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Expected uncertainty in satellite–derived estimates of the surface radiation budget at high latitudes

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Abstract. An analysis of spatial and temporal variations of the polar radiation budget will undoubtedly require the use of multispectral satellite data. How well we can estimate the radiation balance depends on how well we can estimate the physical and microphysical properties of the surface and atmosphere that directly affect it, e.g., surface temperature and albedo, cloud droplet effective radius, cloud optical depth, cloud thickness, and cloud height. Here we examine our current ability to estimate the high-latitude surface radiation budget using visible and thermal satellite data. The method for estimating radiative fluxes incorporates estimates of surface and atmospheric parameters, so the accuracy with which these can be retrieved from satellite data is first assessed. The effects of errors in the estimates of these parameters on the surface net radiation during summer and winter are quantified, and the relative sensitivity of the net radiation budget to errors in individual parameters is assessed. The combined uncertainty is then determined and examined in light of validation data in the Arctic. The results show upper and lower bounds for the uncertainties between 7.9 and 41 W m^{-2} for instantaneous retrievals of net radiation. By far, the largest portion of the uncertainty in net radiation is associated with errors in the retrieval of surface temperature and surface albedo. Although improvements in retrievals are desirable, currently available methods can provide surface net radiation in the Arctic with uncertainties similar to those of surface-based climatologies.

Introduction

The radiation balance of the polar regions is significantly modulated by clouds, aerosols, and greenhouse gases which in turn influence global atmospheric and oceanic circulations via complicated radiative–dynamical interactions. High latitude response to changes in clouds, aerosols, and radiatively active gases within the atmosphere remains an uncertainty in evaluating climate change on a global scale. While much remains to be learned, it is clear that the surface radiation budget of the polar regions is very different from that of lower latitudes. For example, surface net radiation for high-latitude snow–covered regions tends to be greater during cloudy periods than under clear skies [*Curry et al.*, 1993; *Tsay et al.*, 1989; *Schwerdtfeger*, 1984; *Stone et al.*, 1989; *Stone and Kahl*, 1991], whereas the annual mean net effect of clouds globally is to cool the Earth's surface. The net radiative effect of clouds is determined by the competing effects of shortwave cooling (the albedo effect) and longwave warming due to cloud thermal emissions [e.g., *Ramanathan et al.*, 1989]. The effect of clouds on the net radiation balance of the surface/atmosphere system is very complex, particularly in the central Arctic where nonlinear feedbacks occur between the ice/snow/ocean surfaces and the clouds which in turn radiatively modulate the surface properties [*Curry et al.*, 1993].

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The most comprehensive, long-term information on Arctic radiative fluxes is nearly 30 years old. The climatologies of *Marshunova* [1961], *Marshunova and Chernigovskiy* [1966], and *Vowinckel and Orvig* [1962, 1963, 1964] are based on information from a sparse network of drifting stations, ice islands, and coastal stations. While some of the coastal stations have provided reliable long-term records of radiation balance components [*Ohmura and Gilgen*, 1991], for the ice-covered areas of the Arctic Ocean these climatologies rely on drifting station records with highly variable temporal and spatial deployment histories. Further, drifting stations are generally established on large multiyear ice floes or ice islands and measurements are therefore more representative of thick ice areas where the energy fluxes through the ice are small [*Makshtas*, 1991]. *Fletcher* [1966] reviewed the information then available on radiative fluxes. He questions *Gavrilova*'s [1961] estimates that total solar radiation in the Arctic is known to an accuracy of 2.5% for annual fluxes and 5-10% for monthly fluxes, absorbed solar radiation to 10-15%, outgoing longwave to 15-20%, and the radiation balance to 20-30% on the basis that differences between Marshunova's and Vowinckel and Orvigs' climatologies are much greater than the estimated accuracies. However, he concluded that the compilation of *Marshunova* [1961] probably represented the most accurate description of the radiation climate in the Arctic. *Ohmura* [1981] arrived at the same conclusion almost 20 years later. The record from Russian drifting stations continues until 1991 [*Marshunova and Mishin*, 1994] but has not yet been processed into a comprehensive climatology.

Because it is impractical to make polar–wide surface measurements of the radiation balance, the use of spaceborne platforms to remotely monitor these regions will be necessary. A thorough evaluation of the radiative effects of the intervening atmosphere is needed before satellite radiance measurements can be interpreted unambiguously. This need for the development and validation of data sets of surface radiation balance components derived from satellites was clearly identified by the World Climate Research Programme [*Raschke et al.*, 1992]. Digital imagery of suitable temporal and spatial resolution needed to study intervening atmospheric effects is routinely available, but methods to utilize this data for radiation climate studies in the polar regions are just emerging.

Reviews of techniques to infer surface radiative fluxes from top of the atmosphere (TOA) radiances are provided by *Schmetz* [1989], *Raschke et al.* [1992], and *Schweiger and Key* [1994], where problems with the application of such techniques to the polar regions are also discussed. Median root-mean-square errors (RMSE) of satellite-derived solar fluxes for lower latitudes are near 5% for monthly sums, near 9% for daily sums, and 5-50% for hourly sums [*Schmetz*, 1989]. Using data from the International Satellite Cloud Climatology Project (ISCCP), *Rossow and Zhang* [1995] conduct sensitivity studies and estimate the uncertainty in downwelling shortwave and longwave radiation fluxes to be on the order of 10-20 W m^{-2} for regionally and daily averaged values but point out that errors in the polar regions are potentially larger. Their estimates are confirmed by comparisons with surface measurements.

To date, only a small number of case studies have been conducted in the polar regions. Using surface and aircraft measurements from the Fram Strait area during the Arktis-88 experiment, *Bauer and Raschke* [1990] found that satellite-derived solar irradiances were underestimated by 30-50 W m^{-2} or 10%. They found these errors to be particularly large near the ice edge where the resolution of the advanced very high resolution radiometer (AVHRR) sensor is insufficient to distinguish ice free and ice-covered areas. Satellite-retrieved surface albedos were lower by up to 0.2 than those measured on the ground, which contributed to the error in downwelling shortwave fluxes. Combining a discrete-ordinate radiative transfer model [*Stamnes et al.*, 1988] for the inversion of satellite radiances to cloud transmissivities and a two-stream model for the calculation of radiative fluxes at the surface, *Kergomard et al.* [1993] found a 10 W m^{-2} agreement between satellite-retrieved fluxes and those measured on board a ship in Fram Strait on August 31, 1988. *Schweiger and Key* [1994] performed the first large-scale study of surface and TOA radiation budgets using satellite data. In that study the monthly cloud product of the ISCCP was used with a radiative transfer model to compute surface and TOA radiative fluxes. However, validation could only be done with the historical radiation climatologies, so that the accuracy of their results is difficult to assess. Using a similar method but with 3-hourly ISCCP data, *Rossow and Zhang* [1995] compare computed radiative fluxes with surface measurements at Barrow and South Pole station for October 1986. They find errors in downwelling shortwave fluxes for daily means to be on the order of 10-25 W m^{-2}. Downwelling longwave fluxes were found to be poorly correlated with surface measurements.

In this paper we examine our current ability to estimate the surface net radiation budget at high latitudes from visible and thermal infrared satellite data, specifically the AVHRR. In contrast to the global analyses described above, the underlying method [*Key*, 1995, 1996b] for the retrieval of surface and atmospheric physical properties, as well as the computation of radiative fluxes, was developed to account for the unique features of the polar regions. Uncertainties in the estimate of surface and cloud parameters are assessed, and their individual and combined influence on estimates of the surface radiation budget is determined.

Approach

The method for estimating radiative fluxes addressed here incorporates estimates of surface and atmospheric parameters, so the accuracy with which these can be retrieved from satellite data must also be assessed. Both empirical and theoretical methods are briefly described and the uncertainty in measuring each of these parameters is given. Uncertainties are derived from validation results where available and are root-mean-square errors (the square root of the mean squared difference) computed from the differences between ensembles of satellite-derived and hourly surface observations. In this context, "uncertainty" is to be understood as a measure of the average unsigned difference between an individual satellite measurement and a validation datum in the same sense that a standard deviation relates differences between individual values and the mean of a population. For parameter retrieval methods lacking validation data, the uncertainty is represented as a fixed percentage of some reference value. The effects of errors in the estimates of surface and atmospheric parameters on the components of the surface radiation balance during summer and winter over open water and snow-covered surfaces are quantified, and the relative sensitivity of the net radiation budget to errors in individual parameters is assessed. The combined uncertainty is then determined and compared to surface measurements of shortwave, longwave, and net radiation. Although the uncertainty estimates presented here are based on results using a specific collection of retrieval methods for high-latitude geophysical parameter retrieval [*Key*, 1995, 1996b], within the limits discussed later, results are applicable to the calculation of surface fluxes using different approaches. Results are presented to allow for "back of the envelope" calculations of uncertainties in the fluxes based on different uncertainty estimates for the relevant parameters. Even though, for example, one may only be able to estimate cloud fraction to within 20% rather than our estimated uncertainty of 10%, the information provided here can still be used to obtain an estimate of the uncertainty in flux estimates.

Parameter Retrieval

In this section we briefly describe the geophysical parameters that are retrieved from satellite data for use in the estimation of high-latitude radiative fluxes, how they are retrieved, and their known or probable accuracies. See *Key* [1995, 1996b] for more details.

Surface Parameters

Surface skin temperature T_s and surface broadband albedo α_s are indicators of many physical aspects of the surface such as snow and ice thickness, grain size, and water content. They occur explicitly in the energy balance equation, and therefore their retrieval from satellite data is desirable. The temperature of the ice surface, which may actually be snow or a mixture of snow, bare ice, and open water, can be retrieved under clear sky conditions using the AVHRR split-window channels in a manner similar to that used in sea surface temperature retrieval. *Key and Haefliger* [1992] first presented such a procedure which utilized Arctic rawinsonde data and modeled snow emissivities with a radiative transfer model to simulate AVHRR brightness temperatures. *Key and*

Collins [1997] refined that procedure and expanded the geographic applicability. The surface temperature predictor equation has the form

$$T_s = a + bT_4 + c(T_4 - T_5) + d(T_4 - T_5)(\sec\theta - 1) \quad (1)$$

where T_4 and T_5 are the channel 4 (11 μm) and 5 (12 μm) brightness temperatures, θ is the sensor scan angle, and *a, b, c,* and *d* are coefficients determined through linear regression.

From comparison with buoy measurements and surface measurements in the field [e.g., *Key et al.*, 1994; *Key*, 1996b], errors in clear sky T_s are on the order of 0.5 K for summer and 0.5-2 K for winter conditions. These errors are largely a result of inaccuracies in cloud detection, which is particularly problematic when lower tropospheric ice crystals are present. Equating the clear sky temperatures to cloudy sky conditions for radiative flux calculations does, of course, introduce additional error on the order of 1-5 K. In the sensitivity studies we use an uncertainty of 1 K for summer, 3 K for winter over snow, and 4 K for cloudy conditions.

Narrowband surface albedo is retrieved by correcting the satellite radiance for anisotropic reflectance and atmospheric attenuation using a method modified from *Lindsay and Rothrock* [1994]. To correct for the angular dependence of reflectance on the sun-satellite-surface geometry, the TOA anisotropic reflectance factors of *Taylor and Stowe* [1984] are used. The atmospheric correction is based on the relationship

$$\rho_t = a + b\rho_s \quad (2)$$

where ρ_t is the TOA reflectance, ρ_s is the surface reflectance, and *a* and *b* are regression coefficients specific to certain amounts of ozone, water vapor, and aerosols [*Koepke*, 1989].

DeAbreu et al. [1994] follow these steps and compare satellite-derived albedos to in situ data. Since there is no onboard calibration of the AVHRR shortwave channels, time-dependent calibration coefficients were employed. However, calibration is still the largest source of uncertainty, with unknown aerosol amounts and questionable anisotropic reflectance factors being important contributors. Uncertainty for snow is on the order of 0.05, absolute. The uncertainty in albedo retrieval over open water is probably less than that for snow, given the weaker dependence on viewing geometry if specular reflectance effects are excluded through proper selection of Sun and viewing angles. Lacking any validation for open water, we use a value of 0.01 for the uncertainty [*Zhang et al.*, 1995].

Cloud Parameters

Because the retrieval of surface temperature and albedo as described above are done for clear sky only, accurate cloud detection is critical. A variety of methods have been utilized, employing spectral and textural features, thresholding, statistical classifiers, and neural networks. In the presence of solar radiation, spectral features alone should provide enough information for surface/cloud discrimination. During the polar night, clouds are often warmer than the surface, rendering simple temperature thresholding methods useless. Brightness temperature differences can be useful, but clear sky and optically thick clouds may still be indistinguishable.

Our error assessment for cloud detection here assumes a spectral thresholding method, but one that incorporates time; that is, the temporal variability of each location is examined under the assumption that clear sky spectral characteristics will change little over short periods of time. This methodology is utilized in the

TABLE 1. Downwelling Shortwave, Downwelling Longwave, and Net Flux Sensitivities for Clear Summer Over Snow and Over Open Water

Parameter	Reference Value	Error, ±	Shortwave Down Difference, %	Shortwave Down $\Delta F/\Delta x$	Longwave Down Difference, %	Longwave Down $\Delta F/\Delta x$	Net Difference, %	Net $\Delta F/\Delta x$
				Snow				
T_s, K	272	1	0.0	0.00	< 0.1	< 0.01	4.3	-4.51
α_s, at 0.6 m	0.6	0.05	0.4	30.30	---	---	11.9	-250.80
O_3, g m^{-2}*	7.15	0.1	0.01	-0.5	< 0.1	0.30	< 0.1	0.05
PW, mm	11.9	2.4 (20%)	0.7	-1.01	0.7	0.70	0.1	-0.053
τ_h	0.08	+0.22	9.4	-144.50	1.8	19.36	10.2	-48.96
T(*z*), K	---	2-3	0.4	-0.50	4.1	3.20	8.4	2.96
				Water				
T_s, K	271.4	1	0.0	0.00	< 0.1	< 0.01	2.0	-4.48
α_s	0.07	0.01	0.1	25.00	---	---	1.3	-301.50
O_3, g m^{-2}	7.15	0.1	< 0.1	-0.45	< 0.1	0.30	0.01	-0.15
PW, mm	11.9	2.4 (20%)	0.7	-1.00	0.7	0.70	0.2	-0.23
τ_h	0.08	+0.22	10.8	-158.96	1.8	19.36	12.3	-128.64
T(*z*), K	---	2-3 K	0.5	-0.52	4.1	3.20	3.5	2.68

Solar zenith angle in all summer calculations is 70°. Variables are defined as follows: T_s is surface temperature, α_s is surface albedo, O_3 is ozone, *PW* is precipitable water, τ_h is aerosol optical depth, and *T(z)* is the temperature profile. Numbers in parentheses denote the percent errors that correspond to the actual errors shown.

*1 Dobson unit = 0.021416667 g m^{-2}

International Satellite Cloud Climatology Project [*Rossow and Garder*, 1993], and has been applied to Arctic conditions by *Key and Barry* [1989] and modified by *Key* [1996b]. With this procedure we estimate the error in cloud fraction A_c to be 10% (relative) during the polar day and 15% during the polar night, determined by comparisons to manual interpretations of AVHRR imagery. Reference values are based on the results of *Schweiger and Key* [1992].

Cloud particle effective radius *Re* and liquid or ice water content can be related empirically to the single scattering albedo, extinction, and the asymmetry parameter. While cloud water content is not directly retrievable from satellite data, the optical depth τ_c can be estimated. *Nakajima and King* [1990] showed that the effective radius and optical depth exhibit a nearly orthogonal relationship in the reflectances of one absorbing and one nonabsorbing wavelength, e.g., AVHRR channels 1 (0.6 μm) or 2 (0.9 μm) and 3 (3.7 μm). This idea works well over surfaces with low reflectances, but the solution becomes ambiguous at small optical depths over surfaces such as snow and ice. At night a similar approach can be used to estimate τ_c. Employing brightness temperature differences between all thermal channels can help resolve the cloud top vertical position, an additional unknown.

Uncertainties in the daytime retrieval of cloud optical depth and particle effective radius arise from uncertain calibration of the shortwave channels, incorrect representations of the scattering phase function in the modeled data, and uncertainties in the surface albedo. At night the uncertainties are due primarily to the potentially small signal-to-noise ratio in channel 3 and the use of clear sky surface temperature in lieu of the actual surface temperature under the cloud. Lacking any validation data, we place a potential error of 50% on optical depth and errors of 2 and 10 μm for water and ice cloud effective radii, respectively. Reference values are chosen to be consistent with results of *Leontyeva and Stamnes* [1993] and *Ebert and Curry* [1992].

Cloud top height Z_c and temperature are determined from the channel 4 brightness temperature, the temperature profile, and the cloud optical depth. For thick clouds the cloud top temperature is simply the brightness temperature. For optically thin clouds the height and temperature are adjusted to take account of the surface contribution to the upwelling radiation. The cloud physical thickness is determined from the cloud top height, optical depth, and the assumed water content. Uncertainties in cloud top height are primarily a function of uncertainties in optical depth and the temperature profile. Lacking validation data, we use an uncertainty in cloud top height of 500 m in summer liquid clouds and 1000 m in winter ice clouds. Reference heights are chosen to represent Arctic stratus cloud in the summer and cirrus cloud in winter.

Other Parameters

Uncertainties in temperature profiles are based on studies using the Tiros Operational Vertical Sounder (TOVS). With the improved initialization inversion (3I) method, modified for use in the polar regions [*Francis*, 1994a], it has been found that while low-level inversions can be retrieved, they are generally less intense than those observed with radiosondes. Also, summer retrievals are better than winter retrievals. We use errors in the temperature profile *T(z)* determined for typical winter conditions, with differences between 3I retrievals and radiosonde data on the order of 3 K in the lower troposphere to 1-2 K in the middle and upper troposphere [*Francis*, 1994b; S.J.S. Khalsa, personal communication, 1994]. In the sensitivity tests the water vapor density is held constant when the temperatures are varied. Comparison of humidity profiles from TOVS with radiosonde data from north polar drifting stations provides an uncertainty for precipitable water PW of 20%. (J. Francis, personal communication, 1995). In the sensitivity tests, mean radiosonde temperature and humidity profiles from Arctic coastal and drifting stations during summer (June, July, August) and winter (December, January, February) are used as the reference case.

Total column ozone amount O_3 is taken from climatological means contained in the ISCCP C2 (monthly) cloud data product for the years 1984-1990. The uncertainties used in the sensitivity tests are the standard deviations for the summer and winter months poleward of 62.5°N latitude.

Aerosol optical depth τ_h is, in general, not retrievable from the AVHRR over highly reflective surfaces such as snow and ice. In the sensitivity testing a background aerosol optical depth of 0.08 is used with an Arctic haze optical model for the reference case. The difference between the normal tropospheric aerosol loading and a

TABLE 2. Downwelling Longwave and Net Flux Sensitivities for Clear Winter Over Snow and Over Open Water

Parameter	Reference Value	Error, ±	Longwave Down: Difference, %	Longwave Down: $\Delta F/\Delta x$	Net: Difference, %	Net: $\Delta F/\Delta x$
			Snow			
T_s, K	242	3	< 0.1	< 0.01	16.6	-3.18
O_3, g m^{-2}	7.22	0.37	0.1	0.19	0.1	0.21
PW, mm	2.0	0.4 (20%)	1.5	5.03	3.49	5.00
τ_h	0.08	+0.22	4.4	27.45	10.4	27.14
T(z) (K)	---	2-3	5.4	2.11	12.7	2.08
			Water			
T_s, K	272	1	< 0.1	< 0.01	2.6	-4.51
O_3, g m^{-2}	7.22	0.37	0.1	0.21	< 0.1	0.19
PW, mm	2.0	0.4 (20%)	1.5	5.01	1.2	5.00
τ_h	0.08	+0.22	4.5	27.91	3.5	27.64
T(z), K	---	2-3 K	5.4	2.11	4.2	2.09

See Table 1 for definitions.

TABLE 3. Downwelling Shortwave, Downwelling Longwave, and Net Flux Sensitivities for Cloudy Summer Over Snow

			Shortwave Down		Longwave Down		Net	
Parameter	Reference Value	Error, ±	Difference, %	$\Delta F/\Delta x$	Difference, %	$\Delta F/\Delta x$	Difference, %	$\Delta F/\Delta x$
T_s, K	268	4	0.0	0.00	0.1	0.05	16.2	-4.26
α_s, at 0.6 m	0.6	0.05	2.5	104.8	---	---	5.9	-123.50
O_3, g m^{-2}	7.15	0.1	< 0.1	-0.35	< 0.1	0.05	< 0.1	-0.10
PW, mm	11.9	2.4 (20%)	0.6	-0.48	0.2	0.17	0.4	-0.18
T(z), K	---	2-3	0.5	-0.31	4.3	4.22	11.5	4.02
Re, m	8	2	0.9	0.95	0.1	0.20	1.3	0.69
Z_c, m	1500	500	0.3	-0.001	0.4	-0.002	1.44	-0.003
A_c	0.8	0.08 (10%)	6.4	-166.5	2.0	73.8	1.7	-22.56
τ_c	10	5 (50%)	13.7	-5.64	0.5	0.30	13.7	-2.89

Assumed cloud type is stratus with a liquid water content of 0.2 g m^{-3}. *Re* is the cloud particle effective radius, Z_c is the cloud top height, A_c is the cloud fraction, and τ_c is the cloud optical depth. Numbers in parentheses denote the percent errors that correspond to the actual errors shown.

high loading situation representative of a springtime "Arctic haze" event with an aerosol optical depth of 0.3 [*Stone et al.*, 1993] is used as the uncertainty. The use of this uncertainty somewhat exaggerates the importance of aerosol loading. Since high-aerosol loading events are seasonal in the Arctic (spring time), uncertainties due to aerosols are much smaller during other times of the year. Of course, the aerosol optical depth can be substantially higher than this as a result of volcanic aerosols in the stratosphere, as was the case following the 1991 eruption of Mount Pinatubo [*Stone et al.*, 1993]. Tests for the influence of aerosols on fluxes are only done under clear conditions.

Flux Sensitivities

The estimated uncertainties in the retrieved values of surface and cloud properties are now used to assess the accuracy with which surface radiative fluxes can be estimated using satellite data. Since radiative fluxes vary nonlinearly with respect to the parameters under investigation, their sensitivity to errors varies over the range of the input parameter. Uncertainties in fluxes are therefore estimated for a set of reference values that represent the mean values. Downwelling shortwave, downwelling longwave, and net radiative fluxes at the surface are then computed for these reference cases and for the reference values plus and minus the uncertainties in estimating the individual parameters from satellite data. Results are summarized by season for clear and cloudy conditions. In the clear sky analyses, snow and open water surfaces are considered separately. The following analysis and discussion focuses on the sensitivity of net radiation because it best describes the importance of radiative processes for the energy exchange at the surface. For those interested in using satellite retrievals of downwelling radiative fluxes, e.g., as forcing fields in sea ice models, sensitivities for these quantities are also given.

The model used to calculate radiative fluxes was modified from *Tsay et al.* [1989] by replacing the discrete-ordinate solution of the radiative transfer equation with a two-stream approximation [*Toon et al.*, 1989]. Gaseous absorption is parameterized using an exponential sum-fitting technique with 24 bands in the shortwave region [*Slingo and Schrecker*, 1982] and 105 bands at 20 cm^{-1} intervals in the longwave. Cloud single scattering properties are parameterized using the scheme of *Hu and Stamnes* [1993] for water cloud and *Ebert and Curry* [1993] for ice cloud. See *Key* [1996a] for more details.

Tables 1 to 4 contain the reference values for the parameters, their estimated uncertainty, the percent change in surface radiative fluxes due to the uncertainty, and the rate of change of the fluxes with respect to a unit change in each parameter value. The percent change in the radiative flux is the error in estimating the flux given the uncertainty in estimating the individual parameter. This value allows us to assess which parameter retrieval methods need to be

TABLE 4. Downwelling Longwave and Net Flux Sensitivities for Cloudy Winter Over Snow

			Longwave Down		Net	
Parameter	Reference Value	Error, ±	Difference, %	$\Delta F/\Delta x$	Difference, %	$\Delta F/\Delta x$
T_s, K	247	4	< 0.1	0.01	33.0	-3.37
O_3, g m^{-2}	7.22	0.37	< 0.1	0.10	0.1	0.1
PW, mm	2.0	0.4 (20%)	0.5	2.28	2.2	2.25
T(z), K	---	2-3	5.2	2.50	21.2	2.47
Re, m	40	10	1.0	0.18	4.3	0.17
Z_c, m	6000	1000	2.6	-0.004	10.6	-0.004
A_c	0.6	0.09 (15%)	2.9	55.33	12.1	54.78
τ_c	5	2.5 (50%)	5.0	3.37	20.4	3.33

Assumed cloud type is cirrus with an ice water content of 0.03 g m^{-3}.

improved. For the net flux the sign convention is such that a positive value indicates an energy gain by the surface.

Tables 1 and 2 list the parameters used in the flux sensitivity studies for typical Arctic summer and winter clear sky conditions. Snow and open water surfaces are considered separately. The results are shown graphically for net radiation in Figures 1 and 2. Net flux values based on the reference cases are shown as stars; the bars give the overall range in the flux corresponding to the errors listed in the tables. Plus signs in Figures 1 and 2 are the net flux values for positive errors in the indicated parameter; minus signs show the direction of change in net flux for a decrease in the parameter value.

It is clear from the tables that expected errors in the retrieval of surface albedo, aerosols, and surface temperature yield the largest uncertainty in the surface net flux under clear sky conditions. The relative insensitivity of the downwelling longwave flux to changes in surface temperature is a result of holding the atmospheric temperatures constant in our sensitivity calculations to establish independent sensitivities. Uncertainty in aerosol estimates is a large contributor to the uncertainty of the radiation balance under clear conditions. This is particularly so over open water since aerosols increase the planetary albedo and decrease the downwelling shortwave flux. Note also that increased aerosol amounts have opposite effects on the net flux in summer and winter over open water. In summer an increase in aerosol amount decreases the net flux at the surface, whereas in winter the net flux would increase owing to the increase in the downwelling longwave flux. In winter, estimated errors in the temperature profile have a significant effect on the surface radiation balance. The large uncertainty due to aerosols may come as a surprise. It is largely due to underlying assumptions we make regarding the uncertainty of this parameter. As noted previously, we assume that nothing is known about the aerosol loading of the atmosphere and consider the typical range as the uncertainty. In reality, depending on the season or weather pattern, some assumptions regarding aerosol loading can be made. In the range of ozone considered (plus and minus 1 standard deviation), this parameter is relatively unimportant for net flux calculations.

Results for the cloudy sky tests are given in Tables 3 and 4. Net radiation sensitivities are shown in Figure 3. As in the clear sky cases, probable errors in the retrieval of surface temperature and albedo have a large effect on the net surface flux. Errors in temperature profiles have a significant impact on net radiation in both winter and summer. Errors in cloud effective radius and cloud thickness are acceptable for summer conditions but need to be reduced for wintertime. Cloud amount and optical depth also exert a significant influence on the net flux, and their retrievals from satellite data should be improved.

Propagation of Errors

The discussion in the previous section dealt only with the error in estimates of surface radiation as a function of the uncertainty in the measurement of an individual surface or cloud parameter. Can these uncertainties be combined to provide a single value summarizing the uncertainty in estimates of the surface net radiative flux?

Suppose that x and y are two variables measured with uncertainty σ_x and σ_y and the measured values are used to compute a function F. For example, x may be the surface temperature, y the cloud thickness, and F the downwelling longwave flux. If the uncertainties in x and y are independent and random, then the uncertainty in F is

$$\sigma_F = \sqrt{\left(\frac{\partial F}{\partial x}\sigma_x\right)^2 + \left(\frac{\partial F}{\partial y}\sigma_y\right)^2} \quad (3)$$

This expression can be expanded to any number of independent variables. If, however, the variables x and y are not independent, then the covariance between them σ_{xy}, which has units xy, must be considered

$$\sigma_F = \sqrt{\left(\frac{\partial F}{\partial x}\sigma_x\right)^2 + \left(\frac{\partial F}{\partial y}\sigma_y\right)^2 + \frac{\partial F}{\partial x}\frac{\partial F}{\partial y}2\sigma_{xy}} \quad (4)$$

Note that if x and y are negatively correlated, then the total error estimated by (4) may be less than that estimated using (3).

Unfortunately, data needed to estimate the covariance between all pairs of variables are often not available. If the covariance between pairs of variables is not known, then it can be shown [*Taylor*, 1982] that the total uncertainty will never exceed

$$\sigma_F \le \left|\frac{\partial F}{\partial x}\right|\sigma_x + \left|\frac{\partial F}{\partial y}\right|\sigma_y \quad (5)$$

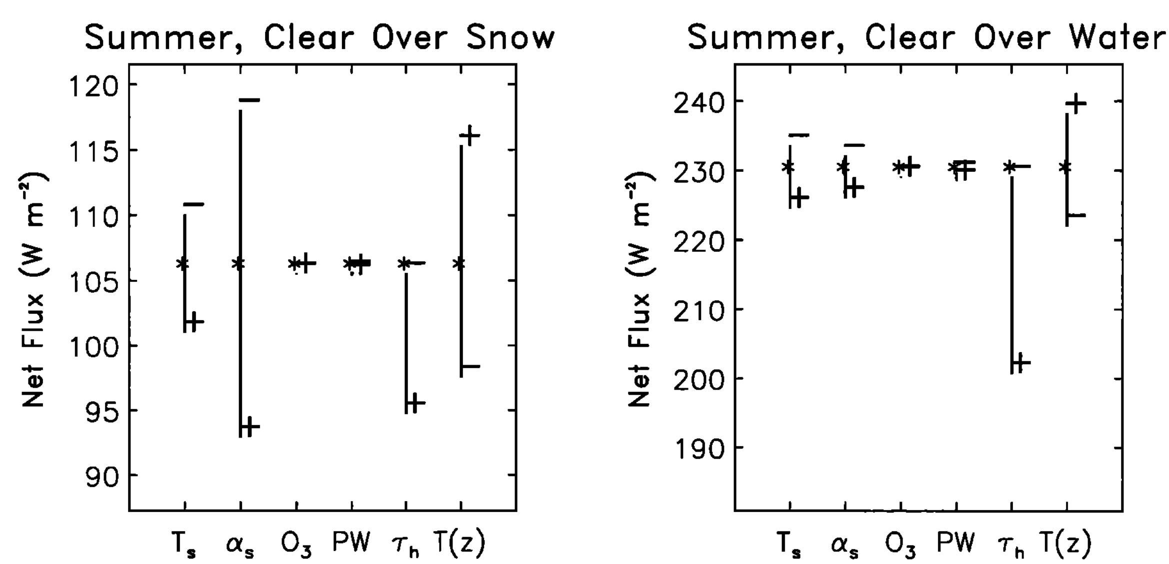

Figure 1. Sensitivity of the net surface radiative flux to expected errors in parameters retrieved under clear sky conditions, for both snow and open water conditions in summer.

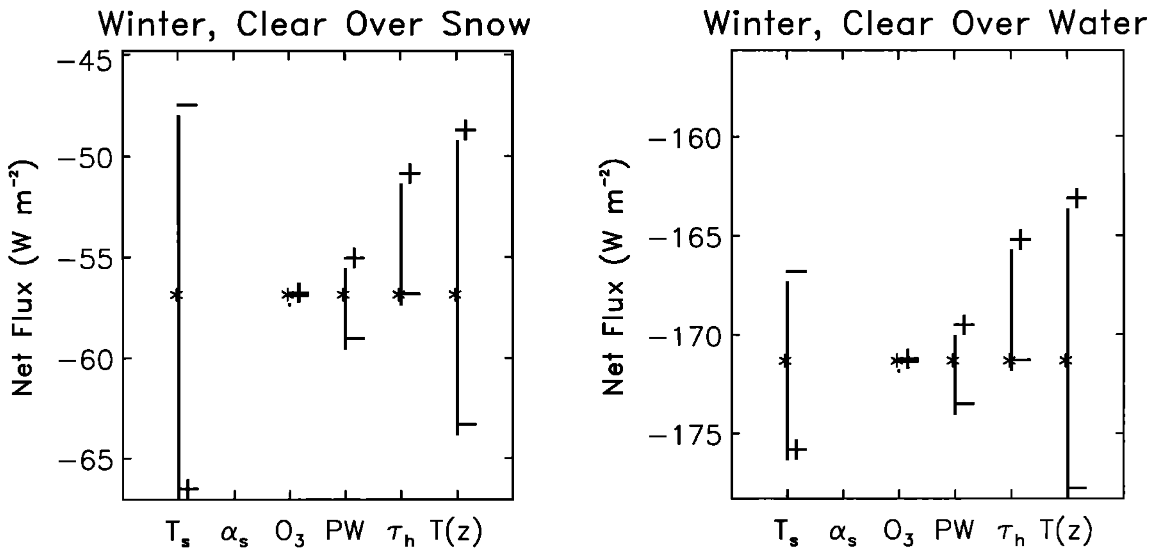

Figure 2. Sensitivity of the net surface radiative flux to expected errors in parameters retrieved under clear sky conditions, for both snow and open water conditions in winter.

Tables 1-4 give an estimate of the partial derivatives needed in (3), (4), and (5), computed using finite differences ($\Delta F/\Delta x$). These partial derivatives may be used for back of the envelope calculations of the sensitivity of fluxes to errors in parameter estimates different from the ones used in this study. However, owing to the nonlinearities in $\partial F/\partial x$, they should only be applied to situations similar to the listed reference values.

Table 5 gives the combined uncertainty in estimating the surface radiative fluxes from satellite data (AVHRR) for each of the conditions in Tables 1 to 4, assuming independence between the variables, as defined by (3). This assumption is reasonable for some pairs of variables but probably incorrect for others. Therefore the maximum uncertainty as defined by (5) is also given.

Application

The parameter retrieval methods described above have been applied to an annual cycle of AVHRR data covering the Beaufort Sea north of Alaska. Simultaneous ground measurements were obtained for Barrow, Alaska, and are used for comparison to the satellite-derived quantities. Barrow data were collected by National Oceanic and Atmospheric Administration personnel at the Climate Monitoring and Diagnostic Laboratory (CMDL) baseline observatory (71.32°N,156.61°W) near Barrow, Alaska (BRW). Downwelling and upwelling shortwave and longwave radiation are measured continuously at BRW [*Stone et al.*, 1996]. Although situated on the Arctic tundra, where complete melting of the snow occurs each summer, the site is generally considered to be representative of an Arctic maritime climate because the prevailing winds are northeasterly, off the Beaufort Sea; all observations are made within 2 km of the coast. It is a very cloudy region and one of high relative humidity. Surface albedo varies from about 0.18 during summer months to over 0.86 when snow covered. The data used in this study have been carefully error-checked and calibrated. Shortwave irradiance measurements are accurate to within 3%, on average, with systematically greater uncertainties as

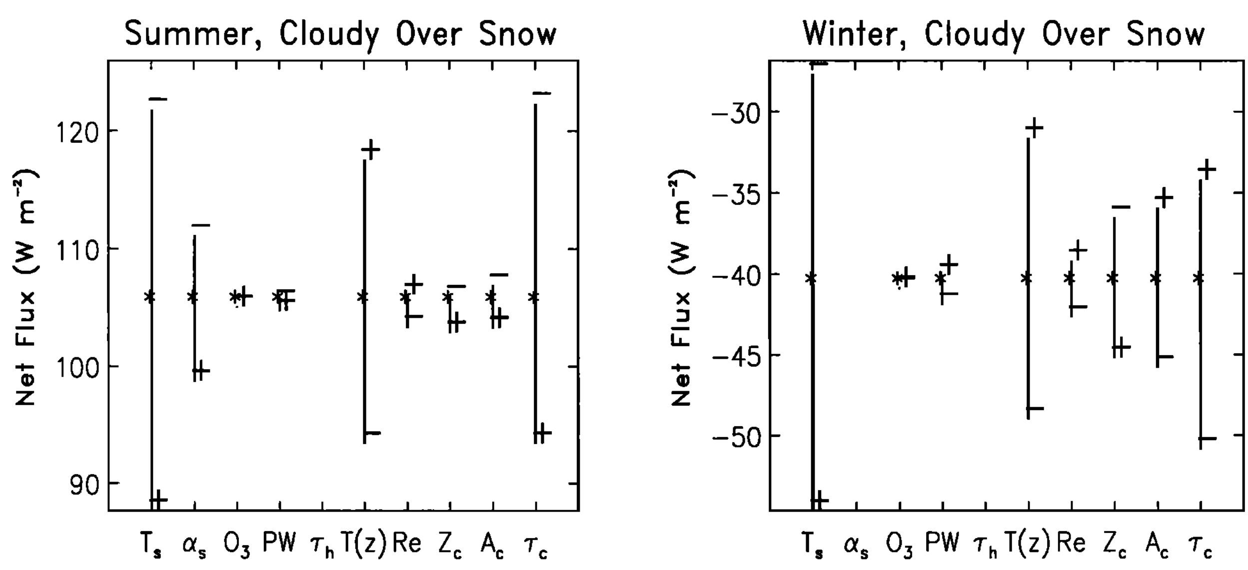

Figure 3. Sensitivity of the net surface radiative flux to expected errors in parameters retrieved under cloudy conditions (snow only) in summer and winter.

TABLE 5. Combined Uncertainty in Estimating the Surface Radiative Fluxes

Conditions	Shortwave Down		Longwave Down		Net	
	Uncertainty, Independence	Maximum Uncertainty	Uncertainty, Independence	Maximum Uncertainty	Uncertainty, Independence	Maximum Uncertainty
Clear summer over snow	32.0	37.2	10.6	15.6	19.3	36.8
Clear summer over water	35.1	39.2	10.6	15.6	29.9	44.4
Clear winter over snow	---	---	9.7	15.5	13.6	24.9
Clear winter over water	---	---	9.8	15.6	10.7	20.0
Cloudy summer over snow	31.7	51.4	14.1	22.3	26.3	54.9
Cloudy winter over snow	---	---	14.0	29.3	19.3	42.4

All values are in watts per square meter.

the signal diminishes with increasing zenith angle. The longwave data have been shown to be accurate to within about 1%. See *Stone et al.* [1996] for further details.

Retrievals of the surface downwelling shortwave and longwave radiative fluxes using AVHRR local area coverage data, approximately 1.1 km at nadir, were done using the methods described in previous sections with data from mid-1992 through mid-1993. A comparison of results for the pixel covering the Barrow area and the surface observations is shown for clear and cloudy conditions in Figure 4 for the downwelling shortwave flux during spring, summer, and fall, Figure 5 is for the downwelling longwave flux during winter, and Figure 6 is for the net flux in winter. The RMSE values given in the figures clearly fall within the ranges of the predicted combined errors shown in Table 5. In agreement with our error estimates, net fluxes show the largest retrieval errors. Errors in the downwelling and upwelling estimates both contribute to the net flux errors. Upwelling longwave radiation during winter further suffers from a systematic problem: if upwelling longwave radiation is estimated from the surface temperature retrieved under clear skies, upwelling longwave radiation will be biased low because temperatures under cloudy skies tend to be higher, typically by several degrees.

Discussion and Conclusions

Our study shows that the largest uncertainties in estimating the surface radiation budget using the methods described by *Key* [1995, 1996b] are associated with the retrieval of surface temperature albedo and aerosols. In summer, surfaces with melting snow or bare ice represent the largest fraction of the Arctic surface area. Over these areas when skies are clear, uncertainties in the surface albedo are the largest contributor to uncertainty in surface net radiation. However, the importance of aerosols is exaggerated by the fact that we assume a rather large uncertainty, nearly 300%. If, in the absence of actual measurements, assumptions of aerosol loading can be made, this uncertainty can be reduced. Further, owing to the fact that the Arctic tends to be very cloudy during summer, error statistics will be weighted toward cloudy cases. This further reduces the impact of aerosols on the overall uncertainty. Errors in temperature profiles are a significant source of the net flux uncertainty at all times. Under cloudy skies, errors in surface temperature dominate the error in the surface energy balance. Further improvements in satellite retrieval algorithms should therefore focus on reducing errors in the retrieval of surface temperature, surface albedo, and lower tropospheric temperatures. Although the direct contribution of errors in cloud parameters to the uncertainty in the net radiation budget is less than that of the surface parameters, they also contribute indirectly. Results from validation studies indicate that errors in the retrievals of surface parameters are largely a result of uncertainties in cloud detection.

Zhang et al. [1995] find that the uncertainty associated with clouds plays only a small role in uncertainties in downwelling shortwave and longwave radiation on a global basis. However,

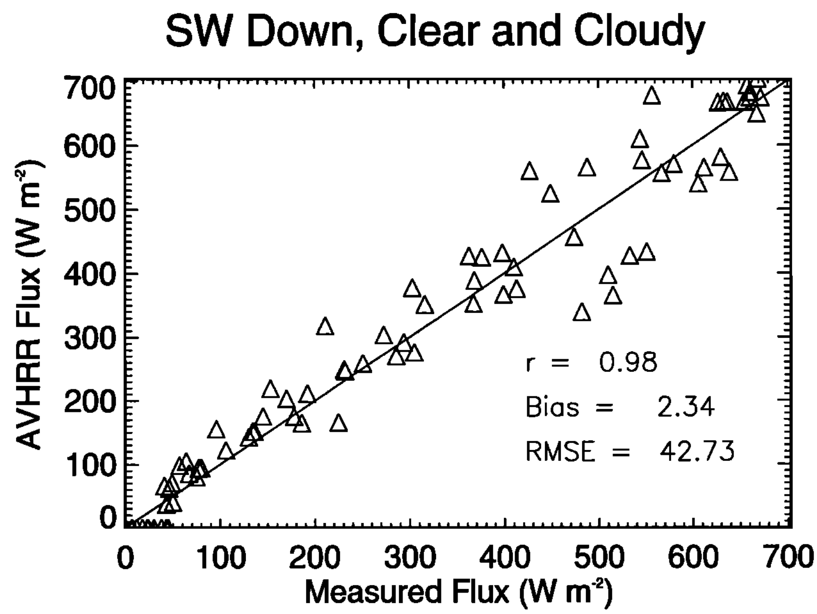

Figure 4. Comparison of satellite-derived and surface measurements of the downwelling shortwave flux for Barrow, Alaska, during 1992 and 1993.

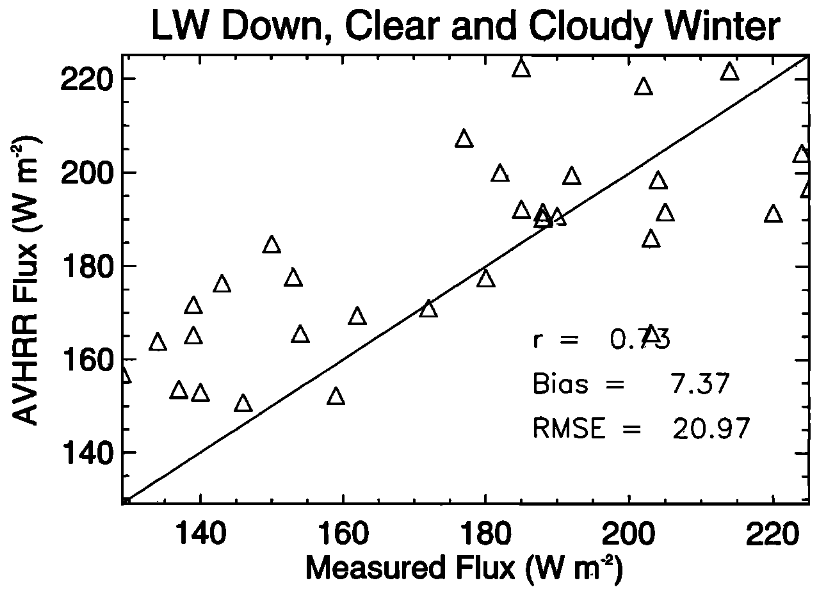

Figure 5. Comparison of satellite-derived and surface measurements of the downwelling longwave flux for Barrow, Alaska, during 1992 and 1993.

they conclude that this is not true for the polar regions. Our results confirm the importance of the surface parameters but also highlight the sensitivity of the surface radiative fluxes to uncertainties in certain cloud characteristics. We find that uncertainties in cloud fraction play a minor role in the surface radiation budget compared to surface temperature and albedo. However, uncertainties in cloud optical depth, although yet unvalidated and therefore assumed to be rather large, are a significant contributor to the error in net flux estimates.

Validation studies using hourly surface radiation measurements at Barrow, Alaska, indicate that downwelling shortwave and longwave fluxes can be estimated with root-mean-square errors in the range of 25 to 40 W m^{-2}. These fall within the ranges of the predicted combined errors. Even so, we expect that some of the observed errors are due to uncertainties that were not accounted for, e.g., comparing areal (pixel) observations to point (in situ) measurements.

The combined uncertainties are, at present, on the same order as those estimated for surface-based climatologies. However, satellite retrievals provide a much higher spatial resolution. The question of how well we need to measure surface radiative fluxes and, consequently, what kind of uncertainties we can allow in the measurement of those variables that are needed for their calculation is deceptively simple. Even though a value of 10 W m^{-2} for monthly fluxes is frequently cited as a requirement for climate change studies [*Raschke et al.*, 1992], the answer is obviously dependent on the application. When modeling large-scale ice thermodynamics with a focus on interannual variability, a large uncer-

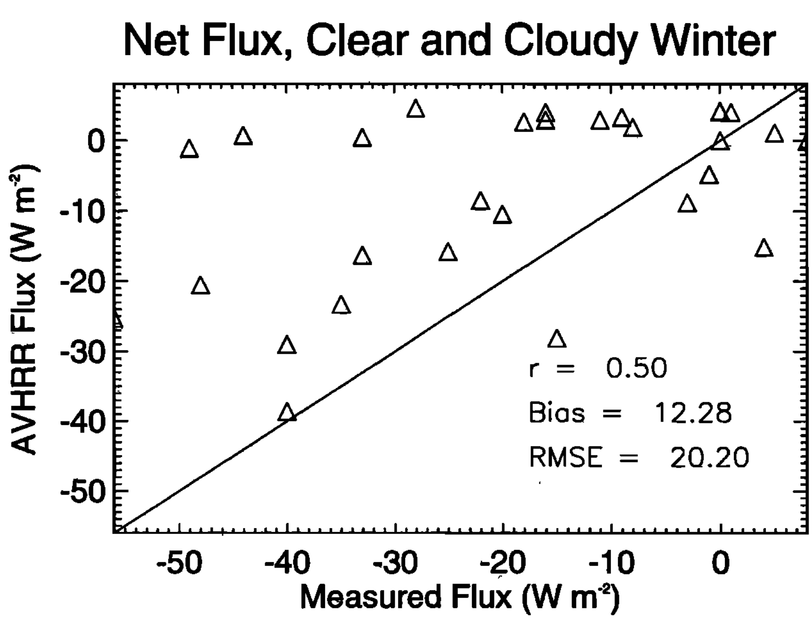

Figure 6. Comparison of satellite-derived and surface measurements of the net radiative flux for Barrow, Alaska, during 1992 and 1993.

tainty in daily forcing fields is most likely acceptable if errors are random. Conversely, investigating processes during melt onset or freeze-up will probably require a high accuracy of daily values. Additionally, some research questions will be affected by biases while others will not.

In order to shed some light on the required accuracy question, we have compared our estimated uncertainties with the variability of surface fluxes at different timescales. Table 6 shows estimated uncertainties in surface fluxes and compares them to observed variability at different timescales. As a proxy for observed variability, radiative fluxes parameterized based on 30 years of cloud, temperature, and humidity measurements from Russian drifting stations were used (R. Lindsay, personal communication, 1996). Variability at different timescales was calculated using a wavelet transform band-pass filter [*Lindsay et al.*, 1996]. Values shown for the observed variability for 1 or 8 days corresponds to the RMS difference of adjacent, nonoverlapping averages. For the monthly values it is the interannual variability of monthly averages. Retrieval uncertainties are calculated from the uncertainties determined above (Table 5) by assuming a random distribution of errors and adjusting for the likely number of observations at each time-scale. For each time-averaging period the uncertainty decreases by the square root of the number of observations. Uncertainties at the daily timescale are assumed to be those estimated from instantaneous values because using satellite data, often only one observation will be available per day. Also given (in parentheses) is the amount of variance in the observed data that could be explained in the presence of these uncertainties. Table 6 shows that assuming independence of errors, in summer, 82% of the variance in downwelling shortwave, 57% in downwelling longwave, and 91% in net radiation could be observed from satellite at monthly timescales. At daily timescales, uncertainties are too large to observe any of the natural variability. However, multiple observations per day will clearly reduce the uncertainty at this timescale. It should be noted that applications need to carefully consider the implications of random versus systematic errors. In the current analysis we have not separated these uncertainties, and the uncertainty estimates in Table 6 assume random errors with a zero mean. Information in the table may provide some guidance in deciding if satellite-derived surface fluxes using currently available data and algorithms are accurate enough for a particular application. Researchers interested in defining science requirements for algorithms may also use information provided in Table 6 in combination with $\Delta F/\Delta x$ values given in Tables 1-4 to define the required retrieval accuracy of a particular parameter with respect to desired amount of observable natural variability.

We conclude that the accuracy in estimating radiation budgets from satellite that we can currently achieve is appropriate for a wide range of process studies at monthly timescales. In order to detect short-term variability, further improvements, particularly in cloud detection and calibration, are warranted. The detection of interannual variation appears to be possible at monthly timescales. However, the detection of long-term trends associated with climate signals will have to rely on the absence of systematic retrieval errors. Future work should include the validation of retrieval algorithms using in situ data from experiments such as the Beaufort and Arctic Storms Experiment (BASE) and Surface HEat Budget of the Arctic Ocean (SHEBA). These field campaigns will allow us to better quantify retrieval accuracies for individual parameters, as well as the combined accuracy of radiative flux estimates. The long time period covered by the SHEBA experiment will be particularly useful to detect and eliminate potential seasonal biases in the retrievals.

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TABLE 6. Uncertainties in Satellite-Derived Surface Fluxes in the Context of Observed Natural Variability at Different Timescales

	Shortwave Down			Longwave Down			Net Radiation		
	Independent	Maximum	Sigma	Independent	Maximum	Sigma	Independent	Maximum	Sigma
					Summer				
Monthly (n = 30)	5.78 (82%)	9.38 (53%)	13.7	2.57 (57%)	4.08 (-)	3.9	4.8 (91%)	10.2 (60%)	16.2
8 days (n = 8)	11.2 (37%)	18.17 (-)	14.22	4.98 (35%)	7.88 (-)	6.21	9.29 (-)	19.41 (-)	6.03
Daily (n = 1)	31.7 (-)	51.4 (-)	10.0	14.1 (-)	22.3 (-)	6.7	26.3 (-)	54.9 (-)	3.0
Daily in 32-day period	31.7 (-)	51.4 (-)	32.25	14.1 (0.22)	22.3 (-)	15.9	26.3 (-)	54.9 (-)	13.1
					Winter				
Monthly (n = 30)	---	---	---	2.55 (96%)	5.3 (83%)	13.1	3.52 (-)	7.74 (-)	3.4
8 days (n = 8)	---	---	---	4.94 (81%)	10.36 (16%)	11.45	6.82 (-)	14.9 (-)	2.8
Daily (n = 1)	---	---	---	14.0 (-)	29.3 (-)	11.8	19.3 (-)	42.4 (-)	4.7
Daily in 32-day period	----	---	----	14.0 (0.71)	29.3 (-)	26.0	19.3 (-)	42.4 (-)	8.8

Uncertainties are in watts per square meter for downwelling shortwave, longwave and net radiation in the context of observed variability at different timescales, where n is the number of observations. Columns labeled "Independent" give the uncertainties assuming that parameters going into the radiative transfer calculations are uncorrelated. "Maximum" gives the maximum possible uncertainty, and "sigma" gives the standard deviation at monthly, 8 day, and daily timescales. Explained variances are given in parentheses.

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