A NEGATIVE FEEDBACK MECHANISM FOR THE LONG-TERM STABILIZATION OF EARTH'S SURFACE TEMPERATURE

James C. G. Wickett and P. B. Reay
Space Physics Research Laboratory, University of Michigan, Ann Arbor, Michigan, 48109

J. F. Kasting
National Center for Atmospheric Research, Boulder, Colorado, 80302

Abstract. We suspect that the partial pressure of carbon dioxide in the atmosphere is buffered, over geological time scales, by a negative feedback mechanism in which the rate of weathering of silicate minerals follows the depletion of carbonate minerals. The reaction is the same as that which occurs in an ocean, where the two compounds can exist in a steady-state equilibrium. Although the negative feedback is non-linear, the equilibrium is stable because the atmospheric carbon dioxide is released to the atmosphere at a rate that is proportional to the amount of carbon dioxide in the atmosphere. This equilibration is achieved by the release of carbon dioxide from the ocean and its uptake by the atmosphere, which occurs in a steady-state equilibrium.

Introduction

Speculation concerning the evolution of the terrestrial atmosphere is constrained by the presence of the coupled sun. As pointed out by Sagan and Mullen [1977], there is a conflict between our understanding of secular evolution, which implies that the habitability of the Sun has increased by possibly 15 percent over the age of the solar system (Neiman and Boyd, 1977), and the geological record of weathering processes of silicate deposition that extends back in time to 3.5x10^9 years before the present (Lam, 1987). Earth would have been too cold to sustain liquid water on its surface unless the greenhouse effect, the albedo effect, and the surface of the ocean are too warm for the greenhouse effect to be effective. The albedo effect is the amount of heat energy received from the Sun by the Earth, which in turn is reflected back into space. The greenhouse effect is caused by the absorption of infrared radiation by greenhouse gases, such as carbon dioxide, water vapor, and methane, which trap heat in the atmosphere and prevent it from escaping to space.

Carbon dioxide is released by volcanoes and meteorites from the solid earth to the atmosphere, and oceans at a rate estimated by Houghton (1979) to be (3.1511 x 10^18 g) per year. Volcanoes, earthquakes, and landslides can release large amounts of carbon in the form of carbon dioxide, but the rate of release is relatively small compared to the rate of carbon dioxide in the atmosphere. This equilibration is achieved by the release of carbon dioxide from the ocean and its uptake by the atmosphere, which occurs in a steady-state equilibrium.

Copyright 1981 by the American Geophysical Union.

Paper number U14677.
148-0222/91/005-09-10.00

0776
TABLE 1: Morphoclinal Classification and Silicate Weathering Rates [Nyebeck, 1979]

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Runoff, mm yr⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-15</td>
<td></td>
</tr>
<tr>
<td>15-25</td>
<td></td>
</tr>
<tr>
<td>&gt;25</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Runoff, mm yr⁻¹</th>
<th>Runoff type</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;30</td>
<td>Wet, 1.25</td>
</tr>
<tr>
<td>30-120</td>
<td>Wet, 3.5</td>
</tr>
<tr>
<td>120-280</td>
<td>Very wet, 3.75</td>
</tr>
<tr>
<td>280-630</td>
<td>Very wet, 1.5</td>
</tr>
<tr>
<td>&gt;630</td>
<td>Very wet, 1.0</td>
</tr>
</tbody>
</table>

Weathering rates are expressed in 10⁶ g m⁻² yr⁻¹ of dissolved SiO₂. Parentheses signify poorly determined values.

Walker et al.: Mechanism for Temperature Stabilization

9777
against a secular change in solar luminosity. This mechanism, which has been shown to be effective in producing both a secular and a rapid temperature change, is not yet fully understood.

Effects of Fossil Fuel Disruption

A number of experimental studies of the albedo and radiation has been conducted, but results are not yet conclusive. The consensus is that the increase in solar luminosity is not yet sufficient to explain the observed changes in the Earth's climate. Further studies are needed to better understand the mechanisms involved.
Fig. 1. The logarithm of the concentration of dissolved silica (mg l⁻¹) in river water [Heydack, 1979]: (a) as a function of runoff in various annual temperatures (°C); (b) as a function of annual average temperature. The dashed line shows the slope of the temperature dependence deducted from the laboratory data of Lagache [1963].

\[ \log [\text{Si}] = -3.3 + 0.65 \times \text{runoff} \times 10^{-4} \]  
\[ \text{runoff} \, \text{cm yr}^{-1} \]  
\[ \text{temperature} \, \text{°C} \]

Aged annual precipitation [Sellers, 1965] is approximately proportional to the saturated vapor pressure of water at the monthly averaged annual mean temperature, a dependence of precipitation: \( \exp ([t - 253]/14.3) \). Climatological models of Hanabe and Stouffer [1980], Wetherald and Manabe [1975], and Manabe and Stouffer [1980] show a much weaker dependence of globally averaged runoff on the average global temperature, however, approximately \( \exp ([t - 385]/60) \). We shall adopt the constructive estimate, noting that a stronger dependence of runoff on temperature would provide a more effective temperature buffer.

Thus, combining the direct temperature dependence of the evaporation rate deduced from the data of Lagache and weighback with the weak temperature dependence of runoff implied by the work of Hanabe and colleagues and the pressure dependence deduced from the laboratory experiments of Lagache we obtain for the global rate of albedo wettering

\[ \Delta \text{albedo} = \frac{1}{100} \exp \left( -\frac{125}{T_1} \right) \]

where \( \Delta \text{albedo} \) is the departure of global average temperature from its present day value of 285 K [Sellers, 1965], \( T_1 \) is the present day rate of albedo wettering, and \( P_0 \) is the current partial pressure of \( \text{CO}_2 \).

To maintain a balanced flow of carbon through the ocean-atmosphere system, the average rate of algal wetting must always have been very nearly proportional to the rate of release of \( \text{CO}_2 \) by volcanism and metamorphism, which we designate \( \gamma \). Changes in the mass of fluid carbon corresponding, for example, to changes in the bicarbonate ion concentration in the water became negligible when converted into rates of throughput by dividing by geological areas of the type.

Equating \( N a \gamma \) to \( N a \gamma \) and rearranging \( \gamma \) we obtain an expression for \( \text{CO}_2 \) partial pressure

\[ \frac{P_{\text{CO}_2}}{P_0} = \frac{10^{10}}{3} \exp \left( -\frac{4.5}{T_1} \right) \]

Dependence of Global Average Temperature on Carbon Dioxide Partial Pressure

We estimate average surface temperature, \( T_s \), under varying conditions by separating the greenhouse effect due to water vapor and carbon dioxide

\[ T_s = T_a + T_b (P_0) + T_b (\text{CO}_2) \]

An expression that ignores the effect of overlap in the absorption bands of the two species. In this expression, \( T_a \) is the effective temperature, dependence on incident solar flux, planetary albedo, and the slab factor Looby and Walker [1973; Hudson-Sellers and Meadows, 1976], while \( T_b \) refers to the incident and surface temperature resulting from the atmospheric greenhouse.

For the greenhouse effect of water vapor we have used the results of Roeser and Walker [1966] as quoted by Hudson-Sellers and Meadows [1976], together with the assumption that the surface pressure of water vapor is one-quarter of the saturated vapor pressure at the average surface temperature. For surface temperatures not too different from the present average at 25°C the results are closely expressed by the expression

\[ T_b (P_0) = 29.7 \times 0.3 \times (T_s - 253) \]

Although vapor pressure increases exponentially with increasing temperature, the greenhouse effect increases logarithmically with vapor pressure, due to saturation of the absorption bands, so a linear dependence of greenhouse effect on surface temperature results.

To estimate the greenhouse effect due to carbon dioxide we have used the results of Owen et al. [1979]. By subtracting from this quoted surface temperatures from \( T_a \) and \( T_b (P_0) \) we find

\[ T_b (\text{CO}_2) = 2.3 \times 10^{-3} \]

This expression agrees quite well with values for the greenhouse effect for a pure \( \text{CO}_2 \) atm.
sphere given by Brundage-Sellers (1975). Our simple expressions ignore the dependence on the surface temperature and on temperature.

Combining these expressions and scaling the variables to terms of departures from the present global average surface temperature of 288°K and the present effective temperature of 255°K (Hodges and Waler, 1972), we obtain

$$\Delta T = 2\Delta T_e + 4.6 \left( \frac{\alpha}{T_e} \right) + 4.6$$

where $\Delta T = T_e - 288°K$ and $\alpha = T_e - 255°K$.

This expression reproduces the results of Ramsay et al., from which it was derived. It yields a temperature decrease of 1.1°K in response to a doubling of the carbon dioxide pressure, which can be reproduced with a typical value of 7°K obtained in detailed studies (Hudson-Westerval and Meadows, 1979, Oort, 1979; Mann and Stoffers, 1972, 1980; Schellart and Massey, 1961). A more detailed parametrization of the dependence of temperature on carbon dioxide partial pressure would result in a more strongly buffered temperature, particularly at low partial pressures.

Response of the Climate-Carbon Dioxide System to External Perturbations

In this highly simplified representation, the feedback system that couples carbon dioxide partial pressure and surface temperature is described by two equations. Equation (a) expresses the dependence of carbon dioxide pressure $p$ on surface temperature $(T_e, T_e - 288°K)$ and rate of release of $CO_2$ by volcanoes and metamorphism. Equation (b) expresses the dependence of surface temperature on effective temperature $T_e$ (a function of solar luminosity and albedo) and $CO_2$ pressure. The controlling factors external to the system are $T_e$ and $T_e$.

Figure 2 shows how surface temperature and $CO_2$ partial pressure vary with effective temperature for various values of the volcanic and metamorphic rate of CO$_2$ release. The broken line shows the surface temperature variation for a situation of no ice sheet (constant $r$).

The feedback mechanism that we have postulated reduces surface temperature change by about 1°K for $r = 0$ (the maximum $r$, $r_{max}$ release rate). Larger $CO_2$ release rates yield more $CO_2$ and stronger feedback. The increase of temperature plots reflecting winter feedback at the lowest $CO_2$ partial pressures that correspond to higher effective temperatures. One parameterization of the $CO_2$ greenhouse effect probably underestimates the feedback at low partial pressures.

Effective temperature varies with the fourth root of solar luminosity, other factors being equal, in a reduction of solar luminosity by 25% only to earth albedo corresponds to $T_e = 18°K$, which yields $T_a = 6°K$ for $T_e = 0°K$. With the parameters we have postulated, our proposed feedback mechanism cannot solve the problem of the earth's future temperature; although it reduces the magnitude of the problem considerably. Factors that may have yielded higher $CO_2$ partial pressures and, therefore, a warmer surface early in earth history include underrapid release of $CO_2$ by volcanoes and metamorphism, low land areas exposed to weathering, and less terrestrial vegetation yielding less effective greenhouse. The possible impact of the minor of these factors is illustrated by the curves for different values of $T_e$. In Figure 2, the same curves illustrate the impact of land area since cooling land area is equivalent to an increased relative rate at the present level of approximation.

Conclusion

We have attempted a qualitative evaluation of our proposed feedback mechanism in the full...
realization that our simple parametrization of the problem may be grossly in error. Existing computational schemes should permit immediate improved numerical experiments after calibrating, but more study is needed of the temperature and partial pressure dependence of the weathering rate. A model that incorporates additional variation in temperature, runoff, and exposed land area could be particularly interesting.

Regardless of inadequacies in our quantita
tive model, we feel that a working concept of a sky刊登
mechanism involving the greenhouse effect of carbon dioxide and the temperature dependence of silicate weathering is likely to be correct. In particular, the weathering rate may fall off very slowly at tempera
tures below the freezing point of water due to the cessation of normal processes of precipitation, evaporation, and runoff. The corresponding increase in the rate of consumption of carbon dioxide might well be sufficient to exert the so-called "ice catastrophe," which affects models of global energy balance in the presence of ice albedo feedback (Budyko, 1971; Sellers, 1969; Geisler, 1975; Kiehl and Schlesinger, 1979). If global glaciation were so great, the rate of albedo weathering would fall very slowly to zero, and carbon dioxide should accumulate in the atmosphere at whatever rate it is released from volcanoes. Even the present rate of volcanism would yield 1 bar of carbon dioxide in only 10 million years. The resultant large greenhouse effect could melt the ice cover in a geologi
cally short period of time.

The mechanism proposed, in which carbon dioxide pressure and consequently carbon dioxide temperature dependence of weathering are controlled by the temperature dependence of the rate of consump
tion of carbon dioxide by the weathering of silicate minerals, may impact our understanding of the evolution of the atmosphere of Mars and Venus. Such implications are not deep. It is worth noting that the mechanism may lose its force when we think that the atmosphere falls much below modern terrestrial values, as a result of increasing solar luminosity or decreasing
rate of volcanic release of carbon dioxide, and the greenhouse effect of carbon dioxide becomes negligible compared with the solar insolation. If we then consider the steady-state equilibrium of carbon dioxide as well as the steady increase of average surface temperature.

Acknowledgments. The problem that this paper addresses was brought to our attention by the work of the Pittsburgh Polychronology research Group of the University of Califomia at Los Angeles. We have received helpful advice from R. E. Dickinson, R. J. Deevey, and R. D. Smith, and we are particularly grateful to J. A. Bristow and R. S. Grubb (both
in our attention in this field of research in Vosneck. The manuscript has been approved, in part, by the National Aeronautics and Space Administration under grant NAS9-174. The National Center for Atmospheric Research is supported by the National Science Foundation.

References


(Received October 22, 1980; Revised May 21, 1981; accepted May 29, 1981.)