An Updated Climate Feedback Diagram

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Abstract

An update of the Kellogg and Schneider climate feedback diagram that incorporates thermal inertia, meltwater, and vegetation feedbacks, and more clearly distinguishes external forcing and heat fluxes, is presented. This diagram will be of use in helping to understand the complex interactions in the climate system that can feed back on surface air temperature.

The complex interactions of the climate system that result in changes in surface air temperature can be thought of as feedback mechanisms (Schneider and Dickinson, 1974). A feedback mechanism is an interaction in which an initially imposed change in a variable, say surface air temperature, causes some other variable to change, say snow cover, that then acts to modify the original change. For example, lower temperatures might produce more snow, which would increase the albedo of the system. The higher albedo causes less solar radiation to be absorbed by the system, which causes it to be cooler still, producing even more snow. This is an example of a positive feedback, where the initially imposed change is amplified, and the resulting temperature is lower than it would have been without the interaction with the snow. There are also negative feedbacks, the prime example of which is the temperature-radiation feedback (Schneider and Dickinson, 1974). Understanding feedback mechanisms has become such an important part of climate research that an entire book (Hansen and Takahashi, 1984) has been recently published on the subject; it only discusses *some* of the feedback mechanisms.

Kellogg and Schneider (1974) attempted to clarify these feedback relationships in a diagram that indicates how different parts of the climate system interact with each other to cause the temperature to change. In recently reviewing this diagram, I noticed several aspects of it that I thought could be improved; especially the incorporation of important feedbacks that were not recognized at the time of its construction. Therefore, I have produced a new and improved version of their diagram (Fig. 1). In what follows, I will explain the changes made. I hope that the new diagram will be of use in explaining these feedback relationships and, as pointed out by Kellogg and Schneider, in realizing the enormous complexity of the climate system.

Three new climate elements have been added to the diagram: vegetation, thermal inertia, and meltwater.

The addition of "vegetation" produces the most new feedbacks. These include vegetation-albedo, vegetation-evaporation, and vegetation-atmospheric composition feedbacks. Vegetation-albedo feedbacks are reviewed by Dickinson and Hanson (1984) and, as they point out, were recognized because of the influential papers of Charney (1975), Cess (1978), and Sagan *et al.* (1979). When vegetation is removed from land by, perhaps, overgrazing, the resulting

change in surface albedo can affect the atmospheric circulation in such a way as to lessen rainfall and so make it harder to reestablish vegetation. It has been suggested that this mechanism may have been an important desertification process in the Sahel and in India. Vegetation-evaporation feedbacks are only now being investigated in detail in climate models (Dickinson, 1984; Rind, 1984). Changing vegetation can alter the evapotranspiration rate and the resulting difference in atmospheric water content can feed back on the atmospheric circulation, producing changes. Increases in vegetation can also reduce atmospheric carbon dioxide and increase oxygen; decreases have an opposite effect. Trace gases are also affected by vegetation.

"Thermal inertia" is another new element. It is different from all the other elements in that it refers to the rate of change of temperature rather than to a physical portion of the climate system. Its inclusion produces the sea-ice-thermal-inertia and mixing-depth-thermal-inertia feedbacks. Either more sea ice or a smaller mixing depth in the ocean will lower the thermal inertia, allowing temperature to change more rapidly in response to a net energy imbalance. Less sea ice and a greater mixing depth have the opposite effect. When temperatures are at the freezing point, the latent heat of fusion due to melting or freezing slows down imposed temperature changes, but the net effect still is more rapid temperature changes when ice is present. It insulates the atmosphere from the ocean mixed layer, allowing imposed energy imbalances to change the temperatures of only the ice surface and the air, but not of the entire mixed layer.

The third new element is "meltwater," which refers to the lowered albedo of snow and ice surfaces produced by higher temperatures. The meltwater-albedo and sea-ice-thermal-inertia feedbacks were discussed by Robock (1983). The sea-ice-thermal-inertia feedback was found to be a strongly positive one. To my knowledge, the mixing-depth-thermal-inertia feedback has not been investigated in a seasonal climate model.

In order to clarify the relationships between climate elements, external forcings, heat fluxes, and temperature, the diagram has been drawn with different fonts. External forcings are indicated in underlined italics. Net energy balance and thermal inertia are included explicitly, and therefore the feedback loop is completed, with the causes of temperature change indicated. Thermal inertia is indicated in italic capitals and a dashed box to indicate its special relationship to the other variables. Temperature effects on other elements are indicated with darker arrows. All heat-flux components are indicated in rounded boxes. The mysterious climate element "surface vapor per square unit" (Kellogg and Schneider, 1974) has been eliminated. Surface and planetary albedo are both included explicitly to clarify their respective relationships.

I am sure that any active climate researcher could quibble with details of the diagram, and probably add a few arrows
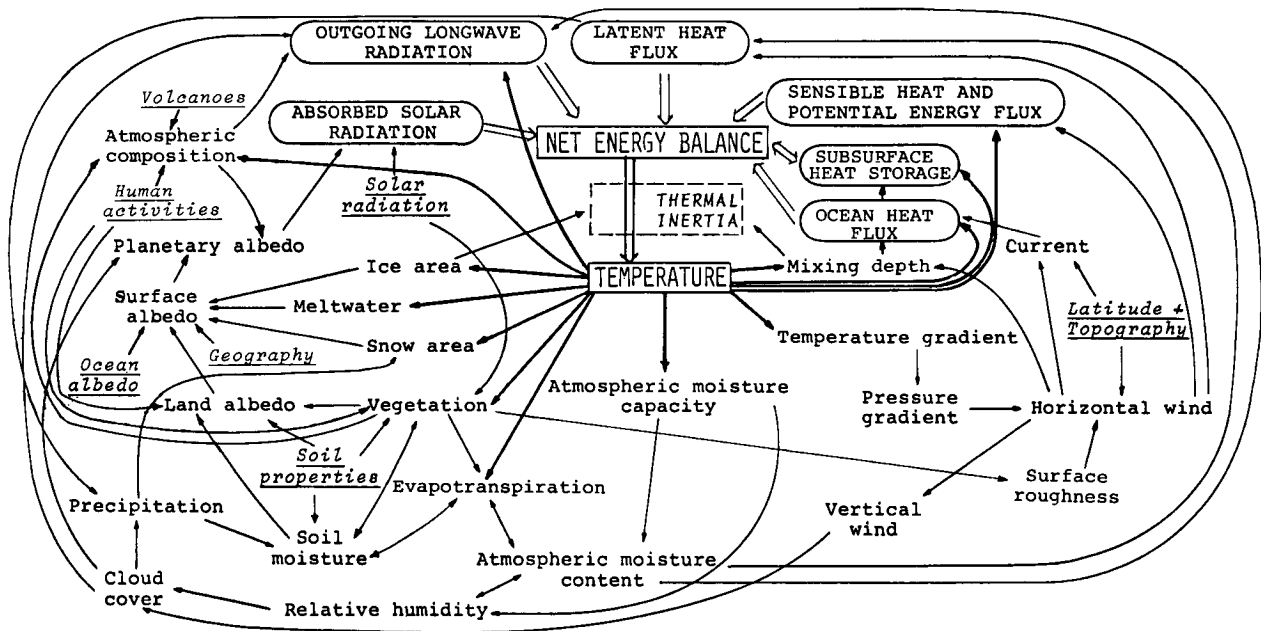
FIG. 1. Climate feedback diagram.

here and there. I tried to make the diagram as simple as possible with as few arrow crossings as possible while still retaining the important climate relationships. It is hoped that it will be a valuable tool both for teaching about climate and for climate modelers to explain to others those feedbacks that are included in their models.

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