Will Statistics Give the Sensitivity of the Global Climate System?

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Abstract. I discuss here mathematical analyses associated with the estimation of climate sensitivity (λ), a fundamental property of our climate system. Despite its importance, however, a large gap exists between model-based and observation-based values of λ. Statistics seems to be effective to characterize λ although a further progress is necessary.

1. What is the climate?

"The climate" can be regarded as a system consisting of the atmosphere, oceans, land, and cryosphere while the conventional definition of climate is "long-term weather statistics" [1]. The state of each subsystem of the climate system is represented by characteristic state variables. For instance, the state of the atmosphere can be described by the variables such as temperature, humidity, clouds, winds, precipitation, trace gases and aerosol distribution. In a similar manner, the state of the ocean can be represented by temperature, salinity, currents, and marine biota.

"Externals" of the climate system will affect the states of the climate; primarily important externals are the sun, volcanic emissions, anthropogenic emission of greenhouse gases, and changes in the land-use.

Although the strongest greenhouse gas is water vapor, the most famous greenhouse gas is carbon dioxide because its extensive release from human activity is thought to increase the global temperature and to cause climate changes.

2. Radiative forcing and climate sensitivity

The greenhouse gases trap heat (infrared radiation) emitted from the earth surfaces, and finally increase the temperature. This function is approximated as TOA (Top of the Atmosphere) radiative forcing, RF. For instance, the RF corresponding to the increase in carbon dioxide concentration during the past 250 years (from 280 ppm to 370 ppm) is around 1.5 W/m^2. That is, a heat source of this magnitude is placed at the TOA (tropopause, in reality) to express the radiative effect of the CO_2 increase. For some aerosols, RF is large negative; that is, they have a cooling effect although the value of RF's are not accurately estimated.

It is usually assumed that RF's from different sources can be added to give total RF. The coefficient connecting the total RF (ΔRF) and the change in temperature (ΔT) is the climate sensitivity (λ) as Eq. 1 shows.

$$\Delta T = \lambda \Delta RF \qquad (1)$$

Sometimes, depending on authors, λ^{-1} is used instead of λ as the definition of the climate sensitivity.

3. Feedback in the climate system.

When RF is given to the climate system, the system will respond. The most basic response of the climate system is to attain the thermal equilibrium between solar radiation (mostly visible light) absorbed by the earth surface and infrared radiation from the atmosphere to the space. Besides this, changes in the climate system associated with the addition of different kinds of RF's are important. For instance, the doubling of carbon dioxide concentration gives a temperature increase of 1-1.5 ℃ after the system reached a new thermal equilibrium state. This increase in temperature would increase the amount of water vapor (due to evaporation) in the atmosphere to give another temperature increase. Thus, in this case, positive feedback has taken place. On the other hand, when the water vapor is converted into cloud, reflection of sun light will increase to give a decrease in temperature; this is negative feedback. These mechanisms are called water vapor-cloud feedback, which largely affect the magnitude of λ in Eq. 1.

4. Estimation of the climate sensitivity

Until recently, the values of λ had been estimated mainly by model-based computer simulations because observation-based estimation was difficult. Typical values are 0.54 ～ 1.22 K/W m^{-2}, which give 2.0 ～ 4.5 ℃ (central value, 3.0 ℃) for the doubling of carbon dioxide.

However, thanks to the development of global observations (e.g., satellite-based temperature measurements), it is now becoming to be able to estimate λ "experimentally" (that is, estimation based on observations). Table 1 shows those values in the form of ΔT at doubled CO_2, together with some information including methods employed.

Table 1. Recent observation-based $\Delta T2\times CO_2$

1. Forster & Gregory, J. Climate, 2006
   *Energy budget from satellite data
   1.0 ～ 4.1℃ Central value **1.6℃**
2. Schwartz, J. Geophys. Res., Nov. 2007
   *Based on oceanic heat capacity, and time constant of temperature changes
   0.6 ～ 1.6℃ Central value **1.1℃**
3. Chylek et al., J. Geophys. Res., Dec. 2007
   *Insolation change due to aerosol, and heat transfer to ocean
   0.9～1.8℃ Central value **1.3℃**

4.1. Forster & Gregory's work

Their work [2] is epochal in a sense that it showed effectiveness of observation-based measurements of λ. They followed the definition of λ to estimate its value. They utilize the energy budget (shortwave input minus longwave output) and global temperature variations observed with satellites. Figure 1 shows their typical result; the vertical axis (Q-N) denotes the energy budget, and the horizontal axis (DT) the global temperature change. From the slope, they obtained λ. Their result that the central value for λ is 1.6 K/Wm^{-2} is surprising because it is only about half that based on the models. They suggested other important points as well; only one model out of ten IPCC (International Pannell on Climate Change) AR4 models fitted their results on the radiation from clouds. Moreover, they claim that the standard approach using volcano eruptions for testing climate models is not adequate.

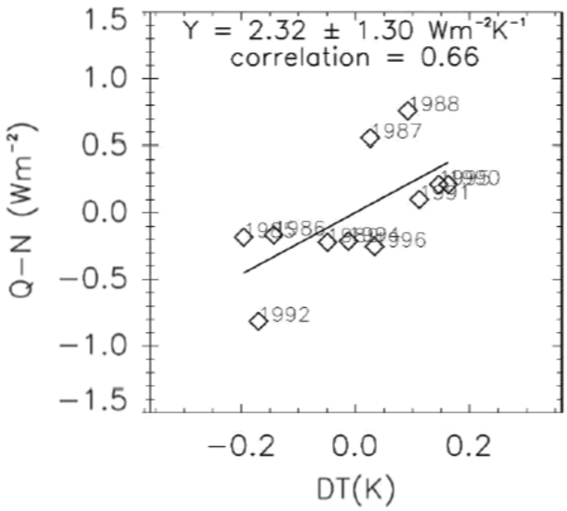

Fig. 1. Relation between energy budget and temperature changes observed by satellites (from Forster & Gregory, 2006).

4.2. Schwartz's work.

Schwartz [3] employed statistical approach, so that I describe his results a little in detail here. His idea is based on Eq. 2, where the solar radiation Q and the earth radiation E are considered.

$$dH/dt = C\,dT_S/dt = Q - E. \qquad (2)$$

Here, H is the heat content in the climate system, C the effective heat capacity of the climate system, and T_S the global and annual mean surface temperature. Q is expressed as γJ where γ is planetary coalbedo (= 1 – albedo: where albedo stands for whiteness or reflectance) and J is a quarter the solar constant. By considering Stefan-Boltzmann relation, $E = \varepsilon\sigma T_S^4$, Eq. 3 is obtained.

$$C\,dT_S/dt = \gamma J - \varepsilon\sigma T_S^4 \qquad (3)$$

For small perturbations (step-function radiation forcing, in particular), Eqs.4 and 5 are assumed.

$$F = Q - E \qquad (4)$$

$$T_S = T_{S,0} + \Delta T_S \qquad (5)$$

Thus, Eqs. 6 and 7 hold.

$$\Delta T_S(t) = \Delta T_S(\infty)\,(1 - e^{-t/\tau}) \qquad (6)$$
$$\Delta T_S(\infty) = F/(4\,\varepsilon\sigma T_S^3) = \lambda F \qquad (7)$$

For τ and λ, Eqs. 8 and 9 are obtained.

$$\tau = \quad C/(4\,\varepsilon\sigma T_S^3) = C\,T_{S,0}\,/(\gamma J) \qquad (8)$$
$$\lambda = T_{S,0}\,/(\gamma J) \qquad (9)$$

From Eqs. 8 and 9, λ is obtained as Eq. 10.

$$\lambda = \tau\,/\,C \qquad (10)$$

Thus, the climate sensitivity can be obtained from the heat capacity of the climate system and the response time constant of the climate system against the change in RF.

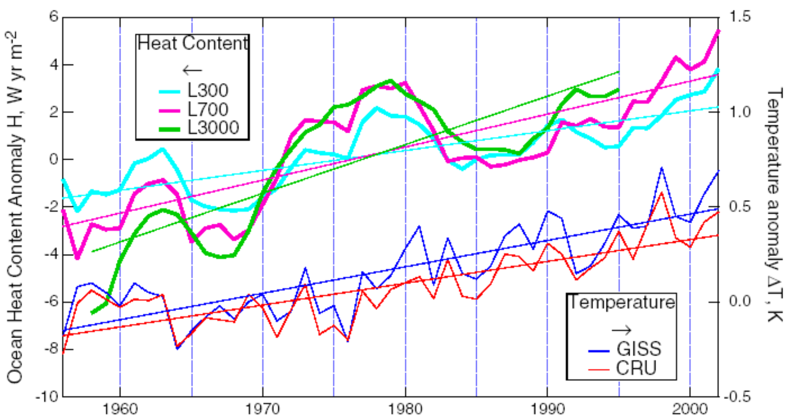

Fig. 2. Estimation of effective heat capacity from the ocean heat content and global mean temperature. From Schwartz 2007.

Schwartz estimated the heat capacity C from the measurements of ocean heat content and the global surface temperature observed during recent 40 years as shown in Fig. 2. His result was $C = 16.7 \pm 7.0$ W yr m^{-2} K^{-1}, which corresponds to ca. 100 m of the ocean layer. The heat content down to the depth of 3000 m was not very different from other depths; this shows inhomogeneous heating of the oceans. Moreover, the heat content largely fluctuates due to unknown processes.

The response time was estimated from autocorrelation of the global mean temperature anomaly data as shown in Fig. 3. The top figure is the original temperature anomaly data, the middle (normalized residual) is obtained by removing trend, and the bottom is the autocorrelation (r) of the residual data with lag Δt.

Schwartz assumes a first-order Markov process, and approximates that r decays exponentially. From this assumption, the time constant is estimated by calculating the slope of ln r versus t. Thus, he obtained 5 ± 1 yr as the asymptotic value of τ.

From the values of C and τ, using eq. 10, the value of λ is obtained as follows.

$$\lambda = \tau/C = 0.30 \pm 0.14 \text{ K/(W m}^{-2}) \quad (11)$$

Corresponding ΔT for doubled CO_2 concentration is,

$$\Delta T_{2xCO_2} = 1.1 \pm 0.5 \text{ K} \quad (12)$$

There arise several questions on this estimation. The first question is whether the small λ is theoretically reasonable or not. The second question is whether the analysis is reasonable or not.

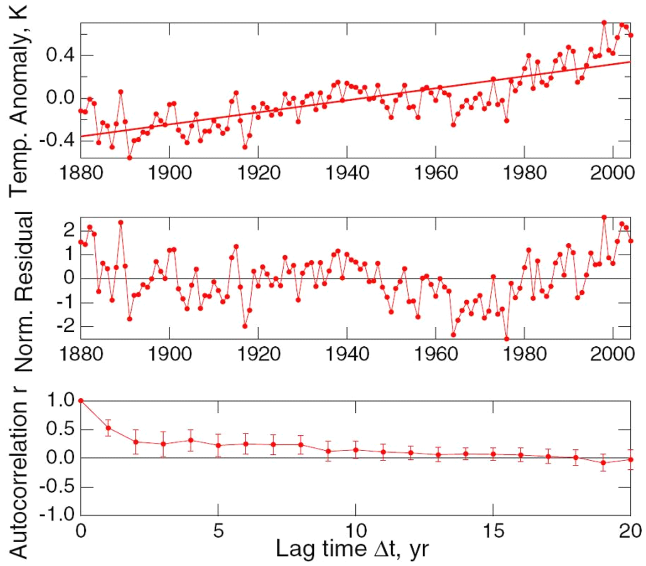

Fig. 3. Top, original temperature data: middle, trend-removed time series: bottom, autocorrelation r with lag Δt. From Schwartz 2007.

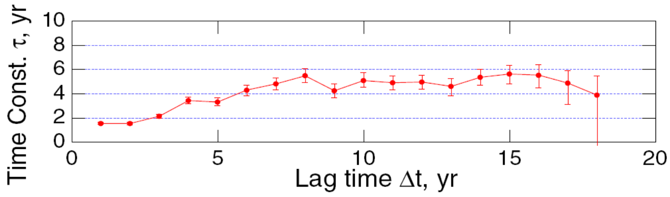

Fig. 4. Time constant obtained from the slope of ln r vs. t. From Schwartz 2007.

On the first point, it is known that most climate models give considerably longer time constants, 20～30 yr, which result in large values of λ. Thus, it is essential whether or not the time constant can be such short from the theoretical point of view. As a conclusion, it is basically possible when the treatment of Dickinson and Schaudt (hereafter, DS 98) [4] is considered. They employed zero-dimensional model to analyze the behavior of time response of the atmosphere-ocean system, and have shown that overall time constant of the system could be much shorter than the time constant of each subsystem. Thus, DS 98 theoretically supports the estimation of Schwartz. Conversely, the estimation Schwartz can be regarded to support the theoretical conclusion of DS98.

On the second point, that is, the analysis of Schwartz might be questionable because it assumes a simple exponential form for the decay of τ, neglecting long memory in the climate system. The strongest reason for this question is, for instance, that the climate system should be multi-exponential at least, and it should have long memory. In fact, DS98 shows the time dependence of their zero-dimensional system is not simple exponential. Moreover, the value of r tends to be negative for long t. It should be noted, however, that the analysis of Schwartz also takes into account that the autocorrelation curve is non-exponential by considering the asymptotic behavior of τ as shown in Fig. 4. Thus, for the first approximation, the assumption of Schwartz seems valid.

5. Statistical analysis of Kärner.

Kärner [5, 6] has employed the analysis of increments in the temperature time series data, instead of the temperature itself. This is because the temperature is often non-stational; that is, its time-mean is not constant. In fact, Schwartz has removed the time trend from the temperature data in his analysis. Kärner has shown that the increments of the temperature time series have rather stable distribution, and hence, show persistency [5].

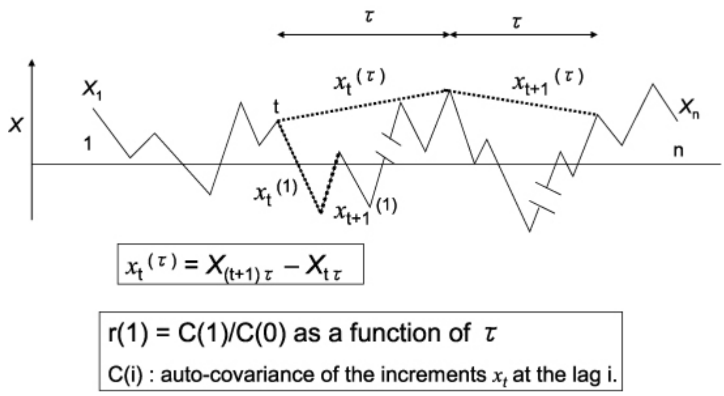

Fig. 5. Estimating autocorrelation of increments with different ranges. From Kärner 2005.

According to his idea, the autocorrelation of the increments will reflect the property of feedback mechanisms in the system [6]. When the autocorrelation is positive, there is a tendency that increments continue to have the same sign, and hence, positive feedback prevails. Conversely, for the negative autocorrelation, the feedback in the system should be negative.

Figure 5 explains the procedure for estimating autocorrelation between increments with different ranges. The discrete time series X_t has n members. Increments $x_t^{(\tau)}$ are calculated for different range of steps τ, and then, auto-covariance is obtained with changing lag. The quantity r(1) (C(1) normalized by C(0)) in Fig. 5 shows, according to its definition, relation between the increments. In particular, based on Kärner's idea, it represents the feedback in the system.

The temperature data measured by the satellites were employed in his analysis because they cover the whole earth except a small area of the polar regions.

Figure 6 shows typical data for the monthly temperature anomaly observed by satellites (measured with microwave sounding units); Kärner used daily data also, although not shown in the Fig. 6 for the sake of simplicity.

In addition, the positive peaks at 1983 and at 1992 for the stratosphere temperature are the result of large volcanic eruptions, which induced temperature decreases in the troposphere. The positive peak at 1998 for the troposphere is due to a large El Niño.

Figure 7 shows the correlation r(1) of increments of each temperature data (stratosphere, troposphere and solar radiation) as a function of increment range.

For the troposphere and the solar radiation, r(1) is mostly negative except for short increment range (several days). On the other hand, r(1) for the stratosphere takes positive values for the increment range up to around 50 days. According to Kärner's discussion, this shows that feedback in the troposphere is largely negative.

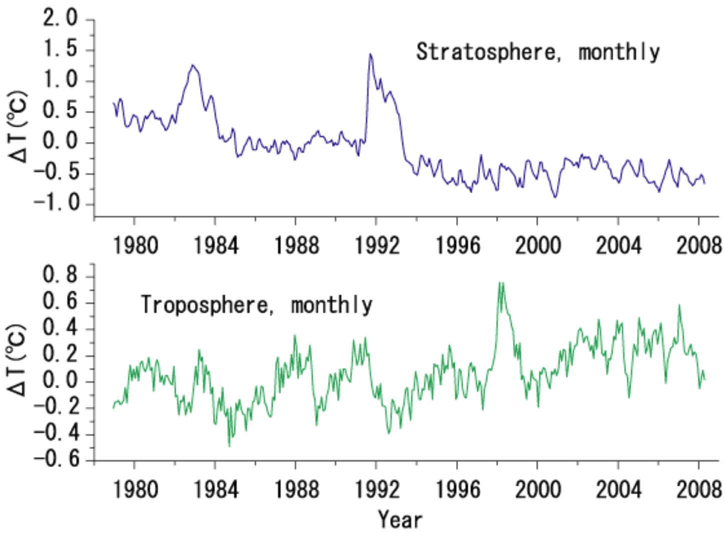

Fig. 6. Monthly temperature anomaly data for stratosphere (top) and troposphere (bottom). From http://www.nsstc.uah.edu/data/msu/

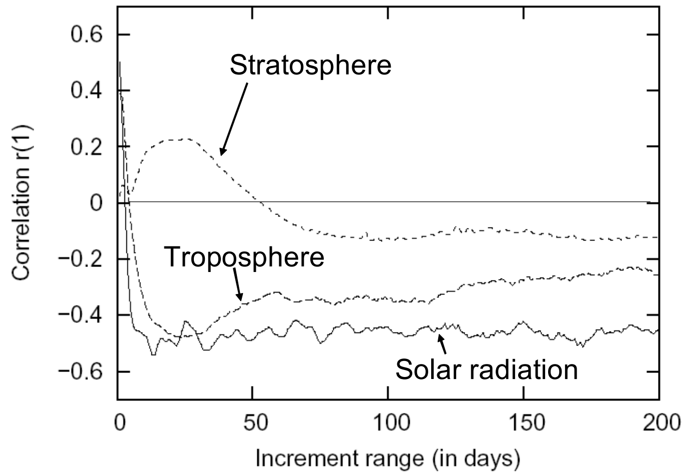

Fig. 7. Correlation of increments of temperature data (Kärner 2005) for stratosphere, troposphere and solar radiation.

6. Origin of negative feedback.

A question, then, arises; what is the origin of the negative feedback climate in the troposphere? Kärner considers different possibilities; e.g., the negative feedback of the solar radiation directly determines the sign of feedback in the troposphere. He even suggests that day-and-night cycle itself might induce the negative feedback.

It is, however, necessary to consider the origin of the negative feedback from more physical point of view if possible.

Spencer et al. discussed how tropical clouds respond to changes in surface temperature [7].

They identified 15 temperature oscillations during the period of 2000 – 2005 as shown in fig. 8 A, where averaged temperature change is plotted as a function of time (day) with the temperature peak placed at time zero. They showed that clouds consisting of ice largely decreased during the course of the temperature change (Fig. 8 B). This means that longwave radiation from the earth to the space increases during this period, which suggests a mechanism called "infrared iris," a controversial idea related to negative feedback of the climate system.

Although detailed mechanisms of the feedback as well as exact values of λ are still to be clarified, the negative feedback suggested by Kärner and other researchers thus seems plausible.

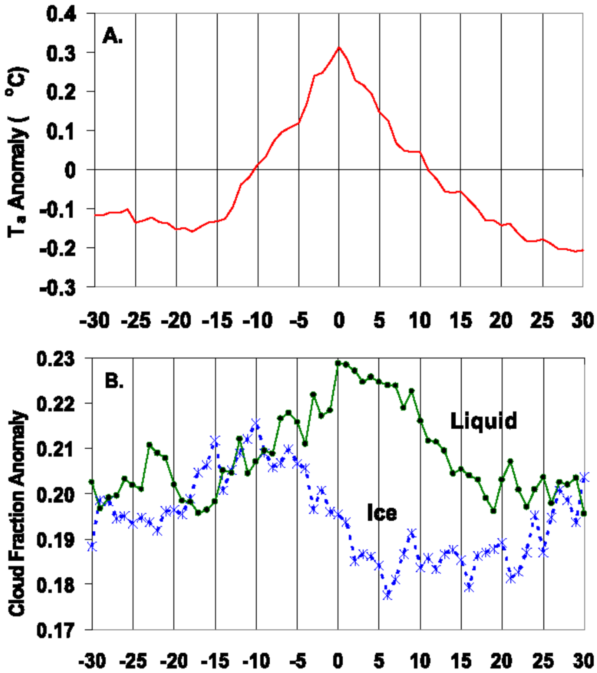

Fig. 8. Temperature changes (A) and cloud changes (B) associated with tropical intraseasonal oscillations. (Spencer et al., 2007)

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