Biotic pump of atmospheric moisture as driver of the hydrological cycle on land

Oral presentation in Session CL22 Climate: Past, Present and Future: Land-atmosphere coupling in past, present and future climate (solicited)

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Text presented below refers to swf files of the presentation that can be viewed at http://www.biotic-regulation.pl.ru/egu2007 following the links below.

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This presentation text is supposed to be read while viewing the corresponding swf files.

http://www.biotic-regulation.pl.ru/egu2007/kadr1.swf
http://www.biotic-regulation.pl.ru/egu2007/kadr2.swf
This talk will be about forests, about deforestation and its consequences for the regional atmospheric circulation and hydrological cycle.

http://www.biotic-regulation.pl.ru/egu2007/kadr3.swf
I will describe the phenomenon of biotic pump of atmospheric moisture, which consists in the fact that a regionally significant natural forest cover draws moist air from the ocean to the continent.

http://www.biotic-regulation.pl.ru/egu2007/kadr4.swf
This presentation is structured along three major issues.

First, I show that there is a critical value of the vertical gradient of air temperature, beyond which moist atmosphere cannot be static and that this critical value is equal to 1.2 Kelvins per kilometer.

When this critical gradient is exceeded, the stationary state of moist atmosphere is not static, but dynamic, with moist air near the surface flowing from areas with low, to areas with high, evaporation. This circulation principle will be illustrated.

Finally, I will discuss how, via control of evaporation, vegetation cover can dictate the properties of atmospheric circulation. I will show how the action of forest moisture pump profoundly affects the dependence of continental precipitation on distance from the ocean.

http://www.biotic-regulation.pl.ru/egu2007/kadr5.swf
First, to the non-equilibrium moist atmosphere.

Atmospheric water vapor is under the action of two independent factors, gravity and temperature.

Static equilibrium of water vapor in the gravitational field is realized when change of gas pressure per unit height equals weight of gas in unit volume. In the static state water vapor partial pressure exponentially decreases with height and drops twofold per each nine kilometers. This blue line and the left axis on the graph show the relative change with height of the static water vapor pressure.

On the other hand, water vapor is a condensable gas and its pressure cannot be higher than the saturated pressure. Saturated pressure of water vapor depends exponentially on temperature, as prescribed by the well-known Clausius-Clapeyron law. It decreases approximately twofold per each ten degrees of temperature drop. This red line and the right axis on the graph show the relative decrease of saturated pressure with absolute temperature in degrees Kelvin decreasing in the upward direction.

Water vapor can be in static equilibrium, if only its equilibrium pressure is not higher than saturated pressure! And this is under control of the vertical temperature gradient.

For example, in the situation currently shown in the graph, when the vertical temperature lapse rate is half a Kelvin per kilometer, static equilibrium of water vapor is possible, because the blue, equilibrium line at any height goes to the left of the red, saturated line. However, as we increase the temperature gradient, we can see that the red line starts to approach the blue line and coincides with it at a critical gradient of 1.2 Kelvins per kilometer.

At this gradient static equilibrium is still possible; water vapor is static and saturated in the entire atmosphere.

However, when the temperature gradient is increased even further, for example, to the observed 6.5 Kelvins per kilometer, we can see that the static equilibrium of water vapor becomes impossible, because the static pressure exceeds the saturated pressure, and the blue line goes to the right of the red line.

http://www.biotic-regulation.pl.ru/egu2007/kadr6.swf

Now we turn to an important issue.

Since water vapor is out of static equilibrium, moist atmosphere as a whole cannot be in static equilibrium either. This statement is very important for the understanding of atmospheric processes, because currently hydrostatic equilibrium of atmosphere is invariably considered in the atmospheric science as a reference average state of the atmosphere.

Let us have a look at what kind of processes occur in gases. Consider three boxes that have two compartments each separated by a gas-impermeable membrane. The compartments are filled with different gases, condensable and non-condensable. In the first two boxes the temperature in both compartments is the same, while in the third box temperature in the upper compartment is lower than in the lower compartment. The membrane is removed at the initial moment of time.

If the pressure of different gases in the two compartments is the same, as here, after the membrane is removed, there appears a diffusional flux of gases. It stops as soon as the concentrations in the two compartments equate. No dynamic processes, no forces, no wind arise.

In contrast, if gas pressure in the compartments is different, after the membrane is removed, we can see a dynamic flow, a wind under the action of the pressure gradient force (white arrow). As soon as pressure in the two compartments equate, the force disappears and the dynamic flow ceases.

Now consider condensable and non-condensable gases in a temperature gradient. Even if at the initial moment of time there is no pressure gradient, but only a concentration gradient, as in the first picture, after the membrane is removed, the condensable gas starts to propagate diffusionally into the upper cold compartment. It condenses there and there appears a shortage of pressure and an upward force arises causing the upwelling dynamic flow of the whole mixture. This illustrates, in agreement with the fundamentals of gas physics, that static equilibrium of moist atmosphere in a sufficiently large temperature gradient is impossible.

http://www.biotic-regulation.pl.ru/egu2007/kadr7.swf
The upward-directed force acting in the moist atmosphere and making moist air rise is equal to the difference between the non-equilibrium pressure gradient and weight of unit volume of water vapor. This force exists as long as there is evaporation from the surface, which compensates for the on-going condensation of water vapor. Therefore it is natural to call this force the evaporative force.

The stationary vertical velocity of air movement is, on a regional average, proportional to the flux of evaporation.

http://www.biotic-regulation.pl.ru/egu2007/kadr8.swf
Therefore, where the evaporation flux is higher, there appears a more intense upwelling flux of moist air, which causes surface horizontal flow of air from the adjacent areas with lower evaporation.

This circulation is maintained as long as there is evaporation. The on-going condensation sustains the non-equilibrium pressure shortage of water vapor, which makes moist air rise.

This circulation principle, horizontal surface air flow from low to high evaporation, provides clues to the major patterns of atmospheric circulation found on Earth.

http://www.biotic-regulation.pl.ru/egu2007/kadr9.swf
I will dwell on two contrasting cases.

In deserts evaporation is virtually zero, so if a desert borders with the ocean, horizontal surface air flow will be always directed from land to the ocean. That is, the desert appears to be locked for moist air year round. This type of circulation is observed, for example, in the Sakhara region.

In contrast, if land is covered by an extensive natural forest which has high leaf area index and, hence, large evaporative surface, land evaporation will be higher than in the ocean. In this case the predominant direction of surface air flow will be from ocean to land. Moisture brought from the ocean will rise and precipitate on land, creating an intense hydrological cycle and large river runoff. Depleted from moisture, air will return to the ocean in the upper atmosphere. This is the essence of the biotic pump of atmospheric moisture.

It is clear from this consideration that elimination of forest cover ultimately leads to complete desertification of land. This process occurs via the intermediate stages of monsoon-like circulation, when under particular physical conditions the surface air flow is directed either from ocean to land or vice versa.

http://www.biotic-regulation.pl.ru/egu2007/kadr10.swf
As can be expected, biotic moisture pump affects the precipitation on land in a signifcant way. We have studied the dependence of annual precipitation on distance

from the ocean in world's major forest-covered (Amazon, Equatorial Africa, Siberia and North-America) and unforested regions, including West Africa and Australia. Marked differences were found.

http://www.biotic-regulation.pl.ru/egu2007/kadr11.swf
In the non-forested regions, precipitation drops abruptly with increasing distance from the ocean, reducing by several times over several hundred kilometers.

http://www.biotic-regulation.pl.ru/egu2007/kadr12.swf
In contrast, in forest-covered world regions precipitation does not decrease over thousands kilometers inland.

http://www.biotic-regulation.pl.ru/egu2007/kadr13.swf
This evidence is a direct hydrological and climatological manifestation of the physical principles that have been just formulated.

http://www.biotic-regulation.pl.ru/egu2007/kadr14.swf
To conclusions.

The proposed physical mechanism of atmospheric circulation based on the evaporative force significantly impacts atmospheric phenomena and open wide perspectives for further studies.

To the degree the regional vegetation cover determines the evaporation flux, it can control atmospheric circulation patterns.

Regional deforestation should lead to a significant reduction of regional precipitation.

http://www.biotic-regulation.pl.ru/egu2007/kadr15.swf
Accounting for the biotic moisture moisture mechanism is critical for solving the ever aggravating problems of water security.

The continuous, regular drag of moist air by forests stabilises the regional water cycle against droughts, fires and floods.

Increasing patchiness of vegetation cover adds irregularity to regional atmospheric circulation and hydrological cycle.

Degradation of land and the remaining natural vegetation cover over the European subcontinent, especially including the processes in the North-West of Russia, are responsible for the declining precipitation and river flow in Europe.

http://www.biotic-regulation.pl.ru/egu2007/kadr16.swf

These results have recently been published in the Hydrology and Earth System Sciences journal of EGU, following an extensive discussion.

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Thank you.