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On the ocean heat engine, stiffness of chaotic systems and climate prediction

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ABSTRACT

The oceans are looked on as a heat engine, and the points are made, firstly, that the effect operating this engine is modest, and, secondly, that the engine efficiency is extremely small. It is argued that a parameter, called the "thermal stiffness", generally increases when certain phenomena: new instabilities, turbulence, noise, etc., appear in thermodynamically forced systems. For the ocean system, this indicates that the temperature rise associated with the greenhouse effect may be overestimated in numerical ocean models which do not include, or do not properly resolve, such phenomena.

1. The oceans as a heat engine

An engineer looking at the oceans may compare this system to a "heat engine". This engine is fuelled by a surface heat flux as well as by mechanical energy from the overlying atmosphere, and its output is the kinetic energy associated with the general ocean circulation, which is the "flywheel" of the engine. It may also be useful for oceanographers to think in terms of such an engine: for one thing, it will focus their attention on some important overall parameters of the ocean circulation, such as the input and output powers, the stored flywheel energy, the efficiency etc. I have made some rough estimates of such "engine parameters"; the details of the underlying calculation will appear elsewhere.

Firstly, we look at the oceans as a "black box", with two inputs: the surface heat flux Q and the wind-stress $\vec{\tau}$, and a temperature variable T and the flywheel kinetic energy K as outputs. An oceanographic modeler may ask if I have forgotten the haline driving, the net evaporation, which is known to contribute essentially to the circulation, but in the "grand picture", where only the primary inputs are shown, the haline driving translates to a heat input. Latent heat transformations cause the main salinity changes and corresponding density changes of the water, and this heat component is already considered in Q.

It is not obvious how we should define Q. We may consider the total heat flux going into the ocean surface, which is mainly the incoming solar radiation, minus the reflected part; we may alternatively consider the net heat flux with outgoing long-wave radiation, etc., subtracted out. From the engineers viewpoint, the first consideration is the more correct one, since we ought to count the energy "waste", obtained in the transformation of high-quality energy (solar radiation) to low-quality energy (long-wave radiation).

The total heat taken up by the ocean is found to be of order 10^{14} KW, using an albedo of 0.15. The net heat flux going through the ocean system, entering in certain surface regions and leaving in other regions, is much smaller, of order $5 \cdot 10^{9}$ KW, possibly as high as 10^{10} KW, depending on the estimate of the wind-stress. Of course, the mechanical energy input by the wind is used more effectively than the heat, to drive the engine; it contributes essentially to ocean circulation. Water is a very ineffective medium for a thermodynamic engine (unless we bring it to boiling): we get only small density changes out of heating and cooling, and a vast amount of heat in the latent form is needed to produce the density changes associated with the salinity. It should be pointed out that it is not really the density changes, and the "buoyancy work", which create energy for the ocean circulation, although it may appear so in models using the Boussinesq approximation. In the real oceans, the net buoyancy work

$$-\frac{\partial}{\partial t}\iiint g\rho z \, \mathrm{d}V$$

is actually zero, as should be obvious if we interpret this quantity as the work associated with a vertical shift in the masspoint of the entire system. The work comes from the expansion and contraction of fluid elements at different pressures, and as the engineer knows, we can operate such an engine only by expanding at a higher pressure, and contracting at a lower pressure. An additional comment may be made here about the geothermal heating at the ocean bottom: although this is not more than about 1/1000 of the surface heating, it may not be negligible as a source for the ocean circulation, for this heat is delivered at a very high pressure, over 500 atmospheres on average.

The mechanical output of our ocean heat engine is the kinetic energy K of the ocean circulation, or the ocean "flywheel", with the main contribution coming from the upper part of the horizontal gyres. This energy (here it is an energy amount, and not a power measure) is estimated to be of order 10^{14} KWs, which is not a very impressive figure, only that which the sun contributes on the input side in 1 s. More interesting to the engineer is the power that can be drawn from this flywheel. In the real oceans, this power is taken up in dissipative processes, but, in principle, it could be utilized in some ingenious mechanical device to generate electricity, etc. This power is not easily determined, as the dissipation in the real oceans (that part associated with the large-scale gyres) is difficult to estimate. I have, however, tried to estimate the spin-down time, from which the power can be found (dividing the kinetic energy of the flywheel with this time). During a spin-down, it is not mainly kinetic energy which is used up; the main energy pool lies in the available potential energy (potential energy associated with sloping isopycnals) associated with the circulation. This potential energy is at least 100 × the kinetic energy (the factor is $(L/L_{\mathrm{d}})^2$, where L is the horizontal scale, L_{d} the internal deformation radius, see Gill, 1982). Calculation of the conversion from potential to kinetic energy is problematic, since rectifying oceans eddies may be involved, and in the end, I can only conclude that the spindown time should lie in the range from a decade to a century. This will give an output power in the range from $3 \cdot 10^7$ to $3 \cdot 10^8$ KW. In any case, we see that the engine efficiency, defined as the ratio of output to input power, is exceedingly small, less than 1/1000, if we use the net heat flux as input, and less than $1/10^6$ if we use the total heat flux. Engineers are, of course, used to efficiencies in the range of tens of percent.

We can open our "black box" shown in Fig. 1a, and look at the structure of the engine represented by the "sub-box model" with connections, as shown in Fig. 1b (this also resembles the flow-diagram a modeler may use to time-step the relevant equations). The figure should be self explanatory, and I only feel a need to comment here on the connection which runs from the T-box

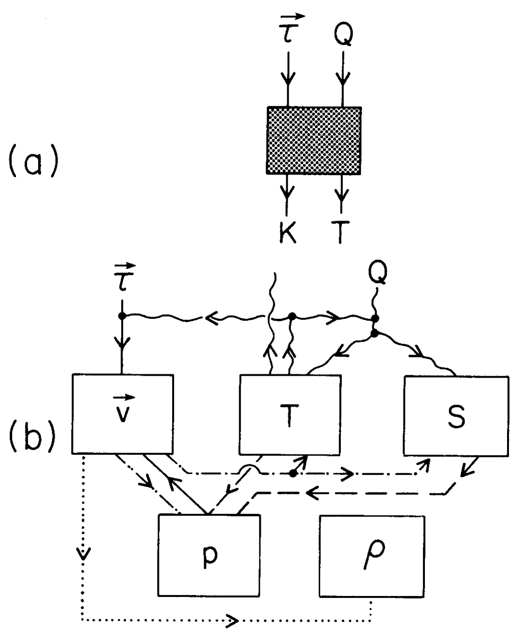

Fig. 1. (a) An ocean "black box", with the surface heat flux Q and the wind-stess as inputs, and a temperature variable T and the energy of the "flywheel" K as outputs. (b) Structure of the ocean heat engine in a physically complete (acoustic) mode. The box variables are current velocity $\vec{v}$, pressure p, temperature T, salinity S, and density ρ; the inputs are again a surface heat flux Q and the wind-stress $\vec{\tau}$. The connections are marked as follows: dynamics —→—, state equation ——→—, advection and diffusion —·→·—, continuity ··>···, thermal inputs and feedbacks , —··→—·· pressure effect from sea level (integrated vertical surface velocity).

to the input lines, and the open-ended connection, which disappears in the atmosphere. The first connection represents the boundary layer feedback from the ocean surface temperature: the wind-stress and heat flux change with the ocean surface temperature, as, for example, is expressed through the "bulk formulas". The open-ended connection is meant to represent a long-range feedback, the "teleconnections", which run through the atmosphere on a global scale, and which in the end also couples back to the surface fluxes. The feedbacks mentioned are believed to be important for the variability of the ocean-atmosphere on the inter-annual time scales, and contribute to such phenomenon as the El Niño/Southern Oscillation. It is noticed that the concept of input functions with feedbacks is lost if we take the really "grand look" at the ocean and atmosphere, and consider these as part of a single thermodynamic engine, driven by solar radiation. The inputs Q and τ then become internally determined variables and all that we can require is that they should have matching values from the oceanic and atmospheric sides.

2. Simplified thermodynamic engines, and the stiffness parameter

In this section, we will consider an entire family of thermodynamic engines, in the form of "fluid loops", or interconnected "fluid boxes", driven by external heat sources and sinks. Examples of such engines can be found in a review paper (Welander, 1986); apart from my own studies, I would like to mention works on some systems of this type done by Claes Rooth and Henry Stommel, to which references are given in Welander (1986).

We will be looking for some common features of this family of engines, and, in particular, the temperature response in some part of the system when we change the heat input from one steady value to another. We put such an engine in our "black box" and carry out the following experiment. A steady thermal input signal x_i (for example, a steady heat flux) is applied; we let the system settle down, and then measure the steady or statistically steady output signal $\bar{x}_0$ (for example, a temperature or temperature difference resulting from the thermal forcing). The experiment is then repeated for a slightly changed steady input, and a new quantity S, which I have called the "thermal stiffness" of the system, is defined:

$$S = \left| \frac{\partial \bar{x}_0}{\partial x_i} \right|^{-1}.$$

A small stiffness obviously means a strong response, and a large stiffness a weak response, when the input value is changed. Before stating a general rule regarding the thermal stiffness, which I believe holds for èngines in the defined family, it may be of value to work out a specific example. The example chosen is a circular fluid loop placed in a vertical plane and subjected to a given heat flux vertically as well as horizontally (see Fig. 2). The system has inertia and frictional and thermal dissipation, described by a Rayleigh law. This is a variant of a thermal oscillator studied first by the author (Welander, 1967), which has been explored in some detail by Louis Howard and Willem Malkus (see, for example, Maulkus, 1972). The system is governed by three ordinary differential equations of the so-called "Lorenz type":

$$\dot{x} + \omega y + \varepsilon x = Q_0, \tag{1}$$

$$\dot{y} - \omega x + \varepsilon y = Q_1, \tag{2}$$

$$\dot{\omega} + r\omega = ay, \tag{3}$$

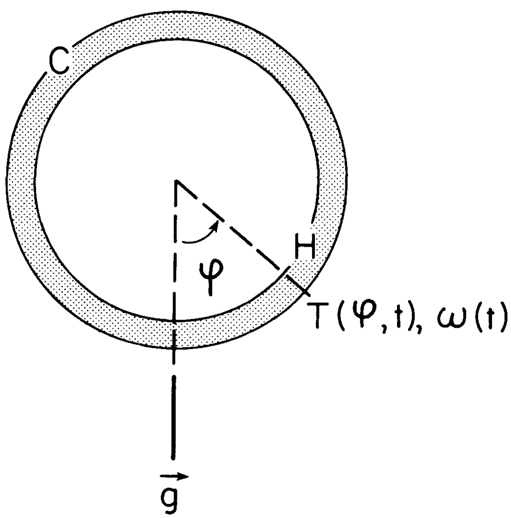

Fig. 2. The circular Howard-Malkus loop, described by eqs. (1, 2, 3) in the text. The loop sits in a vertical plane, heat is added or removed at given rate along the loop. See text for further details.

where $x = \oint T \cos \varphi \, d\varphi$, $y = \oint T \sin \varphi \, d\varphi$ are two temperature variable and $\omega = \dot{\varphi}$ is the angular velocity of the fluid, all being functions of time alone. Further, $Q_0 = \oint Q \cos \varphi \, d\varphi$, $Q_1 = \oint Q \sin \varphi \, d\varphi$ are the heat fluxes applied vertically and horizontally, respectively. The constant a, r and ε describe the torque coupling (y represents a buoyancy torque which accelerates the loop), the frictional dissipation and the thermal dissipation, respectively.

The system has a steady state with warm fluid rising on the right side and cold fluid sinking on the left side, assuming Q_0 and Q_1 positive; for small forcing, the steady solution is

$$x = \frac{Q_0}{\varepsilon}, \qquad y = \frac{Q_1}{\varepsilon}, \qquad \omega = \frac{aQ_1}{r\varepsilon}.$$

For larger forcing, the steady solution is obtained by solving a cubic equation, which results from eqs. (1, 2, 3) when $\dot{x} = \dot{y} = \dot{\omega} = 0$. Above a critical amplitude for the forcing, the steady solution may be unstable, and the system may eventually settle down into a chaotic behavior.

We will assume a constant ratio between Q_1 and Q_0 and use Q_1 as our input variable, y as our output variable, defining the thermal stiffness as

$$S = \left| \frac{\partial \bar{y}}{\partial Q_1} \right|^{-1}.$$

We calculate $\bar{y}$ as function of Q_1 in two situations: (a) the analytically calculated steady state, and (b) the numerically calculated statistically steady state, which differs from the steady state when the instabilities are free to develop. The resulting curves are shown in Fig. 3. From the figure, we find the stiffness as the inverse slope (the slope measured from the $\bar{y}$-axis). It is seen that the two curves start to differ when Q_1 is above a certain critical value, and that the instabilities which develop act to increase the stiffness. I have come to the conclusion that such behavior of the thermal stiffness is not a special result for the system described here, but a characteristic of the entire family of "thermodynamic engines." New instabilities have the effect of increasing the stiffness in the definition given. (It is, however, not to be seen as an absolute law, since I have been able to theoretically construct a special heat engine, of the self-oscillating type, in which the temperature responds more strongly when instabilities develop.) Finally, it is believed that the qualitative behavior of the stiffness, as described here, also applies to more complex thermally forced systems, and in particular, to the coupled ocean-atmosphere system.

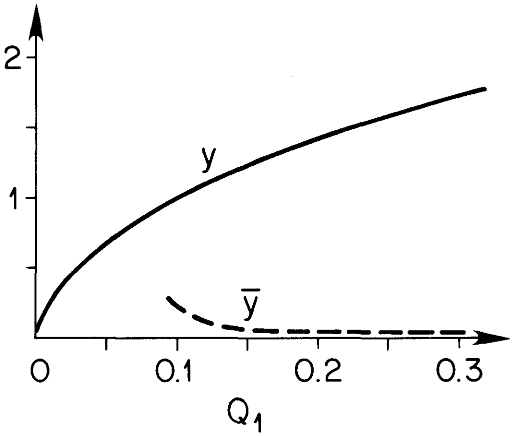

Fig. 3. The steady state (full drawn curve) and statistical steady state (dashed curve) as a function of Q_1 in a numerical example, calculated from eqs. (1, 2, 3). Parameter values (non-dimensional): $Q_1/Q_0 = 0.1$, $a = r = 1$, $\varepsilon = 0.2$. The dashed curve has a "fine structure", which is not shown in the figure, due to the appearance of successive instabilities. See text for further details.

3. Comments on the problem of global warming

The thermal stiffness of the ocean-atmosphere system is a relevant parameter when considering the problem of global warming: we want to know the change in temperature at some location, or the changes in global mean temperature, when the thermal input is modified by presence of "greenhouse gases". Numerical models have been used to hindcast as well as predict the warming which should be a consequence of adding such gases to the atmosphere. With regard to the warming which already may have taken place, from, say, 1850 to 1990, the calculated values for the increase in global mean temperature is about 1°C (range from 0.5° to 1.5°, see, for example, Jones and Wigley, 1990). However, the data do not indicate a warming of more than 0.5°C, and at present it seems impossible to determine whether this change is part of the natural climatic variability or caused by the greenhouse gases. It has been argued by some atmospheric scientists (for example, Richard Lindzen at MIT) that the numerical models may overestimate the warming due to greenhouse gases because certain negative feedbacks in the atmosphere are left out. Since most natural feedbacks have a dampening rather than amplifying effect, this point may be a valid one. One may, however, also explain a possible "over-prediction" of the global warming by the numerical models in terms of the rule about thermal stiffness discussed in Section 2. If some processes involving new instabilities are left out, the models are likely to underestimate the thermal stiffness of the ocean-atmosphere system, i.e., the global warming is likely to be overestimated. If this is true, we ought to find less global warming predicted as the numerical models become further developed, allowing finer resolution and bringing in new processes which can contribute to new instabilities; thus the idea can be tested within the framework of model calculations alone.

The track record of the large numerical ocean atmosphere models, with regard to hindcasting or predicting climatic variations, does not appear to be a good one. Maybe the modelers have become overconfident after having success in simulating the present climatic state. There has, of course, been some "tuning" of the models to obtain the wanted result, and this may show up in an unfavorable way when it comes to predicting new climatic states, where we go from a point calculation in parameter space to a calculation involving derivatives in this space. A pessimist may feel that the problem of climate prediction today is at the same stage as weather prediction in days gone by, when "the same weather as today" was the best prediction for tomorrow. If real trends in climate are observed, one may go from there to a trend-following prediction, or possibly some more sophisticated prediction based on time-series analysis. At this time, it appears to this author that the problem of climate prediction may fare best in the hands of mathematicians and statisticians. Of course, one expects that the physical modelers will eventually catch up, but this may not happen until we understand better which processes are critical for climate variability. The availability of larger and faster computers will not alone take care of the problem: the key will lie in our improved physical understanding of the exceedingly complex system represented by the coupled ocean atmosphere "heat engine".

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