Yearly impact of submonthly rain fluctuations on the Indian Ocean salinity

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[1] We investigate the impact of submonthly rain fluctuations on the daily-to-interannual variations of the salinity in the tropical Indian Ocean. A three-year record of daily observed precipitation and wind are used to force an Indian Ocean model in two experiments that differ only by their rain forcing, which is either daily- (*Exp_day*) or monthly- (*Exp_month*) averaged. Results show that submonthly precipitations significantly impact the Surface Layer Salinity (SLS) in the northern and eastern Bay of Bengal during the wet season from May to November. In September when the Bay reaches its SLS minimum, the Andaman Sea is saltier by as much as 1.3 psu for *Exp_day*. The frequency shift between the submonthly rain forcing and the yearly salinity response is due to accumulation in time of nonlinear mechanisms: sudden rain deficits increase the SLS by entraining salty waters from below, whereas rain excesses are inefficient to decrease the salinity of the thick surface layer. **Citation:** Illig, S., and C. Perigaud (2007), Yearly impact of submonthly rain fluctuations on the Indian Ocean salinity, *Geophys. Res. Lett.*, *34*, L12609, doi:10.1029/2007GL029655.

1. Background

[2] Tropical oceans under heavy rainfall have a thick barrier layer of low salinity [*Lukas and Lindstrom*, 1991] that can prevent vertical mixing of temperature and plays an important role in climate variations [*Delcroix et al.*, 2005; *Murtugudde and Busalacchi*, 1998; *Maes et al.*, 2002]. In particular, the Indian Ocean which undergoes drastic changes in rainfall with the Monsoons every year was recognized very early as an ocean where the variation of temperatures and currents could not be explained without considering salinity changes [*Cooper*, 1988]. Indeed, climatological rainfall in conjunction with the wind forcing in an Indian Ocean Model (IOM) is necessary to reproduce realistic Wyrtki jets in October each year [*Han et al.*, 1999]. Also, adding monthly-averaged interannual rain anomalies is necessary to reproduce the 1994 and 1997 cooling events in the eastern Indian Ocean [*Perigaud et al.*, 2003].

[3] Yet, actual precipitation does not vary smoothly from one month to the next: during any given month, it undergoes drastic fluctuations from day to day. The Tropical Rainfall Measurement Mission (TRMM satellite launched in 1997) provides the first opportunity to observe precipitation over the tropical oceans at periods as short as a day [*Bowman*, 2005]. Here, using TRMM precipitation data to force an IOM, we investigate how submonthly rain fluctuations modify the tropical Indian Ocean variability.

[4] We use TRMM data starting in July 1999, when winds provided by the QuikSCAT satellite become available. We force the IOM either by monthly- or daily-averaged TRMM rain and QuikSCAT wind data. The complete analysis and validation of the model results is reported by C. Perigaud and S. Illig (manuscript in preparation, 2007). Validation of the simulated Sea Level Height (SLH) with TOPEX-Jason data shows that the submonthly fluctuations of wind significantly improve SLH compare to monthly wind forcing, whereas as in work by *Perigaud and McCreary* [2003] the rain fluctuations do not impact on SLH. Rather, it is on the model temperature and salinity that the rain impact is significant. The present paper focuses on the impact on salinity.

2. Data and Model

[5] In this paper, we use wind stress and precipitation estimated from satellite observations and IOM simulations. The IOM is the nonlinear $4\frac{1}{2}$-layer model with salinity, thermodynamics and mixed-layer physics with a $0.5^\circ \times 0.5^\circ$ spatial resolution described by *Han et al.* [1999]. We have thoroughly analyzed experiments with this IOM for climate signals forced by monthly-averaged rains [*Perigaud et al.*, 2003]. The river runoff is simulated as in *Han et al* [1999], except that salinity close to the river mouths and the mass transports into the Bay of Bengal (BB) have been improved with more recent and complete data sets. The model landmask has also been refined. This model allows for the approximate isolation of the primary processes affecting salinity, while maintaining sufficient complexity to achieve reasonable solutions.

[6] The IOM is forced by wind stress and air-sea fluxes as follows. We use the daily $0.5^\circ \times 0.5^\circ$ gridded wind-stress components from the CERSAT (www.ifremer.fr/cersat/en/data/data.htm) estimated from the scatterometer measurements on board QuikSCAT. The air-sea heat fluxes are computed by applying bulk formulae to the model Sea Surface Temperature (SST) and climatological atmospheric fields, as in *Han et al.* [1999]. This choice of air-sea heat fluxes serves as a reference for ocean/atmosphere coupled experiments as explained by *Perigaud and McCreary* [2003], knowing that using prescribed atmospheric conditions in the bulk formulae artificially drives the model SST [see *Neelin et al.*, 1994]. We have performed additional experiments with different choices for air-sea heat fluxes. Note that we have found that the results presented in the paper are not sensitive to this choice. The model surface salinity is forced by net water fluxes: evaporation minus precipitation. The former is proportional to the latent heat,

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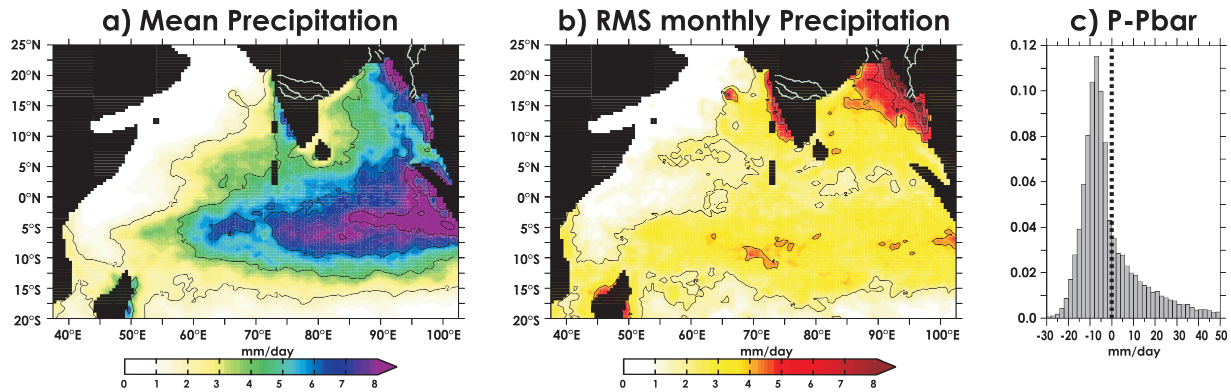

Figure 1. Observed TRMM precipitation. (a) Three-year mean. Contour Interval (CI) is 2 mm/day. (b) RMS variability of monthly-averaged precipitation (Pbar). CI is 2 mm/day. (c) Histogram of the daily precipitation relative to their monthly averages (*P–Pbar*) in the Andaman Sea for the months of June to September during the 3 years.

and the latter comes from the 1/4° × 1/4° gridded 3-hourly TRMM 3B42(V6) product, available at ftp://lake.nascom.nasa.gov/data/TRMM.

[7] In order to examine the effects of submonthly rain fluctuations on the salinity, we integrate the IOM in two experiments as follows. Initially, observed wind-stress and rain data are monthly averaged to determine the climatological forcing over 2000–2005 which is used to spin up the model from rest during 20 years. Then, from January 1st 2000 to December 31 2002, both experiments are forced by the QuikSCAT daily wind-stress. They differ in their rain forcing only: *Exp_day* is forced by TRMM daily-averaged data, while *Exp_month* is forced by their monthly-averaged values. In both cases, values are linearly interpolated onto the model time step (i.e. 0.8 hours). Unless specified otherwise, model outputs are daily averaged and the analyses presented in this paper cover the 1096 days of the 3-year twin experiments.

3. Rain Forcing of the Two Experiments

[8] The South Equatorial Eastern Indian Ocean (SEEIO) and the Eastern Bay of Bengal (EBB) are the 2 regions where it rains a lot on average over the year (Figure 1a). The SEEIO is the only region where the precipitation rates are important throughout the year (6 mm/day to 9 mm/day on average each month). In contrast, precipitation in the EBB are very seasonal (Figure 1b) with dry winters (less than ~1 mmm/day on average) and wet summers (more than ~10 mm/day on average).

[9] Most striking is that the variability of precipitation occurs at subseasonal frequencies. On average across the Indian Ocean north of 20°S, 84% of the rain energy is contained in the 2-to-30 day band (not shown). When we linearly interpolate 2 consecutive monthly-averaged values onto the model time step in *Exp_month*, we loose some energy primarily in the 2-to-60 day band as expected. It is important to keep in mind that the precipitation signal is non-gaussian (Figure 1c). It is dominated by sudden heavy precipitation events, intersected by longer periods of less abundant rain.

[10] The importance of the sudden rain fluctuations is also clearly seen by comparing the daily- and monthly-time series of rain. In SSEIO, daily fluctuations up to 30–40 mm/day show up in any month of the year. Similarly, in the northern region of the EBB, extrema as large as 100 mm/day are found each summer. Figure 2a illustrates the situation in the Andaman Sea [95°E–98°E; 8°N–15°N]: the rain signal is dominated by brief daily events frequently occurring with peaks of 30–50 mm/day from April/May to September/October every year. It is in the Andaman Sea that all 3 signals, the mean, the seasonal and the submonthly have a maximum amplitude.

4. Model Response in Surface Layer Salinity

[11] On average in time, the Surface Layer Salinity (SLS) of the BB is significantly lower than elsewhere in the Indian Ocean (Figure 3a). This is because the Bay receives fresh water from both heavy precipitation and important river

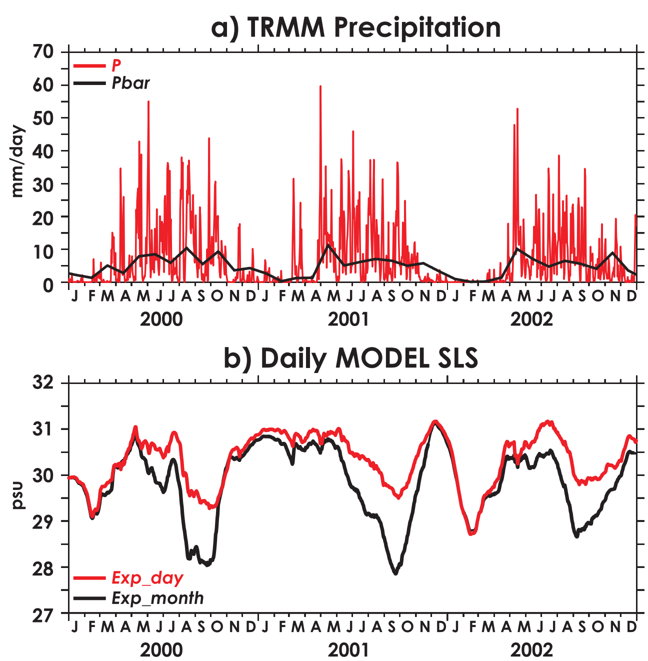

Figure 2. Time series averaged in the Andaman Sea: (a) daily P (red) and monthly Pbar (black). (b) Surface Layer Salinity (SLS) from *Exp_day* (red) and *Exp_month* (black).

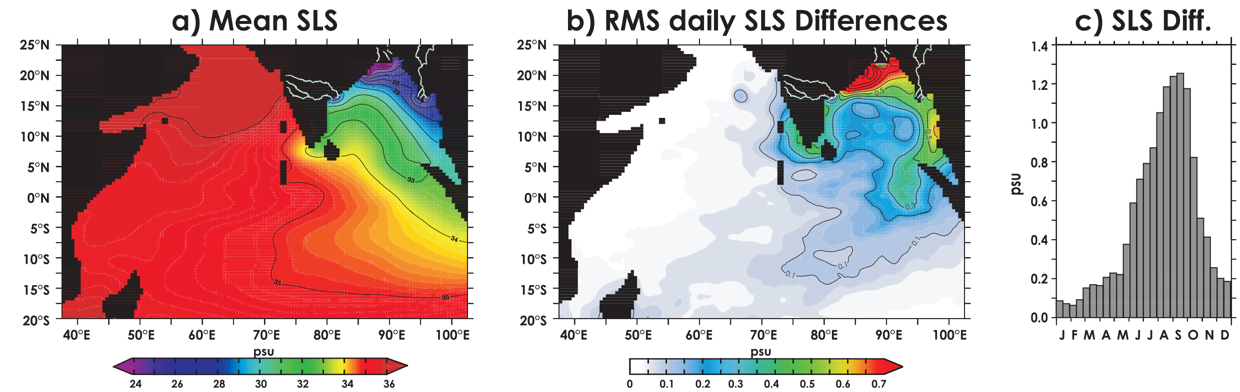

Figure 3. Model Surface Layer Salinity (SLS). (a) Three-year mean. CI is 1 psu. (b) RMS variability of daily SLS differences between *Exp_day* and *Exp_month*. CI is 0.1 psu. (c) Fortnight-averaged SLS differences between the 2 experiments averaged in the Andaman Sea presented as a function of months averaged over the 3 years.

runoff. The SLS is as low as ~25 psu close to the Bay coastline, and maximum values in the interior of the Bay and East of Sri Lanka stay below ~35 psu. The map of RMS daily differences in SLS between the two experiments (Figure 3b) shows that the impact of the submonthly rain forcing is maximum in the Bay. The differences are significant (larger than 0.3 psu) all around the BB with a maximum in the North BB, where the RMS differences reach 0.7 psu. Note that this northern maximum is located where the mean SLS is minimum in the vicinity of the Ganges river mouth (Figure 3a), to the West of where the mean and seasonal rain signals have their maxima (compare with Figures 1a and 1b). In addition, the SLS differences have a secondary maximum of 0.5 psu in the Andaman Sea. This is where the difference in rain forcings between the two experiments is largest.

[12] Let us focus on the Andaman Sea. Compare the time series of SLS in Figure 2b with Figure 2a. Strikingly, the sudden rain events do not trigger SLS fluctuations at 2-to-30 days: *Exp_day* simulates a smooth SLS seasonal signal like *Exp_month*. The difference shows up every year between late Spring and Fall. The IOM thus simulates a drastic frequency shift from submonthly rain forcing to a yearly SLS response. The amplitude of the impact has the same order as the seasonal signal itself: each September, *Exp_month* reaches a minimum of ~28 psu, whereas the annual September minima of *Exp_day* remain above ~29 psu. In late Fall, *Exp_month* recovers from its lower salinity to reach the same maximal values as *Exp_day*, i.e. 30.5 to 31.5 psu between January and June. The histogram of SLS differences (Figure 3c) illustrates That the submonthly rain impact is larger than 0.5 psu between June and October and has a peak above 1.2 psu in September. It also highlights an asymmetry between the increasing and decreasing SLS differences: it takes several months of sudden rain fluctuations to reach the maximum impact on SLS at the end of the wet season, whereas the SLS recovery to ~31 psu in December is relatively rapid.

[13] To validate these results, we use the climatological signal from the NODC (Levitus) World Ocean Atlas 1998 (http://www.cdc.noaa.gov/cdc/data.nodc.woa98.html) and the ECCO model outputs over 2000–2002 (http://ecco.jpl.nasa.gov/). For comparison with the IOM layer outputs, we take the averages of Levitus and ECCO salinity over the IOM simulated Surface Layer Thickness (SLT). Comparing the SLS time series averaged in the Andaman Sea (see Figure S1 in auxiliary materials[1]) suggests that the signal simulated by *Exp_day* is more realistic than the one simulated by *Exp_month*: the salinity decrease between Spring and Fall simulated by *Exp_day* is ~2 psu, in better agreement with the 1.5 psu observed by Levitus climatology than with the ~3 psu simulated by *Exp_month*. ECCO has weaker amplitude (~0.7 psu) than all other signals, but it is also in better agreement with *Exp_day* than *Exp_month*. Note that model discrepancies with Levitus can be as large as 1 psu. Indeed, to be consistent with the fine model grids, in situ measurements with a better spatial resolution are needed in this region of high SLS gradients. We are thus limited in the validation we can perform, but we can focus on the mechanisms that explain the shift in frequency from the daily rain forcing to the once/year SLS signal.

5. Mechanisms

[14] Because the monthly-averages of the rain forcing are the same in both experiments, the only mechanisms that allow significant differences in monthly-averaged SLS are nonlinear. In order to determine which process(es) govern(s) these differences, we examine the rates of change between two subsequent model time steps for each term of the SLS equation: namely, the net surface forcing ($\frac{E-P}{SLT} \times SLS$), the horizontal advection, the vertical entrainment/detrainment and the horizontal mixing. For both experiments, the terms vary significantly at high-frequencies (even within the day). So we integrate each term in time over 2 weeks and display the fortnight salt increments in Figures 4a–4d as a function of months on average over the 3 years.

[15] Results show that for both experiments, the total SLS changes in the Andaman Sea (Figure 4a) are almost fully explained by the sum of the net surface forcing, horizontal advection and vertical entrainment. Even in *Exp_day*, the evaporation variability remains small: it varies by less than 1 mm/day, relative to its year mean of ~5 mm/day (see Figure S2 in auxiliary materials). Therefore, the surface

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL029655.

forcing slightly increases the SLS during the dry winter, whereas it freshens it during the wet season (Figure 4b). Moreover, from May to September (MJJAS), the horizontal advection (Figure 4c) and the vertical entrainment (Figure 4d) have a significant contribution on SLS, with opposite tendencies. The horizontal advection of fresh waters coming from the North decreases the SLS, while the entrainment of the salty subsurface waters increases it.

[16] Let us now focus on the differences between *Exp_day* and *Exp_month* (see red and blue shadings in Figures 4a–4d). During MJJAS, with a slightly thinner SLT (see Figure S3 in auxiliary materials) and a saltier SLS, the surface forcing simulated by *Exp_day* is slightly larger. By accumulation in time, the rain excesses contribute to freshen the SLS of *Exp_day* via the surface forcing slightly more than the rain deficits (see blue shading in Figure 4b). Similarly, the zonal advection from the North freshens the SLS more for *Exp_day* than for *Exp_month* (see blue shading in Figure 4c). More importantly, the accumulated vertical entrainment of salty subsurface waters bring two to three times more salt to the surface in 14 days for *Exp_day* than for *Exp_month* (see red shading in Figure 4d). Thus, it is mostly the vertical entrainment activated by submonthly rain forcing during the wet season that explains the differences between the 2 experiments.

[17] In order to further characterize the relationship between vertical processes and rain fluctuations, for both experiments, the daily entrainment/detrainment simulated during the wet season is presented as a function of Evaporation minus Precipitation (E−P) (Figure 4e). Results for *Exp_month* show that, regardless of the sign of, the model simulates slow entrainment from the subsurface ($\leq$0.5 m/day; see black dots in Figure 4e). It is triggered there in summer by the wind forcing and is associated with the seasonal thickening of the SLT. By contrast, for *Exp_ day* (see color dots in Figure 4e), both entrainment and detrainment can happen for large rain events. Strikingly, for the numerous rain deficits ($P \leq Pbar$, i.e. $P \leq 10$ mm/day), there is almost no detrainment and the simulated entrainments are larger than 0.5 m/day. When it scarcely rains ($E-P \approx$ 5 mm/day), the entrainment becomes extremely intense, as high as 2 to 5 m/day. This is because the stability of the density stratification is decreased, favoring more vertical mixing of the upper ocean. It is important to understand that neither the rain nor the vertical entrainment/detrainment of the ocean has a Gaussian distribution (Figure 1c). Thus, during the wet season, frequent small rain deficits are more efficient at increasing the SLS in entraining salty waters from the subsurface than sudden large excesses at decreasing the salinity of the thick surface layer. By accumulation in time, this nonlinearity results in a saltier surface ocean in *Exp_day* than in *Exp_month* which lasts for many weeks at the end of the rainy season.

[18] In the SEEIO, the SLS excesses of *Exp_day* compared to *Exp_month* remain smaller than 0.4 psu. They are

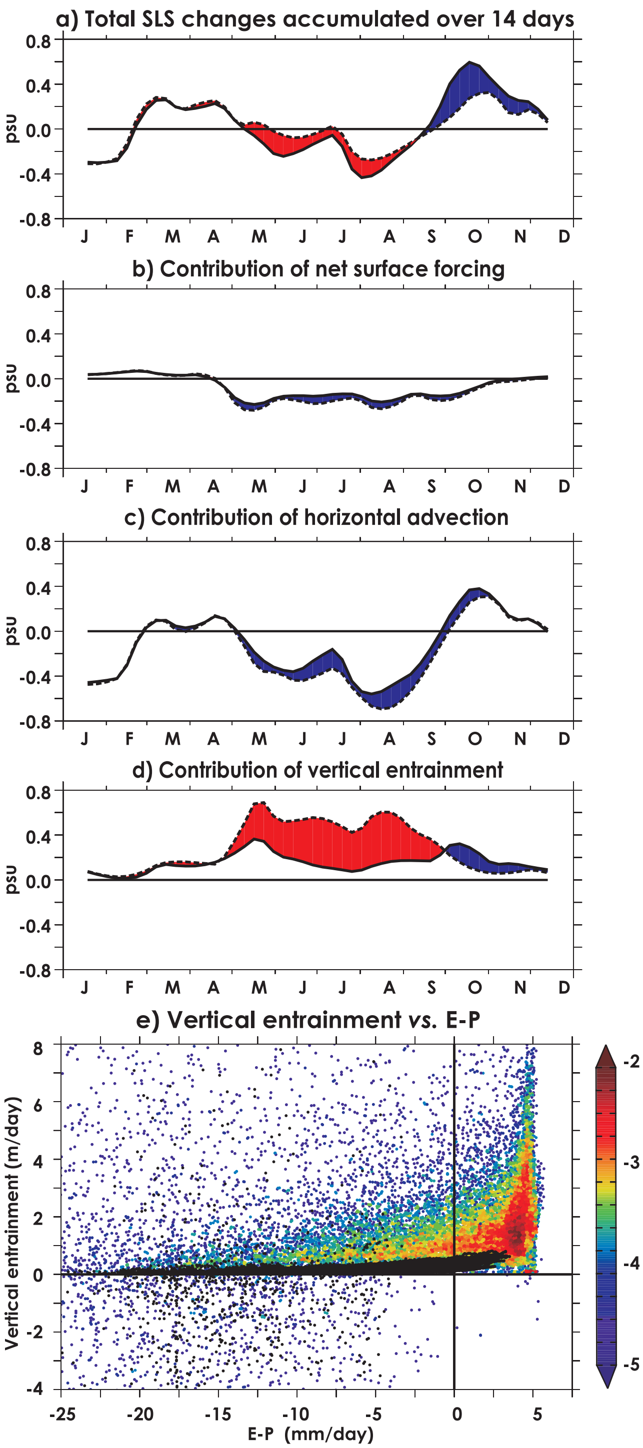

Figure 4. Mechanisms in the Andaman Sea. (a) Surface Layer Salinity (SLS) rates of change per model time step accumulated over 14 day increments for *Exp_day* (dashed line) and *Exp_month* (plain line). Results are presented as a function of months averaged over the 3 years. Contribution of (b) the net surface forcing, (c) the horizontal advection and (d) the vertical entrainment to the total SLS increments. Red (blue) shadings correspond to *Exp_day* line over (under) *Exp_month* line. (e) Distribution of daily-averaged vertical entrainment as a function of the daily Evaporation minus Precipitation (E-P) for *Exp_day* (color) and *Exp_month* (black). Computation is performed for the months of June to September for the 3 years. The color code indicates in a Log scale the density of points per box units: $\Delta P \times \Delta W = 0.25$ mm/day $\times$ 0.072 m/day.

largest in JASO one month later than in the NEBB (not shown). Sudden rain deficits also trigger intense vertical entrainment there. However, because the upper-ocean is weakly vertically stratified in salinity, the vertical mixing is almost ineffective at increasing the SLS. It is the horizontal advection from the NEBB that brings saltier surface waters for *Exp_day*.

[19] At the end of the rainy season in October in the Andaman Sea, the net surface forcing term becomes negligible for both experiments. The vertical entrainment in *Exp_day* decreases to the level of *Exp_month*, still contributing to increase the SLS. In contrast to previous months, the horizontal advection from the South increases the SLS, as the Wyrtki jets bring salty waters from the Western Equatorial Indian Ocean to Java and along the eastern BB into the Andaman Sea. So, in October–November, the horizontal advection and the vertical entrainment have similar amplitudes, and they both contribute to increase the SLS. In addition, these two terms are weaker in *Exp_day* than in *Exp_month*: the nonlinearity of these 2 terms as a function of rain explains why *Exp_month* recovers faster the January salinity values than *Exp_day*.

6. Summary and Perspectives

[20] In this paper, we investigate the impact of submonthly rain fluctuations on the Indian Ocean salinity based on simulations of an IOM forced by observed satellite wind stress and precipitation. For that, we perform twin experiments that differ only by their rain forcing, which is either daily- or monthly- averaged. The impact of daily rains on temperatures and surface currents in the IOM are reported elsewhere. Results here show that submonthly rains have an impact larger than ~1 psu on the SLS signal in the BB once per year during the wet season, with a maximum in October. The main mechanism that explains the shift in frequency from the daily rain forcing to the once/year SLS signal is that frequent small rain deficits are more efficient at increasing the SLS in entraining salty waters from the subsurface than sudden large excesses at decreasing the salinity of the thick surface layer. Because it rains a lot, the salinity does decrease towards a minimum in October in both experiments, but the accumulation in time of sudden entrainment of subsurface salt due to short Monsoon breaks throughout summer results in greater SLS during October of the *Exp_day* solution.

[21] These model results appear robust: similar conclusions were obtained with an Indian OGCM forced by daily- or monthly- averaged AGCM net water forcing. In addition, the existing data sets suggest that using daily rains to force the model improves the simulated SLS minimum in October, but data are not sufficiently comprehensive to validate this conclusion for sure. Our study points out the need for more SLS data. Note that the ~1 psu amplitude of the impact found on SLS is so large that it should be well observed from satellites such as Aquarius: the requirements of this satellite mission are 0.2 psu accuracy on a monthly basis with 1° spatial resolution. When such SLS data become available, it will be straightforward to ascertain the benefit of TRMM daily estimates over monthly-averaged rain products. Meanwhile, the present results appeal to study the role of submonthly rain and ocean feedback in the coupled ocean/atmosphere/land climate variability.

[22] **Acknowledgments.** The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We express our gratitude to Julian P. McCreary for providing the IOM code and for insightful discussions about Indian Ocean processes. We are very thankful to TRMM and QuikSCAT data providers. Daria Halkides is acknowledged for her careful reading of the manuscript.

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