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Potential predictability of rapid changes in the Atlantic meridional overturning circulation

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[1] We explore the potential predictability of rapid changes in the Atlantic meridional overturning circulation (MOC) using a coupled global climate model (HadCM3). Rapid changes in the temperature and salinity of surface water in the Nordic Seas, and the flow of dense water through Denmark Strait, are found to be precursors to rapid changes in the model's MOC, with a lead time of around 10 years. The mechanism proposed to explain this potential predictability relies on the development of density anomalies in the Nordic Seas which propagate through Denmark Strait and along the deep western boundary current, affecting the overturning. These rapid changes in the MOC have significant, and widespread, climate impacts which are potentially predictable a few years ahead. Whilst the flow through Denmark Strait is too strong in HadCM3, the presence of such potential predictability motivates the monitoring of water properties in the Nordic Seas and Denmark Strait. **Citation:** Hawkins, E., and R. Sutton (2008), Potential predictability of rapid changes in the Atlantic meridional overturning circulation, *Geophys. Res. Lett.*, *35*, L11603, doi:10.1029/2008GL034059.

1. Introduction

[2] Pronounced rapid fluctuations in North Atlantic climate are seen in historical temperature reconstructions [e.g., *Bond et al.*, 1997]. It appears that these events can occur in time periods when there is no driving external forcing, and they must therefore be a component of natural climate variability. A leading hypothesis to explain these changes is variations in the strength of the Atlantic meridional overturning circulation (MOC). An important issue in climate prediction is whether a rapid change in the MOC, similar to those observed in the past, could occur in the future.

[3] In view of the major climatic impacts of a possible future rapid change in the MOC, an 'early warning' system for such an event would be of great value. Assessing the potential to develop an early warning system involves many considerations. Two of the most important questions are:

[4] 1. Are rapid changes in the MOC potentially predictable?

[5] 2. If so, which observations of the ocean state are likely to be of greatest value to constrain predictions?

[6] Question 2 recognises the likely need for a prediction system that utilises observations already available (e.g. Argo, RAPID 26°N array), supplemented by additional observations designed specifically for prediction purposes. It is not clear that the location of current ocean observations, which are designed to monitor the ocean state [e.g. *Cunningham et al.*, 2007], are optimally located for prediction purposes. Note that we are considering the potential predictability of rapid MOC changes, which is distinct from the average predictability considered in earlier work [e.g., *Collins et al.*, 2006]. These 'perfect model' studies found that predictability is strongly dependent on the initial ocean state. Thus we choose to focus on those events that are likely to be of most importance for climate impacts.

[7] Previous studies [e.g., *Griffies and Bryan*, 1997; *Hall and Stouffer*, 2001; *Hawkins and Sutton*, 2007] have shown that changes in deep water formation in the high latitude Atlantic can drive MOC variability. We find convincing evidence that rapid changes in the MOC in a coupled climate model (HadCM3) are potentially predictable from high latitude Atlantic precursors, and discuss the implications of our findings for the design of a possible early warning system.

[8] The paper is structured as follows. In Section 2 we describe the HadCM3 model and identify the rapid MOC change events and their precursors. The mechanism behind these rapid events is discussed in Section 3 and their climatic impacts are illustrated in Section 4. We summarise and discuss the implications of these results for ocean monitoring in Section 5.

2. Model Properties

[9] In the subsequent analysis we use annual mean data from an extended (1600 years) pre-industrial control run of the Hadley Centre climate model (HadCM3) [*Gordon et al.*, 2000]. HadCM3 is a global coupled ocean-atmosphere model with an atmospheric resolution of 2.5° × 3.75° and 19 vertical levels. The ocean component has a resolution of 1.25° × 1.25° with 20 vertical levels. The model does not require flux adjustment to maintain a stable climate, and the mean state is in reasonable agreement with observations [*Gordon et al.*, 2000]. To minimise the effects of any ocean spin-up, we only consider years 501 to 1600 and detrend the remaining data with a second order polynomial.

[10] The largest variability in ocean deep convection is found in the Nordic Seas, but the flow through Denmark Strait (~8.5 Sv) [*Wood et al.*, 1999] is significantly larger than observations (~3.5 Sv) [*Macrander et al.*, 2005], partly because the Strait has been deepened to compensate for errors arising from the modest resolution [*Roberts and Wood*, 1997]. This difference is a caveat to our findings.

[11] Using HadCM3, *Hawkins and Sutton* [2007] (hereinafter referred to as HS07) showed that variability in Nordic Seas surface temperature and salinity leads changes in the MOC on multi-decadal timescales, suggesting potential

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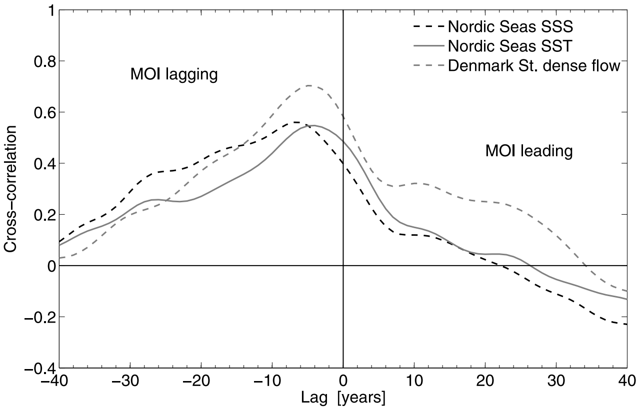

Figure 1. Lagged cross-correlations of the MOI and the flow of dense water through Denmark Strait (dashed grey line), surface salinity (SSS, dashed black line) and surface temperature (SST, solid grey line) in the Nordic Seas, using 1100 years of the HadCM3 control run. All the indices have been decadally smoothed and lead the MOI, with SSS leading SST by about 2 years.

predictability. In this study, we focus on whether the largest and most rapid MOC changes, which are of most importance for potential impacts, may also be predictable.

2.1. Definition of Climate Indices

[12] We define an MOC index (MOI) as the annual mean stream function at 996 m, averaged over the latitude band 27.5°N–32.5°N. This index has a mean overturning of 16.5 Sv, with a standard deviation of 1.06 Sv (or 0.59 Sv when decadally smoothed). We define indices of Nordic Seas surface temperature (SST) and salinity (SSS) as averages over the region 70°N–80°N and 30°W–20°E. These indices are decadally smoothed with standard deviations of 0.43 K and 0.18 psu respectively.

[13] Figure 1 shows the lagged correlations of the Nordic Seas SST (solid grey line) and SSS (dashed black line) indices with the MOI, and demonstrates that, on average, the Nordic Seas changes lead the MOI changes by 5–8 years. Note that the SSS index leads the SST index by about 2 years.

2.2. Rapid Changes in Overturning Strength

[14] The MOI time series in the HadCM3 control run (Figure 2a) shows several large and rapid changes, for both increasing and decreasing MOC states. Three of the largest events, where the MOI changes by about 4σ ($\sim$2 Sv, or $\sim$12% of the mean) in 20–30 years, are shown in Figure 2b (solid black lines). Also shown in Figure 2b are the Nordic Seas SST (solid grey line) and SSS (dashed black line) indices during the same time periods. It is immediately clear that the rapid changes in the surface properties of the Nordic Seas lead the rapid changes in the MOI by about 10 years, with salinity changes leading temperature changes (consistent with Figure 1). This long lead time and large magnitude of the changes (around 0.6 psu and 1.5 K) suggests potential predictability for the MOC through observations of properties of the Nordic Seas.

[15] Also shown in Figure 2b is the southward flow of dense ($\rho > 1027.5$ kg m^{-3}) water through Denmark Strait at 66.2° N (DEN. ST., dashed grey line). This flow also shows large, rapid changes of about 3 Sv (or $\sim$30% of the mean) which lead the MOI, consistent with the Nordic Seas anomalies propagating through Denmark Strait into the North Atlantic where they influence the strength of the overturning. This increase in flow of dense water is due to an increase in the mean density of the overflows rather than an increase in the southward velocity (not shown). Figure 1 also shows that this index has the largest correlation with the MOI when leading by around 5 years.

2.3. Potential Predictability

[16] To utilise this apparent predictability in a practical way requires establishing that the three identified precursors are also good predictors, i.e. does a large change in the precursor always lead to a corresponding change in the MOI? Our capacity to assess this is limited by the small number of events available. It is found (not shown) that of the 8 ‘events’ when all three precursors change by more than 2σ in 10 years, 7 are followed by an MOI change of the correct predicted sign, of which 3 show a change larger than 1.5σ in 10 years. It is also found that, of the three precursors identified, the flow of dense water through Denmark Strait is the most reliable predictor (not shown). Having established this relationship we now focus on the largest rapid events.

3. Mechanism for Rapid Changes

[17] These rapid changes in MOC strength appear to be caused by variations in convection in the Nordic Seas, giving rise to density anomalies which propagate into the North Atlantic and along the deep western boundary at depth. We demonstrate this by concentrating on the rapid increase in the MOI starting around year 1485. Both the rapid increase of the MOI starting around year 775 and the decrease around year 740 have similar features (not shown), but with opposite signs for the rapid decrease.

3.1. Nordic Seas

[18] In the Nordic Seas, relatively cold and fresh Arctic water overlies warm and salty Atlantic water, although this vertical temperature gradient is larger than in HadCM3 than observations [*Gamiz-Fortis and Sutton*, 2007]. The presence of a sub-surface temperature maximum at around 300m in HadCM3 means that an increase in vertical mixing associated with convection raises both SST and SSS, consistent with Figure 2b. HS07 postulated that the reason that SSS leads SST (Figure 1) is that anomalous salinity export from the Arctic creates salty and dense surface waters which aid the initiation of convection.

[19] There are also likely to be stochastic atmospheric influences on convection strength, e.g. by affecting heat loss. *Grist et al.* [2007] found that extreme heat loss events in the Greenland Seas can influence the volume transport of dense water through Denmark Strait in HadCM3, and that heat loss is more important than wind forcing for driving these changes. One of the largest heat loss events found by *Grist et al.* [2007] was in year 758 - intriguingly close to the second rapid event, though they found no major heat loss or gain near the first rapid event. Unfortunately their analysis does not include the later time period shown in Figure 2b due to a lack of the required data. Large anomalies in the North Atlantic Oscillation (NAO) are found near the

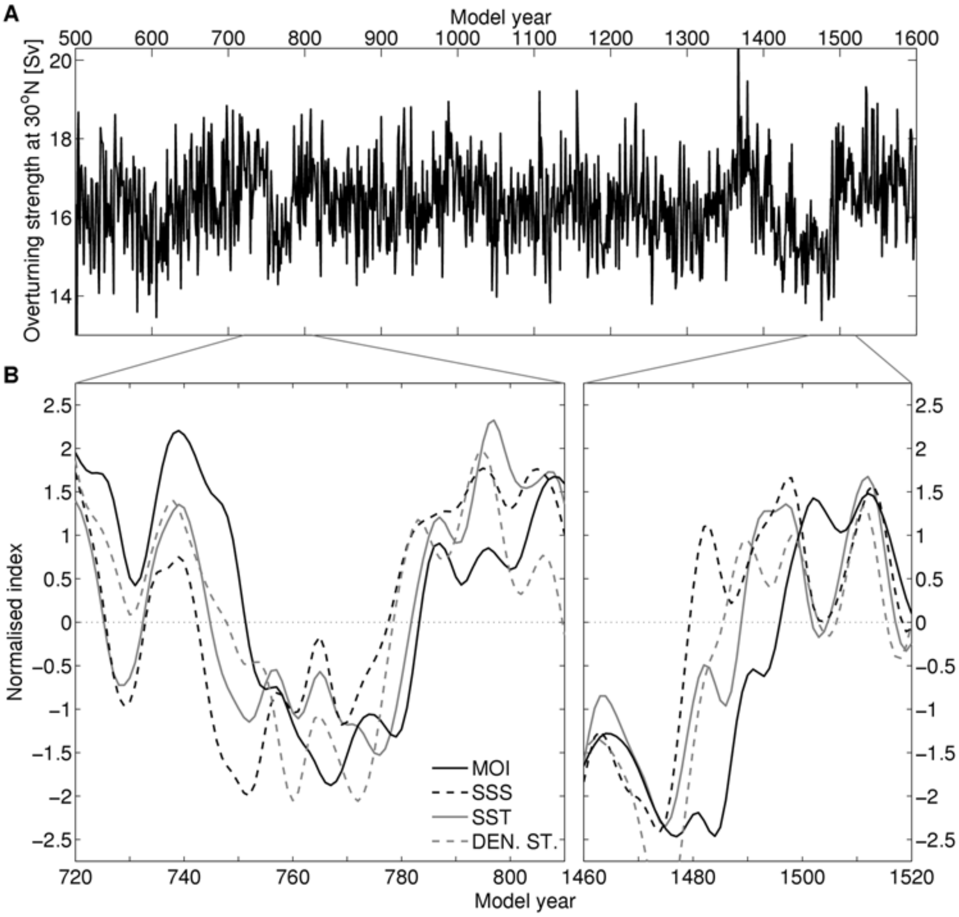

Figure 2. (a) The overturning index (MOI) for the 1100 years analysed. Three rapid changes can easily be seen. (b) Decadally smoothed normalised indices for selected time periods showing rapid changes: Overturning strength (MOI, solid black line), Nordic Seas surface salinity (SSS, dashed black line) and surface temperature (SST, solid grey line), and southward flow of dense (ρ >1027.5 kg m^{-3}) water through Denmark Strait (DEN. ST., dashed grey line).

initiation of two of these rapid events, but they are not the most extreme NAO years in the record. It seems likely therefore that a combination of (unpredictable) factors is influencing the initiation of these rapid events and we therefore focus on what happens after the rapid events have started.

[20] Figure 3 shows the integrated density anomalies from the surface to 800 m (the depth of Denmark Strait in HadCM3) for neighbouring 3 year means starting in year 1478. It can be seen that the density of the upper level waters in the Nordic Seas increases, likely caused by increasing convection. These dense anomalies also appear to propagate towards Denmark Strait from year 1484 to year 1489.

3.2. Sub-Polar Region and Western Boundary

[21] Related dense anomalies are also seen in maps of density integrated from 800 m to 3000 m (Figure 4 - note the years are different from Figure 3). These maps are consistent with an increased flow of dense water through Denmark Strait which descends to deeper levels. This pulse of dense water into the sub-polar region lasts for around 6 years. There is also evidence of a smaller pulse of dense water from years 1496 to 1501 (not shown). Figure 4 also shows that the dense anomalies in the sub-polar region propagate along the western boundary at depth, reaching the tropics several years after exiting the Nordic Seas. This propagation creates a zonal density gradient which, by thermal wind balance, affects the meridional circulation.

4. Surface Temperature Impacts

[22] These rapid changes in the MOC have an impact on the climate of the surrounding regions. Figure 5 shows a composite of the surface air temperature changes between decadal means before and after the rapid events, scaled by local decadal standard deviation.

[23] The dominant feature of this pattern is an overall strong warming over the northern extra-tropics and the Arctic. The mean warming is around 0.5 K over Europe and 1 K over Russia. These features are broadly consistent with previous studies on the impacts of MOC changes in HadCM3 [*Knight et al.*, 2005; *Sutton and Hodson*, 2007]. The exception is the Atlantic cross-equator temperature dipole, which is only weakly present and found in only two of the rapid events considered.

5. Conclusions and Implications

[24] We have described the mechanism behind the largest, most rapid changes in the MOC in a control simulation

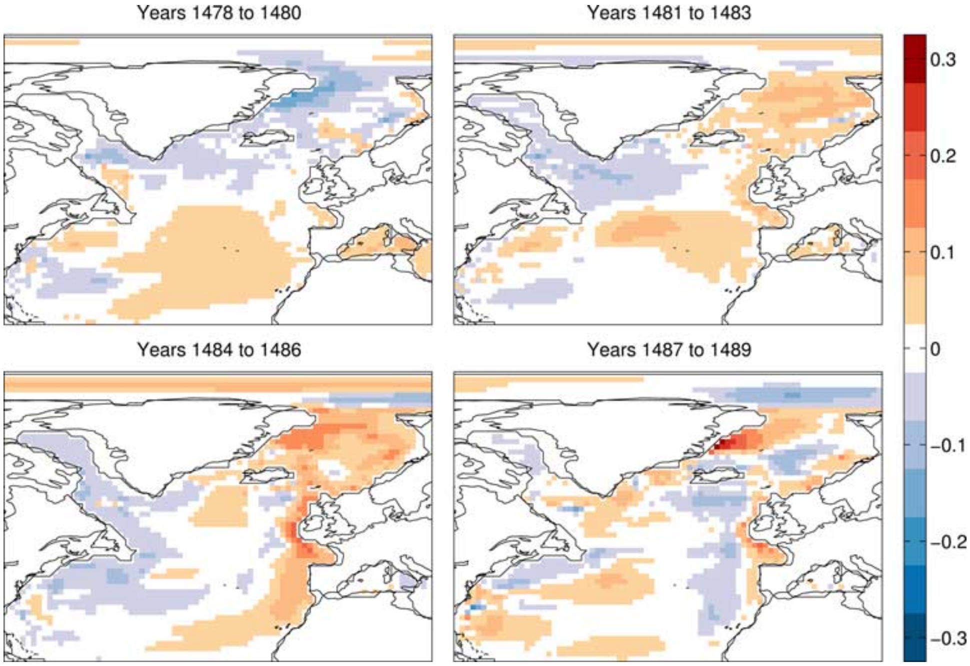

Figure 3. Integrated density anomalies from the surface to 800 m, relative to the control run mean, for averaged 3 year periods as labelled. The thin black contour is the 800 m isobath in HadCM3.

of a GCM (HadCM3) and illustrated how, using observable properties (SST and SSS in the Nordic Seas), these events are potentially predictable. The key physical processes involved in a rapid increase of the MOC are:

[25] 1. a likely increase in convection in the Nordic Seas, influenced by stochastic atmospheric anomalies, creating dense upper layer water,

[26] 2. an associated increase in SSS and SST in the region,

[27] 3. anomalously dense water flowing though Denmark Strait into the sub-polar gyre, and along the deep western boundary current,

[28] 4. an increase of the MOC as a response to these dense anomalies, with opposite signs for a rapid decrease.

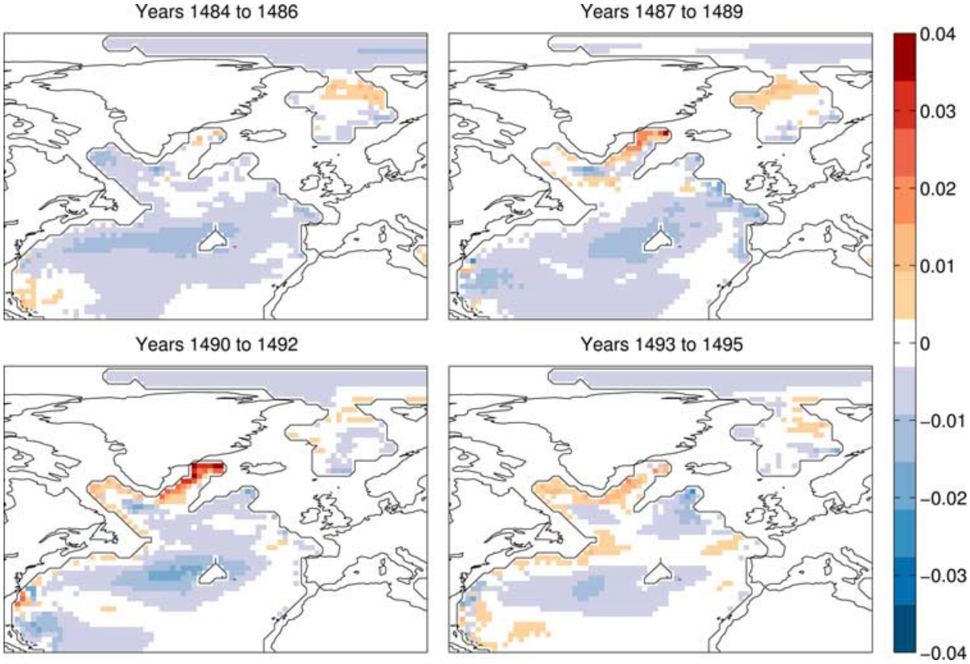

Figure 4. Integrated density anomalies from 800 m to 3000 m, relative to the control run mean, for averaged 3 year periods as labelled. The thin black contour is the 3000 m isobath in HadCM3. Note the years are different from Figure 3.

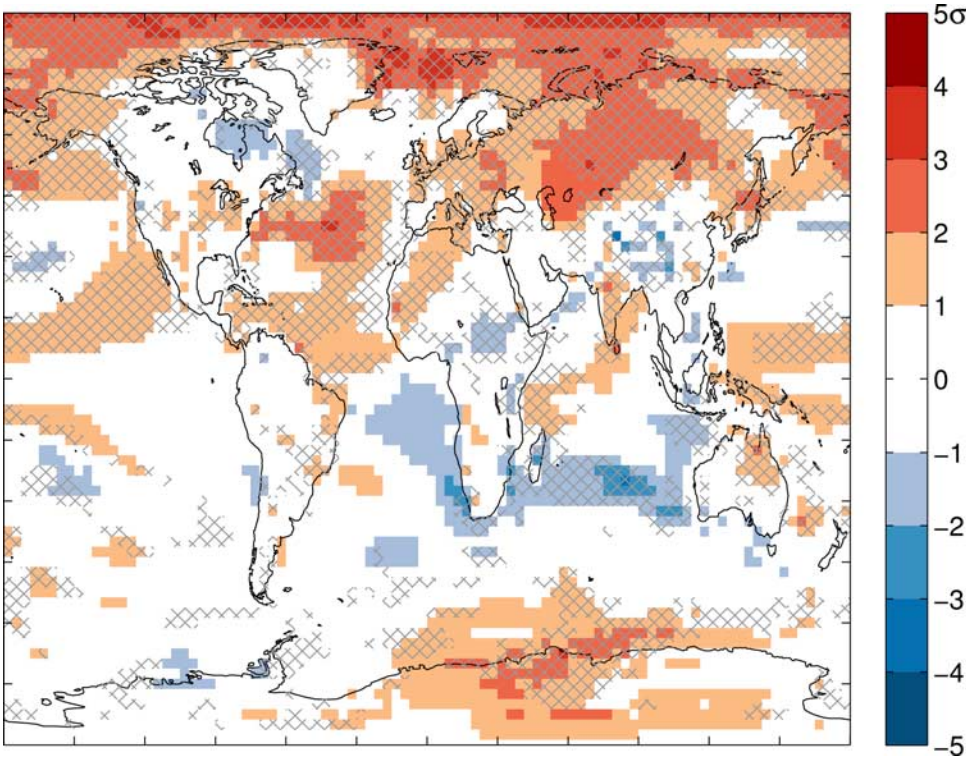

Figure 5. Composite of surface air temperature differences between decadal means before and after each rapid event, scaled by local decadal standard deviation. The figure shows the impact as if all events were rapid increases in the MOI. The hatched regions indicate where the signs of the changes are consistent between each rapid event.

There are also associated large, and consistent, climate impacts over the northern extra-tropics with a strong warming (cooling) for a rapid MOC increase (decrease). If a comparable mechanism occurs in the real ocean - and the similarity between models [e.g. *Griffies and Bryan*, 1997; *Hall and Stouffer*, 2001] is encouraging - then the climate impacts of rapid MOC events could be predicted a few years ahead.

[29] The caveats to these findings are the limitations of the model, which has a relatively coarse resolution and thus does not explicitly resolve the convection or represent the overflows in detail. The flow through Denmark Strait is too strong when compared to observations, and it is possible that the influence of the Nordic Seas on the MOC is enhanced in this model for these reasons. Using the FLAME model, *Getzlaff et al.* [2005] showed that only an eddy permitting resolution (∼1/3°) allowed for the existence of fast propagating boundary waves in the ocean. These fast waves have the potential to cut the travel time of anomalies to the tropics, and reduce the lead time of any prediction. Note that the representation of boundary waves is sensitive to the model grid as well as the resolution [*Hsieh et al.*, 1983].

[30] Notwithstanding the limitations of the model, our findings have implications for an observing strategy. The issue of which observations may be most useful to constrain predictions of the MOC has received much less attention than the issue of MOC monitoring [*Cunningham et al.*, 2007]. Both issues are important, but the observational needs are different. Our findings suggest that for predicting the MOC, and for providing an early warning of possible rapid changes, additional observations located in the high latitude North Atlantic - especially in the Nordic Seas and of the overflows [e.g., *Macrander et al.*, 2005] - are likely to be of greatest value.

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