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Long-term meteorological measurements in Snowdonia with a resilient solar-powered system

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Abstract
Automated meteorological measurements from northern Snowdonia, using a resilient solar-powered station, are here described and presented for the first time. In particular, a long time series of radiative flux measurements has been acquired from 2004-present. Up- and down-welling shortwave global solar irradiance and longwave irradiance have been measured at Snowdon Summit (1085m) and the nearby Marchlyn Mawr (660m). On clear days the Welsh mountains have a significantly greater solar irradiance compared to the top of atmosphere solar irradiance than at other UK mountain sites. Surface albedo measurements over rocky ground near the summit show seasonal variations principally controlled by snow cover. Longwave radiation is dominated by the presence of cloud.

Keywords
Mountain meteorology, albedo, solar radiation, longwave radiation

1. Introduction
Mountain weather and climate have long inspired curiosity. Before flight, mountains were the only way to measure the variation of meteorological parameters with altitude (Barry, 2008). Regular mountain weather observations commenced as science became professionalised in the mid-19th century, and many astronomical observatories were established on mountains for their clear air. These required basic meteorological measurements to correct for atmospheric effects on telescope observations (Burt and Burt, 2018).

Many famous and long-established mountain weather stations are tabulated by Barry (2008), but there are none in the UK. This is due to both the lack of significant mountains, and the technical challenges of maintaining a site in the wet and windy upland regions. The UK’s first mountain weather station was established at its highest point, Ben Nevis (1345m), in 1883 and ran until 1904. The observers were necessarily resident at a summit building, though winter conditions were occasionally too poor for them to leave the building to make measurements (Roy, 2004). Recent digitisation of the Ben Nevis data by citizen scientists has contributed to reanalysis of historic weather events (Burt and Hawkins, 2019). An automatic weather station (AWS) was briefly established at Ben Nevis as part of the same initiative (Amos, 2017), but could only be temporary without the careful engineering required for long-lived measurements. The only long-established mountain weather station in the UK is at Cairn Gorm (1245m), which has run intermittently for over 40 years (Curran et al, 1977). (Unlike Snowdon, Cairn Gorm benefits from year-round mains power.)
Mountains and the development of particle physics are also inextricably linked. The physicist C.T.R. Wilson, who spent a few weeks at the Ben Nevis weather station as a young man, described how his visit inspired a lifetime of atmospheric research (Harrison, 2011). C.T.R. Wilson is most remembered for his Nobel-prize winning development of the cloud chamber, motivated by cloud formation. The cloud chamber made it possible to visualise the tracks of sub-atomic particles (with a different mechanism to atmospheric cloud formation), and in doing so, started the discipline of particle physics. Before particle accelerators, particle physics relied upon galactic cosmic rays (GCR), high-energy particles from space, which lose energy in Earth’s atmosphere by ionisation. Mountain observatories therefore played a significant role by offering a higher count rate and wider variety of sub-atomic particles than those at sea level. Balloon soundings are important for both meteorology and particle physics, (and were used to discover GCR in 1912) but only mountains offered the opportunity for regular measurements. Pic-du-Midi in the Pyrenees was particularly notable in the history of particle physics, with Jungfraujoch in the Swiss Alps significant for both particle physics and meteorology (e.g. Butler, 1982; Flückiger and Bütkofer, 2009; Zander et al, 2008).

Mountain weather and climate remain key factors affecting the biotic and abiotic environment, and are also of interest to the life, work and recreation of many people. In this article we will describe the environmental measurements at Snowdon summit (53.0689\(\text{N},\) 4.0756\(\text{W},\) 1085m). Automated meteorological observations began in 1985, with GCR measurements added in 2005, and both continue to the present day.

2. Snowdon weather stations

The Snowdon summit station has two distinct phases, the Snowdon Weather Stations Project (SWSP) and the Snowdon Space Weather Station. The background, instrument description and some highlights of the meteorological measurements will be discussed for each phase.

2.1 Snowdon Weather Stations Project

Increased interest in climate and environmental change motivated the UK Met Office, working with various universities, to establish SIESAWS (Severe Icing Environment Synoptic Automatic Weather Stations) in the 1980s on Cross Fell, Cairn Gorm and Aonach Mor (Green, 2010). In partnership with the University of Wales in Bangor, this technology was installed on Snowdon (1050m) in 1985. A series of modified instruments recording a standard set of measurements: temperature (-15°C to +25°C), rainfall (50 to 300mm/month), sunlight, wind speed (gusts to 140mph) and wind direction were also installed (Figure 1a). The Snowdonia Weather Stations Project (SWSP) produced an altitudinal profile of weather and climate with the addition of solar-powered AWS at Llanberis (105m) and Clogwyn Station (750m) (Figure 1b). In 2004-5 the summit instrumentation was expanded. The SWSP ran until 2006 when the summit building was demolished for refurbishment. A related project to determine mountain snow cover also ran from 1994-2010, with cumulative snow height determined from the altitude of the snow-capped peaks. Earlier data using the same system and dating back to 1979 was also found,
giving a long time series, and shows a significant decline, of about 50%, in snow cover between 1980 and 2010.

2.2 Space Weather Station

Year-round data acquisition at Snowdon requires solar power, as the summit buildings are not open all year, and the earlier measurements established that wind gusts are too strong for wind turbines. Atmospheric radiation measurements use a Kipp and Zonen CNR1 radiometer for down and up-welling longwave (LW) and shortwave (SW) radiation. Shortwave radiation is important for assessing the potential for solar power in the UK’s uplands, with the LW and energetic particle measurements initially motivated by research into the atmospheric effects of ionisation (e.g. Aplin and Lockwood, 2013). LW and SW radiation, natural radioactivity and GCR (measured using a robust “coincidence counter”, suitable for long-term unattended operation (Aplin and Harrison, 2010)) were recorded using a Campbell CR21X data logger. The instruments were located on the roof of the old summit building (Figure 1a) with power provided by a 90Ah battery and 60W solar panel. Data was sampled every 20s (based on the radiometer response time of 18s) with hourly averages computed and saved by the data logger, and the data regularly downloaded manually.

In 2006 the old summit building was demolished to make way for the new summit building, known as Hafod Eryri, due in 2009. In preparation for this, the equipment, with a new enclosure, 80W solar panel charged by a 90Ah lead acid battery, Campbell CR3000 data logger and GPRS modem for real-time data retrieval, was run at a low-altitude site from 2008-2009 (Aplin and Lockwood, 2013). After 2006, the improved data logger and communications meant that five-minute averages could be stored. Marchlyn Mawr (53.1367N, 4.0691W, 660m, Figure 2a) was established as an interim location (2009-2011) to deal with delays in permissions for the new summit site. Marchlyn had the advantage of year-round mains power, whereas the previous solar system occasionally ran flat in the winter. In 2012 the equipment was re-established in front of the new Hafod Eryri summit building (Figure 2b), but suffered from regular winter power failures. In 2014 it was upgraded with 4 x 27 Ah solar dryfit batteries, including a Schottky diode system to prevent the batteries draining into each other. The estimated maximum power consumption of the existing configuration (Table 1) is 23 W, with a total battery storage capability of 54 W. Since 2014 the system has been continually powered, and based on 2018 data, the power generated ranges from 37 W in winter to 69 W in summer.

Maintaining year-round operation at the summit is challenging due to the cloudiness of the site combined with decreased battery performance at low temperature. However, as indicated above, the system now has a power surplus in summer, so installation of a fifth battery may improve the storage capability and scope for expansion. Other factors that have affected the equipment over the years are a probable lightning strike (now mitigated by a protection system) and waterlogging. Effective waterproofing, including strategically placed drainage holes, is therefore important, as are details such as ensuring the use of single core wires throughout, which are robust to temperature fluctuations. Unreliable modem hardware and
The measurements of LW and SW radiation are presented; we believe these are the first long term data sets of their type. The GCR and natural radioactivity measurements have been published elsewhere (Aplin and Harrison, 2010; Aplin and Williams, 2011; Aplin and Lockwood, 2013) and are not discussed further here.

2.2 Meteorological measurements

Shortwave global solar irradiance \( S_g \) is the longest time series of summit data, summarised in figure 3. The annual climatology is evident, with the sunniest days found in the first half of the year and a decrease in sunshine in the late summer and autumn. In clear skies \( S_g \) is typically 60-80% of the top of the atmosphere global solar irradiance \( S_{TOA} \) due to scattering by water vapour and ozone, and absorption from aerosol (Harding, 1979; Harrison, 2015). Sometimes \( S_g > S_{TOA} \), usually on days with broken cloud, when there is forward scattering and diffraction from cloud edges added to the irradiance measured in full sunshine. This occurs on a few days in Figure 3a, with the greatest exceedance of \( S_{TOA} \), by almost 40%, occurring on December 11\(^{th} \) 2017 (yearday 345). The variability in \( S_g \) does indeed indicate broken cloud that day, a clear example of the charmingly named “silver lining” effect (e.g. Harrison, 2015).

There is very little data at altitude within the UK with which to compare the Snowdonia measurements, but a short (5 day) time series from Cairn Gorm (57.0607N, 3.6066W, 1245m) in 1970 (Harding, 1979), is also shown in figure 3a. (The “silver lining” effect is apparent in the Cairn Gorm data, when \( S_g \) was enhanced during broken cloud on 19 June compared to 20 June, which was clear.) In June \( S_{TOA} \) at Cairn Gorm is slightly lower than \( S_{TOA} \) for Snowdon due to its more northerly latitude; at local noon in mid-June, \( S_{TOA} \) is 1186 Wm\(^{-2} \) for Snowdon and 1137 Wm\(^{-2} \) for Cairn Gorm. Figure 3a indicates that \( S_g \) is comparable between Cairn Gorm and Snowdon. The 20 June 1970 was a clear sky day with maximum \( S_g \) of 820 Wm\(^{-2} \), 72% of \( S_{TOA} \).

During an intensive analysis of the 2004-2005 data, clear days were identified using the LW data (discussed in 2.2.3 below) and satellite images. Four clear sky days were found (all in April or June, consistently with the climatology in Figure 3a) for which the median of the maximum \( S_g \) for each day was 79.1 ± 0.3 % of \( S_{TOA} \) (uncertainty from the standard error of the mean), suggesting that Snowdon air in 2004-2005 was clearer than Cairn Gorm air in 1970. This finding is unexpected, as \( S_g/S_{TOA} \) in clear sky is expected to be enhanced at the higher altitude site (Cairn Gorm) due to less absorption.

To determine whether this effect is significant, the accuracy of the radiometers is considered. The manufacturers of the CNR1 radiometer used in Snowdonia quote an accuracy of ±10% in daily totals (Kipp and Zonen, 2002), consistent with the variability reported by Harding (1979) for similar instruments. Point measurements are more difficult to assess since several types of uncertainty are described (Kipp and Zonen, 2002). However, many of these uncertainties, such
as thermal effects, will be similar due to the comparable conditions expected on four sunny spring lunchtimes at Snowdon. The radiometers were new in 2004, so calibration drift (± 1% / year) seems unlikely, with the most relevant uncertainty quoted as “non-linearity”, ± 2.5% over 0-1000 Wm\(^{-2}\). Applying this conservatively as a 2.5% error in each measurement, gives the maximum solar radiation between 76-82% of \(S_{\text{TOA}}\), which is significantly greater than at Cairn Gorm. This is consistent with previous findings that coastal high-altitude sites were sunnier than inland ones, which for clear days, was attributed to cleaner air at the coast (Harding, 1979). Monteith (1966) found that \(S_d/S_{\text{TOA}}\) was 25% greater at Aberporth (52.14N, 4.571W, 133m) about 100km SSE of Snowdon, than at any other UK site, an effect local to the coast. These findings indicate that the strip of clean coastal air may extend to Snowdonia, which, combined with the altitude effect, give a high \(S_d/S_{\text{TOA}}\) ratio.

2.2.2 Surface reflectivity

The CNR1 instrument includes both downward and upward pointing pyranometers, so upwelling solar radiation data, \(S_u\) can be used to calculate the albedo \(\alpha\), or surface reflectivity \(S_u/S_d\) Figure 4. This is closely related to the type of surface the radiometer is mounted over. The old summit building’s roof was covered with dark felt, of low reflectivity and only occasionally snow covered (albedo \(\alpha=0.7-1\); Coakley, 2003) when the roof was cold enough. The Marchlyn site was grassy, with greater variability in vegetation over the year, and limited snow cover due to its lower altitude and more sheltered position. The current location just below the new Hafod Eryri summit building is rocky, without much seasonal variation, except when it becomes snow covered.

2.2.3 Longwave data

Downwelling longwave (infrared, IR) data \(L_d\) is plotted in figure 5; we believe these are the first UK mountain measurements of this parameter. \(L_d\) is calculated from both the pyranometer (LW sensor) and the instrument temperature (e.g. Harrison, 2015), with this increased complexity reducing the reliability, figure 5(b). The Stefan-Boltzmann law states that the emitted power per unit area \(R = \sigma T^4\) where \(T\) is the brightness temperature and \(\sigma\) the Stefan-Boltzmann constant. \(L_d\) is much less variable than \(S_d\) because the dominant IR radiation is from liquid water clouds, and the summit is often in cloud. The lowest \(L_d\) measurements are obtained under clear sky at night in winter, with the minimum daily median \(L_d\) of 220 Wm\(^{-2}\) corresponding to a brightness temperature of 250K (-23°C) on 11 February 2010 (yearday 42).

2.2.4 Events of interest

The Eyjafjallajökull volcano in Iceland affected UK air space from 15 – 20 April 2010. The same anticyclone that transported the ash effectively from Iceland to the UK led to clear or almost clear skies in North Wales on 15 - 17 April. A volcanic plume over the UK could potentially be detectable through increased aerosol attenuation of \(S_d\) compared to \(S_{\text{TOA}}\). No effect was seen, with a mean \(S_d/S_{\text{TOA}}\) for the three clear days of 78.5 ± 0.6 %, not significantly different to the clear days in 2004-2005 described in 2.2.1 above. Trajectories (Webley et al, 2012) indicate that...
North Wales was not affected by the ash cloud until 19 April, by which time the weather had deteriorated, with cloud dominating the $S_g$ signal. Non-detection of the plume over North Wales is therefore consistent with expectations. Unfortunately the equipment was moved away from the site on 27 April 2011, shortly before the plume from the Grimsvotn eruption passed over the UK.

3. Outreach

Over the years the space weather station has become established as a site for education and outreach. The value of mountain meteorology as a training activity was recognized many years ago (Pedgley, 1974) and numerous undergraduate students have carried out projects based around the data and equipment. The station has been funded as an outreach project since 2007, with a bilingual website providing information about the site and hourly data updates (http://www.bristol.ac.uk/engineering/outreach/snowdon-space-weather-station/). Since 2015 the station has been part of the Royal Astronomical Society’s RAS200 outreach scheme, as one of the project activities is to bring science to the Eisteddfodau, the Welsh language cultural festival (Bowler, 2015). The principal investigator of the Snowdon Space Weather Station has worked with artists, choreographers and primary school children to develop canvases and a dance sequence inspired by cosmic rays and space weather.

4. Discussion and Conclusions

Automated meteorological measurements have taken place at Snowdon Summit since 1985, with snow depth observations extending back to 1979, and including the first long-term atmospheric short- and long-wave radiation data. The entirely solar-powered Snowdon Space Weather Station has been operating since 2004, surviving several winters, gaps in funding, and major works at the summit. A ten-year time series of global solar irradiance data is presented, and Snowdon is found to be a sunnier site than Cairn Gorm in terms of the global solar irradiance compared to the top of atmosphere flux. Spring is climatologically sunnier than autumn with most clear days being recorded in the first half of the year. The downwelling longwave radiation is dominated by liquid water cloud. The first measurements of surface reflectance from this site are presented, and the data from the rocky surface of the mountain recorded since 2012 could potentially be useful for satellite and climate analyses.

Recent analysis indicates that there is spare capacity that could be used to support additional equipment. This is likely to be carried out in collaboration with the original funding bodies for the SWSP project, who have collaborated to reinstate summit weather monitoring in a recently launched site, Snowdon Live (www.snowdon.live). This measures temperature, wind, humidity and dewpoint when the summit building is open (May-October), as part of a warning system for walkers. The Space Weather Station will continue to provide year-round radiative data.
Acknowledgements

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References


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Kipp and Zonen (2002). *CNR1 Net Radiometer Instruction Manual*


### Tables

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<thead>
<tr>
<th>Instrument</th>
<th>Measurement</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>CNR1 net radiometer</td>
<td>Short and longwave upwelling and downwelling radiation</td>
<td>Kipp and Zonen (2002)</td>
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<td>BMD040 pressure sensor</td>
<td>Atmospheric pressure</td>
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Table 1. Instrumentation currently at Snowdon Summit Space Weather Station.
Figure 1 (a) Snowdon Weather Stations Project automatic summit weather station, with the Space Weather Station CNR1 net radiometer shown bottom right, 2004. (Inset) Severe riming in midwinter, 1990s. (b) AWS at Clogwyn Station.
Figure 2 Snowdon Space Weather Station. All the instrumentation except the radiometer is inside the enclosure. (a) CNR1 net radiometer at Marchlyn Mawr (2009-2011). Enclosure is identical to (c) but not shown; solar panel and batteries not required due to mains power supply (b) Existing configuration (since 2012), showing the solar panel, radiometer and enclosure July 2019; photo by A Bale. Photograph was taken from in front of the Hafod Eryri summit building, looking approximately north-north-west.
Figure 3 (a) Daily maxima downwelling shortwave radiation $S_g$ in Snowdonia from May 18th 2004 to October 7th 2019. Most of the data (59%) is from Snowdon Summit (1085m), with the rest from Marchlyn Mawr (660m). The maximum $S_g$ for each day of the year is plotted as a point, with a 28-day moving average as a solid line. The maximum top of atmosphere (TOA) flux for each day of the year at Snowdon Summit is plotted as a dashed line. Reference data points from Cairn Gorm summit (1245m) in June 1970 (Harding, 1979) are shown as crosses. (b) Number of years of $S_g$ data available for each day of the year, out of 11, from 2004-6, 2009-2011 (Marchlyn), 2012, 2014 and 2017-2019.
Figure 4. The ratio of upwelling (reflected) shortwave radiation to downwelling for the three sites the equipment has run at: the old summit building (red triangles), Marchlyn (unfilled blue circles) and in front of the new Hafod Eryri summit building (black diamonds) (a) as an annual climatology (b) as boxplots with the median indicated as a “notch”, whiskers as the first and third quartiles of the data with outliers shown as individual points, and width related to the square root of the number of points in each box.
Figure 5 (a) Daily median downwelling longwave radiation in Snowdonia from May 18th 2004-October 7th 2019. 55% of the data is from Snowdon Summit (1085m), with the rest from Marchlyn Mawr (660m). The median longwave for each day of the year is plotted as a point, with a 14-day moving average as a solid line. (b) number of years of data available for each day of the year, out of 11, from 2004-6, 2009-2011 (Marchlyn), 2012, 2014 and 2017-2019.