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AN ASSESSMENT OF LONG-TERM SURFACE SOLAR FLUX MEASUREMENTS IN POLAR REGIONS FOR TREND DETECTION

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1. INTRODUCTION

Long-term daily shortwave irradiance data is collected by the World Radiation Data Center (WRDC) located at the Main Geophysical Observatory in St. Petersburg, Russia. The data set includes daily measurements from over 1000 sites dispersed throughout the world continuously from 1964 to 1993. This dataset has been used to form the monthly averages by the Global Energy Balance Archive (GEBA) which has been recently updated and made available to the public (Ohmura and Gilgen 1991; Gilgen and Ohmura, 1999). Many of the sites within this dataset are located in polar regions.

Other datasets of long-term shortwave radiation measurements that are used in this study include those from the Climate Monitoring & Diagnostics laboratory (CMDL), which has been in operation since the mid-1970's. This dataset includes a surface site located at the South Pole. The data from each site is available via the internet.

The increase in attention of climate change has recently raised a concern for detecting trends, particularly in atmospheric variables such as temperature. Trend detection requires a long-term dataset and careful use of statistical methods (Weatherhead *et al.* 1998). The uncertainties of trend detection are dependent upon many factors. The most important one is having long-term datasets of at least a decade from instruments that are well maintained and calibrated. During the last decade, several investigators have studied the detection of trends in broad-band pyranometer data for specific sites and regional areas (e.g., Abukumova *et al.* 1996; Liepert and Kukla, 1997; Gilgen *et al*. 1998).

The calibration and maintenance of such broad-band hemispheric instruments has been questioned. In this paper, we present a short review of errors associated with the calibration of broad-band hemispheric measurements of solar irradiance and discuss how new findings affect the way these measurements are interpreted. Then we apply some simple linear regression and trend detection techniques (Weatherhead *et al.* 1998) to long-term radiometric times series from polar sites obtained from the WRDC and CMDL data sets to compare the observed trends and variabilities to these uncertainties.

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2. MEASUREMENTS AND UNCERTAINTIES

Shortwave radiative fluxes are extracted from sites located over the polar regions. Nine out of ten sites are from the WRDC dataset with a minimum coverage of 15 years and a maximum coverage of 24 years. The other site is from the CMDL South Pole Observatory with a temporal coverage of 8 years. The station name, position, elevation, and surface ecosystem type of the stations are shown in Table 1.

Shortwave radiative fluxes between 0.3 and 2.8 mm are measured with thermoelectric pyranometers. The sources of error in the measurements vary from instrument problems like dome and/or detector degradation to errors resulting from differences between the operating environment and the calibration process (see, Gilgen *et al*. 1998; Michalsky *et al*. 1999). These errors are complicated and can result in both bias and/or random errors in the measured flux. For polar regions characterized by low sun conditions, the angular response of the instrument may represent the largest source of bias error. For the purpose of time series analysis errors that change the relative sensitivity of the instrument in time are the most crucial.

An example of an offset generated by the difference between the operating environment and the calibration chamber is seen in the thermal offset problem. The problem is essentially related to the thermal equilibrium of the instrument in its atmospheric environment compared to conditions during calibration. The effect can result in an underestimation of the solar irradiance an unshaded pyranometer without ventilation of about 1.5% (Dr. Martial Haeffelin, personal communication). The effect is still being studied, but it is clear that its dependence on the environmental conditions results in a variable offset. If the environmental climate at the instrument location changes the resulting long-term analysis may be affected.

Other sources of errors from these pyranometers are due to random errors. Though it is difficult sometimes to find the cause of these errors, their effects can mitigated through statistical techniques given knowledge concerning the probability distributions of the errors. Systematic errors, however, such as from a drifting instrument, can be detected and possibly corrected, but only if station information is sufficient. Furthermore, the maintenance of the instruments is extremely important to the quality of the data. Errors that are present in the hourly dataset due to maintenance problems also propagate into the daily, monthly, and yearly averages.

In an error analysis of the GEBA data set by Gilgen *et al.* (1998) all errors were assumed to be random in nature due to the lack of documentation for each particular site in the data base. They assessed the magnitude of the errors by comparing time series of measurements using different installation and maintenance procedures. For example, the SMI instrument was maintained daily, while the ETH was maintained weekly. Also, the SMI instrument was slightly ventilated while the ETH was not. As a result, there was a bias present in the ETH measurements during the winter, which was due to dew and frost accumulating on the instrument. They computed the standard deviations, just for maintenance conditions alone, for the daily, monthly and yearly means of the radiative fluxes at that station to be less than 8 Wm^{-2}, 7 Wm^{-2}, 4 Wm^{-2}, respectively . These errors will be used to evaluate the trends and variability from the station sites in the next section.

Table 1: Global Solar Radiation Stations

Station Name	Position (lat,lon)	Elevation (m)	Surface Ecosystem type
Bergen, Norway	60.2, 5.2	41	Grassland
Lulea, Sweden	65.3, 22.1	17	Forest
Sodankyla, Finland	67.2, 26.4	179	Forest
Reykjavik, Iceland	64.1, -21.5	52	Shrubland
Fedorov, Russia	77.4, 104.2	13	Barren
Alexandrovskoe, Russia	60.3, 77.5	47	Forest
Verkhoyansk, Russia	67.3, 133.2	137	Grassland
Mould Bay, Canada	76.1, -119.2	15	Tundra
Alert, Canada	82.3, -62.2	63	Tundra
South Pole, Antarctica	-89.9, -102.0	2841	Snow and Ice

3. TIME SERIES ANALYSIS

3.1 Yearly Time Series

Yearly means are calculated from daily averaged measurements from the WRDC dataset. The yearly means for the South Pole site (CMDL dataset) are calculated from daily averages of hourly measurements. The contiguous time series are used for the analysis described here. The standard deviation for each time series is calculated. Linear regression is used to estimate trends, which is evaluated at a confidence level of 95% using the Student's t-test of the slope of the regression line. A similar technique for finding trends from radiation data is used in Liepert and Kukla (1997).

In addition, the techniques of Weatherhead *et al.* (1998) are used to determine how many years, n, are required to measure a real trend (within a 90% probability) given the magnitude of the estimated trend, where

$$n = \left[\frac{3.3\,\sigma_N}{\omega} \bullet \sqrt{\frac{1+\phi}{1-\phi}}\right]^{2/3} . \qquad (1)$$

Equation 1 depends on three factors: 1) the size of the trend (ω); 2) the magnitude of variability of the noise (σ_N), where noise N_t (t = 1,....,T) includes autoregressive and random components; and 3) the autocorrelation of the noise (ϕ). It is easier to detect a trend when the trend is large, the σ_N is low, and the ϕ is low; however, when the ϕ is high, for example, it means that one year measurement is highly correlated with the next year's measurement. Such a high ϕ makes it more difficult to determine how long it will take to detect that trend.

3.2 Time Series of Summers

Averages of three months representing the summer for each site, are calculated from the daily or hourly averaged values of the datasets. The same statistics are applied including linear regression and the computation of n in (1). We show results from the seasonal extreme of summer to contrast patterns to the annual averages.

4. RESULTS

In the annual time series (Figure 1), the global shortwave radiation at the surface is increasing for six out of the ten sites chosen here, which include Iceland, Russia, Canada, and Antarctica. The means, mean standard deviations, standard deviations of the noise (σ_N), ϕ, and n for selected sites are shown in Table 2. Also, the and n are shown for these same sites are shown. The maximum increase in global radiation is 7.8 ± 5.1 Wm^{-2} $decade^{-1}$ for the Alert site in Canada. This trend meets the 95% confidence interval of the Student-t test. The ϕ is low with a value of 0.2. The number of years to detect a trend of 7.8 Wm^{-2} $decade^{-1}$ is 10 years with a confidence of 90%. .

The time series of the summer is illustrated in Figure 2. The trends of the summer time series compared to the yearly time series have the same sign; however, the trends for most sites are larger in the summer time series. For example, the maximum increase in global radiation from the sites of the summer time-series is South Pole, Antarctica. It has a trend of 21.4 ± 21.8 Wm^{-2} $decade^{-1}$. For the yearly time series, the trend is only 6.5 ± 10.7 Wm^{-2} $decade^{-1}$. Although the time needed to detect the trend, n, varies from 7 to 3 years, the trends are uncertain because of the large confidence intervals.

For most sites there is not much difference between n from the yearly time series and n from the summer time-series. However, there are sites that do have a larger n in the summer time-series. For example, the site in Verkhoyansk, Russia shows n to be about 16

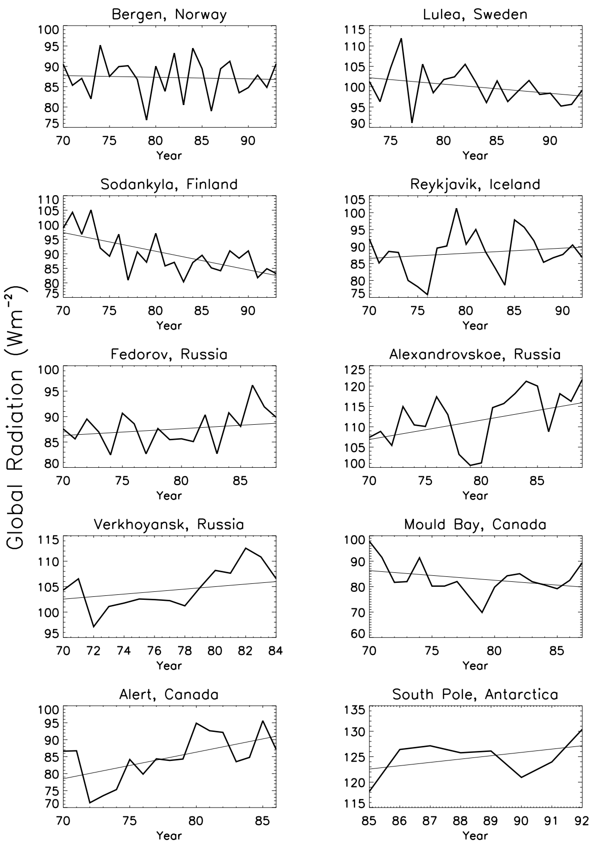

Figure 1: Time series of annual averaged global solar radiation for ten stations located in the polar regions.

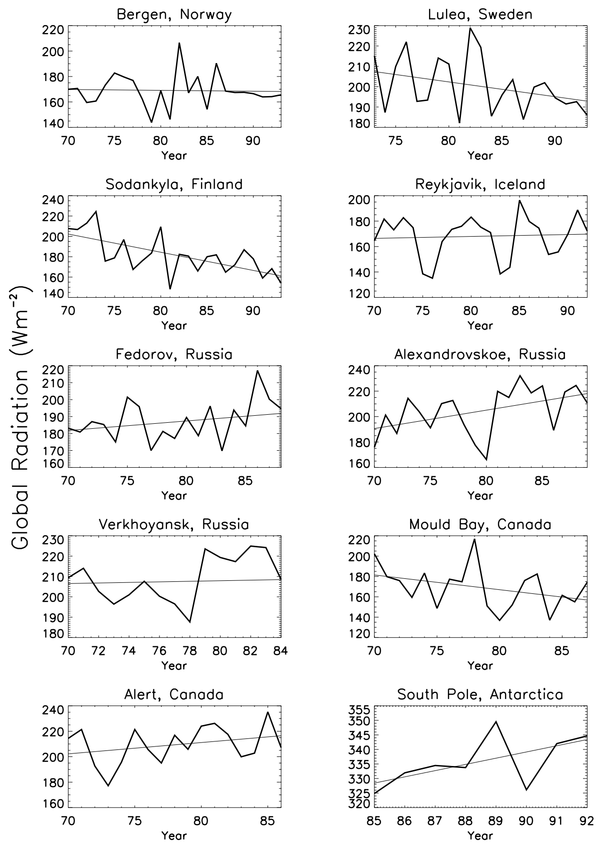

Figure 2: Time series for summer means of the global solar radiation for ten stations located in the polar regions.

years for the yearly time series and 50 years for the summer time series. In these cases, the time needed to detect the trend is longer than the extent of the time series; thus, the trend estimated here is not certain to within a 90% probability.

5. DISCUSSION AND CONCLUSIONS

This study has aimed to contrast instrument uncertainties with the magnitude of statistically significance (defined here at the 95% confidence level) trend signals found in long-term time series from the WRDC and CMDL data base. The simple linear regression trend analysis results from this study indicate a small increase in the yearly global shortwave radiation for six out of the ten sites from Iceland, Russia, Canada, and Antarctica. The rest of the sites display a slight decrease for sites in Norway, Sweden, Finland, and Canada. When compared to the summer yearly time series, almost all sites display a larger magnitude but same sign in trend. This is due to the larger variability of the observed incoming solar radiation during the summer months. For example, the trend at the Sodankyla, Finland site went from -6.4 $\pm$ 2.6 Wm^{-2} for the yearly time-series to -17.9 $\pm$ 7.6 Wm^{-2} for the summer time-series. This means that the trends are accurate within a 95% confidence level because the confidence intervals are smaller than the trend. Also, the trends are certain to within a 90% probability because the time needed to detect these trends are shorter than the extent of the time series.

The trends of some sites are not certain because the 95% confidence interval is greater than the trend and can include zero and the time needed to detect the trend is longer than the extent of its time series. For example, the Verkhoyansk, Russia site for the summer time series has a trend of 2.0 $\pm$ 6.6 Wm^{-2}. The 95% confidence interval is larger than the trend, which significantly increases the uncertainty of the trend. Also, this site shows n to be 16 years for the yearly time series and as much as 50 years for the sumer time series. For the summer time series there is much more variability in the global radiation, especially during 1978 to 1979, which makes it even more difficult to detect the trend. Because

Table 2: Trends per decade with confidence level at 95% with estimted number of years (n) to detect that trend at 90% probability

Site (type of yearly time series)	Mean (Wm^{-2})	Standard Deviation (Wm^{-2})	σ_N (Wm^{-2})	ϕ	Trend (Wm^{-2} $decade^{-1}$)	Extent of time series (years)	n (years)
Alert, Canada (annual)	84.8	6.9	5.7	0.2	7.8 ± 5.1	17	10
Alert, Canada (summer)	209.3	14.7	14.0	0.06	8.9 ± 12.5	17	15
Sodankyla, Finland (annual)	89.9	6.8	5.1	-0.03	-6.4 ± 2.6	24	9
Sodankyla, Finland (summer)	181.7	19.4	14.7	-0.1	-17.9 ± 7.6	24	8
South Pole, Antarctica (annual)	124.9	3.8	3.5	0.01	6.5 ± 10.7	8	7
South Pole, Antarctica (summer)	335.9	8.8	7.0	-0.5	21.4 ± 21.8	8	3
Verkhoyansk, Russia (annual)	105.1	3.8	3.4	0.3	2.9 ± 2.2	15	16
Verkhoyansk, Russia (summer)	207.9	10.5	10.4	0.3	2.0 ± 6.6	15	50

the times needed to detect the trends are longer than the periods of the time series, we cannot determine whether these trends are accurate to within 90% using the current statistIcal model.

For the sites considered here, the magnitudes of the trend estimates per decade are of the same magnitude of random errors for yearly and monthly averaged solar insolation, as estimated from just maintenance differences alone by Gilgen *et al.* (1998). Sometimes it takes the change in global radiation for the entire time series to become larger than these random errors. It takes at least 3 to 50 years before the trends at these sites can be detected or before the change in signal emerges from the variability and random errors associated with these measurements. Also, from these sites there are differences in n to detect the corresponding trends. This means that one site may be better for detecting trends in global radiation than another, which may give implications as to which sites or regions are better suited for measuring global radiation and monitoring its changes.

Besides detecting and knowing the uncertainties of trends, what is important is to determine whether they are actually caused by natural variabilities, e.g., changes in cloudiness, or are caused by errors in the instruments themselves. To determine this requires collaborating evidence from other instruments and/or atmospheric time series data. Ultimately, the accuracy of the data from these sites depends upon the extent to which this collaborating information explains the trends.

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REFERENCES

Abakumova, G. M., E. M. Feigelson, V. Russak, and V. V. Stadnik, 1996: Evaluation of long-term chages in radiation, cloudiness, and surface temperature on the territory of the former Soviet Union. *J. Climate*, **9**, 1319-1327.

Gilgen, H., M. Wild, and A. Ohmura, 1998: Means and trends of shortwave irradiance at the surface estimated from global energy balance archive data. *J. Climate*, **11**, 2042-2061.

—, and A. Ohmura, 1999: The global energy balance archive. *Bull. Amer. Meteor. Soc.*, **80**, 831-850.

Liepert, B. G. and G. J. Kukla, 1997: Decline in global solar radiation with increased horizontal visibility in germany between 1964 and 1990. *J. Climate*, **10**, 2391-2401.

Michalsky, J., E. Dutton, M. Rubes, D. Nelson, T. Stoffel, M. Wesley, M. Splitt, and J. Deluisi, 1999: Optimal Measurement of surface solar shortwave irradiance using current insturmentation. *J. Atmospheric and Oceanic Tech.*, **16**, 55-69.

Ohmura, A. and H. Gilgen, 1991: Global energy balance archive (GEBA), Report 2: The GEBA database: Interactive applications, retrieving data. Züüürcher Geographische Schriften 44, 60 pp.

Weatherhead, E. C., G. C. Reinsel, G. C. Tiao, X. L. Meng, D. Choi, W. Cheang, T. Keller, J. Deluiisi, D. J. Wuebbles, J. B. Kerr, A. J. Miller, S. J. Oltmans, and J.E. Frederick, 1998: Factors affecting the detection of trends: Statistical considerations and applications to environmental data. *J. Geophys. Res.*, **103**, 17149-17161.