

A BRIEF TOUR OF THE CLIMATE MACHINE 2 - ENVIRONMENT SHAPES THE CLIMATE[1]

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As explained in a paper in the preceding issue of EPN [2], the bulk of the climate system is a thermal machine by which the two fluids of the Earth envelope transport energy from low to high latitudes. The present paper emphasizes the role of interactions in the fashioning of the climate.

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Climate – environment interactions

Earth climate depends on the radiation budget: everything that may modify the energy flux (absorbed or escaping) will disturb the Earth climate.

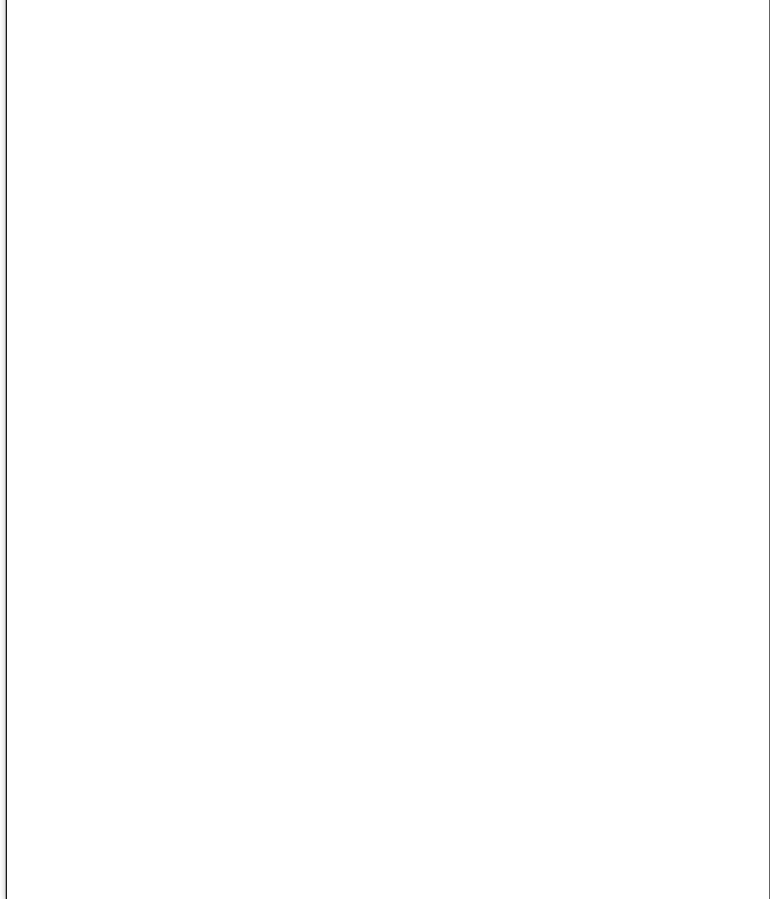
- The incoming energy flux hitting the surface depends first on the sunlight that reaches the Earth. This flux may vary due to variations in solar activity. At time scales of tens of millennia, it also varies with the sun-earth distance that fluctuates with the Earth astronomical parameters: obliquity, eccentricity, precession of the orbit.
- In the visible and near-infrared parts of the light spectrum, the atmosphere is essentially transparent to solar radiation. The bulk of the absorption is due to aerosols such as black carbon. But the solar radiation is also scattered by atmospheric molecules and aerosol particles, and reflected by clouds. The importance and lifetime of clouds depend on aerosols.
- The reflecting power (albedo) of the surface depends on its nature. A snow or ice covered area has a high albedo value, 60 to 90%. However, the presence of vegetation reduces strongly the albedo that can become very small (10%) for dark equatorial forests. The ocean albedo is also very small. The global albedo (30%) is higher than the surface albedo thanks to clouds.
- In the thermal infrared domain *i.e.* that of the flux leaving Earth into space, the atmosphere acts strongly on the radiation. Clouds and aerosols again play a role in the reflection, scattering and absorption processes. But the major contribution is the absorption by greenhouse gasses (see box 1: ingredients of the greenhouse effect) without which life would not exist on Earth.

Continents stand in the way of the ocean circulation. They influence both horizontal and vertical atmospheric circulations: in the presence of mountains, the air is forced to rise and thus to cool, which can lead to water vapour condensation and rainfall, an effect that is particularly marked in Asia where the Himalaya contributes strongly to the strength of the wet monsoon.

Feedbacks

Climate determines the various compartments of the Earth environment: cryosphere, vegetation and fauna types, erosion ... It determines water evaporation, cloud covering, rainfall patterns, lifting of natural aerosols (forest and savannah fires, mineral dust from bare soils). But the changes that are inflicted by climate evolutions to the environment react in turn on the climate and enhance or inhibit these evolutions as will be shown on a few examples.

- The increase in surface temperature leads to an increase of the radiated energy (Stefan-Boltzmann) which lowers the warming. Similarly, due to the vertical gradient of atmospheric temperature, local air warming results in a convective air rise; the rising warm air will be replaced by descending cooler air. These are examples of negative feedbacks.



▲ FIG. 1: Satellite view of south-west Australia in 1999. The limit between cloudy and clear sky areas is also the limit between forest and crops. (source: USGS Earth Radiation Budget Experiment – EOL Meteorological Satellite – 5 visible channel imagery over southwest Australia 1999. http://www.nsstc.uah.edu/~nair/ES/ESidy_area.html)

BOX 1: INGREDIENTS OF THE GREENHOUSE EFFECT

What do we call greenhouse effect?

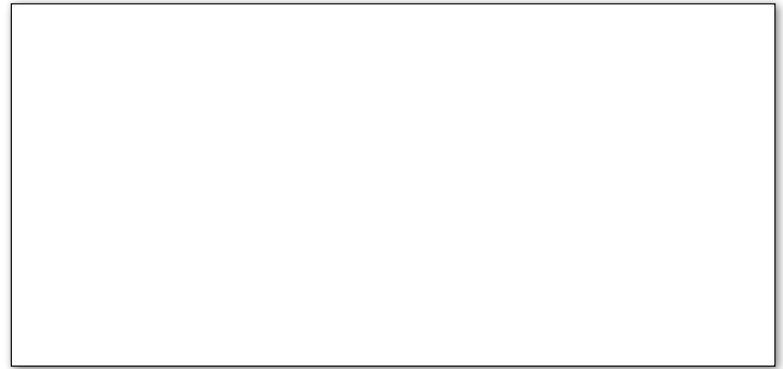
In the absence of atmosphere, an Earth having the same albedo of 30% as our Earth and receiving the same solar flux of 1360 W.m^{-2} would have an average temperature of 255K (-18°C) according to Stefan-Boltzmann law. The average ground temperature of the Earth is 15°C. Calculations of energy transfer in the atmosphere show that this difference between radiative temperature and ground temperature is due to the combined action of various processes including, on one hand, vertical heat transport through the atmosphere, convection, radiation, and on the other hand, scattering, absorption and emission of infrared radiation by atmospheric molecules [3]. The overall phenomenon called greenhouse effect is possible only in an atmosphere with a temperature decreasing with altitude [4]. It involves the vertical structure of the atmosphere and the fact that photons emitted at low altitude are absorbed before they can leave atmosphere. The photons leaving the Earth are emitted in the atmosphere, which consequently cannot be treated like a thin window pane. The name “greenhouse effect” is related to the fact that the atmosphere confines heat thus increasing low altitude temperature similarly to the greenhouse window pane which confines heat inside the greenhouse (albeit by a different process).

Greenhouse effect cannot be overlooked for the understanding of the climate of the Earth but also of the other planets and their passed convulsions [5]. The carbon cycle plays there a role which is necessary to understand the climate evolutions that paleoclimatologists identify by their imprints.

- The beginning of a glacial era involves several positive feedbacks (see box 2).
- There are also more complex cases: warming increases water evaporation. According to Clausius-Clapeyron the atmosphere will possibly contain more water vapour, that will enhance the greenhouse effect and thus the warming. But there will also be more clouds. If these additional clouds are low clouds, they will reduce the warming (parasol effect); however, if these are high cirrus clouds, warming will be enhanced.
- An interesting circumstance is that of the vegetation. Its presence reduces the ground albedo enhancing the solar radiation absorption. But its main climate role is to diminish the greenhouse effect by the large amounts of carbon it stores. Vegetation acts also by evapotranspiration [6]: the humidity that forest delivers to the atmosphere (Figure 1) favours regional rainfalls, a phenomenon which contributed to the “green Sahara” 6000 years ago (Figure 2). A stronger evapotranspiration has also a cooling effect on the surface.

Climate modelling

Let us close this brief tour of the climate machine with an introduction to the role of modelling. The first climate models strived to describe how the atmosphere functions in terms of the physics laws of transport. These include fluid mechanics (Navier-Stokes) in a rotating frame, conservation laws (mass, energy, momentum) and

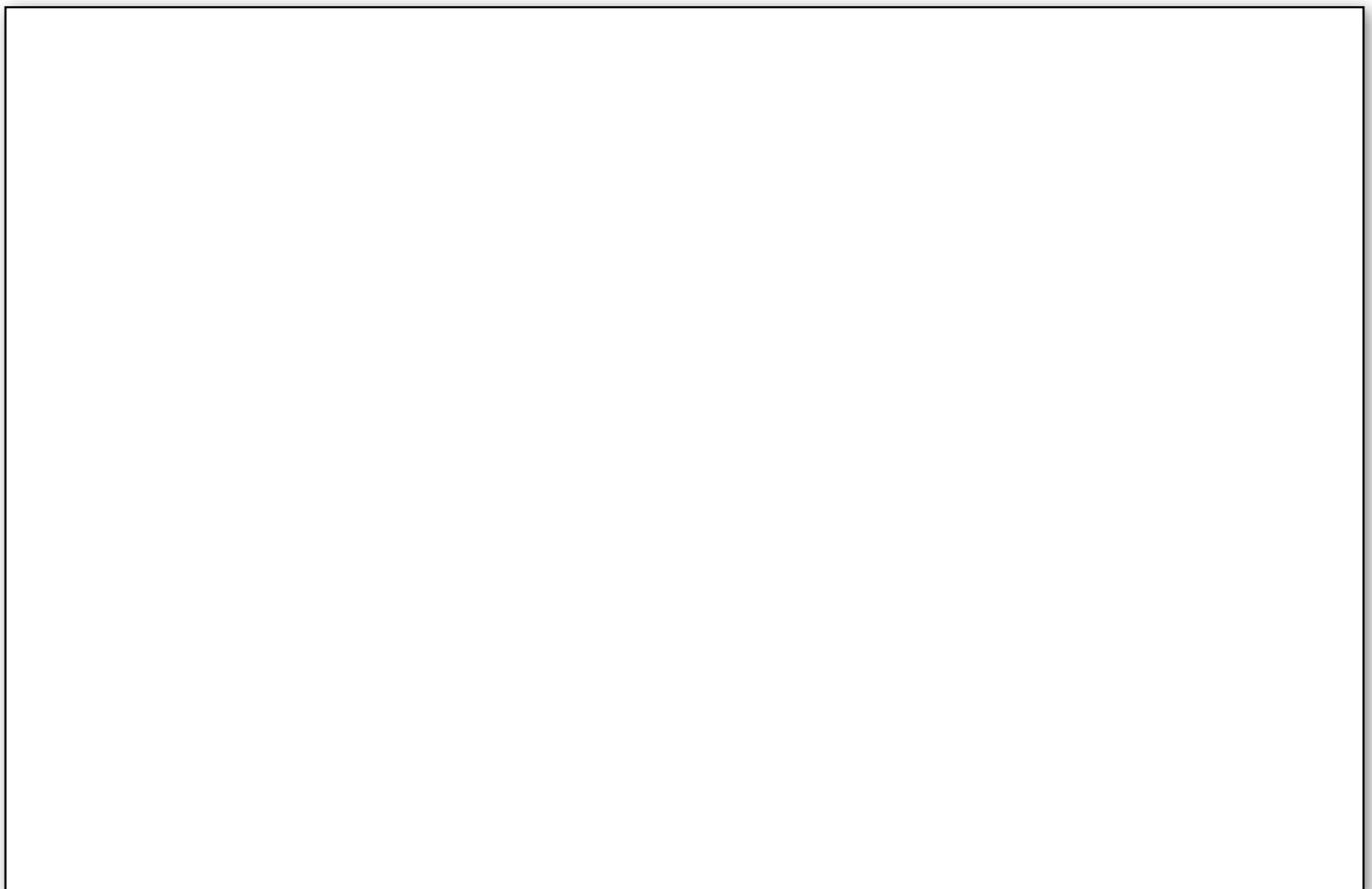


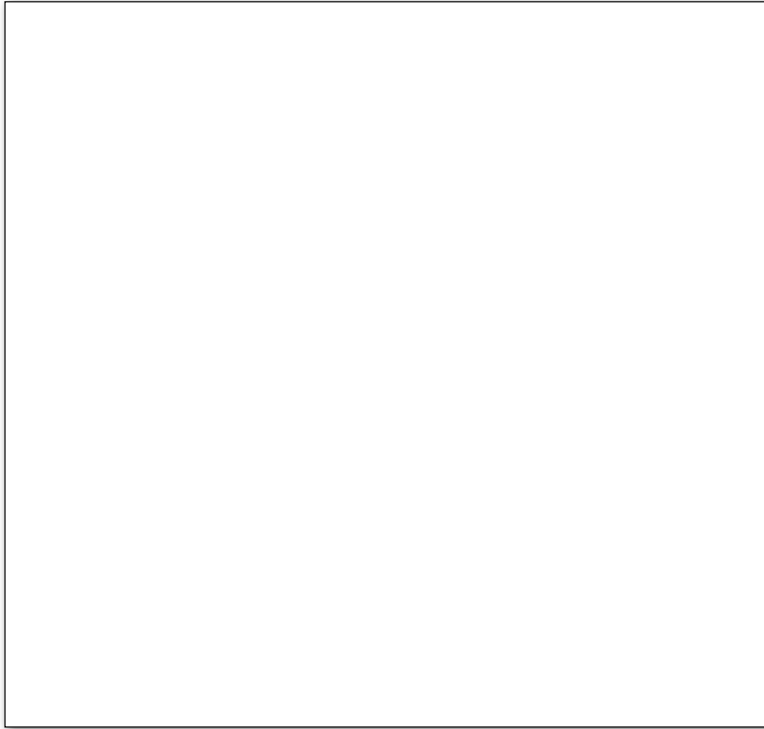
thermodynamics; forces in play are pressure gradient, gravity, Coriolis and friction forces. This atmospheric component of the models is also that of meteorological forecasts. In these models, the environment (sea surface temperature, ground status) was considered as passive. Such models cannot account correctly for the energy redistribution by the atmosphere and the ocean.

An oceanic circulation model was thus coupled to the atmospheric circulation model. A difficult problem to achieve this coupling is due to the various lengths of time typical of the processes involved in the two fluids as indicated on Figure 3. As we saw above, the climate acts on the environment which reacts on the climate. A realistic modelling has to take into account all environment components. It is no more a climate model but an Earth system model (Figure 4) which is used nowadays to describe the climate evolution.

▲ FIG. 2: Rock paintings in Tassili, showing livestock in the green Sahara 6000 years ago.

▼ FIG. 3: Exchange processes of energy, water vapour and greenhouse gases have very different characteristic times ranging from a day to a billion years.

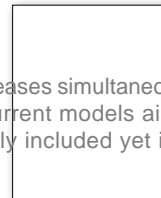




▲ FIG. 4: Evolution over time of climate models. The number of components increases simultaneously as they use more refined descriptions (illustrated by growing cylinders). Current models aim at describing the whole “Earth system”. Notice that ice caps are not routinely included yet in the models.

Such a model requires very large computer resources (computing capacity and time) that make it unusable for cases that require numerous simulations to elucidate specific processes in the present and passed climates. Thus Earth system models are complemented by a hierarchy of more theoretical or simplified models which play a decisive role in the understanding of the general atmosphere and ocean circulation and its interactions with the environment, or to decipher the natural variability of our climate. They play a key role in evaluating feedbacks and climate response to various perturbations of the global radiation budget. They are essential to understand the large changes of the past that are known from natural climate archives. They allow to give meaning to present changes by evaluating the share of natural spontaneous climate variability and of human influence. They are essential too to anticipate future risks. ■

About the Author



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BOX 2: QUATERNARY GLACIATIONS OWE MUCH TO BACKUPS

For 3 millions years, Earth has experienced alternating interglacial eras (like the present period) with one ice cap on Antarctic and one ice cap on Greenland, and glacial eras with two additional enormous caps, one over Northern Europe and one over North America. A glaciation is initiated by specific seasonal conditions: rather mild winters at high northern latitudes with mild temperatures in the tropics so that the atmosphere is wet enough for bringing copious snowfalls; sufficiently cool summers so that the snow accumulated in winter does not completely melt. This requires that the winter solstice is close to perihelion and the summer solstice close to aphelion, with a not too small Earth orbit eccentricity and a strong obliquity. Snow thus stays all year long at high latitudes, which increases the albedo, reduces sun light absorption and causes a cooling. Due to the colder climate, boreal forest is replaced by tundra, a low vegetation yielding a higher albedo in these snow covered areas, thus reducing again solar radiation absorption and increasing the cooling. The colder sea water absorbs significantly more CO₂ which is taken and stored at the ocean bottom by the thermohaline circulation; its atmospheric concentration drops, which reduces strongly the greenhouse effect. At the same time, the microorganism activity at high latitudes decreases, which decreases the methane production. All these processes amplify the cooling. Such processes enabled the accumulation of 42 millions km³ of ice over northern Europe and America 21,000 years ago, lowering the sea level by 120 m.

Read more on this subject

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