# *ACCP NOTES*

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## *The Interdecadal Warming and Cooling of Labrador Sea Water*

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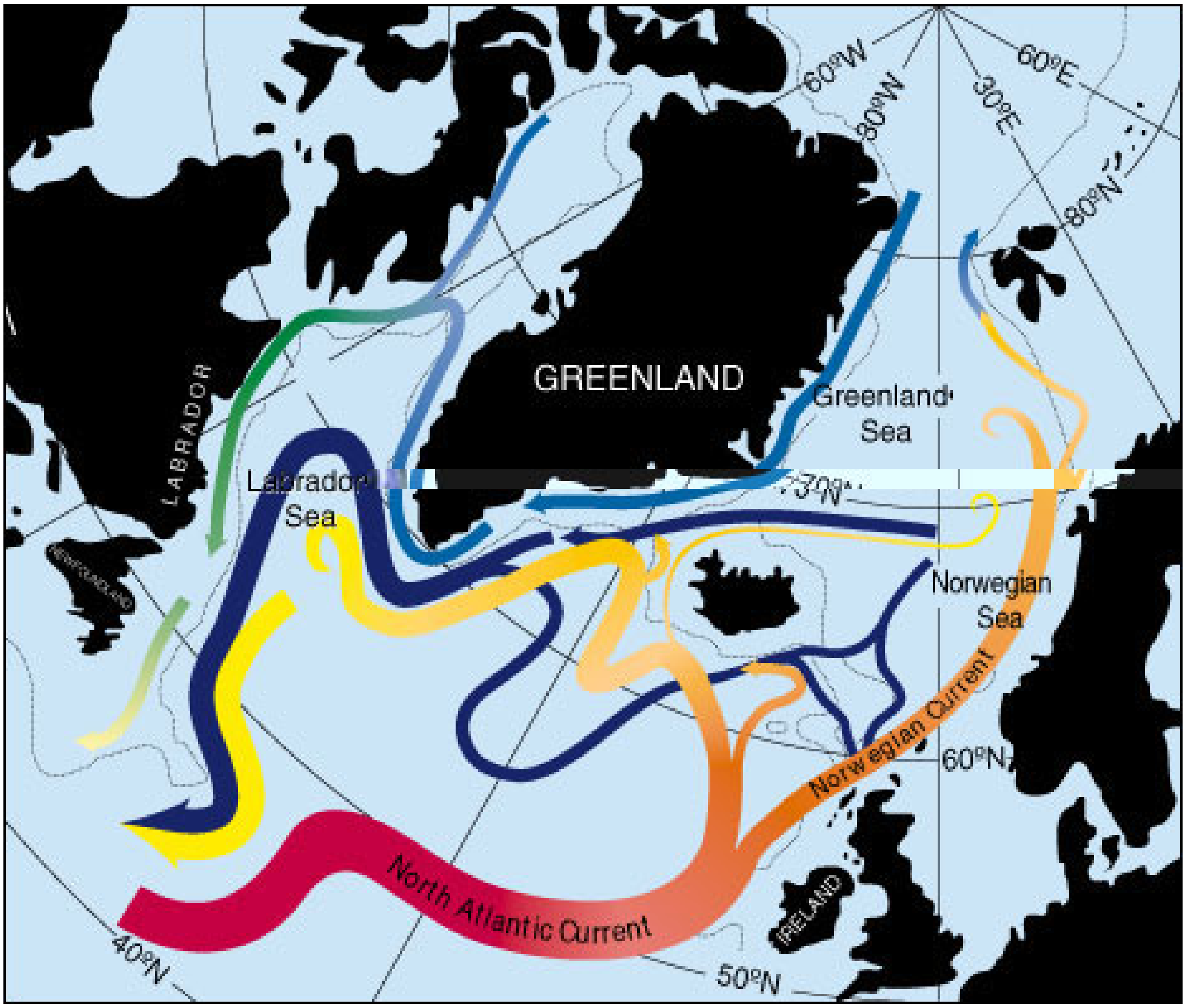
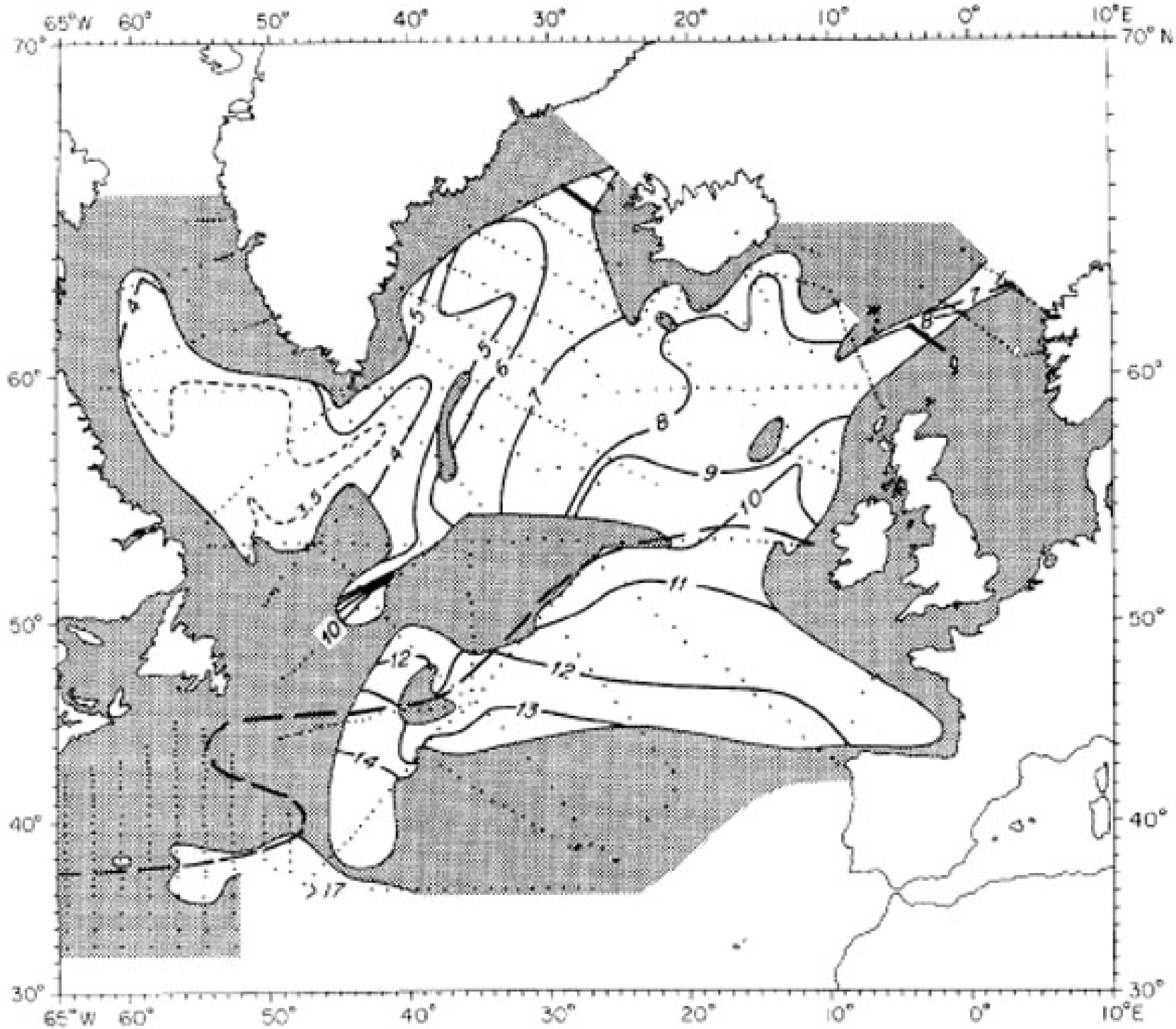
### 1. Introduction: The warming and cooling of Labrador Sea Water in the western subpolar North Atlantic.

The northern North Atlantic is one of the two major sites for the warm to cold water conversion of the global thermohaline overturning circulation. Warm water crosses from the subtropical domain into the subpolar domain near 50°N, Figure 1.




## Figure 1.

There are three distinct elements to the conversion of that warm subtropical water into cold waters: 1.) The conversion of warm water into cold dense waters within the Nordic and Polar Seas, returned to lower latitudes as dense overflows across t he Greenland Scotland ridge system (Worthington, 1970). 2.) The entrain- ment of warm water into Nordic Seas overflows as they descend to deep levels within the subpolar domain (Worthington, 1970), and the transformation of warm water into Labrad or Sea Water (LSW) by cooling along the cyclonic pathway of the subpolar gyre (McCartney and Talley, 1982). The amplitude of this overturning, order 13 Sverdrups, is approximately equally partitioned between these three elements (McCartney and Ta lley, 1984; Schmitz and McCartney, 1993). We focus here on the subpolar transformation pathway producing LSW, and specifically on changes of conditions along that pathway that may be responsible for the observed interdecadal variability of LSW. A long this pathway subtropical waters at about 11°C flowing northwards to the west of Ireland are progressively cooled by about 7°C as they traverse the subpolar gyre to the Labrador Basin, freshening and becoming denser, yielding LSW at temperatu res less than 4°C as the ultimate state of progressive convective transformation following the flow, Figure 2.



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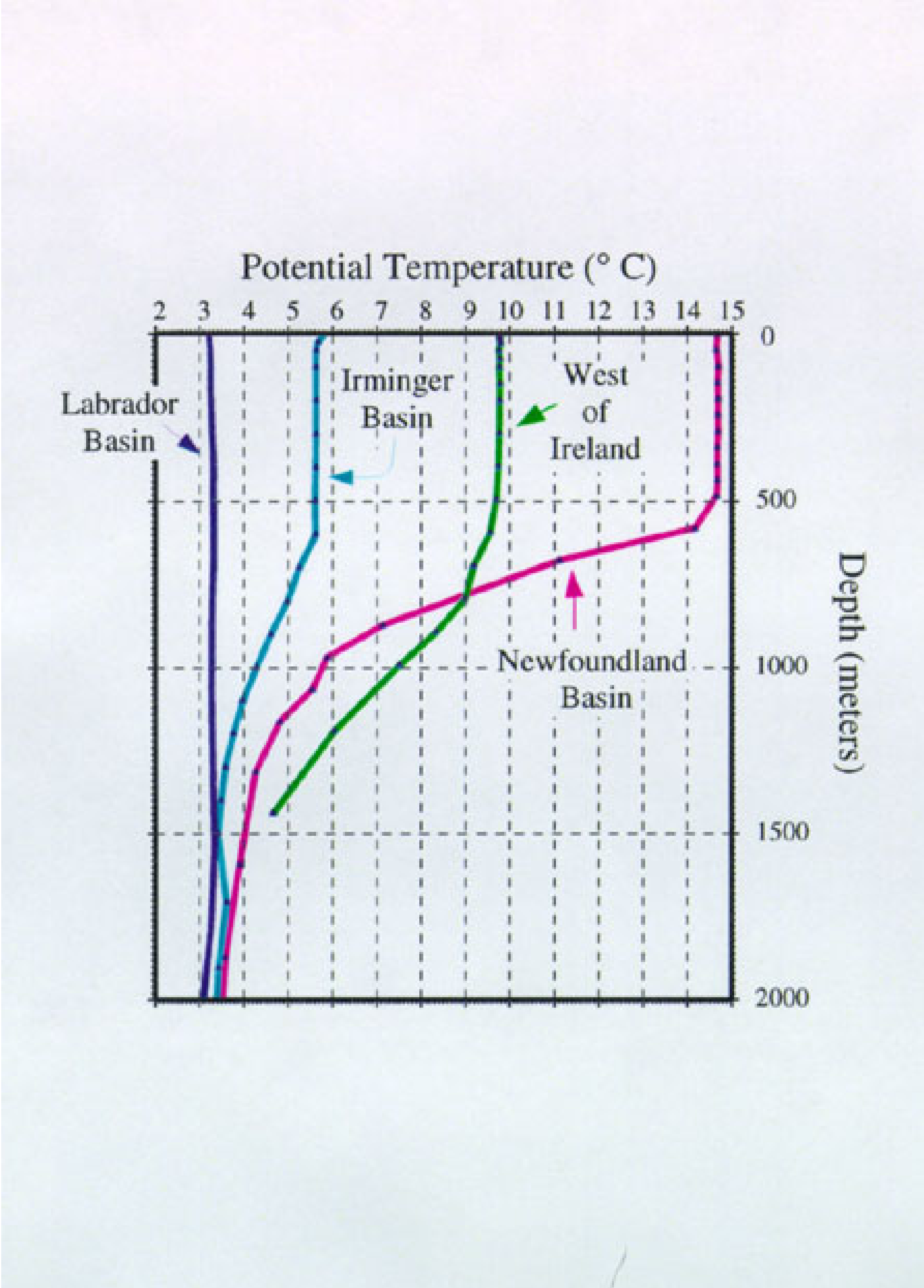
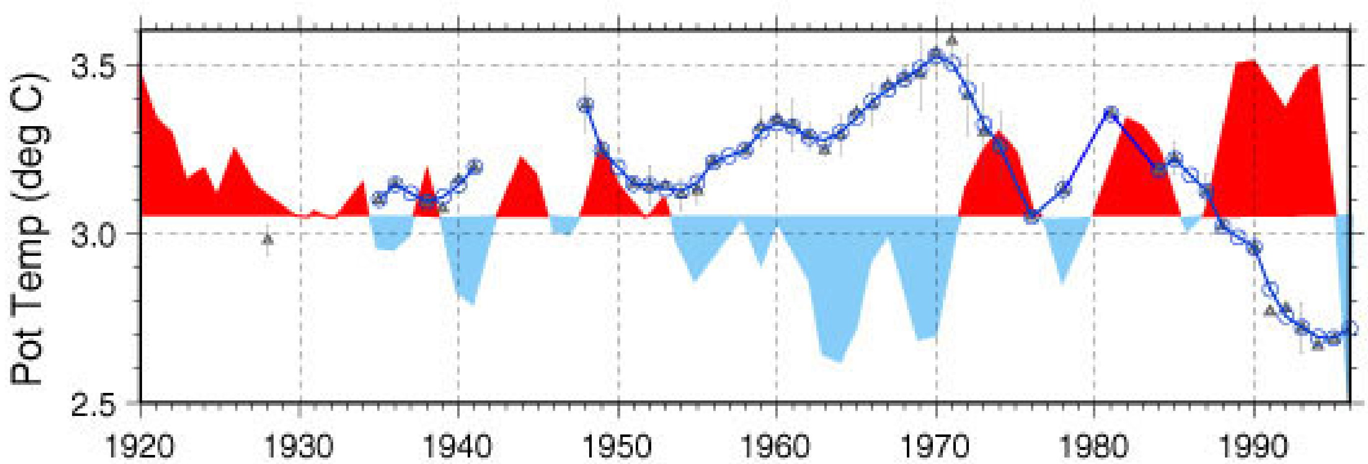
17


**Figure 2.**




This progressive transformation is the Subpolar Mode Water transformation process (SPMW). The agent of the cooling is winter convection following the cyclonic Lagrangian pathway of the upper water column, driven by the liberation of heat from the ocean to the atmosphere, and is manifested by the cooling and deepening of a pycnostad along the pathway. The pycnostad is present all year and reflects the memory of the preceding winter's convective homogenization, before the next winter overturns through that density, mixing the pycnostad with underlying waters and air-sea heat and fresh water fluxes to produce a somewhat denser level convective mixed layer (colder and fresher): the abduction mechanism of Qiu and Hua ng (1995). It is this convection driven transformation following the horizontal flow around the subpolar gyre that converts warm saline water into cold fresh LSW, which is the primary source of the upper part of the North Atlantic Deep Water throughout the North Atlantic (Talley and McCartney, 1982).

The history of characteristics of the LSW in its winter outcrop area in the Labrador Sea (LS) can be well described forward in time from World War II (WWII), with a few pre - WWII observations also available. In Figure 3 we plot the LSW core tem perature data from the central Labrador Sea as available in early 1996. The post war data, 1948 - 1993, has been much studied, beginning with the seminal work by Lazier (1980), who focused on a particularly intensive sampling program in 1964 - 19 73, and continuing with the Talley and McCartney (1982) examination of the more extended time history. From the early 1950's through 1971 LSW very steadily warmed from 3.1 °C to 3.5 °C, a very substantial rise of about 0.4°C over two decades for a water mass that dominates the upper 2000 meters of the Labrador Basin. Of particular recent note are studies by Lazier (1995) and Dickson, et al. (1996), documenting an extended cooling phase starting in winter 1971 - 1972, and continuing throu gh the present: a two decade cooling of about 0.8°C, with an interruption of the trend only for a few years around 1980. We next describe some of the details of these warming and cooling periods, as well as the sparser pre - WWII data.




## Figure 3.

The much sparser pre-WWII data suggests an LSW warming trend from LSW temperatures of 2.9°C in 1928, through 1941, ending either in the WWII data gap with some unknown temperature above 3.2°C or with the last pre - or first post - WWII observati ons at 3.2°C. Brief and slight cooling episodes, 1937 - 1938, 1948 - 1954, and 1958 - 1961, mildly interrupt what is a remarkable 44 year LSW warming trend (2.9 °C to 3.5 °C). The subsequent post - 1971 cooling trend had by 1990 chilled the LSW t o temperatures similar to those of 1928, some 63 years earlier. The cooling has continued in the early 1990s taking the LSW to a coldness unprecedented in the instrumental record (Dickson, et al., 1996). It remains to be seen what extreme state the LSW is destined to reach when the "cycle" bottoms out at a cold extreme and how long the cycle duration extends. In a companion study (Curry and McCartney, this volume) the time - delayed impact of this LSW source history on the sub - thermo cline waters of the subtropics is explored. In this article we examine the relation between this LSW history and the warm to cold water conversion within the subpolar circulation that transforms warm saline subtropical waters into LSW.

Lazier (1980) documented the interannual build up of a low salinity cap progressively from around 1967 - 1968 to a most extreme state in summer 1971, in the LS area where LSW convectively homogenizes in winter. This low salinity cap blocked conv ection to LSW levels, and the LSW warmed and gained salinity until the reinitiation of convection in winter 1971 - 1972, LSW cooled -- and freshened through the mixing of the cold and fresh cap into the connectively homogenized LSW. Dickson, et a l (1988) have drawn attention to a propagating upper ocean low salinity anomaly (the Great Salinity Anomaly, 1968 - 1982) as the cause of the LS low salinity cap as it passed through the LS in the late 1960s. The GSA is described as originating i n 1968 in the East Greenland Current well north of the Denmark Strait, arriving in the northern LS in 1969- 1970 (via advection in the East and West Greenland Currents) and as leaving the LS around 1972 (via advection by the Labrador and North At lantic Currents). Reinitiation of convection beginning in winter 1971 - 1972, coincides with this departure of the GSA, and marks the beginning of the LSW cooling trend, Lazier (1995). The year 1968 indicated by Dickson, et al. (1988) for the ini tiation of the GSA in the Greenland Sea corresponds to the beginning of the interannual build up of the low salinity lid in the LS described by Lazier (1980).

Talley and McCartney (1982) have shown that the period (1964 - 1974) discussed by Lazier (1980) is part of a longer period trend with LSW steadily warming and rising appreciably in salinity. These trends occur on both the LSW core layer and on a ssociated isopycnals. They examined data earlier than that used by Lazier, finding evidence of the warming trend extending forward from WWII. They also noted a comparative coldness of LSW in pre- WWII data compared to post - WWII data suggestive of the warming period beginning before WWII. Progressive isolation of associated density surfaces was clear for the post war data, perceptible from the mid 1950s forward, as the warming trend limited the convective influence to lighter isopycnals , and culminated with the complete isolation of LSW from convection during the GSA transit of the LS. Talley and McCartney also noted that the denser isopycnals exhibited warming from the 1920s through the last year of their analysis, 1974, perha ps indicative of convection to these surfaces early in this century, but isolation since the 1920s, as not even the 1970s reinitiation of convection penetrated deep and dense enough to reach them. Dickson, et al. (1996) show that the now -long cooling trend from 1971 forward has finally reached these long isolated surfaces, with the LSW density at its all time record maximum with LSW convective homogenization at colder than 2.7°C exceeding 2000 meters in convecting depth.

Lazier (1995) finds a second, less dramatic period of build up of a low salinity cap in the LS in 1978 - 1984 associated with the hiatus in the post 1971 LSW cooling trend, and Belkin, et al. (1996), have associated that cap with a LS phase of a second GSA traversing a path similar to the first GSA, but about a decade after the first. So, superimposed on the cooling since 1971 is what may be interpreted as a weaker repeat of the capping of deep convection by lowered upper ocean salinity inhibiting overturning. Since this hiatus appears less striking than the GSA we will call it the Lesser GSA (LGSA) to provide a convenient acronym for our discussion. The GSA then is associated with the final phase of the long (44+ years) LSW wa rming period, while the LGSA is associated with an interruption of the long (24+ years) LSW cooling period since 1971.

## 2. The role of temperature anomalies in Labrador Sea Water variability: The Subpolar Mode Water transformation process and Sea Surface Temperature anomalies.

The GSA and LGSA events have led to some preoccupation with the role of salinity in LSW history. The somewhat different slant we want to put on the interpretation of this LSW history is a focus on temperature rather than salinity: n ot only the LSW temperature, but the temperature distribution along the warm to cold water transformation pathway around the subpolar gyre that produces LSW. This is motivated by a recent SST anomaly study (Hansen and Bezdek, 1996), but also reco gnizes that the SPMW transformation that produces LSW is thermally driven in the sense that convection occurs because of cooling, opposed by freshening, but with the combination of these opposing forcings almost always producing winter convection and densification of the upper water column following the flow over most of the SPMW transformation pathway.

To put the GSA event in perspective, we note that the inhibition of convective overturning to LSW for 1967 - 1971 during the GSA build up in the LS coincides with only the last four years of post - WWII LSW warming trend of about twenty years du ration -- or of the overall LSW warming period pre - and post - WWII of more than forty years duration. This GSA period is short, and involved with about 0.1 °C of the 0.4 °C post - WWII LSW warming or of the overall 0.6 °C LSW warming from 1928 through 1971. For the post -1971 twenty years of LSW cooling the LGSA is a similarly short 5 year perturbation of about 0.1°C superimposed on the 0.8°C total cooling recorded thus far through 1993.

We hypothesize that the LSW warming and cooling trends in the LS reflect the downstream - integrated history of warm or cold conditions along this SPMW transformation pathway. This is suggested by sea surface temperature (SST) data now discussed . The inferred linkage between the SST and the subsurface winter convection and SPMW is the subject of ongoing continued analysis, here we give only preliminary results.

Kushnir (1994), and Deser and Blackmon (1993) have shown that the 1950s and 1960s were generally warm in SST compared to the later years. The post - WWII LSW warming trend in the LS thus occurs during a period of generally warmer SST in the subp olar gyre, while the subsequent LSW cooling trend occurs during a period of cooler SST. Similarly, they show the period from the mid 1920s to WWII as warm in SST compared to earlier in the century, so the less well resolved earlier phase of LSW w arming occurred when SST was warm relative to the preceding decades. It is difficult to bridge the WWII data gap and consider the overall SST history for this century in the context of the progression of LSW warming and cooling from the 1920s to the present because methodology induced SST biases across the 1940s as SST measurements shifted from a dominance of bucket measurements early, to engine intake measurements later.

Hansen and Bezdek (1996) have examined the annual march of January SST anomalies for the post WWII era, Figure 4. They show that while subpolar SST begins (1948 - 1950) anomalously cold (we note in passing that these years show LSW cooling, Figu re 3), from 1951 to 1968 a warm anomaly traverses the subpolar gyre, beginning in the Newfoundland Basin in 1951, branching northwards to the west of Ireland in 1955, passing westward to the south of Iceland in 1960, fading but then reemerging ar ound southern

Greenland and the Labrador Sea in 1965. (SST data from the area south of Iceland reported by Smed, et al., 1982, show that the warm anomaly is visible in the southern Icelandic environs throughout the period 1961, but with a somewha t weaker amplitude in 1962 - 1964. The standard deviation criterion used for the Hansen and Bezdek SST anomaly map, Figure 4, misses this weaker warm anomaly.) The pathway the warm anomaly traverses is the SPMW transformation pathway, Figure 1. I t is this traveling SST signal that dominates the overall post WWII SST warmness of the subpolar gyre in the 1950s and 1960s. Since January SST is tightly linked to the winter convection temperature, this leads to our hypothesis: that this pro pagating warm anomaly, as the extreme SST anomaly signal in a regionally warm subpolar gyre, reflects an abnormal warm phase of the SPMW transformation process. In other words, a given SPMW convection temperature occurred farther downstream aroun d the gyre pathway in the 1950s - 1960. The water coming out of the end of the transformation "pipeline", LSW, trended warm during this period as a response to the warmness of the SPMW transformation system. To be clear on this point, remember th at Figure 4 illustrates anomalies of local SST, not SST itself. The January SST field would resemble the winter mixed layer temperature map, Figure 2. Thus the warm SST anomaly of the Newfoundland basin in 1952 is a SST running warm relative to t he "normal" mixed layer temperatures of 12 - 14°C, while the warm anomaly moving northward past Ireland in 1978 - 58 is relative to a local mixed layer temperature of 9 - 11°C, and the warm anomaly in the Irminger basin off east Greenland in 1966 - 67 is relative to a 4 to 6°C winter mixed layer. And finally, the warm SST anomaly in the LS in 1966 - 68 reflects the warmest state of LSW convection, just before the GSA starts to inhibit vertical convection by its low salinity cap over the LSW in the LS.

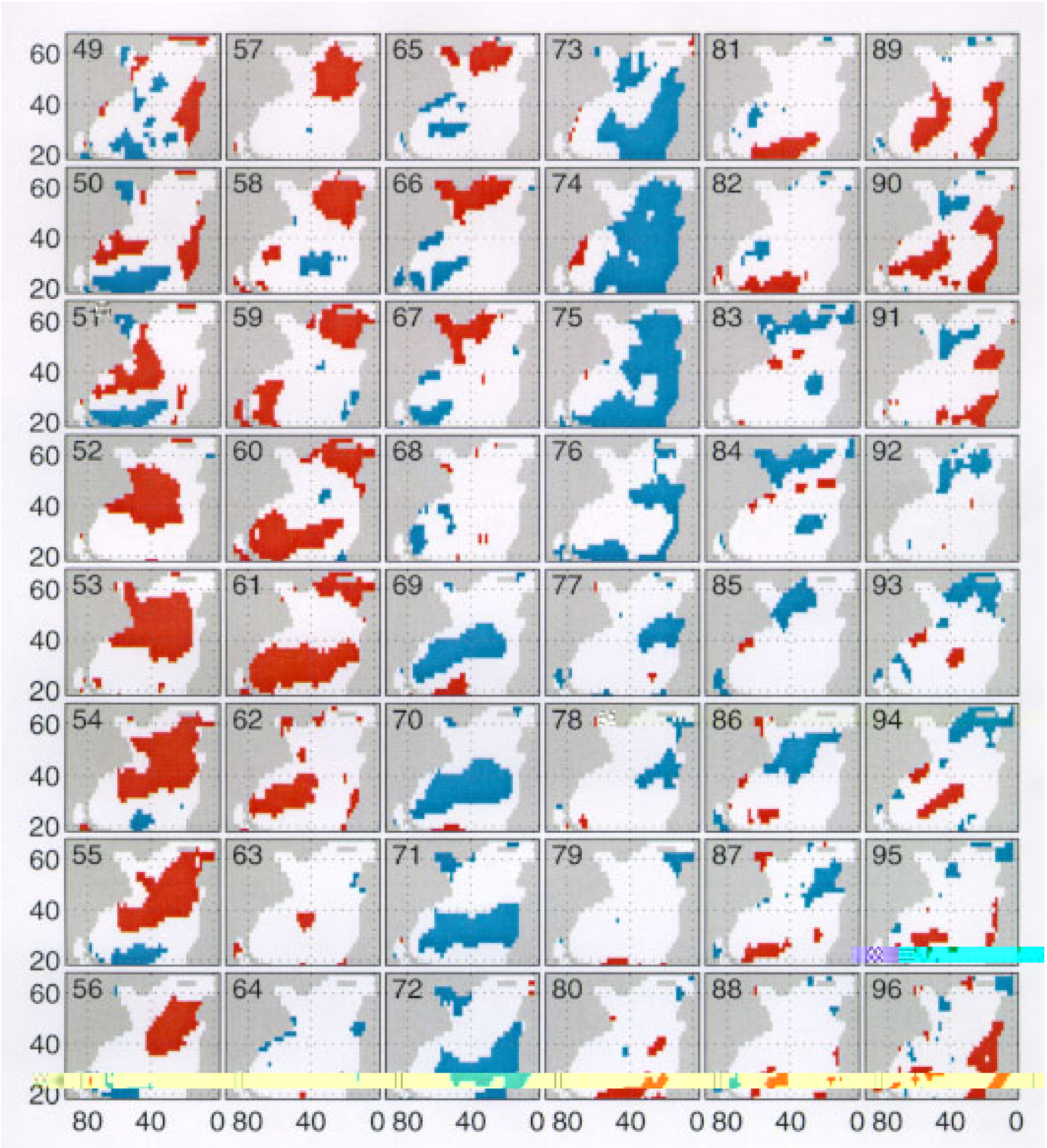



**Figure 4.**

Several mechanisms could explain this warmness along the SPMW transformation pipeline, that is, why the distribution of local winter mixed layer temperature ran warm for an extended period, and why a given SPMW isotherm convected farther downstr eam along the transformation pathway. First, the intensity and/or temperature of the warm water flowing into the subpolar gyre could have increased so that a fixed distribution of heat loss to the atmosphere requires a longer downstream distance to cool the water column past a given SPMW temperature. Second, the distribution of surface heat flux might have weakened for a fixed intensity and temperature of warm inflow, again requiring an increased downstream distance to cool to given temp erature. Third, a weakening of the rate of upwards entrainment into the downstream evolving SPMW could have occurred, perhaps a decline of Ekman suction, so that the mixture of waters homogenized by winter convection has less contribution of upwe lled colder thermocline waters.

Whatever the combination of such things that actually occurs, the result is a warm winter SST anomaly reflecting a warmer than normal winter mixed layer, and for the subsequent period before the next winter's convection, a warm SPMW pycnostad at a given location along the pipeline. This pycnostad is the "memory" mechanism that allows the reappearance downstream in a subsequent winter of the warm anomaly. While in this scenario a given SPMW isotherm is displaced downstream along the tran sformation pipeline, that pipeline is of finite length, ending in the Labrador Basin with the southward turning of the subpolar gyre circulation, with the coldest densest SPMW, the LSW, that the forcing can produce from the SPMW flowing past the southern tip of Greenland. This coldest densest SPMW then runs warm when the upstream conditions along the pipeline run warm. Since the subpolar gyre contains a pool of recirculating LSW (McCartney, 1992) undergoing only partial annual replacemen t by the production of LSW by the SPMW transformation pipeline, this warning integrates in impact with time within the subpolar gyre, as the older, colder LSW is progressively fractionally replaced by/mixed with the newer warmer LSW, to balance t he slow drain LSW from the recirculating pool in the subpolar gyre by the deep western boundary current.

In this SPMW warming scenario of interdecadal duration, the much shorter impact of the GSA is only involved in the very last phase of the LSW warming trend. The GSA may be involved in the demise of the propagating warm SST anomaly, as the latter 's fading in 1968 in the LS, Figure 4, coincides with the build up phase of the GSA there as described by Lazier, 1980. A scenario for such involvement goes as follows. The regional heat flux from the ocean to the atmosphere in the LS, normally d riving the deep convection of the last segment of the SPMW transformation pipeline, is increasingly inhibited in depth of influence by the growing low salinity cap. That heat flux thus acts on a progressively thinner layer, over-cools that layer, killing the warm SST anomaly, establishing normal SST for 1969 - 1971, and subsequently through continued cooling a cold SST anomaly for 1972 - 1973, Figure 2. This interaction is amplified by the known shift in atmospheric circulation around 19 71 that increased the intensity of winds and evaporative heat flux (Deser and Blackmon, 1993). The resulting cold anomaly also propagates, Figure 4, 1972 - 1976, and is physically linked to the subsequent continued propagation of the GSA, as they move in concert across the subpolar North Atlantic to fade away near the Faroe Islands in 1976 at the time Dickson, et al. (1988) show the GSA entering the Norwegian Current. This SST sequence indicates about a twenty year lag between the col d SST anomaly and the GSA passage through the eastern subpolar gyre and the preceding warm SST event responsible for the SPMW transformation pipeline running hot.

Here is a review of the sequence of events. A warm SST event enters the subpolar gyre circulation in the early 1950s, passes northwards in the eastern subpolar gyre in the late 1950s. It impacts the Norwegian Current, as station M (Gammelsrod, e t al, 1992) has warm conditions in 1959 - 1962, but also flows westward in the subpolar gyre to appear in Irminger Sea south of the Denmark Strait through the 1960s, before fading in 1968 in the LS. All during this time the SPMW pipeline runs ano malously warm: a given winter mixed layer temperature occurs farther downstream than usual along the pipeline, and the LSW emerging from the SPMW pipeline trends warm. The first GSA builds north of the Denmark Strait in the late 1960s, perhaps so mehow reflecting the Nordic Seas impact of the part of the warm SST anomaly that passed station M a few years earlier (see the northern part of the black pathways on Figure 1). The GSA advects along the coast of Greenland to the LS in the late 19 60s, initiating the demise of the warm SST anomaly which dominated there in the early 1960s, and reaching maximum GSA strength in 1971. During this buildup of the GSA in the Labrador Basin, the last stage of downstream convective cooling of the a lready warm-running SPMW is completely inhibited by the low salinity lid, so the water emerging from the pipeline into the Labrador basin is warmer than 4°C, and the LSW itself, isolated at depth, continues to warm while the low salinity cap abov e it begins to cool. In 1971/1972, as the GSA fades in the LS, very strong heat fluxes overturn the water column in the LS, reestablishing LSW convection, and mixing what remains of GSA fresh influence in the LS down into the LSW. These high heat fluxes persist the next few years producing a chilled and freshened LSW and a cold SST anomaly, which propagates eastward across the subpolar gyre to pass into the Norwegian Current in the late 1970s. The subpolar gyre January SST's in the 19 70s are not anomalously warm, and sometimes are anomalously cold, and thus the SPMW transformation pipeline is running cooler than in the 1950s and 1960s, which combined with the elevated heat fluxes over the Labrador Basin to support a cooling t rend in the LSW through most of the 1970s and 1980s.

The LGSA does not appear as dramatic. Belkin, et al. (1996), show it arriving in the northern LS in 1982, and having departing southwards by 1984. In the LSW history, Figure 3, this coincides with the hiatus of LSW formation noted first by Lazie r (1995). The SST anomaly time series, Figure 4, shows that as is the case with the GSA, this maximum LGSA period of 1982 -1983 is followed in the LS by a cold SST anomaly 1983 - 1985 -- weaker though, and without an eastward propagation across t he subpolar gyre towards the Norwegian Sea. It is not, however, preceded by a period of anomalously warm SST (Since the anomalies are relative to the 1948 -1992 mean SST, this means that the SST did not run as warm as it did during the warm perio d of the first half of the record). Thus the GSA, perhaps itself triggered by the Nordic Seas impact of the propagating warm SST anomaly, is associated with continuation of the long LSW warming trend, while the LGSA produces merely a few year's h iatus in a long LSW cooling period. This reminds us that overall the SPMW transformation pipeline and its production of LSW are a thermally driven (direct) process, and that the fresh water/salinity involvement only moderates to some degree that process.

The dense LSW results from the direct process of cooling by accumulated heat loss following the Lagrangian pathway of the water column around the southern, eastern and northern "sides" of the subpolar gyre. This cooling involves the liberation o f heat to the atmosphere, entrainment of cooler thermocline waters into the deepening mixed layer, and, perhaps, a lateral mixing contribution since interior subpolar waters, e.g. subarctic intermediate water, are cooler and fresher along isopycn als than the transformed warmer water. This cooling drives the progressive convection following the flow. This convection is opposed, not reinforced, by the salinity forcing: excess of precipitation over evaporation, entrainment of fresher thermo cline waters into the mixed layer, and the lateral mixing with fresher interior subpolar gyre waters. Generally. the thermal forcing "wins" in the sense that there is deep reaching convection along the Subpolar Mode Water transformation pathway e very winter. The interplay of the path history of temperature and salinity forcing (through the memory of the SPMW of upstream conditions in preceding winters) determines not whether convection occurs, but rather how far downstream along the t ransformation pipeline a given temperature of convection occurs, and, because of the finiteness of the Lagrangian pathway that has buoyancy loss acting on it, that history also determines the most cool and dense SPMW produced -- The LSW emerging from the transformation pipeline.

The warm SST anomaly of the 1950s and 1960s moves very slowly, on the order of 1 cm/sec. One way to estimate a speed is to divide the estimated strength of the warm water transport into the subpolar domain, 13 Sverdrups, by the cross sectional a rea of the wedge of warm thermocline waters that lies west of Ireland through which that transport passes. In the Erika Dan section at 53°30'N (Worthington and Wright, 1972) the SPMW and the underlying thermocline waters warmer than 5°C is a wedg e about 100m at the eastern boundary, extending westwards about 1600 km. That wedge represents the source warm water for the three types of warm to cold water conversion alluded to in the introduction in connection with Figure 1. This calculation gives an average northward speed in the wedge of 1.3 cm/sec, similar to the average drift speed of the SST anomaly. A more refined calculation would have to model the Lagrangian "memory" of the SPMW process and obduction: after a given winter, t he SPMW pycnostads drift downstream with the cyclonic flow of the gyre. In Figure 2 this would correspond to a small progressive counterclockwise twisting of the array of isotherms through the spring and summer. The deepening mixed layer of the n ext fall and winter reexposes the pycnostads, and cools them, driving isotherms back upstream. In a climatically stationary system this would than produce simply a seasonal oscillation of the local SPMW temperature, locally coldest at the end of winter, and warming until the point of time in the fall when the deepening mixed layer reexposes the warmed (by advection) pycnostad, and cools it back down. That climatological mean oscillation supports the net liberation of heat to the atmos phere over the SPMW pathway: accumulation of heat by downstream advection in the warm months, removal of that accumulated heat in the fall and winter. An anomalous pulse of heat advecting into the region can be imagined as propagating with a seas onal modulation: two steps forward, one step back, so to speak. Winter convection vertically distributes the heat anomaly over the winter mixed layer, which then is warmer than usual at locations to which downstream advection has carried the anom aly. In spring and summer the anomalously warm SPMW pycnostad is carried some distance further down the pipeline, only to have the next seasonal cooling phase retract isotherms back upstream -- and mix the anomaly progressively deeper in the wate r column as the convection depth increases downstream. Because, though, the system contains the warm anomaly integral effect, the upstream retraction of isotherms does not restore a given isotherm all the way back to its "normal" location. Ins tead it remains somewhat displaced downstream, until some alteration of air sea exchange, mixing or upstream warm water source conditions allows restoration to a cooler state. To characterize better this downstream evolution one would want to do Lagrangian simulations like that by Woods and Barkman (1986) for the Eighteen Degree Water and by Paillet and Arhan (1996) for the SPMW that subducts into the eastern subtropical gyre, but modeling the obduction process (Qui and Huang, 1995) that dominates along the warm to cold water transformation pipeline of the subpolar gyre.

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