

Linear trends in salinity for the World Ocean, 1955–1998

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[1] Quality controlled oceanographic profile salinity measurements from the World Ocean Database 2001 (WOD01) were used to calculate linear trends of zonally averaged salinity anomalies for running five year periods from 1955–1959 through 1994–1998 for the World Ocean and the Atlantic, Pacific, and Indian Ocean basins from the surface to 3000 meters depth. Each basin exhibits large-scale, coherent trends. Most of the Pacific is freshening with the exception of the subtropical South Pacific. The Atlantic exhibits a deep freshening in the subpolar gyre and a shallower, more intense increase in salinity in the tropics and subtropics. The Indian Ocean is becoming more saline at all latitudes in the upper 150 meter layer, with a subsurface freshening between 40°S and the equator in the 250–1000 meter layer. There is freshening in both the Weddell and Ross Seas. **Citation:** Boyer, T. P., S. Levitus, J. I. Antonov, R. A. Locarnini, and H. E. Garcia (2005), Linear trends in salinity for the World Ocean, 1955–1998, *Geophys. Res. Lett.*, 32, L01604, doi:10.1029/2004GL021791.

1. Introduction

[2] Pressure, temperature, and salinity are the three variables in the equation of state for seawater. The temporal variability of salinity is the least understood for the World Ocean. Quantifying salinity variability is of critical importance for understanding global climate change. It has been suggested that the thermohaline circulation in the North Atlantic could be weakened due to an increase in fresh water in the northern North Atlantic [Rahmstorf, 1995; Manabe and Stouffer, 1995]. Curry *et al.* [2003] document a freshening of the northern North Atlantic and increased salinity in the tropical and subtropical North Atlantic and suggest these changes are a possible consequence of global warming. Salinity changes play a role in sea level change due to the addition or removal of fresh water and due to the haline contraction factor in sea level (density) calculations [Maes, 1998; Antonov *et al.*, 2002]. Most studies of salinity variability have been regional in scope and/or for limited time periods [e.g., Dickson *et al.*, 2002; Levitus, 1989a, 1989b; Wong *et al.*, 1999, 2001]. Many studies have focused on sea surface salinity (SSS) using data from surface measurement at weather stations [e.g., Taylor and Stephens, 1980] or extensive ship-of-opportunity sampling [e.g., Delcroix and Henin, 1991]. Until recently there were not enough archived salinity measurements to estimate global salinity changes from the sea surface to the deep layers of the World Ocean on decadal time scales. Through the efforts of the Global Ocean Data Archeology and Rescue (GODAR) project of the Intergovernmental Ocean-

ographic Commission (IOC) and other programs, substantial amounts of historical and modern salinity data from bottle and CTD casts have been gathered together and quality controlled in the World Ocean Database 2001 (WOD01) [Conkright *et al.*, 2002]. This database and subsequently available data have been combined and analyzed to estimate salinity changes for the period 1955–1998 for the World Ocean. This work examines large-scale trends in salinity over this 44 year period.

2. Method

[3] New climatologies of monthly salinity were prepared using the data from the WOD01 plus additional data received after the publication of the WOD01. This additional data included the final WOCE data as well as Global Temperature and Salinity Pilot Project (GTSP) data through November 15th, 2003 which contained data from ARGO profiling floats. The monthly salinity climatologies were calculated for each 1° latitude/longitude grid box following the method outlined by Boyer *et al.* [2002]. Five-year (pentadal) running mean salinity anomaly fields were then prepared for the periods 1955–1959 through 1994–1998. It was necessary to bin data into pentads due to the scarcity of data in individual years for some parts of the World Ocean. The anomaly is calculated for each 1° latitude/longitude grid box at standard depth levels from the surface to 3000 meters. The anomaly for one salinity value at one depth is the value for salinity minus the corresponding monthly (for the sea surface to 1500 meters depth) or annual (for depths below 1500 meters) climatological mean value for the appropriate 1° grid box. This removes the annual cycle, leaving longer time period salinity changes as the anomalies. All anomaly values for each pentad in the same 1° grid box are then averaged. The mean anomaly fields are then objectively analyzed following the method outlined by Boyer *et al.* [2002] to provide an anomaly value for each 1° grid box. The one difference from Boyer *et al.* [2002] is that the first-guess field for the objective analysis is 0.0. This assures that where there is no data within the radius of influence (the area used to include data in the objective analysis for a given 1° grid box, the largest of which is 880 km) the anomaly will not be calculated and will be set to 0.0. This may result in an underestimation of the salinity anomaly for some areas and some years. The largest source of uncertainty is still, despite the addition of significant amounts of historic data, uneven distribution of data in time and space. Figures S1–S8 in the auxiliary material¹ give a measure of the data coverage for each five-year period, for 100 meters and 1000 meters depth

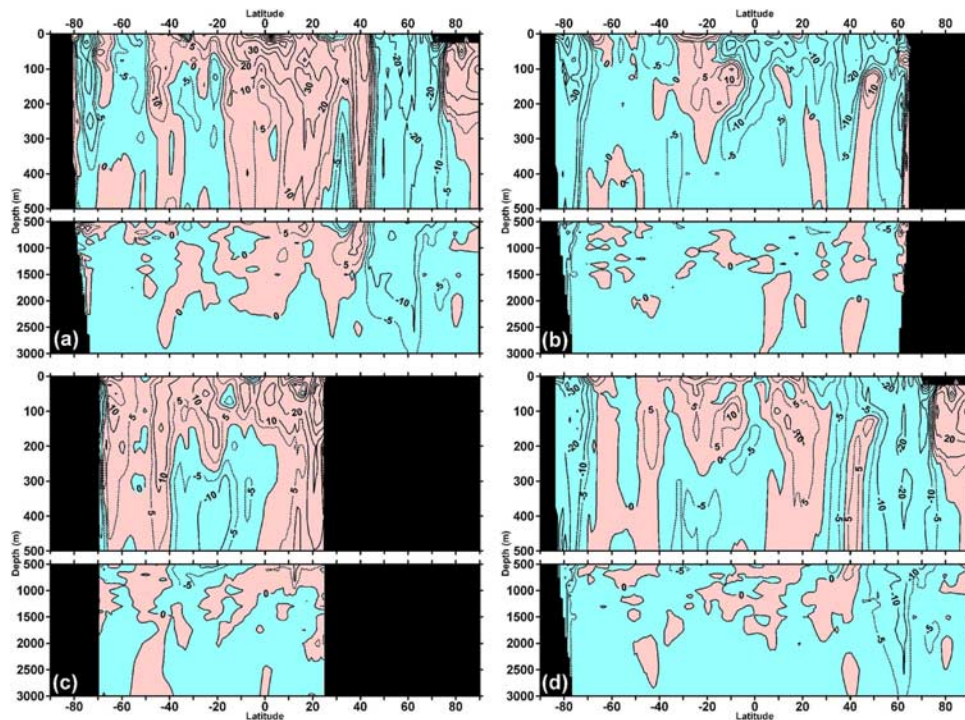


Figure 1. Linear trend in salinity (10^{-4} /year) of the zonally averaged pentadal salinity anomaly 1955–1959 to 1994–1998 for a) the Atlantic Ocean, b) the Pacific Ocean, c) the Indian Ocean, d) the World Ocean. Negative salinity trends are shaded blue. Positive salinity trends are shaded red.

at each latitude belt for the Atlantic, Pacific, Indian, and World Oceans.

3. Results

[4] The linear trends in Figures 1a–1d represent the least-squares fit to the zonal average salinity anomaly at each latitude for each pentad from 1955–1959 through 1994–1998 for the Atlantic, Pacific, and Indian Ocean basins and the World Ocean from the surface to 3000 meters depth. To document the relative importance of the linear trend compared with other interannual and longer scale variability in the 44 year record, Figures 2a–2d show the percent variance accounted for by the linear trend for each basin. We define a significant trend as an increase or decrease in salinity of more than $0.0005/\text{yr}$. This value is greater than two times the standard error of the estimate of the linear trend everywhere in the ocean except for the Arctic, where two times the standard error is slightly larger than $0.0005/\text{yr}$.

3.1. Atlantic Ocean

[5] The Atlantic Ocean exhibits a large freshening (negative salinity trend) in the subpolar gyre from 45°N – 70°N . A large positive salinity trend is present in the subtropics and tropics in both the northern and southern hemisphere. This pattern of freshening in the north and salinification to the south for the North Atlantic was noted by Curry *et al.* [2003]. The linear trend for the subsurface freshening in the north and the salinification in the south of the North Atlantic account for more than 20% and in places exceeds 60% of the variance over the study period. In general our results are characterized by the linear trend accounting for a larger percent variance of subsurface

salinity as compared to surface variability. This reflects the fact that salinity variability is forced entirely at the sea surface. The freshening of the subpolar gyre reaches very deep, with values exceeding $0.0005/\text{yr}$ at 3000 meters. This trend is due in large part to changes in the deep convection in the Labrador Sea and the freshening of the Nordic Seas upstream of the Labrador Sea [Dickson *et al.*, 2002]. The changes in the tropics and subtropics are confined mainly to the upper 500 meters, although around 40°N the increased salinity trend exceeds $0.0005/\text{yr}$ down to 1500 meters depth. The largest salinity increases occur between 20°S and 20°N , with the changes penetrating deeper to the north of the equator. The changes in this area have been attributed to increased evaporation associated with ocean warming [Curry *et al.*, 2003] and possibly to outflow from the Mediterranean Sea, which is increasing in salinity [Bethoux *et al.*, 1998]. An area of subsurface freshening is apparent in the 200–500 meter layer between 30°N and 40°N . The positive trend is confined to shallower depths in the southern hemisphere subtropics in comparison with the northern hemisphere. Our definition of the Atlantic basin includes the entire Arctic Ocean (the Pacific basin ends at the Bering Strait). The large salinity increase in the Arctic close to the surface (above 50 meters) is biased by shelf data for which values can fluctuate greatly due to variability of river runoff and other factors. There is freshening south of 70°S in the Weddell Sea and near the coast of Antarctica.

3.2. Pacific Ocean

[6] The salinity trends in the Pacific Ocean are confined to shallower depths than in the Atlantic Ocean. Regions where the magnitude of the linear trend exceeds $0.0005/\text{yr}$ are confined to the top 500 meters of the water column. The

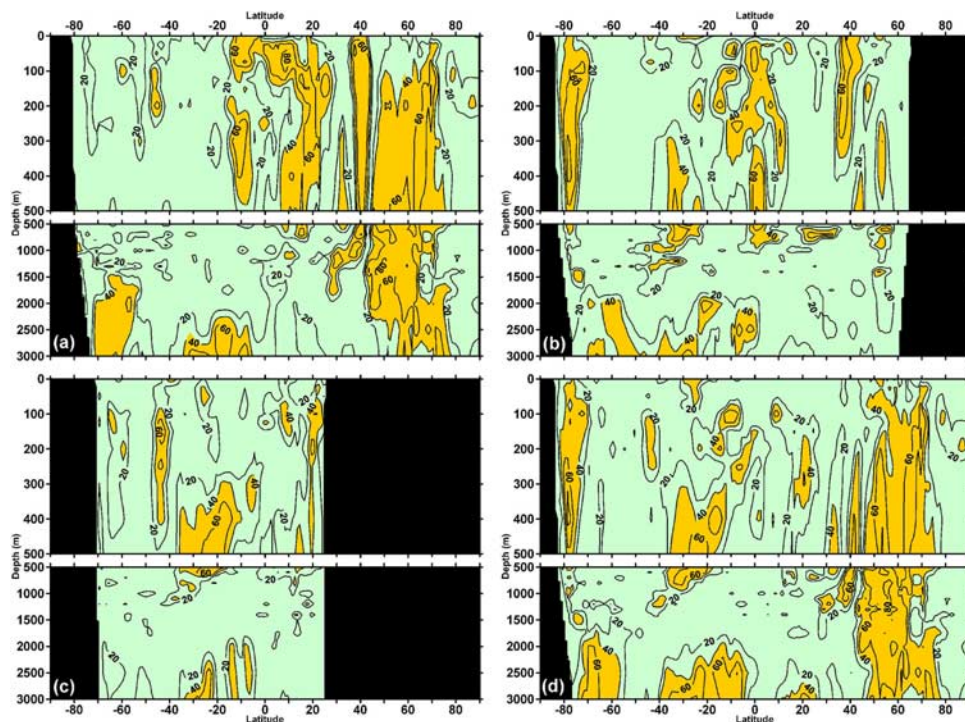


Figure 2. Percent variance accounted for by linear trend of zonally averaged pentadal salinity anomaly 1955–1959 to 1994–1998 for a) the Atlantic Ocean, b) the Pacific Ocean, c) the Indian Ocean, d) the World Ocean. Percent variance $<60\%$ are shaded green. Percent variance $\geq 60\%$ are shaded orange.

exception is the deep freshening south of 70°S . This is the Ross Sea and coastal Antarctica. A freshening in the Ross Sea was reported by *Jacobs et al.* [2002]. Most of the North Pacific, in the 15°S – 60°N region is freshening in the top 100 meters, and for most of this area, the freshening exceeds $0.0005/\text{yr}$ down to 300 meters depth. *Wong et al.* [2001] found that intermediate waters of the North Pacific were freshening, but that near surface waters were increasing in salinity. It should be noted that the time period they investigated was different than ours and they were comparing selected historic data to specific WOCE cruises. The one large area of increasing salinity is in the subtropic South Pacific from the sea surface down to 200 meters depth. This same feature extends northward in subsurface waters (below 100 meters depth) to 5°S . Another subsurface area of salinity increase is at 50°N at 150 meters depth.

3.3. Indian Ocean

[7] The Indian Ocean exhibits linear trends of increasing salinity at almost all latitudes from the surface down to 150 meters depth. The changes are most pronounced north of 10°N . Significant salinity increase trends in this area extend to 1000 meters depth. Below 150 meters depth a large freshening is occurring between 40°S and the equator. The linear trend at the center of this larger freshening exceeds 40 percent of the variance over the study period. *Wong et al.* [1999] note this intermediate water freshening along 32°S from cruise data and attribute it to decreased evaporation–precipitation (E–P) over the southern polar gyre.

3.4. World Ocean

[8] The trends in the World Ocean (Figure 1d) show changes exceeding $0.0005/\text{yr}$ mostly confined to the top

500 meters of the water column. The exceptions are deep freshening trends in the higher latitudes of the Southern Ocean due to the Weddell and Ross Seas, and in the northern hemisphere between 50°N and 75°N due to changes in deep convection in the subpolar gyre of the North Atlantic. Both of these features reach 3000 meters depth (or ocean bottom). In the vicinity of the equator, freshening in the Pacific Ocean nearly cancels out the increases in salinity in the Indian and Atlantic Oceans. In the southern hemisphere subtropics, all basins are increasing in salinity down to 200 meters, with freshening in intermediate waters in the Pacific and Indian. The Atlantic freshening in the intermediate waters occurs further south in the southern hemisphere than in the other two basins. In the northern hemisphere subtropics, the freshening in the Pacific is less than the large increases in salinity in the Indian and Atlantic Oceans and there is a net salinity increase for the World Ocean at these latitudes.

4. Discussion

[9] From the sea surface to 3000 meters depth, large-scale spatially coherent salinity trend patterns for the time period 1955–1998 are apparent for the World Ocean, revealing remarkable similarities and differences in the Atlantic, Pacific, and Indian Oceans. The subpolar gyres of both the Atlantic and Pacific Ocean show freshening trends. However, the tropics and subtropics in the Atlantic, Pacific, and Indian Oceans show differing trends. The freshening in the Pacific in the tropics and subtropics lessens the overall effect on the World Ocean of the increased salinity in the Indian and Atlantic at the same latitudes. Within the individual basins, there is large-scale

freshening in the Pacific Ocean, except for the upper subtropical South Pacific. There is a large salinity increase in the Indian above 150 meters, which reaches deeper depths north of the equator and south of 40°S, with freshening intermediate waters in between. The Atlantic exhibits a bimodal pattern in the northern hemisphere, with deep freshening in the subpolar gyre and salinification in the tropics and subtropics to depths of 500 meters. With respects to depth, significant changes in the Pacific are mostly limited to the top 500 meters, in the Indian to the top 1000 meters, while in the Atlantic, significant changes reach to 3000 meters.

[10] Electronic versions of the pentadal salinity anomaly fields used in this study and data distribution maps by pentadal compositing periods for selected depths are available at www.nodc.noaa.gov/OC5/indprod.html.

[11] **Acknowledgments.** This work was supported by the NOAA OGP Climate Change Data and Detection Program. We thank the many scientists, technicians, data center staff, and data managers for their contributions of data to the World Data Center system which has allowed us to compile the database used in this work. We also thank our colleagues at the Ocean Climate Laboratory for their work in constructing the World Ocean Database which made this work possible. The views, opinions, and findings contained in this report are those of the authors, and should not be construed as an official NOAA or U.S. Government position, policy, or decision.

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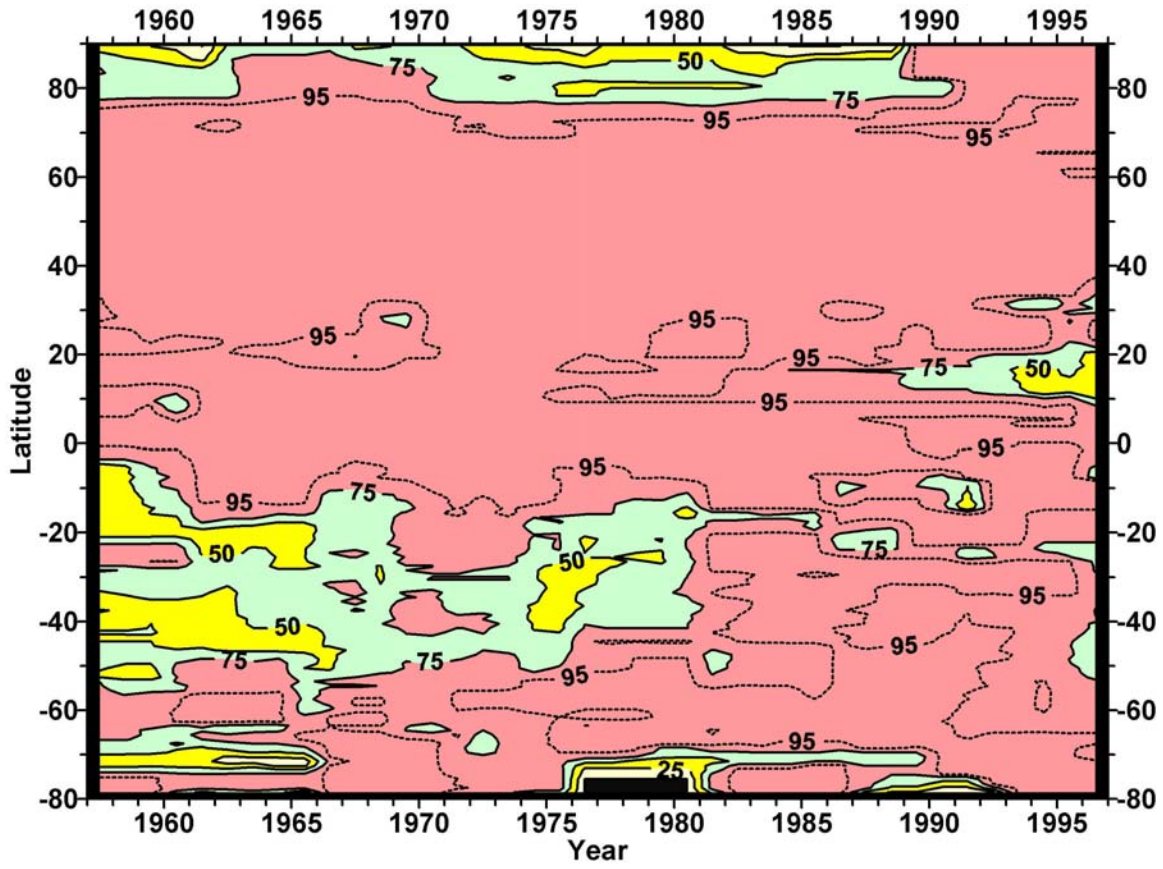


Figure S1. Percent of 1-degree grid boxes for which there are three or more grid boxes with salinity means within the smallest radius of influence for objective analysis (444 km) for each latitude belt at 100 meters depth for the Atlantic Ocean. Red shading signifies $\geq 75\%$, green $\geq 50\%$ and $< 75\%$, yellow $\geq 25\%$ and $< 50\%$, tan $> 0\%$ and $< 25\%$, black = 0% .

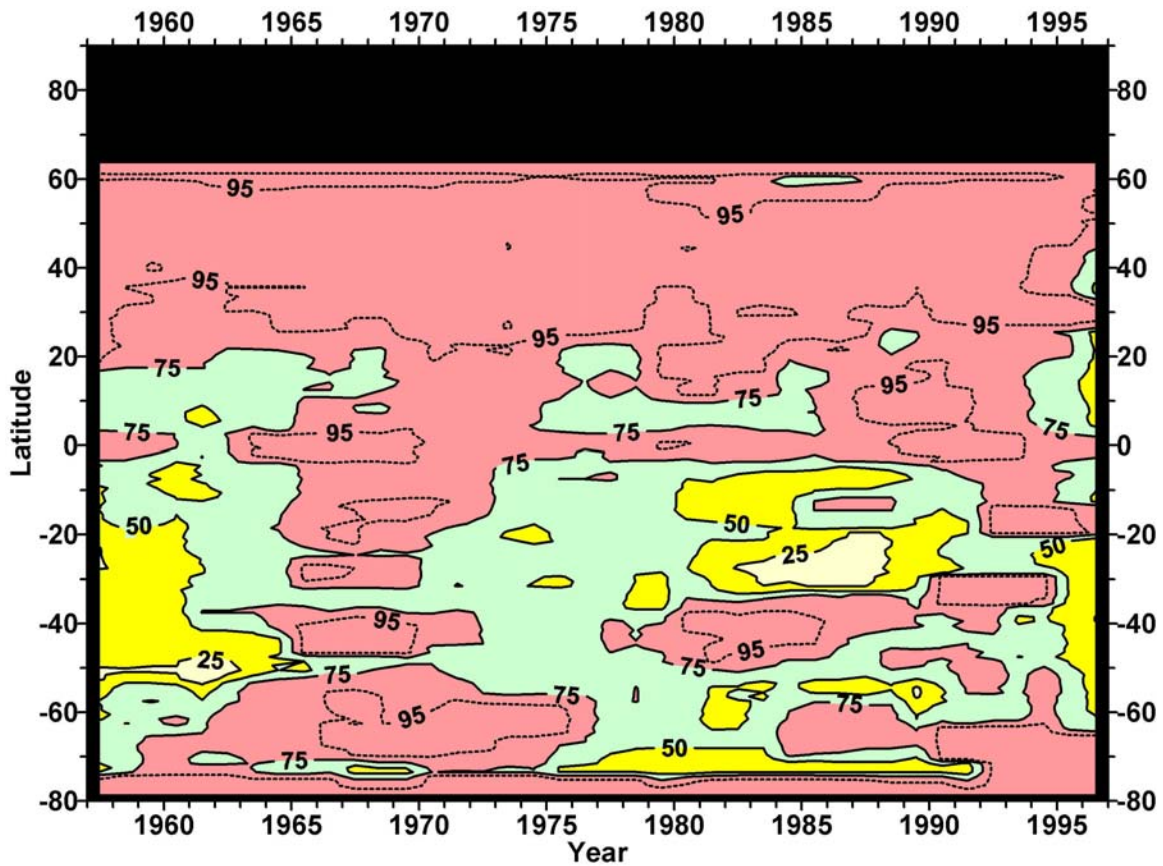


Figure S2. Percent of 1-degree grid boxes for which there are three or more grid boxes with salinity means within the smallest radius of influence for objective analysis (444 km) for each latitude belt at 100 meters depth for the Pacific Ocean. Red shading signifies $\geq 75\%$, green $\geq 50\%$ and $< 75\%$, yellow $\geq 25\%$ and $< 50\%$, tan $> 0\%$ and $< 25\%$, black = 0% .

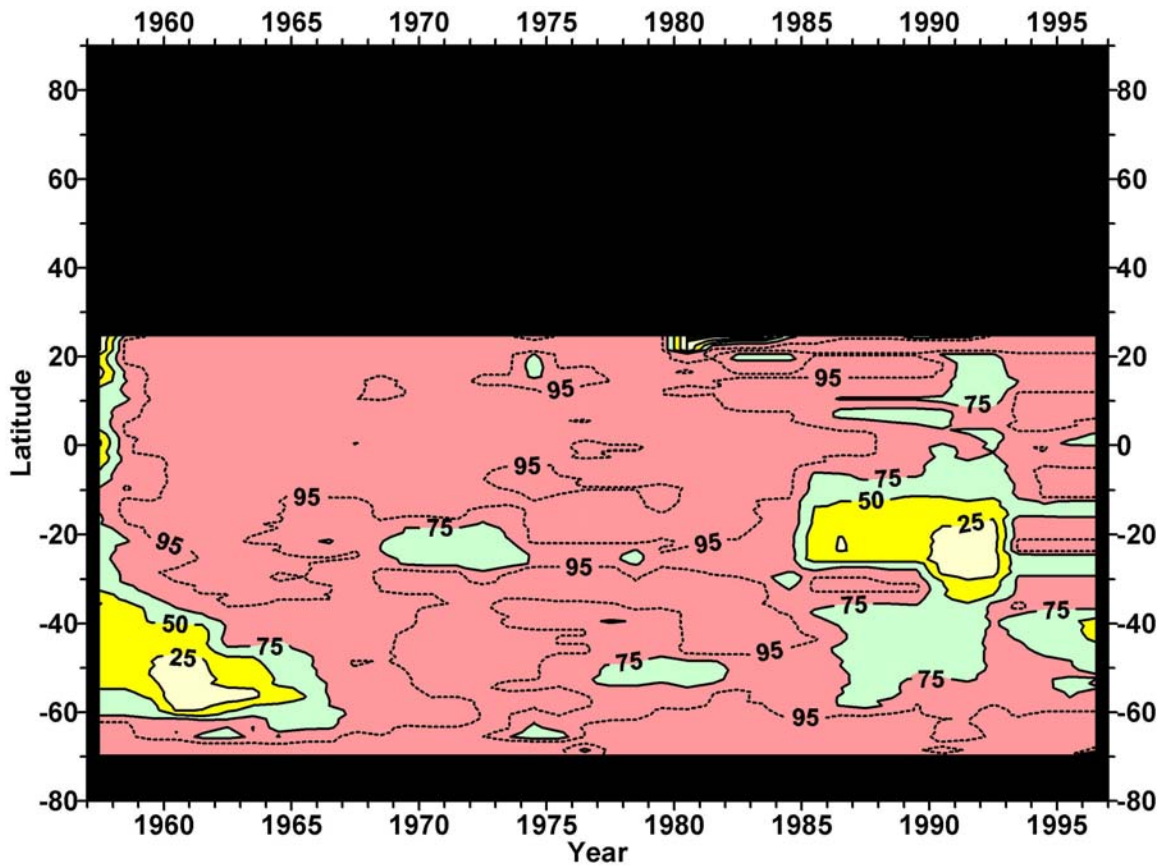


Figure S3. Percent of 1-degree grid boxes for which there are three or more grid boxes with salinity means within the smallest radius of influence for objective analysis (444 km) for each latitude belt at 100 meters depth for the Indian Ocean. Red shading signifies $\geq 75\%$, green $\geq 50\%$ and $< 75\%$, yellow $\geq 25\%$ and $< 50\%$, tan $> 0\%$ and $< 25\%$, black = 0% .

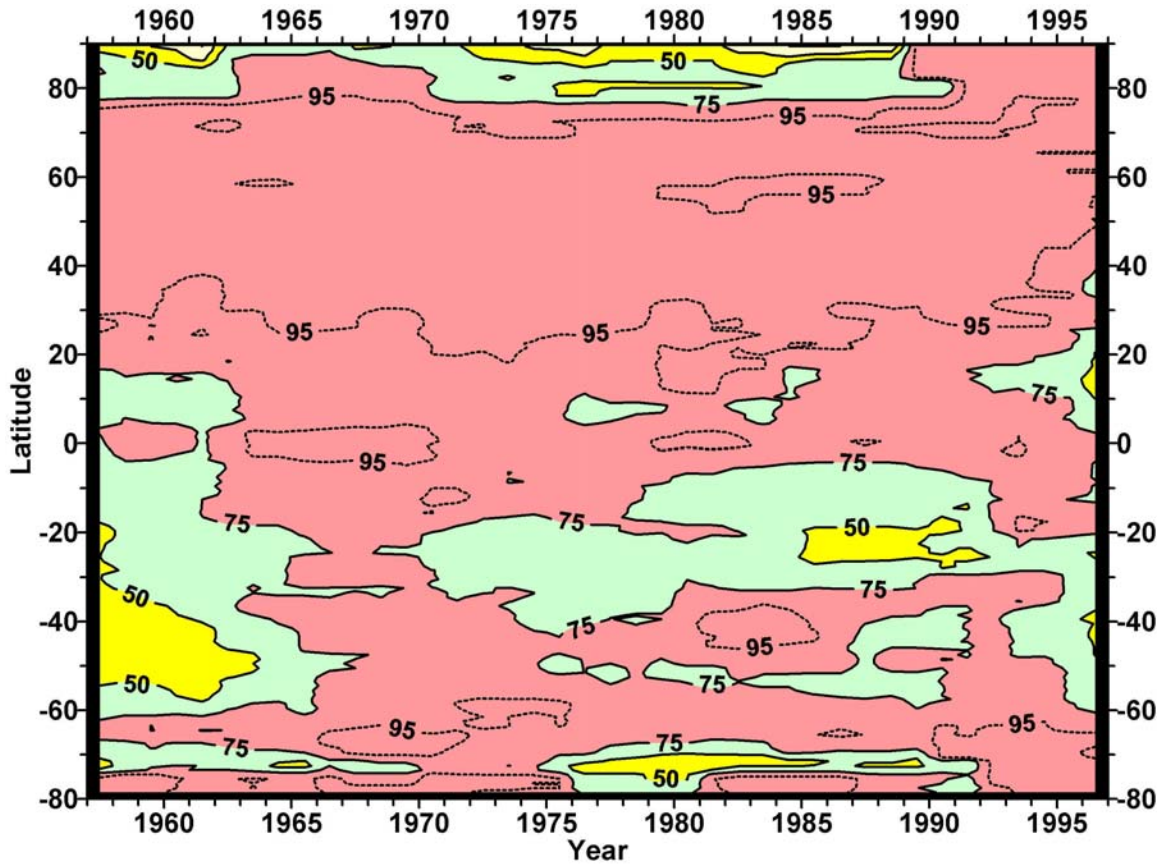


Figure S4. Percent of 1-degree grid boxes for which there are three or more grid boxes with salinity means within the smallest radius of influence for objective analysis (444 km) for each latitude belt at 100 meters depth for the World Ocean. Red shading signifies $\geq 75\%$, green $\geq 50\%$ and $< 75\%$, yellow $\geq 25\%$ and $< 50\%$, tan $> 0\%$ and $< 25\%$, black = 0% .

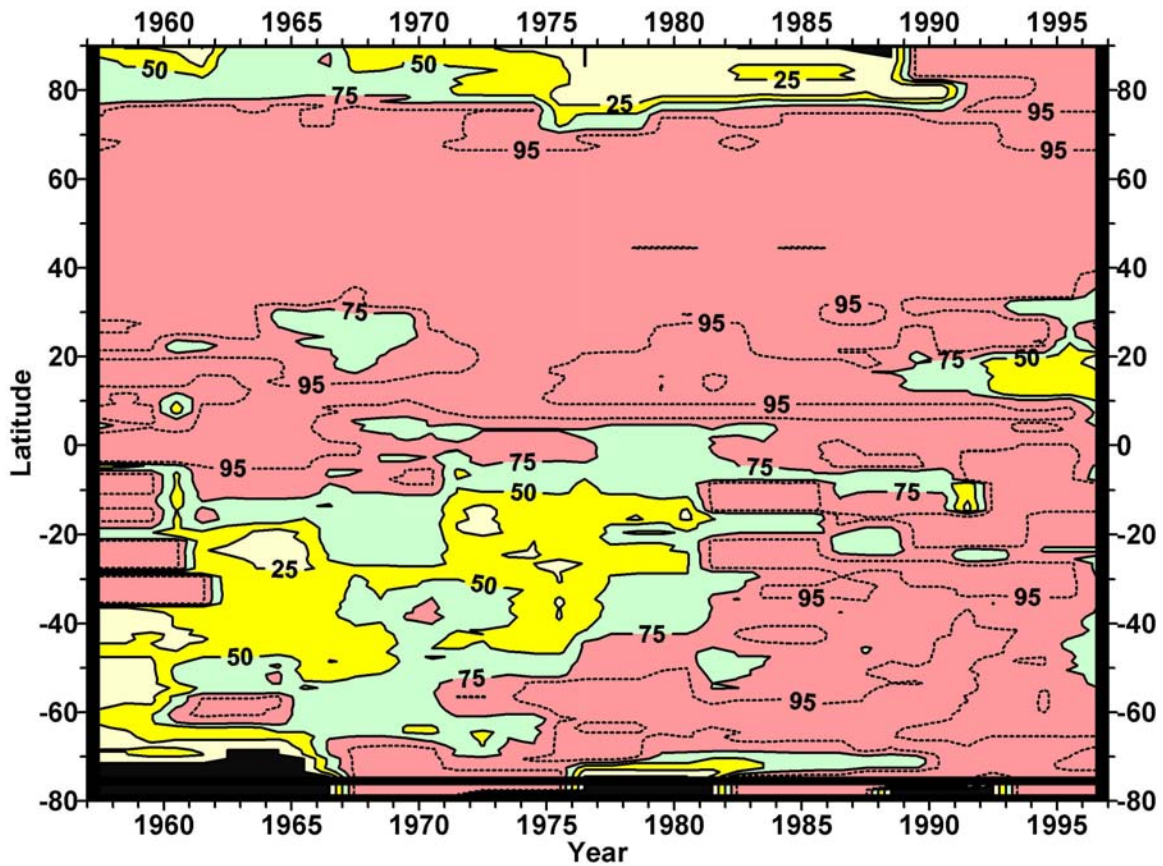


Figure S5. Percent of 1-degree grid boxes for which there are three or more grid boxes with salinity means within the smallest radius of influence for objective analysis (444 km) for each latitude belt at 1000 meters depth for the Atlantic Ocean. Red shading signifies $\geq 75\%$, green $\geq 50\%$ and $< 75\%$, yellow $\geq 25\%$ and $< 50\%$, tan $> 0\%$ and $< 25\%$, black = 0%.

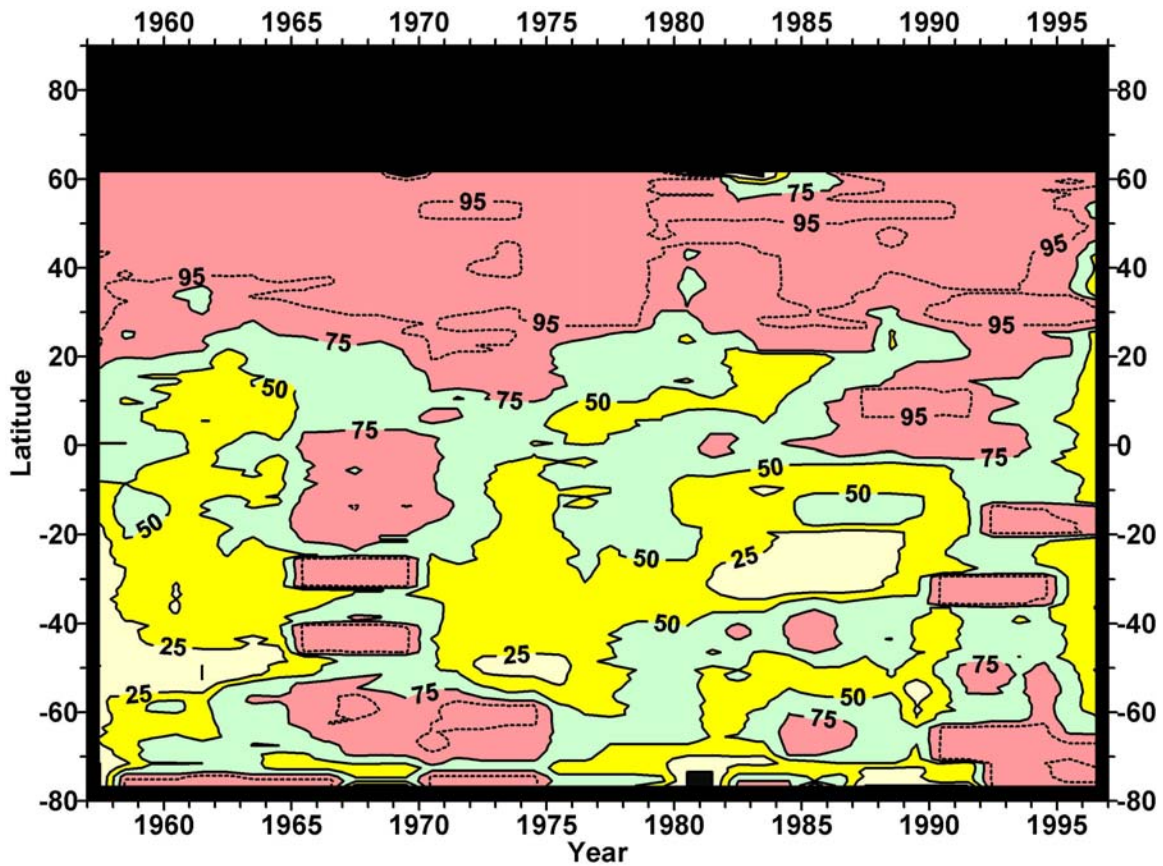


Figure S6. Percent of 1-degree grid boxes for which there are three or more grid boxes with salinity means within the smallest radius of influence for objective analysis (444 km) for each latitude belt at 1000 meters depth for the Pacific Ocean. Red shading signifies $\geq 75\%$, green $\geq 50\%$ and $< 75\%$, yellow $\geq 25\%$ and $< 50\%$, tan $> 0\%$ and $< 25\%$, black = 0%.

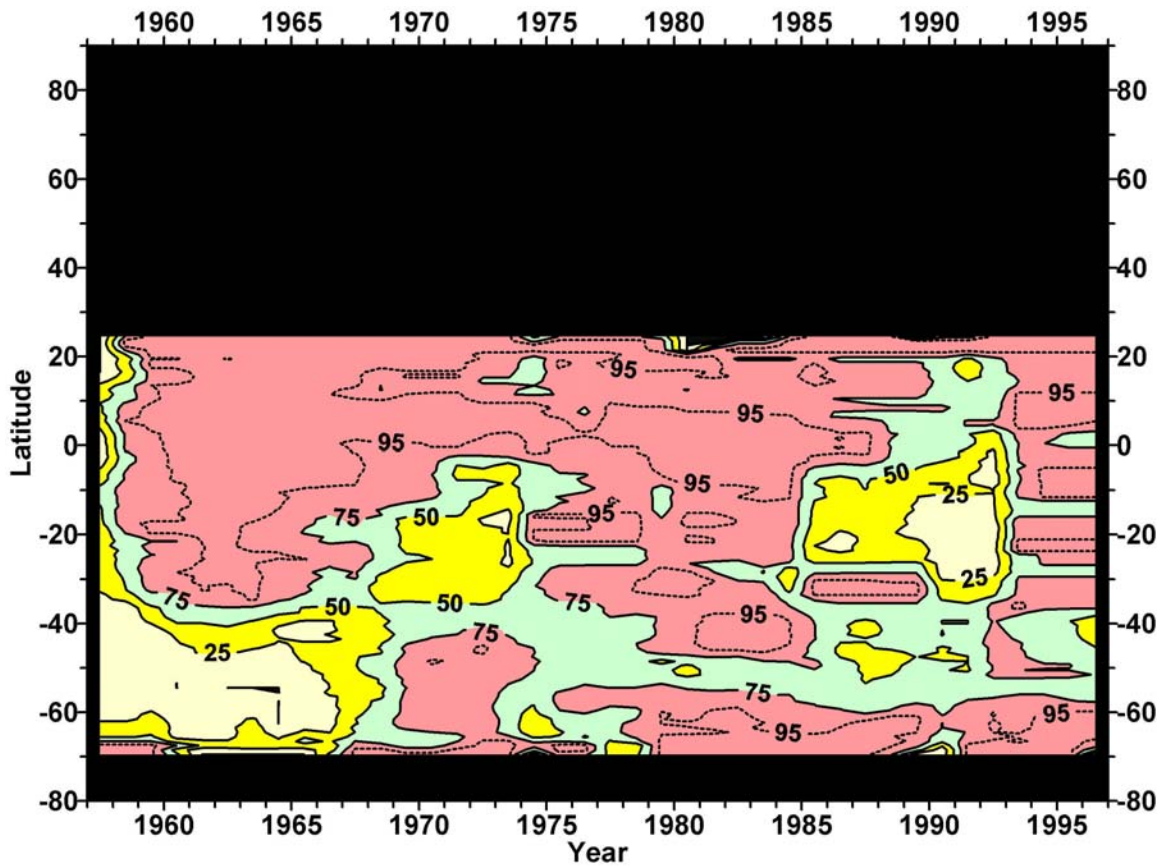


Figure S7. Percent of 1-degree grid boxes for which there are three or more grid boxes with salinity means within the smallest radius of influence for objective analysis (444 km) for each latitude belt at 100 meters depth for the Indian Ocean. Red shading signifies $\geq 75\%$, green $\geq 50\%$ and $< 75\%$, yellow $\geq 25\%$ and $< 50\%$, tan $> 0\%$ and $< 25\%$, black = 0%.

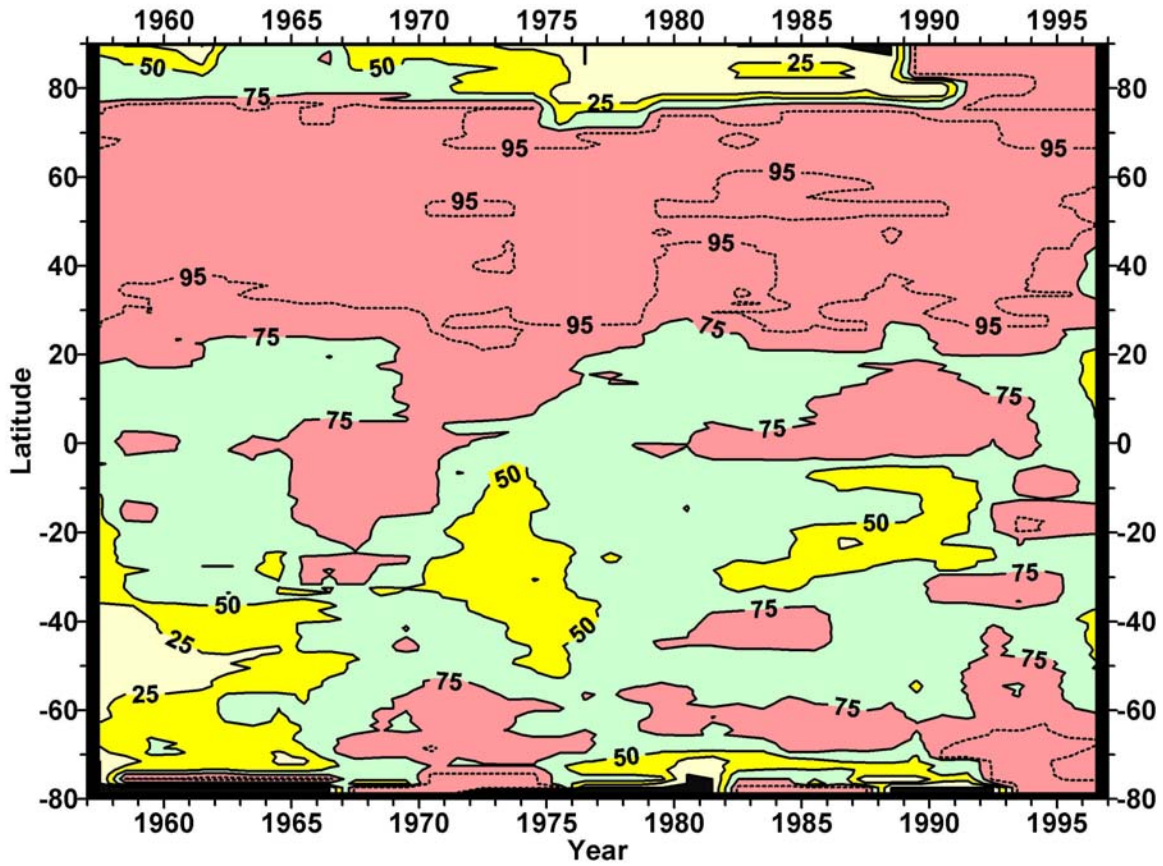


Figure S8. Percent of 1-degree grid boxes for which there are three or more grid boxes with salinity means within the smallest radius of influence for objective analysis (444 km) for each latitude belt at 100 meters depth for the World Ocean. Red shading signifies $\geq 75\%$, green $\geq 50\%$ and $< 75\%$, yellow $\geq 25\%$ and $< 50\%$, tan $> 0\%$ and $< 25\%$, black = 0%.