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Foreword: International Space Science Institute (ISSI) Workshop on Observing and Modeling Earth's Energy Flows

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The Earth's climate, as well as planetary climates in general, is broadly regulated by three fundamental parameters: the total solar irradiance, the planetary albedo and the planetary emissivity. Observations from series of different satellites during the last three decades indicate that these three quantities are generally very stable. The total solar irradiation of some 1,361 W/m^2 at 1 A.U. varies within 1 W/m^2 during the 11-year solar cycle (Fröhlich 2012). The albedo is close to 29 % with minute changes from year to year but with marked zonal differences (Stevens and Schwartz 2012). The only exception to the overall stability is a minor *decrease* in the planetary emissivity (the ratio between the radiation to space and the radiation from the surface of the Earth). This is a consequence of the increase in atmospheric greenhouse gas amounts making the atmosphere gradually more opaque to long-wave terrestrial radiation. As a consequence, radiation processes are slightly out of balance as less heat is leaving the Earth in the form of thermal radiation than the amount of heat from the incoming solar radiation. Present space-based systems cannot yet measure this imbalance, but the effect can be inferred from the increase in heat in the oceans where most of the heat accumulates. Minor amounts of heat are used to melt ice and to warm the atmosphere and the surface of the Earth.

The reverse is happening when there is a volcanic eruption that emits particles that reflect solar radiation. In this case less heat is entering the Earth's system than leaving it and a cooling take place, as the system is moving toward another equilibrium. In reality the Earth's system is never in equilibrium as it is continuously exposed to disturbances in its energy balance. In addition to external and anthropogenic effects there are natural processes in the Earth's system caused by variations in the cloud cover, in the exchange of heat between ocean and atmosphere, in the surface conditions such as snow and ice cover, and in changes in the three-dimensional distribution of water vapor. Other changes in the energy balance include land vegetation that affects both the surface albedo and the surface fluxes of heat and water.

Some of the processes now affecting the Earth's climate system are relatively well understood, and others less so. The radiative effect of the greenhouse gases added to the

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atmosphere since the beginning of the industrialization at the end of the eighteenth century is equivalent to a reduction in the outgoing radiation to space by some 2.8 W/m^2. Less well understood are the radiative effects of anthropogenic aerosols, but an overall cooling effect of the order of 1 W/m^2 is suggested. The Earth has partly adjusted to this by increasing its surface temperature by 0.6–0.8 °C during the same period, but the radiation balance has not yet been restored. Based on the ongoing warming of the oceans the radiation imbalance during the last decades is estimated to be of the order of 0.5 W/m^2 with generally higher values in later years. Other associated changes of importance for the Earth's climate follow a temperature increase, including an increasing amount of water vapor in the atmosphere. The water vapor amount adjusts rapidly to atmospheric temperature by about 6–7 % for each degree of warming.

The scientific papers in the present volume address different observational and modeling aspects of the Earth's energy flows. It represents the outcome of the second workshop held within the ISSI Earth Science Programme The workshop took place from 10 to 14 January, 2011, in Bern, Switzerland, with the objective of providing an in-depth overview of the Earth's energy flows. The participants in the workshop were experts in a wide range of disciplines and included solar physicists, experts on space observations, atmospheric radiation experts, meteorologists, oceanographers and climate modelers.

While the radiative forcing of the Earth has undergone many changes over time with consequences for the climate, the scientific interest and public concern during the last few decades have been focused on anthropogenic changes of the composition of the atmosphere and its effects on the climate. During the last 50 years, CO_2 amounts have increased by 75 ppm or by almost 25 %. The amounts of other important greenhouse gases, CH_4, N_2O and the CFCs, have also increased significantly. Such rapid increases were not previously encountered during the long history of our planet. During the same time, anthropogenic aerosols have also increased and affected the radiation balance by offsetting part of the greenhouse warming.

The ability of the greenhouse gases including water vapor to absorb long-wave radiation, such as the heat radiation from the Earth, has been known since the nineteenth century as described in the presentation by Kandel (2012). The main effect of the greenhouse gases is to warm the lower atmosphere, the troposphere, and to cool the lower stratosphere. Such a warming signature is presently observed, suggesting that the increasing amounts of greenhouse gases are the main cause of the observed global warming. A corresponding contribution by solar radiation would have had a different signature, as the warming in this case would encompass the full depth of the atmosphere. Furthermore, as documented in this issue, the best estimate of surface and lower tropospheric temperature suggests that the solar influence is small compared to the anthropogenic forcing. It appears that the modulation of low altitude clouds by galactic cosmic rays is unlikely to provide an explanation to the observed temperature increase (Lockwood 2012).

Three central issues were at the forefront of the Workshop: *Firstly*, how accurately can we estimate the present forcing of the Earth's system? *Secondly*, how well do we know the flow of energy in the Earth's system? *Thirdly*, how well can we determine the response to the forcing, including the internal energy feedbacks of the Earth's system?

The external radiative forcing of the system is the solar irradiation and its variation, anthropogenic greenhouse gases and aerosols, plus aerosols from volcanic eruptions.

We know that the Earth presently is receiving more heat than it emits, although present observations cannot yet measure this imbalance. However, as is shown in some of the papers in this issue, the imbalance can be estimated from the accumulation of heat in the Earth's system where some 90 % ends up in the oceans. For the period 1993–2008 Lyman

(2012) has estimated the heat flux in the upper 700 m of the ocean, normalized for the full area of the Earth, to be 0.64 ± 0.11 W/m^2. For shorter periods, variations in the trends are considerable, suggesting that the irregular warming of the lower atmosphere and the surface of the Earth is probably related to the irregular warming of the deeper parts of the ocean (Trenberth and Fasullo 2012).

The energy flow within the atmosphere and between the ocean, land and atmosphere and the energy fluxes in global and annual average are known to within 1–2 W/m^2 but with slightly larger values (say ±5 W/m^2) for the atmospheric absorption of solar radiation and the down-welling long-wave radiation at the surface. The workshop identified the need to determine these factors more accurately.

Perhaps, the most difficult problem is to estimate or calculate the climate response to forcing perturbations; most of the presentations and discussions at the workshop were concerned with exploring a multitude of issues in this context that need to be better understood.

The direct effect of increasing the amounts of greenhouse gases in equilibrium is straightforward to calculate as it can in principle be obtained from the Stefan–Boltzmann equation. That readily shows that a relative change in radiative forcing, dF, is related to temperature change, dT, as $\mathrm{d}F/F = 4\mathrm{d}T/T$, where the forcing is measured in W/m^2 and the temperature in degrees Kelvin. A doubling of CO_2 is equivalent to ~3.7 W/m^2 which means that the corresponding increase in temperature, dT, is about 1.1 K. This is the increased equilibrium temperature that the system will gradually approach.

What significantly complicate the situation are the feedback processes of the Earth's system that will either decrease or increase this value. Atmospheric water vapor follows temperature and will act as a positive feedback factor as water vapor in itself is a powerful greenhouse gas. Surface albedo is also likely to exercise a positive feedback as melting ice and snow at higher temperatures are likely to lead to reduced reflectivity of solar radiation. However, the largest problem is related to clouds. Clouds reflect solar radiation and consequently cool the Earth's system, but clouds also enhance the absorption of terrestrial radiation. The reflected amount dominates, so the combined effect indicates a net cooling by some 20 W/m^2. Of particular importance here are stratiform clouds over the oceans at low latitudes where they act as powerful regulators of the global temperature. Any changes in the amount of clouds in these areas will have a major influence on how the global temperature will evolve. The reason for this is the large difference in albedo of these clouds compared to the underlying ocean. The possible cloud feedback, that is how a warmer climate in turn will affect the clouds, is poorly understood. It is also the main reason that climate models such as those used within the Intergovernmental Panel for Climate Change (IPCC) provide such widely different results.

The reason for the comparatively slow and irregular warming of the Earth's system during the last century is still in many respects an open scientific issue. A possible explanation by Schwartz (2012) is the different response timescales between the atmosphere and upper ocean areas, on the one hand, and the deep ocean, on the other hand. The upper layers determine what we might call transient climate sensitivity while the deep ocean determines the equilibrium response. The timescales of the two compartments differ widely, from the order of a decade for the upper ocean layer to several 100 years when we include the lower ocean compartment. Schwartz's results suggest that transient processes with a modest warming might be more representative of the present century while the planet over longer times will gradually approach a higher surface temperature as it moves toward radiation equilibrium.

The present issue includes the majority of papers presented at the workshop and includes a summary of each of the different subsections. In spite of impressive scientific progress in recent years, the need for continuous space observations must be highlighted. Firstly, because of the complexity of the Earth's energy flows including their high variability in time and space (mainly because of clouds), that will require a comprehensive sampling that must satisfactorily cover the diurnal cycle in different parts of the world. Secondly, a long-term commitment to Earth's radiation measurements is essential because of low-frequency variations caused by both external (solar and volcanic) and anthropogenic effects, as well by different internal variations of the climate system.

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