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The role of water vapor and solar radiation in determining temperature changes and trends measured at Armagh, 1881–2000

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[1] A 120 year series of climate measurements at Armagh Observatory, a rural site in Northern Ireland, was analyzed to yield monthly, seasonal, and annual values of long- and short-wave irradiances which were then related to the measured changes in air temperature. Three quarters of the significant increase and large decadal variations in atmospheric long-wave radiation was associated with the concurrent changes measured in specific humidity; the remaining quarter was associated with increases in the concentrations of carbon dioxide and other anthropogenic radiatively active gases. Significant but smaller long-term decreases in short-wave solar irradiance reduced by half the net, all-wave radiation forcing at the surface. Together the changes in long- and short-wave irradiances at Armagh accounted for more than three quarters of the interannual variations in mean annual temperatures. Climate sensitivity to long-wave forcing at the surface, 0.121°C per W m^{-2}, was 5 times greater than that to short-wave forcing, and two possible explanations for this difference, water vapor feedback and changes in atmospheric circulation, are discussed.

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1. Introduction

[2] The downwelling fluxes of short-wave solar radiation $E_{g\downarrow}$ and long-wave atmospheric radiation $E_{l\downarrow}$ reaching the Earth's surface supply the latent heat which transforms liquid water at the surface into the water vapor of the atmosphere. When and where evaporation at the surface is limited by the availability of water the surplus radiant energy provides the sensible heat which heats the atmosphere. The energy used by plants to fix carbon dioxide from the atmosphere is provided by the approximately half of $E_{g\downarrow}$ that is within the photosynthetically active wave bands. Clearly information on these radiation fluxes and their changes, i.e., radiation forcing at the surface RF, should contribute to our understanding of the Earth's water and carbon cycles as well as of the causes and consequences of climate change on a local scale.

[3] The committee of the U.S. National Research Council which reexamined the relevance of the concept of radiative forcing to climate change studies stressed the need to consider the vertical as well as regional variations in radiative forcing [*National Research Council* (*NRC*), 2005]. The absence of such studies can largely be explained by the small number and short duration of reliable series of radiation measurements; the few such series of $E_{g\downarrow}$ measurements available are restricted to the last 50 years while the even fewer series of $E_{l\downarrow}$ measurements are limited to the last 25 years.

[4] Following the recommendation of the NRC report and in order to assess the contribution of changes in the atmosphere's water content, the most important of the radiatively active gases, this study examines the relative importance of long- and short-wave radiative forcing at the surface and their relationships to changes in the air temperature as measured during the last 120 years at Armagh Observatory, a rural site in Northern Ireland.

2. Methods

2.1. Measurements

[5] Sunshine duration SD, air temperature T, relative humidity RH, and air pressure Pa, measurements over the 1881 and 2000 period at Armagh Observatory (6°39′W, 54°21′, 64 m MSL), a rural site in the temperate climate of Northern Ireland, were used in this study. Detailed descriptions of the site, instruments and data processing methods used to allow for changes in instruments and their exposure have been documented for SD (C. J. Butler et al., Daily, monthly, seasonal and annual hours of bright sunshine, 1889–2004, Armagh Observatory Climate Series, vol. 10, 2005, http://climate.arm.ac.uk/calibrated/sun), T (C. J. Butler et al., Daily, mean monthly, seasonal and annual, maximum and minimum temperatures, Armagh Observatory Climate Series, vol. 2, 2005, http://climate.arm.ac.uk/calibrated/airtemp/yellow-textD.pdf) and RH (C. J. Butler and A. M. García-Suárez, Daily, mean monthly, seasonal and annual humidity, 1838–2008,

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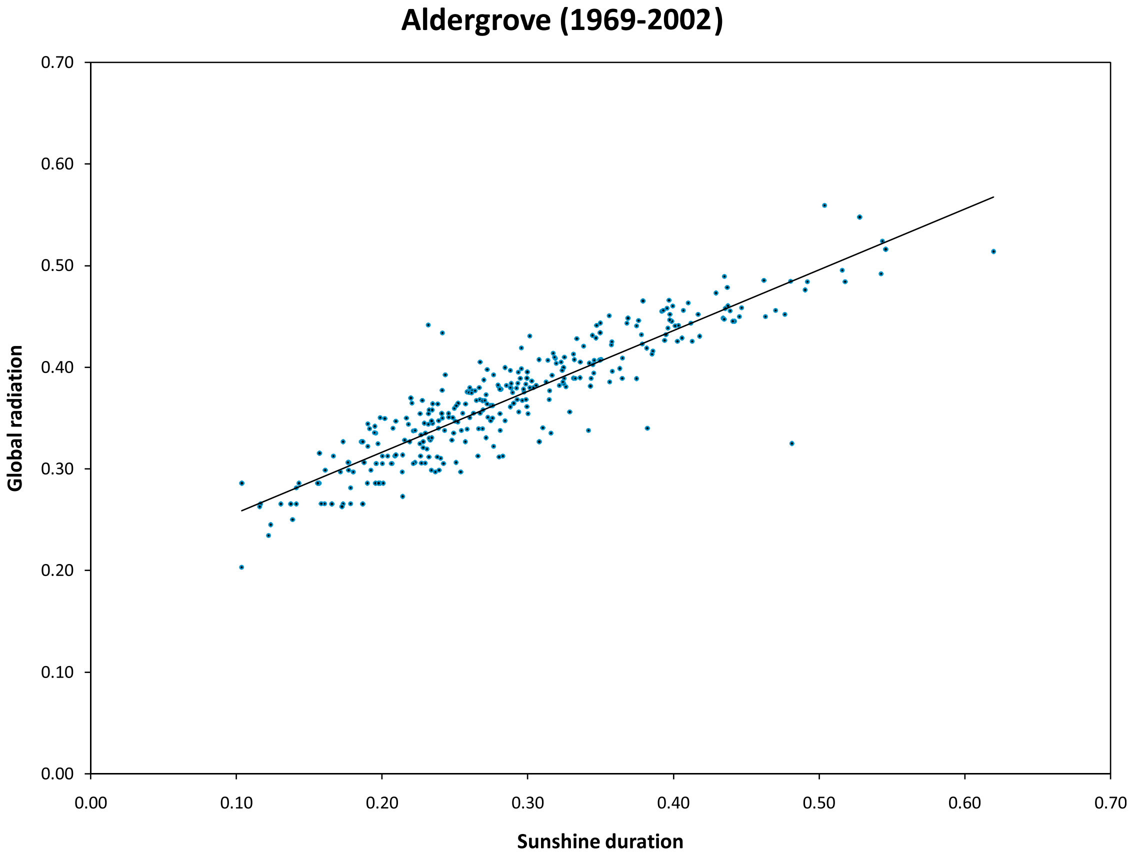

Figure 1. Relationship between global radiation and sunshine duration at Aldergrove, 1969–2002. Mean monthly values expressed as fractions of potential values.

corrected for time of observation, Armagh Observatory Climate Series, vol. 13, in preparation, 2010). Evidence that the temperature measurements at the Observatory were not affected by urbanization over the last three decades of the 20th century has been presented [*Coughlin and Butler*, 1998]. The statistical significance of the measured changes in the SD, T and specific humidity q was examined using both the nonparametric Mann-Kendall test recommended by the World Meteorological Organization to avoid the auto correlation commonly found in climate time series [*Sneyers*, 1990], and standard parametric methods.

2.2. Calculations

[6] Short-wave global radiation at the Earth's surface $E_{g\downarrow}$, at Armagh was estimated from the measurements of sunshine duration using a relationship established between 395 mean monthly measurements of SD and those of $E_{g\downarrow}$ measured between 1969 and 2002 at Aldergrove (6°13′W, 54°39′N, 68m MSL), an open airfield site 20 km NE of Armagh. The linear relationship shown in Figure 1 was: $E_{g\downarrow}/E_{o\downarrow} = 0.598\ SD/SD_o + 0.197$, $R^2 = 0.819$, $P < 0.001$, where $E_{o\downarrow}$ represents values of solar irradiance at the top of the atmosphere and SD_o the potential sunshine duration i.e., day length, for individual monthly values.

[7] Long-wave atmospheric radiation at the Earth's surface $E_{l\downarrow}$, at Armagh was estimated in two stages. In the first the effect of the atmosphere's water content—at contemporary levels of the other radiatively active gases—was calculated using monthly mean values of specific humidity q, calculated from the mean air temperature, relative humidity and air pressure measured at Armagh. Values of q were used to estimate $E_{l\downarrow}$ on the basis of the relationship established between 164 mean monthly values of q and those of $E_{l\downarrow}$ measured between 1982 and 1995 at Valentia (51°56′N, 10°15′W, 9 m MSL), Met Eireann's observatory on the SW coast of Ireland, an unpolluted site 355 km SW of Armagh. The power function fitted to the data shown in Figure 2 was

$$E_{l\downarrow} = 192.4\ q^{0.273}, R^2 = 0.701, P < 0.001.$$

The calculated values of $E_{l\downarrow}$ were then corrected for the effect of the increasing concentrations of the radiatively active gases other than water vapor, i.e., carbon dioxide, methane, nitrous oxide, etc. The values of RF at the tropopause since 1750 cited by *Gohar and Shine* [2007] were used for this correction, the value at the midyear of the Valentia series, was taken as the reference; for earlier years the differences were subtracted and for later years differences were added. As in the IPCC reports the values of RF due to anthropogenic radiatively active gases used for our corrections were calculated on the basis of the increasing concentrations of such gases listed at (http://data.giss.nasa.gov/modelforce/ghgases/GHGs.1850-2000.txt).

3. Results

3.1. Climate Time Trends

[8] Annual values of sunshine duration, mean and diurnal air temperature range and specific humidity at Armagh are

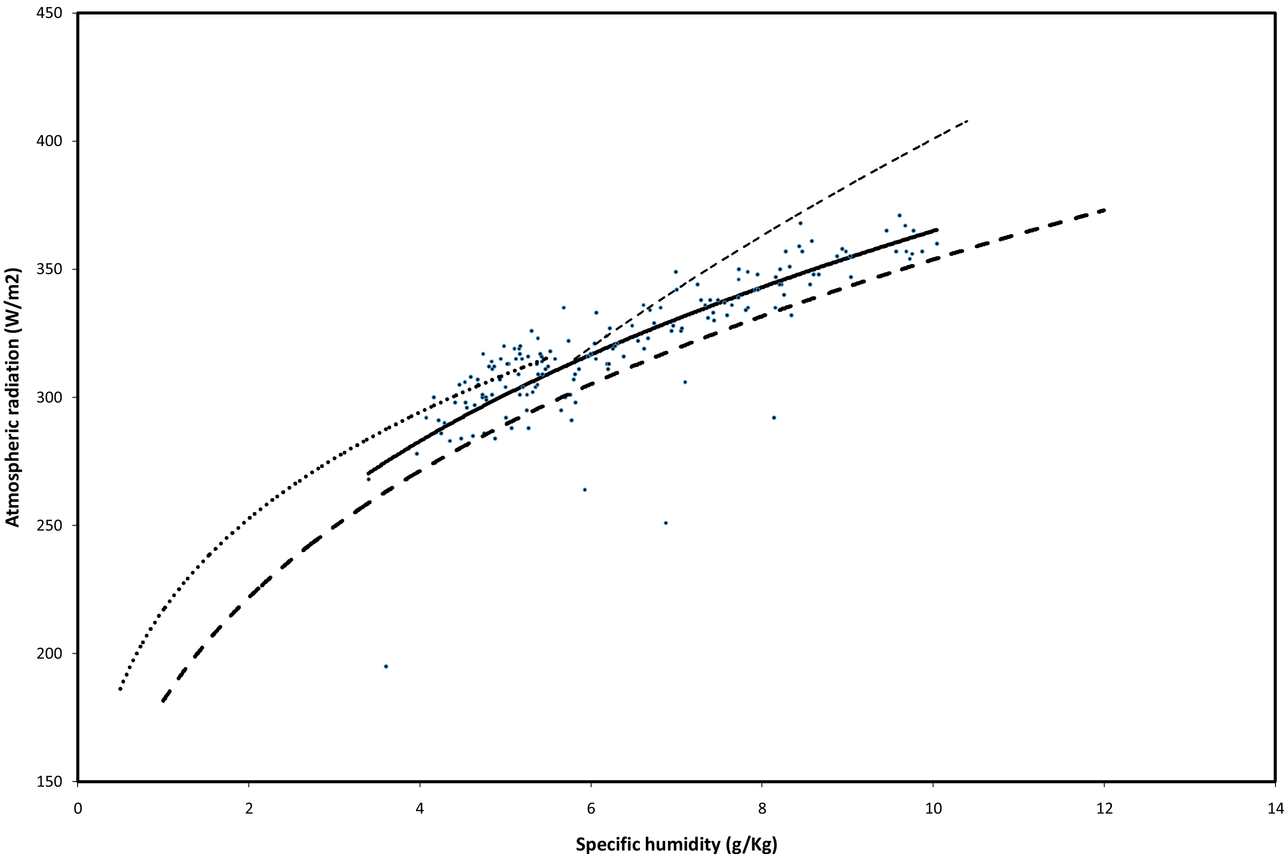

Figure 2. Relationship between atmospheric radiation and specific humidity at Valentia, 1982–1995; individual mean monthly values are shown as points. The lines represent the fitted power relationships derived from measurements at the seven sites detailed below: Solid line denotes Valentia (51°56′N, 10°15′W, 9 m. MSL), 1982–1995. $E_{l\downarrow} = 192.4\ q^{0.28}$; $R^2 = 0.70$. Short-dashed line denotes Dead Sea: Quidron (31°40′N, 35°27′E, −395 m MSL) 1982–1985 $E_{l\downarrow} = 144.2\ q^{0.44}$; $R^2 = 0.81$ [*Stanhill*, 1987]. Long-dashed line denotes Switzerland: Locarno Monti (8°47′N, 46°10′E, 366 m MSL), Payerne (6°58′N, 46°49′E, 490 m MSL), Davos (9°50′N, 46°48′E, 1645 m MSL), Jungfraujoch (7°57′N, 46°32′E, 3574 m MSL) 2001–2005 $E_{l\downarrow} = 181.4\ q^{0.29}$; $R^2 = 0.96$ [*Ruckstuhl et al.*, 2007]. Dotted line denotes Antarctic Peninsula: King Sejong (62°13′S, 58°47′W, 10 m MSL) $E_{l\downarrow} = 216.8\ q^{0.22}$; $R^2 = 0.56$ [*Cho et al.*, 2008].

shown as normalized anomalies in Figure 3. Sharp rises in T and SD occurred during the last 20 years of both the 19th and 20th centuries with lesser reductions between 1940 and 1980. The time course in DTR was inverse to those of T and SD Analyses with the nonparametric Mann-Kendall test showed that the change in SD over the entire series was statistically significant ($P < 0.05$) as were the changes in trends shown by the crossovers of the values of ut and ut1 statistics, i.e., the decrease in SD starting at 1910 and the increase starting in 1980. The overall trends of increasing air temperatures were highly significant for mean, maximum and minimum annual temperatures, the absence of crossovers of the forward and backward ut and ut1 values indicating that the changes in trends occurring during the series were not significant. The overall downward trend in annual diurnal temperature range was significant but the changes in the DTR trend occurring at the beginnings of the 20th and 21st centuries were not. Nonparametric analysis showed a significant trend existed in the annual values of specific humidity.

[9] Parametric analysis by linear regression of temperature on year of measurement showed the increases in maximum, minimum and mean annual temperatures which occurred over the whole period of measurement, averaging 0.60, 0.86 and 0.74°C per century, respectively, were all highly significant ($P < 0.001$) as was the decrease in diurnal temperature range −0.23°C per century ($P < 0.01$). The overall decrease in sunshine duration at Armagh, −51.7 h per century, was not statistically significant. The increase in specific humidity over this period, averaging 0.36 g kg^{-1} per century, although small was statistically highly significant ($P < 0.001$). This increase, expressed as a function of the increase in air temperature, was 8.0% per degree C, similar to the value of 7.5% expected from the Clausius-Clapeyron relation.

3.2. Changes in Short- and Long-Wave Radiation Fluxes

[10] Annual mean values of long-wave radiation reaching the surface at Armagh, both those resulting from changes in concentrations of water vapor and those including changes

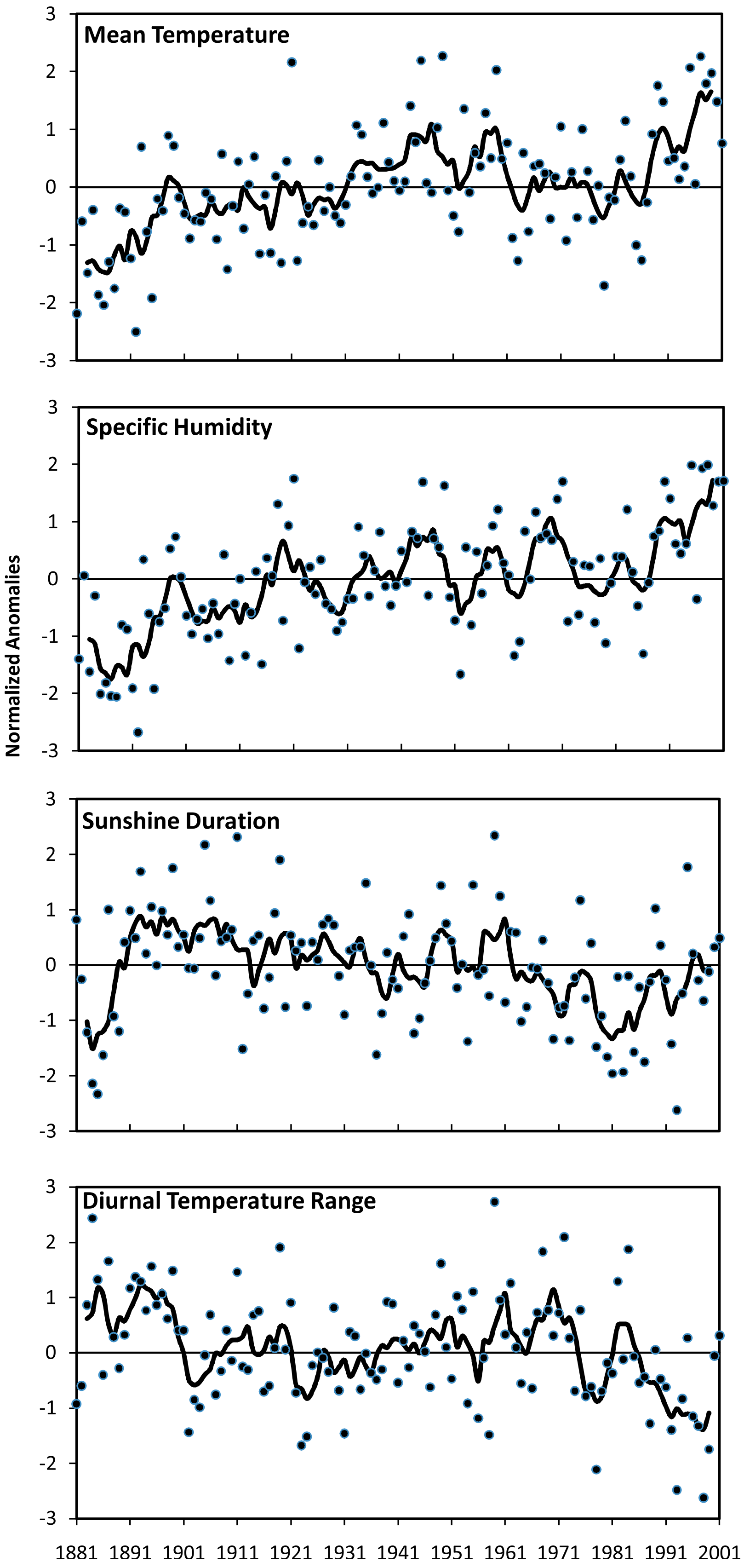

Figure 3. Annual values of sunshine duration, mean and diurnal air temperature range, and specific humidity measured at Armagh, 1881–2000. Points represent annual anomalies normalized to the median values of the series; lines represent running 5 year averages.

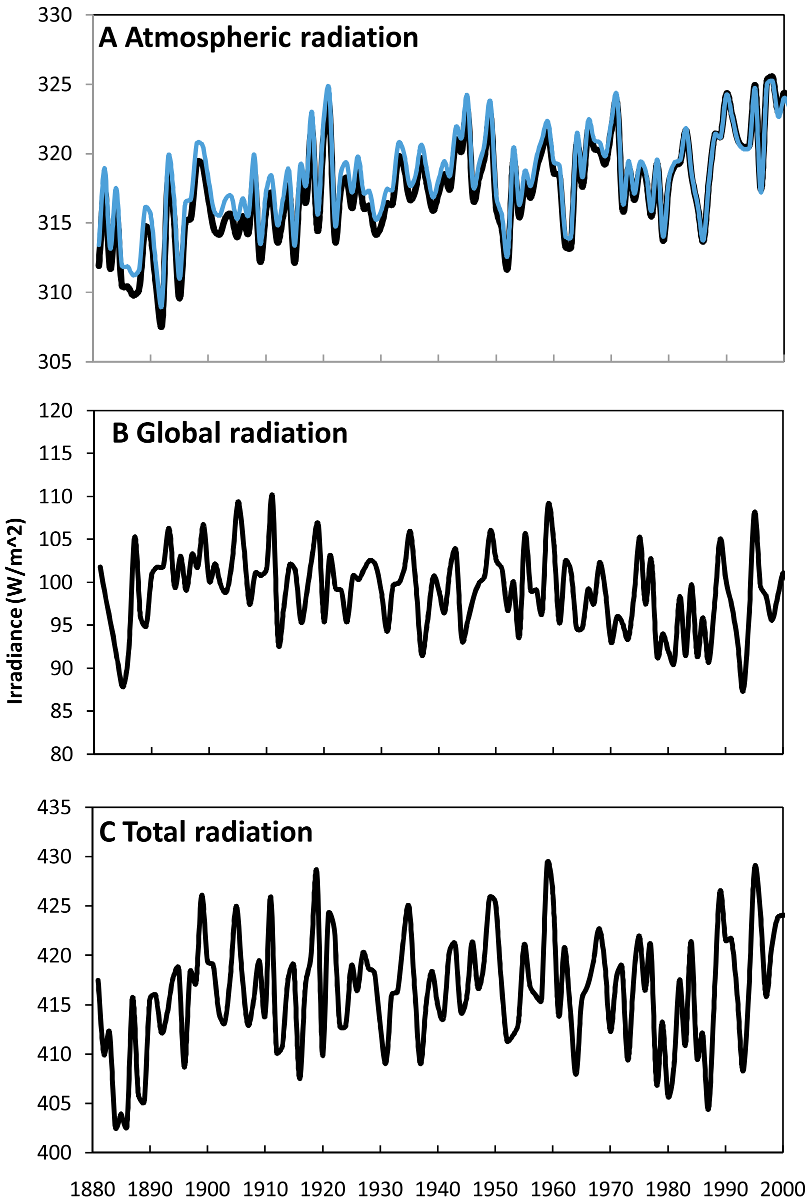

Figure 4. Annual values of downwelling radiation at Armagh, 1881–2000, W m^{-2}. (a) Atmospheric long-wave radiation $E_{l\downarrow}$ due to changes in water vapor concentrations (blue line) and after adjustment for changes in concentrations of other greenhouse gases (black line). (b) Global short-wave radiation $E_{g\downarrow}$. (c) Total all-wave radiation $E_{t\downarrow}$.

of the other, anthropogenic radiatively active gases, are shown in Figure 4a. The interannual variations due to changes in water vapor concentrations are irregular but far larger than the small but monotonic increases due to the rising concentration of the anthropogenic radiatively active gases. The magnitude of the mean annual radiation fluxes, their interannual variability and linear time trends are summarized in Table 1 together with similar data for the means of the three midwinter months, December, January and February and the three midsummer months, June, July and August. In absolute energy terms the interannual range in annual mean values of $E_{l\downarrow}$, was similar to that in short-wave irradiance, although in relative terms differences in $E_{g\downarrow}$ were larger (Figure 4b). Annual values of the total of these two fluxes, i.e., the total all-wave incident radiation $E_{t\downarrow}$, are shown in Figure 4c. Time trends in annual values of $E_{g\downarrow}$, $E_{l\downarrow}$ and $E_{t\downarrow}$ were significant; the increase in long-wave radiation averaged 6.39 W m^{-2} per century ($P > 0.001$); the decrease in the annual short-wave flux was less than half, 2.88 W m^{-2} per century ($P > 0.05$) resulting in a net increase in the sum of the two radiation fluxes of 3.30 W m^{-2} per century ($P > 0.05$). Trends in mean summer month values of long- and short-wave radiation fluxes were similar to the trends in annual values; there were no significant trends in midwinter means (Table 1).

3.3. Effects of Short- and Long-Wave Radiation Fluxes on Air Temperatures

[11] Relationships between mean annual values of maximum, minimum, mean air temperatures and the diurnal temperature range DTR, and the mean annual values of

Table 1. Atmospheric, Global, and Total All-Wave Radiation at Armagh, 1881–2001[a]

	$E_l\downarrow$ (Water Vapor)	$E_l\downarrow$ (Water Vapor + Other Greenhouse Gases)	$E_g\downarrow$	$E_t\downarrow$
	Annual Means and Trends			
Mean (W m^{-2})	318.7	318.1	99.1	416.5
St. Deviation (W m^{-2})	7.49	8.77	4.56	5.82
Coefficient of variation (%)	2.4	2.8	4.6	1.4
Range (W m^{-2})	28.6	12.4	22.7	26.7
Linear regression on year				
Slope (W m^{-2} yr^{-1})	0.051	0.065	−0.029	0.036
Intercept (W m^{-2})	224.4	191.9	156.8	345.9
R^2	0.278***	0.386***	0.051*	0.046*
	Summer Means and Trends			
Mean (W m^{-2})	344.7	344.3	164	508.3
St. Deviation (W m^{-2})	8.21		11.97	12.86
Coefficient of variation (%)	2.4		7.3	2.5
Range (W m^{-2})	11.6	21	61.95	66.34
Linear regression on year				
Slope (W m^{-2} yr^{-1})	0.054	0.07	−0.051	0.015
Intercept (W m^{-2})	240.9	208.5	263	478.3
R^2	0.175***	0.249***	0.021 NS	0.0017 NS
	Winter Means and Trends			
Mean (W m^{-2})	291.9	295.2	29.46	324.6
St. Deviation (W m^{-2})	8.46	5.73	2.01	6.27
Coefficient of variation (%)	2.9	1.9	6.8	1.9
Range (W m^{-2})	12	31	9.7	31.8
Linear regression on year				
Slope (W m^{-2} yr^{-1})	0.005	0.018	0.001	0.019
Intercept (W m^{-2} yr^{-1})	288.5	259.5	28	287.5
R^2	0.001 NS	0.012 NS	0.001 NS	0.011 NS

[a] Levels of significance: ***, $P < 0.001$; **, $P < 0.01$; *, $P < 0.05$, NS > P.0.05.

short-wave, long-wave and total downwelling radiation are presented in Table 2, together with their statistical significances. The slopes of the linear relationships of temperatures to radiation fluxes; that is, the climatic sensitivities are in units of °C per W m^{-2}. The same parameters derived from multilinear regressions of temperatures on both short- and long-wave radiation are also tabulated. Seasonal values of these relationships for the means of the three midwinter and the three midsummer months are also presented in Table 2.

4. Discussion

4.1. Accuracy of Estimates of Radiation Fluxes

[12] The accuracy of the short-wave radiation estimates was assessed from an error analysis of the linear equation relating measurements of $E_{g\downarrow}$ to those of SD at Aldergrove. In relative terms the RMSE of $E_{g\downarrow}/E_{o\downarrow}$ was 0.026 with a standard error of 1.3% of the mean value: so that in absolute terms the error of estimate was 1.3 W m^{-2} at the mean value of $E_{g\downarrow}$, 99.1 W m^{-2}. On the basis of the square root law the uncertainties in the estimates of annual totals of $E_{g\downarrow}$ can be expected to be smaller than those of monthly values by $\sqrt{12} = 3.14$. The value of the slope and intercept at Aldergrove are similar to those previously reported for the long-established and widely employed Angstrom-Prescott relationship used in this study [*Linacre*, 1992; *Akinogle*, 2008]. The accuracy of the estimates of the effect of water vapor concentration on long-wave radiative forcing at contemporary levels of the other radiatively active gases was assessed from an error analysis of the power equation based on $E_{l\downarrow}$ and q measurements at Valentia Observatory between 1982 and 1995. The RMSE of monthly values was 14.2 W m^{-2}, 4.3% of the mean value of $E_{l\downarrow}$; an error term comparable to the 10 W m^{-2} uncertainty in direct measurements made with state of the art instrumentation under field conditions [*Dong et al.*, 2006]. The validity of using the Valentia relationship at Armagh is strengthened by its agreement with those derived from measurement at six other sites with very different climatic conditions, ranging from those of the Antarctic Peninsula to the Dead Sea (Figure 2). The anomalously high value of the exponent at the Dead Sea may be explained by the unique depth of the atmosphere at this site and its heavy aerosol load [*Stanhill and Cohen*, 2009]. The study at the four Swiss sites showed that surface measurements of q provided as accurate a proxy for $E_{l\downarrow}$ as the total water content of the atmospheric column and that the four sites shared the same relationship despite their tenfold range in altitudes [*Ruckstuhl et al.*, 2007]. These results support the assumption that changes in $E_{l\downarrow}$ at the surface caused by changes in concentrations of the anthropogenic radiatively active gases are the same as those calculated to occur at the tropopause, an assumption based on the well mixed distribution of these gases [*Ramaswamy et al.*, 2001; *NRC*, 2005]. Experimental evidence showing agreement between the value of RF at the surface measured by spectrometry at a Canadian site and the calculated value of RF at the tropopause has been presented [*Evans and Puckrin*, 1999]. In the absence of any information to the contrary the effects of changes in the concentration of anthropogenic radiatively active gases and those of water vapor were assumed to be additive.

Table 2. Relationships Between Air Temperatures T (°C) and Surface Radiation Fluxes E (W m^{-2}), Armagh, 1881–2000[a]

	T max	T min	T mean	T DTR
		Annual Relationships		
$E_{l\downarrow}$	$T = 0.111E - 22.48$ $R^2 = 0.616$ ***	$T = 0.130\ E - 35.56$ $R^2 = 0.791$ ***	$T = 0.120\ E - 29.02$ $R^2 = 0.774$ ***	$T = -0.019\ E + 13.085$ $R^2 = 0.046$
$E_{g\downarrow}$	$T = 0.33E + 9.48$ $R^2 = 0.088$ ***	$T = 0.006E + 5.07$ $R^2 = 0.02$ NS	$T = 0.020E + 7.27$ $R^2 = 0.032$ *	$T = 0.028E + 4.41$ $R^2 = 0.158$ **
$E_{t\downarrow}$	$T = 0.039E - 3.96$ $R^2 = 0.196$ ***	$T = 0.026E - 5.09$ $R^2 = 0.079$ ***	$T = 0.033E - 4.35$ $R^2 = 0.144$***	$T = 0.014E + 1.50$ $R^2 = 0.061$ **
$E_{l\downarrow}$ and $E_{g\downarrow}$	$T = 0.113\ El\downarrow +$ $0.036\ E_g\downarrow - 26.534$ $R^2 = 0.719$ ***	$T = 0.130\ E_{l\downarrow} +$ $0.009\ E_{g\downarrow} - 36.564$ $R^2 = 0.797$***	$T = 0.121E_{l\downarrow} +$ $0.023E_{g\downarrow} - 31.549$ $R^2 = 0.816$***	$T = 0.018E_l +$ $0.027E_{g\downarrow} - 10.030$ $R^2 = 0.198$***
		Summer Relationships		
$E_{l\downarrow}$	$T = 0.144E - 31.04$ $R^2 = 0.553$***	$T = 0.115E - 29.37$ $R^2 = 0.767$ ***	$T = 0.130E - 30.20$ $R^2 = 0.722$***	$T = 0.029E - 1.66$ $R^2 = 0.051$*
$E_{g\downarrow}$	$T = 0.049E + 10.41$ $R^2 = 0.391$***	$T = 0.016E + 7.53$ $R^2 = 0.094$***	$T = 0.033E + 8.97$ $R^2 = 0.280$ ***	$T = 0.033E + 2.88$ $R^2 = 0.397$ ***
$E_{t\downarrow}$	$T = 0.046E - 4.98$ $R^2 = 0.391$***	$T = 0.018E + 0.956$ $R^2 = 0.131$***	$T = 0.032E - 2.012$ $R^2 = 0.306$ ***	$T = 0.028E - 5.94$ $R^2 = 0.326$ ***
$E_{l\downarrow}$ and $E_{g\downarrow}$	$T = 0.121E_{l\downarrow} +$ $0.071E_{g\downarrow} - 29.21$ $R^2 = 0.757$***	$T = 0.112E_{l\downarrow} +$ $0.005E_{g\downarrow} - 29.13$ $R^2 = 0.774$ ***	$T = 0.117E_{l\downarrow} -$ $0.021E_{g\downarrow} - 29.17$ $R^2 = 0.826$ ***	$T = 0.009E_{l\downarrow} + 0.032E_g$ $R^2 = 0.402$ ***
		Winter Relationships		
$E_{l\downarrow}$	$T = 0.163E - 40.66$ $R^2 = 0.872$ ***	$T = 0.175E - 49.71$ $R^2 = 0.909$ ***	$T = 0.169E - 45.18$ $R^2 = 0.923$ ***	$T = -\ 0.012E - 0.01$ $R^2 = 0.033$ NS
$E_{g\downarrow}$	$T = 0.641E + 6.14$ $R^2 = 0.007$ NS	$T = -0.038E + 3.01$ $R^2 = 0.005$ NS	$T = -0.024E + 1.50$ $R^2 = 0.061$ **	$T = 0.079E + 3.14$ $R^2 = 0.168$ ***
$E_{t\downarrow}$	$T = 0.022E + 0.10$ $R^2 = 0.022$ NS	$T = 0.014E - 2.68$ $R^2 = 0.007$ NS	$T = 0.018E + 1.29$ $R^2 = 0.013$ NS	$T = 0.008E + 2.79$ $R^2 = 0.018$ NS
$E_{l\downarrow}$ and $E_{g\downarrow}$	$T = 0.162E_{l\downarrow} +$ $0.052E_{g\downarrow} - 41.96$ $R^2 = 0.880$ ***	$T = 0.173E_{l\downarrow} -$ $0.026E_{g\downarrow} - 48.49$ $R^2 = 0.910$ ***	$T = 0.167E_{l\downarrow} +$ $0.013E_{g\downarrow} - 45.23$ $R^2 = 0.922$ ***	$T = -0.011E_{l\downarrow} +$ $0.078E_{g\downarrow} + 6.53$ $R^2 = 0.196$ ***

[a] Level of significance: ***, $P < 0.001$; **, $P < 0.01$; *, $P < 0.05$, NS $P > 0.05$.

4.2. Interactions Between Atmospheric Long-Wave Radiation and Air Temperature

[13] Before discussing the temperature responses to radiative forcing presented in Table 2 it is important to note the complex interactions existing between these two parameters. Increases in $E_{l\downarrow}$ will increase Ta by radiative heating which in turn will lead to greater emissions of $E_{l\downarrow}$ from the heated atmosphere. A second positive feedback is to be expected in a non-water-limiting environment such as that of Northern Ireland where precipitation exceeds evaporation. In such regions the heated atmosphere will have a greater water content leading to higher emissions of $E_{l\downarrow}$ as shown in Figure 2. The importance of the role of the water feedback effect in the recent temperature increases in Central Europe has been analyzed [*Philipona et al.*, 2005]. These complex feedback mechanisms, together with that attributable to the absorption of $E_{g\downarrow}$ by water vapor, point to the need for caution in assigning a causal role to the changes in the concentrations of water vapor and of the other anthropogenic radiatively active gases in determining changes in air temperature.

4.3. Relative Importance of Short- and Long-Wave Radiative Forcing in Determining Temperature Changes at Armagh

[14] The results presented in Table 2 indicate that the degree of correlation between mean annual values of air temperature and those of radiation depends on which measures of temperature and radiation are considered. In general fluctuations in air temperature were more closely related to long-wave than to short-wave radiation except in the case of the diurnal temperature range. The data presented in Table 1 show that although the mean value of $E_{l\downarrow}$ was greater than that of $E_{g\downarrow}$, its interannual variability was both absolutely and relatively less than that of the short-wave flux. Annual and midwinter mean values of $E_{g\downarrow}$ and $E_{l\downarrow}$ were not significantly correlated, $P > 0.05$, but the means of the midsummer months were, $P < 0.01$, although the coefficient of determination was small, $R^2 = 0.005$.

[15] The degree of correlation with all four temperature indices increased when the effects of annual changes in both short- and long-wave radiation values were independently derived by the use of multilinear regression equations (Table 2).This was in marked contrast to the decrease which occurred when values of short- and long-wave radiation were summed; here correlations with temperatures were lower than those obtained using only the long-wave flux.

[16] Seasonal relationships between radiation and temperature are shown in Table 2 for the means of the three summer and three winter months. The highest correlations with, and greatest climate sensitivity to, atmospheric long-wave radiation occurred during the midwinter months for mean, maximum and minimum temperatures whereas midsummer temperatures were the most highly correlated with global short-wave radiation. An anomalous negative correlation was found between $E_{g\downarrow}$ and minimum and mean air temperature in midwinter possibly due to the different influence of changes in cloud cover on these two parameters. Multilinear regression analysis showed that the highest correlations and

greatest climate sensitivity to both long- and short-wave radiation occurred in the winter months; by contrast there was no significant relationship between the sum of the two radiation fluxes and temperatures, neither for annual nor seasonal relationships. In this connection it is noted that seasonal differences were found in the rates of the air temperature increases measured at Armagh; during the autumn and spring months the increase in temperatures exceeded those occurring in the winter and summer months and in the annual values [*Butler et al.*, 2007].

[17] Climate sensitivity at the surface, represented by the slopes of the annual mean air temperature to radiation relationships, differed markedly between $E_{l\downarrow}$ and $E_{g\downarrow}$, the mean values for maximum, minimum and mean temperature averaged 0.121°C/W m $^{-2}$ for long-wave radiation, 5 times the mean value of climate sensitivity for short-wave radiation, 0.023°C/W m^{-2}. Similar values for the sensitivity coefficients for long- and short-wave fluxes, 0.125 and 0.023°C/W m^{-2}, respectively, were obtained from the multilinear regression equation (Table 2). The greater temperature sensitivity to fluctuations in long-wave radiation can be explained as resulting from a strong positive feedback from the increase in water vapor which in turn is attributable to heating due to increased concentrations of anthropogenic gases radiatively active in the long-wave spectrum. An additional causal mechanism would result from a linkage between specific humidity and the prevailing synoptic situation: Assuming that the wetter air masses are warmer would lead to advective heating supplementing radiative heating.

[18] Over 80% of the interannual variation in mean annual temperatures was associated with the variations in downwelling radiation, with slightly lower degrees of correlation for minimum and maximum temperatures ($R^2 = 0.82$, 0.80 and 0.72, respectively). The correlations between the short-wave fluxes and air temperature were lower than those with long-wave irradiances but were statistically significant except in the case of minimum temperatures (Table 2). Significant relationships between time series of mean air temperatures and solar radiation, in most cases represented by sunshine duration, have previously been reported from Taiwan [*Liu et al.*, 2002], UK [*Perry*, 2006], Switzerland [*Rebetz and Benison*, 1998], Iberia [*Sanchez-Lorenzo et al.*, 2007], United States [*Stanhill and Cohen*, 2005], Japan [*Stanhill and Cohen*, 2008] and Israel [*Stanhill and Cohen*, 2009].

[19] The overall magnitude and trend in global radiation shown in Figure 4b is consistent with the direct measurements made during the last 30 to 40 years at three nearby sites, Aldergrove, Eskdalemuir and Lerwick: all show mean irradiances around 100 W m^{-2} and small negative trends between −0.3 and −0.6% per decade [*Stanhill*, 2005]. This trend at the surface differs markedly from the small long-term increase in the solar flux at the top of the atmosphere reported by *Lockwood and Frohlich* [2007] as occurring until 1985. After this year a decrease of 0.13 W m^{-2} in the extra-terrestrial flux took place while the surface flux at Armagh increased by 0.48 W m^{-2} over the same period.

[20] Evidence that the results presented in this study are of more than purely local significance is provided by the similarity of climate trends measured at Armagh to those at three other Irish sites with long-term records: in all four series the periodicities appear to be linked with those of the North Atlantic Oscillation [*Butler et al.*, 2007]. On a larger spatial scale the increase in mean annual air temperature measured at Armagh, 0.74°C over the last century, was similar to the mean for the land surfaces of the Northern Hemisphere over the same period, 0.63°C [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. On the global scale the mean annual value of $E_{l\downarrow}$ at Armagh, 318 W m^{-2}, was similar to the mean value at the Earth's surface, 345 W m^{-2} [*Wild et al.*, 2001]; by contrast the mean annual value of $E_{g\downarrow}$ at Armagh, 99 W m^{-2}, was approximately only half of the global mean value of 180 W m^{-2} [*Wild et al.*, 1998].

5. Conclusions

[21] Significant interannual fluctuations and long-term trends in the water content of the lower atmosphere were measured at Armagh in the last 120 years causing large variations in the atmospheric radiation reaching the surface. The net increase due to increase in specific humidity, 4.8 W m^{-2} per century, was equivalent to three quarters of the total increase in long-wave irradiance; the remaining quarter was associated with the increases in the concentrations of other, anthropogenic radiatively active gases: carbon dioxide, methane, nitrogen oxides, etc. Together these changes resulted in a total long-wave radiation forcing of 6.2 W m^{-2} during the 20th century.

[22] Interannual variations in the flux of global, short-wave radiation reaching the surface at Armagh over the same period were of similar magnitude to those in long-wave radiation: the two fluxes were not correlated. The long-term decrease in global radiation of 2.9 W m^{-2} per century was significant, reducing the increase in long-wave radiative forcing by approximately half. Although the cause of the decrease in solar irradiance is beyond the scope of this study the role of changes in the extent and the optical properties of cloud cover is almost certainly important meriting investigation.

[23] The significant long-term increases in the surface air temperature measured at Armagh in the last century, 0.60, 0.86 and 0.74°C for annual maximum, minimum and mean, respectively, are comparable to the mean global changes. Eighty percent of these increases in the annual mean temperatures were associated with those in the downwelling radiation fluxes.

[24] The temperature sensitivity to radiative forcing in the long-wave 0.125°C per W m^2, was significantly greater than that to short-wave forcing, 0.023°C per W m^2. One explanation for this greater sensitivity is the existence of positive interactions between $E_{l\downarrow}$ and Ta resulting from increases in the water content of the atmosphere at the site: Another is the advection of heat and water resulting from synoptic changes. Both explanations require further investigation.

[25] Further studies are needed to establish whether the variations and trends in specific humidity at sites in different climates are of comparable magnitude and significance in explaining the temperature changes to those measured at Armagh during the last century.

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