The effect of aerosol on on-going climate change

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The cause for the global temperature change of the last one hundred years is investigated in light of the earth's energy balance. The material used for the present paper is mostly observed at the earth's surface or from the space. While the enhanced greenhouse effect steadily increased, the aerosol effect fluctuated as a result of the decadal variation in aerosol emission. A cooling period witnessed for 30 years in the middle of the 20th Century is considered to have been caused by aerosol effect that surpassed the enhanced greenhouse effect. This cooling episode coincided with the period of declining surface global solar radiation, which was subsequently coined as the Global Dimming. The Mie-scattering theory can however explain only half of the decrease. The remaining half is considered due to the increase in cloud, which has been confirmed by the observations at the surface and from the space. Thus the ongoing climate warming is caused by a delicate imbalance between the increasing rates of greenhouse gases and of aerosol. The turning point of the total radiation from the negative to the positive phases is estimated to have happened sometime in the 1970s, which corresponds to the end of the cooling period and the beginning of the unprecedented warming. In the near future it is possible that the temperature trend may turn negative, if the aerosol effect overtakes the greenhouse effect. The currently observed slowing down of the warming after 2005 may well be the result of the increasing aerosol.

現温暖化におけるエアロゾルの効果

大村　纂

二十世紀初頭以来の百余年間は人為的温室効果による温暖化の時代と言われる．たしかに 1900 年以来全球平均でほぼ 1 ℃昇温した．しかし，温度変化を注意して見ると単調増加ではない．1910 年から 30 年間昇温した後，1940 年から 1970 年までの 30 年間昇温が停まっただけでなく，0.1℃強寒冷化した．その後再び昇温に転じ 1970 年からの 40 年間だけで 0.9℃温暖化した．これは全球平均の話で，この通りの変化を示した地域はないが，二十世紀初期の温暖化と，それに続く寒冷化そして最近の顕著な温暖化という三相変化は位相をわずかに異にしてほぼ全球で見られる．従って，二十世紀中葉に現れた寒冷化は全球的現象であった．この 30 年にわたる全球規模での温暖化トレンドからの逸出は ENSO やその他多く知られている振動現象では説明できない．この寒冷化の原因が分からなければ二十世紀全般にわたる温度変化の原因も正確には理解できないことになり，又将来の予測もおぼつかないことになる．したがって，本論文では，二相の温暖化に挟まれた寒冷化の原因を極める．

そのために，本論文では甚だ基礎的になるが気候システムにおける温度生成過程を熱力学第一法則に基づいて考える．地球表面の温度生成における放射の占める役割を認識し，二十世紀初頭以来観測された全天太陽放射，直達放射と大気の透過度を分析する．全天太陽放射の経年変化から二十世紀初頭から 1950 年にかけての第一次グローバル・ブライトニング（全天太陽放射の増加期），1950 年代から 80 年代にかけてのグローバル・デイミング（全天太陽放射の減少期），更に 80 年代から 2005 年にかけての第二次グローバル・ブライトニングの 3 時代が認識される．その間に観測されたデイミングとブライトニング間の大気の透過度の変化は 0.05 であった．この透過度の変化に相当するエアロゾルの直接効果（ミー散乱）だけでは全天放射の変動量の約 50％しか再現できないことが判り，残りの 50％はエアロゾルの間接効果，即ち雲の経年変化に帰着される．エアロゾルによる光学行程と雲量の相関はきわめて高く，この時期のエアロゾル間接効果と思われる雲の変動は全雲量で 4 ％，日照時間では日に 0.4 時間に相当する．この雲量の変動は地上と衛星から観測された結果である．

グローバル・デイミングの続いていた期間は全天太陽放射の減少率が長波放射の増加率を上回り全放射率が減少していたことが判明し，これが気温低下を引き起こしたと考えられる．続く 1980 年代からの第二次グローバル・ブライトニング期では増加に転じた全天太陽放射と既に増加傾向にあった長波放射が相まって全放射の増加率は 6.6 Wm^{-2}/decade となり，年間 0.035°Cとなる観測時代最大の気温上昇率をもたらす結果となる．このように現在進行中の温暖化は温室効果ガスの増加率とエアロゾルの増加率のバランスの微妙な崩れの結果であり，近い将来においてもエアロゾルの増加率がある程度大きくなり温室効果の上昇率を越すことが生じれば，寒冷化が起こりえる．現に 2000 年代に入ってから温暖化が鈍っているのは，決して温室効果が減少したためではなく，エアロゾルの効果が増加している結果である可能性が高い．

1. Introduction

Radiation is the primary heat source and the ultimate heat sink of the climate system. Further, radiation mainly determines the thermal condition of the atmosphere and the ocean. Consequently, changes in radiation are the causes of most climate changes. Traditionally, radiation was believed to be very stable (Budyko 1971) and effective only for climate changes of very long time scales, such as the climate change of an ice age and interglacial type. Later, climatic variations of a century time scale were investigated through the changes of the greenhouse gas content (Manabe et al. 1991). The processes of climate variations of the decadal time scale remained unexplained. The investigation of climate change of this type in the recent century is the objective of the present paper. This period has abundant observational material, making process studies possible. In the present article air temperature and radiation will be given a priority as they have relatively long and homogenous time series.

2. Synopsis of the temperature change during the twentieth century

The general characteristics of the global temperature of the last century are presented in Figure 1. The original data are monthly means of CRUTEM3v produced at the Climate Research Unit of the University of East Anglia. For the sake of comparison the time series is presented for the period of the entire observation. The global temperature variation of the last one hundred years is often mentioned as the century of warming with a trend of 0.010°C/a. It is however not a simple, monotonic warming but is characterized by the first three thirty-year periods and the last ten-year period. The first thirty-year period from 1910 to 1940 was a time of warming with an annual trend of +0.012°C/a. This period was followed by thirty years of cooling (from 1941 to 1970 with annual trend of −0.003°C/a), which was then followed by the steepest warming of the last three decades of the twentieth century (1971 to 2000 with 0.014°C/a). These were trends in global mean temperature, and there is no single site in the world that shows exactly the same trends as depicted above. For example the mean temperature in Europe follows a similar pattern as the global mean, but its phase began approximately ten years later. For example, the earlier temperature peak appeared in early 1950s, instead of the beginning of the 1940s. The warming trend continues to present in Europe, unlike the global mean that shows a slight cooling after year 2000. The last ten-year period is however too short to show a meaningful trend. The main focus of the present study is the thirty-year period of cooling in the middle of the twentieth century. The greenhouse effect alone can not explain the cooling of this period, and some other mechanism must have been at work at the same time.

3. Temperature determining processes

Temperature is determined as a result of the energy balance. This statement can be formulated

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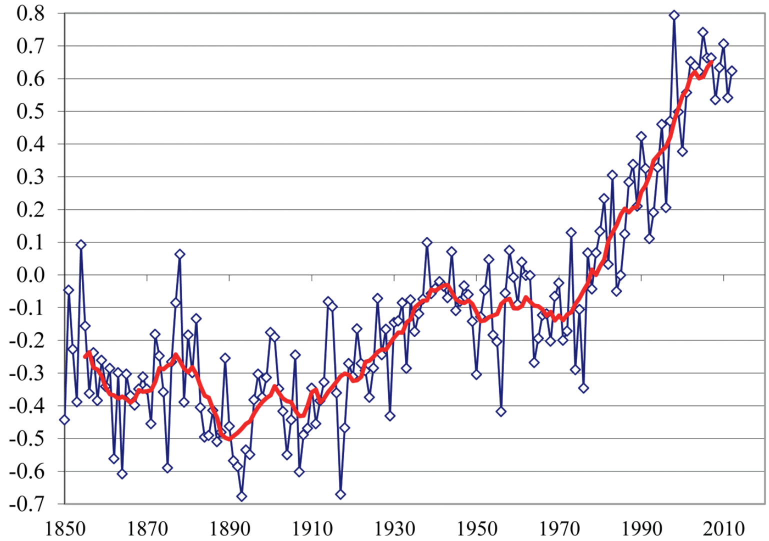

Figure 1：Global annual mean air temperature as interpreted in CRUTEM3v of the Climate Research Unit of the University of East Anglia. The ordinate is the deviation from the 1961-1990 mean in Centigrade. The blue diamonds are annual values and the thick red line is the 11-year running mean.

with the first law of thermodynamics in the following manner for the atmosphere (Eq. 1) and the earth's surface (Eq. 2), respectively:

$$\frac{\partial(c_p\rho T)}{\partial t}+\nabla\cdot(c_p\rho T\vec{V})+\nabla\vec{R}-L_vK=0, \qquad (1)$$

where the first two terms represent enthalpy, the third term is radiative divergence, and the last term, the rate of release of condensation heat;
and then,

$$S(1-a)+L\downarrow+H+L_vE+C=\sigma T^4+m, \qquad (2)$$

where the first term on the left hand side is the absorbed solar radiation, being a albedo; the second term is terrestrial counter radiation from the atmosphere; the third and fourth terms are turbulent sensible and latent heat fluxes, respectively; the fifth term is the sub-surface heat flux. The first term on right hand side is the outgoing terrestrial radiation from the surface, and the second term is the rate of heat consumption due to melt. Although these two equations are individually written in this manner, they essentially have the same content of energy conservation. The information on the temperature determination is contained in the first two terms in Eq. (1), but also in the third term. For the steady state the third term alone carries the role of temperature determination. The temperature is also in the first term on right hand side in Eq. (2). In the present article, the author is concerned with Eq. (2), as we investigate the temperature change near the earth's surface.

Eq. (2) shows how the temperature is formed as a result of the energy budget. This equation, written in a rather unconventional manner, requires some explanation. The terms that are determined entirely by other fluxes are placed on right hand side, while those on left hand side are independent of each other, although related. The first term on the right hand side is the blackbody emission, and the result of the surface temperature determined as a consequence of all other terms on left hand side. The second term, latent heat of fusion, is in fact the rate of the heat storage, and is equivalent to the local change, that is dependent on divergence of fluxes. These two terms are uniquely determinable, although two variables in one equation give the impression that the solution is difficult. These two terms are never simultaneously variable. When the first term is variable, that is not attaining the melting point, the second term is a constant and zero. If the second term is not a constant, the surface is melting at variable melting rates, and the first term must be a constant at 315.6 Wm^{-2}, corresponding to the black emission of 0°C or 273.15 K. Thus Eq. (2) is solvable for the temperature and the melting rate simultaneously with one equation. The mean state of the present global energy balance for the earth's surface is presented in Figure 2. Terrestrial upwelling irradiance, 389 Wm^{-2} is the consequence of the energy balance, which brings about the mean surface temperature of 14.7°C (287.8 K).

Further, the degree of variability of the temperature as a consequence of a change in the terms on left

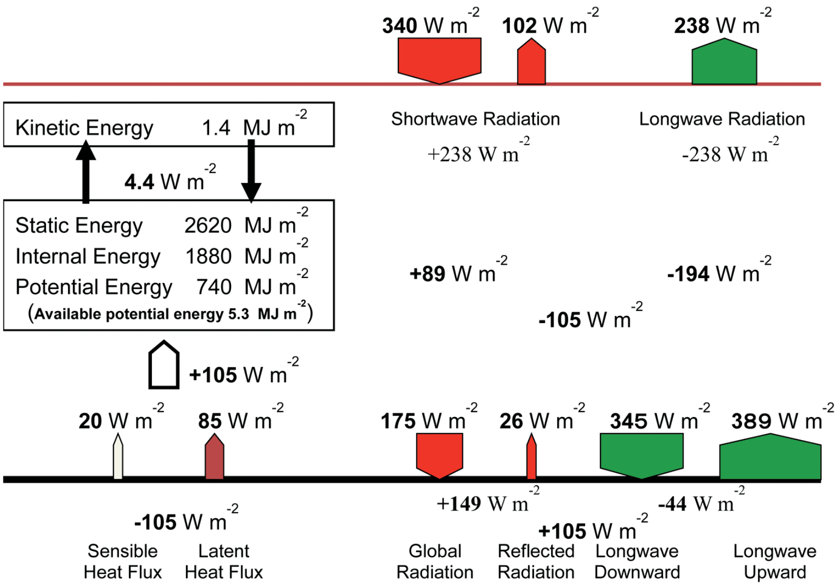

Figure 2: Mean state of the global energy balance [Wm^{-2}]

hand side is the definition of the temperature sensitivity, which is often synonymously treated as the climate sensitivity. For example $\frac{\partial T}{\partial L\downarrow}$ indicates the warming as a result of the enhanced greenhouse effect. This is the base for understanding the warming trend observed in the last one hundred years. However, it is difficult to understand the thirty-year cooling period observed from 1941 to 1970. In Europe, the cooling period appeared ten years later from 1951 to 1980. There must have been another term or terms that worked simultaneously to cause the cooling trend. This problem is the main theme of the following sections.

4. Decadal variation of radiation

The first work that clearly related climate changes to decadal variation of solar radiation was Budyko (1971). It was however not clear if he meant the variation in solar radiation outside the atmosphere or at the bottom of the atmosphere. If he meant the former, this meant the change in Total Solar Irradiance (TSI, or the solar constant). If he meant the latter, the work represents the discovery of a phenomenon, which we presently call the solar dimming, and brightening. The reason of this uncertainty is the absence of the data on which he constructed his argument on climate changes of the 20th century. In another work (Budyko 1980), he states that the global irradiance on the earth's surface is so stable that only several years' data suffice to characterize the radiation climate of the site. It is unclear what kind of mechanisms he envisaged to be the cause for the variation of solar radiation. One of the earliest articles, pointing to the possibility of measurable decadal fluctuations of global solar radiation is Ohmura and Lang (1989). They attributed the cause of the change in global solar radiation to the change in cloud amount. Several works in the following years offered different explanations (Russak 1990; Stanhill and Moreshet 1992; Liepert et al. 1994). All these works reported a generally decreasing trend of global solar radiation. Wild et al. (2005) reported a generally increasing trend for the period after 1990. These decreasing and increasing trends are subsequently coined as global dimming and brightening, respectively. These works are based on the observational data, which are traceable to World Radiometric Reference (WRR). The operational observations carried out by the Baseline Surface Radiation Network (BSRN) use instruments with the WRR traceability, and are accurate to within 3 Wm^{-2}. Since the ranges of variation found are 8 to 10 Wm^{-2}, it was clear that the detected variations were not artifact but a change in the environment. It took nevertheless more than ten years until the scientific community realized the importance of the decadal variation in solar radiation in the atmosphere. The long-term homogenized time series of the global solar radiation are presented in Figure 3. This is an updated version of the time-series of observed global solar radiation that became the basic material for the discovery of global dimming and brightening. The absolute values of the annual mean global solar radiation among the five stations differ

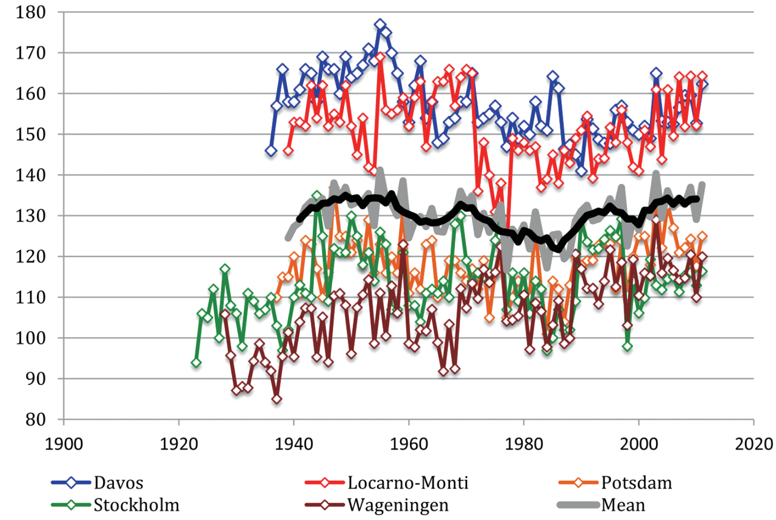

Figure 3：Annual mean global solar radiation observed at long-term stations. Unit is Wm^{-2}. The thick black line in the middle indicates the 5 years running mean of the means of all stations.

greatly mainly due to the latitude and cloud cover differences (Locarno-Monti, 46°N, annual total cloud amount: 53%, sunshine duration hours: 6.1 h/d; Stockholm, 59°N, annual total cloud amount: 60%, sunshine duration hours: 5.2 h/d). The temporal courses of the irradiance at these sites however are similar. The mean global solar radiation of the five sites is added in a thick grey line. The figure shows that the decadal global temperature closely follows the course of the mean global solar radiation. The influence of solar radiation on global mean air temperature was discussed in detail by Wild et al. (2004). The effect of total (solar plus terrestrial) incoming radiation on air temperature was discussed by Ohmura (2009).

The cause of the decadal fluctuation of surface global solar radiation was further investigated. The observation period suited for this type of study was the fifty years from 1957 to 2007. There are only five sites worldwide where all necessary observations for this type of analysis were made: global solar radiation, direct solar radiation, total cloud amount, and sunshine duration hours. The five sites are Feodosia on the Black Sea, Moscow in Russia, Tartu in Estonia, Davos in Switzerland and Tateno in Japan. The fifty-year period contains the first 30 years of dimming and the following 20 years of brightening. The changes in global radiation during the dimming and brightening phases are −7.1 and +6.3 Wm^{-2}, respectively. The total zenith transmittance decreased by 0.036 from 0.758 to 0.722 from 1960 to 1980. Similarly, from 1990 to 2005, the transmittance changed by 0.057 from 0.725 to 0.782. The changes in total zenith transmittance of the atmosphere allow a calculation of the changes in global solar irradiance that are due to aerosol direct effect by Mie-scattering. The details of the calculation are presented in Ohmura (2009). They are −2.9 and +3.8 Wm^{-2}, for the dimming and brightening periods, respectively. This result indicates that the weights for the aerosol direct and indirect effects are about fifty and fifty percent. Since a homogenous set of observation of cloud is only available after 1969, the effect of cloud was evaluated only for the brightening period from 1990 to 2005. As 3.8 Wm^{-2} is found to be due to the aerosol direct effect, the complementary 2.5 Wm^{-2} is interpreted to be due to the aerosol indirect effect, which corresponds to 4% in total cloud amount, and 0.4 h/day of sunshine duration hours, based on the station observations. The course of the 25 years of International Satellite Cloud Climatology Project (ISCCP) observation of the total cloud amount is presented in Figure 4a. The change in the global mean total cloud amount from 1990 to 2005 in the ISSCP satellite observation also gives 4% decrease. This decreasing trend is also depicted in the decline of the global mean planetary albedo in Fig. 4b observed by Clouds and Earth's Radiant System (CERES), which measured TOA irradiances from 2000 to the present with the highest accuracy to date. The decrease in planetary albedo during the first decade of the 2000s corresponds to 0.005. The decrease in total cloud, aerosol and surface albedo for the period from 1979 to 2011 is reported in a satellite-based work by Herman et al. (2013). A close examination of the figures of this paper reveals that the decreasing trends in fact happened during the 25 years from 1983 to 2008, and

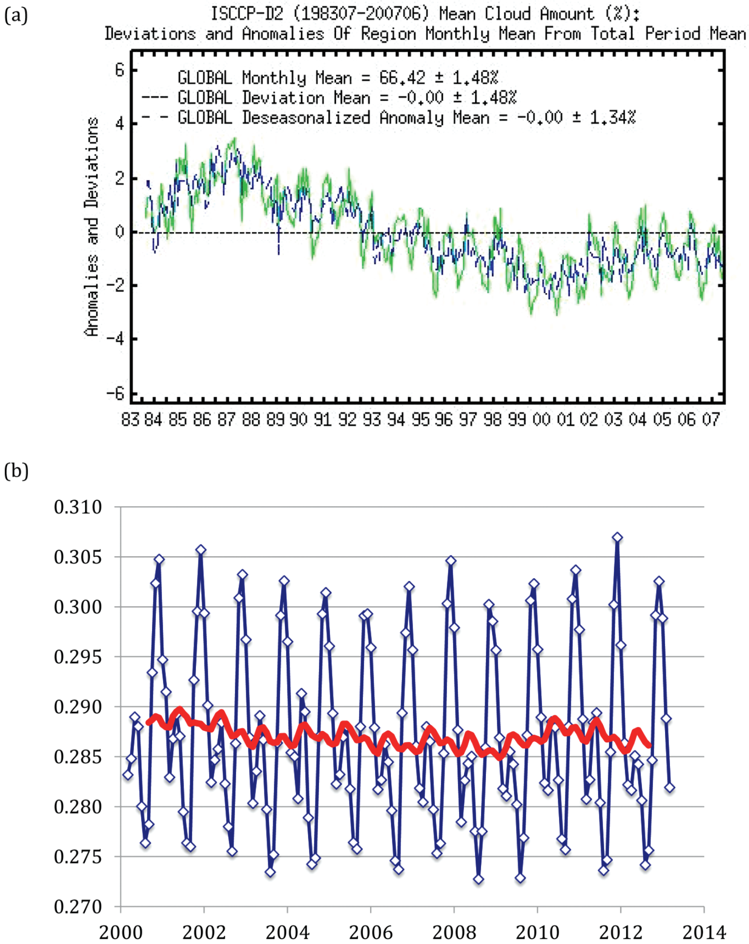

Figure 4 : Satellite observations of the global mean total cloud amount (a), and planetary albedo of the earth (b). The cloud observation is from ISCCP-D2, and the planetary albedo is obtained from CERES.

the reflectivity reported is in fact TOA reflectivity, even though they used the term, surface reflectivity in the title of the article. The reported decreasing rates match very well with the present findings.

The decadal variations of the observed solar and terrestrial radiation are summarised in Table 1. In the middle of the twentieth century, there was indeed a period when the magnitude of the solar radiation reduction exceeded the rate of the growing greenhouse effect, resulting in the decrease in total radiation and cooling. The turning point of total radiation from negative to positive trends is estimated to have happened sometime during the 1970s. The table presents the climate sensitivity evaluated using the irradiance and temperature variations during the dimming and brightening phases. Despite the climatic difference between the dimming and brightening phases, the temperature sensitivities against total irradiance change are remarkably similar. They are 0.060 K/Wm^{-2} during the dimming, and 0.053 K/Wm^{-2} during the brightening. These values are smaller than those extracted from the GCM experiments. The difference is due to the fact that the present sensitivity is evaluated through changes in nature, and contains all feedback processes, especially the temperature/water vapour feedback.

Table 1 : Decadal Variations in Solar and Terrestrial Radiation, Total Radiation, Air Temperature, and the Temperature Sensitivity by Radiation Change

	Solar radiation	Terrestrial	Total	Temperature change	Sensitivity (T/R)
	Wm^{-2}/decade			K/decade	$K/(Wm^{-2})$
1955-1985	−2.5	+1.0	−1.5	−0.09	0.060
1986-2005	+4.1	+2.5	+6.6	−0.35	0.053

5. Conclusion

The cooling in the middle of the otherwise warming twentieth century is most likely caused by aerosol. The Mie-scattering process explains about half of the total variation found in global solar radiation. The remaining half is attributed to the change in cloud, which shows a corresponding variation in observed cloud amount both at the surface and from satellites. These coordinated changes can be identified as the aerosol indirect effect. Although a further division of the indirect effect into the first kind (cloud amount) and the second kind (cloud albedo) is not attempted in the present study, the importance of the aerosol indirect effect of the first kind is unmistakable, as the change in cloud amount shows the coordinating course with the change in transmittance and radiation.

It is most likely that the 20th century temperature change consists of a delicate imbalance between the greenhouse and aerosol effects. The total radiation is estimated to have turned positive sometime in 1970s as a result of the acceleration of the greenhouse effect and the decline of the aerosol effect. This time-point corresponds to the end of the mid-twentieth century cooling and the beginning of the unprecedented warming. It is possible that the temperature trend may turn into cooling in the future, if the aerosol effect exceeds the greenhouse effect. A slowing down of the warming observed during the last decade may well be the result of the growing aerosol concentration on the global scale.

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