SURFACE FLUXES IN HIGH-LATITUDE REGIONS

Sarah Gille [1], Mark Bourassa [2], Cecilia Bitz [3], David Carlson [4], Ivana Cerovecki [5], Meghan F. Cronin [6], William M. Drennan[7], Chris Fairall [8], Ross Hoffman [9], Gudrun Magnusdottir [10], Rachel Pinker [11], Ian Renfrew [12], Mark Serreze [13], Kevin Speer [14], Lynne Talley [15], Gary Wick [16]

(1) Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, Mail Code 0230, La Jolla, CA 92093-0230 USA, Email: sgille@ucsd.edu
(2) Center for Ocean-Atmospheric Prediction Studies (COAPS), Florida State University, 2035 E. Paul Dirac Dr., 200 RM Johnson Bldg., Tallahassee, FL 32306-2840, USA, Email: bourassa@coaps.fsu.edu
(3) Atmospheric Sciences, MB 351640, University of Washington, Seattle WA 98195-1640 USA, Email: bitz@atmos.washington.edu
(4) International Polar Year 2007-2008 International Programme Office, British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK, Email: ipy.djc@gmail.com
(5) Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, Mail Code 0230, La Jolla, CA 92093-0230 USA, Email: icerovec@ucsd.edu
(6) NOAA Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115, USA, Email: *Meghan.F.Cronin@noaa.gov*
(7) RSMAS/AMP, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA, Email: wdrennan@rsmas.miami.edu
(8) NOAA/ESRL/PSD, R/PSD3, 325 Broadway, Boulder, CO 80305-3328, USA, Email: Chris.Fairall@noaa.gov
(9) Atmospheric and Environmental Research, Inc., 131 Hartwell Ave., Lexington, MA 02421-3136, USA, Email: rhoffman@aer.com
(10) University of California, Croul Hall 3321, Mail Code: 3100, Irvine, CA 92697, USA, Email: gudrun@uci.edu
(11) Department of Meteorology, University of Maryland, College Park, Maryland 2074, USA, Email: pinker@atmos.umd.edu
(12) School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK, Email: i.renfrew@uea.ac.uk
(13) National Snow and Ice Data Center, 449 UCB, University of Colorado, Boulder, CO, 80309-0449, USA, Email: serreze@kryos.colorado.edu
(14) Florida State University, Rm 431a OSB, Tallahassee, FL 32306-4320, USA, Email: kspeer@ocean.fsu.edu
(15) Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive, Mail Code 0230, La Jolla, CA 92093-0230 USA, Email: ltalley@ucsd.edu
(16) NOAA/ESRL/PSD, R/PSD2 325 Broadway, Boulder, CO 80305-3328, USA, Email: Gary.A.Wick@noaa.gov

ABSTRACT

Improving knowledge of air-sea exchanges of heat, momentum, fresh water, and gas is critical to understanding climate, and this is particularly true in high latitude regions, where anthropogenic climate change is predicted to be exceptionally rapid. Existing gridded flux products can differ substantially, and in many cases there is no clear consensus about which flux products are most reliable. Progress on air-sea fluxes will require a combination of efforts, including a concerted plan to make better use of ships of opportunity to collect meteorological data, targeted efforts to deploy a few flux moorings in high wind regions, and improved satellite retrievals of flux related variables.

1. INTRODUCTION

Surface fluxes determine how momentum, heat, freshwater, and gas exchange between the atmosphere and the ocean. Thus, surface fluxes play a critical role in the climate system. While fluxes at temperate latitudes have been measured in recent years through an extensive array of flux buoys (e.g. [1]), high latitude fluxes are relatively under-sampled. Our objective in this paper is to outline some of the challenges associated with determining surface fluxes from high latitudes and to offer strategies for improving our estimates of high latitude surface fluxes. This work is the product of the US CLIVAR Working Group on High Latitude Surface Fluxes. (See [2,3] for summaries of working group objectives.) The findings presented here are a condensed version of ideas presented in a longer manuscript in preparation for the *Bulletin of the American Meteorological Society*.

2. BACKGROUND: MEASURING FLUXES AT HIGH LATITUDE

To date no moored surface flux buoys have been deployed in the Southern Ocean and only a few meteorological buoys have been placed in the high latitude north Atlantic or Pacific Oceans, none of which have measured fluxes directly. Ship observations of direct fluxes (i.e., not bulk fluxes) have been limited to a number of limited duration field campaigns, primarily for the recent International Polar Year (IPY). These have included the Southern Ocean Gas Exchange Experiment (GasEx3), which measured ocean-atmosphere CO_2 fluxes in high winds at southern high latitudes, and the Greenland Flow Distortion Experiment [4], which measured direct air-sea fluxes off southeast Greenland from low-flying aircraft [5]. This paucity of observations is particularly troublesome, because surface fluxes of momentum, heat, and gas are all strongly dependent on wind speed, and winds over high latitude oceans are among the strongest in the world, sometimes exceeding 20 m s^{-1} in contrast with temperate latitude winds that are typically less than 14 m s^{-1} [6]. High winds drive high waves, sea spray, and bubbles, all of which can alter air sea fluxes in ways that might not be predictable on the basis of temperate latitude measurements. Open ocean sampling is further complicated by cold weather; by icing conditions, which can coat instruments; and by the small Rossby radius of high latitude oceans, which suggests a need for high spatial resolution sampling.

Arguably, the most extensive surface flux measurements at high latitudes were made over multi-year sea ice during the Surface Heat Budget of the Arctic Ocean Project (SHEBA; [7]). SHEBA scientists maintained multiple flux sites while their ice camp drifted for a year in the Beaufort Gyre [8]. As a result of warming in the Arctic, however, some of the SHEBA region is now open water in summer, implying that some of the best-sampled conditions are those that are least likely to exist through the coming century. Changes in ice correspond to significant changes both in albedo and air-sea fluxes and thus may have a significant impact on climate. Leads in seasonal ice are potentially important conduits for surface fluxes, but they form a hostile environment for ships, and they make the sea ice too unstable to allow long-term ice camps. Moreover, leads have small spatial scales that are challenging to resolve with either in situ or satellite-based sampling plans.

Given the challenges in measuring surface fluxes in situ at high latitudes, there are serious concerns both about the reliability of the bulk formulas used to estimate surface fluxes from meteorological data and also about the reliability of high-latitude gridded flux products derived from satellite data and/or numerical weather prediction analyses and reanalyses. While satellite scatterometer wind measurement have provided some guidance for estimating momentum fluxes over the open ocean [9], remote sensing data have provided less complete information for other types of fluxes. Heat fluxes can differ in some cases by more than their annual mean (e.g. [10,11]). For example, Figure 1 shows differences in the 5^{th}, 25^{th}, 50^{th}, 75^{th}, and 95^{th} percentiles for sensible heat fluxes in the Northern Hemisphere for a range of commonly used products. Not only do the means differ substantially, but the ranges of values and the frequency of extreme events also differ. Freshwater fluxes, which incorporate ice melt as well as precipitation minus evaporation, also pose serious challenges, because precipitation rates can vary over distances of just a few kilometers, and snowfall rate estimates can often have 100% uncertainties (see [12]). Gas fluxes depend on wind, which can be measured via satellite (e.g. [13,14]), but near surface partial pressures of CO_2 are still only available as in situ observations (e.g. [15,16]).

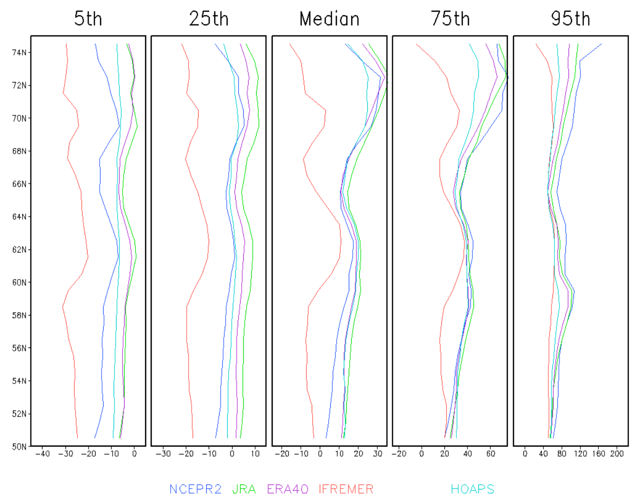

Figure 1. Comparison of oceanic sensible heat fluxes from readily available products: NCEP2, JMA, ERA40, IFREMER, and HOAPS. Each box shows zonally averaged monthly fluxes for either the 5th, 25th, 50th, 75th, or 95th percentile. The period for comparison (for which all products are available) is 03/1992 through 12/2000.

3. SCIENCE ENABLED BY SURFACE FLUX ESTIMATES

Science questions to be addressed with surface fluxes cover a broad spectrum of topics. From a large-scale ocean circulation perspective, we would like to be able to assess how surface fluxes alter the density of upper ocean water and contribute to the global meridional overturning circulation (e.g. [17]). From an atmospheric perspective, we hope to assess feedbacks between turbulent surface heat fluxes and large-scale atmospheric flows (see [18]). And from a sea ice perspective, we would like to obtain better estimates of the surface energy budget and corresponding ice albedo (e.g. [19,20]). All of these applications require improving heat flux accuracies by about an order of magnitude to achieve about 10 W m^{-2}, with corresponding improvements in bulk formulas for wind dependence, particularly at wind speeds exceeding about 14-20 m s^{-1}. In Figure 2 we summarize the spatial and temporal resolution and the accuracy required for heat and momentum fluxes for a range of research applications. (For a few specific applications, see for example [10,17-21].)

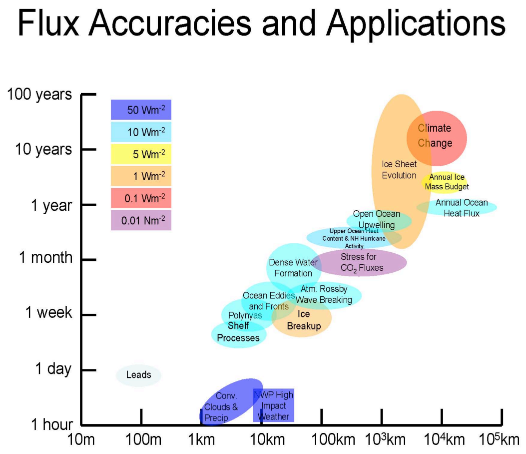

Figure 2. Schematic showing spatial and temporal sampling requirements for a range of common high-latitude applications. Fluxes expressed in W m^{-2} refer to total heat fluxes (including radiative and turbulent processes). Fluxes expressed in N m^{-2} refer to momentum fluxes (i.e. wind stress). Note that many of these accuracy requirements are rough guesses: much more work will be required to improve these estimates. The estimates that are based on more detailed analyses are ENSO, ice breakup, ice sheet evolution, and climate change.

4. MOVING FORWARD: STRATEGIES FOR IMPROVING HIGH-LATITUDE FLUXES

Developing a specific plan to improve surface fluxes will take a concerted community effort. To begin to forge a plan, we will host a workshop jointly with the SeaFlux program March 17-19, 2010, in Boulder, Colorado. Here we offer some suggestions for strategies for moving forward in refining estimates of surface fluxes.

1. *Analyze the existing data.* Although high latitude data are sparse, meteorological sensors have been installed on the Antarctic support vessels in recent years, and a number of IPY programs collected observations in adverse high latitude conditions. A first step toward improving fluxes is to complete archiving and analysis of flux-related data from IPY field programs [22,23] to analyze new satellite observations, and to coordinate this analysis with an examination of basic meteorological quantities from ship meteorological sensors [24].
2. *Expand field observations.* Year-round observations of fluxes and of the variables used to compute them from bulk formulae are needed, both from dedicated field campaigns with well-calibrated instruments and also from strategically sited flux moorings located in regions of persistently strong winds and in regions with a wide variety of air-sea heat flux conditions. It is critical to obtain reference quality flux measurements, particularly for wind speeds greater than 14 m s^{-1}, with temperature, wave heights, and precipitation patterns that characterize the full range of high latitude conditions. Crucially important data are expected from planned high latitude moorings through the OceanSITES (55°S in the Pacific and 42°S in the Atlantic, at the Agulhas Return Current air-sea flux site (42°S), and south of Tasmania; [25,26]). For radiative fluxes, additional observations are desired for long-wave radiation, clouds, ice extent, and aerosol optical properties.
3. *Expand use of ships of opportunity and autonomous instruments.* Although rising fuel costs may lead to reduced opportunities for seagoing work, tourist vessels continue to carry passengers to Antarctica and into the Arctic, and we would benefit if we could find ways to mount flux instrumentation aboard these ships.
4. *Make full use of satellite data, and expand the satellite observing system.* Important as in situ measurements are, ultimately the adverse conditions of high latitude oceans, and the vast size of the regions that need to be observed mean that we will need to rely on satellite data to obtain a complete picture of air-sea fluxes [24]. This might require making full use of relatively new atmospheric profilers, such as the Advanced Microwave Sounding Unit (AMSU) and the Atmospheric Infrared Sounder (AIRS) (e.g. [27, 28]), and it might also require launch of additional sensors, such as a second scatterometer to provide better high-frequency sampling of fast-moving polar storms [29].
5. *Improve understanding of the physics underlying air-sea fluxes.* Finally, efforts to improve high latitude surface fluxes will require continued efforts to probe the physics governing these fluxes, through a combination of lab experiments and in situ process studies aimed at probing the effects of bubbles, sea spray, high winds, and ice [24]. The resulting improved understanding of the physics will then need to be incorporated into the bulk formulae.

In summary, present day estimates of high latitude air-sea fluxes have substantial uncertainties associated with poorly understood physics at high wind speeds and poor sampling in conditions made adverse by high winds, cold, and ice. New research will be possible if flux uncertainties can be reduced by about an order of magnitude, and we believe that this will be possible through a concerted community effort that includes deployment of flux moorings at high latitudes, shipboard experimentation, and extensive analysis of existing in situ and remotely sensed data.

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