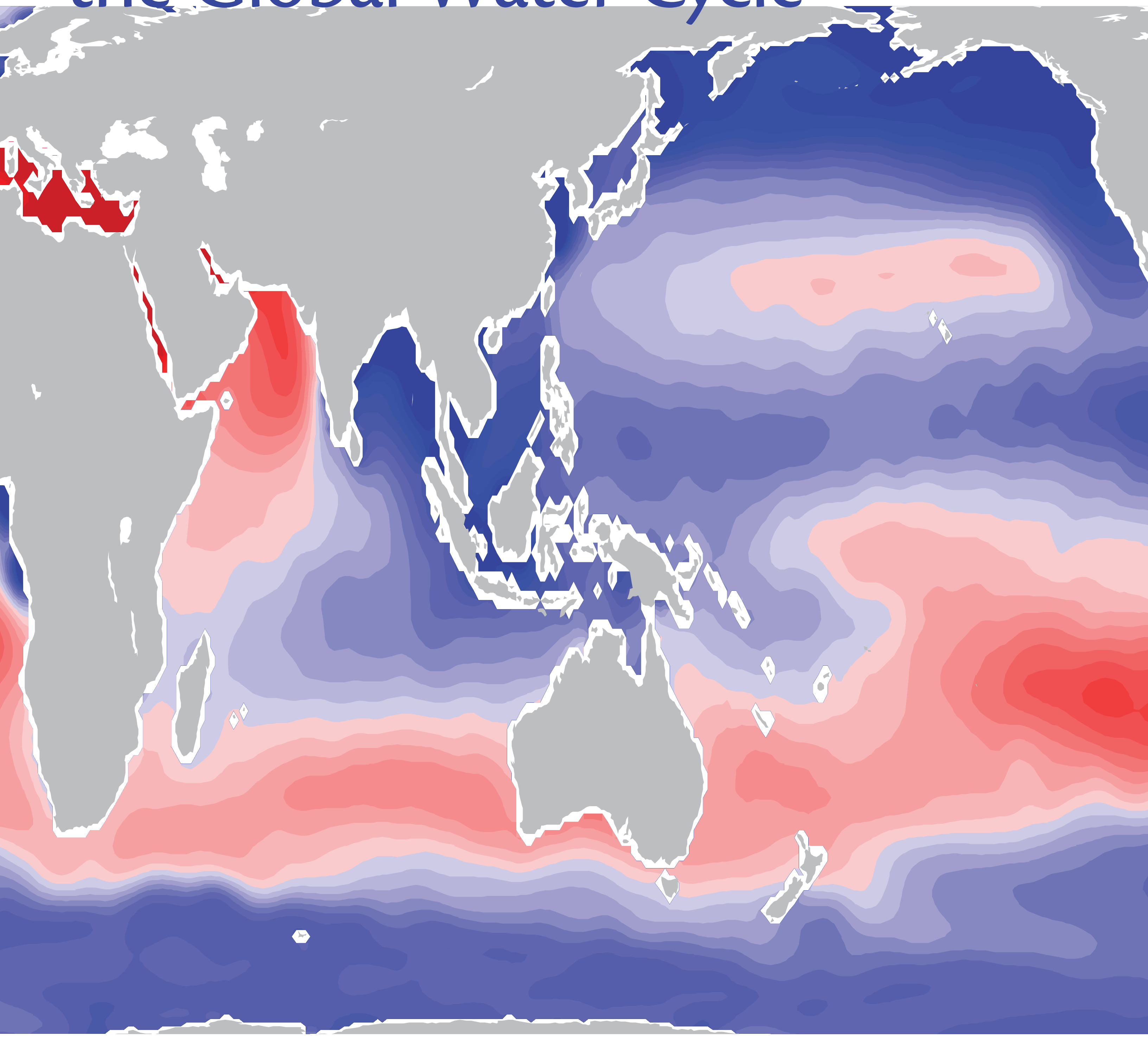
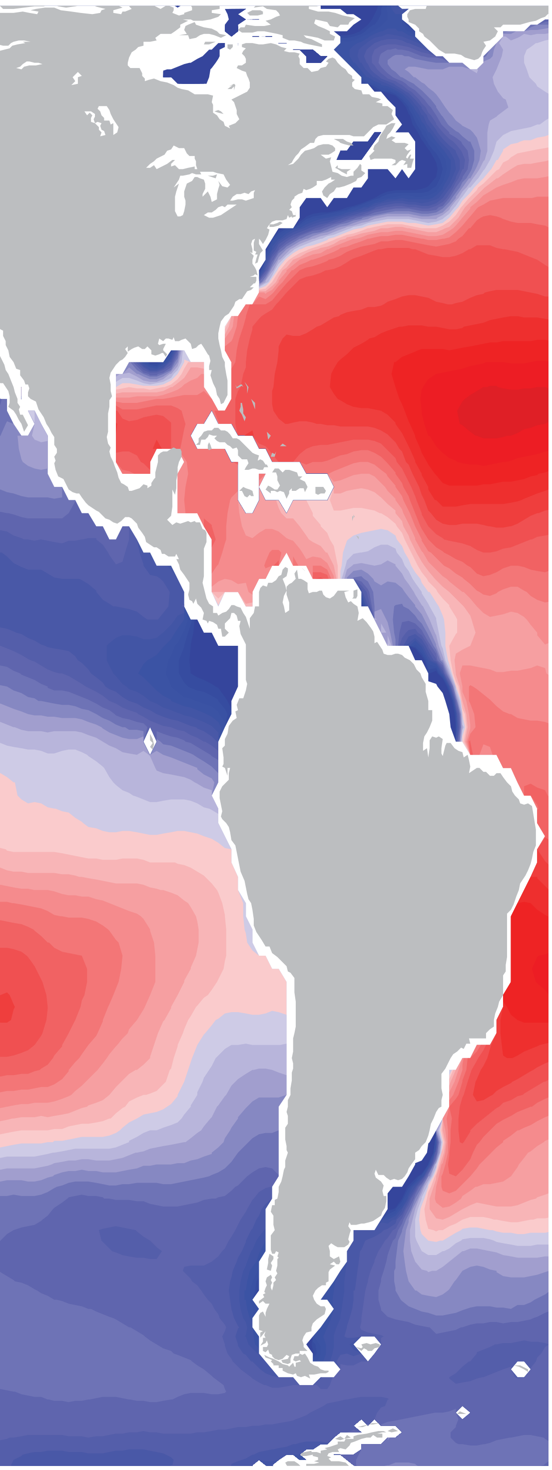
BY GARY LAGERLOEF, RAYMOND SCHMITT, JULIAN SCHANZE, AND HSUN-YING KAO

The Ocean and the Global Water Cycle





ABSTRACT. More than three-fourths of the global water cycle consists of the annual rainfall and evaporation freshwater exchange between the ocean and atmosphere. The water cycle is expected to intensify in a warmer climate, with shifting large-scale rainfall and drought patterns. Ocean salinity variations in recent decades provide a clear indicator of such changes and offer a key index for monitoring future climate variability related to the hydrologic cycle. In this sense, the ocean behaves like a rain gauge. This simple idea will also contribute to resolving the major discrepancies among rainfall climatologies. Addressing these problems requires a full understanding of complex upper ocean processes such as mixing and advection that balance the net freshwater flux at the surface. The global surface salinity measurement system, including both in situ instruments and satellites, along with regional upper ocean process studies, will soon be in place to advance these studies.

INTRODUCTION

No climate issue will have as much impact on society as changes in the global water cycle; water is fundamental to all life and key to modern civilization as we know it. Yet, when we assess what we actually know about the water cycle, we find great holes in our knowledge because a vast part of the water cycle occurs, unmonitored, over the global ocean. The water cycle is expected to be extremely sensitive to change in mean atmospheric temperatures, such that even modest warming is expected to intensify droughts and floods, and lead to stronger storms (Milly et al., 2002; Schmitt, 2008). How will we come understand and anticipate such changes, when fully 86% percent of atmospheric water vapor comes from the ocean and 78% of Earth's rain falls on the ocean (Baumgartner and Reichel, 1975)? We have few rain gauges in the ocean and no long-term network of meteorological stations with century-long records to tell us about past climate variability. The water cycle is primarily an ocean-atmosphere phenomenon, and we must look to the ocean to begin to understand it.

In this article, we make the case that ocean salinities provide a key indicator of the water cycle. Salinities increase when water evaporates and decrease with precipitation and river input. New tools for measuring salinity, including satellites, are allowing oceanographers to advance our understanding of the water cycle over the ocean and providing fresh insights into how the ocean itself responds to the water cycle.

THE GLOBAL WATER CYCLE

Baumgartner and Reichel (1975) compiled estimates of evaporation (E), precipitation (P), and river flows (R) over land and ocean. Their "World Water Balance" had little on which to base its oceanic estimates aside from

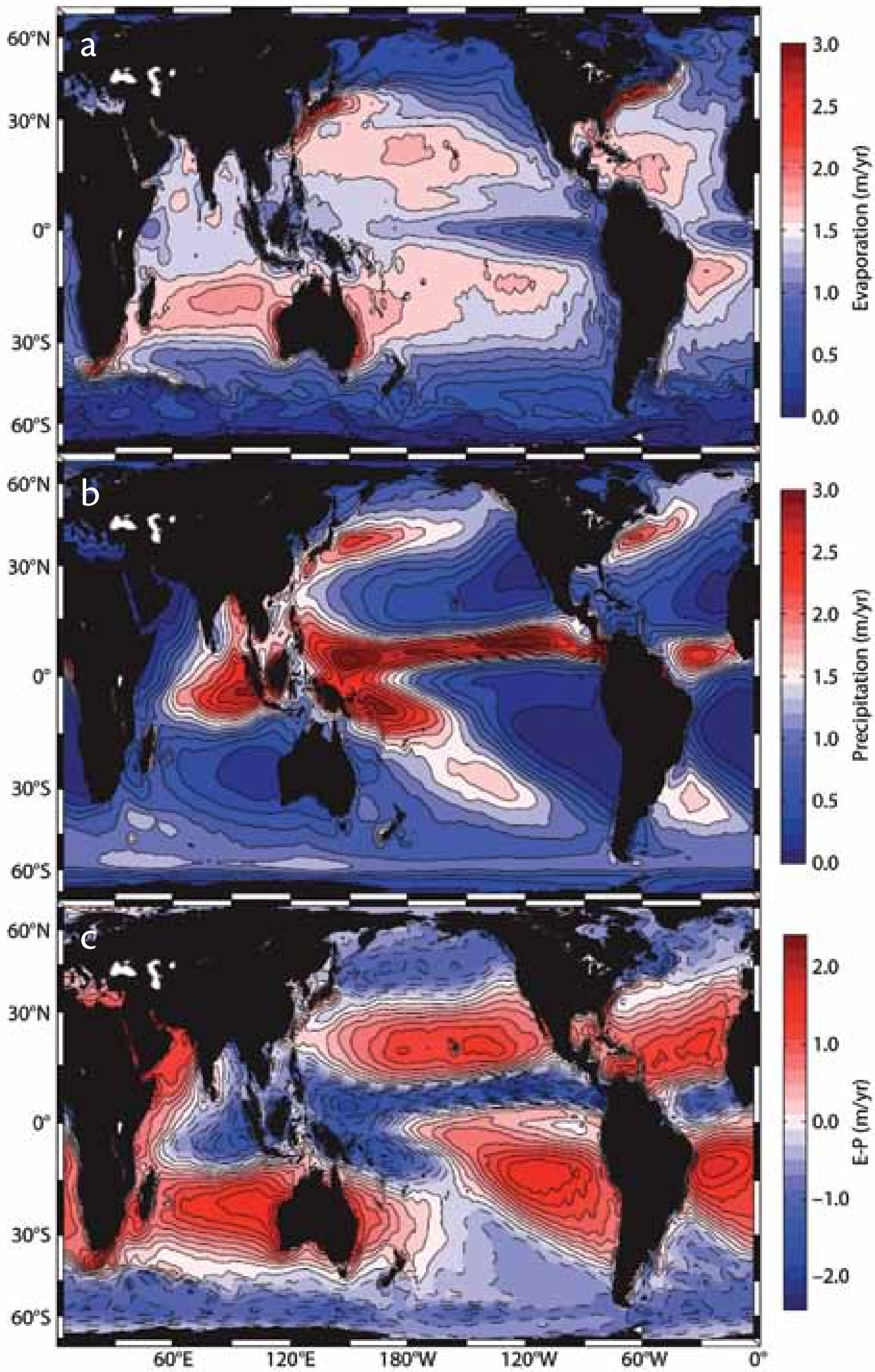


Figure 1. Global annual average evaporation *E* (a), precipitation *P* (b), and *E-P* (c) maps for 2005–2008. All subtropical ocean gyres and subtropical marginal seas are dominated by excess *E*, while the regions of the Intertropical Convergence Zone (ITCZ) and the Indonesian Throughflow as well as most temperate and subpolar latitudes are dominated by excess *P*. The maximum evaporative imbalance of 2.22 m yr^{-1} occurs in the Red Sea, while the net precipitation excess of 2.59 m yr^{-1} occurs near the Colombian Pacific coast in the ITCZ. *From Schanze et al. (in press), except for years 2005–2008*

rain records from a few island stations and early bulk formulae estimates of evaporation. Nevertheless, their general schema has proven surprisingly consistent with more modern estimates. Their oceanic estimate lacked details such as *E* and *P* features associated with western boundary currents, but the sums proved not far from later works (Schmitt et al., 1989). They also incorrectly described the redistribution of water by the ocean, but Wijffels et al. (1992) provided an oceanographically consistent picture. Dai and Trenberth (2002) introduced more detail on riverine inputs and used reanalysis products to examine global *E-P*. Most recently, Schanze et al. (in press) developed a water budget estimate that is based on oceanic observations and detailed river data. They combine evaporation estimates from the "Objectively Analyzed" ocean-atmosphere flux product (OAFlux) of Yu and Weller (2006) with satellite estimates of rainfall and the latest river data to generate new maps of the water cycle over the global ocean.

Figure 1a shows the mean evaporation over the global ocean for 2005–2008. Strong evaporation patterns over western boundary currents and the subtropical gyres are evident. Precipitation

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patterns (Figure 1b) show highs in the Intertropical Convergence Zone, the South Pacific Convergence Zone, and the western boundary currents. The net result for *E-P* (Figure 1c) is a pattern of evaporative dominance under the subtropical highs, relatively small net flux in the western boundary currents, and precipitative dominance in the tropical convergence zones and at high latitudes.

Evaporation from the global ocean is estimated to be ~ 13 Sv (1 Sverdrup = 10^6 m^3 s^{-1}), and the precipitation sums to ~ 12.2 Sv. The difference of 0.8 Sv compares with the estimate of river input of 1.2 Sv. The apparent imbalance of ~ 0.4 Sv excess is smaller than the estimated error bars. Sea level rise due to melting glaciers is only ~ 0.01 Sv, so cannot account for the imbalance. Global groundwater flows are poorly known but generally estimated to be similarly small (Cable et al., 1996). Likely sources of error include scant data in the southern oceans and a possible underestimate of evaporation in very-high-wind conditions. Other surface flux climatologies display similar patterns, but the range of the estimates is quite large and unlikely to be significantly improved in the near future.

A key issue is that all this water transport out of and back into the ocean causes changes in sea surface salinity. This fact has been recognized since Wüst (1936) and is illustrated with Figure 2, a plot of global mean annual ocean surface salinity, where the correspondence between surface salinity and *E-P* is easily recognized. This correspondence suggests that trends in ocean salinity could be the very best indicators of a changing global water cycle, as they are natural integrators of the differences between large and uncertain evaporation and precipitation estimates.

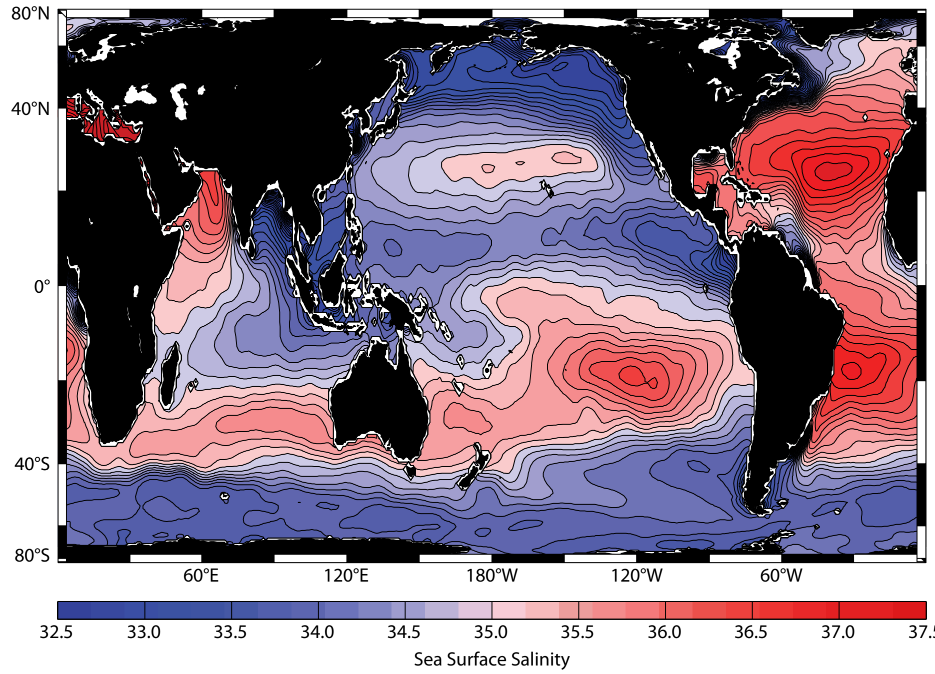

Figure 2. Global surface salinity from the World Ocean Atlas. There are significant salinity maxima associated with each subtropical high, maintained by evaporation under the trades and Ekman convergence. Regional lows are found under the Intertropical Convergence Zone and near large river outflows such as the Amazon. The Atlantic is notably saltier, probably due to the transport of water vapor to the Pacific across Central America (Weyl, 1968).

SALINITY AS OCEAN INDICATOR OF WATER CYCLE

As noted earlier, a key climate question for society is whether the water cycle is presently changing. The exponential dependence of the vapor pressure of water on temperature suggests that a 1°C increase in mean surface temperature could result in a 7% increase in the vapor-carrying capacity of the atmosphere (Schmitt, 2008). There may be compensating effects in the atmosphere to mitigate such a strong response (Schneider et al., 2010) but the size of any response is of intense interest. To date, the evidence on land has been mixed—most variables such as river flows, evaporation, or precipitation estimates show little trend (Dai et al., 2009). In contrast, oceanographic data on salinity provide a very distinct message on water cycle trends. A variety of studies dating back many years has documented variability and trends in surface salinity (Brewer et al., 1983; Freeland et al., 1997; Curry et al., 2003; Boyer et al., 2005; Gordon and Giulivi, 2008), with the overall result coming down firmly in support of a strengthening of the water cycle. Durack and Wijffels (2010) provide the most recent and complete summary of this intensification. They quantify 50-year trends in global surface salinity, and show salinification of the subtropical gyres, freshening of tropical and high-latitude rainfall regions, and growing contrast between an increasingly salty Atlantic and an increasingly fresh Pacific. This salinity contrast is the prime reason that the Atlantic supports a meridional overturning circulation (MOC) and the Pacific does not. Or, more succinctly, the lower surface salinity of the North Pacific, due to high precipitation rates, inhibits deep convection in the Pacific (Warren, 1983; Emile-Geay et al., 2003). But, the observed increasing salt contrasts serve as the best indication yet of an intensifying water cycle. We argue that this is to be expected, because the water cycle is predominantly an ocean-atmosphere phenomenon, and the terrestrial portion is small by comparison (Schmitt, 1995).

It is important to recognize that these decadal ocean salinity trends are statistically significant, yet can result from very small long-term changes in *E-P*. For example, the surface mixed layer salinity trend in the subtropical North Atlantic during the late twentieth century was equivalent to a few centimeters per year net *E-P* imbalance if it was due solely to surface forcing (Curry et al., 2003; Gordon and Giulivi, 2008). This imbalance remains one to two orders of magnitude smaller than the uncertainties among *E-P* climatologies (see below). At this time, it is not possible to identify such small trends in atmospheric data sets due to their large uncertainties, leaving ocean salinity as a key indicator for trends in the global water cycle. However, another complication is that the well-known North Atlantic freshening trend of the 1960s–1990s (Dickson et al., 2002) has reversed in recent years (Holliday et al., 2008). Hakkinen and Rhines (2009) suggest that recent temperature and salinity increases in the Atlantic inflow from the eastern subpolar gyre to the Fram Strait are likely attributed to changes in ocean circulation, as measured by surface drifters and satellite altimetry. If such increasing salinity trends continue in the North Atlantic, then hypothetically it is less likely that the MOC will slow or shut down, as has often been suggested (Broecker, 1987; Alley et al., 2003; Haupt and Seidov, 2007). One job ahead of us is also to understand the role circulation plays in observed long-term salinity trends. In any case, changes in ocean salinity do represent fundamental changes in the global water cycle, whether they are in the atmospheric limb through *E-P* changes, or the oceanic limb through changes in advection, or both.

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UNCERTAINTIES OF THE MARINE FRESHWATER BUDGET: HOW WELL DO WE KNOW THE GLOBAL WATER CYCLE OVER THE OCEAN?

To fully understand what causes the long-term trends we see in ocean salinity, we must first understand the uncertainties in the marine freshwater budget. As a whole, the global average freshwater flux for the ocean (*E-P-R*) is in approximate balance to within the measurement uncertainties using one pair of satellite-derived precipitation (Global Precipitation Climatology Project [GPCP]) and evaporation (OAFlux) data sets along with a new river input (*R*) estimate (Schanze et al., in press). However, the global budget appears far from closed when *E* and *P* from some contemporary reanalysis fields (such as ERA-40) are analyzed in the same way (Table 1 in Schanze et al., in press). This lack of closure lends credibility to the satellite-derived fields, but the differences between these and the model fields, as well as among other satellite fields (Large and Yeager, 2009), remain an obstacle to closing the global marine freshwater budget with confidence.

Qualitatively, the spatial pattern of the net *E-P* mean climatology (e.g., Figure 1c) is very familiar: wet tropics, dry subtropics, and wet temperate to subpolar regions. What differs among the various analyses are the details and magnitudes. Oceanographically, the other side of the closure problem is to understand how ocean circulation and mixing compensate for these regional *E-P* imbalances. The meridional freshwater transport by oceanic circulation is traditionally estimated indirectly by integrating the net surface flux within each basin (e.g., Wijffels, 2001; Large and Yeager, 2009; Schanze et al., in press) and comparing that indirect estimate with direct ocean transport estimates along zonal hydrographic sections. These indirect calculations differ substantially, depending on the mix of *E* and *P* climatologies that are used, and thus are subject to unknown errors in the surface fluxes (Wijffels, 2001). Large and Yeager (2009) carefully assessed the variations among several rainfall climatologies and developed a blended climatology, retaining what they considered the most reliable satellite-derived fields by region and latitude range (Figure 3a). Their derived global meridional freshwater transports for the global ocean, Atlantic Ocean, and Indo-Pacific basins are shown in Figure 3b. The shaded area shows that the uncertainty range due to the spread among the various precipitation fields is a significant fraction of the transport estimate. Comparisons with hydrographic sections were within the error bars of four hydrographic sections in the Northern Hemisphere, but were the opposite sign in two South Atlantic transects (Figure 3b). Therefore, some significant gaps remain between what we can infer about ocean freshwater transport from atmospheric *E-P* climatologies versus what we can infer from oceanographic measurements.

Ocean state estimation (Lee et al., 2009) presents another approach to the freshwater closure problem that depicts the mismatch in two dimensions. Stammer et al. (2004) showed a map of the implied mean net freshwater flux (*E-P*) computed as part of the Estimating the Circulation and Climate of the Ocean (ECCO) ocean model optimization over the period 1992 through 2001, and the difference between this and the NCEP climatology. The computed flux was the "best" estimate to be in equilibrium with the ocean as it is represented by the ECCO ocean state estimation. The differences with NCEP revealed extensive regions in excess of 0.5 m yr^{-1} in the tropics, subtropics, and Southern Ocean, and smaller regions exceeding 1 m yr^{-1}. The regional differences are comparable in magnitude to the mean flux over much of the ocean area. These patterns depict where the ocean according to ECCO is not in equilibrium with the atmosphere according to NCEP, and further illustrates the present-day gap in resolving the true flux climatology from both sides of the air-sea interface.

From these studies we see that significant problems with balancing the marine freshwater budget still exist, given the uncertainties in the net *E-P* climatology over the ocean. These problems complicate our ability to trace the causes of the long-term salinity trends described above. Nevertheless, these salinity trends do serve as a robust indicator of climatic changes in the hydrologic cycle, and these changes imply that the ocean acts as an effective long-term rain gauge. The rain-gauge concept can also be used to reduce the uncertainties in climatologic surface fluxes. This problem presents an important challenge for oceanography. It requires developing a much better

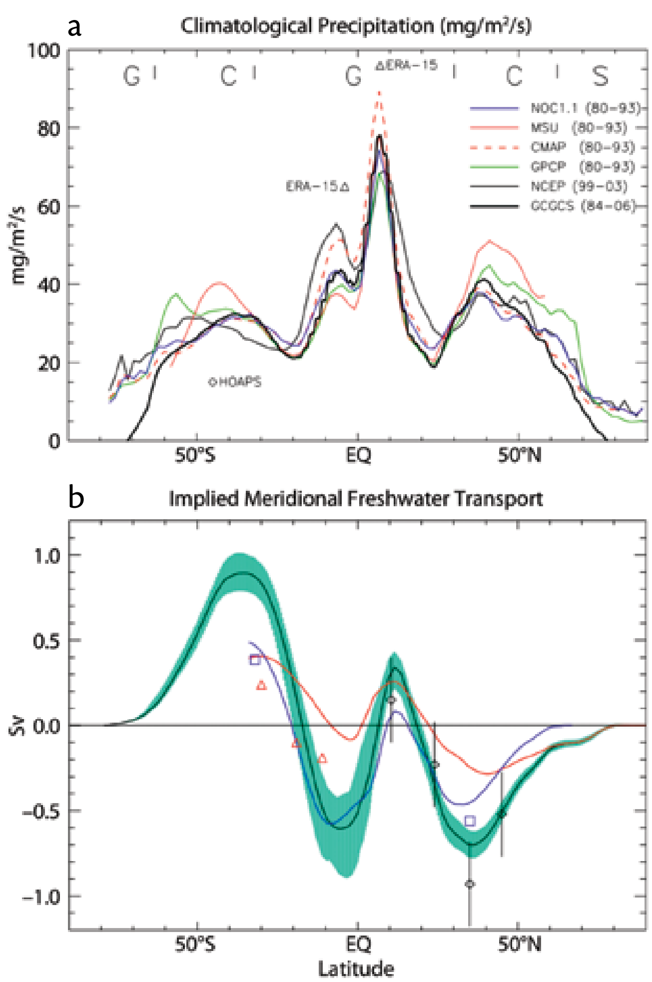

Figure 3. (a) Zonal averaged precipitation climatologies from various sources showing the range of differences. Units: 100 mg/m²/s = 3.1 m yr^{-1}. (b) Illustration of the present uncertainty in estimating the net poleward freshwater ocean transport in Sv. Indirect estimates from net *E-P* shown for the Atlantic (red), Indo-Pacific (blue), and global (black) for the period 1984–2006, with the shaded area showing the range from the various *E-P* data sets. Triangle, square, and diamond symbols colored as above for ocean basins are hydrographic transect estimates from Wijffels (2001), with error bars for the global transects shown. Shading indicates the range by individual years. *Reprinted with permission from Springer Science+Business Media, Large and Yeager (2009) Figures 5 and 10, © 2008 Springer-Verlag*

understanding of the near-surface physical processes that balance the net *E-P* freshwater flux, and with a residual uncertainty that is significantly smaller than that of *E-P*.

A TRIAL BALANCE OF SURFACE FLUXES: THE NEAR-SURFACE FRESHWATER (OR SALINITY) BUDGET

The key ocean surface processes that must be addressed include the local time derivative of salinity, horizontal advection, and vertical and horizontal small-scale mixing processes. The conventional approach to analyzing the balance with atmospheric fluxes is to consider a homogeneous surface mixed layer. Here, we use a simplified salt budget equation for the surface mixed layer to illustrate some basic concepts:

$$\frac{\partial S}{\partial t} + \vec{U} \cdot \nabla S = \frac{S(E\text{-}P)}{H} + \textit{mixing processes}. \tag{1}$$

S is the mixed layer salinity, $\vec{U}$ is the vertical average mixed layer horizontal velocity vector, ∇S is the horizontal salinity gradient, their dot product is the horizontal salt divergence (or equivalently freshwater convergence) in the mixed layer, and H is the mixed-layer depth. The aim is to close this budget through observation, modeling, and analysis, but we are far from achieving that result, given the magnitude of uncertainties in the terms in Equation 1. The $\partial S/\partial t$ term (time derivative or trend) is very small on climatic time scales, as noted above, and thus is the small residual difference between the other much-larger terms. It is instructive, therefore, to compare these larger terms in order to understand their patterns and relative magnitudes. We focus here on comparing the middle two terms in (1) as a trial balance. This initial step indicates the relative importance of the surface circulation to balancing *E-P*. The differences between these two terms will contain unknown relative biases and, more importantly, will identify the regions where we can anticipate that the ill-defined *mixing processes* are significant to maintaining the balance. *Mixing processes* encompass vertical mixing, subduction, double diffusion, eddies, and other mechanisms that mix and diffuse salt and freshwater horizontally within the mixed layer and vertically across the base of the mixed layer.

This analysis covers years 2005–2008 when the requisite simultaneous global satellite and extensive new in situ salinity data are available from Argo. The Argo array (Roemmich et al., 2009) provided more than 9000 globally distributed in situ temperature-salinity profiles per month, from which global objective analysis 1 x 1 degree monthly profiles were obtained from the Scripps Institution of Oceanography Web site (ftp://kakapo.ucsd.edu/pub/argo/Global_Marine_Argo_Atlas/RG_ArgoClim_Full.nc). From these profiles, we extracted the surface salinity S and computed the mixed-layer depth H as the depth where density exceeds the surface value by 0.125 kg m^{-3}. For the surface velocity fields, $\vec{U}$, we used the satellite-based Ocean Surface Current Analyses-Real time (OSCAR) data derived from sea surface height and vector wind data with linear geostrophic and Ekman dynamics (Dohan and Maximenko, 2010). *P* and *E* fields are, respectively, from the GPCP and OAFlux data sets described above. For comparison, we also evaluated a separate satellite-based Passive Microwave Water Cycle (PMWC) data set (years 2005–2006 only) produced for the NASA Energy and Water Cycle Study (NEWS) described by Hilburn (2009). PMWC includes precipitation and evaporation fields computed from a unified set of intercalibrated satellite microwave data and algorithms.

Figure 4a depicts the zonal averaged *E-P* using the four *E-P* combinations in the GPCP (*P* only), OAFlux (*E* only), and PMWC (*P* and *E*) data sets. The spread among these data offers another example of the *E-P* uncertainty range. The noticeable differences in higher latitudes are primarily the biases between GPCP and PMWC precipitation estimates. Figure 4b is the calculation $S(E\text{-}P)/H$ to illustrate the corresponding term in Equation 1.

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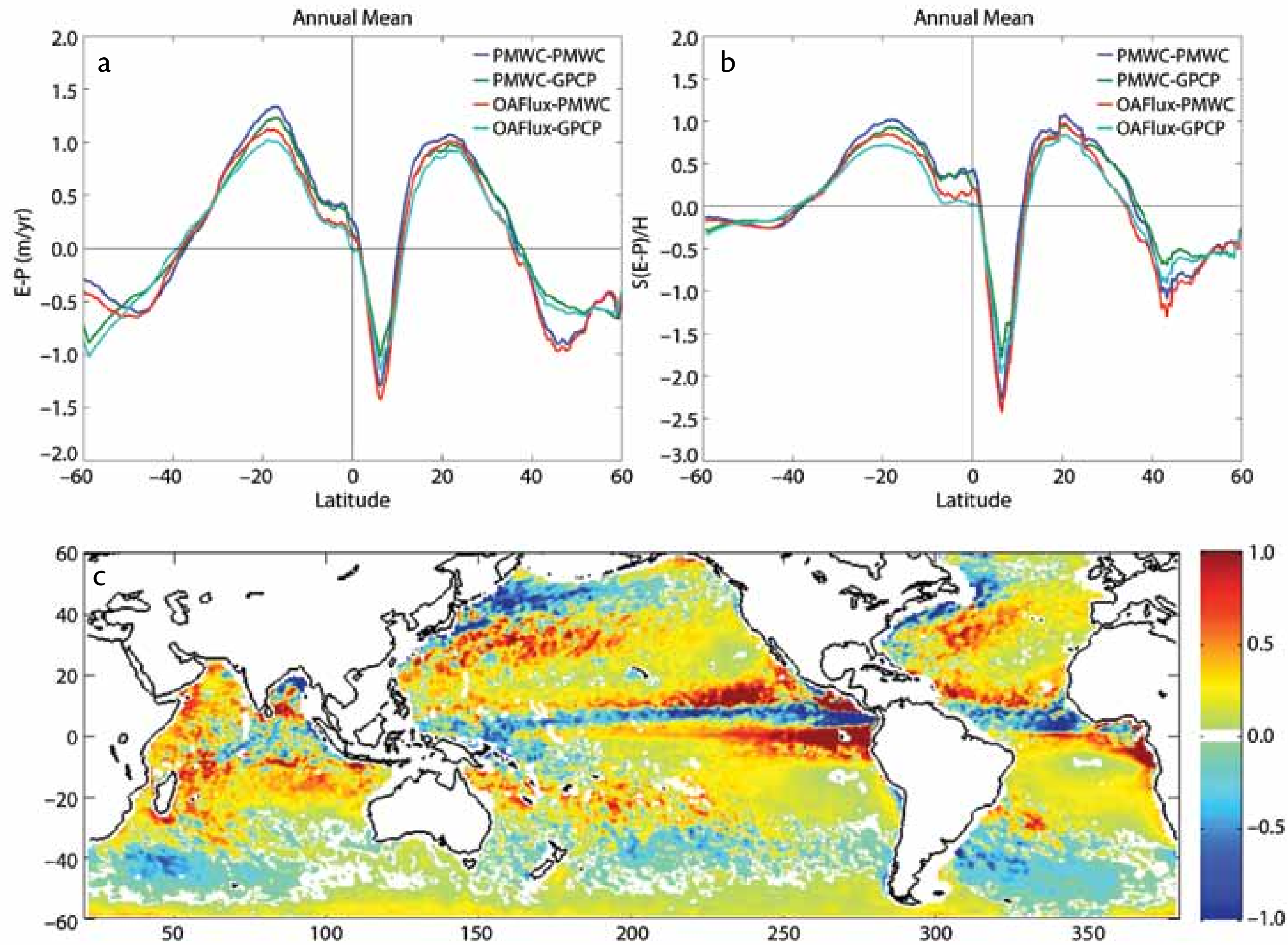

Figure 4. (a) Zonally averaged *E-P*, 2005–2006 mean, for the four *E-P* combinations in the Global Precipitation Climatology Project (GPCP), "Objectively Analyzed" ocean-atmosphere flux product (OAFlux), and Passive Microwave Water Cycle (PMWC) data sets. Units: m yr^{-1}. (b) Same as (a) except *S(E-P)/H* to convert the flux to the equivalent salinity tendency in Equation 1. Units: psu yr^{-1}. (c) Difference map of *S(E-P)/H* from PMWC minus *S(E-P)/H* from the OAFlux-GPCP combination. Units: psu yr^{-1}.

The same basic meridional structure remains, whereas the amplitudes are scaled anew mainly by the variation in estimated *H*, which reduces somewhat the spread in higher latitudes. Although the spread among the *E-P* estimates appears to be much less than the scale of the meridional variations, the zonal averages obscure most of the detail. The difference map of *S(E-P)/H* from PMWC minus *S(E-P)/H* from the OAFlux-GPCP combination (Figure 4c) reveals considerable spatial structure to the bias between the respective flux fields, particularly in the eastern tropical Pacific and tropical Atlantic. Such major differences among these very similar data sets further emphasize the scale of uncertainty and the difficulty of closing the freshwater budget over the ocean on these regional scales. The remaining terms in Equation 1, which are all oceanographic, must be resolved to much better accuracy to identify the errors among the various atmospheric *E-P* analyses.

The next step is to calculate the contribution that the surface circulation makes, via the second term in Equation 1, to the oceanic transport of freshwater and salt that compensates the regional *E-P* distribution in the atmosphere. For this comparison, Figure 5 (top) shows the four-year average (2005–2008) *S(E-P)/H* map and the zonal average for each year using GPCP (*P*) and OAFlux (*E*). The interannual variability, especially in the tropics, is comparable to the variations among the different *E-P* analyses in the previous figure. The surface horizontal divergence term $\vec{U} \cdot \nabla S$ (Figure 5, middle) bears many large-scale similarities to the

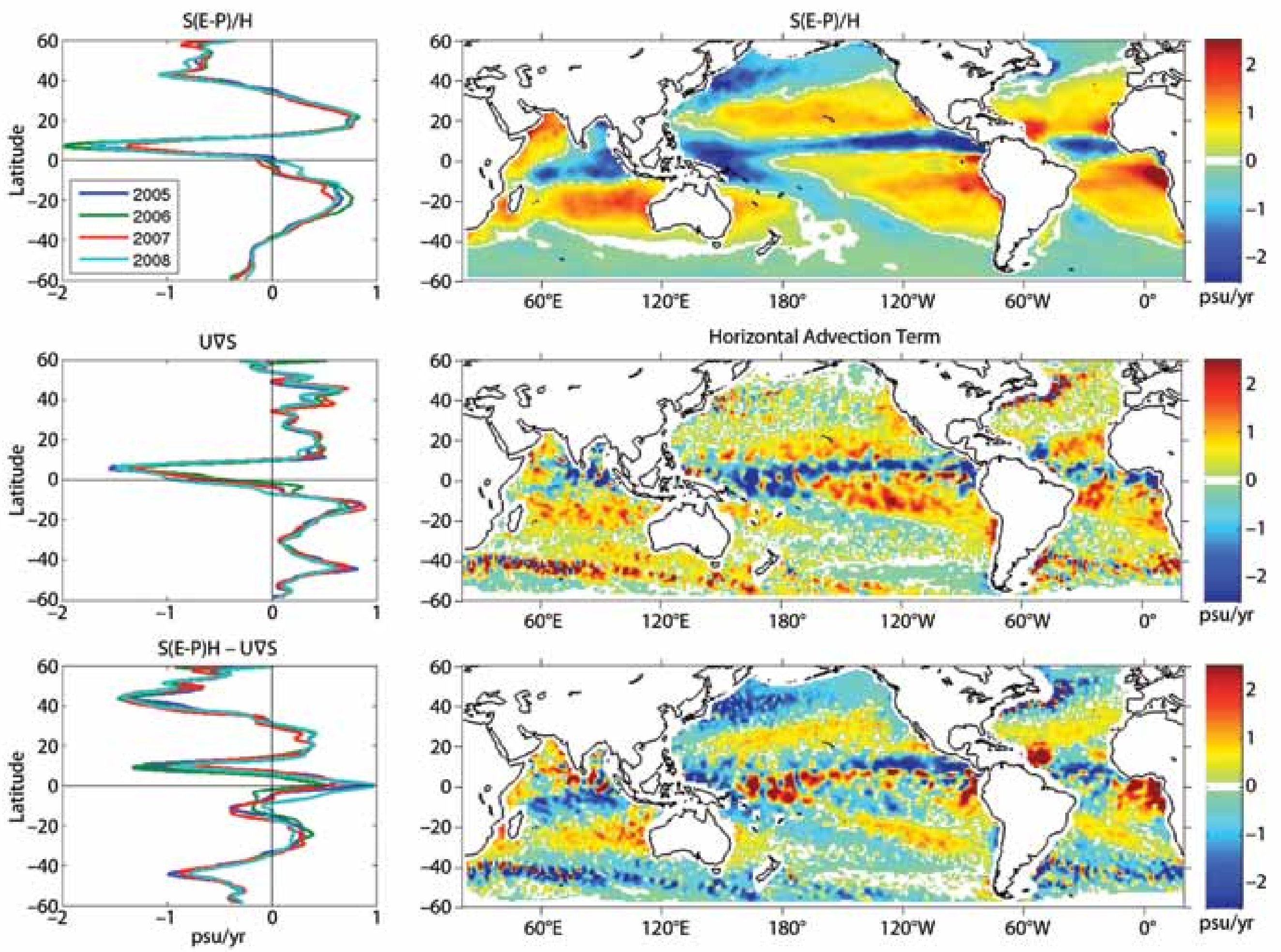

Figure 5. (top) Atmospheric forcing term *S(E-P)/H* in Equation 1 averaged for 2005–2008 using Global Precipitation Climatology Project (GPCP) (*P*) and "Objectively Analyzed" ocean-atmosphere flux product (OAFlux) (*E*) data sets. (middle) Horizontal salinity advection term in Equation 1 for the same years. (bottom) The difference field. Left-hand column shows zonal averages of the respective maps by individual year.

net *E-P* map in the tropics, and zonal averages of the two terms have similar magnitude. Generally, the evaporation-dominated regions are partially compensated by salinity divergence (or equivalently freshwater convergence), while the narrow tropical rain-dominated band is largely compensated by salinity convergence (freshwater divergence). In the higher latitude zones, however, the picture appears quite different; the surface layer salinity divergence remains > 0 at all latitudes (zonal average) outside of the tropics, and does not appear to compensate for the net precipitation.

The difference calculation,

$$\frac{S(E\text{-}P)}{H} - \vec{U} \cdot \nabla S$$

(Figure 5, bottom) accounts for unknown bias errors in these two terms (the likely scale of the *S(E-P)/H* bias is shown in Figure 4c), the four-year salinity trend (relatively small and not shown), and the unknown *mixing process*. We interpret much of the difference pattern to represent *mixing processes*, and note particularly that the magnitude is about the same as the other two terms. This term is strongly negative poleward of 30° latitude in both hemispheres. In these regions, evidently, *mixing processes* must significantly offset both excess precipitation and horizontal salinity divergence. The zonal average

$$\frac{S(E\text{-}P)}{H} - \vec{U} \cdot \nabla S$$

differences in the tropics result because the two terms are slightly offset in latitude, and where vertical processes must also play a role as part of the complex tropical circulation and overturning cells.

The discussion in this section indicates that both horizontal surface advection and *mixing processes* (as represented in Figure 5, bottom) are of nearly equal importance to balancing the net freshwater flux at the surface. The relative importance varies significantly from one ocean region to another. These global maps therefore indicate where these terms dominate respectively, and will require the most research focus to understand and reduce their uncertainties when applied to the budget analysis in Equation 1.

FUTURE DIRECTIONS

Several recent and near-future developments will significantly advance progress in understanding the water cycle. First and foremost are advances to the salinity observing system that contribute directly to measuring the first two terms in Equation 1 (Lagerloef et al., 2010). In particular, the Argo array, which has been fully operational since 2005, provides unprecedented broad synoptic sampling that is mapped into smooth salinity fields used in the preliminary calculations described above. Furthermore, the vertical profiles from Argo allow synoptic analysis of the mixed-layer depth H as well as data to validate mixed layer models that will be necessary to resolve the mixing processes in Equation 1.

Satellite measurements of sea surface salinity (SSS) will soon provide significantly higher sampling resolution globally with the potential to transform our understanding of spatial and temporal SSS variability. The European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission, launched in November 2009, is presently undergoing calibration and validation, while NASA's Aquarius/SAC-D mission will be launched in 2011 (Lagerloef et al., 2008; Lagerloef and Font, 2010). These new space-borne SSS measurements will significantly improve the estimates of the first two terms in Equation 1 and thus the understanding of the marine freshwater cycle and the air-sea budget. Indeed, the overarching scientific goal for measuring salinity from space is to understand the links among ocean circulation, the global water cycle, and climate.

Although the first three terms in Equation 1 will be readily computed from various satellite and in situ observations, *mixing processes* will require modeling such things as entrainment due to convection and shear-driven turbulence, extinction of turbulence by buoyant surface layers formed by rainfall and heating, double-diffusion arising from excess surface evaporation, lateral processes due to inertial waves, and eddies that mix and transport salt in the surface layer. Vertical mixing and convection processes are clearly factors, given that long-term salinity trends penetrate to intermediate depths (Boyer, 2005; Durack and Wijffels, 2010). Global and synoptic quantification of the rates and mechanisms that govern vertical transport between the surface and interior will be important and challenging research topics. Satellite-based SSS and in situ observations will provide essential data to constrain such models and how they are implemented.

One set of oceanic regimes that has become a focus for studying these processes is the surface salinity maximum (S-max) regions of the subtropical gyres. These areas tend to be characterized by low precipitation, an excess of evaporation, and a convergent surface Ekman flow due to the location in the central subtropical gyre. Eddy energy is a relative minimum, and, at the S-max, horizontal gradients are nil by definition. Thus, such areas come closest in approach to a one-dimensional (vertical) balance between surface fluxes and subsurface mixing. Of course, the mean subduction of surface waters and the seasonal cycle must be accounted for, but such regions promise to be the simplest sites to attempt salinity budgeting on a regional scale.

A start on studying the salinity budget will be undertaken in 2012 in a North Atlantic field program called Salinity Processes in the Upper-ocean Regional Study (SPURS). Some of the questions to be addressed in SPURS are:

1. What are the physical processes responsible for the location, magnitude, and maintenance of the subtropical Atlantic sea surface and subsurface salinity maximum? How is S-max formed and dissipated?
   a. Given the seasonal cycle in $(E\text{-}P)/H$, why there is no seasonal cycle in SSS?
   b. What is the propagation pathway for salt?

> "SEVERAL RECENT AND NEAR-FUTURE DEVELOPMENTS WILL SIGNIFICANTLY ADVANCE PROGRESS IN UNDERSTANDING THE WATER CYCLE."

c. How does the Atlantic subtropical S-max compare with the other (four) S-maxes of the Pacific and Indian oceans and of the South Atlantic?
2. How will the ocean respond to changes in thermal and freshwater forcing associated with a changing climate?
3. How will the shallow meridional overturning circulation be altered?
4. What is the nature of the cascade of salinity variance from the largest (climate) scales down to dissipation scales of a few millimeters?
5. What new information must be supplied to ocean models in order for these questions to be adequately examined?

These questions will be addressed by a combination of Eulerian and Lagrangian measurements from ships, autonomous platforms, and satellites, and by modeling. It is envisioned that a future SPURS will address the challenges of a high-precipitation regime, where advection and eddy processes tend to be stronger, and vertical mixing has a different character due to freshwater buoyancy forcing.

Closing the freshwater budget over the ocean will make several valuable contributions to climate research: (1) diagnosing the changes in the global water cycle that account for the observed long-term salinity trends, (2) applying the ocean as an effective rain gauge to reduce the uncertainty of atmospheric *E-P* analyses, (3) constraining evaporation, which in turn constrains the equivalent latent heating in the global energy budget, and (4) gaining insights that will eventually be applied to improving the way these terms are represented in state-of-the-art coupled climate models, and improving the models' fidelity in representing the global water cycle and ocean state in future climate predictions.

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