

Seasonal inflow of warm water onto the southern Weddell Sea continental shelf, Antarctica

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[1] To capture the austral summer to winter transition in water mass properties over the southern Weddell Sea continental shelf and slope region, 19 Weddell seals were tagged with miniaturized conductivity–temperature–depth sensors in February 2011. During the following 8 months the instruments yielded about 9000 temperature–salinity profiles from a previously undersampled area. This allows, for the first time, a description of the seasonality of warm water intrusions onto the shelf, as well as its southward extent towards the Filchner Ice Shelf. A temperature section across the Filchner Depression and eastern shelf shows a pronounced decrease in warm water inflow from summer to winter, further supported by an almost 3-year long time series from a shelf–break mooring. The seasonal variability is related to the surface wind stress and an associated deepening of the off-shelf core of Warm Deep Water. **Citation:** Årthun, M., K. W. Nicholls, K. Makinson, M. A. Fedak, and L. Boehme (2012), Seasonal inflow of warm water onto the southern Weddell Sea continental shelf, Antarctica, *Geophys. Res. Lett.*, 39, L17601, doi:10.1029/2012GL052856.

1. Introduction

[2] Import of warm waters onto the Antarctic continental shelf has a major influence on the heat and salt budget of the coastal ocean, and is a potential heat source for ice shelf basal melt [Rignot and Jacobs, 2002; Pritchard et al., 2012]. Intrusions of warm water onto the southern Weddell Sea continental shelf also play an important role in the formation of Antarctic Bottom Water [Foster and Carmack, 1976; Nicholls et al., 2009], a principal component in the global thermohaline circulation.

[3] In the southeastern Weddell Sea (Figure 1) Warm Deep Water (WDW) flows westward along the continental slope as the southern limb of the Weddell Gyre, while the shelf is dominated by colder and fresher water masses [Fahrbach et al., 1992]. The resultant north–south density gradient, denoting the Antarctic Slope Front, is associated

with a strong westward current [Fahrbach et al., 1992; Heywood et al., 1998]. Closer to the Antarctic continent a westward flowing coastal current is supported by the prevailing easterly winds [Heywood et al., 1998]. In the southeastern Weddell Sea where the continental shelf is narrow these currents are difficult to differentiate [Heywood et al., 1998], and are often collectively referred to as the Antarctic Coastal Current (ACoC) [Fahrbach et al., 1992; Núñez-Riboni and Fahrbach, 2009]. The ACoC follows the shelf break until it passes the floating portion of Stancomb–Wills Ice Stream, whereupon one branch turns southward and follows the Luitpold Coast towards Filchner Ice Front (Figure 1) [Foldvik et al., 1985; Nicholls et al., 2009]. Several further incursions onto the shelf of modified WDW (MWDW: $T > -1.7^{\circ}\text{C}$, $S < 34.6$ [Foster and Carmack, 1976]) are observed as the slope branch of the ACoC continues westward, most notably across shelf break sills at 32°W [Foldvik et al., 1985; Nicholls et al., 2009] and 44°W [Nicholls et al., 2008].

[4] Recent model results [Hellmer et al., 2012] suggest that the inflow of warm water on the eastern side of Filchner Depression (Figure 1) could be of vital importance to the future state of the Filchner–Ronne Ice Shelf. Thus far, this region has been sporadically sampled, and only during summer, with a focus on the export of cold, dense water masses from the shelf [e.g., Foldvik et al., 2004]. The lack of wintertime observations has meant that it has not yet been possible to establish whether the inflow exhibits a significant seasonality. Pronounced seasonal variability in circulation and water masses has been observed both upstream [Núñez-Riboni and Fahrbach, 2009] and downstream [Gordon et al., 2010] of the Filchner continental shelf, and also in the strength of the modeled overflow from the Filchner Depression [Wang et al., 2012].

[5] This paper describes the seasonality of the flow of MWDW onto the Filchner continental shelf using data from instrumented Weddell seals (*Leptonychotes weddellii*) and an almost 3-year long temperature time series from a shelf–break mooring. Previous applications of animal–borne sensors in the Southern Ocean and adjacent shelf seas [e.g., Boehme et al., 2008; Nicholls et al., 2008] have proved the viability of this approach. In the Weddell Sea, four Weddell seals equipped with Conductivity–Temperature–Depth (CTD) sensors during the austral winter of 2007 allowed a good data coverage of the southern continental shelf and shelf break region [Nicholls et al., 2008]. Here we present data from 19 seals, representing the first comprehensive wintertime hydrographic survey over the southeastern Weddell Sea continental shelf, and a unique

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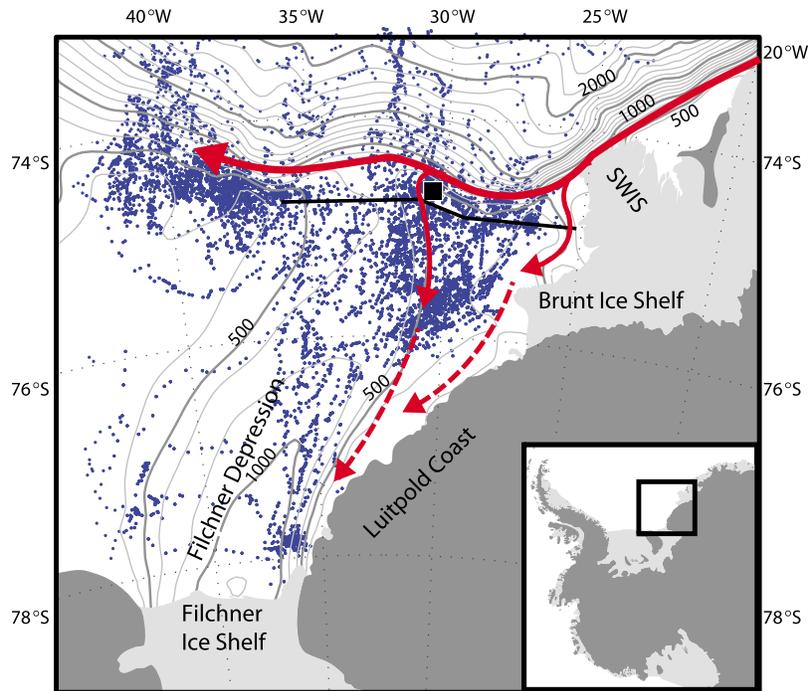


Figure 1. Map of the southeastern Weddell Sea and adjacent ice shelves (SWIS: Stancomb–Wills Ice Stream). Bathymetry contours (BEDMAP [Lythe *et al.*, 2001]) are drawn every 200 m (thin lines) and every 500 m (thick lines). The location of TS-profiles are shown by blue dots, the black square indicates the position of a mooring (cf. text), while the black line shows the east–west temperature section displayed in Figure 2. Red arrows show the circulation of the Antarctic Coastal Current and locations of observed on-shelf flow as described in the text, dashed arrows pointing to the seasonal propagation of warm water.

dataset to elucidate the seasonal evolution of ocean conditions.

2. Data

[6] We use hydrographic data collected by 19 Weddell seals equipped with CTD–Satellite Relay Data Loggers (CTD–SRDL). The tags have been developed by the Sea Mammal Research Unit (SMRU) at the University of St Andrews, UK. A technical description is given in *Boehme et al.* [2009]. The tags are glued to the seal’s fur (procedure detailed in *Nicholls et al.* [2008]) and fall off during the next moult, thus potentially providing many months of data. A total of ~ 9000 temperature (T)–salinity (S) profiles were collected between February and October 2011, covering a substantial part of the southeastern continental shelf (Figure 1). Each profile contains 20 TS -pairs at uniform pressure intervals as a function of dive depth. Over the continental shelf (water depth less than 500 m) the profiles often reach the sea floor, with 74% of the profiles going deeper than 400 m. In the Filchner Depression profiles extend below 600 m (716 profiles), and even reach >900 m on a few occasions.

[7] Prior to analysis, the data were calibrated using concurrent ship–based observations by the RRS James Clark Ross. The accuracy of the post–processed data is 0.02 and 0.005°C for salinity and temperature, respectively, for depths up to 2000 m [*Boehme et al.*, 2009].

[8] Results based on seal data are further supported by data from a mooring deployed at the shelf break (74.67°S, 30.5°W; Figure 1) between 2007 and 2009. The mooring

had 5 temperature sensors evenly spaced between 459 m (10 m above bottom) and 269 m. One sensor (319 m) malfunctioned shortly after deployment and is not used. Temperature was recorded every 5 minutes, from which daily mean values were calculated.

[9] The correspondence between wind strength and coastal current [*Fahrbach et al.*, 1992; *Núñez-Riboni and Fahrbach*, 2009] suggests a close coupling between atmosphere and ocean. *Wang et al.* [2012] found a strong correlation between the wind stress curl over the southern Weddell Sea and both the coastal current transport and shelf water export from the Filchner Depression. Seasonal change in warm water inflow is thus discussed with respect to atmospheric forcing using the daily wind stress curl. The wind stress curl is calculated for the area 0–30°W, 65–74°S, using wind speed data on a 0.75° grid from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim analyses fields. The drag coefficient is calculated as a function of sea ice concentration following *Andreas et al.* [2010], using the closest grid point. This parameterization is for the marginal ice zone and is considered suitable for the southeastern Weddell Sea. Daily sea ice concentration data are obtained from the National Snow and Ice Data Center (NSIDC, USA) on a 25 km \times 25 km grid.

3. MWDW Inflow

[10] A temperature section covering the Filchner Depression and eastern continental shelf clearly shows MWDW flowing onto the shelf in summer (February–April; Figure 2a). Along the eastern slope of the depression MWDW is found

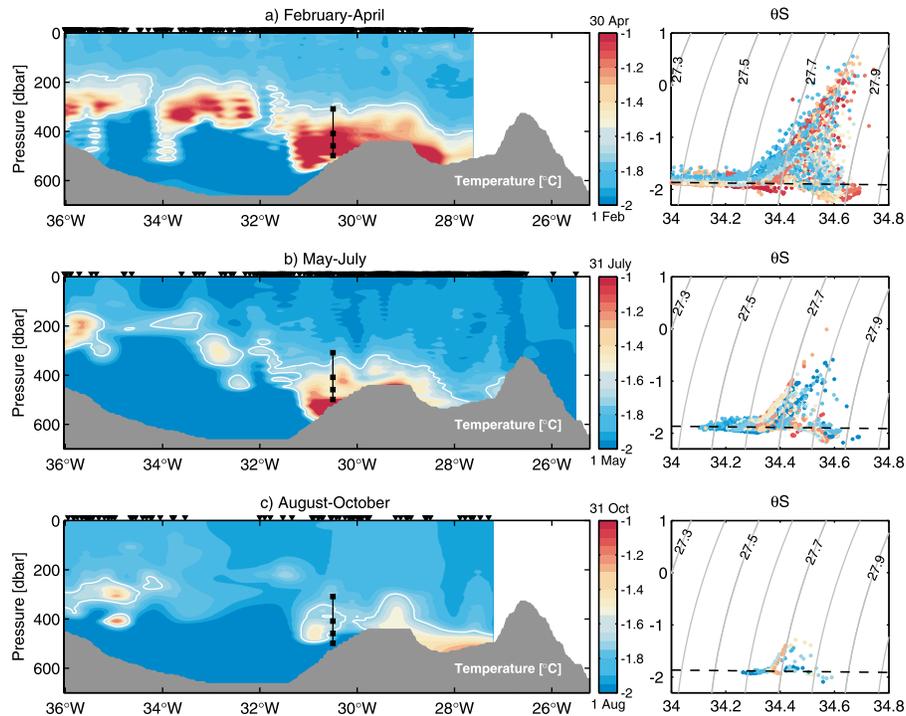


Figure 2. (left) Temperature section along the shelf edge and across the Filchner Depression (Figure 1; profiles included are from within 0.25° latitude southward of the black line) and (right) corresponding potential temperature–salinity (θS)–diagram based on seal profiles from (a) summer, (b) autumn, and (c) winter 2011. Black triangles show the location of individual profiles. The white contour lines in the sections are the -1.7°C isotherm, which corresponds to the lower temperature limit of MWDW [Foster and Carmack, 1976]. The position of the mooring and temperature sensors is indicated by the black line and squares. The color coding in the θS –diagrams corresponds to the date of individual profiles (shared colorbar with sections). The dashed horizontal line shows the surface pressure freezing point.

between 300–500 m, whereas the inflow is shallower over the western and central depression. MWDW also enters the shelf via the eastern trough between 27°W and 29°W . Maximum temperatures over this period are $>0^\circ\text{C}$. During autumn (May–July; Figure 2b) the MWDW core on the eastern side of the Filchner Depression is colder, with maximum temperatures of -0.6°C . Warmer water ($T=0.0^\circ\text{C}$) is found near the sea floor at 29°W . In winter (August–October; Figure 2c) a small amount of MWDW with temperatures between -1.3°C and -1.5°C is observed, mainly within the lower 100 m in the eastern trough. A localized temperature maximum (0.1°C) is observed at 400 m at 35°W (not seen in the θS –diagram as no salinity values were received for this profile).

[11] The seasonality of inflowing MWDW is corroborated by results from a mooring deployed at the shelf break between 2007 and 2009 (Figure 3). The highest average temperature (\pm one standard deviation) is observed at 459 m in March ($-0.90 \pm 0.18^\circ\text{C}$), while the temperature minimum at this depth ($-1.73 \pm 0.17^\circ\text{C}$) is observed in September. The summer to winter temperature decrease is fairly abrupt, about 0.7°C in 60 days (March–May) in 2008 and 2009, whereas a prolonged transition took place in 2007. Note, however, that in winter 2011 the warmest water is found west of the mooring (Figure 2c) and might therefore not have been detected during the mooring deployment. The temperature variability recorded by the upper-most sensor (269 m) is much less pronounced ($-1.84 \pm 0.03^\circ\text{C}$) and the time series contains no sign of MWDW intrusions.

[12] Upon entering the continental shelf the MWDW initially flows southward along the 400–450 m depth contour [Nicholls *et al.*, 2009]. Data coverage on the central shelf (76 – 77°S) is not sufficient to adequately resolve any seasonality. However, the temporal variability in hydrography is well resolved on the southernmost part of the shelf, close to the Filchner Ice Shelf front, as a result of a dedicated measurement campaign by one seal (tagged at 77.84°S , 36.35°W) providing 451 profiles between February and October). In February, the maximum temperature observed is -1.3°C (Figure 4a). The temperature then gradually decreases with no signature of MWDW being observed during winter. The presumably weaker MWDW inflow in

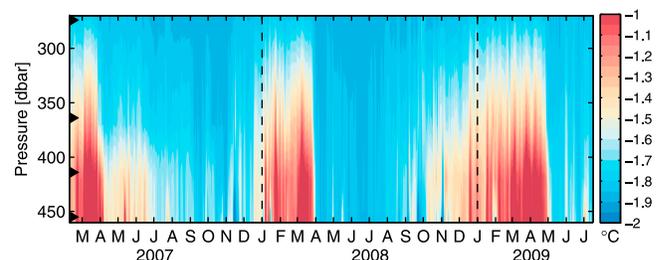


Figure 3. Daily mean temperatures from mooring S4E at 30.5°W , 74.67°S (Figure 1). The data have been linearly interpolated onto a 1 day times 10 dbar grid. The depth of individual instruments are indicated by black triangles.

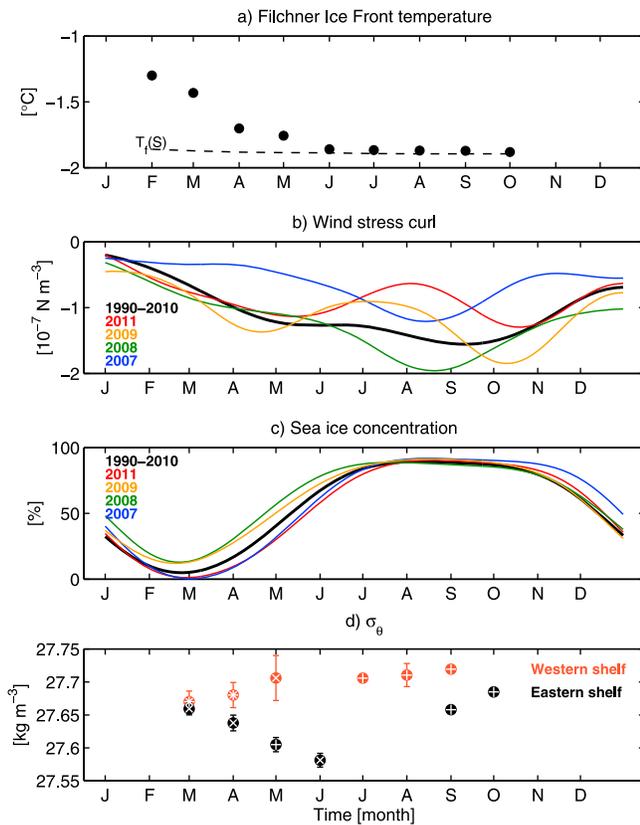


Figure 4. (a) Seal-derived time series of monthly maximum temperature from the Filchner Ice Front. The dashed line shows the surface freezing temperature ($T_f(S)$). (b, c) Wind stress curl and sea ice concentration as a function of month for the area $0\text{--}30^\circ\text{W}$, $65\text{--}74^\circ\text{S}$. The data in Figures 4b and 4c were smoothed using a second-order low-pass Butterworth filter with a cut-off period of 60 days. (d) Seasonal density (σ_θ) variations at 200 m in the region of MWDW inflow (eastern shelf: $30.5\text{--}31^\circ\text{W}$, $74.5\text{--}74.75^\circ\text{S}$) and on the shelf west of Filchner Depression (western shelf: $35\text{--}40^\circ\text{W}$, $74.5\text{--}75^\circ\text{S}$). The error bars indicate one standard deviation based on available data, with the number of TS -profiles indicated by +: <10 , x: >10 ; *: >100 .

autumn/winter thus loses its characteristics before reaching the Filchner Ice Front.

4. Mechanisms for Seasonality

[13] As warm water is present on the shelf slope year round, and the temperature of the ACoC shows no seasonality at 740 m [Mathiot *et al.*, 2011] the observed seasonal variability in MWDW inflow must be due to changes in cross-shelf exchange. Here, we will show that a seasonal change in wind forcing has the potential to alter on-shelf advection of MWDW. Several other mechanisms may also be relevant in transporting MWDW up and onto the continental shelf, e.g., continental shelf waves and tides [e.g., Foster *et al.*, 1987]. Although these other processes can not account for the seasonal variability, there is some seasonality in tidally induced mixing as a result of changes in stratification [Pereira *et al.*, 2002].

[14] Seasonal shifts in stratification over the shelf are likely to alter shelf edge exchanges. Along the eastern Weddell Sea coast prevailing easterly winds force an onshore Ekman transport in the surface layer and a resulting depression of the thermocline [Smedsrud *et al.*, 2006]. Enhanced downwelling as a result of stronger winds can thus reduce the inflow of MWDW by forcing the warmer and more saline MWDW downward below the depth of the continental shelf. The presence of sea ice also influences the atmosphere–ocean momentum transfer, and can, depending on its characteristics, lead to either increased or reduced momentum transfer [e.g., Andreas *et al.*, 2010]. Indeed, Núñez-Riboni and Fahrbach [2009] found that sea ice concentrations make a significant contribution to the seasonal cycle of the ACoC, acting to increase the velocity of the ACoC during autumn.

[15] Figure 4b shows the smoothed wind stress curl for the area immediately east of the inflow region, where sea ice has been taken into account using the effective drag coefficient parameterization by Andreas *et al.* [2010]. The observed seasonality in sea ice is shown in Figure 4c. The average seasonal cycle (1990–2010) is characterized by weak cyclonic winds in summer followed by a steady strengthening of the curl towards a September maximum. All years display similar behavior during the transition from summer to autumn. The effect of stronger cyclonic winds on cross-shelf exchange is manifested in the density of the inflowing water (Figure 4d); a freshening of the inflowing water between summer and autumn being consistent with a depression of the isopycnals at the shelf break, as also shown in a recent model study by Wang *et al.* [2012]. The wintertime reduction of on-shelf transport of MWDW thus results from a change in TS -properties on the continental slope rather than a reduced inflow strength. Higher densities in September and October follow weaker wind stress between July and September, leading to relaxation in the isopycnals. In contrast, the seasonal density evolution on the continental shelf west of the Filchner Depression, less influenced by upwelling of MWDW (not shown), display a gradual summer to winter increase (Figure 4d) as a result of salt input from sea ice formation (there is a 0.27 increase in surface salinity increase between March and September) and wintertime convection.

[16] Changes in wind forcing influence other aspects of the shelf and slope circulation. Eddy overturning of the Antarctic Slope Front and advection of MWDW onto the continental shelf off Dronning Maud Land are weaker for stronger winds, and therefore during winter, when the near-bottom boundary layer is dominated by the bottom Ekman transport [Nøst *et al.*, 2011]. Different mechanisms are thus consistent with reduced inflow of MWDW during winter as a result of stronger cyclonic winds. Their relative importance can not be assessed using the present dataset, although the latter process might be less applicable to the wider Filchner continental shelf, west of 25°W , as ice shelf basal melting as a source of local buoyancy on the shelf is needed in order for MWDW advection to occur [Nøst *et al.*, 2011].

[17] The impact of variable wind is also apparent in the time series of inflow temperature (Figure 3). The weaker wind stress curl in 2007 (Figure 4b) is associated with relatively high temperatures throughout autumn and early winter (May–July) compared with 2008 and 2009. The difference is most striking between 2007 and 2008, the latter having the

strongest wind stress curl and the lowest water column temperatures during winter (June–August). The influence of weaker winds during winter (July–September) 2011 is not easy to assess based on the available data, but it can not be ruled out that this reduction maintains a weak wintertime inflow of MWDW (Figure 2c). The interannual wind stress variability is almost exclusively determined by wind speed (not shown), and not related to variability in sea ice concentration (Figure 4c).

[18] Our results agree with model studies by Wang *et al.* [2012] and Hellmer *et al.* [2012] on the pronounced impact of wind forcing on water mass exchange across the shelf break in the southeastern Weddell Sea. In agreement with results presented here, Wang *et al.* [2012] found that the wintertime flow onto the Filchner continental shelf was associated with a fresher water mass as a result of wind-driven changes in off-shelf stratification. On the other hand, future projections by Hellmer *et al.* [2012] show that a long-term increasing trend in the local surface stress can lead to a substantial increase in the on-shelf transport of warm water. This occurs as a warmer atmosphere reduces the formation of sea ice along the Weddell Sea coast, thus weakening the density difference between on-shelf and off-shelf waters and, hence, the blocking effect of the slope front. As a result, the enhanced surface stress redirects the ACoC southward into the Filchner Depression, eventually leading to a continuous warm inflow. The response to long-term changes is thus contrary to what is suggested by the seasonal cycle, and highlights the complex atmosphere–ice–ocean interaction in this region.

5. Conclusions

[19] We have presented unique observations from a previously undersampled region, allowing us to explore the seasonality in ocean conditions over the southeastern Weddell Sea continental shelf, in particular the on-shelf flow of warm MWDW. Using 19 instrumented Weddell seals we obtained ~9000 *TS*-profiles for the period February to October 2011. The data suggest a persistent inflow of MWDW, although substantially weaker during winter. This is corroborated by results from a mooring deployed at the shelf break between 2007 and 2009. The reduced wintertime inflow seems to be related to seasonal changes in wind forcing; stronger easterly winds (negative wind stress curl) during winter drives the off-shelf core of MWDW downward below the shelf break. A reduction in sub-surface density in the inflow region between March and June supports this mechanism.

[20] Intrusions of warm water and its sensitivity to winds implies that the oceanographic regime of the southern Weddell Sea might be affected by larger-scale climate modes such as the Southern Annular Mode (SAM) and El Niño/Southern Oscillation; a positive SAM phase being associated with stronger westerly winds and increased wind stress curl [Turner, 2004]. This connection to SAM makes the southern Weddell Sea susceptible to significant decadal variability [Hellmer *et al.*, 2009]. In addition, changes in local atmospheric forcing and associated changes in the applied surface stress can have a substantial impact on the inflow of warm water onto the shelf, and consequently on basal melt rates for the Filchner–Ronne Ice Shelf [Hellmer *et al.*, 2012]. Interestingly, the observation-based seasonality in warm water inflow and its wind dependence presented here contrasts with

the results of Hellmer *et al.* [2012], in that we find a stronger surface stress leading to a weaker, rather than a stronger, inflow of off-shelf warm waters. Further investigation of the shelf–slope exchange of MWDW and its variability is warranted.

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