High-Latitude Ocean and Sea Ice Surface Fluxes: Challenges for Climate Research

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Short summary: High latitudes present extreme conditions for the measurement and estimation of air–sea fluxes, limiting understanding of related physical processes and feedbacks that are important elements of the Earth's climate.

Abstract: Polar regions have great sensitivity to climate forcing; however, understanding of the physical processes coupling the atmosphere and ocean in these regions is relatively poor. Improving our knowledge of high-latitude surface fluxes will require close collaboration among meteorologists, oceanographers, ice physicists, and climatologists and between observationalists and modelers, as well as new combinations of in situ measurements and satellite remote sensing. This article describes the deficiencies in our current state of knowledge about air–sea surface fluxes in high latitudes, the sensitivity of various high-latitude processes to changes in surface fluxes and the scientific requirements for surface fluxes at high latitudes. We inventory the reasons, both logistical and physical, why existing flux products do not meet these requirements. Capturing an annual cycle in fluxes requires that instruments function through long periods of cold polar darkness, often far from support services, in situations subject to icing and extreme wave conditions. Furthermore, frequent cloud cover in high latitudes restricts the availability of surface and atmospheric data from visible and infrared (IR) wavelength satellite sensors. Recommendations for improving high-latitude fluxes include (1) acquiring more in situ observations; (2) developing improved satellite flux observing capabilities; (3) making observations and flux products more accessible; and (4) encouraging flux intercomparisons.

1. Introduction

High-latitude climate change can manifest itself in astonishing ways. Arctic sea ice extent at the end of the melt season in September is declining at a mean rate of 12% per decade, with a record seasonal minimum in 2007 (Comiso et al. 2008). In 2001–02, the Larsen B Ice Shelf on the Antarctic Peninsula collapsed in a matter of months (Rignot et al. 2004), and in 2008, the Wilkins Ice Shelf collapsed equally quickly (Scambos et al. 2009). Ocean heat content is rising rapidly in high-latitude regions of both hemispheres (e.g., Gille 2002; Karcher et al. 2003; Purkey and Johnson 2010). In a broad sense, these observed changes are consistent with projections of anthropogenic climate change reported in the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR4) (Randall et al. 2007). A common element in high-latitude climate changes is a dependence on surface fluxes, i.e., the exchange of heat, momentum, and material between the ocean, atmosphere, and sea ice.

Surface fluxes at high latitudes reflect a broad range of processes, as depicted schematically in Fig. 1 (the basic concepts defining surface fluxes are outlined in Sidebar #1.) Were the magnitude and variations in these fluxes well known, they would provide enormous insights into aspects of the climate system, including the evolution of sea ice mass, meridional heat and salinity transport, and large-scale variability within the climate system (e.g. the North Atlantic Oscillation, the Annular Modes, the Pacific Decadal Oscillation, and even ENSO teleconnections). However, the magnitude and variations of surface fluxes at high latitudes are poorly known, leading to large uncertainties in the present climate state at high latitudes (e.g., Dong et al. 2007; Cerovecki et al. 2011b; Vancoppenolle et al. 2011; Kwok and Untersteiner 2011) and limiting our ability to validate climate models used to project twenty-first-century climate (Christensen et al. 2007). Improving our knowledge of high-latitude surface fluxes will require close collaboration among meteorologists, oceanographers, ice physicists, and climatologists; new combinations of in situ measurements and satellite remote sensing (e.g., improvements upon Bourassa et al. 2010b); and close interaction between observationalists and modelers.

This article, an outcome of the US CLIVAR Working Group on High Latitude Surface Fluxes Workshop (http://www.usclivar.org/hlat.php), describes the scientific requirements for surface fluxes at high latitudes, which we define to include the Arctic and the Subarctic Ocean, and the Southern Ocean.

We inventory the reasons, both logistical and physical, why existing flux products do not meet these requirements. We conclude with suggestions for improving high-latitude flux estimates. Our focus is on ocean–atmosphere fluxes and radiative fluxes over high-latitude seas and sea ice. We do not consider fluxes over land surfaces or freshwater fluxes from land to ocean. The recent SWIPA (Snow, Water, Ice, Permafrost of the Arctic) assessment (Arctic Monitoring and Assessment Programme, 2011, http://www.amap.no/swipa/) provides an up-to-date description of surface and lateral fluxes and net mass changes of the Greenland ice sheet, and addresses requirements for measuring carbon fluxes over tundra and terrestrial permafrost regions.

2. Unique Challenges and Desired Accuracies

High-latitude fluxes differ markedly from those in temperate regions because of the presence of ice, frequent high wind speeds (Fig. 2), low winter temperatures, both large and small seasonal temperature ranges, and pronounced variability on local scales, particularly along sea ice margins and leads (linear openings in the ice cover). As a result, physical understanding gained in temperate regions is not necessarily applicable to high latitudes. The high-latitude environment also poses logistical challenges. Capturing an annual cycle in fluxes, for example, requires that instruments function through long periods of cold polar darkness, often far from support services, in situations subject to icing and extreme wave conditions. These logistical challenges are reflected in a relative paucity of standard surface and upper-air meteorological data and an almost complete absence of moored[1] or free-drifting sensor systems in large areas of the polar oceans, particularly those covered with seasonal or perennial ice. Frequent cloud cover in high latitudes restricts the availability of surface and atmospheric data from visible and infrared (IR) wavelength satellite sensors. This lack of information reduces the quality

1 The first meteorological mooring in the Southern Ocean was deployed in March 2010, at 140°E, 47° S, by the Australian Integrated Marine Observing System (Trull et al. 2010). It measures wind, temperature, humidity, atmospheric pressure, solar radiation, and precipitation but not turbulent fluxes. A second mooring that was deployed in the Agulhas Return Current at 30°E, 38.5°S in November 2010, broke loose from its anchor after less than 7 weeks. Similar difficulties occurred in the northern high latitudes (Moore et al. 2008),

of data assimilation products from numerical weather prediction (NWP) centers such as the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP). More numerous and more accurate in situ and satellite observations are required.

In view of the importance of high-latitude surface fluxes and the challenges in measuring them, it is reasonable to ask what accuracy is needed for different applications. Sidebar #2 highlights a wide range of applications that make use of surface flux observations. In Fig. 3, we summarize flux accuracy requirements that have emerged from discussions with researchers representing atmospheric science, oceanography, and Arctic sea ice physics. The consensus is that the shortcomings in high-latitude observing systems and NWP are too great to allow for the determination of precise accuracy requirements for most processes. The values shown in Fig. 3 are therefore rough estimates to be refined as observing systems and NWP systems improve.

Climate processes occur on a suite of space and time scales with different accuracy requirements and challenges (Fig. 3). For measurements of smaller scale processes (<100km), such as those governing a cold-air outbreak off the coast of Greenland (see Fig. 4; Petersen and Renfrew 2009), in situ observations of variables such as temperature and wind speed are typically well sampled, and observational error is dominated by random errors. However, NWP products can have large errors on these small scales because they cannot resolve small-scale features (Fig. 4). For large-scale processes, such as zonally averaged monthly fluxes (Fig. 5), individual observations are averaged, which reduces random errors by a factor of the square root of the number of independent observations, meaning that random errors have little impact. Instead errors are dominated by biases in observations (which are typically small compared to random uncertainty in individual observations) or biases in parameterizations. On the large scale, fluxes from NWP are typically limited by biases in parameterizations and related physical assumptions. Therefore, for the smaller scale processes it is essential to have accurate individual observations or model representation, whereas larger scale studies require low biases. Importantly, some processes do not respond linearly to the forcing; for such processes it is critically important to properly represent the distribution of fluxes. In current products these distributions differ enormously as demonstrated by the discrepancies in the median as well as the 5^{th} and 95^{th} percentiles of sensible and latent heat flux estimates shown in Fig. 5.

3. Improving the Accuracy of Fluxes

The specific shortcomings in high-latitude surface fluxes result from a number of distinct issues. Here we discuss problems stemming from flux parameterizations, observational errors, and sampling errors.

a. Flux Parameterizations

Some flux estimates fail in part because they are calculated using parameterizations that have not been optimized for high-latitude conditions. Whereas surface turbulent fluxes can be measured directly with specialized sensors placed on suitable platforms over the ocean (e.g., Ho et al. 2007; Wanninkhof et al. 2009), most applications require estimates distributed over a broader range in space and time than can be achieved with dedicated flux sensors. Thus, direct in situ flux observations are used to develop and tune indirect parameterizations, known as *bulk flux algorithms*, which allow fluxes to be calculated from more easily measured variables such as wind speed and sea surface temperature. Bulk flux algorithms have been in use for decades (see e.g., Blanc 1985; Curry et al. 2004). Advances in understanding the physical processes involved in air–sea exchange and in observing technologies have promoted steady improvements in the sophistication and accuracy of these algorithms. Bulk-flux algorithms are also used in retrievals of turbulent fluxes from satellite observations (Bourassa et al. 2010b). They have been used extensively to estimate the heat balance of the oceans from historic weather observations from volunteer observing ships (WCRP 2000), and they form the basis for describing the atmosphere–ocean boundary interactions in virtually all climate and NWP models.

There are two dominant sources of error in bulk algorithms: 1) the choice of the transfer coefficient and 2) the accuracy of the routinely observed variables used to compute the fluxes. Transfer coefficients for momentum (Fig. 6a), sensible or latent heat flux (Fig. 6b), and gas exchange (Fig. 6c) vary with wind speed, and coefficient estimates derived from different sources can differ dramatically, as the solid lines in Fig. 6 illustrate. The transfer coefficients are largely functions of wind speed (relative to the water surface) and air–sea temperature differences; C_D is also a function of sea state. A problem in high latitudes is the relatively high likelihood of extreme conditions, for which bulk algorithms are less reliably tuned. Regional biases in fluxes occur when some of these dependencies are approximated or ignored (e.g., Renfrew et al. 2002). In some cases, bulk parameterizations may simply be introducing an unnecessary layer of complication in the effort to determine surface fluxes. Accurate retrievals of stress or $\mathbf{u}_*$ (see Table 1) would remove the problems associated with the C_D dependence on sea state (e.g., Fairall et al. 1996; Bourassa 2006). For example, since centimeter-scale radar backscatter is more closely tied to stress than to wind (Bourassa et al. 2010a), scatterometers can probably be tuned to measure stress and hence determine $\mathbf{u}_*$. Tuning stress retrievals and transfer coefficients for highly atypical conditions, or conditions that are adverse to in situ sensors, will be a challenge given the paucity of observations and the importance of physical processes that are not yet well modeled in current parameterizations: for example, sea spray at very high wind speeds (Andreas et al. 2008), rain (Weissman and Bourassa, 2011), and mixed ice and water (Alam and Curry, 1997). These conditions occur regularly in high latitudes, and are linked to processes that are important to climate.

Different challenges arise for estimating radiative fluxes, which include shortwave radiation from the sun and longwave radiation emitted from the ocean surface and from the atmosphere. Shortwave (solar) fluxes are commonly estimated from satellite observations using empirical, statistical, and/or physically based methods (Schmetz 1989, 1991, 1993; Pinker et al. 1995; Whitlock et al. 1995; Wielicki et al. 1995). The downward shortwave flux at the surface depends on the shortwave flux at the top of the atmosphere and on the fraction of this flux that is transmitted through the atmosphere. The transmittance depends on the composition of the atmosphere (e.g., amount of water vapor and ozone, optical thickness of cloud and aerosols), and on the distance the radiation travels through the atmosphere (modified by the solar zenith angle and scattering). The upward shortwave flux at the surface is then calculated by multiplying the surface downward flux by the surface albedo. Uncertainties in the shortwave fluxes stem from the substantial uncertainties in the atmospheric transmittance and surface albedo. Estimates of radiative fluxes from different satellite-based products disagree strongly in polar regions (Fig. 7). Estimates from the Surface Heat Budget of the Arctic Ocean (SHEBA) project and from high-latitude buoy and land stations suggest that satellite-based analysis provide downward shortwave radiative fluxes to within ~10-40 W m^{-2} of direct surface observations (e.g. Perovich et al. 1999; Curry et al. 2002; Niu et al. 2010; Niu and Pinker 2011). This uncertainty is too large for most climate applications; however, much of this difference could be due to representativeness differences (i.e. due to comparing surface observations at one location in a very inhomogeneous environment to satellite estimates averaged over larger spatial scales.)

Estimating longwave surface radiative fluxes from satellites is also challenging. Downwelling long-wave surface radiation is controlled by the vertical profiles of temperature, gaseous absorbers, clouds, and aerosols. In contrast to the tropics, at high latitudes the moisture content of the atmosphere is low. As a result, the high-latitude atmosphere is semitransparent in some infrared bands that are normally opaque (Turner and Mlawer 2010). An especially formidable issue is that the longwave flux depends strongly on the cloud-base height, which is not as yet detectable from satellite, and quantities measured by satellite are not directly correlated to downwelling radiation. Consequently, downwelling longwave radiation is often estimated as a function of a bulk atmospheric temperature approximated by air temperature at the ground and an estimated broadband atmospheric emissivity. For cloudless skies, more than half the longwave flux received at the ground comes from emissions in the lowest 100 m (Zhao et al. 1994), because the lowest atmospheric layers are relatively warmer than higher layers and intercept some of the radiation emitted by higher layers. Estimating the upward longwave flux is more direct and simply calculated from surface temperature and emissivity of the surface.

Estimated downward longwave fluxes have been evaluated against surface observations in a number of land-based studies (e.g., König-Langlo and Augstein 1994; Key et al. 1996; Guest 1998; Makshtas et al. 1999) and are typically accurate to ~10-30 W m^{-2} at high latitudes (Perovich et al. 1999; Nussbaumer and Pinker, 2011). For example, the parameterization of König-Langlo and Augstein (1994) reproduced the observations with root-mean-square (RMS) differences of less than 16 W m^{-2}. Though these accuracies are reasonable, like the shortwave flux accuracies, they are insufficient to meet the requirements indicated in Fig. 3 for many applications. For short time and small spatial scales, the largest sources of uncertainty in radiative fluxes are thought to stem from algorithm implementation problems associated with issues such as diurnal corrections and radiance-to-flux conversions (Wielicki et al. 1995).

Radiative fluxes are also computed as an output from NWP reanalyses (sometimes in combination with satellite data) or global climate models. Model-based approaches have the apparent advantage of providing dynamically consistent fields with all relevant variables including cloud cover and atmospheric aerosol concentrations. However, satellite-based approaches have generally proven more successful than models that resolve scales larger than 100 km. For example, Liu et al. (2005) found that the surface downward shortwave radiative fluxes derived from satellites are more accurate than those from the NCEP and ECMWF reanalysis datasets because of better information on cloud properties. Sorteberg et al. (2007) found that the 20 coupled models used in the IPCC Fourth Assessment Report have large biases in surface fluxes, particularly over marginal ice zones. The models significantly underestimate both downward and upward longwave radiation in winter.

Different issues exist for precipitation fluxes. Satellite retrievals are of poor quality over cloudy and snow- and ice-covered surfaces (e.g. Gruber and Levizzani, 2008; Sapiano, 2009), and it appears that better estimates can be obtained from atmospheric reanalyses (Serreze et al. 2005) or from combinations of satellite plus reanalysis and/or station data (Huffman et al. 1997; Xie and Arkin 1997). However, precipitation biases in reanalysis fields can be very large (Serreze and Hurst 2000), in part because of errors in radiative transfer parameterizations, and in part because of model microphysics and transport errors leading to incorrect input to the radiative transfer model.

b. Observation Errors

Even if flux parameterizations were perfect, one is still left with the problem of obtaining high-quality observations. Observation error refers to error characteristics of single observations. For some sensors these are serious concerns. For example, gauge errors in measured precipitation for Arctic stations can exceed 100% in winter (Yang, 1999). For other sensors, such as those that are well maintained on ships and buoys, the observations needed for input to bulk formulas have sufficiently small random errors for many applications. Substantial biases can occur due to the lack of important metadata for observations collected on ships, such as the physical height of sensors, and whether the anemometer at the time of observation is on the leeward or windward side of the ship Bradley and Fairall, 2006). Polar conditions are also very harsh on instruments, which can necessitate special equipment or frequent maintenance.

Satellite observations vary in reliability. Scatterometer wind observations have consistent accuracies for individual sensors but are not yet intercalibrated, particularly for high wind speeds (Bourassa et al. 2010c). Unfortunately, available scatterometers do not fully resolve the tight gradients that occur along fronts and within strong extratropical cyclones, nor do they provide temporal resolution needed to track rapidly evolving storms. Moreover, since the demise of QuikSCAT in November 2009, researchers have relied more on ASCAT, which is less affected by precipitation but has a narrower swath than QuikSCAT, limiting the view of large-scale storms. In addition, ASCAT is currently calibrated differently than QuikSCAT for 10-meter winds, $U_{10,} > 15 ms^{-1}$. For extreme winds found in strong mid-latitude cyclones these difference can exceed 10 m s^{-1} (Bourassa et al. 2010c).

Satellites can be quite effective for observing sea surface temperatures (SSTs). Microwave sensors perform well through cloudy conditions, but infrared sensors, which are required to resolve small-scale features, are thwarted by clouds, resulting in little or no high-resolution data in perennially cloudy regions, such as parts of the Southern Ocean. Furthermore, microwave satellite instruments are ineffective closer to a shoreline or ice (areas of great interest) than their resolution. The new generation of SST products optimally blending in situ, microwave, and infrared observations provide a way forward (e.g., Donlon et al. 2007). New satellite observations are improving estimates of surface albedo and aerosols (e.g., Schaaf et al. 2002; Remer et al. 2005; Kahn et al. 2005), although the dominant error source still stems from calibration uncertainties in satellite instruments. There are very large differences between estimates from NWP, satellites, and in situ products (Smith et al. 2010). Recent techniques for retrieving air temperature and humidity (Jackson et al. 2006, 2009; Jackson and Wick 2010; Roberts et al. 2010; Dong et al. 2010) have yielded improved estimates over a wider range of conditions. These retrievals have noise that is mildly worse than in situ observations; however, they have substantial biases over the very cold water that characterizes high latitudes. The impact of these improvements on turbulent fluxes remains to be determined (Bourassa et al. 2010b).

Some studies make use of NWP estimates of SST, air temperature, humidity, and other variables to obtain surface fluxes. These estimates typically have large regional biases (Smith et al. 2010). When the NWP parameterizations are implemented in coupled climate models, biases in the input to bulk flux parameterizations can introduce larger errors in the fluxes and feedbacks in the coupled systems. Transfer coefficients in climate models have been modified to account for these biases. However, this type of tuning means that any modeled response to changes in wind, temperature, and humidity is likely inaccurate, which is a serious problem in high latitudes, where several key climate processes (including ocean uptake of heat and water mass transformation) are sensitive to the magnitude of energy fluxes and to the directional stress.

Ultimately, improved observations of air–sea temperature differences and measurements of stress will improve the accuracy of CO_2 flux retrievals from satellites. The largest sources of error in CO_2 fluxes are insufficient sampling of the highly variable winds in polar latitudes, large changes in pCO_2 across the air-sea interface in areas of differing biological activity (Martz et al. 2009), and indirect methods of regionally estimating oceanic pCO_2 from satellite observations. These atmospheric and aqueous pCO_2 estimates require ongoing validation from sparse observations collected by research vessels. Satellites currently lack the ability to measure atmospheric pCO_2 with sufficient accuracy at the desired resolution; however, lidar (Wilson et al. 2007) and the Atmospheric Infrared Sounder (AIRS, Engelen et al., 2004; Engelen and McNally, 2005; Engelen and Stephens, 2004; Strow and Hannon, 2009) show promise for the future.

For radiative fluxes, observational errors are similarly important. Shi and Long (2004) discussed accuracy limits of ground observations. Clouds are major modulators of the shortwave radiation budgets; however, information on their physical properties and vertical structure is not readily available, particularly in polar regions, in part since ice or snow and low clouds are difficult to distinguish in satellite data. Since, satellites are critical for obtaining estimates of radiative fluxes, particularly for long time scales and large space scales, one important step forward is to compare satellite-based downward surface flux estimates against ground measurements. At most latitude ranges, globally distributed ground measurements have improved over the last 12 years with the advent of the GEWEX Baseline Surface Radiation Network (Ohmura et al. 1998; Michalsky et al. 1999), with recent studies reporting agreement within 10 Wm^{-2} on a monthly time scale (e.g., Charlock and Alberta, 1996; Stackhouse et al. 2004). A similar high-latitude network is needed.

c. Sampling Errors

The third major challenge for obtaining quality surface fluxes is sampling errors. This refers to error characteristics associated with under-sampling natural variability. Important cases of under-sampling also occur when observations are made conditionally, e.g., only in clear or non-precipitating conditions. Under-sampling can result in large and non-Gaussian errors (Gulev et al. 2007a, b) and spatial/temporal inhomogeneity in error characteristics (Schlax et al. 2001). Furthermore, scales smaller than the scale of the observation network will alias onto the larger scales that are resolved. High-latitude sampling errors are large because there are so few observations, and there are large changes in variables over relatively small times and distances. In situ radiative flux data for high latitudes come from land-based radiometer measurements, and there relatively few in situ observations of shortwave or longwave radiative fluxes over high-latitude oceans. Flux moorings have not been deployed routinely in any high-latitude region. In situ ocean data that are available have hence been limited largely to collections from ships. In regions with major shipping routes, volunteer observing ships (VOS) now provide enough data to calculate surface energy fluxes, although monthly averages still have large errors (Berry and Kent, 2011). However, south of 30°S and poleward of 50°N there are few ship observations, coupled with large natural variability, which results in very poor matches between VOS products and satellite products (e.g., Risien and Chelton 2008). For studies of the upper-ocean heat content, profiling Argo floats have been a boon. However, Argo's target of sampling at 10-day temporal resolution and 3^{o} spatial resolution precludes resolving details of spatial and temporal surface flux variations. High-inclination polar orbiting satellites have relatively good sampling in polar regions; however, the natural variability of winds and clouds is also quite large, resulting in large sampling errors. Further, since cloud amount and type is tied to synoptic weather patterns, IR sensors provide only a conditional sampling of meteorological conditions.

In some cases relevant data, particularly those affecting radiative fluxes, are simply not part of the observational data stream. The high albedo of snow and ice, together with the cold and fairly dry atmosphere, results in a surface net radiation deficit for most months. Cloud cover typically reduces the radiation deficit (Pietroni et al. 2008) by absorbing upward longwave radiation and reemitting some of it back toward the surface. Thus, Pietroni et al. (2008) concluded that differences in longwave radiation distributions between two Antarctic sites, one near the coast and one in the interior, were strongly related to differences in cloud cover. Cloud-related scattering of shortwave radiation is also unusually important in this region. However, the characteristics of clouds and aerosols in polar regions, and in particular their small-scale variation depending on surface type, are poorly known and not routinely measured (Lubin and Vogelmann 2006).

Sampling problems are compounded by the fact that fluxes at high latitudes vary over shorter spatiotemporal scales than fluxes at lower latitudes. For surface turbulent fluxes, length-scales over the high-latitude open ocean are determined by the first baroclinic Rossby radius, which can be 20 km or less (Chelton et al., 1998) and time scales can range from a couple of days to < 6 hours (e.g. Condron et al., 2008; Jiang et al., 2011), because high-latitude storms evolve quickly. Physics at meter to kilometer scales also matters: breaking waves and whitecaps are of first order importance in production of sea spray (Andreas and Monahan, 2000; Andreas and Emmanuel, 2001; Lewis and Schwartz, 2004; Fairall et al., 2009), in gas transfer (e.g., Woolf, 2005), and of some importance in wind-stress relationships (e.g, Mueller and Veron, 2009).

Precipitation is notoriously difficult to determine. For example, Serreze et al. (2005) estimate that at a coarse grid cell resolution of 175 km, obtaining an accurate assessment of the monthly grid cell precipitation requires typically 3–5 stations within the cell, and more in topographically complex areas. However, for the Arctic terrestrial drainage, only 38% of the 175-km grid cells contain even a single station. The situation is much worse over Antarctica, the Southern Ocean, and the Arctic Ocean. Sampling from satellites can have large errors in these regions because time intervals between observations are in many cases too large compared to the variability associated with storm systems. TRMM, the dedicated precipitation mission, does not reach high latitudes, and other satellite products show anomalously high variability poleward of 50^o latitude and in ice-covered areas (Sapiano, 2009). Furthermore, satellite observations with large footprints have insufficient spatial resolution to capture the spatial variability found in this typically inhomogeneous environment. Because of the nonlinear response to precipitation, microwave-only precipitation retrievals are prone to the so-called beam-filling problem (North and Polyak 1996): the satellite footprint or beam is not uniformly filled by precipitation.

Ultimately, it is anticipated that NWP products with finer resolution and improved assimilation will help resolve the sampling problem. The higher resolution fields released by ECMWF and other NWP producers in support of the Year of Tropical Convection (e.g. Waliser and Moncrieff 2008) are a first effort at this. However, routine, high-resolution NWP reanalyses with sufficient accuracy appear to be decades in the future and will require considerable development of the basic flux physics (or flux parameterizations) embedded in the model. We recommend the further development of high-latitude reanalysis products, including the improvement of flux parameterizations, to address many of these difficulties. However, we note that efforts to advance reanalyses and improve parameterizations are likely to require better data.

4. Summary: Key needs

Obtaining improved estimates of high-latitude surface fluxes will require a multifaceted effort. Coordinated sets of targeted observations are needed to refine flux parameterizations for high-latitude conditions and to provide calibration and validation data. Given the difficult working conditions at high latitudes and the vast region involved, satellites and numerical weather prediction models will necessarily play a key role. This situation will likely require a multinational array of satellites designed to provide good temporal and spatial sampling, carefully selected instrumentation, and improved retrieval techniques aimed at minimizing errors in stress, air temperature, humidity, and cloud aerosol properties.

Our recommendation is for the development of an expanded high-latitude observational network that is sustained and optimized to improve physical parameterizations. New Arctic and Antarctic reanalyses should be pursued, with goals of refining data retrieval algorithms and assessing different models for boundary layers and fluxes in the presence of ice. Improving surface flux estimates in high-latitude regions will require broad community involvement. Planning documents generated for International Polar Year (IPY) and post-IPY activities have begun to articulate priorities (e.g., Dickson 2006; Rintoul et al. 2010). Some key ideas for improving fluxes emerged from discussions at a March 2010 workshop jointly organized by SeaFlux and the US CLIVAR Working Group on High Latitude Surface Fluxes (summarized in sidebar #3). As a follow-up to the workshop and other post-IPY discussion, it is critical that the community continue to seek consensus for plans to improve high-latitude surface fluxes.

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Sidebar 1: Primer: What is an air–sea flux?

Air–sea fluxes represent the exchange of energy and material between the ocean and lower atmosphere (Curry et al. 2004). They include the net fluxes of momentum (stress) from wind, energy (downward and reflected shortwave radiation, downward and emitted longwave radiation, latent heat flux, and sensible heat flux), and mass (Fig. 1). Mass fluxes encompass a broad number of variables including moisture (precipitation and deposition, evaporation or sublimation, and runoff or ice melt) and gases (e.g., CO_2) as well as atmospheric aerosols (solid or liquid particles), which can, for example, supply salt to the atmosphere, provide chlorine that can contribute to ozone depletion, or deliver iron-rich dust derived on land to the ocean, spurring biological growth.

Wind stress, sensible and latent heat fluxes, gas exchange, and evaporation are classified as turbulent fluxes. These fluxes depend on nonlinear, co-varying terms, meaning that errors in representing small-scale features can translate into significant errors even in large-scale averaged fields. Depending upon the space and time scales being investigated (Fig. 3), these fluxes could be averaged over a wide range of surface and meteorological conditions. Turbulent fluxes on the time scales of intense storms (roughly one day) can be very large compared to long-term averages. Although turbulent fluxes can be measured directly, they are typically parameterized (see Table 1) (e.g., Curry et al. 2004). At high latitudes, low-level winds can be enhanced by orography and reduced friction over some types of ice, leading to intense katabatic winds and low-level orographic jets, and consequently strong air–sea momentum exchange along coastlines. Openings in the ice (i.e. leads and polynyas) can lead to small-scale variations in air–sea turbulent heat fluxes, with strong heat exchange in open water (Fig. 1). Small-scale ocean currents and eddies can also modify turbulent heat fluxes.

Radiative fluxes at the surface include downwelling and upwelling (reflected) shortwave radiation (originating from the sun) as well as downwelling and upwelling longwave radiation (emitted by the atmosphere and the surface, respectively.) Radiative fluxes exhibit unique characteristics at high-latitude regions. For the downwelling shortwave, the major modulators at high latitudes are the low solar angle and the polar night; the surface albedo that determines the reflected part varies strongly between ice, snow, and water, and this is further complicated by the surface variability during melt periods and by dust and carbonaceous aerosol deposition. Downwelling longwave radiation is controlled largely by cloud cover, which is high at high latitudes, and by water vapor concentration, which is small at high latitudes. The upwelling long-wave radiation depends on surface temperature, which differs widely between the ice and the open water bodies and is not well known in areas with ice. Furthermore, small changes in shortwave reflectivity and long-wave emissivity can alter the energy budget sufficiently to cause substantial growth or melting of ice. All the radiative fluxes vary with cloud cover and aerosol content, which in turn can depend on a number of regional factors such as blowing snow and ice sublimation.

Net freshwater fluxes into the ocean are determined by the oceanic salinity flux, runoff (including melting land ice). precipitation (P, which includes rain and snow), and evaporation (E) , the latter two often viewed in the combined term of net precipitation, or P−E. The salinity flux is also proportional to “P−E” since salinity is the dilution of (conserved) salt by (non-conserved) freshwater. An important factor for ocean freshwater and salinity balances in regions with sea ice is the fractionation of water and salt in a process called brine rejection: sea ice is greatly depleted in salt, and most of the salt enters the underlying seawater, where it increases the seawater density. When the sea ice melts, the resulting seawater is significantly freshened and hence lighter. When sea ice, which can be thought of as seawater of very low salinity, is transported from one region to another, an advective freshwater (and salinity) flux between the regions arises. Ice and brine formation are modulated locally by the intermixed areas of open water, organic slicks, new ice, existing bare ice, snow-covered ice, and melt ponds; these interact with overlying regions of haze, low cloud, and clear sky, and are also affected by sunlight reflection and gaseous deposition (e.g., of mercury). Subtle changes in heat or momentum fluxes cause, and respond to, rapid water phase change.

Table 1. Bulk formulas used to parameterize turbulent heat fluxes. The equations rely on differences between variables measured at known heights (e.g., 10 meters) above the ocean surface (e.g., $\mathbf{U}_{10}$) and those measured at the surface (e.g., $\mathbf{U}_{s}$). Terms include the friction velocity, $\mathbf{u}_{*}$, which is a complicated function of the wind shear ($\mathbf{U}_{10} - \mathbf{U}_{s}$), waves, and the atmospheric stratification; air density (ρ); and air–sea differences in temperature ($T_{10} - T_s$), humidity ($q_{10} - q_s$), or gas concentration ($G_{s,aq} - G_{10}/H$). Here θ_* and q_* are scaling parameters analogous to u_*, C_p is the specific heat of air, L_v is the latent heat of vaporization, and H is the Henry's law constant. The transfer coefficients (C_D, C_H, C_E, C_G), for momentum, specific heat, latent heat, and gas exchange, respectively, account for differences in scale and can include additional dependence on variability, $\mathbf{u}_{*}$, and atmospheric stability.

Momentum (wind stress)	$\boldsymbol{\tau} = \rho\, \mathbf{u}_* \lvert\mathbf{u}_*\rvert = \rho\, C_D\, (\mathbf{U}_{10} - \mathbf{U}_s)\, \lvert(\mathbf{U}_{10} - \mathbf{U}_s)\rvert$
Sensible heat flux	$Q_S = -\rho\, C_p\, \theta_* \lvert\mathbf{u}_*\rvert = \rho\, C_p\, C_H\, (T_{10} - T_s)\, \lvert(\mathbf{U}_{10} - \mathbf{U}_s)\rvert$
Evaporation	$E = -\rho\, q_* \lvert\mathbf{u}_*\rvert = \rho\, C_E\, (q_{10} - q_s)\, \lvert(\mathbf{U}_{10} - \mathbf{U}_s)\rvert$
Latent heat flux	$Q_L = -\rho\, L_\mathrm{v}\, q_* \lvert\mathbf{u}_*\rvert \approx L_v\, E$
Air-sea gas exchange	$F_G = C_G\, (G_{s,aq} - G_{10}/H)\, \lvert(\mathbf{U}_{10} - \mathbf{U}_s)\rvert$

Sidebar 2: Examples: Surfaces Fluxes From a Climate Research Perspective

Surface flux products are widely used in the fields of oceanography, glaciology, sea ice dynamics, and atmospheric dynamics. Science questions address time scales from hours to decades, resulting in a diversity in related accuracy requirements. Here we provide a few examples.

a. From a long-term climate change perspective

Over the last few decades a number of aspects of the climate system have changed substantially. In the ocean, observed long-term warming trends from 1993–2003 can be explained by a mean ocean heat gain of just 0.86 ± 0.12 W m^{-2} (Hansen et al. 2005). For sea ice, a 1 W m^{-2} flux imbalance equates to a 10-cm ice melt in a year, which represents a significant fraction of the ice budget. Basin-scale changes in ocean salinity associated with global change correspond to small changes in air–sea freshwater flux on the order of 0.05 psu/decade (Boyer et al. 2005) concentrated in the top 200 m. This is equivalent to a change in liquid P-E of 3 cm yr^{-1}. Similarly, North Atlantic freshwater flux anomalies sufficient to slow deep convection (Curry and Mauritzen 2005) derive from river runoff and ice melt, and are equivalent to P-E of almost 1 cm yr^{-1} over the area of the Arctic and North Atlantic. These climate change signals of O (1 W m^{-2}) for heat and O (1 cm yr^{-1}) for freshwater are far below any currently estimated observational accuracy globally or in polar regions, even in averaged estimates computed from many independent samples. Hence, long-term changes in these fluxes are more effectively diagnosed by observing the ocean temperature and salinity changes as integrators of heat and freshwater fluxes (e.g., Hansen et al. 2005; Levitus et al. 2005; Boyer et al. 2005, 2007; Domingues et al. 2007; Wunsch et al. 2007; Hosoda et al. 2009; Levitus et al. 2009; Durack and Wijffels, 2010). Capabilities of current observing systems should not be a deterrent to efforts at improvement; significant scientific gains could be made if the uncertainty in heat and freshwater flux estimates (as crudely estimated by the spread in modern products) could be improved by an order of magnitude and if available products were consistently released with high-quality uncertainty and bias information.

b. From an ocean circulation perspective

The ocean circulation is driven primarily by wind stress curl patterns that deform sea level and thermocline fields, and by heat and moisture fluxes that alter water density. Since the curl patterns are caused in large part by zonal and meridional variations in the wind direction (e.g., easterly trades in the tropics, westerly jet stream at midlatitudes), from the ocean circulation perspective it is necessary to resolve not only the wind stress magnitude, but also its direction. Water density and hence circulation are also modified by ventilation of the mixed layer through air–sea heat and freshwater fluxes. After the water mass is subducted into the interior ocean, its properties remain relatively unchanged as it circulates through the global ocean. The high-latitude ocean surface formation of ocean bottom water is a critical component of the global ocean circulation. At high latitudes, surface cooling produces deeper mixing and ventilation. Salinity becomes a major factor controlling density where temperatures approach the freezing point. Thus, analysis of high-latitude ocean processes depends on accurate surface heat and freshwater fluxes, including freshwater fluxes linked to ice formation, export, and melt. For example, buoyancy gain by excess precipitation and buoyancy loss by ocean heat loss are apparently of comparable importance in estimating Subantarctic Mode Water formation, which dominates the upper ocean just north of the Antarctic Circumpolar Current (Cerovecki et al. 2011b). Calculation of surface water mass transformation rates from air–sea fluxes requires accurate and unbiased fluxes. Using the best available data products, Dong et al. (2007) found that the zonally averaged imbalance can be 50 W m^{-2}, and locally, the upper-ocean heat balance can have a root-mean-squared (RMS) misfit of more than 200 W m^{-2} at any given location, and 130 W m^{-2} in a global RMS-averaged sense. Such large errors make it difficult to discern the details of the upper-ocean heat storage and meridional overturning circulation. If RMS errors could be reduced to 10 W m^{-2} for weekly to monthly time scales, the situation would clearly improve. Achieving such accuracy requires much better sampling and a reduction in biases: strong winter storms account for much of the evaporation (outside of western boundary currents; Scott 2011).

c. From an atmospheric circulation perspective

Winter land-surface flux anomalies can drive a quasi-stationary wave response that might reinforce or attenuate climatological stationary waves propagating into the stratosphere, resulting in either a negative or positive tropospheric annular mode response (e.g., Smith et al 2011). When considering high-latitude surface fluxes due to opening or closing of sea-ice cover in particular, studies have shown that certain "hotspots" for turbulent heat flux anomalies exhibit significant feedback between atmospheric circulation patterns and modes of variability of sea ice. In the Northern Hemisphere, the Barents Sea is such a location for the North Atlantic Oscillation (e.g., Strong et al 2009), the Bering Sea for the West Pacific pattern (e.g., Matthewman and Magnusdottir 2011a). In the Southern Hemisphere, no single pattern dominates in atmospheric variability and its interaction with sea-ice anomalies; rather a superposition of the Pacific South America pattern and a quasi-stationary zonal wave train dominate in interacting with sea ice anomalies (e.g., Yuan and Li 2008, Matthewman and Magnusdottir 2011b). Turbulent energy fluxes resulting from the opening up of previously ice-covered areas of the Arctic are especially large in boreal winter, averaging O(50-70 W m^{-2}) (Alam and Curry 1997). The understanding, detection, and modeling of these feedbacks would be improved if heat fluxes were accurate to 10 W m^{-2} at 5–10-km spatial resolution and hourly time resolution. This would require much more frequent sampling from satellites, increased accuracy in mean values, and reduced random errors.

d. From a sea ice mass balance perspective

Arctic sea ice is a highly visible indicator of climate change. The range in recent and projected future ice extent and volume from different models remains large, reflected in the surface energy fluxes simulated both for the observational era and for future scenarios. Models are sensitive to small perturbations in sea ice albedo (Bitz et al. 2006), and intermodel scatter in absorbed solar radiation, due in part to differences in the surface albedo simulation, is a particular concern (Holland et al. 2010). Air–sea heat fluxes can also play a role in determining ice thickness: Perovich et al. (2008) showed that solar heating of open water in leads warms the upper ocean sufficiently to erode Arctic sea ice mass from below. Ultimately, reduced ice thicknesses feed back on ocean–atmosphere processes by changing the albedo (Brandt et al 2005) as well as the conductive and turbulent heat fluxes and emitted (upward) surface longwave radiation through the ice.

The formation and presence of ice provokes a step-function change in radiative, heat, momentum, and gas fluxes (e.g., Fig. 4). Ice formation and accumulation processes, which can include snow refreezing (common in the Antarctic) and vertical migration of frazil ice and dissolution, erosion, and break-up processes, remain highly complicated. These processes can occur on length scales too small to be detected remotely or modeled explicitly with current technology. As stable multiyear ice declines, annual ice processes and extent will dominate air–sea interaction and high-latitude fluxes.

Sidebar 3: Recommendations for Improving High-Latitude Fluxes

The myriad problems identified with high-latitude surface fluxes call for concerted efforts to identify pathways toward improvement. With this is mind, the US CLIVAR Working Group on High Latitude Surface Fluxes and the SeaFlux program together organized a workshop in Boulder, Colorado, 17-19 March 2010 (Bourassa et al. 2010b; Gille et al. 2010). The workshop attracted approximately 70 participants and included time for open discussion about priority strategies for improving flux estimates. The issues summarized here represent topics for which community consensus seems clear.

1. *Acquire more in situ observations.* The dearth of observations in both high-wind open ocean regimes and ice-covered regimes means that all additional flux-relevant data are desirable. This

includes standard meteorological data needed to compute fluxes from bulk parameterizations (e.g., from the Shipboard Automated Meteorological and Oceanographic Systems (SAMOS) program) as well as direct flux observations. A network of moorings (such as the Southern Ocean Flux Station, deployed southwest of Tasmania in March 2010 as part of the Australian Integrated Marine Observing System; Trull et al, 2010) would be desirable for capturing year-round meteorological variability at fixed positions. Having large numbers of independent samples is particularly important to reduce uncertainties in spatially and temporally averaged flux estimates and in tuning satellite observations. Given the pitfalls associated with bulk parameterizations, direct measurements of fluxes are also important. These are more likely to be achieved from semiautonomous instrumentation that can be placed on board research vessels, either during limited-duration process studies (such as GasEx) or as part of routine observations from research vessels operating in high latitudes, which would allow light maintenance of the instrumentation (such as the US NSF-sponsored Antarctic vessels or a NOAA-sponsored Arctic ship). Aircraft observations are also important, particularly in marginal ice zones, though some aircraft have had difficulties operating at low elevations in icy regimes; ultimately, unmanned aerial vehicles (UAVs) may have a role in acquiring near surface atmospheric measurements.

Limited-duration process studies play an important role both in increasing the general inventory of observations and also, more importantly, in helping to improve our understanding of physical processes that govern fluxes. There is strong community consensus for an updated version of the Surface Heat Budget of the Arctic Ocean (SHEBA) project and also for an Antarctic analog to SHEBA aimed at capturing differences between Arctic and Antarctic sea ice zones

2. *Develop improved satellite flux observing capabilities.* Important as in situ measurements are, ultimately the adverse conditions of high-latitude oceans, the vast size of the regions that need

to be observed, and the small spatial/temporal scales of the variability mean that we will need to rely on satellite data to obtain a complete picture of air–sea fluxes. Satellite sensors are now able to measure most of the relevant variables with some degree of accuracy, including ocean wind or wind stress (scatterometry), sea surface temperature (infrared or microwave radiometers), and near surface air temperature and humidity (atmospheric profiles such as the Advanced Microwave Sounding Unit, AMSU, and the Atmospheric Infrared Sounder, AIRS). The next stages underway are focused on developing improved retrieval algorithms that push the limits of flux measurement capabilities from existing instruments. Ultimately, there is broad interest in developing a coordinated system of satellite instruments for heat and momentum fluxes. These could fly either on board a single satellite or on multiple satellites flying in formation as a "Flux-Train," analogous to the current series of atmospheric satellites known as the A-Train. For time scales typical of the synoptic scale in the atmosphere, an accuracy of 5 Wm^{-2} in net energy fluxes is considered a desirable, albeit challenging, target for the combined satellite and in situ observing system. Additional preliminary work will need to be completed to determine the extent to which this is possible with current satellite technology.

3. *Make observations and flux products more accessible.* Along with the need for more observations of high-latitude fluxes comes a parallel need to improve access to observations and the flux products derived from them (such as NWP reanalyses). This involves a number of issues that will benefit a broad range of user communities. Workshop participants noted that data users sometimes select flux-related data products primarily on the basis of the time period covered, the specific variables available, or even the convenience of finding data, without considering the appropriateness of the dataset for a particular application. To address these existing difficulties, first, flux-related data need to be easy to find. Although high-latitude data are sparse, meteorological sensors have been installed on the Antarctic support vessels in recent

years, and a number of recent programs have collected observations in adverse high-latitude conditions. Flux-related measurements from field programs, ships of opportunity, and satellites need to be archived. Data collectors and product developers are encouraged to provide their data to centers, where users can easily identify and cross-compare a wide range of measurements and/or flux products that may be relevant for their work. More importantly, data providers and data centers need to release flux-relevant data along with a full set of metadata explaining the origins of the data and the inherent uncertainties.

4. *Encourage flux intercomparison*. Users of flux products often struggle to select a single flux product from among the plethora of options derived using different methods, all with different strengths and deficiencies. Given the lack of clear community consensus about how best to determine fluxes, a better approach is to intercompare multiple products (e.g., Dong et al. 2007; Cerovecki et al. 2011a). Data providers in particular recommended that users take time to evaluate multiple flux products and to consider whether a particular flux product is suited for various applications. In a multiproduct approach, the variability among different products can serve as a crude measure of the robustness of results. While workshop participants suggested that a multiproduct approach is nearly always appropriate, they were also enthusiastic about establishing an organized effort to coordinate flux-product intercomparisons and synthesize the results. For example, one suggestion was to develop a specific set of metrics (e.g., determining the resolution of products, biases, and uncertainties) and techniques (e.g., power density spectra) for evaluating flux data products that could be disseminated along with the data themselves. A step beyond establishing metrics for flux evaluation would be a global effort to improve surface flux estimates analogous to the effort of the Group for High-Resolution Sea Surface Temperature (GHRSST).

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Figure Captions

Figure 1. Schematic of surface fluxes and related processes for high latitudes. Radiative fluxes are both shortwave (SW) and longwave (LW). Surface turbulent fluxes are stress, sensible heat (SHF), and latent heat (LHF). Ocean surface moisture fluxes are precipitation and evaporation (proportional to LHF). Processes specific to high-latitude regimes can modify fluxes. These include strong katabatic winds, effects due to ice cover and small-scale open patches of water associated with leads and polynyas, air-sea temperature differences that vary on the scale of eddies and fronts (i.e., on the scale of the oceanic Rossby radius, which can be short at high latitudes), and enhanced fresh water input associated with blowing snow.

Figure 2. Frequency of winds exceeding 25m/s for the QuikSCAT observations from July 1999 through June 2009, based on Remote Sensing Systems' Ku2001 algorithm. Statistics are computed by averaging vector winds from the original satellite swath measurements into 0.25° by 0.25° bins. Northern Hemisphere extreme winds are associated with topography (e.g. around Greenland, see Renfrew et al. 2008) and western boundary currents and occur in boreal winter; Southern Hemisphere events are more widespread and occur year around. Locations with less than approximately 51% of possible observations are plotted as white, thereby excluding some regions with too much seasonal ice.

Figure 3. Spatial and temporal scales for high-latitude processes and the recommended accuracy of related surface fluxes. These accuracies are estimates from a wide range of scientists working on related processes. The accuracy requirements are difficult to determine or validate, as the modeling and observational errors, as well as the validity of assumptions, in current estimates are not sufficiently well understood to quantify requirements.

Figure 4. Boundary-layer observations of a cold-air outbreak off the east coast of Greenland during an instrumented aircraft flight on 5 March 2007, as a function of distance from the coast. Panels show (top) 2-m temperature (red) and sea surface temperature (blue); (middle) 10-meter wind speed; and (bottom) surface sensible (red) and latent (blue) heat fluxes calculated using the eddy covariance method (taken from Petersen and Renfrew 2009) as a function of distance. The observations are averaged into 12-km runs (circles). Interpolated estimates from ECMWF operational analyses (solid line) and the much coarser resolution NCEP global reanalyses (dashed line) are also plotted. The plots show a rapid warming from over the sea ice zone (0–30 km) off shore and a jump in wind speed and observed heat fluxes across the ice edge.

Figure 5. Comparison of oceanic sensible (top) and latent (bottom) heat fluxes from readily available products: NCEP2 (blue), JMA (green), ERA40 (purple), IFREMER (red), and HOAPS (cyan). Each box shows zonally averaged (0 through 360 degrees) monthly fluxes for the 5th, 25th, 50th, 75th, or 95th percentiles. The period for comparison (for which all products are available) is March 1992 through December 2000. Clearly there are very large differences in the distribution of fluxes. Note that the range of fluxes (*x*-axis) is not constant, with the range for the 95th percentile being about 4 times the range for the 5th percentile. Furthermore, there is a great deal of regional surface flux variability in all high-latitude seas: product differences are greater on smaller spatial and temporal scales. Details about the data, parameterizations and assumptions used to develop these products are given in Smith et al. (2010).

Figure 6. The 10-m neutral turbulent transfer coefficients (C_{d10n}, C_{E10n}, C_{H10n}) and the CO_2 transfer velocity ($K_{660} = C_G \; |(U_{10} - U_s)|$) as a function of 10-m neutral wind speed from direct surface-based

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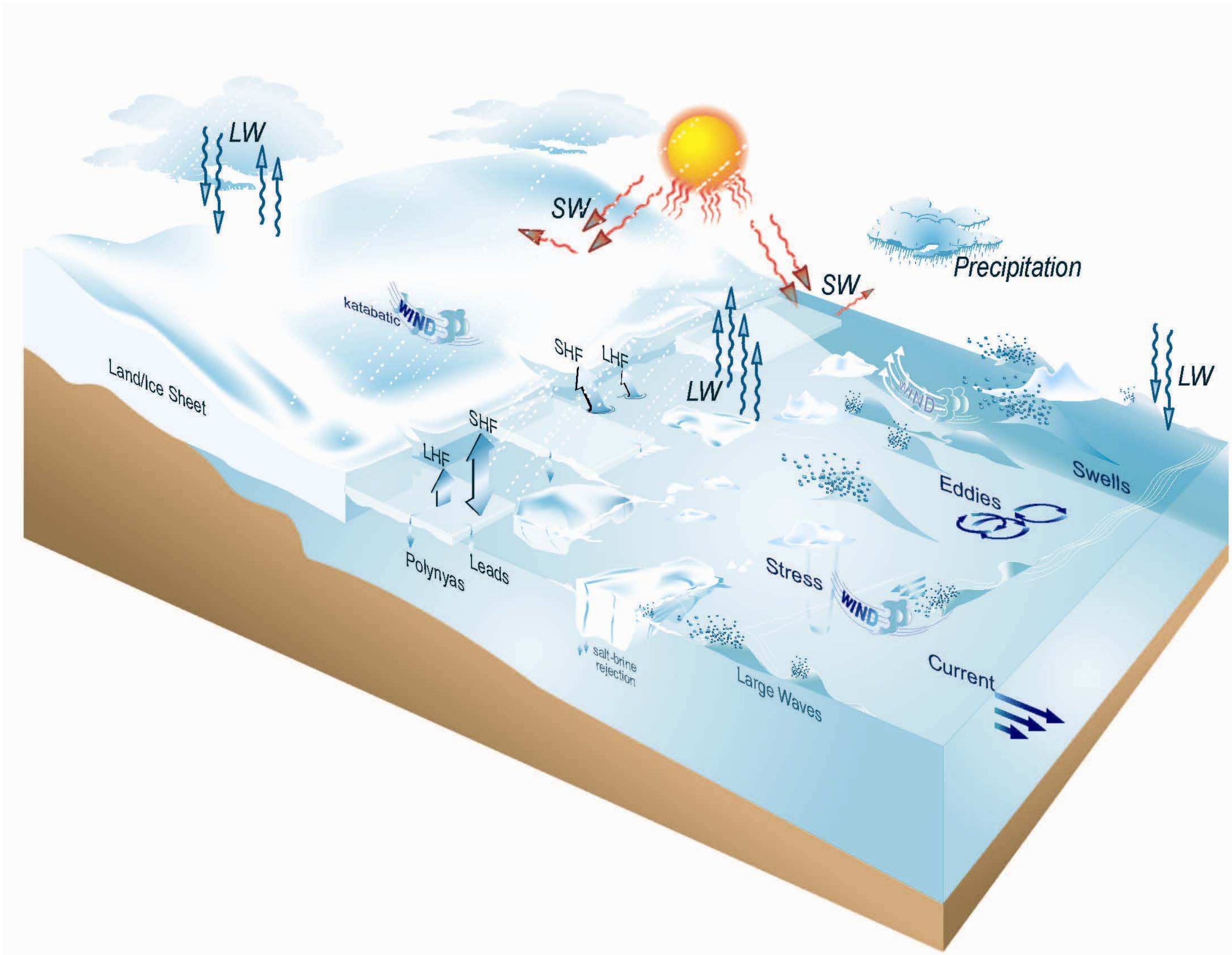
Figures



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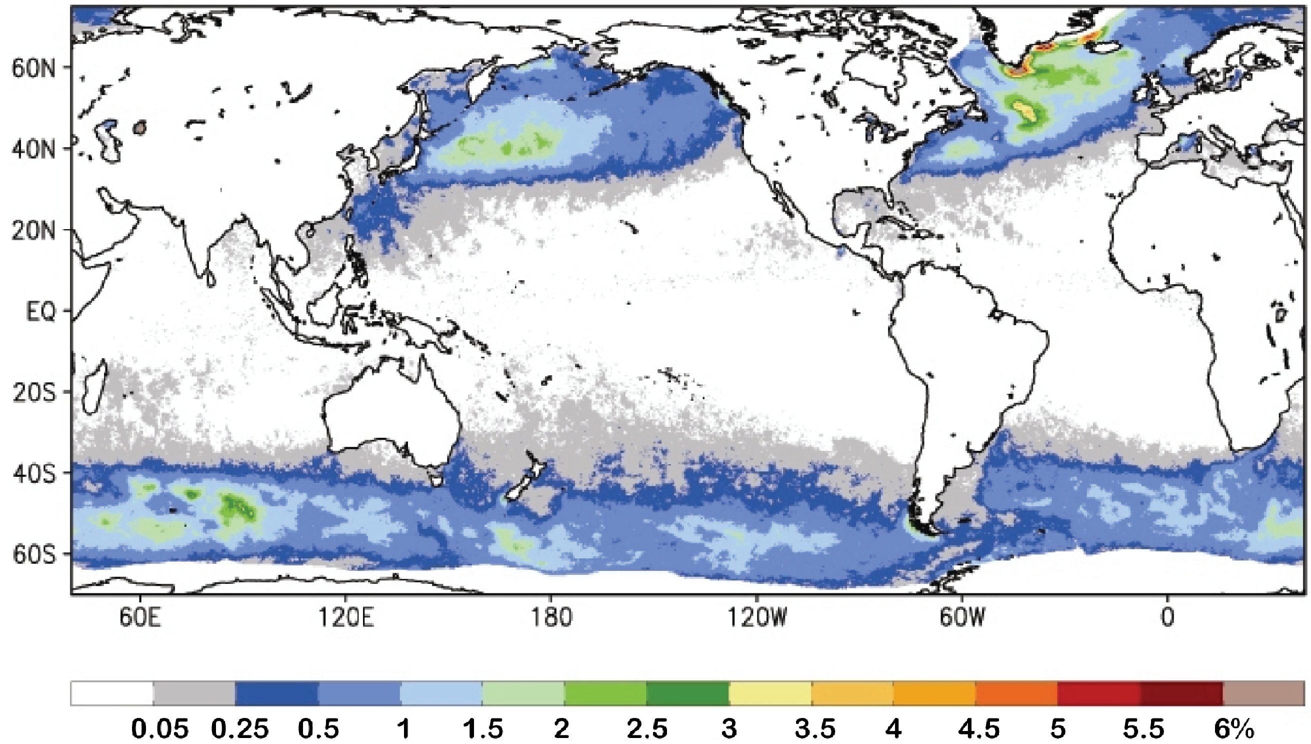

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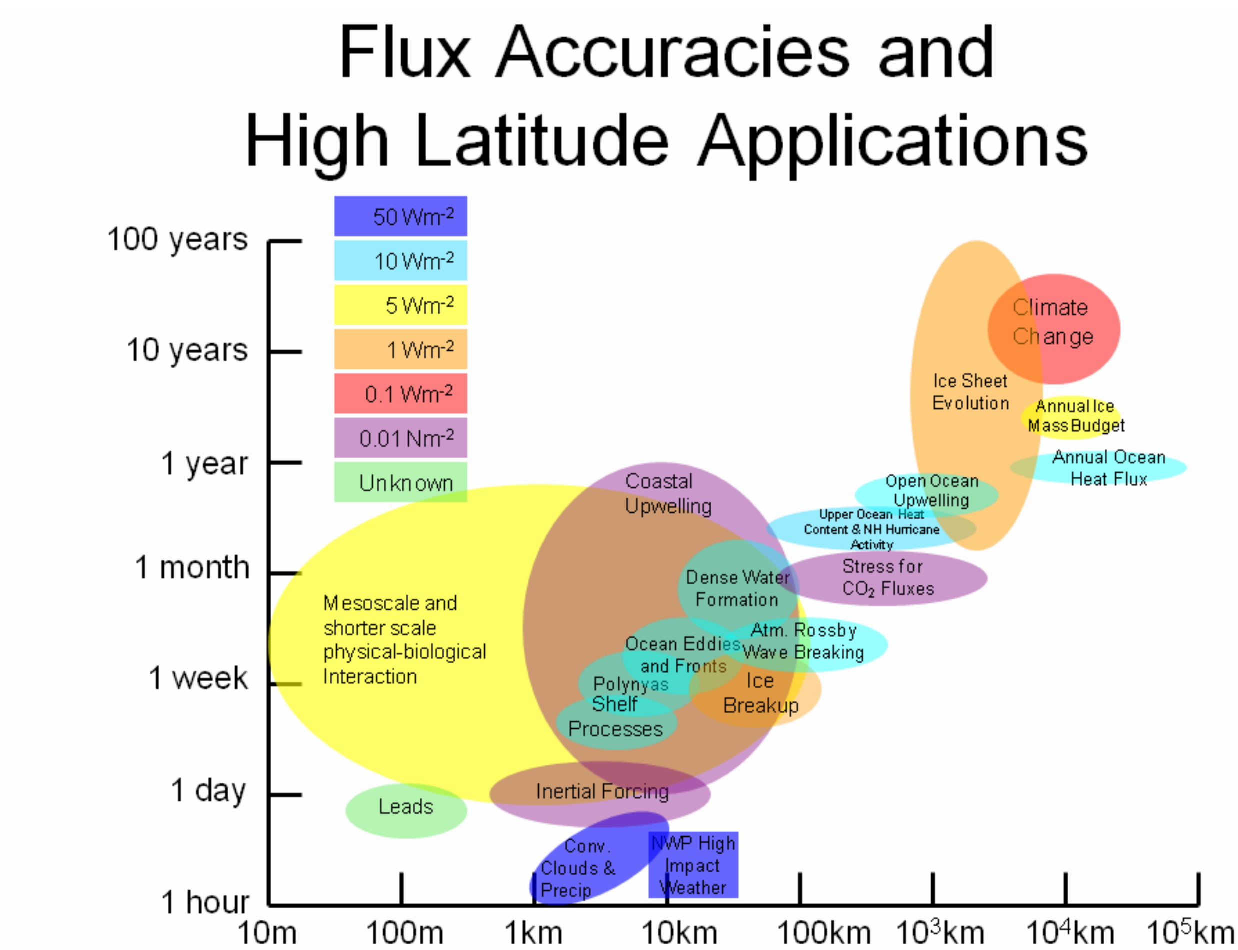

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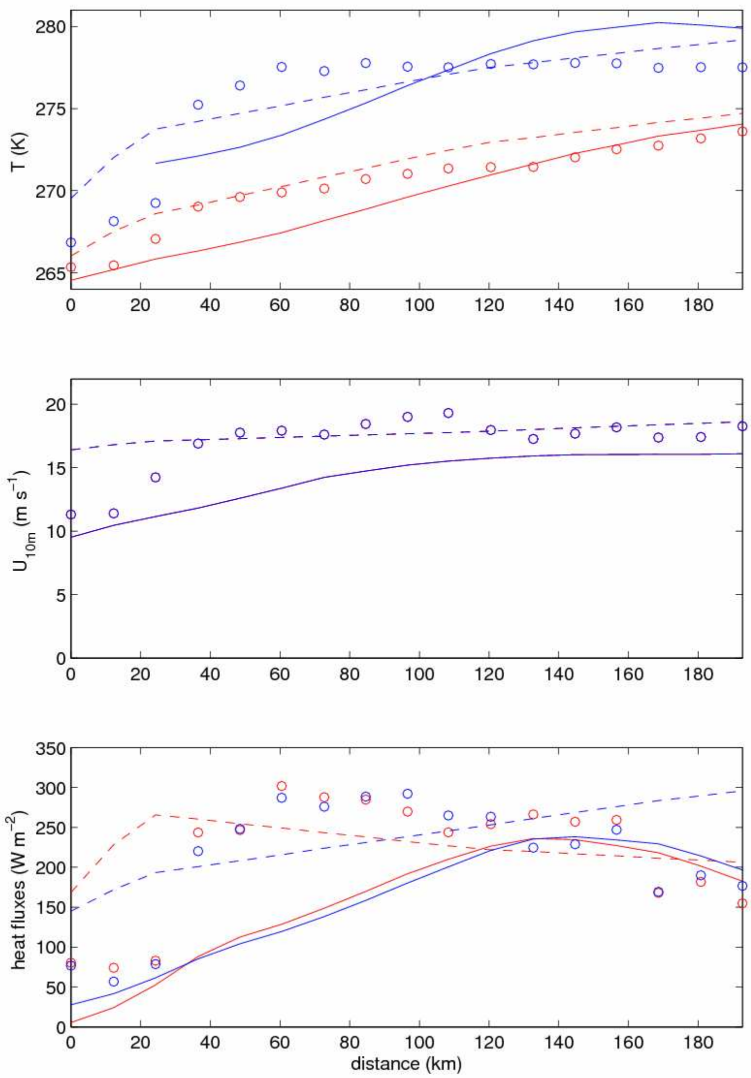

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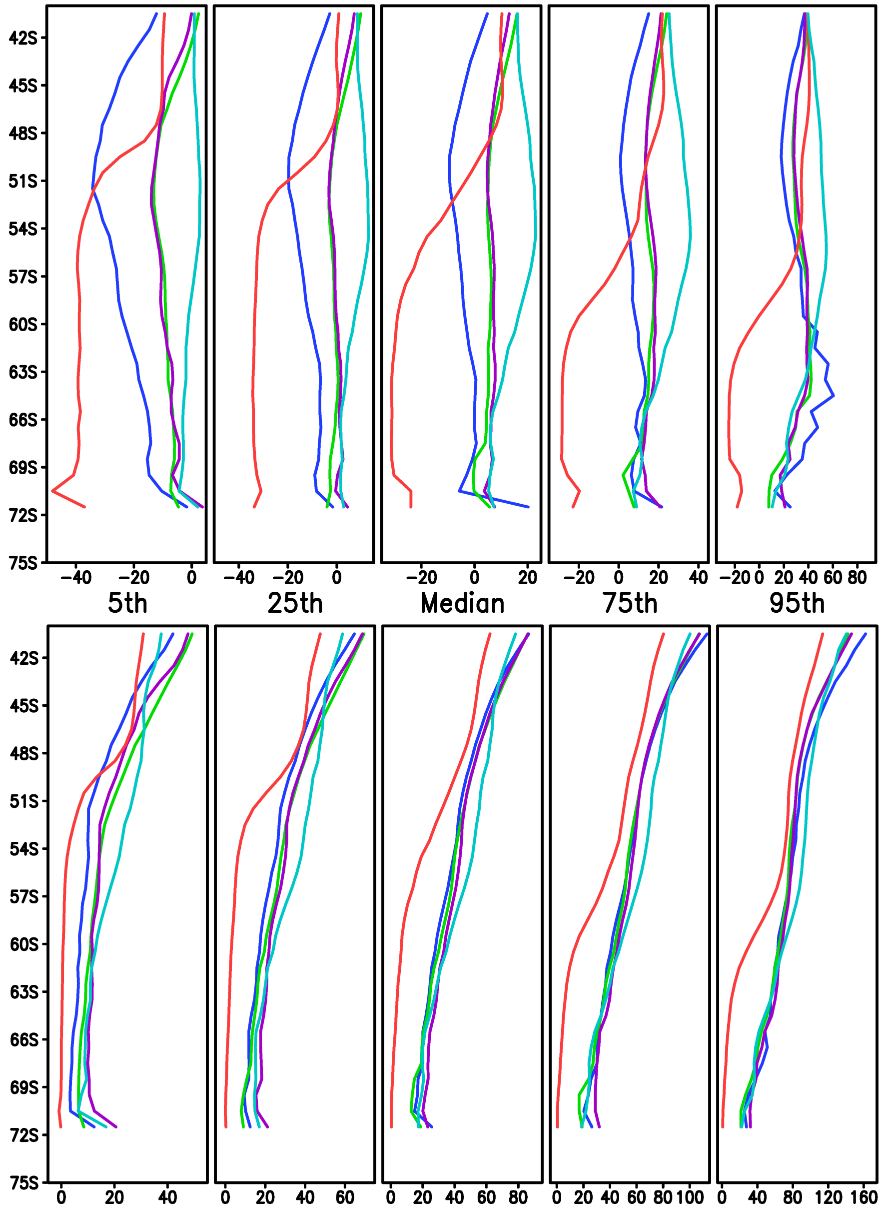

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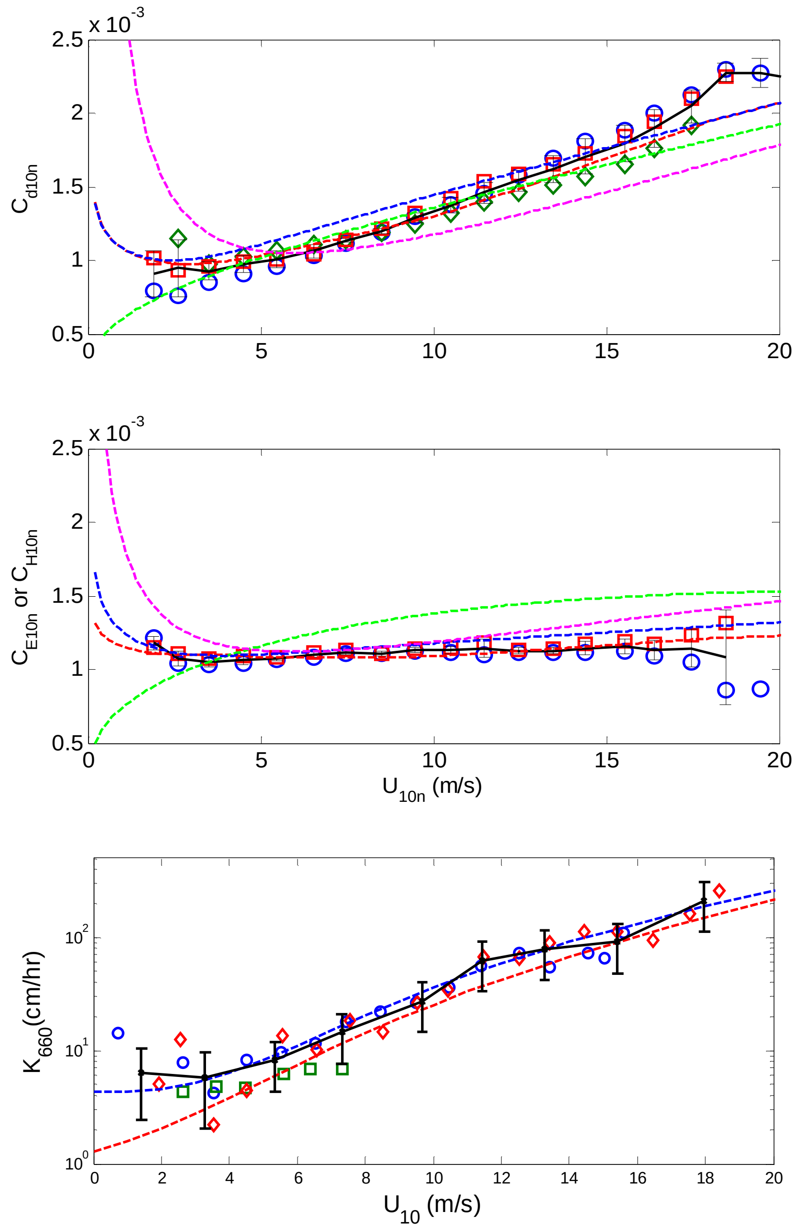

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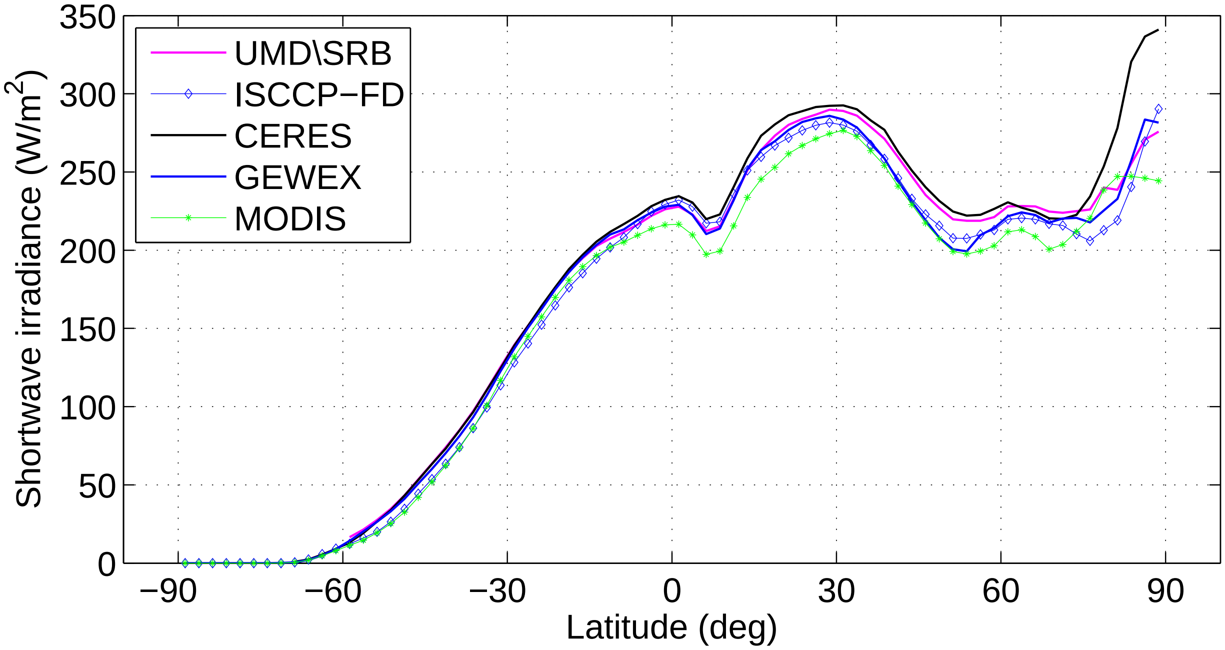

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