

Abstract

The Arctic is a challenging environment for making in-situ radiation measurements. A standard suite of radiation sensors is typically designed to measure the total, direct and diffuse components of incoming and outgoing broadband shortwave (SW) and broadband thermal infrared, or longwave (LW) radiation. Enhancements can include various sensors for measuring irradiance in various narrower bandwidths. Many solar radiation/thermal infrared flux sensors utilize protective glass domes and some are mounted on complex mechanical platforms (solar trackers) that rotate sensors and shading devices that track the sun. High quality measurements require striking a balance between locating sensors in a pristine undisturbed location free of artificial blockage (such as buildings and towers) and providing accessibility to allow operators to clean and maintain the instruments. Three significant sources of erroneous data include solar tracker malfunctions, rime/frost/snow deposition on the instruments and operational problems due to limited operator access in extreme weather conditions. In this study, a comparison is made between the global and component sum (direct [vertical component] + diffuse) shortwave measurements. The difference between these two quantities (that theoretically should be zero) is used to illustrate the magnitude and seasonality of radiation flux measurement problems. The problem of rime/frost/snow deposition is investigated in more detail for one case study utilizing both shortwave and longwave measurements. Solutions to these operational problems are proposed that utilize measurement redundancy, more sophisticated heating and ventilation strategies and a more systematic program of operational support and subsequent data quality protocols.

1 Introduction

The radiative balance of the earth-atmosphere system is crucial for understanding atmospheric processes (Kiehl and Trenberth, 1997; Trenberth et al., 2009), as it plays a

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pivotal role in determining atmospheric circulations (Ohmura et al., 1998). The surface radiation budget plays an especially important role, as the earth surface transforms about 60 % of solar radiation absorbed by the planet to heat (Ohmura et al., 1998). The Arctic has already shown its enhanced sensitivity to the anthropogenic gas induced climate changes (IPCC AR4, 2007), but because the actual mechanisms that produce climate change are surface processes, more extensive research on the Arctic surface radiation budget and an extensive network of surface radiation measurements are needed. Such surface processes are influenced by quantities such as sea-ice extent, permafrost active layer temperatures, seasonal snow cover and depth, glacier advance/retreat rates and vegetation. For example, Kay et al. (2008) showed that enhanced surface radiation due to the decreased cloud cover by 16 percent from 2006 to 2007 alone could enhance surface melt by 0.3 m over the Western Arctic ocean. In recognition of the importance of long-term, climate-grade measurements of the surface radiation budget, a number of Arctic observatories have installed suites of broadband radiation flux sensors (thereafter radiation sensors) for measuring the components of incoming and outgoing shortwave and longwave radiation.

In this paper, we report on unique challenges we have experienced in making surface radiation measurements in Canada at Alert and Eureka, and at Barrow, Alaska. A special emphasis will be placed on Eureka. The suites of radiation sensors deployed at these stations are generally Baseline Surface Radiation Network (BSRN) standard (McArthur, 2004) compliant. The BSRN is a cooperative worldwide network that provides continuous, research-quality surface radiation flux measurements. One of its key missions is to validate GCMs (e.g. Wild et al., 2001) and satellite retrievals of surface radiative processes (e.g. Zhou et al., 2007). Given that, (1) Arctic clouds and their effects on radiative transfer processes are poorly represented in models, and (2) that satellite remote sensing algorithms cannot accurately retrieve Arctic surface and cloud characteristics (Randall et al., 1997), Arctic surface radiation measurements are essential to the eventual understanding of these problems.

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Currently, only six arctic stations have downward and upward radiation measurements. They are Alert (Nunavut, Canada), Barrow (Alaska), Eureka (Nunavut, Canada), Ny-Alesund (Norway), Summit (Greenland), and Tiksi (Russia) (Table 1). Upward radiation measurements at Eureka and Tiksi are supplemented by ancillary instruments on the nearby towers. A list of operators for those stations is shown in Table 1. Of these, only Barrow and Ny-Alesund data have been archived by the BSRN. Operating since 1976, Barrow has the longest record. Figure 1 shows the polar projection map with IASOA (International Arctic Systems for Observing the Atmosphere) stations (Darby et al., 2009), which is a network of value added arctic observatories. Red circles indicate stations that have radiation sensors. From the geospatial sampling point of view, there is a big gap in Russia despite the recent addition of Tiksi. However, there have been various short-term ancillary radiation measurements in Russia such as those of the GEWEX Asian Monsoon Experiments (Yasunari, 2001). There also exists a network of Russian radiation sensors and calibration of those instruments against the BSRN standard compliant instruments is underway in Tiksi (Uttal et al., 2010). Upwelling radiation and surface energy flux measurements are not required by the BSRN. The disadvantage of not having a full suite of radiation and surface energy flux measurements at a monitoring station is shown by the following theoretical consideration of surface energy budget.

Net surface irradiance is characterized by the following equation where LW_{net} is the difference between its downwelling and upwelling longwave components; SW_{net} is the difference between its downwelling and upwelling shortwave components.

$$R_{net} = LW_{net} + SW_{net} = (LW_{\downarrow} - LW_{\uparrow}) + (SW_{\downarrow} - SW_{\uparrow}). \quad (1)$$

BSRN compliant stations may provide adequate measurements to take advantage of the Eq. (1), if there exist additional upwelling radiation measurements. To characterize the surface energy budget fully, additional energy flux measurements of latent (Q_E) and sensible heat fluxes (Q_H) and ground conductive flux (Q_G) are necessary (Box, 2006). Energy conservation dictates that the difference between the surface net radiation and

surface fluxes would be available for residual melting energy (Q_M) includes any error.

$$R_{\text{net}} + (Q_H + Q_E + Q_G) = Q_M + \varepsilon. \quad (2)$$

Without coincident surface net radiation and energy flux measurements, it is impossible to definitively determine how the net radiation at the surface is utilized, which is what models have to simulate correctly.

2 State of arctic radiation data

Current surface irradiance measurements in the arctic are lacking and insufficient. Barrow and Ny Alesund are the only stations with decadal radiation records, starting 1973 and 1988 respectively (Table 1). Certainly, less technically challenging and more established atmospheric measurements in the arctic do not extend as far back as measurements at lower latitudes either. Among the eight IASOA stations, Tiksi has the longest temperature and surface pressure record, which started in 1933. In contrast, the global dataset of atmospheric state variables start well before 20th Century. The Global Historical Climatology Network version 2 temperature database begins in 1850 (Peterson and Vose, 1997), and the International Surface Pressure Databank version 2.2 starts in 1768 (Yin et al., 2008). We have finally started seeing climatological research on the arctic surface radiation budget (Dutton et al., 2006; Dong et al., 2010). Given the accumulation of decadal records allows Sutter (2006) to call for the need for homogenization (bias corrections over time) of arctic data and consistent calibration of radiation sensors for the four polar stations: Barrow, Ny Alesund, Neumayer, and South Pole.

Radiation measurements at high latitudes have many difficulties associated with extreme climate conditions such as rime deposition and snow accumulation on the instruments, solar tracker failures, and calibration temperature compensation (Lanoconelli, 2010). A working group entitled *Cold Climate Issues* was established during the 10th

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BSRN Scientific Review to study possible means to minimize the impact of these problems in BSRN polar data (Dutton, 2008). Here we address those issues by proposing sensible choice of radiation sensors and logistics.

Finally, no scientific measurements are complete without accompanying data quality control (QC) procedures to flag erroneous data. The BSRN recognizes the need for establishing QC procedures using existing methods (informal report, ELEVENTH Baseline Surface Radiation Network (BSRN) Scientific Review and Workshop, Queenstown, New Zealand, 13–16 April 2010). Currently not all the BSRN-recommended quality control procedures are made centrally at the World Radiation Monitoring Center (Lanoconelli, 2010). However, we are in the process of implementing QCRad (Long and Shi, 2006, 2008) quality control procedures on the flux tower radiation measurements at Eureka (Matsui et al., 2010), which will be discussed in the Sect. 4. The QCRad consists of 19 tests that utilize auxiliary data such as case and dome temperatures of the pyrgeometers, station pressure, temperature, and relative humidity to gauge radiation measurements against both physical and climatological limits. The procedures are designed ideally for solar tracker and platform mounted radiometers, and radiometers mounted on a tower or a lifted rail that measure upwelling irradiance.

3 Radiation sensors and solar tracker

BSRN compliant measurements require a solar tracker to measure downwelling radiation (Fig. 2). Tracker-mounted instruments include a shaded pyranometer to measure diffuse shortwave (SW) solar irradiance on a horizontal surface, a pyrhelimeter to measure direct SW solar irradiance normal to the sun's beam, and a shaded pyrgeometer to measure downwelling longwave (LW) thermal infrared irradiance on a horizontal surface (Ohmura et al., 1998; McArthur, 2004. (Shading the up-pointing pyrgeometer helps mitigate solar contamination of the downwelling thermal LW measurement.) Shade disks mounted on the tracker block the direct sun for the shaded measurements. Upwelling global shortwave and longwave irradiance measurements can be made from

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a short tower preferably poleward of the tracker and other measurement platforms to avoid shading of those radiometers, and in close proximity to the tracker location. For redundancy, an unshaded pyranometer that measures global SW may be placed on the shade platform of the solar tracker (but not shaded) or on a separate stand nearby.

5 Many variants of BSRN radiation sensor suite implementations exist. For example, in Tiksi, Russia, two different types of shaded diffuse shortwave sensors are used, and the global shortwave sensor is situated nearby (Fig. 2).

The BSRN recommends that the primary measurement of total solar irradiance should be the sum of the diffuse and direct horizontal components. Michalsky et al. (1999) have shown that the component sum methodology could lower the uncertainty by a factor of 2 or 3 in low sun and cold temperature conditions. Upper panels of Fig. 3 show a comparison of global horizontal irradiance and the sum component for Alert, Barrow, Eureka and BAO (Boulder Atmospheric Observatory in Colorado) for 2008. For the purpose of illustration, the data shown are not quality controlled, and a 45-min running average is applied. Lower panels show the difference between the component sum and the measured global horizontal irradiance. Theoretical values for the difference should be zero. However due to harsh weather conditions and errors inherent to the global solar measurement by a single pyranometer, such as the cosine error of its sensor and thermal offset errors (Gulbrandsen, 1978; Dutton et al., 2001; Philipona, 2002) which are particularly relevant to arctic locations under clear skies, perfect agreement is rarely achieved. A three-year comparison (2008–2010) among three arctic stations and the mid-latitude station reveals that significant differences between global and the component sum irradiance tend to occur in early spring (2009 and 2010 not shown), especially in the arctic. Of the arctic stations Eureka shows the least disagreement. Figure 3 also illustrates the climatological differences between arctic and mid-latitude stations.

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4 The flux tower in Eureka

Eureka is located on the Fosheim Peninsula of Ellesmere Island, Nunavut. There, NOAA monitoring instruments are collocated with a Canadian station called the Surface and Atmospheric Flux, Irradiance and Radiation Extension (SAFIRE) located at 79° 59' 47.50" N, 85° 48' 15.80" W. The SAFIRE building rooftop is instrumented with Environment Canada tracker mounted radiometers that measure shortwave and longwave downwelling irradiance (Fig. 4, left). The NOAA 10.5 m flux tower (Fig. 4, right), erected in 2007, is located about 500 m east of the SAFIRE building. Its coordinates are 79° 59' 43.4" N, 85° 46' 22.9" W. The NOAA tower is instrumented with both up-pointing and down-pointing global horizontal pyranometers (Kipp and Zonen CM22) and pyrgeometers (Eppley PIR). Thus Eureka has two sets of global shortwave and longwave sensors that measure downwelling irradiance, and one set that measures upwelling irradiance. Maintenance of the tower-mounted radiometers in the arctic winter is extremely difficult and dangerous. Manual inspections of downwelling shortwave measurements show frequent erroneous data primarily due to riming.

Figure 5 shows both shortwave measurements from the Environment Canada solar tracker at Eureka along with the flux tower downwelling shortwave and longwave measurements for 26 March 2010. The solar beam, as depicted by the direct horizontal measurement, appears to be blocked before 13:00 UTC, but it dominates diffuse after that time, and appears to follow a cosine response. This suggests strongly that we are looking at clear skies after 13:00 UTC on that day. The Environment Canada global measurement is slightly greater than the component sum prior to about 20:30 UTC, when, according to station records, their diffuse and global instrument domes were cleared of a light frost. This is not uncommon (especially for the global measurement) at low solar elevations. A frosted dome often acts as a reflector/diffuser that reduces the cosine losses – e.g. it enhances the irradiance on the horizontal sensor. This effect is usually not as noticeable on a diffuse sensor that is shaded from the direct sun, but perhaps in this case the diffuse field was non-isotropic. After the cleaning, the

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component sum and global measurements better agree. Because the Environment Canada diffuse and global measurement adjust downward after they are cleared of snow and the direct does not, indicates that the direct irradiance was the only good measurement prior to 13:00 UTC. The magnitude of the NOAA tower global measurement is much greater than all other solar measurements throughout the day, indicating that it was greatly compromised by frost on its dome.

Extraterrestrial radiation at Eureka on 26 March is estimated only about 300 W m^{-2} at solar noon. The deviation of the tower downwelling global shortwave from the Environment Canada shortwave measurement is obvious. The flux tower downwelling shortwave data for this date peaks at nearly 350 W m^{-2} . If this value were correct, a direct normal radiation value of over 1200 W m^{-2} would be necessary. It is also possible that there existed some process that increased global radiation to near the extraterrestrial value, e.g., partly cloudy skies with full direct radiation and highly enhanced diffuse. But, this is highly unlikely on a clear day. It is safe to conclude that riming compromised the tower downwelling global reading.

Prior to 13:00 UTC, the downwelling solar measurements, including the direct beam, are quite a bit less than the clear-sky values afterwards. This may be due to the mountains blocking direct beam, but also may indicate the presence of clouds. The downwelling IR time series shows enhanced values prior to 13:00 UTC, suggesting the existence of overhead cloud cover during that period.

5 Discussion

There are several aspects of arctic instrumentation that could lead to improved radiation measurements.

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Common sense strategy

Measurement improvement can be achieved by common sense strategies such as daily or sub-daily cleaning of the instruments. If riming issues are persistent, this should be noted in the log entries. This is exactly the procedure Environment Canada operators followed on 26 March 2010.

Station Design

Well-designed instrument placement is the key to success for accurate arctic irradiance measurements. Figures 3 and 5 show the benefit of well-attended measurements. The fact that the solar tracker is located on the rooftop of the SAFIRE building where operators reside and have easy access is an asset that should be considered in the design of Arctic radiation measurement stations. It is often not possible to erect a small tower poleward of the tracker location due to various logistical and budgetary concerns. We argue that ancillary down-pointing radiometers on the flux towers such as one in Eureka may supplement the tracker-mounted downwelling measurements, if (1) they are in reasonable proximity, and (2) the surface characteristics beneath the tower are representative of the surrounding area.

Instrument related improvements

Erroneous data due to the tracker operation issues, power failures, and riming on the instrument domes are primary concerns for arctic radiation measurements. During the long polar winter, when the sun is below the horizon all day, the solar trackers are often programmed manually by site operators to believe that they are located in different climate regime where the solar beam is still trackable (e.g. Hawaii) so that they will keep moving to keep the grease and moving components fluid (J. Wendell and R. Albee, personal communication, 2010). The active sun tracking option is turned

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off during this period. The tracker is re-programmed to the correct coordinates a few weeks before the polar sunrise. Whether this procedure is necessary is a matter of debate. Solar trackers in arctic are usually equipped with an Arctic rated blanket to help retain the internally generated heat (Fig. 6). At NOAA/Global Monitoring Division an experiment was conducted in the cold chamber to test the effectiveness of the blanket and a simulated power failure. It was brought to the state of cold soak by being powered off while the chamber temperature was dropped to -70°C . After the power was cycled, the tracker circuit box temperature was brought back to operational temperature by the internal heater and the motors and mechanical gears were deemed operational (J. Wendell and R. Albee, personal communication, 2010). However, we are not certain that the chamber environment sufficiently simulated actual conditions of the early arctic spring. Tracker operation immediately before and during the polar sunrise requires further scrutiny.

Having collocated redundant sensors could remedy some of the issues we have encountered in the Arctic. An example of such redundant sensors is shown in Fig. 7. The top left corner of Fig. 7 shows the Delta-T Devices model SPN-1 radiometer (Myers, 2010) after a riming event at the Storm Peak Lab near Steamboat Springs, Colorado. With no moving parts, the SPN-1 radiometer utilizes 7 small thermopile sensors with various degrees of shading to provide total, diffuse, and direct broadband shortwave measurements regardless of azimuthal orientation. It has a built-in heating system that works down to -20°C to keep dew, frost, rime, and snow off of the dome. The effectiveness of the internal heating system is obvious in the picture. The SPN-1 is not as accurate as a class-1 pyranometer, or component sum measurements. However, the benefit of redundant measurements is obvious when the tracker or the tracker-mounted sensors are not functioning optimally (e.g. due to frost or tracker misalignment). For example, pyrhemeters typically are not equipped with ventilators and thus are more susceptible to riming. During the ARM StormVex campaign (Mace et al., 2010) at Storm Peak Lab (SPL), the radiometer system included an SPN-1 and Eppley PSP (Fig. 7). Figure 8 shows the comparison of those two radiometers for

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25 November 2010. That day was mostly clear, as confirmed by a Total Sky Imager (TSI) movie. The maximum solar elevation was just above 28 degrees. The erroneously enhanced positive downwelling shortwave irradiance that was experienced at the Eureka flux tower due to riming was replicated in the Eppley PSP data on this date.

5 The PSP measurements resemble that of a mostly cloudy sky, but with the direct sun unblocked by “cloud”. Since the sky was mostly clear, the afternoon total shortwave irradiance should nearly match the curve in the morning, only showing small differences due to diurnal changes in water vapor and aerosol loading. But, the Eppley PSP data plotted versus the cosine of the solar zenith angle shows a looping pattern. The PSP
10 values are too high in the morning, but later in the day after the frost on Eppley PSP had melted, the two radiometers show good agreement. Clearly, even though it is less accurate under normal conditions, the frost and rime-free SPN-1 produced the more accurate data on that day than the class-1 instrument. The next task is to develop algorithms and procedures for choosing the “best” measurements at any given time to
15 produce a useful “best estimate” for users.

Versatility of new instruments such as the SPN-1, with its internal heating and ability to produce reasonable total and diffuse SW measurements, opens up a new possible deployment scenario for conditions where fielding a solar tracker is problematic or not feasible and/or riming poses a substantial problem. In those cases, the optimal system might consist of a standard SPN-1 for SW component measurements, a
20 no-shading-pattern SPN-1 for the global shortwave horizontal measurements, and a heated ventilated PIR (or CG-4) for the longwave measurements. It must be noted that the no-shading-pattern SPN-1 is a new concept that has yet to be tested for riming resistance under harsh arctic conditions. Since, by design, conduction through the metal shading pattern helps to more evenly distribute the heating under the SPN-1
25 dome, some decrease in the ability to resist frost and riming in the no-shading-pattern SPN-1 may manifest itself. Nevertheless, the included heating design obviously has an advantage over no heating at all.

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Another possible area of improvement in Arctic radiation measurements is proper and adequate heated ventilation. Figure 9 shows an example of an arctic rated ventilator: the Physikalisch-Meteorologisches Observatorium Davos (PMOD) model VHS with a heated coil under the sun shield and steep sides to enhance its snow shedding ability. Proper arctic rated ventilation systems (e.g. PMOD or Kipp and Zonen) that reduce riming or the build-up of snow are a necessity in the Arctic environment for non-heated instruments. This is especially the case for the longwave sensors because the downwelling IR signal resulting from partial to complete dome ice obscuration may be indistinguishable from legitimate signals from low level clouds (E. Dutton, personal communication, 2010). However, the amount of heating and how the heaters are placed in the ventilator can also contribute to increased IR loss errors in the pyranometer measurements, thus care must be taken in applying this type of ice mitigating strategy.

Putting everything together

We tried to address problems facing the BSRN working group “*Cold Climate Issues*” by identifying issues and providing preliminary results. However more work needs to be done. The ultimate goal is to prevent tracker aiming errors and contamination of the measurements by frost, ice, snow, and rime at all times. The solution will likely have to include several factors such as redundancy of measurements, heating and ventilation of instruments, appropriate operational procedures, data quality assessment and control, and perhaps even new instrument systems design.

6 Conclusions

Making surface radiation measurements in the harsh arctic environment is a challenging endeavor. The handling of polar sunrise and the mitigation of riming issues needs to be addressed in the design of arctic surface radiation stations. This might be achieved

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by carefully designed tracker operation procedures in early spring, having adequate and well-designed radiometer heating and ventilation, and the addition of multi-variable radiometers with an internal heater for redundancy and better quality control. Establishing viable data quality control, strict dome cleaning schedules, homogenization of the data, and consistent calibration procedures are also necessary for the success of the radiation measurements in arctic.

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Table 1. Arctic stations with radiation instruments.

Station	Location	Height	Operating Since	Operator	BSRN Archived
Alert	82°86′67″ N, 64°58′33″ W	210 m	2004 Aug	EC	Candidate
Barrow	71°19′ N, 156°36′ W	8 m	1973	GMD/NOAA	Yes
Eureka	79°59′47.50″ N, 85°48′15.80″ W	10 m	2007	EC	Candidate
Ny Alesund	78°56′ N, 11°57′ E	11 m	1988	AWI	Yes
Summit	72°56′67″ N, 38°48′33″ W	3238 m	2000	NSF	Candidate
Tiksi	35°48′ N, 128°53′ W	32 m	2010	GMD/NOAA	Candidate

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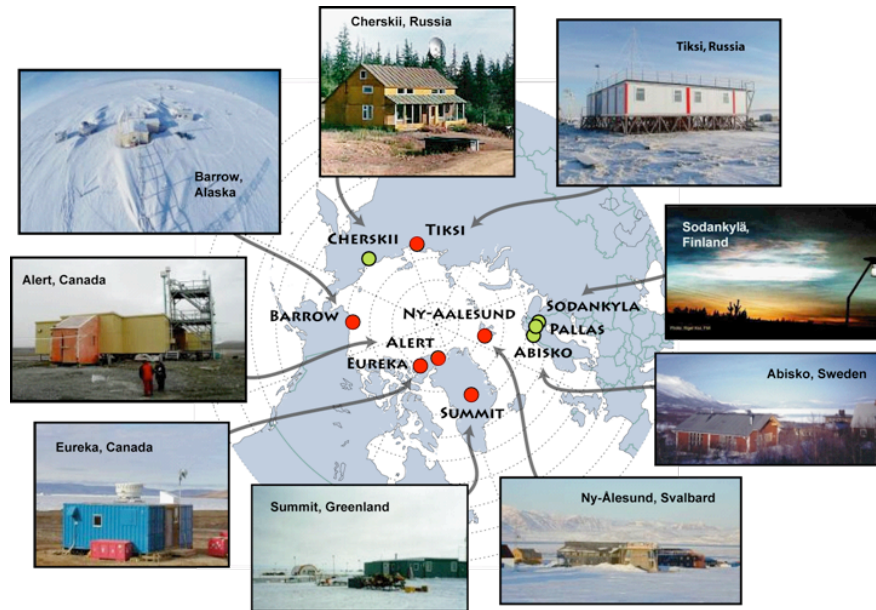


Fig. 1. Polar projection map with IASOA (International Arctic Systems for Observing the Atmosphere) stations (Darby et al., 2009). Red circles mark those stations with radiation instruments.

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Fig. 2. Solar tracker mounted surface radiation sensors in Tiksi, Russia. Shortwave measurements are made by GSW (global shortwave), DIR (direct), and DIF (diffuse) sensors.

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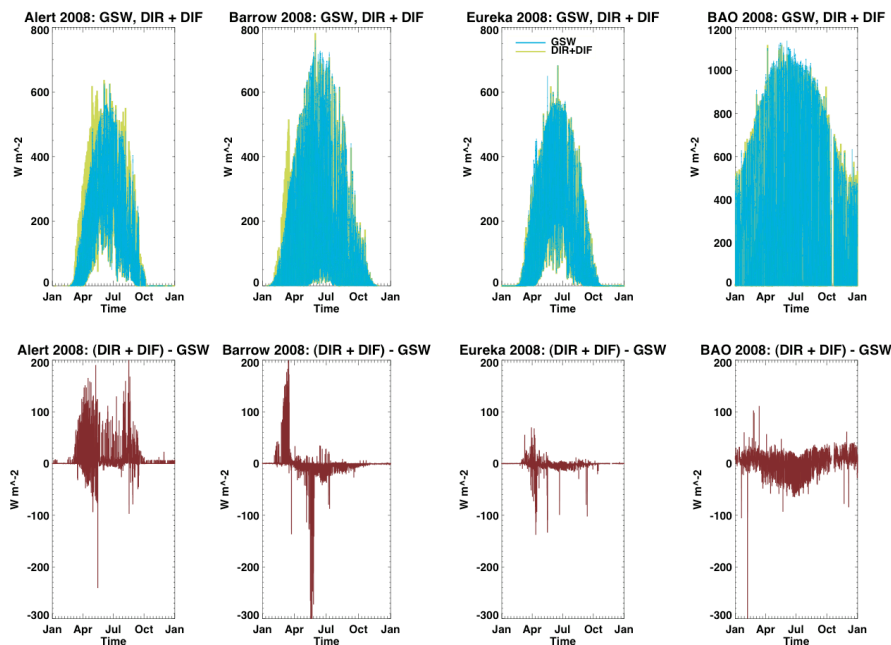


Fig. 3. GSW and DIF+DIR: Comparison of (a) Alert, (b) Barrow, (c) Eureka and (d) BAO (Boulder Atmospheric Laboratory) in 2008. The top panels show GSW and the component sum. The bottom panels show the difference between the component sum and GSW.

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Fig. 4. SAFIRE rooftop is instrumented with tracker-mounted radiometers (left). At 10.5 m height, the flux tower is equipped with four radiometers (right).

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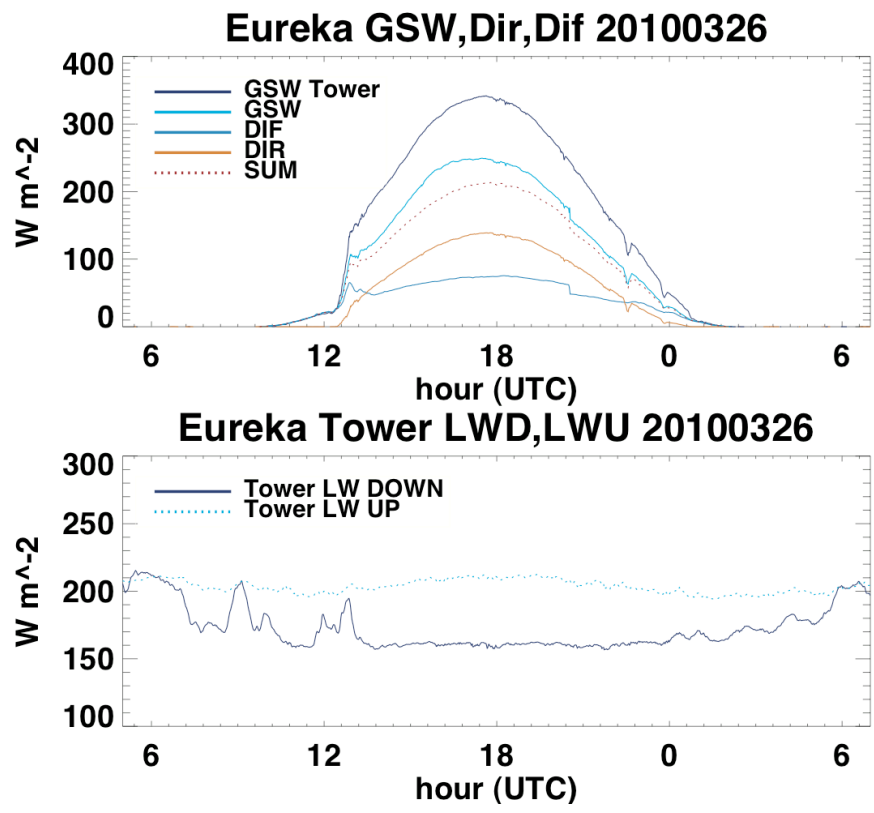


Fig. 5. Clear sky example with flux tower (LW and GSW) and DIF and DIR from SAFIRE in Eureka: 26 March 2010.

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Fig. 6. Example solar tracker and its circuit box wrapped in the arctic rated blanket.

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Fig. 7. SPN-1 radiometer (upper left), ventilated Eppley PSP radiometer (lower left) and ventilated Eppley PIR pyrgeometer (upper right). A thin layer of frost on the PSP's dome is clearly visible.

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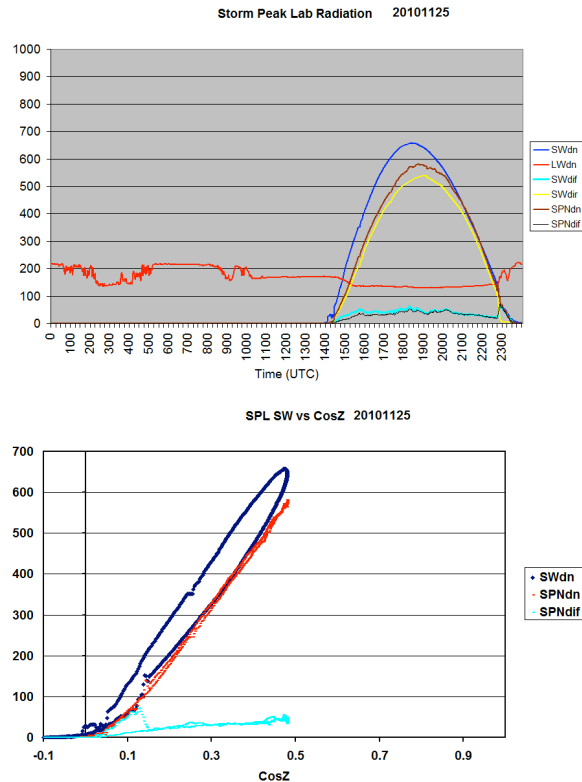


Fig. 8. Comparison of SW by Eppley PSP and SNP-1 deployed at Storm Peak Laboratory on 25 November 2010. Blue curve (top plot) shows enhanced irradiance reading for the first half of the day due to the frost on the dome on PSP compared with brown curve representing the SPN-1 total SW. Eppley data (dark blue line) shows a looping pattern when plotted versus the cosine of the solar zenith angle due to the frost while SNP-1 (red line) shows little sign of the frost (bottom plot). Light blue curve is the SPN-1 measured diffuse SW.

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Fig. 9. Example radiometer with arctic rated ventilator.

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