A BRIEF TOUR OF THE CLIMATE MACHINE

1 - THE CLIMATE MACHINE, A TWO FLUIDS THERMAL ENGINE[1]

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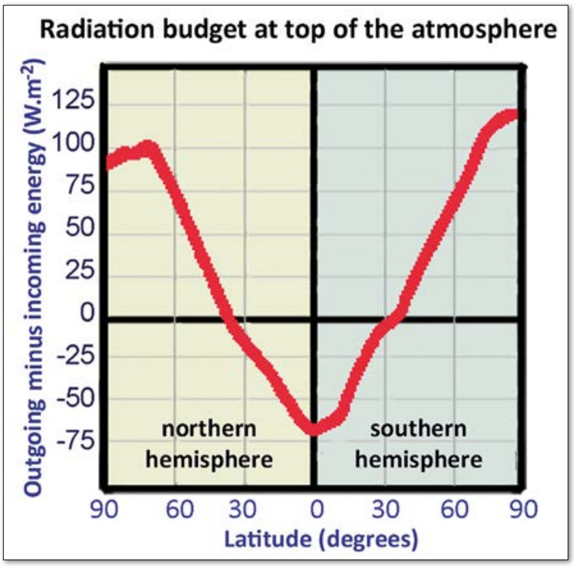
The climate machine is a thermal engine that gets all its heat from the sun and redistributes it on the Earth surface through coupled fluid circulation of the atmosphere and the ocean. Water present on Earth in its three physical states — solid, liquid and gas — plays a key role in the climate.

▼ Climate results primarily from the transport of solar energy by ocean and atmosphere.

Climate: this word usually applies to weather conditions such as temperature, rainfall and wind patterns. Historically, climatology first endeavoured to describe such conditions. Another way to define a climate is to refer to the biosphere which spontaneously develops: vegetation which has long been used to identify various climatic entities, but also fauna that prospers. Concurrently physical sciences have allowed to decrypt and then to model how the climate engine works [2]. Numerous processes in the external envelopes of Earth are interacting with each other. The aim of the present paper is to help the reader get acquainted with the two major actors and mechanisms creating the climate. The role of interactions with the environment will be presented in the next issue of EPN.

The climate machine is a thermal machine that gets its energy from the sun (the geothermal flux amounts to only 0.03% of the solar flux absorbed by the Earth).

The Earth (atmosphere and surface) reflects back to space 30% of the incoming sun energy; the remaining 70% is absorbed and transformed into heat. The excess heat is evacuated into space as electromagnetic radiation, the only form of energy that can propagate in the interstellar vacuum. Since the Earth is a sphere, the amount of energy that it receives from the sun is unequally distributed at the Globe surface, being highest at low latitudes.



◄ **FIG. 1:** Difference between the energy that escapes Earth and the incoming solar energy as a function of latitude (ERBE 1984–2003). Except around 30° N or S, the budget is not balanced. The equator sends back to space only a fraction of what it gets; it is the opposite at high latitudes.

At any point, the average temperature would be stable if the amount of energy escaping Earth were equal to the amount of incoming solar energy. Satellite observations show that this radiation budget is positive (the incoming energy exceeds the escaping energy) in the tropics, and negative in polar regions (Figure 1). Thus, energy is transported from low latitudes to higher latitudes.

Both fluids of the Earth envelope contribute to this transport by roughly the same amount.

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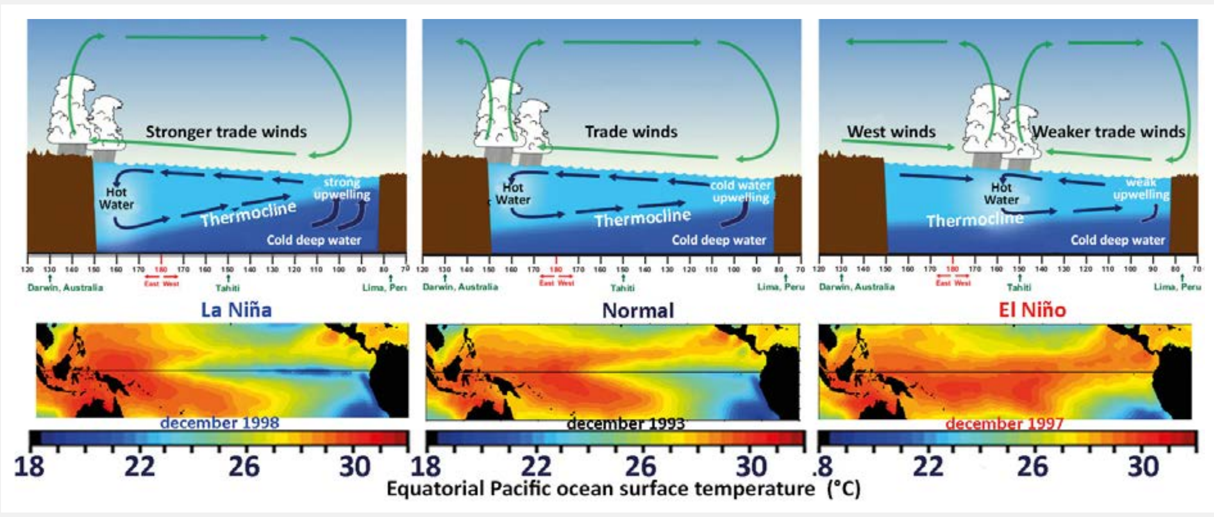
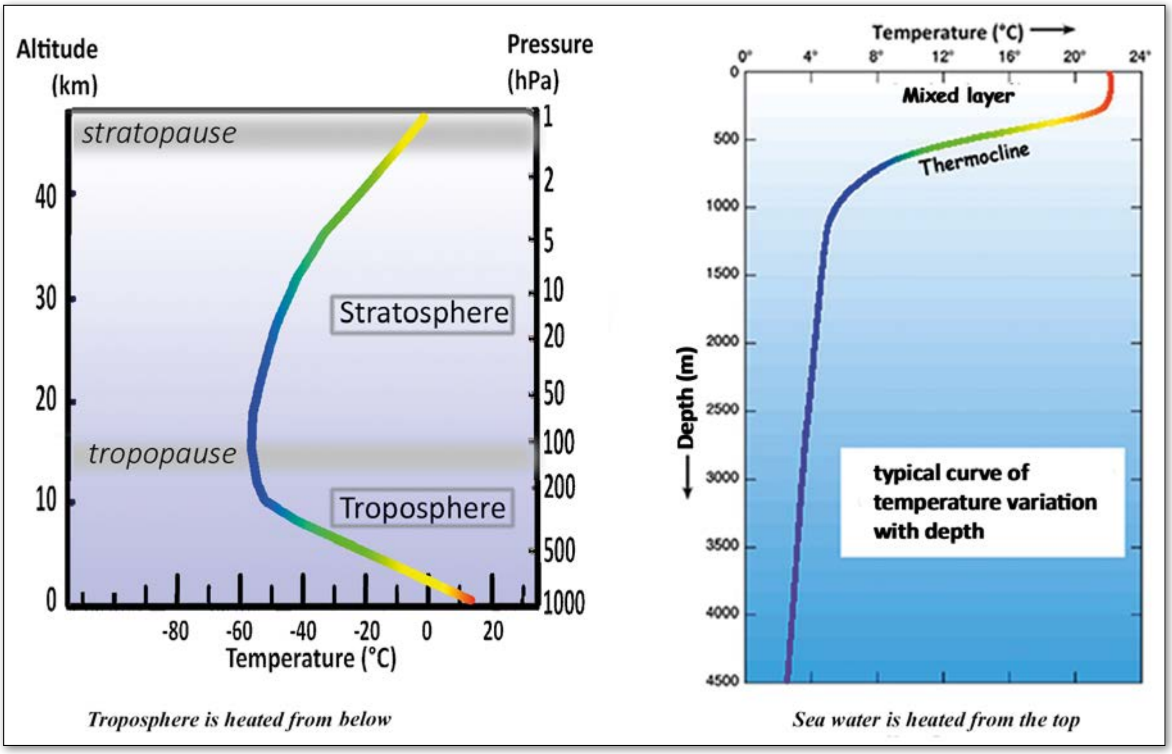
BOX 1: EL NIÑO – LA NIÑA

In the equatorial Pacific ocean, high pressures are normally located on the eastern side, along Peru's coasts, and low pressures on its western side over the Philippines Islands. Every 3 to 7 years, trade winds weaken and warm water flows back eastwards. This El Niño event may produce severe rainfalls on Peru and a strong drought in the Philippines. Away from the intertropical Pacific, a strong El Niño affects also the Indian Ocean and eastwards, as far as the western edge of the Atlantic. An El Niño event is often followed by the reverse phenomenon La Niña, which is characterised by stronger trade winds and the shrinking of the warm pool.



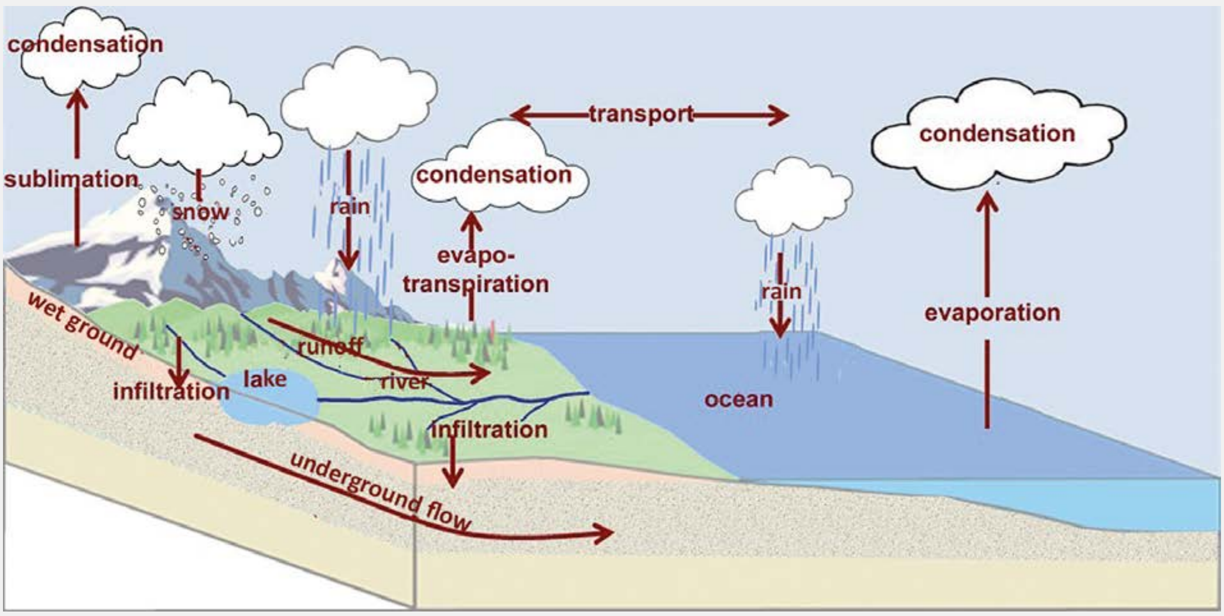
▲ The three states: La Niña, normal and El Niño, correspond to very different ocean and atmosphere patterns in the equatorial Pacific, with strong impacts on surface water temperatures.



▸ **FIG. 2: Typical vertical temperature profile of the atmosphere (left) and of the ocean (right). The troposphere which contains most of the atmospheric mass in the first 10 km is heated from below while the ocean is heated from the top. (The temperature increases with altitude in the stratosphere due to UV radiation absorption by ozone).**

BOX 2: WATER CYCLE

The Earth contains 1.4 billions km^3 of water: about 2.2% in ice mainly in the Antarctic, 95% in the ocean, 1% to 20% in underground waters, the remaining in lakes, rivers, inland seas, cells of living bodies, and only 0.001% in the atmosphere. Ocean evaporates 410,000 km^3 of water per year. Water vapour travels about 1000 km in 15 days in the atmosphere before condensing to build clouds where the water droplets and ice crystals grow by coalescence until their weight exceeds air resistance and they fall down. 110,000 km^3 of water falls on continents where 70,000 km^3 evaporate or sublimate either directly or through evapotranspiration from the vegetation and soil. The remaining 40,000 km^3, run off or infiltrate the ground before reaching oceans by rivers or by underground flow, or by melting of glaciers and icebergs (1,200 km^3 of water). Globally 370,000 km^3 of water come back to the ocean as rainfalls.



Heat transport

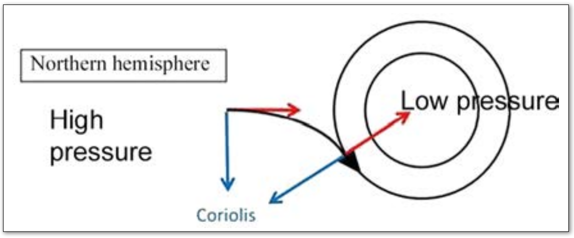
On continental surfaces, the solar radiation is absorbed by the soil; in the ocean, it is absorbed in the first metres below the surface. Heat is thus transmitted to the troposphere from below, while the ocean is heated from the top. Hence, the vertical temperature distribution is completely different between both fluids (Figure 2). Vertical transport is essentially driven by local fluid density. Within the atmosphere, the lifting of air warmer and thus less dense than the surrounding air, and the downwards motion of cold air, occur through convection loops. In the ocean, the density gradients are due to temperature and salinity; water is usually warmer at the sea surface than deeper. When ice forms at the surface of seawater, it rejects salt ions, so the surrounding seawater increases in density, causing it to dive to the sea bottom.

The vertical transport in the atmosphere generates pressure variations which drive horizontal air motion, *i.e.* winds. If the Earth were not rotating, the motion would simply be from high pressures to low pressures. The Coriolis force deflects the motion and thus winds move rightwards in the northern hemisphere, leftwards in the southern hemisphere, letting winds turn around lows (Buys-Ballot); this is called the geostrophic circulation (Figure 3). The global wind pattern is schematically shown in Figure 4.

Winds are altered by the topography and by the roughness of regions they pass through. At the sea-ocean interface, momentum exchange between the two fluids is the source of marine surface currents (down to about 1000 m depth). Due to the Coriolis force, these currents draw large loops in the great ocean basins, the gyres; the Gulf Stream is the western branch of such a gyre.

The world ocean is also crossed by a deep circulation called the thermohaline circulation, which is driven by density, *i.e.* by water temperature and salinity. Water on its way to the high polar latitudes loses heat transmitted to the atmosphere by infrared radiation, sensible heat and evaporation, the latter one making it saltier. Freezing sea water is very cold (-1.8°C). At the ice water interface, salt tends to migrate from solid to liquid phase, releasing brines that further increase water salinity. Being very dense, the water plunges down to the ocean bottom where it starts a long journey through the entire world ocean before it eventually goes up slowly into the surface currents which finally carry it back to its plunging point after a trip that may have lasted 1000 years. This long course is known as the ocean conveyor belt (Figure 5). Thus, the diving of water in the far north is the driving force of the North Atlantic Current that brings the warm water of the Gulf Stream to Europe.

Winds also drive cold water to rise to the surface (the upwellings) on the edges of continents and in the intertropical convergence zone.



◂ FIG. 3: The force caused by the pressure gradient (in red) is balanced by the Coriolis force (in blue). The wind follows the isobars (lines of constant pressure).

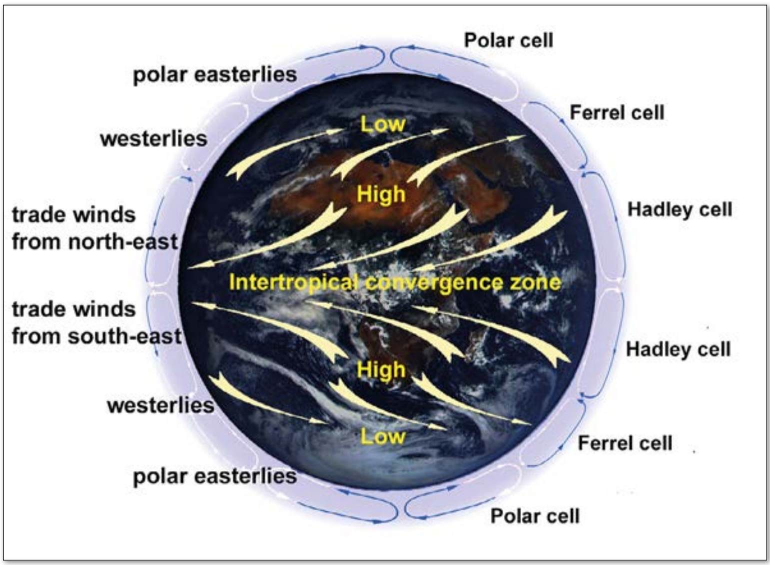
The climate mechanism involves in a tightly coupled way both fluids of the Earth's envelope. At their interface, they exchange heat (sensible and mainly latent), momentum (causing marine surface currents), liquid and gaseous water. The oceans also provide the atmosphere with mineral salt particles from sea-spray, and sulfur compounds (emitted by the plankton). These compounds will oxidise and form condensation nuclei necessary for the formation of clouds. Process times and sizes have very different values in the atmosphere, the surface and the deep ocean : few days in the atmosphere with coherent eddies that may span several thousands km, whereas they do not exceed some hundred km in the ocean but with reaction times ranging from months to millenia. This results in a complex coupled system subject to internal oscillations, the most widely known being the El Niño–La Niña Southern Oscillation (see box 1).

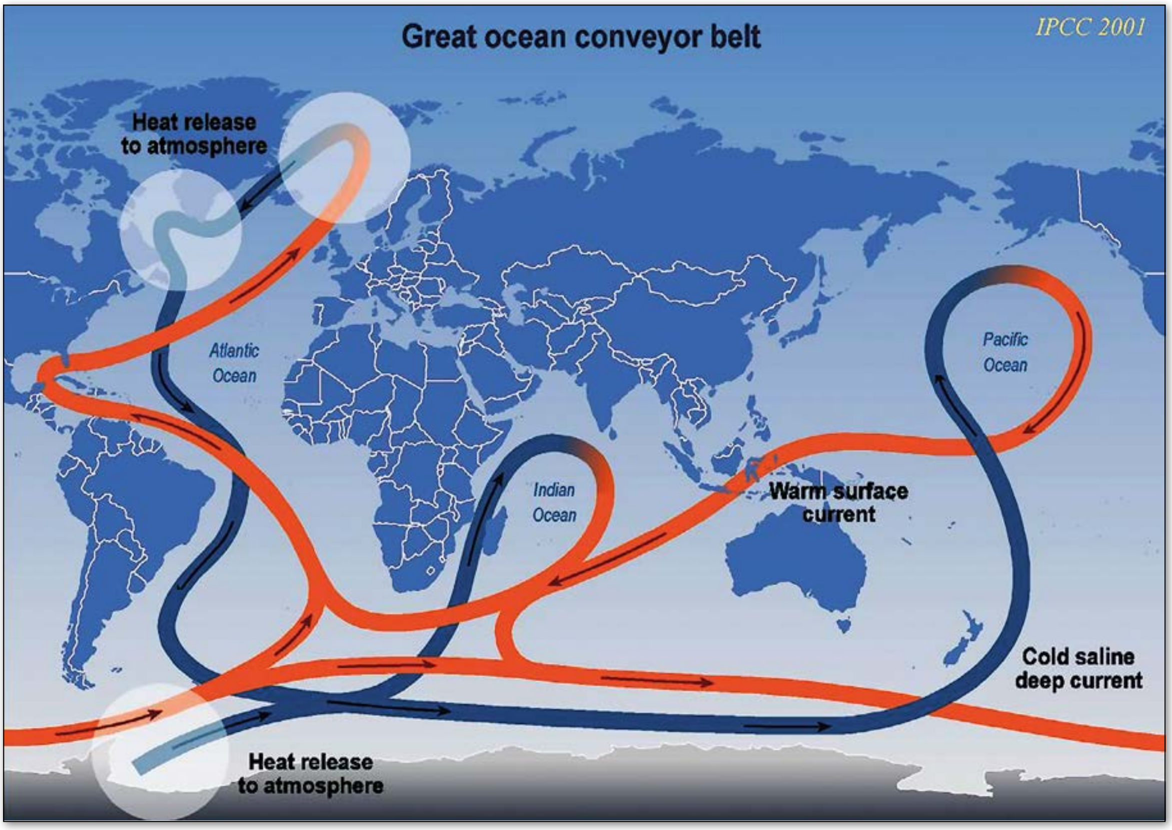
Water in all its states

All three water phases play an essential role in the energy budget and in the way that climate is operating (see box2).

- Evaporation which occurs mainly from the oceans, cools their surface since water vapour brings to the atmosphere its evaporation latent heat. This heat is carried away by the humid air masses and given back to the atmosphere at the condensation location after about 15 days on average. The heat thus delivered maintains deep convections that feed depressions. It acts in building large storm cumulonimbi. It gives their energy to tropical storms (hurricanes, cyclones, typhoons). The convection tied to vapour condensation with intense rainfalls in the intertropical

▾ FIG. 4: Schematic view of the global winds pattern. The polar cell is similar to the Hadley cell (described in the text below) with very dry air going down at the poles. The Ferrel cell results from interactions between hot air masses coming from the Hadley cell and cold air masses coming from the polar cell which generate successive lows and highs in the barometric pressure that are transported in Rossby waves [3]).



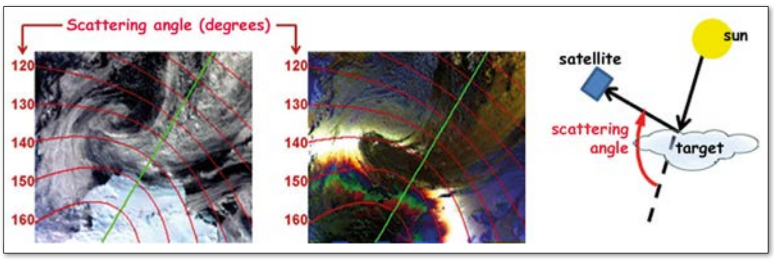


▸ FIG. 5: Thermohaline circulation (conveyor belt). In blue, deep cold water circulation; in red, warm water surface circulation. In the areas of deep water formation, the atmosphere gains heat from the ocean.

zone is responsible for the strong atmospheric ascend that generates the Hadley cell (Figure 4).

- Water vapour is mainly located in the lower troposphere. It accounts for 50% of the natural greenhouse effect. The amount of water that can stay in the atmosphere increases with temperature (Clausius-Clapeyron) by about 7% at customary temperatures.
- Low clouds are made up of liquid water (Figure 6). They screen incident solar radiation (parasol effect). High clouds (cirrus) are made up of ice crystals. They absorb infrared radiation and contribute to heat confinement in the lower troposphere.
- In its solid state water occurs in high clouds, in snow and hail falls, and in the cryosphere: sea ice, continental and alpine glaciers, permafrost, snow on the ground. Due to their very high reflecting efficiency (albedo, up to 90%), snow or ice covered areas limit strongly local absorption of solar radiation. The liquid-ice threshold (0°C for freshwater) is often crossed by water on the Globe surface. When this threshold is crossed, the huge change of albedo results in a non-linear behaviour of the climate: effects are much larger than the initial small change in temperature.

▾ FIG. 6: The same area over the Antarctic measured by the satellite radiometer POLDER in natural light (left) and in polarised light (right). Some of the water clouds seen in the left picture exhibit a rainbow pattern in polarised light. They are partly hidden by high altitude ice clouds which don't polarise light.



Conclusion

The processes occurring in the two fluid envelope of the Earth are only a part of the climate system. As will be shown in the second part of this tour in the climate machine, their various interactions with the Earth environment are essential in fashioning the climate. ■

About the Author

Jean Poitou. Physicist, climatologist. Former deputy director of LSCE. Active in climate related NGOs and in introducing climate science to secondary-school pupils.

Read more on this subject

Le climat : la Terre et les hommes. Jean Poitou, Pascale Braconnot, Valérie Masson-Delmotte. Collection « Une introduction à », EDP Sciences (2015)

Le climat à découvert. Catherine Jeandel, Rémy Mosseri. CNRS Éditions (2011)

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[3] James R. Fleming, Carl-Gustaf Rossby Theorist, instituition builder, bon-vivant, *Phys. Today* 70, **1**, 50 (2017); doi: 10.1063/PT.3.3428

[4] More about greenhouse effect in the second part of this tour of the climate machine, to be published in the next issue of *EuroPhysics News*.