Reply

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ABSTRACT

The comment by Rahmstorf suggests that a numerical problem in Tziperman et al. (1994, TTFB) leads to a noisy $E - P$ field that invalidates TTFB's conclusions. The authors eliminate the noise, caused by the Fourier filtering used in the model, and show that TTFB's conclusions are still valid. Rahmstorf questions whether a critical value in the freshwater forcing separates TTFB's stable and unstable runs. By TTFB's original definition, the unstable runs in both TTFB and in Rahmstorf's comment have most definitely crossed a stability transition point upon switching to mixed boundary conditions. Rahmstorf finally suggests that the instability mechanism active in TTFB is a fast convective mechanism, not the slow advective mechanism proposed in TTFB. The authors show that the timescale of the instability is, in fact, consistent with the advective mechanism.

1. Introduction

In an effort to simulate the air–sea interaction process, modelers often employ "mixed boundary conditions." This involves the use of restored surface temperatures (usually to observed SST) and fixed freshwater fluxes. Hence, in mixed b.c., like in the real system, there is a direct feedback between SST and air–sea heat flux but no feedback between the freshwater flux and the surface salinity. The freshwater flux used in mixed b.c. is usually diagnosed from a steady-state solution of the same model, run out to equilibrium with salinity restoring (the spinup phase).

In the last few years a number of papers have been written on the stability of the thermohaline circulation (THC) as simulated in ocean-only models using mixed boundary conditions. Some of these studies have reported most interesting dynamical behaviors such as THC collapses or initial instabilities followed by strong oscillations. These strongly unstable behaviors might be relevant for explaining large paleoclimatic fluctuations but probably are not relevant to present day climate variability considering that the ocean–atmosphere system seems to be quite stable at present. It seems likely to us that at least some of these strongly unstable behaviors are caused by the use of idealized ocean GCMs that are not in a realistic parameter regime for today's climate.

In order to investigate this possibility, we (Tziperman et al. 1994, hereafter TTFB) examined the stability of the thermohaline circulation using a realistic-geometry primitive equation ocean GCM. We found that carefully formulated mixed boundary conditions lead to a circulation that is stable, as the real ocean appears to be. This was our main goal and our main conclusion. We showed that the development of THC instabilities is dependent on the strength of the freshwater forcing as determined by the time constant used to restore surface salinities in the spinup phase. A salt flux field (implied $E - P$) produced with a relatively strong restoring constant ($1/30$ day^{-1}) causes the THC to be unstable, while a flux field produced with a weaker restoring constant ($1/120$ day^{-1}) allows the overturning to remain completely stable. Both flux fields provide net freshening in the latitude band where sinking occurs in the North Atlantic. However, the flux field derived with the strong restoring constant contains substantially more net freshening, equivalent to an extra 0.7–0.8 m yr^{-1} of fresh water at 60° and 64°N.

The model solutions derived with $1/30$ day^{-1} and $1/120$ day^{-1} salinity restoring times are very similar. Both solutions maintain surface salinity fields that are very close to the observations [the rms deviation between the model solution and the Levitus (1982) surface salinity fields is only 0.22 ppt even for the $1/120$ day^{-1} solution]. The sensitivity of the overturning to this relatively small change in the surface restoring indicated to us that the two solutions must lie close to

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each other yet on either side of a transition point that divides stable from unstable regimes. That is, the stronger freshwater fluxes in the $1/30$ day^{-1} solution seem to push the system into a regime where the THC is unstable. TTFB speculated that the real ocean may be close to a similar transition point itself.

In a commentary on the TTFB paper, Rahmstorf (1996, hereafter R96) challenged our conclusions about the stability of the two solutions and the proximity of TTFB's model to a stability transition point. Rahmstorf argues, first of all, that a numerical artifact has influenced our results. He claims that the unstable solution produced by TTFB's $1/30$ day^{-1} restoring during spinup is not due to excessive freshening overall, but may be due, instead, to more subtle changes in the pattern of convection caused by the spatial noisiness of the diagnosed salt flux distribution. He tries to make the general point that the $1/30$ day^{-1} solution is nowhere close to the kind of transition point envisioned by TTFB. He argues, furthermore, that the instability mechanism that destabilizes the thermohaline circulation is not the advective mechanism postulated in TTFB but is instead a different kind of mechanism involving changes in the location of convection.

We would like to thank Rahmstorf for his commentary. His insights on the role of convective instability certainly help expand one's perspective on this problem. However, in our rebuttal below, we maintain that our initial characterization of this problem is still valid. First, we identify the source of noise in the implied $E - P$ fields. We then eliminate the noise and show explicitly that the noisy $E - P$ is not the cause of the THC instability in TTFB's $1/30$ day^{-1} solution. As far as we can tell, all $1/30$ day^{-1} solutions derived from this model, whether with or without noisy $E - P$, are characterized by an unstable THC. This includes an unstable run presented by R96.

Second, we explain that the R96 commentary seems to be making an incorrect identification of THC instability with a collapse of the overturning circulation. TTFB discussed two model solutions, one of which is unstable and eventually collapses and one which is stable. From these two examples, it is all too easy to equate THC instability with a collapse of the overturning circulation. However, if the overturning changes in any significant way upon switching to mixed boundary conditions, it is unstable, even if it eventually settles down at a new stable level. The ''transition point'' as defined in TTFB separates stable and unstable solutions, not active and collapsed states of the overturning.

Finally, we address the issue of the mechanism of instability and show that the slow evolution of our unstable runs is very different from the fast changes in the R96 unstable run. This seems to suggest that the mechanism in TTFB's unstable run is not the fast convective mechanism of R96. We also suggest that the purely convective instability mechanism advocated in R96 may be an artifact of the use of ocean-only model in the absence of atmospheric stochastic forcing.

2. Is the thermohaline instability in TTFB caused by a noisy $E - P$?

The salt flux field produced by the $1/30$ day^{-1} restoring operation in TTFB includes a line of alternating positive and negative salt fluxes along 56°N in the North Atlantic (see R96 Fig. 1a or TTFB Fig. 1). Rahmstorf attributes the THC instability in TTFB to this $E - P$ noise. Rahmstorf correctly points out that the origin of this feature is four grid boxes with very low salinities in the Baltic Sea. He is able to remove the noise in the flux field by increasing the Levitus salinities at the Baltic points so that the Baltic salinities are more like salinities in the open ocean. When Rahmstorf spins up his version of the TTFB model and switches to mixed boundary conditions, he finds that the overturning in his model is still unstable, as in TTFB's $1/30$ day^{-1} solution, yet it increases to a higher level rather than collapses. Thus Rahmstorf finds himself that there is unstable behavior even in the absence of noise.

Rahmstorf never adequately explains why the Baltic points create so much noise in the diagnosed salt flux field and why a change in Baltic salinities might be expected to eliminate the noise. We would like to provide that explanation here. Low salinities in the Baltic are able to affect diagnosed salt fluxes all the way across the Atlantic because of the Fourier filter used to smooth model property fields in high latitudes. Filtering is necessary because the model's grid spacing in the east–west direction decreases toward the poles. In order to avoid taking very short time steps when the grid spacing becomes very small, every model property field poleward of a specified latitude is expanded as a Fourier series. The high wavenumber components are then removed from the expansion, and an inverse Fourier transform is applied to obtain a filtered field (Manabe et al. 1975).

The strong restoring in TTFB's $1/30$ day^{-1} model run makes the model's surface salinity field closely resemble the Levitus field. This creates a sharp discontinuity at the entrance to the Baltic, which includes large-amplitude high wavenumber components that the filter attempts to remove. In removing the high wavenumber components, the filter modifies model salinities across the basin. The surface Levitus salinity is not filtered and retains the high wavenumber components. When the implied $E - P$ is calculated from the differences between the Levitus and model surface salinity fields at the end of the spinup run, the high wavenumber components reappear in the freshwater forcing field. Reducing the restoring constant to $1/120$ day^{-1} reduces the noise in the flux field because the discontinuity at the entrance to the Baltic is not as strong; the amplitude of the high wavenumber components removed by the filter is small, and there is less propagation of the Baltic effect across the basin.

Filtering of the temperature and salinity fields in TTFB is applied at all grid rows poleward of 45°. By moving the latitude where filtering begins poleward of 60°N we can smooth out the salt flux field without having to modify the Levitus data in the Baltic. This requires using a 15% smaller time step. Given this small penalty in the time step, filtering in the latitude band 45° to 60° need not have been part of the model in the first place. Figure 1 shows a map of the salt flux field diagnosed from a spinup with $1/30$ day^{-1} restoring when the filter is shifted poleward of 62°N. This map shows a smooth $E - P$ field that can be compared directly with the noisy $E - P$ in R96 Fig. 1a or with TTFB Fig. 1.

Figure 2 shows the zonal average of the implied salt flux in the North Atlantic as a function of latitude in four models. The four models include the original $1/120$ day^{-1} and $1/30$ day^{-1} model runs from TTFB (curves 1 and 2, respectively), our new run with the Fourier filter shifted poleward (curve 3) and our rerun of the R96 modified Baltic salinity model (curve 4). All four curves indicate maximum freshening near 60°N. Both the $1/30$ day^{-1} curves with the smooth salt-flux fields (curves 3 and 4) are virtually identical. Both have less net freshening than the TTFB original $1/30$ day^{-1} run, yet more freshening than the TTFB $1/120$ day^{-1} run.

Figure 3 shows time series of the North Atlantic overturning from three of the models shown in figure 2 after they are switched to mixed boundary conditions. The overturning in the TTFB $1/120$ day^{-1} run stays extremely stable (curve 1), while the overturning in the TTFB original $1/30$ day^{-1} run collapses over 250 years (curve 2). Note that the small amplitude internal model noise seen in the $1/120$ day^{-1} case (curve 1) is not amplified by a THC instability because the basic state is stable. Both of the smooth $E - P$ runs using a $1/30$ day^{-1} salinity restoring time, that is, our $1/30$ day^{-1} shifted filtering run (curve 3) and the R96 modified Baltic salinity run (his Fig. 4) are unstable. In the R96 run, the overturning immediately jumps up from 18 to about 33 Sv (Sv ≡ 10^6 m^3 s^{-1}) and then settles after 100 years at about 24 Sv. In our shifted filtering case, the overturning increases slightly at first but then slowly winds down to 14 Sv after 200 years (Fig. 3, curve 3).

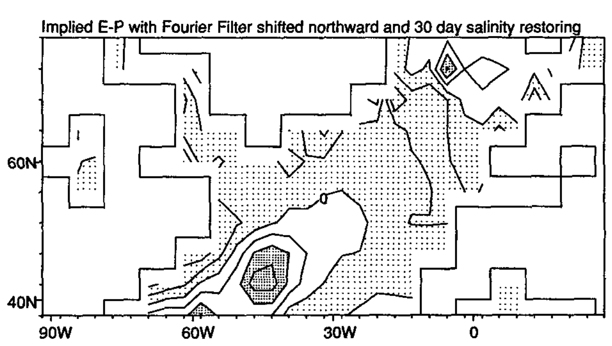

FIG. 1. The smooth implied $E - P$ field obtained by restoring to the original Levitus data used by TTFB, using 30-day salinity restoring time but with Fourier filtering only poleward of 62°, north of the Baltic grid points in the model. Contour interval is 2 m yr^{-1}, negative areas are shaded with light stippling. Note that the noisy features are removed, although the modification to the Baltic salinity proposed by R96 has not been applied.

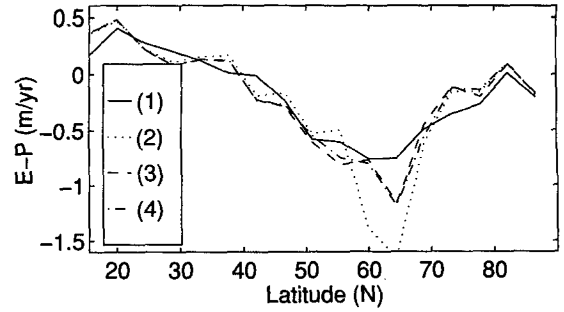

FIG. 2. Zonally averaged implied $E - P$ for: TTFB's run with salinity restoring of $1/120$ day^{-1} (curve 1); TTFB's run with salinity resorting of $1/30$ day^{-1} (curve 2); a run with $\gamma_s = 1/30$ day^{-1} but with the Fourier filter shifter northward (curve 3); a run with $\gamma_s = 1/30$ day^{-1} but with the Baltic salinity adjusted as proposed by R96 (curve 4).

An unstable solution for any physical system is one in which small perturbations are able to grow and drive the system into a new regime. According to this definition, only the overturning in the $1/120$ day^{-1} run is stable upon switching to mixed b.c. The overturning in each of the $1/30$ day^{-1} runs is unstable, although the overturning collapses in only one of the examples. These examples illustrate that the ultimate fate of unstable overturning is almost impossible to predict in a full GCM, which is why TTFB concentrated in their box model stability analysis only on the initial instability process.

These results provide a simple and direct reply to the first of Rahmstorf's criticisms: the noisy $E - P$ field is not responsible for the instability in the TTFB original $1/30$ day^{-1} experiment.

3. Is there a "transition point" in TTFB's system?

In order to illustrate the instability mechanism at work in their GCM, TTFB make use of a simple box model. The overturning in the box model does indeed collapse when high-latitude freshening reaches a certain value. TTFB presented a linearized instability analysis of the box model but explicitly indicated that the analysis applies only to the initial instability of the GCM. Unfortunately, Rahmstorf takes the ultimate fate of the THC instability in the box model as a literal analog to the fate of the overturning in the GCM. He says, ''the transition to a new state with a different NADW formation rate cannot be explained by TTFB's instability model. In this model, when forcing is beyond the critical value, no stable solution with high latitude sinking exists.'' In fact, complex nonlinearities of the GCM, which do not exist in the box model, may lead to a variety of stable states with high-latitude sinking after the initial instability stage.

Rahmstorf refers to a ''critical value'' of the freshwater forcing (i.e., a stability transition point) that separates solutions that collapse upon switching to mixed b.c. and solutions that maintain an active THC. However, the ''transition point,'' as defined in TTFB, separates stable and unstable solutions, not active and collapsed states of the overturning. Thus Rahmstorf uses the term ''critical value'' in an incorrect sense.

When Rahmstorf's modified Baltic model is switched to mixed boundary conditions, he observes that the overturning settles to a new stable level in which high-latitude sinking is active. Rahmstorf takes this to mean that the model freshwater forcing was not initially near a critical value, as he defines it. By our definition, the forcing in Rahmstorf's model has most definitely crossed a critical value in which a stronger negative salt flux has made the initial state unstable. It seems that R96's misunderstanding of TTFB's definition of a transition point leads him to wrongly conclude that there is no stability transition in his own runs.

4. The THC instability mechanism

Rahmstorf argues that the instability occurs because local patterns of convection change under mixed boundary conditions when the surface salinity is allowed to drift away from the Levitus data. He rejects the advective instability mechanism used in TTFB, in which the large-scale salinity gradients slowly interact with the overturning circulation to destabilize the circulation (Walin 1985; Marotzke et al. 1989). He cites the relatively instantaneous changes in his solutions as evidence for the convective mechanism.

We simply do not agree that Rahmstorf's analysis is relevant to the runs presented in TTFB. We note that the overturning changes in our runs with unstable THC, especially the shifted filtering case (Fig. 3, curve 3) are characterized by a very long timescale of hundreds of years, consistent with the advective mechanism analyzed by TTFB. We concede that the small amplitude, short term fluctuations seen in the time series of our unstable runs may be caused by convective noise, but the overall slow drift suggests that the slow advective mechanism is at work in these runs.

The amplitude of the freshwater forcing, which was a dominant factor in TTFB's analysis, does not play any role in the R96 local convective mechanism. We note that (Figs. 2 and 3) there is a correlation between the amplitude of the salinity forcing (as reflected in the regional freshening in the sinking area of the North Atlantic model sector) and THC evolution after the initial THC instability: the model with the least regional freshening evolves at the slowest rate, while the model with the stronger salinity forcing evolves more quickly. This correlation of rate of THC evolution past the initial instability and freshwater forcing amplitude supports TTFB's view that the forcing amplitude is indeed a crucial parameter.

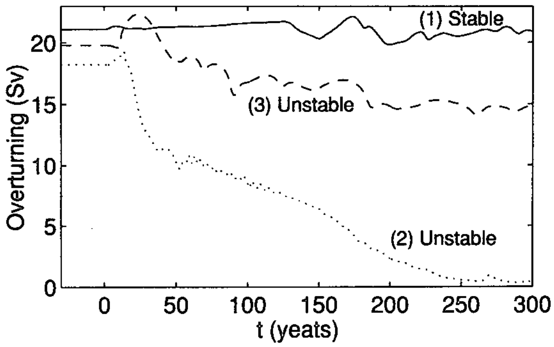

FIG. 3. Time series of the North Atlantic overturning from global model runs under mixed boundary conditions. Curve numbering is like the first 3 curves of Fig. 2.

Ocean-only models with mixed boundary conditions are certainly not the method of choice for investigating the stability of the THC under different freshwater forcings. Using a fully coupled ocean–atmosphere model, Manabe and Stouffer (1993) showed what might happen if atmospheric CO_2 levels are allowed to increase gradually to 2× and 4× preindustrial levels. In their 2× CO_2 case, the overturning declines over several hundred years and slowly recovers after atmospheric CO_2 levels stabilize. In the 4× CO_2 case, the overturning dies out and does not recover. In both cases the changes are very slow, consistent with the advective mechanism of TTFB and not with the convective mechanism of R96.

Rahmstorf argues that the existence of different convective patterns allows his ocean model to access multiple stable states that include active overturning. But one can fairly ask how robust such delicate convective patterns would be in the presence of atmospheric noise. The stochastic nature of the atmosphere's forcing will make it very difficult for the ocean to lock onto a fixed pattern of convection that will survive over the decades needed to produce a stable new level of overturning. It seems likely that the convective patterns advocated in R96 are a feature of noise-free ocean-only models that may not survive in more realistic models or in the actual climate system.

5. Summary

We have shown that the results of TTFB were not affected by the presence of noise in the $E - P$ field. We eliminated this noise and still obtain an unstable solution.

R96's association of a stability transition point with a collapse of the overturning circulation leads him to conclude that there is no stability transition point separating TTFB's stable and unstable runs. We have shown that by TTFB's original definition, the unstable runs in both TTFB and R96 have most definitely crossed a stability transition point beyond which a stronger negative salt flux makes the initial state unstable upon switching to mixed boundary conditions.

We feel that the advective mechanism is the dominant destabilizing mechanism both in the runs presented here and in the presence of a noisy atmosphere. However, the convective and advective mechanisms are not mutually exclusive. They can both play important roles in the destabilization of the THC.

Mixed boundary conditions have a tendency to make the THC unstable. This was the main point of TTFB (see our title). While we have shown here that TTFB's runs under mixed boundary conditions are indeed close to a stability transition point, it is left to future research to examine whether the actual climate system is close to a stability transition point.

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