

# SALINITY AND THE GLOBAL WATER CYCLE

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## ABSTRACT

The global water cycle is mainly an ocean-atmosphere phenomena, yet most studies have focused on the much smaller terrestrial component. Here we show that sea surface salinity has much to tell us about the global water cycle. We review evidence from oceanic salinity data that the water cycle is changing and connect it to trends in estimates of surface fluxes. We also discuss the important interplay between surface water fluxes and upper-ocean mixing processes that arises from buoyancy physics. Connections to the stability of the thermohaline circulation are treated. The strong non-linear dependence of the vapor pressure of water on temperature leads to predictions of an enhanced hydrologic cycle resulting from global warming, which has helped to motivate plans for new salinity sensing satellites SMOS and Aquarius. The in-situ observational requirements for these programs, along with the opportunities provided for new field programs examining the details of the upper-ocean processes affecting sea surface salinity, provide strong motivation to expand our observational capabilities for salinity.

## 1. INTRODUCTION

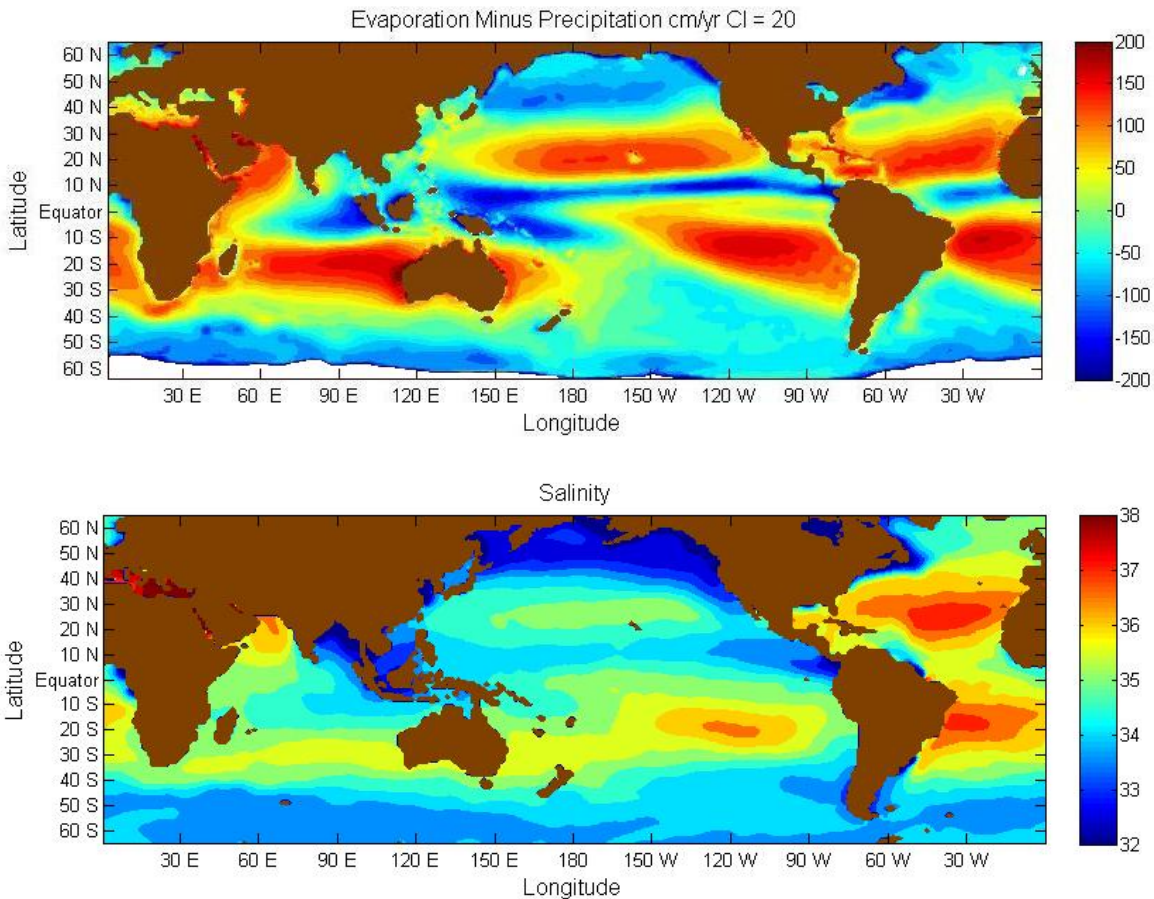
No element of the climate system is as important to society as the global water cycle, yet it is still poorly understood, primarily because most of it occurs over the vast and under-sampled oceans. Salinity is the signature of the water cycle in the ocean, and the oceanographic community has much to offer to advance our understanding of the water cycle and its variability. Estimates of evaporation and precipitation over the ocean suggest an enhancement of the water cycle from the mid-1970s to the present, a trend that is supported by available surface salinity observations. This may be consistent with expectations from global warming, but the decadal climate variability of the ocean is clearly involved as well. In fact, variability in precipitation on land is known to be closely linked to the dominant decadal modes of ocean variability. Thus, improved understanding of oceanic decadal climate would be of great predictive value for freshwater supplies for population centers and the agricultural sector. Trends in

high latitude surface salinity have been popularly suggested as an agent of abrupt change in ocean circulation and climate, but we show that such assumptions are critically dependent on ocean mixing rates. These could respond to freshening in unexpected ways to make abrupt climate change less rather than more likely. Oceanographers need to greatly expand, amplify and sustain salinity observation systems in the years ahead.

It is a commonplace statement that the oceans are the main thermal regulating element of the climate system, but it is also true that they are the reason we have freshwater supplies that have allowed terrestrial life to evolve into our large and highly mechanized human civilization. Nearly 90% of global evaporation comes from the oceans, so its central role in the global water cycle cannot be ignored. Within the ocean, the water cycle has a significant impact on salinity, and thus density, circulation, stratification and mixing. In general, salinity variability accounts for about half as much of the density variance as temperature, usually in a counter-acting way. In this paper we review some of the basic elements of salinity variability and its relation to the global water cycle, trends in both, and suggest that an improved understanding of the role of salinity in the climate system could be key to better decadal forecasts of water supplies.

### 1.1. Mean state of the water cycle and salinity

Wust [1] illustrated the essential linkage of the water cycle to ocean salinity, when he plotted surface salinity (SSS) against estimates of evaporation minus precipitation (E-P). He suggested a simple balance obtained between vertical mixing and E-P that yielded a linear relationship between the two. We now have better data and a better appreciation for the role of advection, but the essential truth remains, surface waters are saltier under the highly evaporative mid-latitude trade wind regions, fresher in the precipitation zones at high latitudes and under the Inter-Tropical Convergence Zone (ITCZ). Figure 1.a, 1.b illustrate the general patterns of both E-P and SSS for the global ocean. Other fundamental features such as the high salinities of the Atlantic relative to the Pacific, and the freshness of



**Figure 1.a** (top) A new estimate of annual average evaporation – precipitation, based on the evaporation climatology of Yu and Weller [2] and satellite-based precipitation estimates from the Global Precipitation Climatology Program (GPCP, available at: <http://precip.gsfc.nasa.gov/>). The units are centimeters per year. **Figure 1.b** (bottom). Average surface salinity of the world ocean, contoured from the World Ocean Database of NODC.

some coastal regions, are also worth noting. Low coastal salinities are invariably related to river and groundwater discharges or melting glaciers, but the Atlantic-Pacific salinity contrast is worth some discussion. In part this salinity contrast is due to the narrowness of the Atlantic; a greater fraction of its surface area is under the influence of dry continental air [3]. But the arrangement of the continents also plays a role, moisture is easily transported to the Pacific across the Central American Isthmus [4], but there is little transport from the Indian Ocean to the Atlantic, and little significant moisture flux from the Sahara desert. Warren [5] also notes that the coolness of the North Pacific relative to the North Atlantic will lead to decreased evaporation as a consequence of the nonlinear dependence of the vapor pressure of water on temperature (at 5°C the vapor pressure is less than a third of its value at 25°C). The resulting higher salinities

and densities help to maintain the Atlantic's status as a site for deep convection, with the thermohaline circulation causing an anomalous northward heat transport in the South Atlantic, thus sustaining the positive feedback between higher temperatures and more evaporation [6].

The spatial patterns and inter-basin contrasts of Evaporation minus Precipitation lead to a need for the oceans to redistribute water around the globe, in order to avoid sea level trends of several meters per year. The redistribution of water by the oceans has been treated in [7], [8], [9], [10], and [11]. The basic pattern of meridional transport arises from the need to return water from the precipitation regions of the tropics and high latitudes to the mid latitude evaporation zones. The interbasin transport of water vapor from Atlantic to Pacific results in a fresher Pacific that stands about 50 cm higher than the Atlantic. This head contributes to the flow of water through Bering Strait, providing

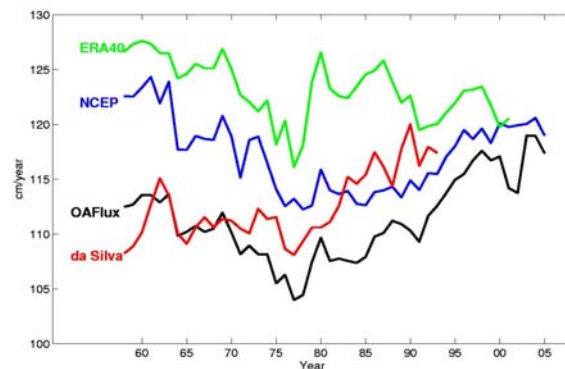
fresher water to the Arctic and returning water to the Atlantic. Reference [7] sketched out the consequences for global transports of water and salt. The transports there are treated as absolutes, rather than freshwater anomalies relative to a reference salinity as is often done for enclosed seas. The resulting non-divergent transport of salt around the Americas is one consequence. Such circulation schemes for the global water cycle are quite different than those originally envisioned by hydrologists [12]. Most recently, [11] has described the shallow, deep and throughflow components of the oceanic transport of freshwater, and how the freshwater cycle maintains the salinity differences between basins and contributes to water mass formation. She finds that the Bering Strait throughflow makes a minor contribution to the Atlantic freshwater balance but is very important to the North Pacific.

We also now appreciate that there are dynamical consequences of the surface mass losses and gains of freshwater over the ocean. The “Goldsbough-Stommel” circulation of Sverdrupian interior flows driven by surface water gains or losses, with western boundary currents to close the circulation, was sketched by [13]. They combine this with the interbasin mass transports to describe a current system that yields a 2 Sv southward flow to counter the Gulf Stream in the western North Atlantic and suggest that it may contribute to a southward displacement of the separation latitude. Thus, the current systems induced by the water cycle cannot be neglected.

## 2. TRENDS IN THE GLOBAL WATER CYCLE AND SALINITY

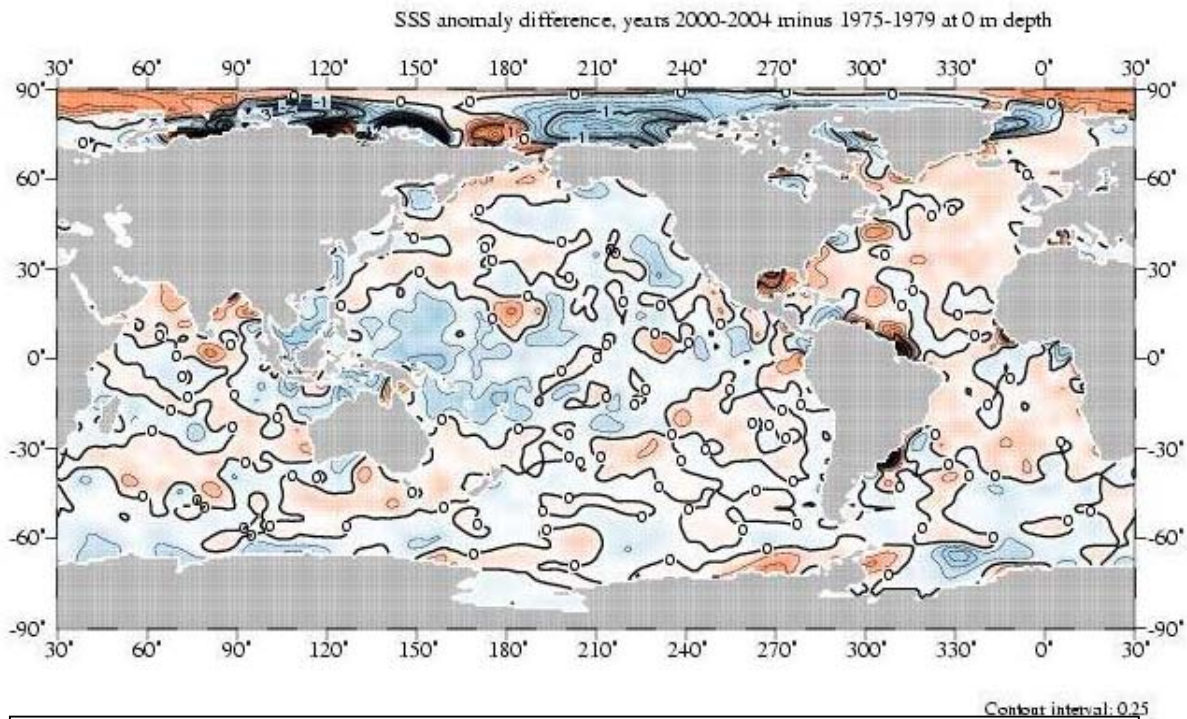
The evaporation and precipitation products now available (figure 1.a) are currently being scrutinized for stationarity of the data sets and other issues. Observing systems change over time and the introduction of various satellites products have improved the estimation of precipitation as well as winds and water vapor content for evaporation. Trends in several evaporation products can be seen in figure 2. The global average annual evaporation is estimated to have reached a minimum in the late 1970's in all four products and has been generally increasing since then in three of the four climatologies. The reliability of such global trends is hard to assess, [14] ascribes it to increasing winds in her OA Flux product. An upward trend in evaporation agrees with expectations from global warming, as the atmosphere warms the greater mobility of water molecules with increasing temperature leads to an increase in the vapor pressure. One way the oceanographer can contribute to this issue is by examining the surface salinity trends for the same time periods. Figure 3.a shows a map of the global difference in surface salinity from the late 1970s to the

early 2000s from the NODC data archives. A widespread salinification in the Atlantic and be seen along with a general freshening pattern in both northern and western tropical regions of the Pacific. A similar pattern is observed in the 50 year SSS trends analysed by [15] in figure 3.b. This suggests that the upward trend in evaporation reinforced the zonal transport of water vapor from Atlantic to Pacific and possibly reinforced the meridional transport patterns in the Pacific. The salinity trends represent far better evidence for a changing global water cycle than any terrestrial data rainfall or river flow data, most of which shows little trend [16]. But we must also acknowledge that the flux estimates remain a challenging area of research and that the salinity data bases remain sparse. Monitoring the future evolution of salinity in the global ocean will be an important contribution that oceanographers can make to the understanding of global climate change.

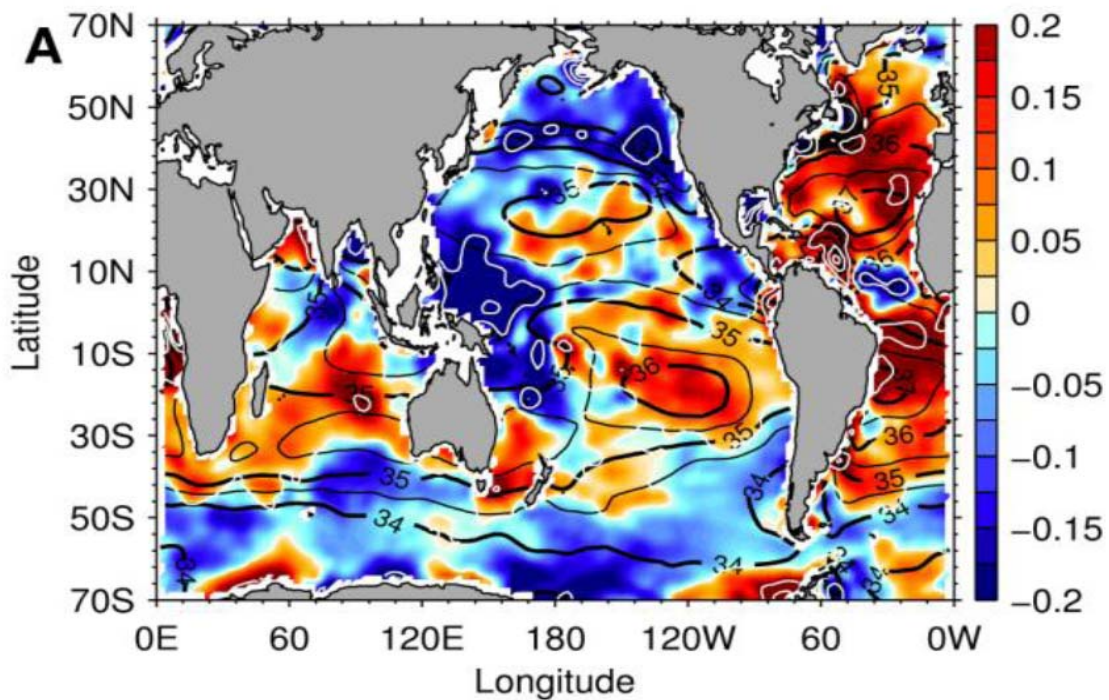


**Figure 2.** Global annual average evaporation from several data products, including the OA Flux of Yu and Weller [2]. A minimum was reached in the late 1970's and a general upward trend is estimated since then in 3 of the 4 estimates.

The apparent trends in salinity and possibly evaporation may be linked to the expected enhancement of the water cycle with global warming. However, the relationship is complex. While precipitable water may increase at the same rate as the saturation specific humidity ( $\sim 7\%$  per degree K of warming), the changes in evaporation and precipitation are likely strongly constrained by energetics to  $\sim 2\%$  increase per degree of warming [17]. This would suggest that the strong trends in observed evaporation in 3 of the 4 data sets since the mid 70s (Figure 2) are unrealistic. It is important to get these trends right since the water cycle plays a substantial role in the Earth's radiation balance (water vapor being the major greenhouse gas) in the transport of heat from the tropics to the poles, and in the weathering processes that help sequester  $\text{CO}_2$  on long time scales [18].



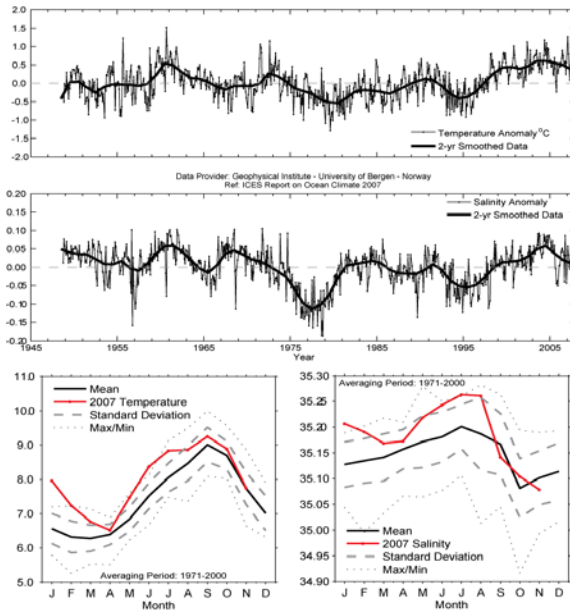
**Figure 3.a** The sea surface salinity anomaly difference between the pentads 2000-2004 and 1975-1979. Orange = positive, blue = negative, Contour Interval = 0.25.



**Figure 3.b.** Fifty year trends in surface salinity from linear least squares fits estimated by [15]. Subtropical salinification, tropical and high latitude freshening, and an enhanced contrast between Atlantic and Pacific all support an intensification of the global water cycle.

### 3. SALINITY VARIABILITY

In addition to long-term trends in salinity, there are available a few continuous records of salinity from time series stations. These are challenging to maintain and require lots of human intervention. But the classic time series from the Labrador Sea Weather Station Bravo from 1964-1974 [19] and the still-ongoing time series from Weather Station Mike in the Norwegian Sea show the strength of seasonal and interannual changes in salinity [20]. They observe both the seasonal cycle and interannual to decadal variability to have an amplitude of  $\sim 0.1$  at a depth of 50 m.



**Figure 4.** Temperature and Salinity variability at 50 m depth at Ocean Weather Station M, one of the few long term salinity records maintained since the 1940s. Top panel, monthly temperature anomaly, with 2-year smoothing, Middle panel, monthly and 2-year smoothed salinity anomaly; bottom panels, annual average cycles of temperature and salinity, their standard deviations and minimums and maximum ranges as well as the 2007 data.

Even larger salinity variability near Bermuda has been noted by [21]. They link the variability to changes in E-P and note that E-P in the Atlantic is well correlated with the Nino 3 index, especially since 1975. This is a period when the Pacific Decadal Oscillation has been in a positive phase. However, satellites that contribute to our estimates of both evaporation and precipitation began to significantly improve surface flux estimates about the same time, so in-homogeneities in the flux

estimate time series may also contribute to the improved correlations.

### 4. SALINITY AND CLIMATE CHANGE

Several studies have suggested that that decadal climate predictability may be possible in variables associated with the thermohaline circulation of the North Atlantic Ocean can be monitored [22], [23]. In particular, salinity variations may be particularly helpful, as freshwater anomalies can modulate the depth of convection in certain regions [24], [25]. On longer time scales, it has often been suggested that an intensified water cycle could freshen surface waters in the North Atlantic sufficiently to slow or even shut down the thermohaline circulation. This has been suggested by paleo-oceanographic data that infer abrupt North Atlantic circulation changes were induced by massive discharges of glacial meltwater when ice-dams broke [26]. Many climate models project a slowing down of the Atlantic meridional circulation [27], [28]. However, such models are suspect on several grounds. For one, they do not properly model the coast-hugging flow of a coastal freshwater discharge, but rather impose it as a general “hosing” of the entire North Atlantic. Secondly, they do not incorporate the effects of changing salinities on the stratification and thus the mixing rate of the ocean. That is, climate models fail to take account of the spatial and temporal variability in the vertical mixing coefficient  $K_\rho$ . Polzin et al [29] documented the broad spatial variations in mixing rate associated with topography and [30] noted the variation with tidal forcing. The mixing rate depends on the turbulent energy dissipation rate as well as the stratification through the formula [31]:

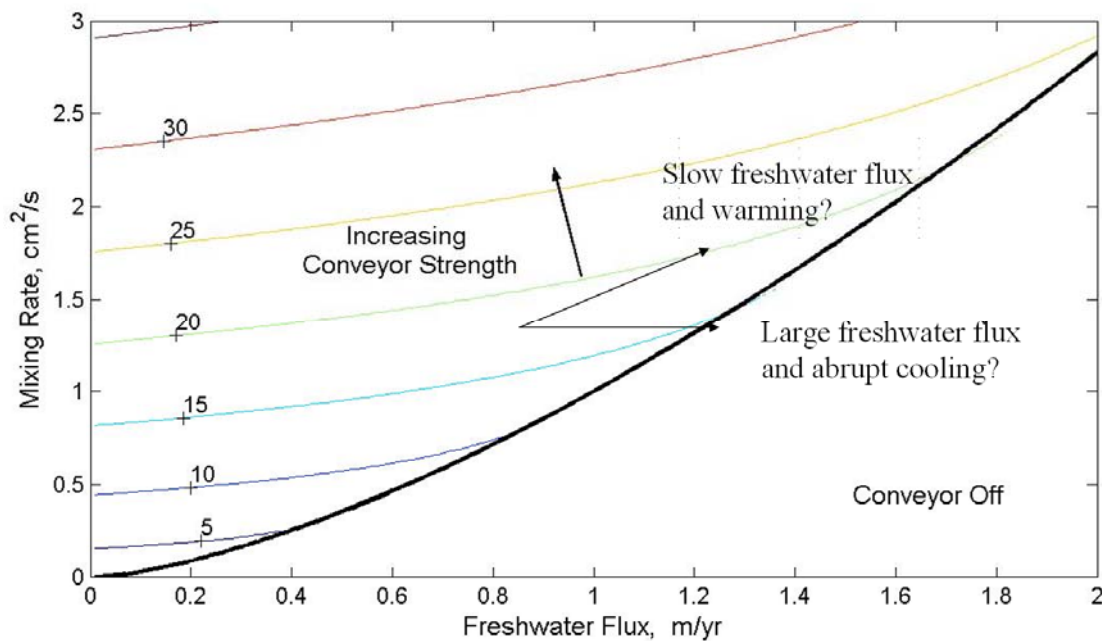
$$K_\rho = 0.2\varepsilon/N^2 \quad (1)$$

Models assume constant and uniform  $K_\rho$  when clearly the stratification and turbulent dissipation rate could be changing. Aside from getting the deep circulation wrong because they do not represent the spatial variations in  $K_\rho$ , models have not generally factored in the response in the mixing rate due to changing stratification. That is, we expect that the energy sources for deep ocean mixing (tides) will remain constant over the times scales of interest but the stratification will certainly respond to changing salinities. In fact, the salinity changes observed in the North Atlantic have penetrated into the deep ocean [32], so a changing stratification is to be expected. Freshening of the deep waters will clearly tend to decrease  $N^2$  with respect to the overlying intermediate waters, so an increase in  $K_\rho$  is predicted.

The response of the thermohaline circulation to both changing freshwater forcing and varying diffusivity has been examined with both theory and numerical runs by Zhang et al [33]. They obtained a relationship in the

freshwater forcing and diffusivity plane that separated the thermal mode from the haline (reversed) mode. That is, with larger mixing rates a larger freshwater forcing could be tolerated before collapse of the thermal mode. Figure 5 below illustrates the theoretical relationship along with contours of the meridional overturning strength. While conventional models would keep the diffusivity fixed and rapidly increasing freshwater fluxes could cause collapse of the MOC, a diffusivity that responded to a slowly increasing freshwater flux could actually cause the MOC to strengthen according to [34] and [35]. This counterintuitive result

arises from the sensitivity of the stratification and mixing rate to salinity, and is just one example of how the freshwater cycle impacts ocean dynamics. Monitoring of mixing rates as proposed by [36] along with changing salinities thus has much to recommend it. The potential trade-offs between oceanic heat and water transports by the MOC and atmospheric transport by storms and the unknown role of salinity in modulating the ocean thermohaline circulation suggests that we have much motivation to come to a better understanding of these key climate processes.



**Figure 5.** Contour plot of the strength of the meridional overturning circulation (in Sverdrups) as a function of the vertical mixing rate and the high latitude freshwater flux magnitude, according to the analysis of Zhang et al, [37]. Points below the black curve are in the “haline” mode, with the direct thermal mode (conveyor) in its off state. A large increment in freshwater flux due to a collapsing ice dam might push the system over the edge and shut off the thermal mode, but a slow freshwater flux increase (as we are experiencing with global warming) could change the deep stratification so as to cause an increase in the mixing rate that leads to a stronger overturning circulation and a warmer rather than cooler North Atlantic.

## 5. THE OCEANS AND TERRESTRIAL RAINFALL

Of course, one reason for advancing understanding of the water cycle is the freshwater supply for civilization. The oceans are by far the source of most atmospheric moisture, and the mobility of water vapor molecules in air is a strongly increasing function of temperature. It has long been known that SST distributions are useful predictors of rainfall on land [38], [39]. Karnaskas and Busalacchi [40] have related eastern tropical Pacific surface temperatures to central American rainfall. Recently, Shanahan et al, [41] found that Atlantic SST variability is largely responsible for the patterns of drought in the West Africa. Using lake sediment data and tree ring reconstructions of the Atlantic Multidecadal Oscillation (AMO), they find that the West African Monsoon is in phase and coherent with the AMO on times scales between 30 and 50 years. The sense is such that warm SST anomalies in the Atlantic produce increased precipitation over West Africa. Clearly, advances in predictability of oceanic SST will be very valuable in agricultural and water use planning. The role of salinity in modulating upper ocean stratification, mixing, and heat storage, as well as in the decadal predictability problem outlined earlier, and its intrinsic linkage to the water cycle, behooves us to expand salinity observing systems.

## 6. THE SALINITY MEASUREMENT CHALLENGE

Clearly, a remarkable success has been achieved with salinity measurements in the ARGO float program [42]. The continuously immersed conductivity sensors used on the floats have proven to be more reliably accurate over multi-year time periods than most sensors deployed from ships, which must break the ocean surface twice with each cast [43].

A central goal of expanding salinity measurements should be to develop a better understanding of what these salinity patterns are telling us about the water cycle. The ARGO float program is rapidly adding to the available subsurface salinity data. However, in order to maintain calibration, the CTD is turned off 5 m beneath the surface. Thus, data on the actual surface salinity, which will be most closely tied to the water cycle, is not growing as fast as we would like. SSS data will be necessary to calibrate/validate the new salinity sensing satellites, SMOS and Aquarius [44]. ARGO floats also have a 10-day gap between surfacings, so data is sparse.

A great potential exists to expand surface salinity measurements using sensors deployed on surface drifters. Reverdin et al, [45] have had some success

with drifter deployed sensors, though some issues with surface heating and temporal drift remain. This is a technology that requires additional development and testing. However, the numerous and widely distributed surface drifters of the Global Drifter Program provide an exceptional opportunity for continuous monitoring of the global surface salinity and an SSS program ought to be initiated. Similarly, maintenance and expansion of thermo-salinographs on volunteer observing ships [46] ought to be encouraged. The operators of the moored sites of the ocean observing system [47, 48] should also make a concerted effort to maintain long term salinity time series, as such records can provide important long term reference records for documentation of the changing salinity field. Finally, in all cases we note the need for ongoing quality control efforts, models and forecasts can only be as good as the data provided to them (garbage in yields garbage out). Salinity remains a challenging variable and quality control efforts must keep pace with expanding data sources [49].

## 7. ACKNOWLEDGMENTS

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