Links between subtropical mid-depth warming/cooling patterns and variations in convection intensity in the subpolar Labrador Sea

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Changes in Labrador Sea Water (LSW) characteristics through time have been correlated to combinations of convection intensity and sea surface salinity anomalies in the Labrador Basin (Clarke and Gascard, 1983; Lazier, 1980, and in press; Talley and McCartney, 1982), and linked also to shifts in atmospheric circulation patterns (Dickson, Lazier, Meincke, Rhines, and Swift, 1996). Using an extensive hydrographic dataset[1], we show the spatial and temporal patterns of temperature and thickness variation at LSW densities (σ_{1500} = 34.62 - 34.72) over the entire North Atlantic Ocean from 1950 - 1995. These patterns trace the advection of temperature and thickness anomalies from the subpolar LSW formation area into the subtropical gyre along the deep western boundary currents, the North Atlantic Current, and through recirculating components of both. But they also show a basin-scale temperature response in both the western and eastern subtropics which lags behind the subpolar signal by 5-7 years. The spatial extent and amplitude of the subtropical signals seem too large to represent a mere advection of the subpolar temperature anomaly. Rather, basin-scale warming appears to reflect a substantial decrease in the volume of LSW entering the subtropical basins and to represent a time-lagged response to weakening of subpolar convection. Re-establishments of strong convection result in increased volumes of LSW entering the subtropics and a time-lagged cooling and thickening of the subtropical density layer.

Figure 1 generalizes the time history of properties at the core of the LSW in its source region and depicts decadal-scale changes in this watermass which are directly related to changes in convection intensity. Periods of strong convection are characterized by cold, fresh, and thick conditions; periods of weak convection result in warmer, saltier, and thinner characteristics. The general warming, salinity increase, and thinning from the 1950s to 1971 abruptly changes with a brief return of strong convection in the early to mid 1970s. The 1980s begin with weak convection, but by 1987, the return of strong convection culminates in the coldest, freshest and thickest conditions ever measured which persist at the time of this writing. The convective

[1] The dataset is based on the Lozier, Owens, and Curry (1995) North Atlantic dataset which has been augmented with CTD data from WHOI and SIO archives, plus all North Atlantic data available from the WOCE Hydrograpic Programme Office. Database management and climatological analyses were done with HydroBase (Curry, 1996).

events of the 1970s and late 1980s were both preceded by a surface buildup of an extremely low salinity cap, the first of which has been called the "Great Salinity Anomaly" (Dickson, Meincke, Malmberg & Lee, 1988) and the second of which appears to be the return of this feature following its circuit around the subpolar gyre (Belkin, Levitus & Antonov, 1995). The downward mixing of this fresh cap dramatically lowered the LSW core salinity. The slight rise in salinities since 1990 reflects the recent deep convection of cold, but higher salinity water underlying the LSW.

Figure 2 shows the thickness of the density layer over the North Atlantic in each of six consecutive time periods spanning approximately eight years each: (A)1950-57, (B) 1958-65, (C) 1966-72, (D) 1973-79, (E) 1980-86, and (F) 1987-94. The LSW is readily distinguished by the thick (> 1000 m) contours in the northwestern portion of the map emanating from the Labrador Basin. In contrast, the more stratified Mediterranean Outflow Water (MOW) is characterized by a relatively thin (< 500 meters) tongue stretching across the Atlantic from the Straits of Gibraltar. These two water masses are mixed by recirculations associated with the deep western boundary current, Gulf Stream and North Atlantic Current creating the intermediate thicknesses between the two sources. The 500 meter contour separates the areas where LSW strongly influences this layer from regions where MOW characteristics predominate.

In its source region, as noted above, the thickness of the LSW layer moves in time through a cycle which directly represents variations in the intensity of wintertime convection. Away from the source, the Slope Water and North Atlantic Current (NAC) are noticeably thin in the 1970s and 1980s, but robustly flooded with LSW in the 1950s, 1960s, and 1990s. South of the Gulf Stream/NAC system the subtropical thickness looks fairly similar in all but panel D (1973-80) when the MOW characteristics (< 500 meters) are extended northward in the eastern basin, and westward in the western basin. Compare the areas around the Azores and south of Bermuda in each panel to see this change.

In place of temperature maps for each time period, figure 3 depicts the temperature difference for one time period compared to the period before it, for a density surface in the middle of the LSW layer (σ_{1500} = 34.67). The first two panels show the onset of warming in the subpolar gyre in the 1950s and 1960s. Panel B indicates that the warm anomaly has spread along the direct advection paths: southward in the western boundary current and eastward in the NAC. In these two time frames, the western subtropical basin, south of the Gulf Stream, shows little temperature change, while the eastern basin shows significant cooling from 30°N to 40°N. In the third panel, the convection pulse of the 1970s creates a cold anomaly in the western subpolar gyre and western portion of the NAC; however, a warm anomaly now occupies both eastern and western subtropical basins. This is the time frame of panel D, figure 2, in which MOW characteristics extend farther north and west. In the fourth panel, convection has gone slack again in the Labrador Basin -- temperature shows little change with perhaps a hint of warming -- but a cold anomaly now dominates the subtropical basins. In the western basin, the Slope Water, DWBC, and the recirculations south of the Gulf Stream have all cooled. The last panel shows intense cooling associated with the 1990s return of strong convection in the Labrador Basin. The cooling has spread southward to the 36°N section (collected in 1993), but has not yet arrived at 24°N (collected in 1992) in the western basin. This basin, south of 30°N, instead has stopped cooling and shows perhaps a hint of warming.

These spatial and temporal patterns show consecutive instances where a temperature anomaly of one sign appears in the Labrador Basin and is rather quickly advected southward and eastward by the boundary current and NAC. One time period later, a subtropical anomaly of the same sign appears in both western and eastern basins which seems to be a lagged response to the subpolar signal. Although this response might reflect an advection of the subpolar temperature anomaly (e.g. the same volume of water, but warmer), we would expect that downstream from a source, a property would be diluted and the amplitude of its signal dampened. However, the magnitude and spatial extent of the subtropical temperature response, especially in the eastern basin, are quite large. We find a partial resolution of this puzzle in realizing that thickness anomalies, which are another property of the LSW source, propagate also into the subtropical basins changing the volume of LSW available to mix with the MOW. A decrease in the amount of LSW relative to MOW results in warmer, saltier properties in this density layer; an increase creates cooler, fresher characteristics. This volume anomaly, rather than the subpolar temperature signal, appears to dominate the subtropical temperature response at these densities.

Figure 4 shows how the thickness anomalies propagate from the subpolar gyre to the subtropical basins by depicting the change in thickness of the LSW density layer of each period compared to the previous period. Like temperature, the subtropical thickness anomalies lag behind the subpolar signal by one time period and are concentrated in the recirculations cells of the DWBC, Gulf Stream and NAC. The location and sign of the thickness anomalies are closely related to that of the temperature anomalies: warm anomalies correspond spatially and temporally to layer thinning, while cold anomalies correspond to layer thickening. The thickness anomalies appear to spread away from their subpolar source and their amplitude diminishes from >500 meters at the source to 100-200 meters in the subtropical basins. From these patterns, we infer that the subtropical temperature anomalies, which are equal or greater in magnitude than the subpolar source signal, reflect a change in LSW volume mixing with the warmer, saltier MOW.

Near the MOW source, the temperature signal is more complicated than this simple inference and reflects the nature of the water mass mixing in this region. The MOW is concentrated in small parcels (meddies) which translate into the intense temperature anomalies that appear to the west of the Mediterranean source. An abrupt LSW front (low salt, high oxygen) at 40°N abuts a buffer region of well-mixed

LSW/MOW from 40°-38°N (Tsuchiya, Talley, and McCartney, 1992). South of 38°N, MOW dominates but parcels of LSW are found as far south as 30°N indicating that in this region, these two watermasses are not homogeneously mixed but concentrated pockets of each are scattered throughout. The large thickness anomalies in the eastern basin extend southward only to 30°N, hence we conclude that the temperature anomalies to the south of this latitude have nothing to do with LSW and the temperature anomalies from 30°-40°N in the eastern basin reflect a combination of LSW influences and the local meddy population.

Because the thickness of the LSW layer at its subpolar source region is directly related to the strength of wintertime convection, the temperature and thickness propagation patterns suggest a strong, and time-delayed, linkage between the intensity of subpolar convective processes and the volume of LSW which enters the subtropics. Figure 5 shows a time-lagged correlation between the temperature change in the 1500-2500 meter layer at Station Panulirus near Bermuda and the LSW thickness variation in the Labrador Basin. The correlation is highest ($r = \sim .5$) at lags of 5 or 6 years and implies that when subpolar convection is strong, the subtropical basins will receive large volumes of LSW five to six years later and result in cool temperatures. Conversely, weaker subpolar convection results in warmer subtropical temperatures a few years later. The temperature at Panulirus correlates better to subpolar thickness than to subpolar temperature: the subpolar temperature peaks before the convective pulse of the 1970s, while the subtropical temperature peaks after (the time-lagged arrival of) the convective pulse. This pattern mirrors the subpolar thickness history in which the layer is thinnest after the 1970s convection event and emphasizes that the subtropical temperature anomaly is more a response to the advected thickness anomaly than to the subpolar temperature anomaly.

From a purely observational point of view, mapping the temperature and thickness anomalies improves our temporal and spatial understanding of the subtropical warming trend which has been reported by several researchers (Roemmich and Wunsch, 1984; Parilla, et al., 1994). The time delay in propagation of the thickness anomalies accounts for the persistence of the mid-depth subtropical warming despite the fact that conditions in the Labrador Basin have turned extremely cold and fresh in the 1990's. It also allows us to predict a significant cooling of the subtropics at these depths later this decade.

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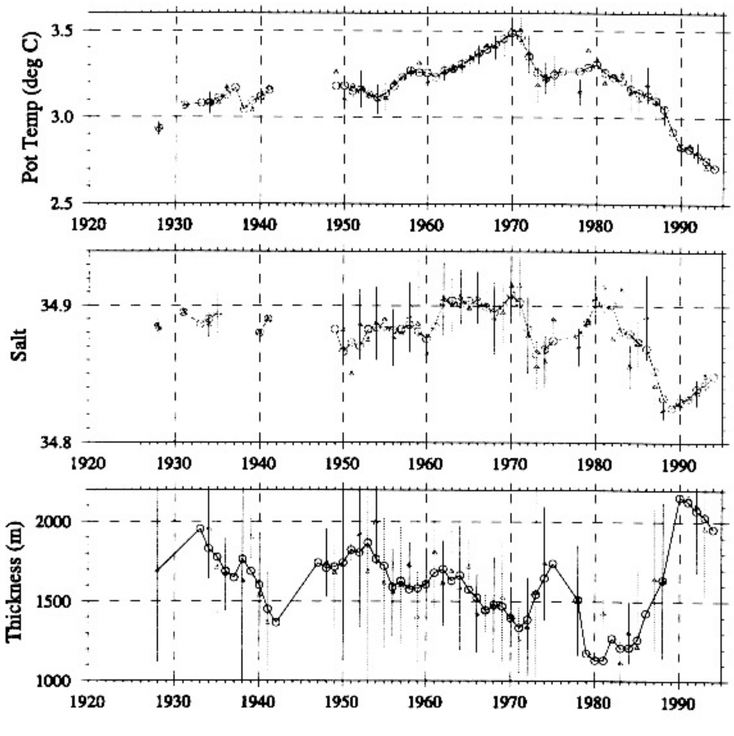


Figure 1: Time history of LSW core properties from a 5° square area in the Labrador Basin. The mean values for each year (triangles) and standard deviations (vertical lines) have been smoothed with a 3-point running filter to produce the curves. Potential temperature and salinity are the values at the lowest observed temperature between 1000-1800 meters. Thickness is the vertical distance between two density surfaces $\sigma1500 = 34.62 - 34.72$.

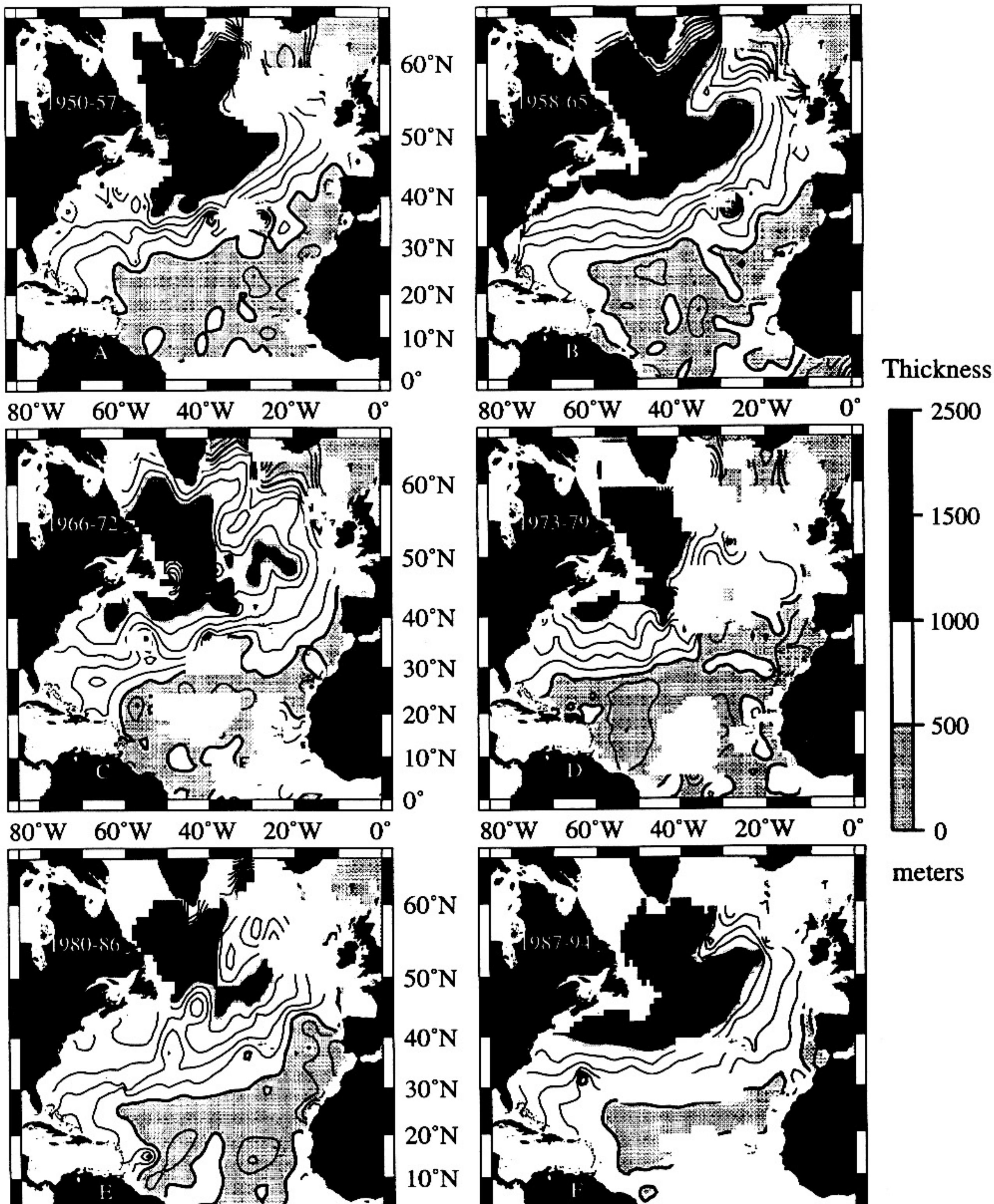
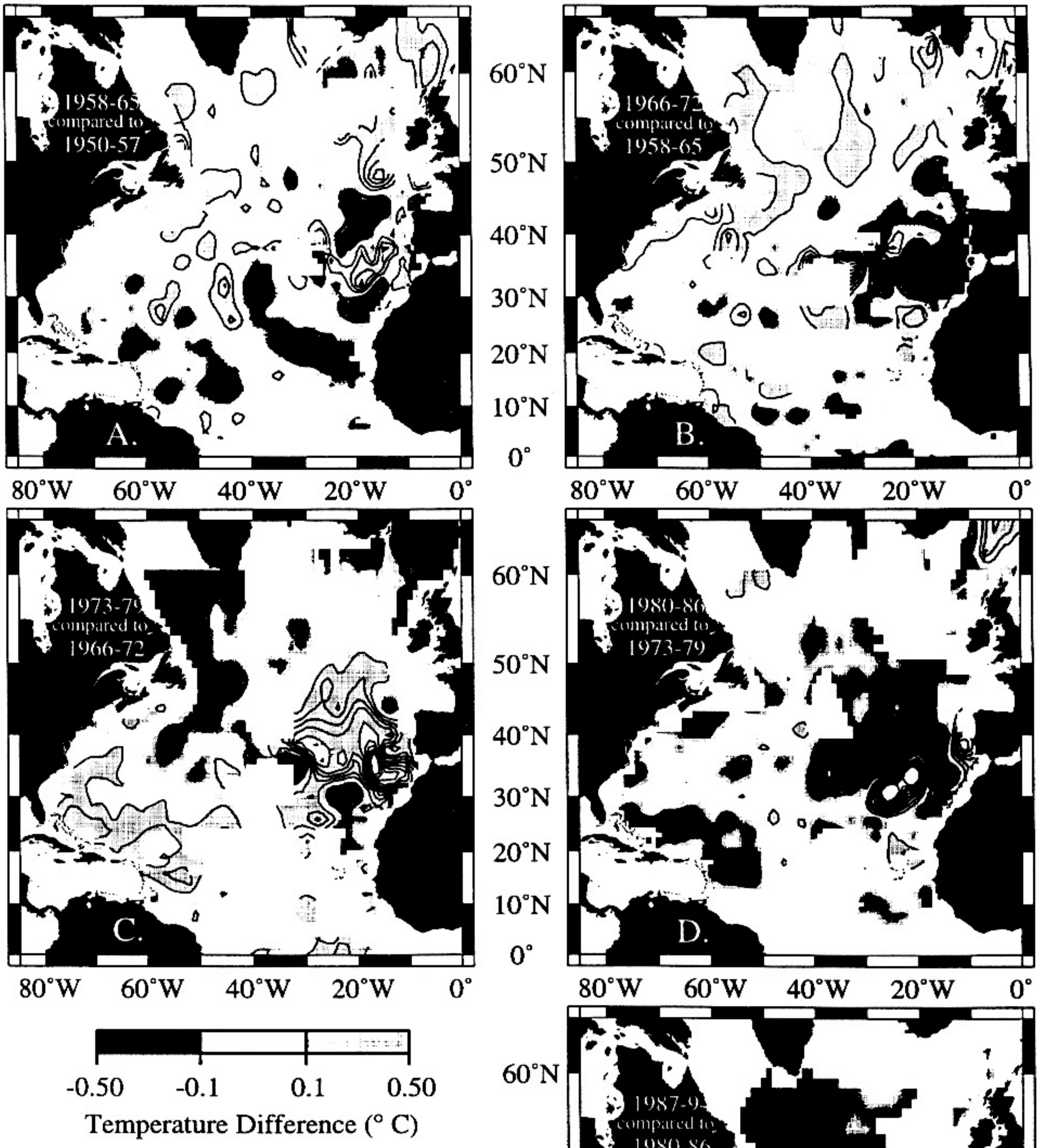


Figure 2: Thickness of LSW layer defined by distance (in meters) between two density surfaces: $\sigma1500 = 34.62$ and 34.72. Each panel represents a time frame spanning 7-8 years. Contours are spaced at 100 meter intervals.



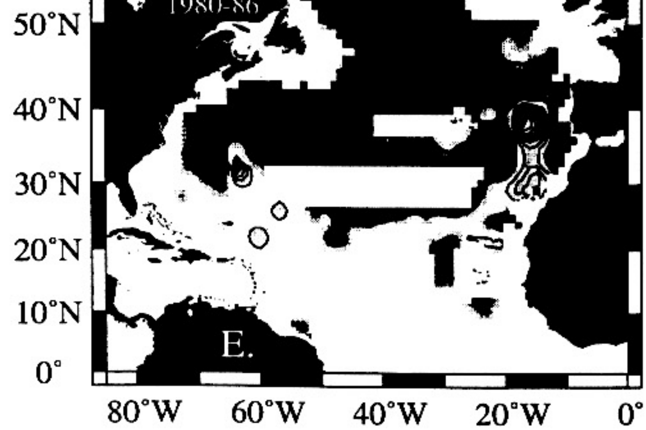
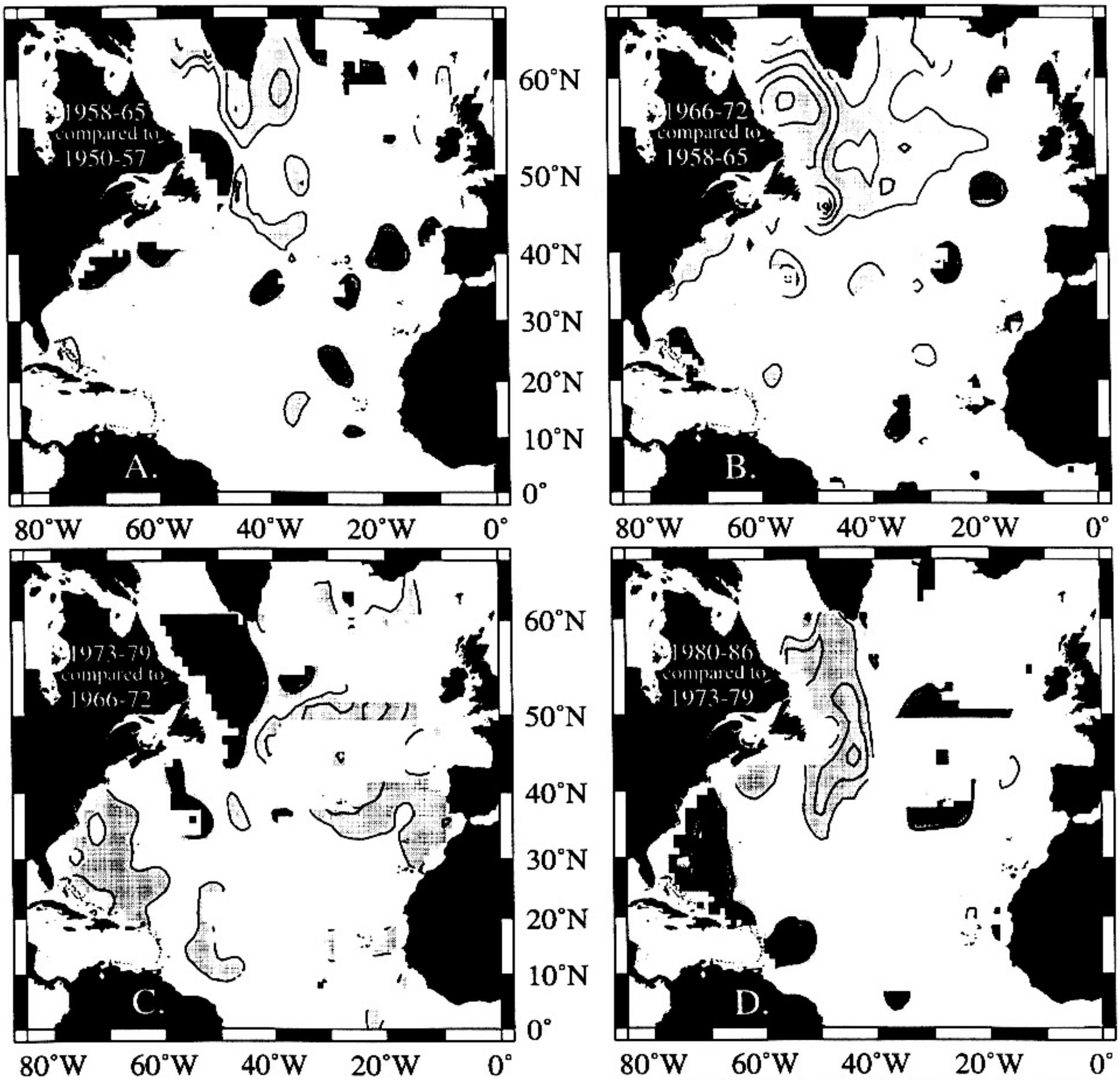
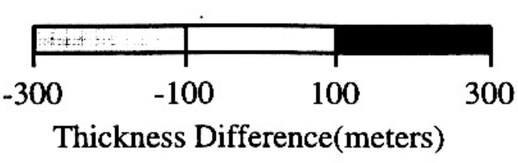


Figure 3: Change in potential temperature on a density surface in the middle of the LSW layer ($\sigma 1500 = 34.67$) for five pairs of consecutive time periods. Warming in the later period compared to the earlier is indicated by light shading and thin contours; dark shading and thick contours correspond to cooling in the later time frame. Contours are spaced at 0.1°C intervals.





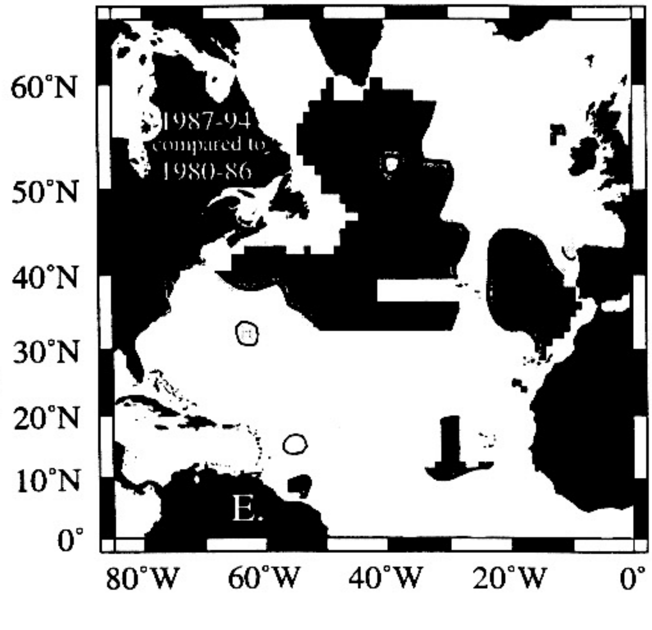
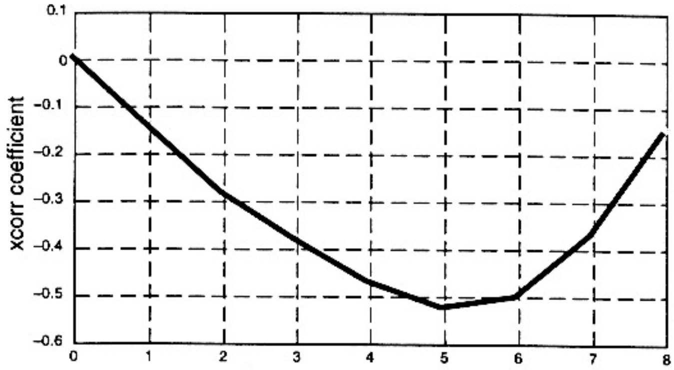


Figure 4: Change in thickness of LSW layer for five pairs of consecutive time periods. Layer thinning in the later time frame compared to the the earlier frame is denoted by light shading and thin contours; dark shading and thick contours correspond to layer thickening. Contours are spaced at 100 meter intervals.



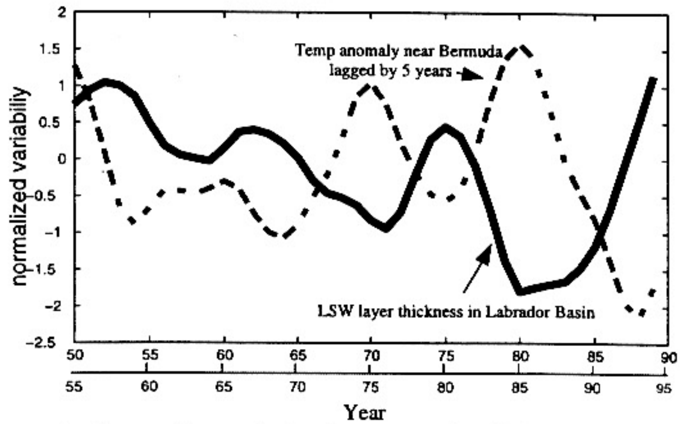


Figure 5: Lagged correlation between the thickness of the LSW layer in its source region (solid line) and the detrended temperature anomaly in the 1500-2500 meter layer (broken curve) from the Panulirus station near Bermuda (Joyce and Robbins, 1996). The upper panel gives the correlation coefficients for 0-8 years.