JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, D00D08, doi:10.1029/2008JD011383, 2009

Decadal changes in shortwave irradiance at the surface in the period from 1960 to 2000 estimated from Global Energy Balance Archive Data

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Received 30 October 2008; revised 12 January 2009; accepted 17 February 2009; published 24 April 2009.

[1] Decadal changes in shortwave irradiance at the Earth's surface are estimated for the period from approximately 1960 through to 2000 from pyranometer records stored in the Global Energy Balance Archive. For this observational period, estimates could be calculated for a total of 140 cells of the International Satellite Cloud Climatology Project grid (an equal area 2.5° × 2.5° grid at the equator) using regression models allowing for station effects. In large regions worldwide, shortwave irradiance decreases in the first half of the observational period, recovers from the decrease in the 1980s, and thereafter increases, in line with previous reports. Years of trend reversals are determined for the grid cells which are best described with a second-order polynomial model. This reversal of the trend is observed in the majority of the grid cells in the interior of Europe and in Japan. In China, shortwave irradiance recovers during the 1990s in the majority of the grid cells in the southeast and northeast from the decrease observed in the period from 1960 through to 1990. A reversal of the trend in the 1980s or early 1990s is also observed for two grid cells in North America, and for the grid cells containing the Kuala Lumpur (Malaysia), Singapore, Casablanca (Morocco), Valparaiso (Chile) sites, and, noticeably, the remote South Pole and American Samoa sites. Negative trends persist, i.e., shortwave radiation decreases, for the observational period 1960 through to 2000 at the European coasts, in central and northwest China, and for three grid cells in India and two in Africa.

Citation: Gilgen, H., A. Roesch, M. Wild, and A. Ohmura (2009), Decadal changes in shortwave irradiance at the surface in the period from 1960 to 2000 estimated from Global Energy Balance Archive Data, *J. Geophys. Res.*, *114*, D00D08, doi:10.1029/2008JD011383.

1. Introduction

[2] Solar radiation intercepted by our planet will either be absorbed or returned to space by scattering and reflection [e.g., *Arking*, 1996; *Wild et al.*, 1998]. The absorbed part of the solar radiation is the source of energy which drives the processes in the atmosphere and the oceans. The incoming solar radiation at the top of the atmosphere undergoes only very small changes [*Fröhlich and Lean*, 1998]. However, systematic long-term (at least 1 decade) changes in the amount of solar radiation reflected and absorbed by the atmosphere (mainly due to changes in the cloud cover and the aerosol load) induce substantial decadal changes in the downwelling solar radiation at the surface. These changes are analyzed using pyranometer records.

[3] Pyranometers measure the solar radiation from the Sun and sky incident on a horizontal surface. The meteorological variable measured with a pyranometer is called global radiation or shortwave irradiance (SWIR). Systematic long-term changes in SWIR were analyzed in a number of local and regional studies [e.g., *Ohmura and Lang*, 1989; *Russak*, 1990; *Dutton et al.*, 1991; *Stanhill and Moreshet*, 1992; *Liepert et al.*, 1994; *Abakumova et al.*, 1996; *Stanhill and Ianetz*, 1997; *Wild*, 2009, and references therein]. In these studies, observations in the period from approximately 1960 through to approximately 1990 were analyzed and SWIR was found to decrease at the rate of 1 to 3 percent (of the mean) per decade. The decadal changes in SWIR thus obtained were attributed to changes in cloud cover and/or changes in absorption and reflection of solar radiation under clear-sky conditions (likely due to changes in aerosol loads).

[4] For the same period, on the basis of the data available in 1997 in the Global Energy Balance Archive (GEBA) [*Gilgen and Ohmura*, 1999], we found that SWIR decreases with approximately 2% per decade in large regions in Africa, Asia, Europe and North America [*Gilgen et al.*, 1998]. In this paper we did not attribute the decadal changes in SWIR to changes in the cloud cover and/or atmospheric clear-sky transmission since it is not possible to separate monthly SWIR values into values for clear-sky and all-sky conditions (unlike in the case of daily values [*Liepert et al.*, 1994] or high-frequency measurements [*Long and Ackermann*, 2000; *Dutton et al.*, 2004; *Wild et al.*, 2005]).

[5] Also using GEBA SWIR records, *Alpert et al.* [2005] selected 144 urban and 174 rural sites (the discriminating

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0148-0227/09/2008JD011383$09.00

threshold is a population of 100,000 persons) and calculated trends for the period from 1964 through to 1989. They found that the negative trends are much stronger at the urban than at the rural sites (-0.41 versus -0.16 $\mathrm{Wm}^{-2}\,\mathrm{a}^{-1}$ in the mean) owing to differences in anthropogenic aerosol emissions. In this study, population is used as a proxy for human activities producing aerosols. Nevertheless, we conclude from *Alpert et al.* [2005] that, in densely populated regions, trends in SWIR are related to trends in aerosol emissions.

[6] As soon as pyranometer measurements for the 1990s had become available, the SWIR was reanalyzed: *Wild et al.* [2005] found a widespread increase of SWIR since the late 1980s and *Dutton et al.* [2006] found, in the period from 1976 through to 2004, a decrease followed by an increase in three records of SWIR (those for South Pole, American Samoa and Boulder, Colorado).

[7] In the present paper, we (1) provide an update of the SWIR data in the GEBA for the period from 1990 through to 2000, (2) critically discuss all SWIR data made available in the GEBA, and (3) reanalyze the trends in the SWIR data for the period from 1960 through to 2000 with the aim to reevaluate, including in the analysis the data that have been available in the GEBA version 2006 and using a uniform method, our earlier results as reported by *Wild et al.* [2005]. This effort is justified, since, via the surface energy balance, decadal changes in SWIR affect the surface temperature, the hydrological cycle, and ecosystems [e.g., *Wild et al.*, 1996, 2004, 2007, 2008; *Ramanathan et al.*, 2001a; *Liepert et al.*, 2004; *Robock and Li*, 2006].

2. Data

[8] Measuring SWIR at the surface and maintaining a network of measuring sites over decades is a formidable task. It can be accomplished on condition that (1) a consensus has been reached on the world standard maintained by the World Radiation Centre (WRC/PMOD) [*Fröhlich*, 1991] which is then used to calibrate the reference instruments (secondary standards) maintained by the organizations (in the majority of cases the national weather services) that measure solar radiation; (2) instruments measuring SWIR are periodically calibrated against the secondary standards, and (3) measurements are guided by best practise recommendations regarding the installation of calibrated instruments, the maintenance schemes, the data acquisition systems and the data archival procedures (for example, in case of the Baseline Surface Radiation Network (BSRN) [*Ohmura et al.*, 1998], the relevant documents are *McArthur*'s [1998] and *Gilgen et al.*'s [1995]). The conditions enumerated above establish standard procedures for the observation of SWIR and also for the subsequent data processing and archiving. If these standards are adhered to by the organizations and individuals who measure SWIR then temporal variations in the resulting data are not due to changes in the observational system.

[9] Usually, pyranometer measurements are averaged to obtain hourly, daily, monthly and yearly values which then are made available to the public in a suitable form depending on the data storage technology. When we started the GEBA in 1985, the SWIR data available at that time suggested to collect monthly values measured at a large number (approximately 500) stations. The limitations of monthly SWIR values (e.g., any analysis is restricted to all-sky conditions) was one of the driving forces to build up the BSRN with the aim to obtain SWIR measurements of high quality and also high temporal resolution (minutes intervals) at a small number (approximately 50) of stations.

[10] Monthly and yearly values of SWIR have been made available in the GEBA for an increasing number of stations located mostly on the continents. The number of SWIR monthly values stored increased from approximately 100,000 to 180,000 and finally to 290,000 in 1991, 1997 and 2006. The data sources are the World Radiation Data Center in St. Petersburg, many national weather services, the BSRN (monthly means calculated from the high-frequency BSRN measurements) and also other institutions such as universities and research laboratories that perform pyranometer measurements.

[11] We do not know in detail to what extent the standards mentioned at the beginning of this section have been adhered to by the organizations that measured the SWIR data now available in the GEBA. Therefore, the SWIR values stored in the GEBA undergo five quality assessment procedures and are flagged accordingly, as described by *Gilgen and Ohmura* [1999]. The mean square error of those SWIR yearly values in the GEBA which have not been flagged as being erroneous is approximately 2% of the mean [*Gilgen et al.*, 1998]. This number also applies to the values inserted since 1997 into the GEBA and duly flagged (except the Chinese data; see section 4) as there is no evidence that the pyranometer measurements have deteriorated since approximately 1990. SWIR yearly values are analyzed in this study on condition that (1) they were available in August 2006 in the GEBA and (2) were not found to be erroneous by any of the GEBA quality assessment procedures.

3. Methods

[12] In section 4, linear models are fitted to SWIR records observed at the stations located in the cells of the ISCCP grid (an equal area 2.5° × 2.5° grid at the equator) under the assumption that the temporal trend thus estimated is representative for the grid cell. This approach is preferred to an analysis of the SWIR records at individual stations for the reasons given in the last paragraph of this section. If a grid cell contains only one station with N observations i, then a polynomial model of order p in the time

$$Y_i = a_0 + a_1 t_i + a_2 t_i^2 + \ldots + a_p t_i^p + e_i, \quad i = 1, \ldots, N, \quad p \leq 3 \tag{1}$$

is estimated, where Y_i is a SWIR yearly value, t_i the time, a_0, a_1,..., a_p the coefficients to be estimated, and e_i the residual. If a cell contains two (or more) stations then a station effect is (station effects are) included in the model as follows (for the case of four stations A, B, C and D):

$$Y_i = a_0 + a_1 t_i + a_2 t_i^2 + \ldots + a_p t_i^p + e_i + \begin{cases} a_{qA} & \text{for } s_i = A \\ \ldots & \\ a_{qD} & \text{for } s_i = D \end{cases}$$
$$i = 1, \ldots, N, \ p \leq 3, \tag{2}$$

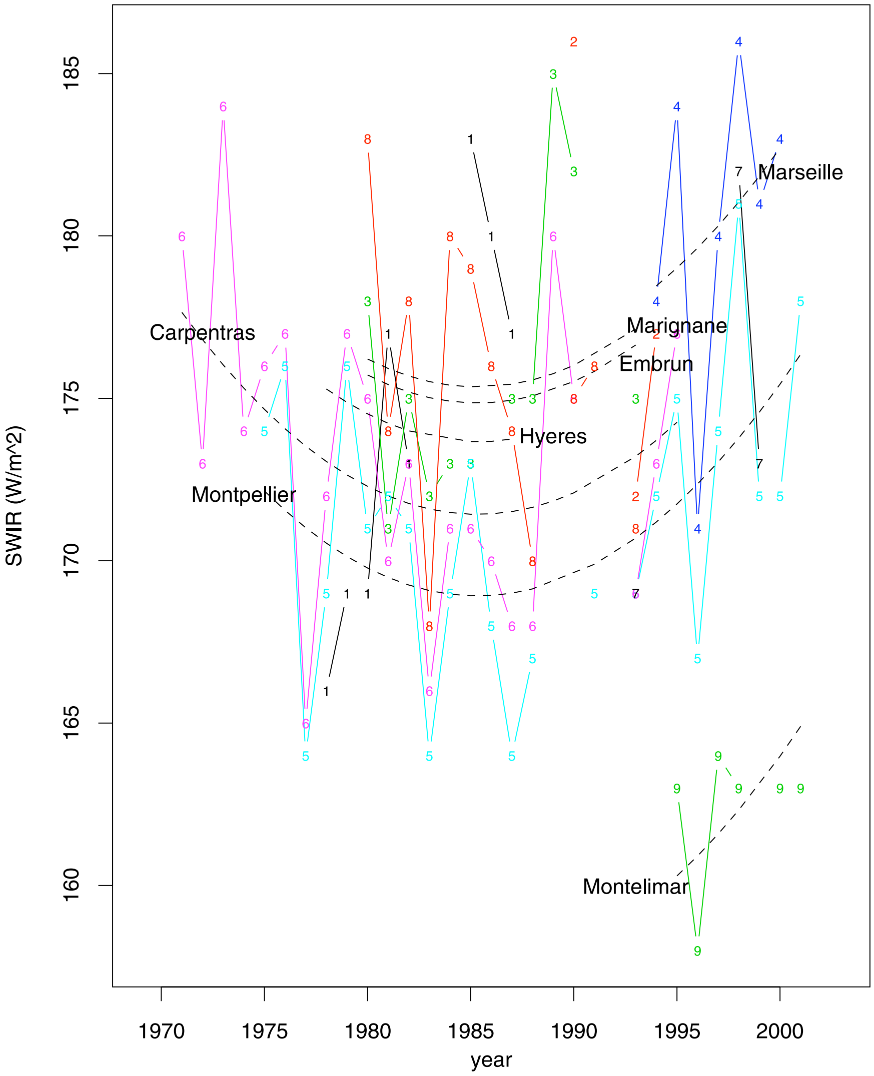

Figure 1. SWIR yearly values (in Wm^{-2}) observed in grid cell (3.463°E–9.932°E, 42.5°N–45.0°N) together with fitted second-order models (dashed lines, plotted for stations with longer records only). These models are identical with respect to time since they share coefficients a_1 and a_2 in model (2) defined in section 3 and their vertical distances (owing to the constant station effects $a_{3A}, \ldots, a_{3I}$ in this model) remain constant. A list of the stations in this cell is given in Table 1.

where s_i is the station, and $a_{qA}, \ldots, a_{qD}$, $q = p + 1$, are the station effects to be estimated. In a plot, obviously, station effects appear as vertical displacements of the estimated models for each station.

[13] Such models were already estimated in our earlier [*Gilgen et al.*, 1998] paper. Both models are linear models (categorical variables such as the station names are admitted as predictor variables in linear models). A comprehensive description, including technical details such as the resolution of the functional overparameterization of model (2), is available [*Gilgen*, 2006, section 3.5].

[14] Time series of SWIR yearly values observed at stations in an ISCCP grid cell are reconcilable with model (2) since (1) climatologies of SWIR change only very slowly with increasing distance between sites [*Whitlock et al.*, 1995; *Gilgen*, 2006, section 4.3.4] and (2) differences of SWIR yearly values observed at neighbor sites (with distances less than 300 km) were, in general, found to be stationary in time when the quality of the data was assessed [*Gilgen and Ohmura*, 1999].

[15] Taking advantage of these properties, model (2) averages the trend in SWIR over the stations in a grid cell. This is demonstrated in Figure 1 using the SWIR yearly values measured at nine stations located in grid cell (3.463°E–6.932°E, 42.5°N–45.0°N). The longest records (those measured at stations Carpentras and Montpellier, see Table 1) decrease until they reach their minima in the 1980s and thereafter increase. Also the shorter records follow this general tendency, with the exception of Hyere station (plotted (line 1) in Figure 1) where SWIR increases in the period from 1978 through to 1987. In the mean over all stations and the period with measurements, the estimated second-order linear model with station effects (vertical translations of the dashed lines) changes from decrease to increase in 1986. From the usual regression diagnostics in Figure 2 (a description is given, for example, in *Gilgen*'s

Table 1. Nine Sites With SWIR Observations Plotted in Figure 1

Station	Longitude (E)	Latitude (N)	Altitude	Observational Period	Site in Figure 1
Hyeres/Ile Levant	6°28′	43°02′	133	1978–1987	1
Toulon/Ile Levant	6°28′	43°02′	110	1990–1994	2
Marignane	5°13′	43°26′	4	1980–1993	3
Marseille/Marignane	5°14′	43°27′	6	1994–2000	4
Montpellier	3°58′	43°35′	5	1975–2001	5
Carpentras	5°03′	44°05′	99	1971–1995	6
Carpentras (BSRN)	5°03′	44°05′	99	1993–1999	7
Embrun	6°30′	44°34′	871	1980–1993	8
Montelimar	4°44′	44°35′	73	1995–2001	9

section 3.3 [2006]) it is concluded that (1) the fit is perfect, i.e., that the model captures the trend, and (2) the data have the statistical properties required for the estimation of linear models. Therefore, statistical tests can be performed with the result that the temporal trend is significant at the 0.01 level.

[16] Compared to our earlier [*Gilgen et al.*, 1998] study, a few changes are made: (1) all stations with SWIR records available in August 2006 in the GEBA and not flagged as being erroneous are sampled in the ISCCP grid, (2) data observed prior to 1950 are not included in the analysis, (3) it is required that, for each grid cell, the data cover at least the period from 1980 through to 2000, (4) grid cells with missing data in three and more contiguous years are excluded, (5) first-, second- and third-order polynomial models in the time with station effects are fitted to the data, and (6) the model with the best fit is selected using common regression diagnostics.

[17] On the one side, assumptions 2, 3, and 4 exclude several long data records from the analysis as reported in detail in section 4, on the other side; however, they favor that possible reversals of the trend in SWIR occurring in general in the 1980s are captured by the models estimated. Nevertheless, second- and third-order polynomial models in the time have limitations: trend reversals occurring in the 1990s (close to the end of the period under analysis) or weak reversals (when SWIR merely levels off following a pronounced decrease) are usually not captured, as is demonstrated by the example in Figure 4.

[18] Under these assumptions, the results obtained are (more or less, depending on the number of stations and observations and the homogeneity of the grid cell with respect to the temporal trend) representative for a grid cell and thus can be compared worldwide. Alternatives to a regionalization of SWIR using the ISCCP grid would be (1) a selection of a station considered to be representative for a region or (2) an averaging of SWIR records over two or more stations and possibly different periods to obtain regional means and trends. Alternative 1 is not feasible since detailed station histories (comparable to those available for BSRN stations) are not available in the GEBA. Alternative 2 was rejected for statistical reasons since the average time series obtained from the original time series has, in most cases, not a stable variance as it is computed, for each time point, from a different number of original yearly SWIR means.

4. Results

[19] For all ISCCP grids cells having SWIR yearly values as required in sections 2 and 3, models (1) or (2) with $p = 1, 2, 3$ are estimated. Under these restrictions, a first- or second-order model was found to be superior to a third-order one for all grid cells. The results are shown in Table 2 and Figure 3.

[20] Table 2 contains the numerical results for each grid cell. Columns 1,. . ., 7 contain its location, the number of stations with pyranometer measurements in the cell, the number of yearly SWIR values measured at these stations, the overall mean and variance of SWIR in Wm^{-2} and $(\mathrm{Wm}^{-2})^2$, and the observational period; columns 8 and 9 hold those statistics of the estimated models which describe the estimated trend: column 8 is the rate of change in percent of the cell mean per decade (in case of a first-order model) or the year of the reversal of the trend as seen in a plot (in case of a second-order model) and column 9 is the significance of the estimated coefficient (a_1 in case of a first-order model, a_2 in case of a second-order model).

[21] In Figure 3, grids cells with temporal changes significant at levels ≤ 0.1 are plotted in color: second-order models having minima are plotted yellow and first-order models increasing or decreasing red or green. On the northern hemisphere, models were estimated for 133 grid cells, with the majority located in Europe as well as China and Japan. On the southern hemisphere, results were obtained for only seven grid cells, since data are scarce. We first present the results for the southern hemisphere, then for the continents on the northern one.

4.1. Southern Hemisphere

[22] On the southern hemisphere, a reversal of the trend was found at the South Pole and in American Samoa (170°34′W, 14°14′S), in line with *Dutton et al.* [2006]. Both are NOAA/CMDL stations, with records going back to 1976. A reversal of the trend was also found at Valparaiso (71°29′W, 33°2′S) station in Chile, a station operated since 1960 by the Technical University Federico Santa Maria. Negative trends were found throughout the periods with observations, both starting in the 1950s, for Bulawayo (28°37′E, 20°9′S) in Zimbabwe and Nampula (39°17′E, 16°9′S) in Mozambique. Insignificant trends were obtained for Maputo (32°36′E, 25°58′S) in Mozambique and for the Fiji Islands (Nandi and Laucala/Suva Bay sites located in grid cell 177.535°E–180.000°E, 20.0°S–17.5°S).

[23] Data are scarce on the southern hemisphere owing to several reasons. In South Africa (and in most countries in Africa), no pyranometer records as required in section 3 are available. For the periods with measurements (subsets of the period from 1950 through to 1990, depending on the country), negative trends were observed [*Gilgen et al.*, 1998].

[24] In Australia, measurements made prior to 1988 are not suitable for trend studies, because the pyranometers

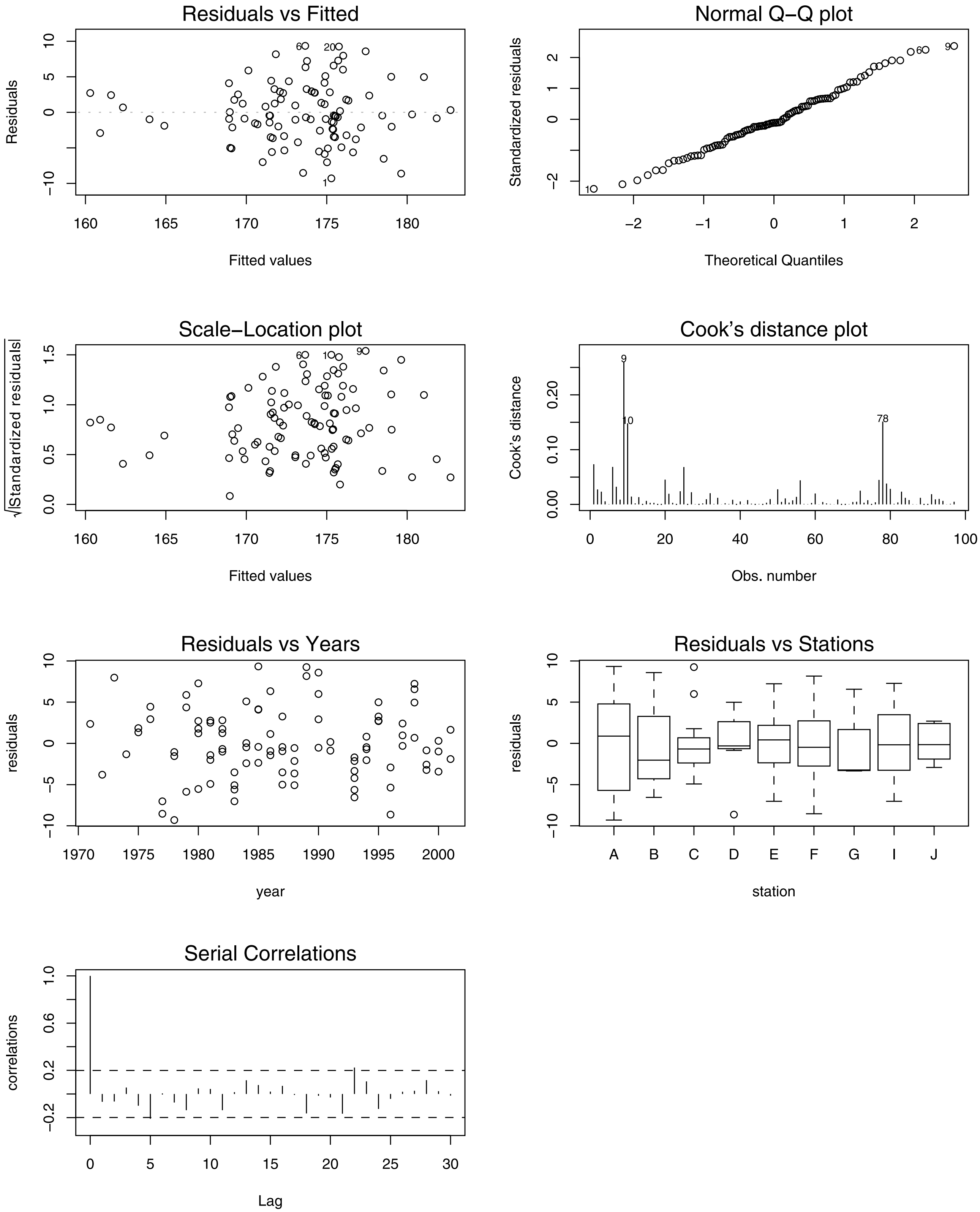

Figure 2. Regression diagnostics [*Gilgen*, 2006, section 3.3] for the second-order linear model with station effects fitted in Figure 1.

were not calibrated. As a surrogate for the calibration, the records were adjusted to some reference, thus wiping out any decadal changes [*Forgan*, 2005]. Since 1988, however, positive trends were observed [*Wild et al.*, 2005].

[25] In New Zealand, no significant trends were estimated for the period from 1960 through to 1990. It is very likely that SWIR was also measured during the last decade of the

Table 2. Estimates of Models 1 and 2 as Defined in Section 3 for the Trend in SWIR Observed in 140 ISCCP Grid Cells[a]

Latitudes	Longitudes	Stn.	Obs.	Mean	Var.	Obs. Period	Rate/Rev.	Sig. of *t* or t^2
−90.0, −87.5	0.000, 120.000	3	29	130	16	1975–2003	1986	**0.0324**
−35.0, −32.5	288.000, 291.000	3	51	170	319	1962–2004	1985	**0.0626**
−27.5, −25.0	30.698, 33.488	5	51	217	133	1955–2002	−0.6	0.2770
−22.5, −20.0	26.866, 29.552	1	40	246	130	1955–2000	−2.1	**0.0001**
−20.0, −17.5	177.353, 180.000	2	21	215	243	1979–2004	−0.4	0.8258
−17.5, −15.0	39.130, 41.739	2	21	246	80	1959–2000	−1.7	**0.0880**
−15.0 −12.5	187.714, 190.286	1	27	221	57	1977–2003	1992	**0.0265**
0.0, 2.5	102.500, 105.000	2	31	189	111	1965–2002	1982	**0.0005**
2.5, 5.0	100.000, 102.500	2	24	188	151	1973–2002	1992	**0.0016**
17.5, 20.0	71.471, 74.118	2	14	228	291	1959–2000	−4.7	**0.0620**
17.5, 20.0	82.059, 84.706	1	15	222	144	1964–2001	−3.2	**0.0000**
17.5, 20.0	203.824, 206.471	1	27	284	145	1977–2003	1.0	0.3360
20.0, 22.5	99.403, 102.090	1	36	179	108	1960–2000	−0.7	0.3890
20.0, 22.5	112.836, 115.522	2	39	163	167	1964–2002	−2.7	**0.0235**
22.5, 25.0	87.273, 90.000	2	14	199	81	1958–2000	−3.2	**0.0000**
22.5, 25.0	100.909, 103.636	1	39	180	125	1961–2000	1989	**0.0462**
22.5, 25.0	106.364, 109.091	1	22	148	83	1960–2000	−2.9	**0.0149**
22.5, 25.0	111.818, 114.545	3	36	148	257	1960–2000	1989	**0.0074**
22.5, 25.0	114.545, 117.273	1	31	164	170	1960–2000	1985	**0.0000**
22.5, 25.0	122.727, 125.455	1	36	177	174	1964–2002	1987	**0.0053**
22.5, 25.0	152.727, 155.455	1	31	217	167	1969–2002	1989	**0.0036**
25.0, 27.5	97.674, 100.465	2	73	186	201	1961–2000	1989	0.2180
25.0, 27.5	100.465, 103.256	2	46	175	127	1961–2000	1980	0.1086
25.0, 27.5	125.581, 128.372	1	41	167	175	1961–2002	1987	**0.0000**
25.0, 27.5	131.163, 133.953	1	40	186	99	1961–2002	1983	**0.0005**
25.0, 27.5	139.535, 142.326	1	31	186	59	1970–2002	1985	**0.0615**
27.5, 30.0	102.857, 105.714	3	41	145	141	1961–2000	3.0	**0.0015**
27.5, 30.0	128.571, 131.429	1	34	138	66	1965–2002	0.5	0.6330
30.0, 32.5	102.439, 105.366	2	60	115	107	1961–2000	−7.3	**0.0000**
30.0, 32.5	111.219, 114.146	1	36	120	174	1961–2000	1991	0.2170
30.0, 32.5	117.073, 120.000	2	72	144	215	1961–2000	1989	**0.0000**
30.0, 32.5	120.000, 122.927	5	114	145	152	1961–2000	1991	**0.0040**
30.0, 32.5	128.780, 131.707	10	98	167	217	1961–2002	1988	**0.0000**
32.5, 35.0	96.000, 99.000	1	34	194	271	1961–2000	−2.7	**0.0184**
32.5, 35.0	108.000, 111.000	2	65	149	237	1961–2000	1993	**0.0031**
32.5, 35.0	111.000, 114.000	2	50	154	117	1961–2000	−1.3	0.1273
32.5, 35.0	129.000, 132.000	14	288	155	202	1961–2002	1984	**0.0000**
32.5, 35.0	132.000, 135.000	9	284	161	191	1961–2002	1983	**0.0000**
32.5, 35.0	135.000, 138.000	5	136	155	202	1961–2002	1981	**0.0000**
32.5, 35.0	138.000, 141.000	5	118	151	212	1973–2002	1982	**0.0000**
32.5, 35.0	351.000, 354.000	1	28	208	30	1972–2002	1983	**0.0010**
35.0, 37.5	77.586, 80.690	1	43	189	104	1958–2000	1986	**0.0004**
35.0, 37.5	93.103, 96.207	1	41	223	44	1959–2000	−0.8	**0.0381**
35.0, 37.5	99.310, 102.414	2	49	191	272	1959–2000	−4.5	**0.0000**
35.0, 37.5	102.414, 105.517	1	39	167	93	1960–2002	−2.6	**0.0000**
35.0, 37.5	108.621, 111.724	2	48	162	97	1962–2000	−3.6	**0.0000**
35.0, 37.5	114.828, 117.931	2	57	157	149	1961–2000	−4.2	**0.0000**
35.0, 37.5	130.345, 133.448	3	65	150	199	1961–2002	1975	**0.0059**
35.0, 37.5	133.448, 136.552	4	124	146	214	1961–2002	1988	**0.0000**
35.0, 37.5	136.552, 139.655	14	260	151	254	1961–2002	1980	**0.0000**
35.0, 37.5	139.655, 142.759	7	200	149	154	1958–2002	1980	**0.0000**
37.5, 40.0	12.857, 16.071	2	44	194	108	1969–2002	1995	0.2250
37.5, 40.0	73.929, 77.143	1	40	185	140	1958–2000	−2.3	**0.0046**
37.5, 40.0	102.857, 106.071	1	40	190	212	1961–2000	1978	**0.0360**
37.5, 40.0	106.071, 109.286	1	34	192	52	1961–2000	−1.6	**0.0020**
37.5, 40.0	109.286, 112.500	2	38	184	97	1961–2000	−2.0	**0.0605**
37.5, 40.0	112.500, 115.714	1	40	170	149	1961–2000	−4.7	**0.0000**
37.5, 40.0	115.714, 118.929	2	84	167	210	1959–2000	−3.9	**0.0000**
37.5, 40.0	118.929, 122.143	2	31	163	97	1968–2000	−4.1	**0.0103**
37.5, 40.0	125.357, 128.571	3	63	154	174	1965–2002	−5.9	**0.0000**
37.5, 40.0	138.214, 141.429	7	278	143	100	1961–2002	1986	**0.0000**
37.5, 40.0	141.429, 144.643	2	47	154	166	1961–2002	1987	**0.0016**
40.0, 42.5	6.667, 10.000	3	39	181	46	1974–2001	1987	**0.0003**
40.0, 42.5	10.000, 13.333	4	45	174	118	1969–2001	−2.1	**0.0036**
40.0, 42.5	13.333, 16.667	7	77	181	128	1964–2002	−2.6	**0.0237**
40.0, 42.5	80.000, 83.333	2	41	186	89	1959–2000	−4.0	**0.0000**
40.0, 42.5	93.333, 96.667	1	42	205	71	1958–2000	−1.4	**0.0002**
40.0, 42.5	113.333, 116.667	1	40	179	193	1961–2000	−5.0	**0.0000**
40.0, 42.5	120.000, 123.333	1	36	166	80	1964–2000	0.9	0.3260
40.0, 42.5	123.333, 126.667	2	67	156	131	1961–2000	1992	**0.0263**
40.0, 42.5	140.000, 143.333	5	166	142	69	1961–2002	1987	**0.0003**
40.0, 42.5	253.333, 256.667	5	55	188	66	1950–2000	1991	**0.0000**
40.0, 42.5	353.333, 356.667	3	21	183	163	1979–2003	−0.4	0.8306

Table 2. (continued)

Latitudes	Longitudes	Stn.	Obs.	Mean	Var.	Obs. Period	Rate/Rev.	Sig. of t or t^2
42.5, 45.0	0.000, 3.462	6	87	157	64	1969–2003	1985	**0.0000**
42.5, 45.0	3.462, 6.923	10	97	173	34	1972–2001	1986	**0.0011**
42.5, 45.0	6.923, 10.385	11	93	166	151	1965–2002	1988	**0.0139**
42.5, 45.0	10.385, 13.846	9	36	155	207	1964–2001	0.2	0.9487
42.5, 45.0	20.769, 24.231	6	68	153	279	1964–2000	1981	**0.0008**
42.5, 45.0	24.231, 27.692	2	37	161	49	1964–2002	1986	**0.0097**
42.5, 45.0	27.692, 31.154	3	28	162	63	1964–2001	1984	**0.0000**
42.5, 45.0	79.615, 83.077	1	40	178	187	1961–2000	−1.9	**0.0635**
42.5, 45.0	86.538, 90.000	3	86	174	149	1959–2000	−3.4	**0.0000**
42.5, 45.0	93.462, 96.923	1	38	201	49	1962–2000	−2.1	**0.0000**
42.5, 45.0	110.769, 114.231	1	35	201	53	1965–2000	−2.1	**0.0000**
42.5, 45.0	121.154, 124.615	1	27	166	101	1962–2000	−1.6	0.1380
42.5, 45.0	124.615, 128.077	1	40	159	99	1959–2000	−0.5	0.5500
42.5, 45.0	128.077, 131.538	1	40	150	125	1960–2000	−2.0	**0.0446**
42.5, 45.0	138.462, 141.923	4	111	137	44	1958–2002	1990	0.1101
42.5, 45.0	141.923, 145.385	4	119	140	67	1974–2002	1990	0.1351
42.5, 45.0	145.385, 148.846	1	27	146	16	1977–2002	1989	**0.0282**
42.5, 45.0	280.385, 283.846	3	55	154	34	1955–2001	−1.6	**0.0006**
42.5, 45.0	356.539, 360.000	7	52	146	51	1978–2001	1.8	**0.0744**
45.0, 47.5	0.000, 3.600	4	80	140	53	1969–2001	0.7	0.3253
45.0, 47.5	3.600, 7.200	10	91	137	72	1950–2004	1980	0.1164
45.0, 47.5	7.200, 10.800	23	237	151	420	1950–2002	1987	**0.0019**
45.0, 47.5	10.800, 14.400	19	151	150	115	1964–2002	1981	0.2341
45.0, 47.5	14.400, 18.000	9	105	137	77	1964–2002	−0.7	0.3133
45.0, 47.5	18.000, 21.600	10	97	147	84	1964–2002	1989	**0.0061**
45.0, 47.5	21.600, 25.200	1	25	148	73	1964–2001	−3.7	**0.0000**
45.0, 47.5	25.200, 28.800	2	47	156	60	1964–2002	2.1	**0.0002**
45.0, 47.5	28.800, 32.400	1	26	141	48	1964–2001	1982	**0.0126**
45.0, 47.5	126.000, 129.600	1	40	150	60	1961–2002	−0.1	0.8710
45.0, 47.5	140.400, 144.000	2	66	135	69	1961–2002	−0.7	0.2023
45.0, 47.5	302.400, 306.000	1	16	132	24	1973–2002	−1.3	0.1941
45.0, 47.5	356.400, 360.000	5	49	147	84	1973–2001	−3.3	**0.0087**
47.5, 50.0	0.000, 3.789	7	95	125	68	1964–2001	1982	0.3849
47.5, 50.0	3.789, 7.579	5	104	123	55	1959–2001	1980	**0.0735**
47.5, 50.0	7.579, 11.368	18	254	127	72	1953–2002	1980	**0.0000**
47.5, 50.0	11.368, 15.158	10	126	124	63	1959–2002	1983	0.2814
47.5, 50.0	15.158, 18.947	15	113	130	78	1964–2001	1979	**0.0170**
47.5, 50.0	87.158, 90.947	1	39	176	45	1961–2000	−1.8	**0.0003**
47.5, 50.0	90.947, 94.737	1	33	156	69	1964–2001	−1.4	0.1078
47.5, 50.0	94.737, 98.526	1	34	163	79	1964–2002	1984	**0.0001**
47.5, 50.0	98.526, 102.316	1	33	152	134	1964–2002	1981	**0.0010**
47.5, 50.0	106.105, 109.895	1	38	157	91	1964–2002	−3.1	**0.0002**
47.5, 50.0	117.474, 121.263	1	28	162	59	1961–2000	−2.9	**0.0000**
47.5, 50.0	356.210, 360.000	3	71	132	40	1968–2002	−0.9	0.1216
50.0, 52.5	0.000, 4.000	8	102	115	53	1959–2001	1.3	**0.0557**
50.0, 52.5	4.000, 8.000	13	221	111	51	1950–2001	0.8	**0.0288**
50.0, 52.5	8.000, 12.000	11	186	114	53	1958–2002	1981	**0.0124**
50.0, 52.5	12.000, 16.000	10	191	118	71	1950–2002	1980	**0.0053**
50.0, 52.5	20.000, 24.000	4	99	117	50	1964–2002	1980	**0.0181**
50.0, 52.5	252.000, 256.000	4	34	161	44	1962–2001	1982	**0.0059**
50.0, 52.5	348.000, 352.000	1	37	112	35	1964–2002	−2.6	**0.0002**
50.0, 52.5	352.000, 356.000	2	49	121	46	1959–2002	−0.6	0.3540
50.0, 52.5	356.000, 360.000	14	206	111	81	1959–2002	1.8	**0.0005**
52.5, 55.0	4.235, 8.471	3	75	117	53	1967–2002	0.1	0.8653
52.5, 55.0	8.471, 12.706	5	103	110	41	1950–2002	1986	0.2904
52.5, 55.0	12.706, 16.941	4	52	121	33	1968–2002	−1.7	**0.0068**
52.5, 55.0	351.529, 355.764	5	121	107	51	1969–2002	1995	**0.0027**
55.0, 57.5	9.000, 13.500	3	42	115	42	1965–2001	−2.1	**0.0240**
55.0, 57.5	351.000, 355.500	2	36	102	36	1971–2002	−3.5	**0.0016**
55.0, 57.5	355.500, 360.000	6	100	98	31	1956–2002	−0.9	**0.0545**
57.5, 60.0	14.400, 19.200	3	59	114	56	1950–2002	1989	0.1045
57.5, 60.0	24.000, 28.800	1	43	111	33	1955–2005	1984	0.1070
60.0, 62.5	20.870, 26.087	7	141	108	46	1958–2002	1990	**0.0242**
60.0, 62.5	354.782, 360.000	1	44	90	24	1952–2002	−1.1	**0.0493**
62.5, 65.0	337.500, 343.125	1	39	89	31	1957–2002	−1.9	**0.0120**
65.0, 67.5	24.828, 31.034	1	47	93	49	1957–2002	−2.9	**0.0000**
70.0, 72.5	203.478, 211.304	1	27	99	8	1977–2003	−0.4	0.6080

[a] Stn. and Obs. denote number of stations and number of yearly values, Mean and Var. are the over-all mean of SWIR in Wm^{-2} and the over-all variance in $(Wm^{-2})^2$, Obs. Period is the observational period, Rate/Rev. is the rate of change (for first-order models) in percent of the cell mean per decade or the year of the trend reversal (for second-order models), and Sig. of t or t^2 is the significance level (bold when less or equal than 0.1 in agreement with Figure 3) of the estimated a_1 or a_2 in these models.

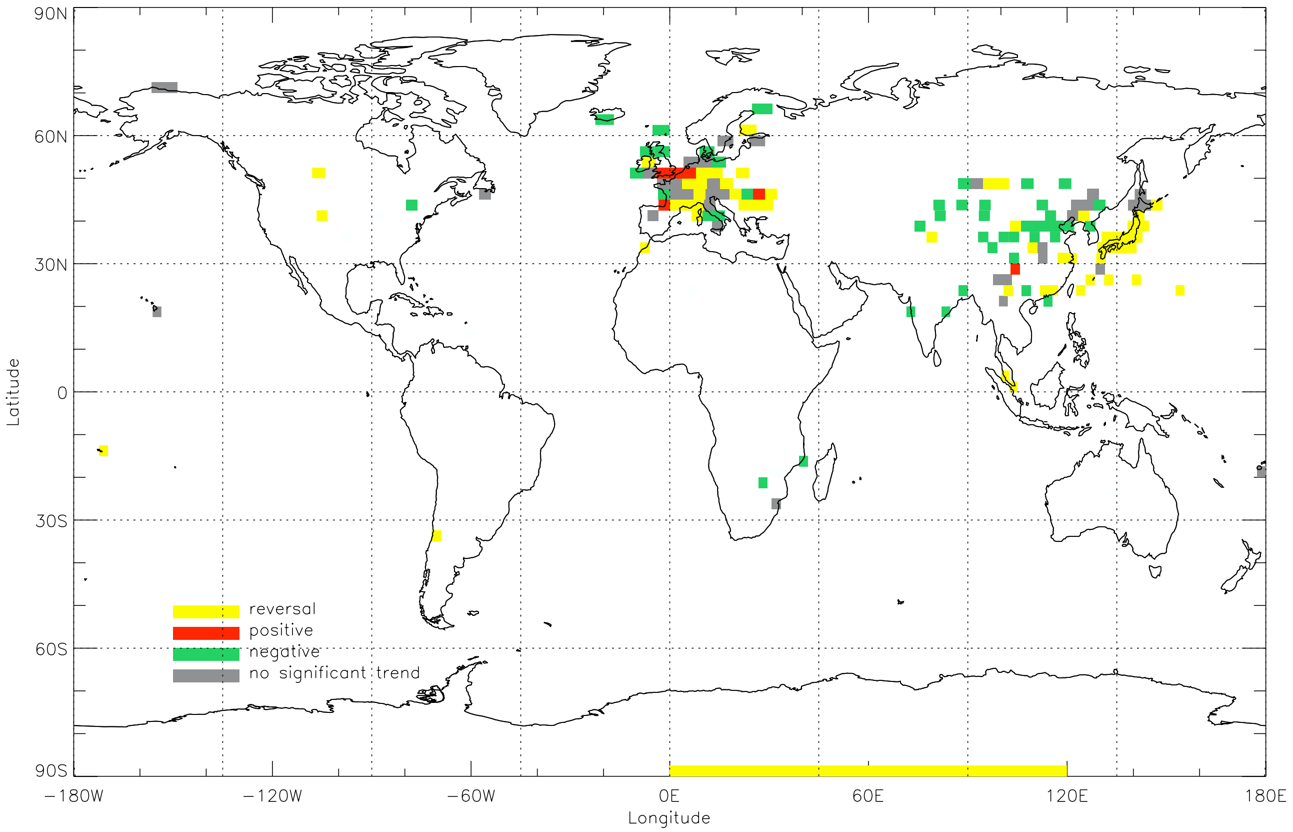

Figure 3. Decadal changes of SWIR in ISCCP grid cells. The observations stem from periods as indicated in Table 2, and, as an additional restriction, it is required that, for each cell, the observations include the period from 1980 through to 2000. Cells plotted yellow, red, or green show trends significant at the 0.1 level or lower.

twentieth century, however, these records were not made available to the GEBA.

[26] In South America in general, no long records of SWIR are available. In Venezuela, SWIR records end in 1996. In Chile, SWIR has been measured since approximately 1990 with thermoelectric pyranometers, in the 1970s and 1980s, however, SWIR was measured with Robitzsch actinographs. The Robitzsch records are, unfortunately, too low [*Gilgen and Ohmura*, 1999]. Also the Valparaiso record is systematically too low, however, it can be used for a trend study for the reason that the maintenance of the site, instruments, and data acquisition system did not change since 1960 (R. Sota, personal communication, 2006).

4.2. Hawaii

[27] For the Mauno Loa Observatory (155°35′W, 19°32′S), a NOAA/CMDL station having records for the period from 1976 through to 2003, no significant changes were found, in line with *Dutton et al.* [2006].

4.3. North America

[28] For NOAA/CMDL station Barrows (156°36′W, 71°19′S), no significant changes were found for the period from 1976 through to 2003, in line with *Dutton et al.* [2006]. In grid cell (89.415°W–83.077°W, 42.5°N–45.0°N), with records measured in the period from 1955 through to 2001 in the Toronto region, SWIR significantly decreases. From records measured at several sites near Boulder, Colorado (including the NOAA/CMDL record), in the period from 1951 through to 2000, SWIR was found to decrease until 1990 and thereafter to increase (grid cell 106.667°W–103.333°W, 40.0°N–42.5°N). A reversal was also found in grid cell (108.0°W–104.0°W, 50.0°N–52.5°N) which includes the BSRN site Regina. There, the trend in SWIR changes its sign in 1982.

[29] In North America, unfortunately, possible reversals of the trend in SWIR occurring in the 1980s and 1990s cannot be estimated for a larger number of grid cells because records are scarce in the 1980s and the early 1990s.

[30] In the United States, the NOAA maintained a relatively dense (approximately 100 sites) pyranometer network from 1950 to 1976 (both years approximately). Thereafter, the National Renewable Energy Laboratory (NREL), a branch of the Department of Energy (DoE) continued the measurements at a few stations for another 5 years. From these records, negative trends were estimated by *Gilgen et al.* [1998].

[31] Since 1985, NREL has operated a pyranometer network of six sites located at Historically Black Colleges and Universities (HBCUs) in the southeastern United States [*Marion*, 1994]. In the 1990s, pyranometer measurements were resumed at the U.S. component of the international BSRN [*Ohmura et al.*, 1998] and ARM [*Stokes and Schwartz*, 1994] sites run by the NOAA, DoE and NASA. These records, however, do not fulfil the requirements defined in section 3 (i.e., they do not reach back as far as

1980) and thus do not allow for estimating those decadal changes in SWIR which occurred since 1980. They do, however, show a tendency for an increase in the 1990s [*Wild et al.*, 2005].

[32] For the period from 1961 through to 1990, NREL also published SWIR surrogates calculated using other surface meteorological observations [*Maxwell et al.*, 1995]. We did not use these surrogates in our previous papers and do not use them in the present one either, since the GEBA only includes SWIR measured by pyranometers.

[33] In Canada, the Meteorological Service published SWIR records measured at a larger number of stations in the period from 1951 to approximately 1988. From these records, negative trends were estimated by *Gilgen et al.* [1998].

[34] In the Spanish-speaking countries of the continent and also in the Caribbean, no SWIR records reconcilable with the requirements defined in section 3 are available.

4.4. Asia Without China

[35] In Japan, SWIR has been observed in a dense network (approximately 100 sites) since approximately 1960. These pyranometer observations were made available to the GEBA by Japan Meteorological Agency. In the majority of the grid cells in Japan, SWIR changes significantly from decrease to increase in the 1980s, in line with the findings of *Wild et al.* [2005]. This reversal is also observed at sites located on islands south of 30°N. Noticeably, these islands are in larger distances from the Japanese main islands and China.

[36] In Korea, SWIR decreases significantly in grid cell (125.357°E–128.571°E, 37.5°N–40.0°N) with sites Seoul, Haeiu and Pyongyang.

[37] In Singapore and Kuala Lumpur (Malaysia), the trend in SWIR changes its sign in 1982 and 1992, respectively.

[38] In India, a general decrease in SWIR for the observational period 1960 through to 2000 was found by *Wild et al.* [2005]. In the 1990s, however, data become scarce. Many values are missing in SWIR records made available by the India Meteorological Department. Under the restrictions formulated in section 3, therefore, changes in SWIR could be determined for only three grid cells, i.e., those with Poona (73°51′E, 18°32′N), Vishakhapatnam (83°14′E, 17°43′N) and Calcutta (88°27′E, 22°39′N) stations. There, SWIR was found to decrease in the period from 1960 through to 2000.

[39] In Mongolia, no significant trend was estimated for Ulaangom station (92°4′E, 49°51′N). Significant trends were estimated at Ulyasutay (96°51′E, 47°45′N) and Muren (100°10′E, 49°38′N) stations, where SWIR changes from decrease to increase in 1984 and 1981, and finally, SWIR decreases at Ulan-Bator station (106°45′E, 47°51′N) from 1964 through to 2002.

[40] In the countries of the former Soviet Union, all pyranometers records end in the 1990s and thus do not meet the requirements of this study as stated in section 3. Consequently, we are not able to estimate possible reversals of the negative trends found by *Abakumova et al.* [1996] and *Gilgen et al.* [1998].

4.5. China

[41] In China, a relatively dense pyranometer network (approximately 40 out of 100 sites have 4 decades of measurements) has been built up and maintained by the Chinese Meteorological Administration. The Chinese pyranometer data are systematically lower than SWIR as estimated by satellite algorithms, likely owing to heavy aerosol loads not represented correctly in the satellite algorithms [*Xia et al.*, 2006]. In line with this result, the Chinese SWIR values available in the GEBA for a few sites were found to be too low by the GEBA quality assessment procedures on the basis of a comparison of SWIR monthly values observed at King's Park station (Hong Kong, 114°10′E, 22°12′N) and Guangzhou station (113°19′E, 23°8′N) in the period from 1988 through to 1992. The too low values were suspected to be due to a systematic calibration and/or data processing error rather than due to large aerosol concentrations [*Gilgen and Ohmura*, 1999]. This conclusion drawn from a data set including observations made by two different national weather services is, however, in contradiction to the results obtained when the GEBA quality assessment procedures were applied to the full Chinese pyranometer data set which has been made available to the GEBA in 2006: less than 10 percent of the Chinese data were flagged as being erroneous. Consequently, the Chinese data not found to be erroneous are included in the analysis. Some doubts, however, remain, since (1) no station histories including records of pyranometer calibrations have been published (at least in English, as far as we know) and (2) the variance of some records is not stable (e.g., the Beijing data in Figure 4) probably owing to changes affecting the accuracy of the observations.

[42] In China, throughout the last 4 decades, SWIR increases significantly only at one site (Emei Shan, 103°20′E, 29°31′N). This site is located at an altitude of approximately 3000 m on an isolated mountain (Emei Shan Natural and Historical Heritage Reserve) and therefore, possibly, this site is not affected by the aerosol burden observed at the majority of the Chinese sites [*Liang and Xia*, 2005].

[43] In southeast China, there are only two grid cells with significantly decreasing SWIR: cell (106.364°E–109.091°E, 22.5°N–25.0°N) with Nanning site and cell (112.386°E–115.522°E, 20.0°N–22.5°N) with the Macau and Hongkong sites. Also the majority of the grid cells in northeast China (provinces of Heilongjiang, Jilin and Liaoning) show no significant decrease.

[44] In northwest and central China, SWIR significantly decreases in the majority of the grid cells. At a few sites in these grid cells, however, SWIR recovers from the earlier decline since approximately 1990. This recovery is not captured by the regression models estimated, owing to the limitations of these models. For example, yearly SWIR values observed at Beijing (116°17′E, 39°56′N) and Tianjin (117°4′E, 39°5′N) sites are plotted in Figure 4. In Figure 4, the very short-term variations of the Beijing record decrease since the late 1980s, presumably owing to the transition from manual to automated observations, and, more relevant for the present study, SWIR increases since 1990. However, this reversal is not captured by the first-order model (and neither by higher-order models which do not fit better than the first-order one). For the period from 1988 through to 2002, a similar increase was found for Guangshou, Kunming, Chengdu, Wuhan, Shanghai, Lanshou, Harbin and Shenyang sites.

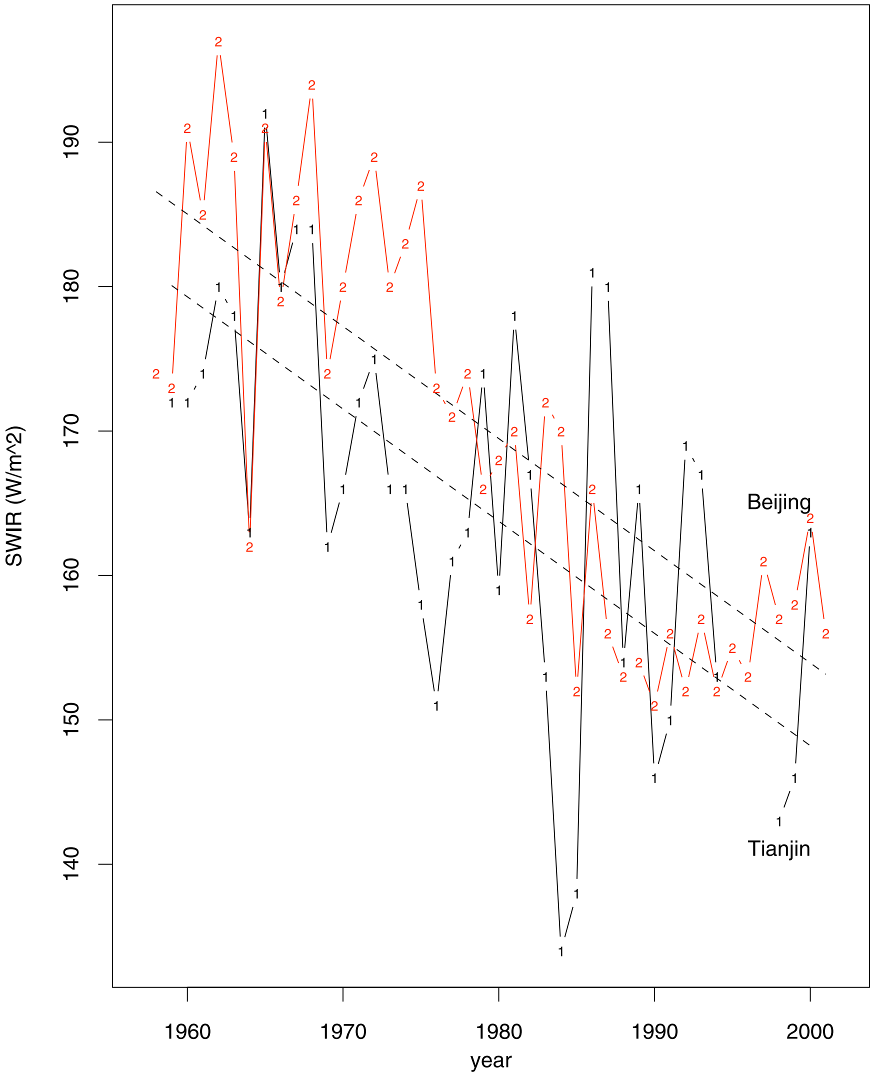

Figure 4. SWIR yearly values (in Wm^{-2}) observed in grid cell (115.714°E–118.929°E, 37.5°N–40.0°N) together with fitted first-order model (dashed lines) with station effect for Tianjin (line 1) and Beijing (line 2) sites.

[45] This result is prima facie in contradiction to the one obtained by *Liang and Xia* [2005]. Liang and Xia fitted first-order models to SWIR yearly means observed at 42 sites, each having 4 decades of observation, and thus found a decrease in SWIR for almost all sites. When a possible reversal of the trend is accounted for by allowing for second-order models, the result becomes similar to the one shown in Figure 3.

4.6. Europe

[46] A dense network of pyranometer stations is maintained by the meteorological authorities of the European countries. From the SWIR records made available to the GEBA until 1997, *Gilgen et al.* [1998] estimated negative trends for the observational period from 1950 through to 1990, except for grid cells in northwest Germany, the Netherlands, Belgium and the UK. There, SWIR increases in this period.

[47] When the SWIR records observed in the last decade of the 20th century are included in the analysis then the results shown in Figure 3 are obtained. In the period as defined in section 3 therefore, SWIR decreases in 12 grid cells, increases in 5 cells and changes from decrease to increase in 19 cells, when the one with Casablanca station in Morocco is included. In 15 grid cells, no significant trend was found. Obviously, in large regions in the interior of Europe, either the negative trend in SWIR has become positive in the 1980s and/or 1990s or, in these decades, SWIR begins to recover from its previous decrease, such that the trends are no more significant.

[48] Positive trends were estimated for south England (in the period from 1960 through to 2000) and for Belgium, the Netherlands and northwest Germany (in the period from 1950 through to 2000) using SWIR records observed at a total of 35 sites (Table 2). In this densely populated region, the heavy aerosol load (smog) of the 1950s has been slowly but continuously reduced owing to deindustrialization. Positive trends were also obtained for grid cells (3.441°W–0°W, 42.5°N–45.0°N) with seven stations for the period from 1978 through to 2001 and for grid cell

(25.2°E–28.8°E, 45.0°N–47.5°N) with station Iasi (Romania) for the period 1964 through to 2002.

[49] Negative trends were obtained in grid cells located at the coasts and also for two stations in grid cell (21.600°E–25.200°E, 45.0°N–47.5°N) in the interior of Europe.

5. Summary and Concluding Remarks

[50] Using pyranometer records from the GEBA for the observational period from approximately 1960 through to 2000, decadal changes in SWIR at the Earth's surface were estimated for 140 cells of the ISCCP grid. The results were obtained by estimating low-order polynomials in the time including station effects using regression techniques. They are given in Table 2 and Figure 3. Although pyranometer records can be representative for a larger region (examples are given by *Dutton et al.* [2006]), the spatial coverage of ground-based pyranometer records cannot compete with satellite records. Advantages of the pyranometer data are, however, (1) their reaching back in presatellite times and (2) their temporal stability due to slow but continuous improvements of instruments and calibration procedures over the observational period.

[51] When the decadal changes in SWIR estimated in this study are compared with the results of *Gilgen et al.* [1998] it becomes evident that in large regions worldwide, in the period from approximately 1960 through to 2000, SWIR recovers in the 1980s from a previous decrease, confirming the findings of *Wild et al.* [2005]. This reversal of the trend is observed at the majority of the sites in interior of Europe and in Japan. In China, there is some evidence that, in the 1990s, SWIR recovers at sites in the southeast and northeast from the decrease observed in the period from 1960 through to 1990. A reversal of the trend in the 1980s or early 1990s is also observed at two sites in North America, and at Kuala Lumpur (Malaysia), Singapore, Casablanca (Morocco), and Valparaiso (Chile) sites, and, noticeably, at the remote South Pole and American Samoa sites.

[52] Negative trends persist for the observational period 1960 through to 2000 at sites located at the European coasts, and in the majority of sites located in northwest and central China. Furthermore, negative trends persist at three sites in India and two in Africa.

[53] It is not possible to separate monthly SWIR values into values for clear-sky and all-sky conditions. Consequently, there is no straightforward method to attribute the estimated decadal changes in SWIR to changes in the cloud cover and/or clear-sky atmospheric transmission. In Europe, however, *Norris and Wild* [2007] found that the reversal (from decrease to increase) of the trend in SWIR was not due to changes in cloud amount, but more likely due to changes in aerosol direct and indirect effects, in line with the trend in aerosol emissions reaching its maximum in the 1980s.

[54] This suggests the following speculations which are arrived at under two assumptions: (1) decadal changes in aerosol emissions and SWIR as observed in Europe are connected with the transition from agrarian to industrial and further to service economies involving growth of population, changes in technology (e.g., substitution of coal with oil) and legislation (e.g., clean air regulations) and (2) more daring, densely populated regions (such as Japan, China or India) undergo a development of their economies and societies similar to the European one. Then it is plausible that, in densely populated regions, decadal trends in aerosol emissions induce decadal trends in SWIR with opposite sign; and, since aerosols are transported over large distances [e.g., *Shaw*, 1981; *Uematsu et al.*, 1983; *Ramanathan et al.*, 2001b; *Prospero et al.*, 2003; *Colarco et al.*, 2003; *Heald et al.*, 2006; *Hadley et al.*, 2007] these trends may also affect SWIR in adjacent regions and possibly even at remote sites. These speculations are reconcilable with (1) the trends in aerosols as reported by *Streets et al.* [2006], (2) the measurements of atmospheric transmission in Figure 12 of *Ohmura* [2006] and (3) the increase in SWIR under clear-sky conditions at remote BSRN sites in the period from 1992 through to 2002 estimated by *Wild et al.* [2005].

[55] **Acknowledgments.** We thank E. G. Dutton, B. W. Forgan, R. Sota, and two anonymous reviewers for their critical comments that helped to improve the paper. We are grateful to the following organizations for their generous support. In the period 1987–1995, the GEBA has been financed by the Swiss National Science Foundation (grants 2.307-0.86, 20-29825.88, 20-29826.90, and 2100-037698.93) and the ETH Zurich (grants 0.330.060.34/4 and 0-20-042-95). Since 1994, the GEBA has been supported by the City of Zurich (unemployed reintegration program), and, since 2001, also by the National Center for Competence in Climate Research (NCCR Climate). We would further like to express our sincere thanks to all those individuals and institutions who and which measured and published the data now available in the GEBA.

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