Homoclinic bifurcation in an ocean circulation box model

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ABSTRACT

The qualitative behaviour of a conceptual ocean box model is investigated. It is a paradigmatic model of the thermohaline ocean circulation of the Atlantic. In a bifurcation study, the two occurring bifurcations, a saddle-node and a Hopf bifurcation, are computed analytically. Using normal form theory, it is shown that the latter bifurcation is always subcritical. The unstable periodic orbit emerging at the Hopf bifurcation vanishes in a homoclinic bifurcation. The results are interpreted with respect to the stability of the thermohaline circulation.

1. Introduction

The thermohaline circulation (THC) of the Atlantic is a deep ocean circulation driven by the density difference between the South (lower) and North Atlantic (higher density) [Rahmstorf, 1996]. Warm, salty water masses from tropical latitudes flow towards the North Atlantic. There, the sea surface is cooled until the stratification of the water column becomes unstable in winter and deep convection events occur. The deep, cold water masses that are formed there flow back towards the South Atlantic at a depth of 2-3 km. The THC can be considered as a conveyor belt which accounts for a large heat transport towards the northern North Atlantic. It warms the western European climate by around 5 K compared to the mean temperature of the northern midlatitudes. A review on the THC can be found in [Weaver and Hughes 1992] and [Rahmstorf, 2000].

Since more than a decade, the present circulation system of the THC is supposed to have at least two stable states [Broecker *et al.*, 1985] – a warm mode (the present one) with strong northern sinking, and a cold mode with weak overturning. Some climate scenarios with CO_2-doubling (compared to pre-industrial levels) show a decrease of the THC within the next century [Stouffer and Manabe, 1999]. The decrease is due to increased freshwater import into the North Atlantic in climate warming scenarios. With respect to future climate change, it is important to study transition mechanisms of the THC.

Ocean circulation is modelled in a hierarchy of models, that is the models vary from simple conceptual models [Stommel, 1961], [Rooth, 1982], [Tziperman *et al.*, 1994] to highly complex general circulation models with some thousand degrees of freedom [Stouffer and Manabe, 1999], [Tziperman, 2000]. Whereas the latter yield the most realistic simulations, conceptual models help to understand underlying mechanisms of the circulation system and to interpret results of more complex models. In our study with a simple ocean box model, we analyze the qualitative behaviour of the THC in the Atlantic. In these simple models, the THC is a bistable system due to the nonlinear advection terms. Most conceptual models exhibit two stable states which correspond to the warm and the cold mode of the THC. In many conceptual box models a saddle-node bifurcation was found to be responsible for the breakdown of the THC. The simplest model can be found in [Stommel, 1961].

In our study, the qualitative behaviour of a simple conceptual model of the interhemispheric THC is investigated. The freshwater fluxes are the main parameters. The model we use was designed to mimic the THC of the Atlantic and consists of two ordinary differential equations describing the dynamical behaviour of the ocean's salt content.

In Sec. 2 the conceptual model we use is described and an analytical bifurcation study is done. For changing freshwater fluxes two bifurcation points are found – a saddle node bifurcation and a Hopf bifurcation. They correspond to different mechanisms how the THC can become unstable. The Hopf bifurcation found is studied in more detail in Sec. 3. Using normal form theory it is shown that the Hopf bifurcation is always subcritical leading to an unstable periodic motion. Thus, there are no stable periodic solutions in this model at all. The unstable periodic orbit emerging at the Hopf bifurcation ends in a homoclinic bifurcation which is studied in Sec. 4. The last Sec. is devoted to conclusions and a final discussion of the results.

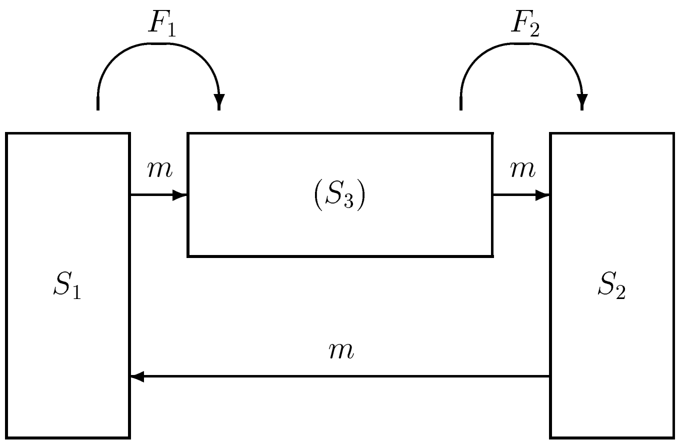

Figure 1: Sketch of the ocean circulation box model. S_1 and S_2 are the free variables of the system.

2. The Ocean Circulation Box Model

2.1 Description

The dynamical system we analyze is a paradigmatic ocean circulation box model covering the large-scale behaviour of the THC. It is based on a more complex 4-box model [Rahmstorf, 1996] and was derived by reduction of the degrees of freedom without changing its qualitative behaviour (see *2.2*).

The model (Fig. 1) is set up as follows: Three boxes of homogeneous salt content represent the deep mixed water columns of the South (box 1) and North Atlantic (box 2) and the upper layer of the tropics (box 3). The box temperatures T_i ($i = 1, 2, 3$) are set to be constant as ocean temperatures are much faster restored to atmospheric temperatures than salt contents change. Each box has the same volume V.

All physical processes in the ocean involved in freshwater transport (except the THC) are represented by the freshwater fluxes F_1 and F_2. This non-THC freshwater transport is performed both by wind driven circulation systems and water vapour transport in the atmosphere.

The dependence of the THC overturning rate on the density difference in the Atlantic is non-trivial. Some authors refer to the classical scaling argument using the thermal wind equation. They find that the overturning rate is proportional to $(\Delta\rho)^{1/3}$. The scaling argument can be applied for a zonal flow, but the continental boundaries induce a secondary meridional flow which is not explained by the scaling argument (sea Rahmstorf [1996] for a discussion). From simulation runs with ocean general circulation models [Rahmstorf, 1996], it can be seen that the overturning rate m is proportional to the density difference between North and South Atlantic:

$$\begin{aligned} m &= k\,(\rho_{\text{North}} - \rho_{\text{South}}) \\ &= k\,(\beta\,(S_2 - S_1) - \alpha T^*), \quad \text{with } T^* = T_{2,\text{const}} - T_{1,\text{const}} \end{aligned} \tag{1}$$

The constants α and β are expansion coefficients for temperature and salt content respectively. The parameter k can be considered as a hydraulic constant and is tunable. We use a linear density equation here that depends on temperature T and salt content S with a reference density ρ_0:

$$\rho = \rho_0 - \alpha T + \beta S \tag{2}$$

The salt content of the three boxes is conserved, that is $S_3 = S_{\text{const}} - S_1 - S_2$. Thus, the dynamical equations read:

$$\dot{S}_1 = \frac{1}{V}\,S_{\text{ref}}F_1 + \frac{1}{V}\,m\,(S_2 - S_1) \tag{3}$$

$$\dot{S}_2 = -\frac{1}{V}\,S_{\text{ref}}F_2 + \frac{1}{V}\,m\,(S_3 - S_2) \tag{4}$$

S_{ref} is a reference salt content which converts the freshwater flux into a salt flux. The following standard parameter values are used: $F_2 = 0.17$ Sv (Sverdrup, a common unit in oceanography: 1 Sv $= 1\times10^6$ m^3 s^{-1}), $S_{\mathrm{ref}} = 35$ psu (practical salinity units), $\alpha = 0.00017$, $\beta = 0.0008$, $k = 23 \times 10^{17}$ m^3 yr^{-1}, $V = 10^{17}$ m^3, $T^* = -2$ K.

2.2 Bifurcation Study

The freshwater flux F_1 is an important bifurcation parameter of this system. It has been changing during climate history and might change with further climate warming [Rahmstorf and Ganopolski, 1999]. Increasing precipitation over the Atlantic or its runoff basin (while evaporation and wind driven transports do not change) would be represented by increasing F_1.

From numerical bifurcation analysis of the more complex model [Rahmstorf, 1996], it is found that, if the control parameter F_1 is varied, both a saddle-node bifurcation and a subcritical Hopf bifurcation corresponding to the emergence of an unstable periodic orbit can occur in the model. In order to compute the bifurcations analytically, we reduce the model's complexity without changing its bifurcation behaviour and end up in the "minimal" box model studied here.

In the following, analytical solutions for the bifurcations in this minimal box model are derived. Here, only solutions for a circulation cell in northward direction are shown. If a circulation in the opposite direction were to be considered, the advection terms would have to be reformulated.

At first, a transformation of the variables is performed to make further calculations easier:

$$\hat{S}_1 = S_1$$

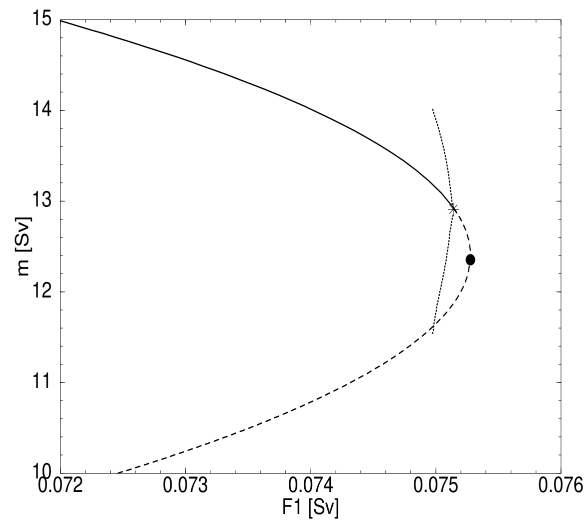

Figure 2: Bifurcation diagram: The Hopf bifurcation (star) destabilizes the THC; at the saddle-node bifurcation (circle), the steady state remains unstable (dashed). The minimum and maximum overturning rate m of the unstable cycle are the dotted lines.

$$\hat{S}_2 = S_2 - S_1$$

Now, the stationary state $\hat{S}_{\mathrm{s,i}}$ (with stationary overturning rate m) in the new variables is computed:

$$\hat{S}_{\mathrm{s,1}} = \frac{1}{3}\left(S_{\mathrm{const}} - \frac{S_{\mathrm{ref}}\,(F_1 + F_2)}{k(\beta\hat{S}_2 - \alpha T^*)}\right) - \hat{S}_{\mathrm{s,2}} \tag{5}$$

$$\hat{S}_{\mathrm{s,2}} = \frac{\alpha T^*}{2\beta} \pm \sqrt{\left(\frac{\alpha T^*}{2\beta}\right)^2 - \frac{S_{\mathrm{ref}} F_1}{k\beta}} \tag{6}$$

Fig. (2) shows the corresponding stationary overturning rate m as a function of the southern freshwater flux F_1. There are two bifurcation points on the parabola which are computed in the following. The stable steady state becomes unstable at a Hopf bifurcation and remains unstable at the subsequent saddle-node bifurcation. In the first ocean box model invented by Stommel [Stommel, 1961], there is only

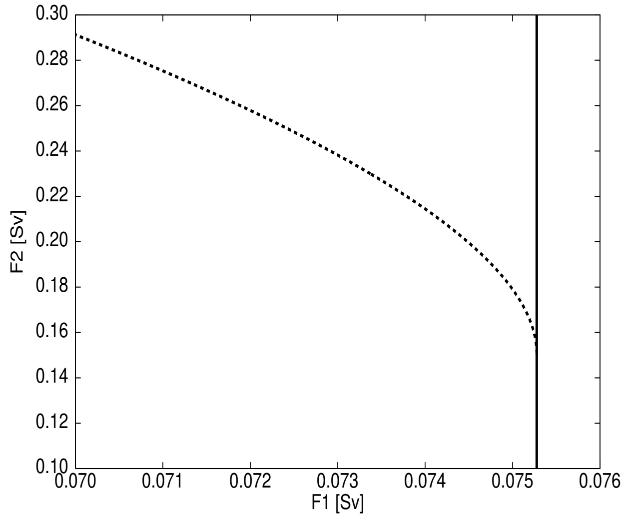

Figure 3: 2-parameter bifurcation diagram. Dotted: Hopf bifurcation; solid: saddle-node bifurcation.

a saddle-node bifurcation whereas in other box models (with at least 3 boxes) the Hopf bifurcation was found, too [Scott *et al.*, 1999], [Tziperman *et al.*, 1994].

Linear stability analysis yields the eigenvalues of the system:

$$\lambda_{1,2} = A \pm \sqrt{A^2 - 3\frac{1}{V^2}\,km\,(2\beta\hat{S}_{s,2} - \alpha T^*)} \qquad \text{with} \tag{7}$$

$$A = \frac{1}{2V}\left(k\beta\left(S_{\text{const}} - 3(\hat{S}_{s,1} + 2\hat{S}_{s,2})\right) + 3k\alpha T^*\right) \tag{8}$$

Saddle-node bifurcations may only occur if one real eigenvalue crosses the imaginary axis. This yields the condition

$$F_1 = \frac{k\alpha^2}{4\beta S_{\text{ref}}}\,T^{*2}\,. \tag{9}$$

Hopf bifurcations occur when two complex-conjugate eigenvalues cross the imaginary axis. Thus, the necessary condition is $A = 0$. Therefore, we can compute F_1 as a function of the other parameters:

$$F_1 = \frac{C}{S_{\mathrm{ref}}} \pm \frac{1}{S_{\mathrm{ref}}}\sqrt{C^2 + S_{\mathrm{ref}}F_2\frac{3\,\frac{\alpha^2}{\beta}kT^{*2} - S_{\mathrm{ref}}F_2}{16}} \qquad \text{with} \tag{10}$$

$$C = \frac{3}{32}\frac{\alpha^2}{\beta}kT^{*2} - \frac{1}{4}S_{\mathrm{ref}}F_2$$

Only a part of the curve described by (10) refers to a Hopf bifurcation. Of course, the eigenvalues have to be purely imaginary, that is, the radicand in (7) has to be negative. This is the case for a positive sign of the square root in (10) in addition to the fact that the curve ends in the Takens-Bogdanov point, where the two bifurcation points meet:

$$T^* = -\sqrt{\frac{2\beta}{k\alpha^2}S_{\mathrm{ref}}F_2} \tag{11}$$

In Fig. 2, it is shown that the stable steady state becomes unstable at the Hopf bifurcation whereas the subsequent saddle-node bifurcation does not change the stability of the steady state. For values of F_1 smaller than the Hopf bifurcation value $F_{1,\mathrm{Hopf}}$, the system is bistable. The second attractor of the system is infinity. This is, of course, an unphysical behaviour. It is due to the advection terms in the ODE system (3-4). The second attractor of the physical system is a weak THC in the opposite direction (that is from box 2 to box 3 to box 1 to box 2). If the physical system is to be described in a correct way, the advection terms should be substituted when the overturning rate m becomes negative. Here, for mathematical consistency, we do not change the system.

The 2-parameter bifurcation diagram Fig. 3 shows the two curves of the bifurcation points and the Takens-Bogdanov point. It is interesting to note that only the Hopf bifurcation depends on both freshwater fluxes. The Takens-Bogdanov point can be interpreted as the minimum F_2 value for the Hopf bifurcation. The latter is always subcritical as will be shown in Sec. 3.

These results clearly show that there are two possible mechanisms that can destabilize the THC: the Hopf and the saddle-node bifurcation. These mechanisms are different in nature: whereas for the saddle-node bifurcation it is simply the advective feedback which is weakened by increased freshwater import into the Atlantic basin, the Hopf bifurcation results from the two freshwater fluxes yielding an unstable oscillation of the overturning rate.

Located on the stable part of the parabola in Fig. 2 but near the Hopf bifurcation, the THC can be destabilized by very small perturbations as the boundary of the basin of attraction is identical with the unstable periodic orbit emerging at the Hopf bifurcation point (sea Sec. 4).

3. Subcritical Hopf Bifurcation Using Normal Form Theory

It makes a big difference whether the Hopf bifurcation is super- or subcritical. The emerging periodic orbit is a stable or unstable one, that is, periodicity of the real ocean on a similar time scale of the THC which can be deduced from paleoclimatic proxy data [Stocker and Mysak, 1992] can or cannot be explained by such a box model. Whether a Hopf bifurcation is sub- or supercritical can analytically be determined using normal form theory. After a transformation of the system variables $(S_1, S_2) \longrightarrow (z_1, z_2)$ so that the stationary state is in (0,0), the variables (z_1, z_2) must further be transformed in a specific way; $(z_1, z_2) \longrightarrow (x, y)$. If the linear operator for the old variables (z_1, z_2) is B (with complex-conjugate eigenvalues $\pm\, i\, \omega$) and T is the transformation matrix, the linear operator Ω for the new variables (x, y) will read at the Hopf bifurcation point:

$$\Omega = T^{-1} B T \qquad \text{with} \quad \Omega = \begin{pmatrix} 0 & -\omega \\ \omega & 0 \end{pmatrix}$$

After the linear transformation of the variables, the system reads as follows:

$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \begin{pmatrix} 0 & -\omega \\ \omega & 0 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} f(x,y) \\ g(x,y) \end{pmatrix} \tag{12}$$

The functions f and g are nonlinear functions which can be expanded in polynomials at the Hopf bifurcation. The general problem can be transformed to the following form [Guckenheimer and Holmes, 1983]:

$$\dot{x} = (d\mu + a\,(x^2 + y^2))\,x - (\omega + c\mu + b\,(x^2 + y^2))\,y \tag{13}$$

$$\dot{y} = (\omega + c\mu + b\,(x^2 + y^2))\,x + (d\mu + a\,(x^2 + y^2))\,y \tag{14}$$

To determine the characteristics of the Hopf bifurcation one has to compute the coefficients in front of the nonlinearities in the polynomials. Now, the coefficient a can be calculated. The sign of a decides whether the Hopf bifurcation is subcritical or supercritical. We use the formula on p. 152 of Guckenheimer and Holmes [1983] for the coefficient a after the normal form transformation for any ODE system like (12):

$$a = \frac{1}{16\omega}(f_{xy}(f_{xx} + f_{yy}) - g_{xy}(g_{xx} + g_{yy}) - f_{xx}g_{xx} + f_{yy}g_{yy}) \tag{15}$$

Here, the terms with triple differentiation are omitted as they are zero in our case.

The resulting Eq. $a = a(F_1(F_2), T^*)$ is tested numerically for reasonable intervals of F_1, F_2 and T^* whether a remains positive. As this is the case (Fig. 4), we

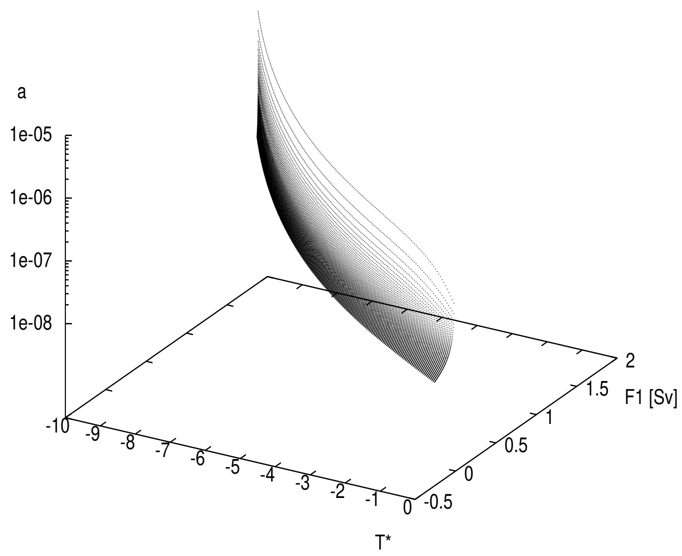

Figure 4: The coefficient a remains positive for large intervals of the important system parameters (-10 K$< T^* < 0$ K; F_2 starting at the Takens-Bogdanov point, increasing by up to 1 Sv; F_1 is a function of F_2, here).

can conclude that the Hopf bifurcation is subcritical for very large intervals of the system parameters, in particular for those parameter intervals which are relevant in oceanography.

Although the THC may be destabilized by a Hopf bifurcation, stable periodic solutions never occur in this conceptual model. Thus, the variability of the real ocean deduced from the analysis of paleoclimatic proxy data cannot be explained in the framework of this simple conceptual box model. Furthermore, this result indicates the following: if the THC became unstable at a Hopf bifurcation in a high-dimensional ocean circulation model, it would be difficult to discover. Neither the bifurcation point itself nor the unstable periodic orbit were easily found.

Only if stochastic fluctuations are taken into account, the influence of the oscillation behaviour around the stationary overturning becomes visible.

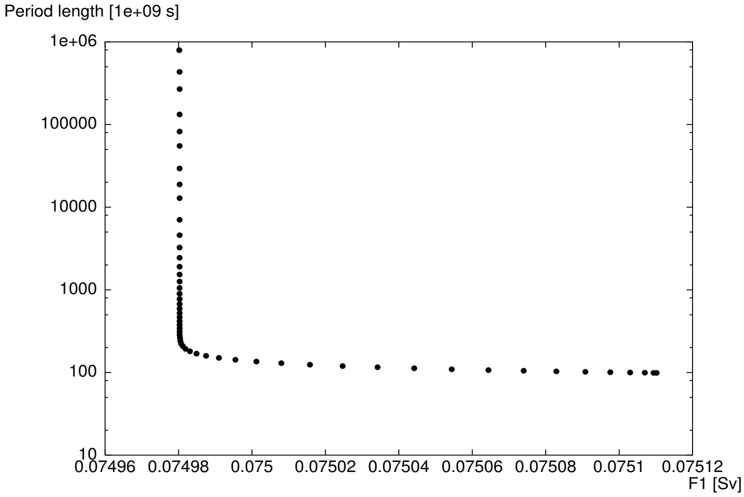

Figure 5: Period length of the unstable orbit. $F_2 = 0.17$ Sv.

4. Homoclinic Bifurcation of the Unstable Periodic Orbit

At the Hopf bifurcation, an unstable periodic orbit emerges. In this two-dimensional model, the periodic orbit is the boundary of the basin of attraction which belongs to the stable steady state (warm mode of the THC). Thus, from an oceanographic point of view, it is interesting to know how the unstable periodic orbit (and thus the basin of attraction) changes in parameter space. Disturbances of the salt contents beyond the basin of attraction would destabilize the THC and switch the system's behaviour to the cold mode of the THC. With bifurcation analysis software [Champneys, 1995], [Doedel *et al.*, 1991], the orbit can be followed until it vanishes in a homoclinic bifurcation. There, the unstable periodic orbit collides with the unstable fixed point, a saddle point, yielding a homoclinic loop. Numerically, it can be found that the period length of the unstable periodic orbit increases towards infinity when the orbit aproaches the homoclinic bifurcation (Fig. 5). The homoclinic orbit can be approximated numerically (Fig. 6).

When the unstable periodic orbit has vanished, the basin of attraction of the stable warm mode is no longer closed.

The homoclinic bifurcation is difficult to interpret in an oceanographic sense. As mentioned in the previous Sec., the unstable periodic orbit is identical with the boundary of the basin of attraction that belongs to the stable fixed point, and as the basin is not very large, even small perturbations may destabilize the THC. With F_1 values smaller than the value of the homoclinic bifurcation, the basin is no longer closed and the chance of destabilizing the THC by perturbations is smaller. We can conclude, that the THC enters a critical regime with F_1 values in between the homoclinic and the Hopf bifurcation.

5. Conclusions

With this simple conceptual box model of the thermohaline circulation we could show that two different bifurcations may lead to transitions of the present-day circulation: a Hopf or a saddle-node bifurcation. The analytic expressions for the bifurcations are deduced so that the dependence on the parameters is clarified. The mechanisms responsible for the breakdown of the THC at these bifurcation points clearly differ in nature: an increasing freshwater import into the Atlantic basin weakens the advective feedback and leads to a saddle-node bifurcation. On the other hand, a combined change of the hemispheric freshwater fluxes (an increase) can yield a subcritical Hopf bifurcation where an unstable periodic orbit emerges. Only the latter bifurcation depends on both freshwater fluxes. When the THC is stable but close to the Hopf bifurcation, it can be destabilized by rather small perturbations since the boundary of the basin of attraction is identical with the unstable periodic orbit emerging at the Hopf bifurcation.

With the help of normal form theory it is shown that the emerging periodic orbit of the Hopf bifurcation is always unstable. At first, this means that variability of

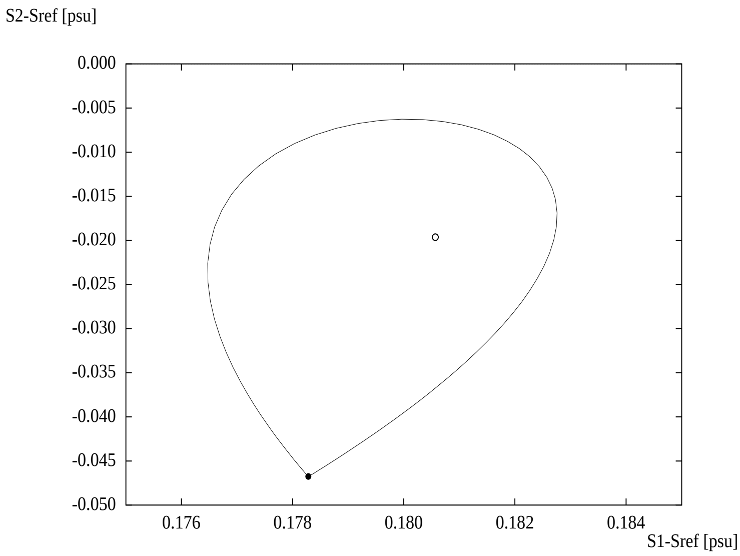

Figure 6: Homoclinic orbit, unstable steady state (filled circle) and stable steady state (empty circle). $F_1 = 0.07498$ Sv, $F_2 = 0.17$ Sv.

the THC on the scale of the Atlantic (deduced from paleoclimatic proxy data or found in simulations with ocean general circulation models) cannot be explained by the unstable periodic orbit found in this box model. Second, if the THC in more complex ocean circulation models became unstable at a subcritical Hopf bifurcation, it would be difficult to find out that it is a Hopf bifurcation since there is no stable periodic solution the THC converges to.

The unstable periodic solution emerging in the Hopf bifurcation is shown to end in a homoclinic bifurcation. Numerically, the homoclinic orbit is approximated. The homoclinic bifurcation is difficult to interpret with respect to the oceanographic application. A critical THC regime in between the homoclinic and Hopf bifurcation can be defined where the THC is easily shut down by small salt content disturbations.

This study shows that based on a simple model valuable information about the sensitivity of the THC can be deduced using techniques from the theory of Nonlinear Dynamics as bifurcation analysis and normal form theory. Especially, mechanisms and reasons for a possible state transition can be clarified.

Acknowledgements.

The authors wish to thank Wolfgang Jansen for help with the bifurcation analysis software. This work was supported by the Deutsche Forschungsgemeinschaft (Sfb 555 and Heisenberg program).

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Figure Captions

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Figure 3: 2-parameter bifurcation diagram. Dotted: Hopf bifurcation; solid: saddle-node bifurcation.

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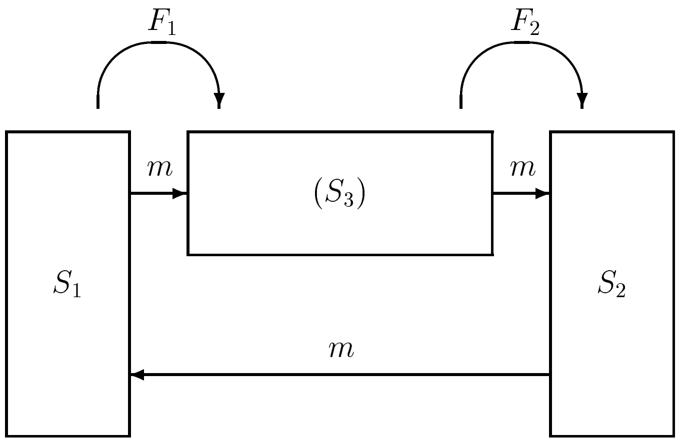

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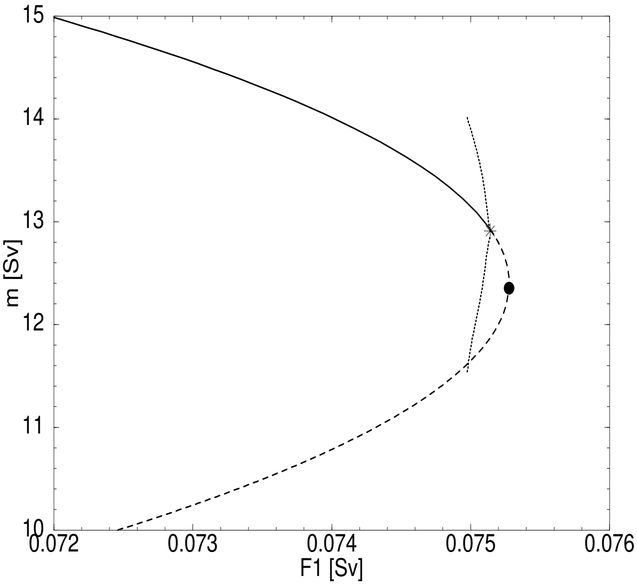

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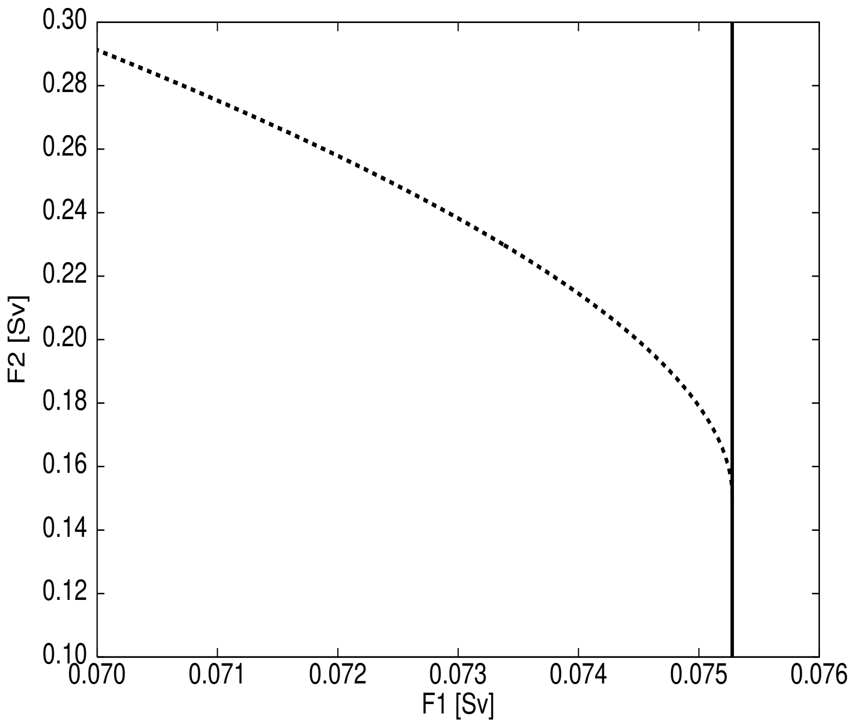
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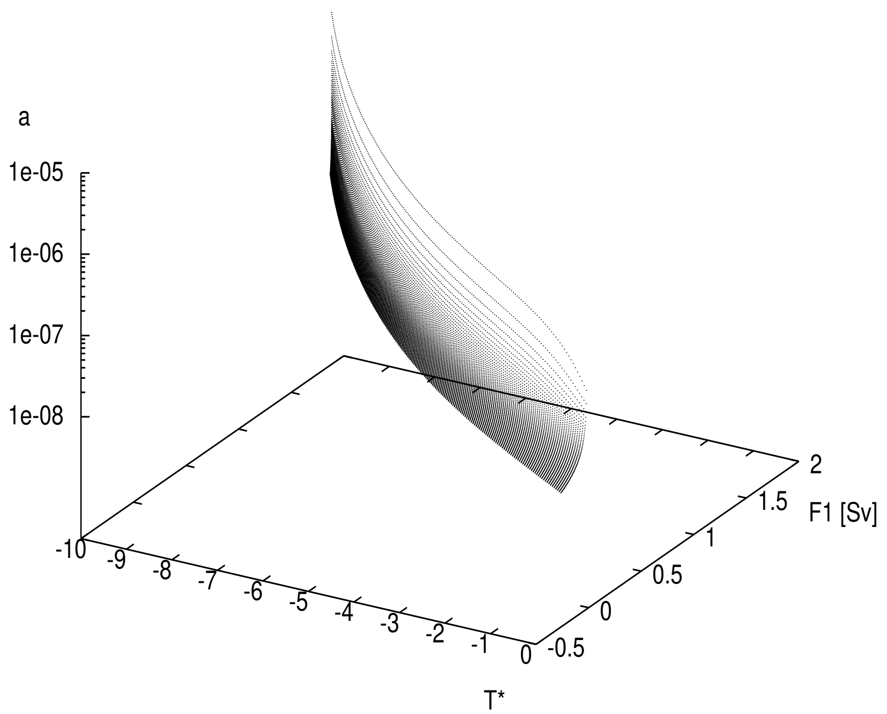
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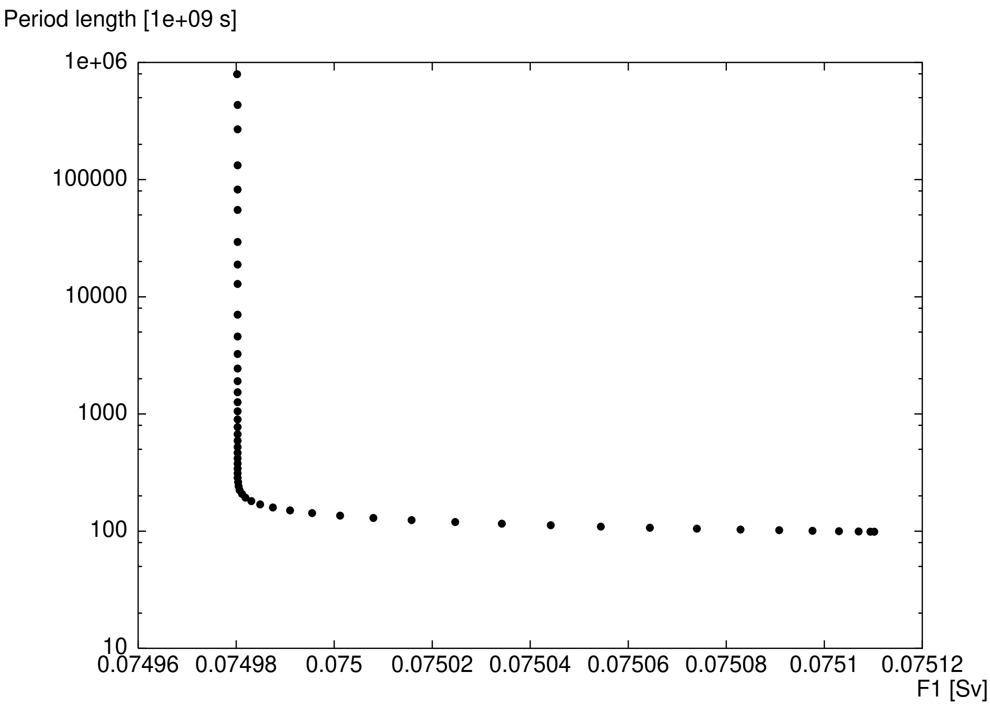
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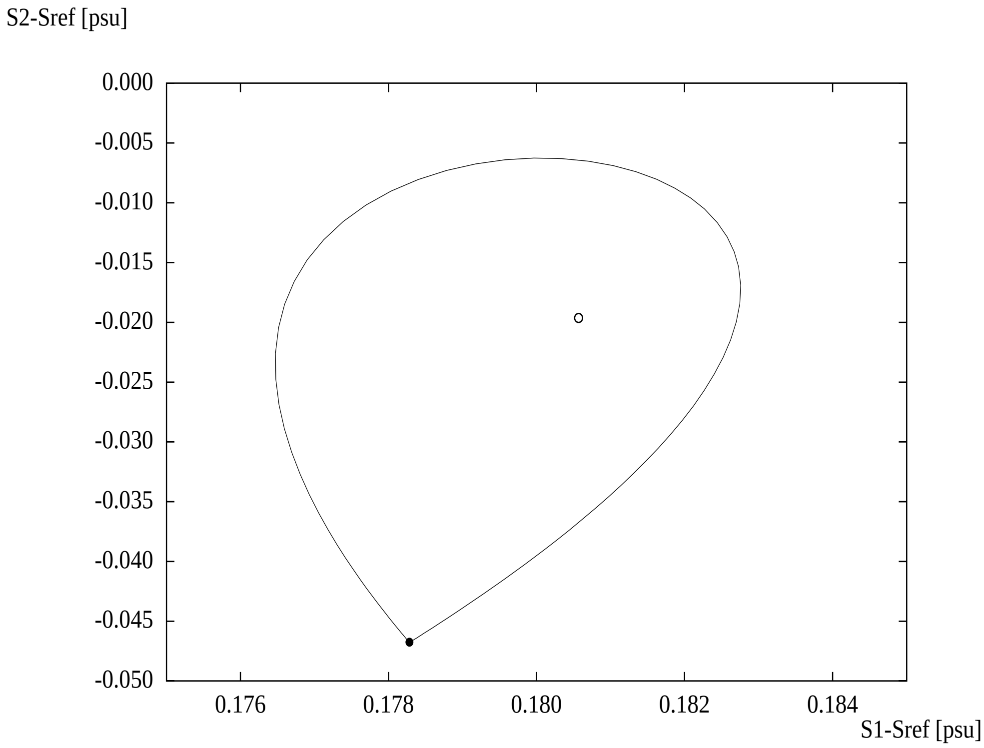
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