diurnal and annual cycles of basic meteorological parameters and the surface fluxes at Eureka and Tiksi. The primary driver of latitudinal and seasonal variations in temperature and other parameters is the seasonally varying pattern of incident sunlight. The solar radiation at the 'top' of the atmosphere is determined by well-known orbital parameters being a function of latitude and time of year. The higher latitudes (e.g., Eureka) generally receive the least cumulative amount of net solar radiation than lower latitudes (e.g., Tiksi) over the entire year. However, because of the combined effects of day length and solar zenith angle, Eureka receives more the incoming solar radiation than Tiksi in the middle of Arctic summer. In other words, annual mean of the incoming solar radiation is larger at Tiksi whereas a daily mean in midsummer is larger at Eureka.

According to our data, the annual course of the surface meteorology and the surface fluxes at Eureka and Tiksi are qualitatively very similar. The air and soil temperatures display the familiar strong seasonal trend with maximum of measured temperatures in midsummer and minimum during winter. During the dark Polar nights and cold seasons, when the ground is covered with snow and air temperatures are sufficiently below freezing, the near-surface environment is generally stably stratified and the hourly averaged turbulent fluxes are quite small and mostly irregular (on average small downward sensible heat flux but upward latent heat and carbon dioxide fluxes). However the magnitude of the turbulent fluxes increases rapidly when the air temperatures rise above freezing during spring melt and eventually reaches a summer maximum. Throughout the summer months strong upward sensible and latent heat fluxes and downward carbon dioxide (uptake by the surface) are observed indicating unstable (convective) stratification on average.

The latitudinal differences in the variations of the incoming short-wave and net radiation lead to temporal and spatial differences in the structure of the atmospheric boundary layer and the uppermost ground layer observed at the Arctic terrestrial sites, namely:

(i) A length of the warm season ("Arctic summer") is obviously shorter at Eureka than at Tiksi because the higher latitudes generally receive the least cumulative amount of net solar radiation over the entire year (annual mean) than lower latitudes.

(ii) Amplitude of the hourly averaged surface fluxes near solar noon is generally less in Eureka than in Tiksi, because the turbulent fluxes are highly correlated with the solar radiation. In Tiksi the sun would rise higher in the sky at local noon on the summer than in Eureka and, therefore, the middle-summer amplitude (values near solar noon) in the incoming 1-hr solar radiation is generally less at Eureka than at Tiksi.

(iii) In this study we also linked the total daily amount of the incoming solar radiation throughout the summer months with the active layer thickness (ALT) and the topsoil temperature observed at the peak of summer. Our study shows that on average the active layer (or thaw line) is about twice deeper and topsoil temperatures in midsummer are about 10°C higher for the sites located at latitudes around 80°N (Canadian Archipelago and Svalbard) than at around 70°N (Alaska and Siberia). Although the behaviour of the solar radiation in summer months qualitatively explains the observed ALT and the topsoil temperatures at these sites, further observations at other sites and numerical or analytical modelling are needed.

(iv) According to our observations, convective surface layer (CBL) in Eureka can reach long-lived quasi-stationary states for about one month centered on the summer solstice. Such long-lived CBL are not observed at Tiksi, although Tiksi is also located within the Arctic Circle where there is 24 hours of continuous daylight in summer. This is because the "nighttime" summer insolation in Tiksi is generally not large enough to overcome the longwave radiative cooling. Longwave radiation from clouds modulates this effect as well at both sites, often being the cause for nocturnal stabilization at Eureka and nocturnal destabilization at Tiksi. The longwave radiation provides the minimum threshold value for the net nighttime solar radiation needed to produce long-lived CBL in the Arctic.

Another marked difference between the two sites is a well pronounced zero-curtain effect observed in Tiksi at fall. The fall zero-curtain effect is associated with the phase transition of water to ice in wetter or/and water saturated soils. It can be assumed, that soils in Eureka are drier than in Tiksi. This fact can also explain the different behavior of the ground heat flux observed in Eureka and in Tiksi.

An accurate determination of energy balance closure and all components of the surface energy budget (SEB) at the air-surface interface are required in a wide variety of applications including atmosphere-land/snow simulations and validation of the surface fluxes predicted by numerical models over different spatial and temporal scales. Surface energy balance closure is a formulation of the conservation of energy principle (the first law of thermodynamics). In other words, the SEB equation is a statement of how the net radiation (available energy flux for the atmosphere-soil system during a warm season) is balanced by turbulent sensible and latent heat fluxes plus ground (conductive) heat flux. Our direct measurements of energy balance for both Arctic sites show that the sum of the turbulent sensible and latent heat fluxes and the ground (conductive) heat flux systematically underestimate the net radiation by about 25-30%. This lack of energy balance closure is a fundamental and pervasive problem in micrometeorology (e.g., Foken, 2008; Panin and Bernhofer 2008; Leuning et al. 2012 and references therein). We discuss a variety of factors which may be responsible for the lack of SEB closure. In particular, various storage terms (e.g., air column energy storage due to radiative and/or sensible heat flux divergence, ground heat storage above the soil flux plate, energy used in photosynthesis, canopy biomass heat storage). For example, our observations show that the photosynthesis storage term is relatively small (about 1-2% of the net radiation), but about 8-12% of the imbalance magnitude. All turbulent fluxes are highly correlated with net radiation because this balance between solar and longwave radiation is the principal energy source for daytime surface warming, evaporation, and photosynthesis. We find that turbulent fluxes of carbon dioxide and sensible heat are closely linked and, on average, change sign synchronously during the diurnal and annual cycles.

CONCLUSIONS

In this study we compare annual cycles of the surface fluxes and other ancillary data to elucidate similarities and differences of the seasons including spring onset of melt and fall onset of freezing at at Eureka (Canadian Arctic Archipelago) and Tiksi (Russia, East Siberia) located at two quite different latitudes (80.0°N and 71.6°N respectively). Although Eureka and Tiksi are located on different continents and at different latitudes, the annual course of the surface meteorology and the surface fluxes are qualitatively very similar, i.e., the air and soil temperatures display a strong seasonal trend with maximum of measured temperatures in midsummer and minimum during winter. However there are noticeable differences between these locations associated primarily with the latitudinal variations.

ACKNOWLEDGEMENTS

The U.S. National Science Foundation's Office of Polar Programs supported AAG, POGP, and RSS with award ARC 11-07428. AAG, APM, and IAR were also supported by the U.S. Civilian Research & Development Foundation (CRDF) with award RUG1-2976-ST-10. APM was also supported by the Russian Foundation for Basic Research with award RFBR 14-05-00677 and CNTP Roshydrometa 1.5.3.2. During the current work EK-A is supported by the NOAA Climate Program office.

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