Seasonal cycle of near-surface freshwater budget in the western tropical Atlantic

V. Romanova,[1,2] A. Köhl,[2] and D. Stammer[2]

Received 15 September 2010; revised 5 April 2011; accepted 14 April 2011; published 13 July 2011.

[1] We investigate differences of the ocean response in the Amazon domain to the seasonal variability of the river discharge that are either introduced via assimilating climatological temperature and salinity or by specifying seasonally varying river runoff. The role of the seasonal cycle of the Amazon freshwater discharge for the evolution of the barrier layer (BL) in the western tropical Atlantic and on the freshwater budget is estimated. During the experiments, three different runoff fields are being applied, including a time-mean runoff, a seasonally varying runoff, and one that results from the GECCO assimilation approach. The simulation forced with a seasonal Amazon discharge appears to be closer to the constrained solution and moves away from the run with a constant runoff, demonstrating that the seasonal variability of the Amazon is an essential contributor in the freshwater forcing of the western tropical Atlantic. The modeled time-mean BL thickness seems to be overestimated by the model relative to the data. On the seasonal timescale, the simulated spatial mean BL is found to vary between 13 and 30 m, with a maximum occurring in July, following the Amazon high discharge period in May. Analyzing the freshwater content balance, we find integrated near-surface freshwater import from the western tropical Atlantic interior of around 0.20 Sv in October–November at 38°W and cumulative freshwater export out of the domain with a maximum of around 0.4 Sv in June as an effect of the Amazon flood in May.

Citation: Romanova, V., A. Köhl, and D. Stammer (2011), Seasonal cycle of near-surface freshwater budget in the western tropical Atlantic, *J. Geophys. Res.*, *116*, C07009, doi:10.1029/2010JC006650.

1. Introduction

[2] For the global ocean, the discharge from rivers is an important source of freshwater which, through its influence on the near-surface stratification and the surface boundary layer, plays an important role in modifying the near-surface circulation. Moreover, depending on the amount of freshwater entering the surface and its horizontal divergence/convergence in the ocean, a haline surface barrier layer (BL) can form which controls the stratification of the upper ocean (above and beyond thermal processes) and thus influences the exchange of heat between the ocean and the atmosphere [*Lukas and Lindstrom*, 1991; *Sprintall and Tomczak*, 1992; *Pailler et al.*, 1999; *Ffield*, 2006; *Foltz and McPhaden*, 2009]. The BL is a layer located in the isothermal mixed layer with its upper boundary coinciding with the start of pycnocline; its lower boundary is defined by the beginning of the thermocline and is characterized by density gradients formed only from the strong salinity stratification.

[3] Based on a global compilation of the NODC, WOCE and Argo databases, it was shown that the BL can be found in almost all regions characterized by high surface freshwater input [*de Boyer Montegut et al.*, 2007; *Mignot et al.*, 2007]. This includes the central tropical Atlantic, where the mixed layer salt balance at 38°W appears to depend mainly on the migration of the Intertropical Convergence Zone (ITCZ) and the associated rainfall [*Foltz et al.*, 2004]. Further to the west, *Masson and Delecluse* [2001] find a significant freshening occurring in May, associated with the seasonally varying Amazon discharge, which appears very important for maintaining the summer BL thickness in the western tropical Atlantic. The authors concluded that the circulation at the Northern Brazilian continental shelf is primarily forced by the seasonal cycle of the Amazon runoff, but that it is the ocean circulation and associated transport processes that set the phase of the surface salinity seasonal cycle. *Ferry and Reverdin* [2004], who studied the salt budget of the western tropical Atlantic based on model results, showed that the horizontal advection plays a prominent role in setting the salinity anomalies; however, the authors could not successfully simulate a well-established BL when anomalous freshwater was presented in the area. A numerical study of the Amazon plume by *Nikiema et al.* [2007] suggests some wind impact on the detailed structure of the Amazon freshwater plume and the associated salinity front; however, the wind impact remains only of secondary importance for the distribution of the fresh Amazon waters.

[4] The area of the Amazon plume was investigated during several observational programs (e.g., AmasSeds [*Rockwell at al.*, 1995]; REVIZEE [*Silva et al.*, 2005];

[1]Potsdam Institute for Climate Impact Research, Potsdam, Germany.
[2]Zentrum fuer Meeres- und Klimaforschung, Institut fuer Meereskunde, Universität Hamburg, Hamburg, Germany.

0148-0227/11/2010JC006650

PIRATA [*Foltz et al.*, 2004]). However, the impact of the Amazon on the western tropical Atlantic remains to be of scientific interest. To some extent this is motivated by the fact that the Amazon is the largest river in the world with an annual-mean freshwater discharge of 6642 km3/year, i.e., about 17% of the net freshwater input from all rivers (about 1Sv, see also *Dai and Trenberth* [2002]). Nevertheless, information about temporal variability of the Amazon outflow is sparse and remains error prone, even on the seasonal cycle. More work is therefore required to improve our understanding of the response of the western tropical freshwater content and BL to the seasonal cycle of the Amazon runoff.

[5] In this study we attempt to better understand processes contributing to the BL formation in the western tropical Atlantic by studying the sensitivity of the freshwater balance in the vicinity off the Amazon mouth on details of the time-varying Amazon runoff and by comparing them with contributions from ocean processes. The study is based on a global numerical simulation, but focuses in its analysis on the Amazon domain.

[6] Three experiments were performed, which use identical model parameters but differ in the imposed runoff fields, including the use of a time-mean runoff and a seasonally varying runoff field as provided by *Dai and Trenberth* [2002] and one estimated through the GECCO assimilation procedure so as to best reproduce observed ocean parameters. Besides testing the sensitivity of the western tropical Atlantic to details of the runoff forcing, this latter experiment provides also a pilot test of improving estimates of time-varying runoff through ocean state estimation.

[7] The remaining paper is organized as follows: Section 2 describes the methodology and the model setup, and section 3 provides an estimate of the runoff estimated during the GECCO optimization run. Section 4 describes the surface freshwater content during periods of maximum and minimum Amazon freshwater discharge, associated circulation patterns and the seasonal variability of the BL. Section 5 investigates the relative contribution of the advection term to the freshwater balance in the studied domain, and concluding remarks are provided in section 6.

2. Model Description and Experimental Setup

[8] Our study is based on the MIT (Massachusetts Institute of Technology) General Circulation Model [*Marshall et al.* 1997a, 1997b; *Adcroft et al.* 1997] and the state estimation framework which was built around it by the Estimation of the Circulation and Climate of the Ocean (ECCO) consortium [*Stammer et al.*, 2004], to which GECCO is the German contributor [*Köhl and Stammer*, 2008]. The model uses the hydrostatic approximation and a free surface formulation. The surface mixed layer turbulence closure applies the K profile parametrization of *Large et al.* [1994] (KPP scheme) and the *Gent and McWilliams* [1990] eddy parametrization scheme is used. The primitive equations are solved on a quasi-global grid from 80°S to 80°N with 1° horizontal resolution on 23 nonequidistant levels starting from 10 m surface thickness and reaching 50 m at 160 m depth.

[9] Three experiments were performed, each lasting for 14 months in duration after being initialized from the *Levitus et al.* [1994] climatological January temperature and salinity. The first run was based on the original model configuration, henceforth referred to as reference run. It was forced by the NCEP Reanalysis 1 (R1) twice per day wind stress data and once per day net surface heat and freshwater (evaporation-precipitation) fields. In addition, the time-mean river runoff provided by *Fekete et al.* [1999] is added as a time constant to the freshwater flux. Finally, the net NCEP freshwater flux is transformed to a virtual salt flux [*Barnier*, 1998] without using a restoring term.

[10] The second experiment, which below is referred to as the amazon run, is identical to the reference run, except that freshwater fluxes are modified to account for the seasonal cycle of the Amazon runoff. To do so, the freshwater flux at the Amazon mouth was modulated in time through a scale factor to mimic the seasonal cycle provided by *Dai and Trenberth* [2002] (see Figure 1a).

[11] The last run was performed in the same configuration as the reference run, but using surface forcing fields which were estimated using the GECCO estimation framework, called optimization run. Following *Stammer et al.* [2004], we use this approach here to estimate net surface freshwater fluxes required to bring the model into consistency with the *Levitus et al.* [1994] salinity climatology. During the optimization, the control vector includes the initial conditions of the temperature and salinity, and daily heat and freshwater fluxes as well as wind stress. During the optimization, the model's salinities and temperatures were constrained over the whole water column by the climatological monthly mean salinity and temperature fields with uniform global errors given by *Levitus et al.* [1994], i.e., surface forcing fields were estimated jointly with ocean transport processes that best reproduce the climatological hydrographic conditions of the Amazon mouth (among other parts of the world ocean). Technically, the assimilation was performed over 63 iterations, until further adjustments in the freshwater flux corrections become sufficiently small. The resulting estimate of surface freshwater forcing was used as a third runoff field. In this respect, the optimization run results from driving the forward model with the estimated surface net freshwater fluxes, instead of NCEP R1 surface freshwater flux fields.

[12] Although the river runoff is not a control parameter, the surface freshwater flux adjustments near coastal regions can compensate for erroneous discharge values. *Romanova et al.* [2010] discussed the value of the approach in adjusting of the surface freshwater flux fields and found that the most corrections are along the coastal regions associated with inaccurate continental runoff. See also *Stammer et al.* [2004] for a discussion of the quality of the resulting heat and momentum fluxes.

[13] All three runs were performed for the year 1992, which is characterized by strongly expressed seasonal variability aiming to get a pronounced response in the sensitivity experiments. The analyses presented below are based on monthly averaged model output fields.

3. Estimated Runoff and Near-Surface Salinity

[14] The Amazon runoff as it is being estimated by the optimization experiment is shown in Figure 1a, jointly with the prescribed annual-mean river runoff for the reference and the seasonally varying runoff in the amazon experi-

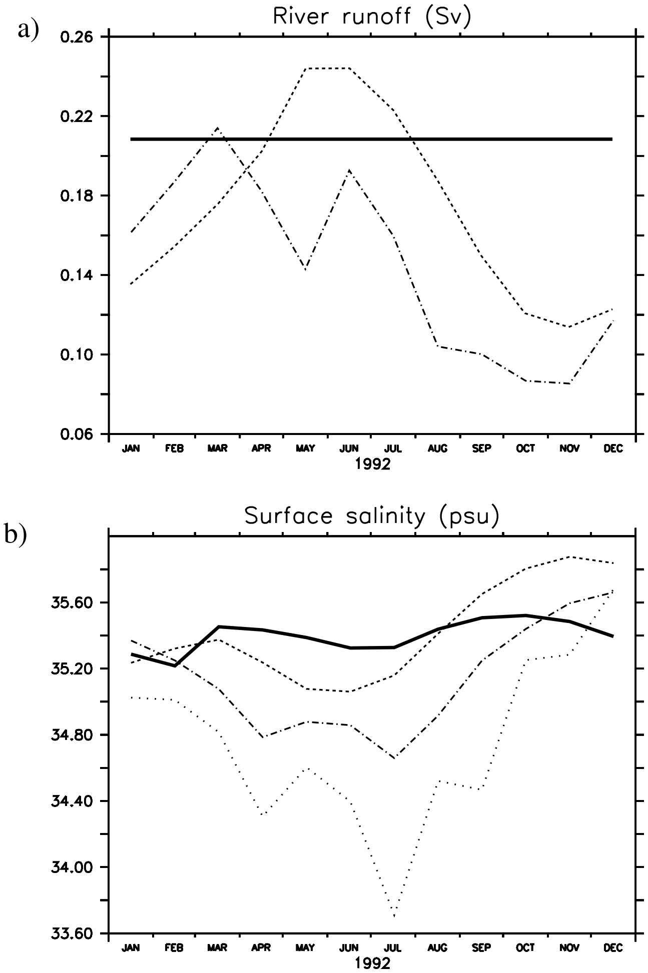

Figure 1. (a) Amazon runoff and (b) near-surface salinity averaged in the domain of 2°S:10°N and 38°W:60°W down to a depth of 135 m for reference run with a constant runoff of value around 0.21 Sv (solid line); amazon run forced with a seasonal cycle of the Amazon runoff as proposed by *Dai and Trenberth* [2002] (dashed line); optimization run with corrected runoff as a result from assimilating salinity and temperature climatology given by *Levitus et al.* [1994] (dot-dashed line). In Figure 1b the dotted curve additionally shows the averaged salinity of *Levitus et al.* [1994] data.

ments. Figure 1a illustrates nicely that the optimization, by assimilating the salinity and temperature profiles of *Levitus et al.* [1994], is capable to estimate a pronounced seasonal cycle in the freshwater forcing off the Amazon mouth that is similar in amplitude to the data given by *Dai and Trenberth* [2002]. Nevertheless, a discrepancy exists in the annual mean value showing an offset of about 0.05 Sv in the optimized runoff, beside a phase shift of one month (the optimization is leading). In this context we recall, however, that our runoff estimate is assessed through the adjustment of the net surface freshwater flux $P - E + R$ (precipitation minus evaporation plus runoff) in the vicinity of the Amazon mouth and therefore includes the correction to the atmospheric fluxes. A separation of the adjustments only for the river runoff is not feasible, as the control vector will always represent the net surface freshwater fluxes. We note, however, that the seasonal cycle in the NCEP surface freshwater forcing is not large and the improvement in the seasonal variability of the runoff is obvious, recalling that the optimization started from a constant (in time) value.

[15] Not unexpected, the salinity field simulated by the optimization experiment follows closely the seasonal cycle of the *Levitus et al.* [1994] salinity (see Figure 1b), including the additional salinity minimum in April that is represented as an additional runoff maximum in March. The latter is not seen in the estimate provided by *Dai and Trenberth* [2002]; however, the surface averaged salinities over the top 135 m simulated in the amazon run nevertheless follows a clear seasonal cycle, albeit slightly shifted in time. In contrast, in the reference run, in which a seasonally varying forcing is only imposed through the NCEP surface freshwater fluxes, the lack of a seasonal cycle in the simulated salinity looms large.

4. Seasonality of the Freshwater Content and Barrier Layer Thickness

4.1. Vertically Integrated Freshwater Content

[16] To analyze the response of the western tropical Atlantic to the seasonal cycle of the Amazon runoff, we diagnosed the vertically integrated freshwater content (FWC) of the upper ocean per unit area, calculated from the simulated salinities in the Amazon domain ranging from 60°W to 38°W and 2°S to 10°N at the surface as

$$\mathrm{FWC} = \int \left(1 - S/S_{ref}\right) dz \tag{1}$$

Here, S is the salinity (in psu), and S_{ref} = 35 psu is the reference salinity.

[17] Results are shown in Figure 2 for the upper layer together with the velocity field for May and October, respectively, representing the distribution of the water masses during the maximum and minimum Amazon river runoff. Also shown are fields of FWC as they result from the Levitus climatology for May and October, respectively. These fields reveal that during May the high discharge of water from the Amazon leads to an enhanced upper ocean freshwater content. However, the runoff from the Orinoco river situated further northwest along the South American Coast appears also as an important source for the regional freshwater budget. During October, its imprint disappears, leaving behind only a plume of Amazon freshwater that in our study region is being advected eastward along 8°N.

[18] In the reference run, the observed salinity distribution is hardly reproduced during both seasons. In particular, the Amazon plume seems to be advected along the North Brazil continental shelf in May with no imprint of the Orinoco runoff visible at all. Moreover, the zonally advected Amazon plume appears displaced meridionally between 4°N and 8°N during October. The situation is substantially improved in the amazon experiment, but still shows deficiencies relative to the observed FWC distribution; e.g., in October the signature of the Amazon outflow is essentially absent in the simulation.

[19] As was to be expected, the optimization run shows best results, including a second freshwater peak at the

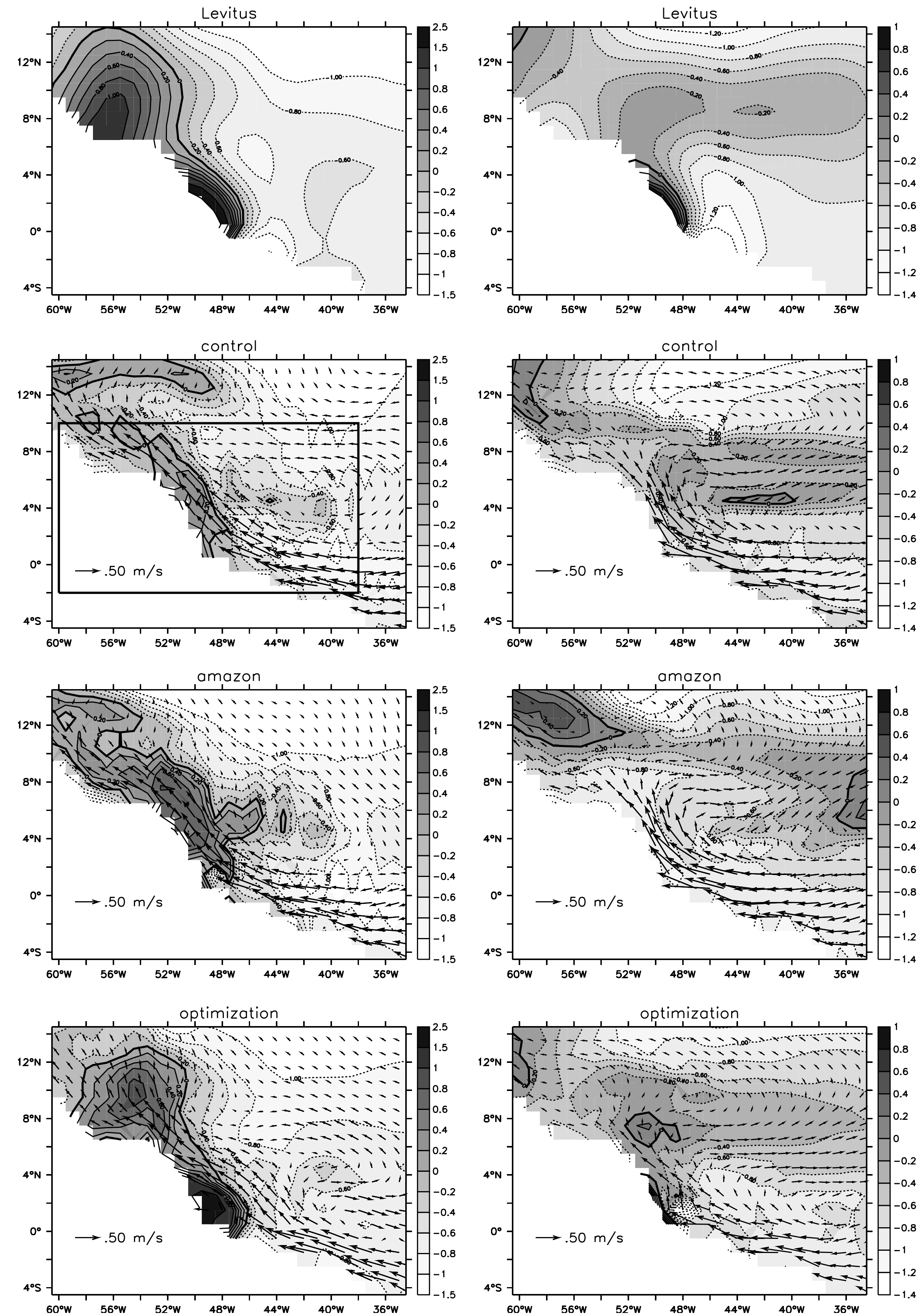
Levitus
Levitus
control
control
amazon
amazon
optimization
optimization
.50 m/s
60°W 56°W 52°W 48°W 44°W 40°W 36°W
4°S 0° 4°N 8°N 12°N

Figure 2

Orinoco location, which is not represented in the two forward runs due to the lack of the Orinoco seasonal cycle in these experiments. The flow is mainly northwestward and only a small part flows to the east due to the winter weakening of the NECC. In October, when the Amazon reaches its lowest point of discharge (compare Figure 1a), the accumulated freshwater is carried by the North Brazil Current, and additionally to the east at 6°N by the NECC; only a small fraction is brought along the northeast coast by the Guyana Current into the Caribbean Sea. The comparison suggests that geographical details in the freshwater forcing and its temporal variability matters for simulating the observed plume of freshwater and its advection in the western tropical Atlantic. In particular, the need to include a seasonal cycle in the runoff fields to obtain more realistic seasonal variability of the salinity fields is indicated. We also note that smaller rivers like the Orinoco do show a substantial effect on the freshwater budget of the region.

4.2. Pathways of the Amazon Freshwater Plume

[20] To highlight the detailed pathways of the Amazon discharge that influences the evolution of the BL, we show in Figure 3 the trajectories of 20 off-line floats which were seeded in January at the mouth of the river in a column at 1.5°N and 47°W in the upper 30 m. In Figure 3 the float locations in May and October for the three runs are shown together with the trajectories starting at the position, where floats were seeded. Monthly velocities were linearly interpolated on the float positions to calculate trajectories forward in time following the earlier application of *Köhl* [2010] for tracing different types of water masses for the Denmark Strait overflow. Although the three experiments show qualitatively similar results, the optimization run differs from the reference and the amazon run in the seasonal surface water mass distribution due to the corrected surface velocity fields and show that the seasonal variability in the water transports are to a large extent determined by the surface velocity field. However, the implemented seasonal runoff in the amazon run alters the trajectories, showing more distinct differentiation between the northern and eastern split of the flow. The pathways of the Amazon waters for the optimization run shows floats clustering close to the shore in May (floats still stay in the location of their release in October where stranded). Another part of fresh Amazon waters, similar for all three experiments, propagates to the North and splits into two parts. One part of the freshwater masses is advected to the North reaching the Caribbean Islands in October, and a second part is carried to the East by the intensified NECC in summer.

4.3. BL Thickness

[21] To diagnose the impact of the seasonal cycle of the Amazon freshwater discharge and the detailed pathways of the associated FWC on the BL of the western tropical Atlantic, the BL was computed from the three runs as the difference of the mixed layer, calculated using a density criterion ($\Delta\sigma = 0.125$), and the depth of the isothermal layer is based on $\Delta T = 0.5$°C. To define the region of waters influenced by the river discharge, a mask is applied, such that the cells with salinities greater than 36 psu are excluded assuming that they represent the ambient saline ocean. Results are shown in Figure 4 as annual mean BL thicknesses for the three runs. The maximum thickness value of BL reaches 90 m at the center of the plume in the reference run, and is lower for the run forced with seasonal variability of the amazon and the optimization runs (80 m and 50 m, respectively), and only 45 m for Levitus data (not shown), respectively. We note that the salinity constraints in the optimized run cause a thinner BL compared to the forward runs.

[22] Table 1 lists the time mean BL thickness, the thicknesses for the months of high (April–June), transition (July–September), and low (October–December) Amazon discharge periods and the averaged maximum and minimum values for the domain. The available data from *Sprintall and Tomczak* [1992], *Silva et al.* [2005] and *de Boyer Montegut et al.* [2007] are also included for comparison. Generally, the modeled mean BL thicknesses for the Amazon domain exceed the estimates from the available observational data by more than a factor of two, and the maximum model thickness is found two months later than in the data. However, the remarkable feature of the seasonal cycle is that the run forced with the seasonal runoff is very close to the constrained run in contrast to the forward run where such a seasonality is not seen. The deviations from the mean can reach 8 m increase in July and 8 m decrease in October for the assimilation run in contrast to the amazon run in which the seasonal deviation from the mean is only 2 m and is more consistent with *de Boyer Montegut et al.* [2007] data. However, both data set from *Silva et al.* [2005] and *de Boyer Montegut et al.* [2007] show a slight decrease of the BL thickness in the Amazon transition period (Table 1) which is not reproduced in the model simulations.

[23] Seasonal anomalies relative to the annual mean of the BL are plotted in Figure 4d. Obviously, the reference run cannot produce a seasonal cycle of the BL but instead shows a strong drift. The drift is much reduced in the amazon run which mostly agrees in its seasonal cycle with the more stable optimization run. We conclude that a seasonal cycle in the runoff seems essential in simulating the observed salinity structure as are details of the geographic pattern of the forcing. It also seems that the assimilation run which is being constrained by observed ocean salinities seems capable in estimating the seasonal cycle in runoff.

5. Balance of the FWC in the Amazon Domain

[24] To assess in detail major contributors to the seasonal cycle of the freshwater content of the western tropical Atlantic, we compute from each experiment the rate of change of the FWC, the surface freshwater forcing over the area, and the convergence of freshwater due to the advection at the lateral

Figure 2. Surface currents and surface freshwater content (m) in (left) May and (right) October for *Levitus et al.* [1994] and three experiments: reference run with constant annual Amazon runoff; amazon run forced with the seasonal cycle of the Amazon runoff as proposed by *Dai and Trenberth* [2002]; and optimization run.

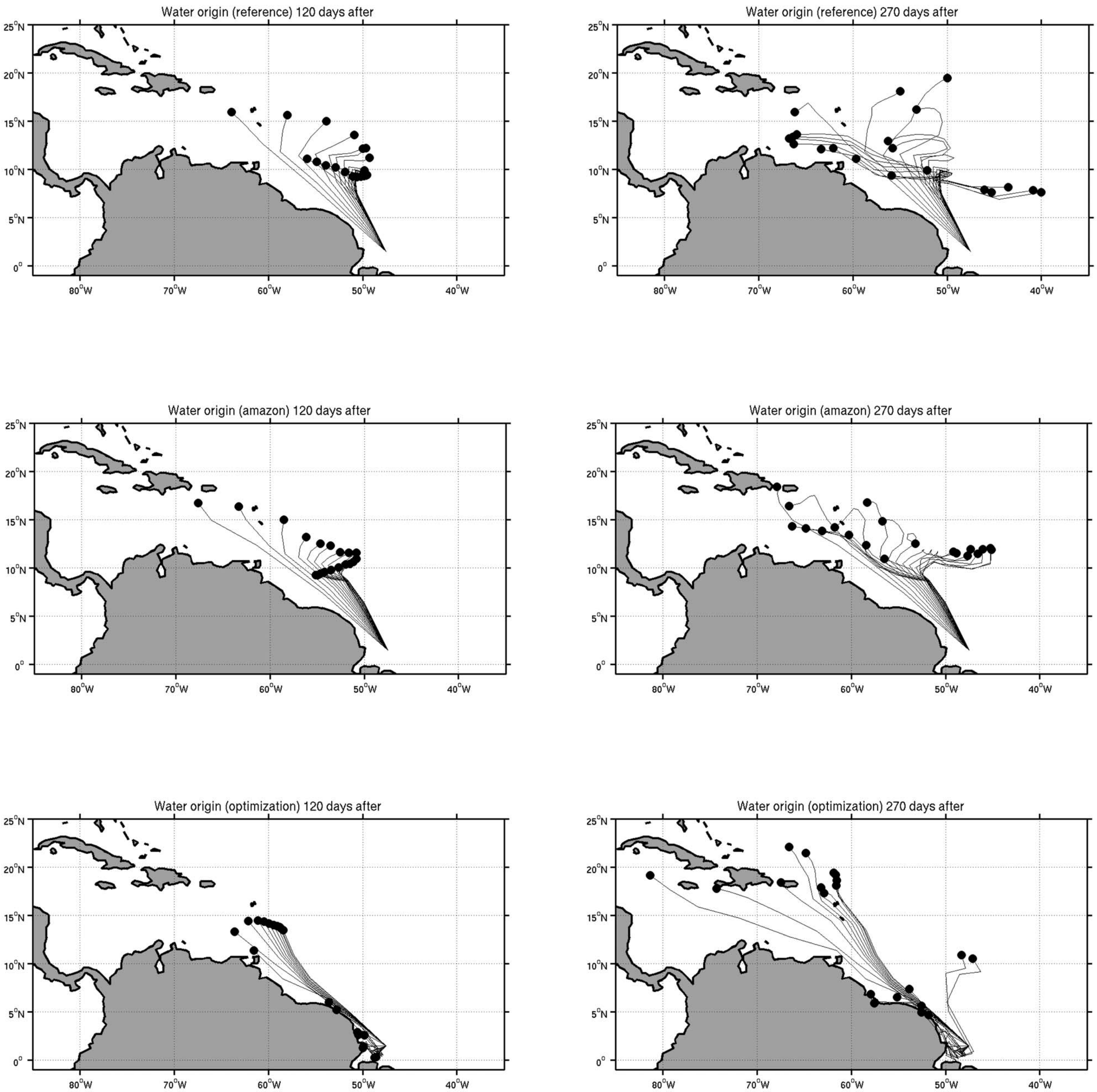

Figure 3. Forward float positions in (left) May and (right) October and the associated trajectories after seeding 20 floats at the Amazon mouth for the reference, amazon and optimization runs. The floats do not sink deeper than 100 m.

and vertical boundary, which are linked according to the equation of conservation:

$$\partial t\left(\int_A \int_{-h}^{0} \mathrm{FW} dA dz\right) = \int_{-h}^{0} u_E \mathrm{FW} - u_W \mathrm{FW} dz + \int_{-h}^{0} v_S \mathrm{FW} - v_N \mathrm{FW} dz + \int_A w \mathrm{FW} dA|_{z=-h} + \int_A (P - E + R) dA + F$$

FW is the freshwater calculated from the salinity and is equal to $(1 - S/S_{ref})$, where $S_{ref} = 35$ psu, A is the horizontal area located between 2°S and 10°N and 38°W and 60°W and h is the depth set to 135 m. The velocity components represent the zonal velocities across the eastern and western boundary (u_E, u_W) and the meridional velocities across the southern and northern boundary (v_S, v_N), and w is the vertical velocity. The term $P - E + R$ is the net freshwater flux at the surface boundary of the domain as introduced above, and represents the external source for the system. The left hand side term of the equation describes the freshwater content convergence or the storage in the domain. The horizontal and vertical

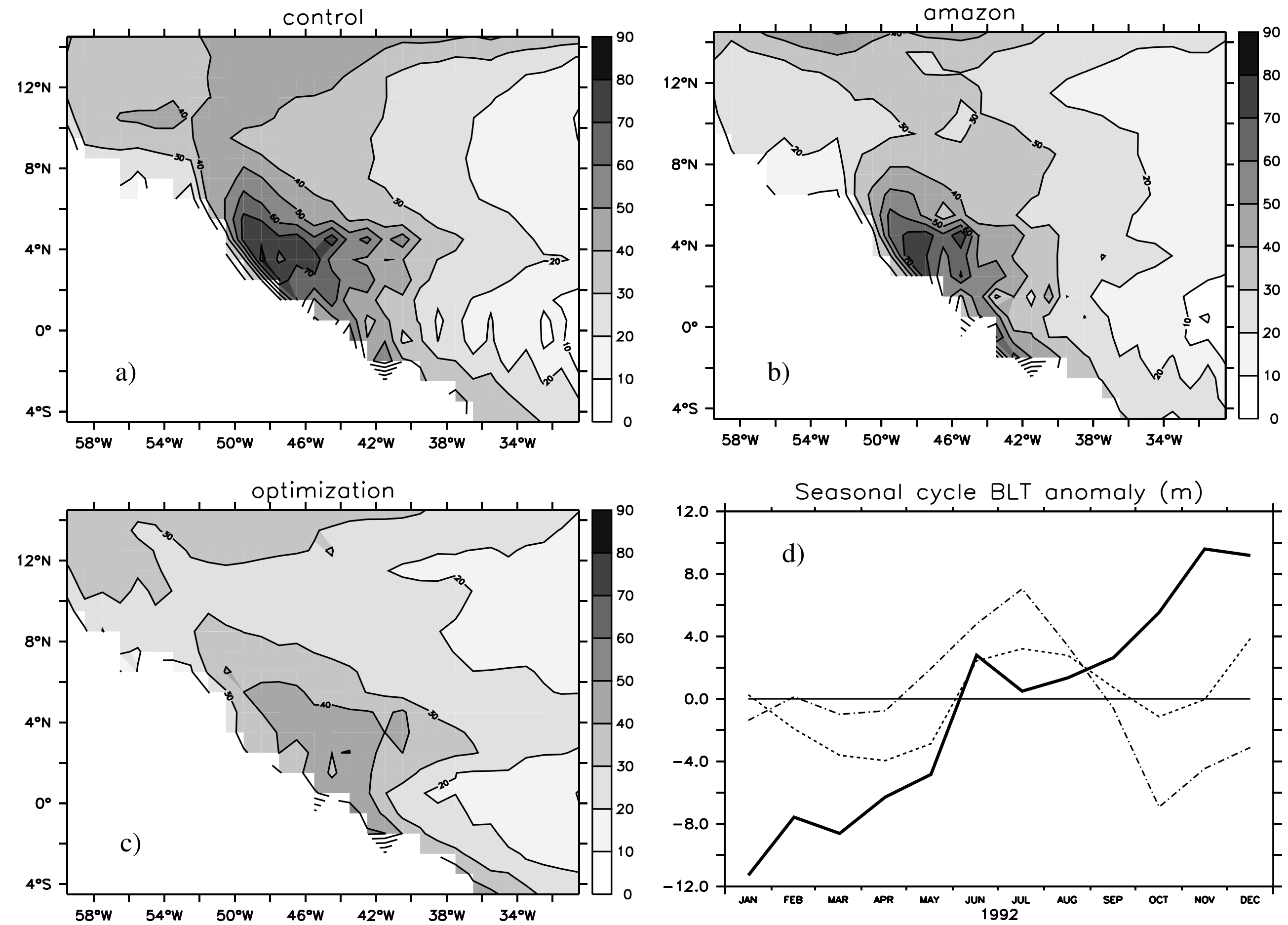

Figure 4. Annual mean barrier layer thickness for the (a) reference run, (b) the amazon run forced with the seasonal variability of the Amazon runoff and (c) the optimization run. (d) The seasonal anomalies relative to the time mean. The solid, dashed, and dot-dashed curves show results from the reference, amazon, and optimization runs, respectively. The units are in m.

advections at a constant depth h are given by the first three terms of the right side of the equation. And finally, F accounts for the turbulent diffusion, which is estimated through the remaining residual part of the balance equation.

5.1. Freshwater Transport due to Advection

[25] Figure 5 shows the integrated FWC transports over the upper 135 m due to advection across the lateral boundaries of the domain. The depth is chosen such that it includes the mixed layer depth and the isothermal layer for the three experiments. Positive values indicate import of freshwater into the domain. The transport at 38°W is composed from two parts: transports from the South Equatorial Current, which continues into the North Brazil Current and imports water masses into the domain, and transport from the North Equatorial Counter Current, which exports water masses to the central Atlantic. These two currents are in opposite directions north of the equator and their net transport results in a supply of freshwater (or salt export) for most of the year, except for the reference run. The maximum of around 0.25 Sv is found in September and October, when the NECC is well established (Figure 5a). The rest of the year is characterized by a low freshwater import of about 0.02 Sv. In spring, while the NECC is weakened, the flow is restricted to be northwestward and advects freshwater along the coast into the Caribbean Sea, a feature that is clearly seen in the amazon and optimization runs. The seasonal cycle of the control run differs from the amazon and optimization runs and shows large unrealistic freshwater export at 38°W from January to May.

[26] At the northern boundary of the domain (Figure 5b), the surface freshwater provided by the Amazon river and the contribution from the advection across 38°W is exported mainly from end of May until November. During this

Table 1. Estimates of the Barrier Layer Thickness (in m) for the Three Model Experiments and Data Observation[a]

Data/Amazon Discharge	High	Transition	Low	Mean BL Thickness
Reference	25	29	36	29
Amazon	19	23	22	22
Optimization	22	23	15	20
Sprintall and Tomczak [1992]	50		25	
Levitus et al. [1994]	24	18	14	21
Silva et al. [2005]	16	3	7	
de Boyer Montegut et al. [2007]	9	6	9	8

[a]Estimates are averaged over an area restricted between 2°S, 10°N and 60°W, 38°W.

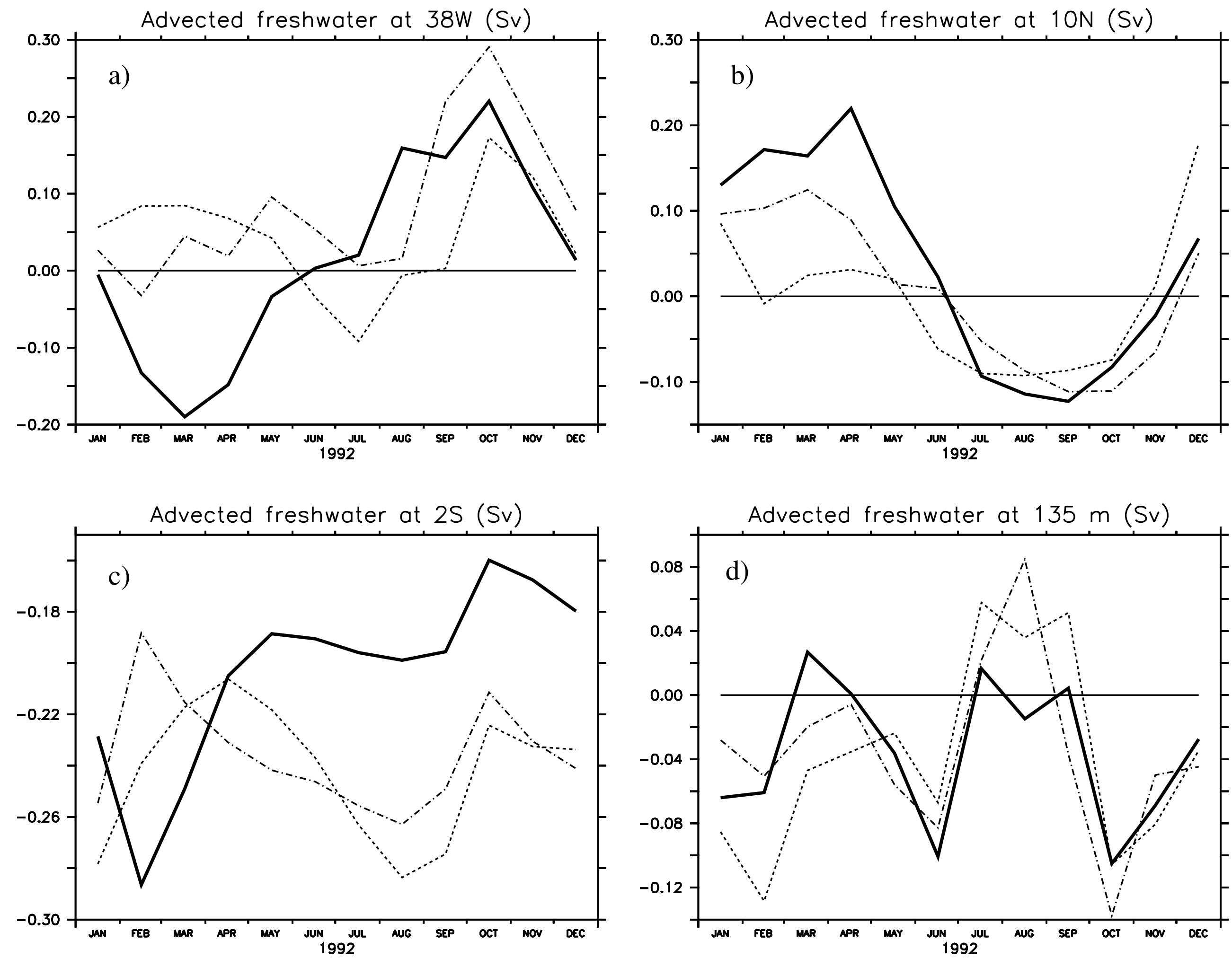

Figure 5. Net freshwater lateral and vertical transport due to advection in the Amazon domain at 38°W, 10°N and 2°S and at a depth of 135 m. The solid, dashed, and dot-dashed curves show results from the reference, amazon, and optimization runs, respectively. The positive values indicate import of freshwater into the domain. The units are in Sv.

period, the Amazon domain is loosing persistently freshwater due to advection through the northern boundary with maximum export (negative values) of around 0.13 Sv similarly for the three experiments. During the rest of the year, and mainly in winter months, the simulations show near surface freshwater import rather than export from the North. The corresponding spring freshwater import in the amazon experiment stays close to zero, whereas the reference run shows large freshwater import into the domain.

[27] Finally, the transport at 2°S (Figure 5c) is due to the North Brazil Current and results in transporting saltier waters into the Amazon domain. Thus, the freshwater transport at this lateral border is negative (out of the domain) for all model results. The resulting seasonal cycle for the advection differs substantially for the three experiments. However, similar features are found in the amazon and the optimization run which suggest a minimum freshwater export two times in the year: once in March/April in a time period of freshwater accumulation due to the Amazon high discharge period, and once in October, when the freshwater is advected mainly from the interior of the Western Tropical Atlantic. The reference run also shows freshwater export from the domain, but the amplitude and phase differ significantly from the other two experiments. The reason why the modeled near-surface advection shows larger freshwater advection at the southern boundary compared to the northern one is owing to the fact that water entering the domain is of higher salinity while the water leaving the domain is of similar salinity as compared with the interior salinity.

[28] The advective transport at 60°W is carried by only one model grid box (not shown) and it is represented by values of two orders smaller than the estimated ones for the other lateral boundaries. And finally, the vertical freshwater advection at a depth of 135 m is calculated and shown in Figure 5d. The vertical advection is small for the three experiments and ranges from −0.08 Sv to 0.08 Sv. The seasonal variability is similar for the three experiments showing an annual freshwater sink.

5.2. Freshwater Content Budget

[29] In the optimization run the freshwater storage (i.e., temporal derivative of FWC) has its maximum in March/

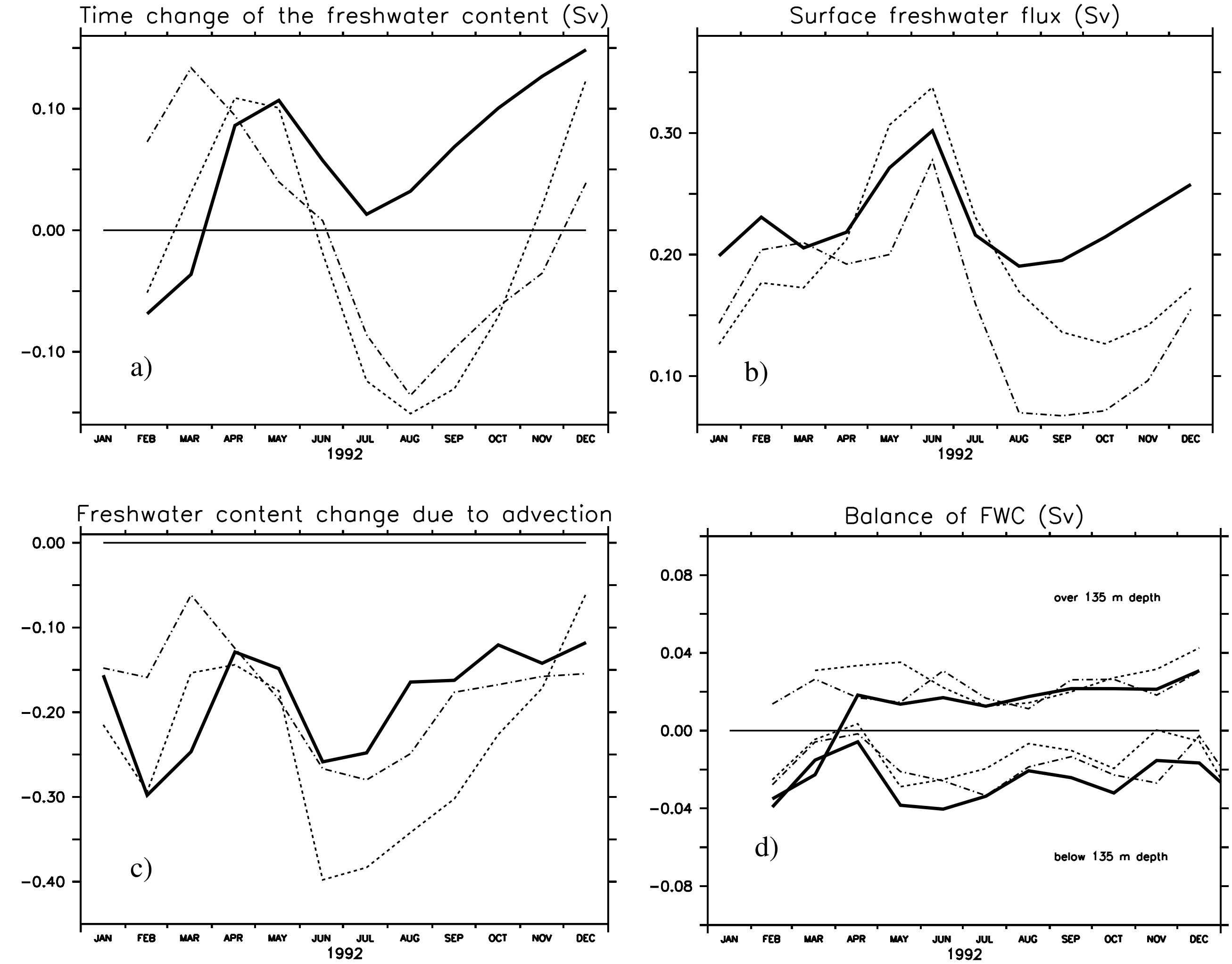

Figure 6. (a) Time derivative of the freshwater content; (b) surface freshwater flux; (c) freshwater content change due to advection in the domain at the lateral and horizontal boundaries of the domain, shown separately in Figure 5; and (d) the balance of the fluxes for the surface layer (in the investigated region) and for the layer below the lower boundary at 135 m. The solid, dashed, and dot-dashed curves show results from the reference, amazon, and optimization runs, respectively. The units are in Sv.

April and its minimum in August, consistent with the Amazon discharge seasonal cycle (Figure 6a). The seasonal cycle of the amazon run is mostly similar to the optimization run in phase and amplitude, but both differ substantially from the reference run, which shows mostly positive values associated with a strong upward drift in the FWC (compare Figure 4).

[30] Figure 6b shows time series of the net surface fluxes integrated over the Amazon domain for the three experiments. The seasonal cycle in the freshwater flux for the reference run originates from the seasonal cycle of NCEP for year 1992 which is added to a constant value of 0.21 Sv, representing the annual mean runoff in the Amazon domain, calculated from *Fekete et al.* [1999] data. The maximum freshwater input for the three experiments occurs in June, a month later than the Amazon runoff maximum in May. The extra supply of freshwater is due to the increased precipitation in the boreal summer linked to the northward migration of the ITCZ. The minimum surface freshwater occur in September/October for the constrained run and the run forced with the Amazon seasonal cycle. The seasonal variability in the amazon and optimization experiments is primarily modulated by the Amazon river amplitude and phase.

[31] Convergence time series due to advection of the freshwater fluxes are shown in Figure 6c which represent the sum of the advected FWC through lateral and vertical boundaries shown in Figure 5 and the advection through 60°W. It yields a permanent freshwater export out of the domain with maximum values in June of about 0.40 Sv for the amazon run, followed by the optimization experiment with around 0.27 Sv, and similar for the reference run with 0.25 Sv. The change of the freshwater content due to advection in the domain depends mainly on the saline waters imported from the south through the Brazil Current.

[32] The freshwater content budget for the Amazon domain is shown in Figure 6d. It represents the temporal change in freshwater storage minus the monthly sum of the advected freshwater through the lateral and vertical boundaries of the domain. The latter includes the surface fresh-

water flux and the river runoff. Except for the first two months in the reference run, the balance yields a missing flux of about 0.02 Sv that transports freshwater into the domain. In order to test whether this flux is associated with vertical exchange, the additional balance for the volume below 135 m was considered. Neglecting the vertical exchange between these two volumes should cause an equal imbalance of opposing sign in both volumes if this is the dominant missing process. Residuals for both balances above and below 135 m are shown in Figure 6d and approximatively compensate each other. Remaining residuals have to be related to lateral diffusion or eddy advection and the fact that the calculation of the balance is based on monthly mean values which renders the time derivative to be only approximatively compatible with the period over which the fluxes are computed. The neglected vertical flux can be either due to eddy advection or due to diapycnal fluxes. Calculating the required diffusion coefficient reveals a value of around 10^{-4} m^2/s, one order larger than the background value, which is expected since the mixing layer reaches below the mixed layer. The latter is situated just above the interface between those two volumes. Note, that the mean salinity in the upper volume is larger than in the lower volume and the associated gradient at the interface accommodates a positive diffusive freshwater flux into the upper volume.

6. Discussion

[33] Based on three numerical experiments, the seasonal variability of the freshwater content of the western tropical Atlantic and its relation to the time-varying freshwater forcing through the Amazon river are investigated with an emphasis on the seasonal cycle. The sensitivity of the freshwater exchange of the studied region with the surrounding Atlantic to details of the varying runoff forcing are analyzed together with the changes in the associated barrier layer. One experiment considers a constant freshwater discharge all the year round, the second uses the seasonal cycle of the Amazon to modify the freshwater forcing field. In a third experiment the runoff as estimated by assimilating the monthly mean *Levitus et al.* [1994] salinity and temperature climatology was used to test the potential of ocean state estimation to improve estimates of the time-varying river runoff together with the net freshwater fluxes over the ocean.

[34] In the experiments which take into account the seasonal information of the river discharge, the Amazon plume of less saline waters is more distinctly developed to the Northwest along the coast after the maximum of the river discharge in May. We find improvement of the annual development of the plume in the run with implemented seasonal variability such that the freshwater content distribution and the BL variability are closer to the results from the run assimilating observational data. However, the amplitudes differ for both runs, which are also different from the available independent data. It seems that the model results overestimate the amplitude for the mean, maximum and minimum BL thickness approximately 2 times, yielding mean BL thickness of 20 m and ranging from 13 to 30 m. The discrepancy with the recent estimations [*Silva et al.*, 2005; *de Boyer Montegut et al.*, 2007] may be due to not well represented model small scale physics, in the region where the eddy parametrization should respond to the certain conditions of stable stratified waters and due to a limited data base since only climatological data was included in the assimilation run. But we note the improvement of these two runs compared to the control run, where the seasonal BL variability is unable to be reproduced.

[35] The domain is fed by the saline waters from the Brazil Current and the model successfully simulates the winter weakening and summer intensification of the NECC on behalf of the Guyana Current and is consistent with the previous studies on the volume transports in the Western Equatorial Atlantic [*Schott and Boening*, 1991; *Schott et al.*, 2003].The pathway of the Amazon freshwater plume shows a split of the water masses as one part is advected to the North and enters the Caribbean Sea and the other part propagates to the west joining the NECC. The constrained solution prompts for strong wind dependence, forcing some fresh water masses to stay close to the shore during the whole year. However, in our model results, freshwater is permanently exported out of the domain with a maximum of around 0.4 Sv in June, following the Amazon maximum surface freshwater input in May.

[36] Our study confirms that the seasonal runoff forcing appears to be an important part of the surface freshwater variability for the Amazon domain in terms of reproducing the seasonal cycle of the BL and the freshwater transport. Based on the strong seasonal response of one of the major rivers, we can assume that the seasonal variability of all rivers in the world can partly modify the ocean current system.

[37] To improve the understanding of the seasonal dynamics in regions of large freshwater input in the mouths of the largest rivers, major efforts are ongoing in climate research with the satellite missions SMOS (ESA) and AQUARIUS/SAC-D (NASA) targeted to measure the sea surface salinity over the ocean. It is expected that new insights will emerge about the net surface freshwater fluxes and in ocean transports especially along the coastal regions, where the in situ measurements of the continental runoff are not sufficient to provide insight into the ocean dynamics and variability. Ocean state estimation provides a large potential for merging those new observations with other ocean data and with the dynamics of ocean circulation models to provide improved estimates of surface freshwater forcing and runoff. In this respect, the present study establishes a pilot application which in the near future will be extended to incorporate also SMOS and AQUARIUS/SAC-D data.

[38] **Acknowledgments.** This study was performed in accord with future investigations through satellite mission SMOS (ESA). V.R. acknowledges support from the BMBF funded through the GOCE-GARND-II and Nordatlantik projects during her stay at the University of Hamburg where the research was initiated and the experiments were performed at Deutsches Klimarechenzentrum. Partially funded also through the BMBF SMOS CAl/Val effort at the University of Hamburg. It is a contribution to the TIPI and the DFG-funded CliSAP excellence initiative of the University of Hamburg.

References

Adcroft, A., C. Hill, and J. Marshall (1997), The representation of topography by shaved cells in a height coordinate model, *Mon. Weather Rev.*, *125*(9), 2293–2315.

Barnier, B. (1998), Forcing the ocean, in *Ocean Modeling and Parameterization*, *NATO ASI Ser., Ser. C.*, edited by E. P. Chassignet and J. Verron, pp. 45–80, Kluwer Acad., Boston, Mass.
Dai, A., and K. Trenberth (2002), Estimates of freshwater discharge from continents: latitudinal and seasonal variations, *J. Hydrometeorology*, *3*, 660–687.
de Boyer Montegut, C., J. Mignot, A. Lazar, and S. Cravatte (2007), Control of salinity on the mixed layer depth in the world ocean: 1. General description, *J. Geophys. Res.*, *112*, C06011, doi:10.1029/2006JC003953.
Fekete, B. M., C. J. Vorosmarty, and W. Grabs (1999), An improved global spatially-distributed runoff data set based on observed river discharge and simulated water balance, report, 35 pp., Complex Syst. Res. Cent., Univ. of N. H., Durham.
Ferry, N., and G. Reverdin (2004), Sea surface salinity interannual variability in the western tropical Atlantic: An ocean general circulation model study, *J. Geophys. Res.*, *109*, C05026, doi:10.1029/2003JC002122.
Ffield, A. (2006), Amazon and Orinoco River plumes and NBC rings: Bystanders or participants in hurricane events?, *J. Clim.*, *20*, 316–333.
Foltz, G. R., and M. J. McPhaden (2009), Impact of barrier layer thickness on SST in the central tropical North Atlantic, *J. Clim.*, *22*, 285–299.
Foltz, G. R., S. A. Grodsky, J. A. Carton, and M. J. McPhaden (2004), Seasonal salt budget of the northwestern tropical Atlantic Ocean along 38W, *J. Geophys. Res.*, *109*, C03052, doi:10.1029/2003JC002111.
Gent, P. R., and J. McWilliams (1990), Isopycnal mixing in ocean circulation models. *J. Phys. Oceanogr.*, *20*, 150–155.
Köhl, A. (2010), Variable source regions of Denmark Strait and Faroe Bank Channel overflow waters, *Tellus, Ser. A*, *62*, 551–568.
Köhl, A., and D. Stammer (2008), Variability of the Meridional Overturning in the North Atlantic from the 50-Year GECCO State Estimation, *J. Phys. Oceanogr.*, *38*, 1913–1930, doi:10.1175/2008JPO3775.1
Large, W. G., J. C. Williams, and S. C. Doney (1994), Ocean vertical mixing: A review and a model with a nonlocal boundary layer parameterization. *Rev. Geophys.*, *32*, 363–403.
Levitus, S., R. Burgett, and T. Boyer (1994), *World Ocean Atlas 1994*, vol. 3, *Salinity*, and vol. 4, *Temperature, NOAA Atlas NESDIS 3 and 4*, U.S. Dep. of Commerce, Washington, D. C.
Lukas, R., and E. Lindstrom (1991), The mixed layer of the western equatorial Pacific Ocean, *J. Geophys. Res.*, *96*, 3343–3457
Marshall, J., A. Adcroft, C. Hill, L. Perelman, and C. Heisey (1997a), A finite-volume, incompressible Navier-Stokes model for studies of the ocean on parallel computers, *J. Geophys.*, *102*, 5753–5766.
Marshall, J., C. Hill, L. Perelman, and A. Adcroft (1997b), Hydrostatic, quasi-hydrostatic and non-hydrostatic ocean modeling, *J. Geophys. Res.*, *102*, 5733–5752.
Masson, S., and P. Delecluse (2001), Influence of the Amazon river runoff on the tropical Atlantic, *Phys. Chem. Earth, Ser. B*, *26*, 137–142.
Mignot, J., C. de Boyer Montegut, A. Lazar, and S. Cravatte (2007), Control of salinity on the mixed layer depth in the world ocean: 2. Tropical areas, *J. Geophys. Res.*, *112*, C10010, doi:10.1029/2006JC003954.
Nikiema, O., J. L. Devenon, and M. Balkoti (2007), Numerical modeling of Amazon River plume, *Cont. Shelf Res.*, *27*, 873–899.
Pailler, K., B. Bourles, and Y. Gouriou (1999), The barrier layer in the western tropical Atlantic Ocean, *Geophys. Res. Lett.*, *26*, 2069–2072, doi:10.1029/1999GL900492.
Rockwell, W. G., R. C. Beardsley, S. J. Lentz, J. Candela, R. Limeburner, W. E. Johns, B. M. Castro, and I. D. Soares (1995), Physical oceanography of the Amazon shelf, *Cont. Shelf Res.*, *16*, 575–616.
Romanova, V., A. Köhl, D. Stammer, C. Klepp, A. Andersson, and S. Bakan (2010), Sea surface freshwater flux estimates from GECCO, HOAPS and NCEP. *Tellus, Ser. A*, *62*, 435–452. doi: 10.1111/j.1600-0870.2010.00447.x
Schott, F., and C. W. Boening (1991), The WOCE model in the Western Equatorial Atlantic: Upper layer circulation, *J. Geophys. Res.*, *96*, 6993–7004.
Schott, F. A., M. Dengler, P. Brandt, K. Affler, J. Fischer, B. Bourlés, Y. Gouriou, R. L. Molinari, and M. Rhein (2003), The zonal currents and transports at 35°W in the tropical Atlantic, *Geophys. Res. Lett.*, *30*(7), 1349, doi:10.1029/2002GL016849.
Silva, A., M. Araujo, C. Medeiros, M. Silva, and B. Bourles (2005), Seasonal changes in the mixed and barrier layers in the western equatorial Atlantic, *Brazil. J. Oceanogr.*, *53*, 83–98.
Sprintall, J., and M. Tomczak (1992), Evidence of the barrier layer in the surface layer of the tropics, *J. Geophys. Res.*, *97*, 7305–7316.
Stammer, D., K. Ueyoshi, A. Köhl, W. G. Large, S. A. Josey, and C. Wunsch (2004), Estimating air-sea fluxes of heat, freshwater, and momentum through global ocean data assimilation, *J. Geophys. Res.*, *109*, C05023, doi:10.1029/2003JC002082.

A. Köhl and D. Stammer, Zentrum fuer Meeres- und Klimaforschung, Institut fuer Meereskunde, Universität Hamburg, KlimaCampus, Grindelberg 5, D-20144 Hamburg, Germany.

V. Romanova, Research Domain 1, Potsdam Institute for Climate Impact Research, D-14412 Potsdam, Germany. (vanya.romanova@pik-potsdam.de)