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Intense and small freshwater pools from rainfall investigated during SPURS-2 on November 9  
2017 in the eastern tropical Pacific.

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## Abstract

1 During the SPURS-2 2017 tropical Pacific cruise, two drifters were deployed on November 9.  
2 The drifters measured temperature and salinity in the top 36 cm, wave spectra, and the noise  
3 of rain drops. During a short nearly-circular survey with a 1.8-km radius around the drifters,  
4 the R/V Revelle measured air-sea fluxes, as well as temperature and salinity stratification in  
5 the top 1 m from a towed surface salinity profiler (SSP). A C-band weather radar measuring  
6 rain rate within 1 to 100 km range of the ship observed discrete rain cells organized in a  
7 system moving from the southeast to the northwest. Some of the intense rain cells were small-  
8 scale (1 km in diameter or less) with short lifetimes, yet dropped more than 5 cm of water in  
9 half an hour near the drifters, whereas the ship measured short rain episodes totaling 1.3 cm of  
10 rainfall mostly accompanied by very low wind. The data indicate a large spatial heterogeneity  
11 in temperature and salinity, with near-surface freshening of up to 9 psu measured at different  
12 times by the two drifters (separated by less than 500 m) and by the SSP. The drifters indicate  
13 deepening of the fresh and cool surface layer during the rain which then thinned during the  
14 following 40 minutes with very low wind speed ( $<2$  m/s). Patchy surface-trapped cold and  
15 fresh layers were also observed by the SSP east of the drifters. The high spatial and temporal  
16 variability of rainfall and surface-trapped fresh pools is discussed.

17

18 Plain language summary

19 We present data illustrating remarkably low surface salinity for the open ocean, outside of the  
20 high latitudes near the sea ice or of river plumes. This event was observed by two  
21 instrumented drifters and a towed instrument during the R/V Revelle SPURS-2 2017 cruise  
22 near 10°N/125°W on November 9 2017. The large surface-trapped fresh and cold signal was  
23 observed for up to an hour after the rain, and was associated with low to very low surface  
24 wind. The data illustrate a large patchiness of the fresh and cold surface pool induced by  
25 intense but short lived rain events, at spatial scales of 1 km or less. Radar and ship  
26 meteorological data also illustrate a large spatial variability of the total rain accumulation,  
27 which in some places, such as near the drifters, exceeded 5 cm, whereas it was barely 1 cm, 1  
28 or 2 km away. An estimate of the fresh layer thickness suggests that the fresh surface layer  
29 was up to 30 cm thick under the most intense rain, but shallowed afterwards to be on the order  
30 of 20 cm.

31

## 32 1. Introduction

33 The second Salinity Processes in the Upper Ocean Regional Study (SPURS-2) project is  
34 aimed at understanding the impact of rain on surface salinity, upper ocean stratification and  
35 circulation in the ITCZ of the near-equatorial Pacific Ocean (near 10°N, 125°W). The scales  
36 investigated range from the time-scale of a rain event of a few minutes duration to the  
37 seasonal time scale; vertical scales of a few cm to a few tens of meters; and horizontal scales  
38 from one to hundreds of kilometers (Lindstrom et al., 2019). Earlier studies have shown a fast  
39 local response to rain events, with surface freshening proportional to the rain intensity  
40 (Drushka et al., 2016; Bellenger et al., 2017), to a power of the rain intensity (Asher et al.,  
41 2014), or to the rain accumulation (ten Doeschate et al., 2019) and inversely proportional to  
42 the wind speed (Asher et al., 2014; Drushka et al., 2016; Drushka et al., 2019). The thickness  
43 and vertical extent of the initial fresh pool is proportional to the wind speed (Thompson et al.  
44 2019). The strongly-stratified near-surface fresh pools have been shown to often have a short  
45 lifetime after the rain (e.g., less than one hour), with a duration dependent on wind intensity  
46 (Reverdin et al., 2012; Drushka et al., 2016). In low-wind conditions, fresh pools have been  
47 observed to persist for more than 10 hours (Price, 1979; Thompson et al., 2019). Bellenger et  
48 al. (2017) also suggested the influence of horizontal spreading of the pools by gravity  
49 currents, which have been documented in the tropical oceans (Soloviev and Lukas, 1997;  
50 Soloviev et al., 2002) and in numerical model simulations (Soloviev et al., 2015). Horizontal  
51 spreading would result in shallower pools and hence increased vertical mixing, particularly  
52 with initial conditions of small pools and moderate winds. A temperature cooling signal is  
53 usually associated with the rain freshening due to the colder temperatures of raindrops. In  
54 addition, heat loss to the atmosphere trapped in the near-surface stratified layers results in  
55 more cooling, particularly during night-time rain events (Reverdin et al., 2012; Bellenger et  
56 al., 2017).

57

58 The observations that have been used to provide information on surface freshening from rain  
59 include measurements from drifters (Reverdin et al., 2012; Hormann et al., 2015; Centurioni  
60 et al., 2015; Dong et al., 2017; Volkov et al., 2019), profiling floats (ten Doeschate et al.,  
61 2019; Drucker and Riser, 2014), surface-following platforms (Asher et al., 2014; Drushka et  
62 al., 2019), gliders (Shcherbina et al., 2019), or ships (Soloviev and Lukas 1997, 2006,  
63 Wijesekera et al. 1999, Thompson et al. 2019). In most cases, either the local history of rain

64 and wind or the spatial extent of the fresh pools and their evolution is not well documented.  
65 Recently, at much larger scales (50 to 100 km), rain-induced freshening has been investigated  
66 from satellite missions with band-L radiometric imagery. Boutin et al. (2016) and Supply et  
67 al. (2018, 2019) have illustrated that at those scales freshening depends on total rainfall  
68 amount but less on large-scale winds (with a weaker response at winds stronger than 6-8 m/s,  
69 Supply et al., 2019). Supply et al. (2018) also documented a short duration (an hour or less) of  
70 some of the large freshwater pools. On the other hand, what happens at the O(100 m to 1km)  
71 scales of small rain events in terms of the impacts of wind and rain, and how the small-scale  
72 variability integrates to produce the larger scale response, has not been well documented.

73

74 Late at night on November 9, 2017 during the SPURS-2 cruise on R/V Revelle, the presence  
75 of nearby rain cells was observed to the south-east of the ship by the SEA-POL rain radar on  
76 R/V Revelle (Rutledge et al., 2019). The region cut across by the ship (coming from the  
77 south) presented little horizontal gradients of surface temperature and salinity and had not  
78 experienced any rain in the last 12 hours according to IMERG products (Huffman et al.,  
79 2019) with winds of at least 5 m/s. The deployment site was within a large-scale eastward  
80 flow on the order of 0.2 m/s according to altimetry and satellite-derived currents from the  
81 OSCAR product, and the subsurface currents measured by the ship's VM-ADCP at 17-m  
82 depth were to the south-east until 15:30 GMT between 5 and 25 cm/s.

83

84 Two drifter sets were deployed starting at 13:30 GMT, and the ship then did a dedicated  
85 survey around them. Here, we use data from the two instrumented drifters and a near-surface  
86 salinity profiler (SSP, Drushka et al., 2019) towed by the R/V Revelle to illustrate the rain  
87 events and their signature in the ocean. These upper ocean data, along with the rain and wind  
88 history, allow investigation of the variability of salinity and temperature in the upper meter of  
89 the ocean, both in time (over more than 90 minutes) and partially in space (over the surveyed  
90 region of approximately 10 km<sup>2</sup>). We will present the instrumentation, describe the data, and  
91 discuss the role that the rain and wind forcing played in generating the observed strong spatio-  
92 temporal variability. It is notable that the salinity data shows, to our knowledge, the lowest  
93 observed surface salinity in the open ocean. This low surface salinity persisted for at least half  
94 an hour after the rain stopped.

95

## 96 2. Data

### 97 2.1 drifters



98 Each drifter set consisted of three individual instrument platforms connected with 8 m of  
99 floating line. The first platform was a SC40 SVP surface drifter (NKE Instrumentation) with  
100 a small CARTHE drogue hanging between ~42 to ~80-cm depth. The second was a CARTHE  
101 drifter (PacificGyre) with a drogue between 25 cm and 63 cm below the surface (assuming  
102 the line is taut and drogue is vertical) (. Novelli and Guigand, 2017).

103 The third and final platform of the set was a 5-cm thick, drogue-free SURPACT float (Sea  
104 Mammal Research Unit [SMRU], University of St Andrews). The package thus responds to a  
105 mix of conditions very close to the sea surface (due to the surface elements, in particular the  
106 SC40 drifter large surface sphere) down to the deepest part of the drogue near 80 cm (Fig. 2).

107

108 The SC40 drifter has a water temperature probe 20 cm below the surface, under the spherical  
109 surface float. In a previous study of large daily warming events with weak winds (Reverdin et  
110 al., 2010), SC40 drifters were found to measure temperature at a water depth of 18 cm. The  
111 SC40 drifter also has temperature (T) and conductivity (C) probes placed on a frame at 36-cm  
112 depth, below the perturbing effect of the surface float, that are used to estimate salinity (S).

113 The T probe at 18 cm is assumed to have a time sensitivity of at least 1 minute, and this  
114 measurement is slightly influenced by the temperature inside the hull (which is seen during  
115 the first 20 minutes after deployment when the inside temperature has not yet fully adjusted to  
116 sea temperature). As this temperature is likely to vary slowly after the initial adjustment,  
117 relative T variations on short time scales closely portray the changes in the water flowing near  
118 the hull. The T probe at 36 cm has a time sensitivity on the order of 1 s and thus can capture  
119 much faster fluctuations in T. The SC40 reports data every five minutes (data are averaged  
120 over a period of 30 seconds before the transmission time). Drifter positions are measured with  
121 a GPS, giving ~10-m horizontal accuracy.

122

123 The SURPACT float consists of a circular annular disk with a tag at its center. The tag  
124 originates from classical SMRU sea mammal tags (Roquet et al., 2011), but has been  
125 ballasted to have a lower center of mass. Every 3 seconds, it reports T and C (using an  
126 inductive sensor) from a Valeport CTD probe that is located under the tag at 4-5 cm below the  
127 water surface, and was calibrated by the manufacturer with uncertainties on T less than  
128 0.01°C and on S on the order of 0.02 psu in the upper range of salinity observed.

129 Uncertainties in S might be larger at the low salinities (such as 24 psu), but are not expected

130 to exceed 0.1 psu, thus less than 1% of the dynamical range explored. The float has been  
131 designed to minimize vertical mixing, and thus the measurements at the C-T sensors depth are  
132 likely representative of a layer within the top 10 cm of the ocean. The location of the CTD  
133 probe under the tag also protects it from the largest bubbles. In addition, the tag reports  
134 vertical acceleration at 6.15 Hz. Wave spectra are estimated from the vertical component of  
135 acceleration by assuming that the SURPACT follows the vertical displacement of the sea  
136 surface. This assumption should hold for wave periods between 8 s and 0.5 s: at longer  
137 periods, the accelerometer is not sensitive enough for the swells, whereas at periods shorter  
138 than 0.5 s there is a strong influence from the float elements (Reverdin et al., 2013). In earlier  
139 deployments (Reverdin et al., 2013), the whole spectrum was used to estimate the wind,  
140 leading to possible delays of wave spectra with respect to the wind changes. During this  
141 deployment, we also witnessed such effects during the early period (before 14:00 GMT), with  
142 an unusual accelerometer spectrum with an energy gap centered near 2 s. Thus, as we are  
143 particularly interested in fast changes in local winds, we will only consider waves with the  
144 shortest periods (near 0.75 s; thus, wavelength close to 50 cm), which are expected to be  
145 rather responsive to fast changes in local wind. We thus use the energy of 0.75 s waves as a  
146 proxy for wind speed.

147 Finally, the SURPACT reports sound spectra every 3 seconds recorded by a microphone  
148 under a purpose-made cupola on top of the tag. The data are processed in 7 channels ranging  
149 from 63 Hz to 16 kHz by a MSGEQ7 Graphic Equalizer Rain Sensor. In conditions with no  
150 wave breaking such as for the record analyzed here, the sound spectra outputs can be used to  
151 estimate the rainfall rate, as is done for agricultural use of similar sensors or with other  
152 acoustic rain gauges. This was qualitatively tested in laboratory conditions (by the Sea  
153 Mammal Research Unit based in St Andrews, Scotland, as well as at LOCEAN). The results  
154 are very insensitive to other sources of noise, such as rain on the sea, animal or nearby engine  
155 noise, contrary to sub-surface hydrophone measurements (Nystuen and Amitai, 2003). This  
156 was also checked during the cruise prior to this deployment with another SURPACT unit  
157 attached to an instrumented mooring: the acoustic sensors reported correctly without  
158 saturation for rain rates up to 4 cm/hr. Of the 7 spectral channels, channel 5 (2.5 kHz) was  
159 found to be most sensitive to rain. During the SPURS-2 deployment, channels 4 to 6 (1 kHz  
160 to 6.25 kHz) were often saturated, indicating heavier rain. We thus use channel 3 (400 Hz),  
161 the highest frequency not to saturate. However, this frequency band is also sensitive to wave  
162 splash on the cupola. It is questionable that this channel output is linear with respect to rain

163 rate, and the power level of the spectra should be interpreted mostly as a scaling of rain rate,  
164 with largest uncertainties at rain rates larger than 4 cm/hr. The cupolas of the two SURPACTs  
165 deployed were different, one being less spherical than the other; this difference in shape is  
166 expected to have an impact on the response, which was not quantified. All the SURPACT  
167 float measurements are time-averaged and reported every 21 s. The wave accelerometer  
168 spectrum is further smoothed spectrally and averaged over 63 s (so that each reported value  
169 represents 18 degrees of freedom). To produce vertical profiles, we combine the SURPACT  
170 T-S data at 4-cm with the SC40 T-S data at 18-cm and 36-cm, subsampling the SURPACT  
171 records at the times of the SC40 measurements every 5-minutes.

172

173 The two drifter sets were deployed at around 13:10 to 13:13 GMT during westerly winds of 4  
174 m/s and were tracked starting at 13:14 GMT (04:56 local time, thus well before sun rise) at  
175 10.51°N, 124.148W, when they were 312 m apart (Figure 1). The distance between them  
176 never exceeded 500 m before 15:30 GMT. The largest increase in drifter separation (nearly  
177 100 m) is seen during the rain between 14:00 and 14:30 GMT, when the southern drifter  
178 (“drifter S”) drifted more rapidly in the southeast direction than the northern drifter (“drifter  
179 N”). It is possible that the velocity difference between the drifters is related to different  
180 horizontal momentum input by the rain drops or wind gusts in the stratified surface layer  
181 between the two drifters, or some divergence of the freshwater near the surface (with more  
182 rainfall at drifter N than S), or even a surface gravity current induced by the gradient of  
183 freshwater input. Before the wind strengthened at 15:15 GMT, the drifters drifted eastward or  
184 south-eastward at an average speed of 15 cm/s. After 15:15 GMT, it is likely that the drifters  
185 started experiencing weak easterly momentum input from the wind, which strengthened after  
186 15:30 GMT; by 15:40 GMT, drifter velocities were close to 0 cm/s, i.e., speed decreased by  
187 15 cm/s after 15:15 GMT.

## 188 2.2 SSP data

189 Throughout the drifter deployment, the SSP was towed in the water outside of the ship’s wake  
190 (90 m slightly starboard) at a speed close to 2 m/s. The SSP measures T and S at 4 depths  
191 using CTDs mounted on its keel at 0.12 m, 0.23 m, 0.54 m, and 1.1 m below water line  
192 (Drushka et al., 2019; Fig. 2). In addition to the CTDs, water from the surface (~5 cm depth)  
193 is sampled continuously using a ‘sea snake’ (a floating device to pump near-surface water and  
194 measure near-surface temperature). The T is measured using a SBE 56 sensor mounted

195 alongside the ‘sea snake’ inlet and salinity is measured by a SBE 45 TSG mounted on the SSP  
196 (Drushka et al., 2019). Because of the debubbler used for the sea snake TSG, its response time  
197 was longer than that of the four keel-mounted CTDs. Furthermore, the sea snake TSG was  
198 also lagged in time relative to the CTDs due to the volume in the tubing and debubbler.  
199 During periods of weak stratification when the CTDs and TSG should measure the same T  
200 and S, we found that the T-S data from the sea snake need to be advanced by 10 s to optimize  
201 the correlation with T-S data from the CTDs. Spikes in salinity due to bubbles were removed  
202 from the data, and a 15-s median-filter was applied separately to the T and S data of each  
203 sensor, which are then reported every second. Remaining noise is present in salinity, in  
204 particular for the upper sensors, but at a level which is small compared with the signals  
205 investigated.

206

### 207 2.3 Meteorological measurements

208 Meteorological measurements were made aboard the ship and provided by the SPURS-2  
209 community dataset (Clayson et al., 2019). The data selected were always from instruments on  
210 the upwind side of the ship. Here we use measurements of wind speed and rain rate, as well as  
211 heat flux estimates. These data are available as 1-minute averages (thus 120 m of ship track).  
212 Since the SSP was towed 90 m aft of the meteorological sensors, we shifted the  
213 meteorological data by 45 seconds to collocate them with the SSP data, assuming that the  
214 meteorological variability recorded is spatially frozen, and assuming that the wind  
215 measurements were made from sensors located forward on the ship.

216

217 The SEA-POL dual-polarization C-band Doppler weather radar mounted on the R/V Revelle  
218 provided maps of rain rate close to the sea surface every five minutes at distance from the  
219 ship of 1 km to 100 km (Rutledge et al., 2019a,b). The data were recorded throughout the two  
220 minutes after the round 5 minutes times (e.g., 14:00, 14:05 GMT ...). They have been post-  
221 processed and are provided on a 1 km square grid. Rain estimates within 60° of the aft  
222 direction of the ship were not measured to avoid illuminating the superstructure of the ship.

223

### 224 3. Observations

225 After deploying the drifters, the R/V Revelle traveled northward 1.8 km from the drifters and  
226 then followed a circular track around the drifters at 2 m/s towing the SSP. At the ship, rain  
227 rates up to 5 cm/hr were measured, accompanied by wind speed below 3 m/s until 14:50  
228 GMT (Figure 1,3). Heavy rain and weak winds were also measured by the drifters, with weak

229 winds persisting until 15:10 GMT. Sustained easterly winds of 4 m/s were measured at the  
230 ship after 14:50 GMT (Figure 3). The drifters were then recovered at 17:45 GMT (Fig. 1). We  
231 will focus on the 90-minute time period between 13:50 and 15:20 GMT, which had high rain  
232 rate and low wind at first and then featured higher wind conditions and mixing of the top  
233 layer of the ocean (Figure 3).

234

### 235 3.1 The meteorological records

236 We first comment on the meteorological data from the R/V Revelle (Fig. 3a) and on the sound  
237 and wave spectra measured by drifters N and S (Fig. 3b, 3c). The wind is moderate (4 m/s)  
238 prior to the drifter deployment and quickly decreases to values of 0 to 2 m/s between 13:55  
239 and 14:50 GMT. The wind direction is variable, but usually remains westerly. Close to 14:55  
240 GMT a front is crossed, with wind intensity increasing to 5 m/s and wind direction shifting to  
241 easterly. A larger wind speed increase happened suddenly after 15:30 GMT with a small shift  
242 of direction to ENE (not shown). These wind changes are coincident with changes in the  
243 power spectra of the vertical accelerometer of the two SURPACTs, a proxy for wave energy.  
244 The wave spectra time series show a decrease of the maximum energy in acceleration found  
245 near 1.5s at 14:00 GMT (not shown). The ‘shorter’ wave spectral power (at 0.75s) (proxy of  
246 the wind) is very low between 14:00 and 15:00 GMT, thus a slightly different timing than  
247 from the ship’s wind speed records. For example, the increase in 0.75s wave spectral power  
248 happens 15 minutes later than the wind speed increase at 14:55. This indicates spatial  
249 gradients of the winds on that 1-2 km distance (Fig. 1). There are also noticeable differences  
250 between the two SURPACT records (separated by ~400 m) on time scales less than 10  
251 minutes. For example, a small peak in 0.75s wave energy is observed by SURPACT-N  
252 around 15:05 that is not witnessed by SURPACT-S, consistent with wind variability on scales  
253 of a few hundreds of m.

254 The ship rainfall record (Fig. 3) indicates an isolated rain event (near 13:30 GMT, when wind  
255 is still near 4 m/s), a set of large rain events between 14:00 to 14:30 GMT, often at rates  
256 larger than 2 cm/hr (and up to 5 cm/hr), and an isolated weaker rain event at 14:32 GMT. The  
257 last rain event happens when wind is <2 m/s. Throughout the entire 90 min period, rain  
258 intensity varies by more than a factor of two between successive peaks and troughs separated  
259 by a few minutes and a few hundred meters. The SURPACT microphone records (lower  
260 panels of Fig. 3) indicate a similar overall sequence of rain events, but starting several  
261 minutes earlier at 13:48 GMT and persisting for nearly half an hour. If one assumes that the

262 acoustic response to rainfall is linear, Fig. 3 suggests a large intermittency in rain, with local  
263 minima in rain rate observed by the two SURPACTs around 14:03 and 14:20 GMT. Although  
264 wind speed appears somewhat weaker during rain in this event, they are not significantly  
265 correlated over this short record.

266 During the drifter deployment period, the ship's air sea heat flux estimate (without the cooling  
267 effect caused by the deposition of colder rain drops) indicated a small loss (on the order of 45  
268  $\text{W/m}^2$ , not shown), which would induce a vertically integrated temperature cooling on the  
269 order of  $0.040 \text{ }^\circ\text{C m h}^{-1}$  between 13:50 to 15:00 GMT. Because of the short distance  
270 separating the drifters from the ship, we tentatively estimate that this might also be the  
271 cooling magnitude due to the heat fluxes at the location of the drifters until the wind increases  
272 locally at 15:15 GMT.

### 273 3.2 Near-surface temperature and salinity

274 On Figure 3, we also plot the near surface ( $\sim 5$  cm depth) T and S signal measured by the SSP  
275 and the two SURPACTs. Before the rain starts, all three platforms show similar values and no  
276 vertical stratification. The agreement between the three platforms indicates that, at least in the  
277 northern part of the ship's survey, there is no large spatial gradient in salinity or temperature  
278 present over horizontal scales of 1-2 km. After the rain begins, all three records show  
279 extremely large surface cooling and freshening, all exceeding  $1^\circ\text{C}$  and 7 psu, and with the  
280 extremum of  $1.3^\circ\text{C}$  and 9.5 psu during event B measured by SURPACT-N (the northern  
281 SURPACT). The salinity changes also imply significant changes in surface water density,  
282 dominated by S variability (T variability reduces by roughly 5% the density variability  
283 induced by S changes).

284 However, the timing of the cooling and freshening observed from the three platforms is  
285 different, as shown by the three time series (Fig. 3). Although the two SURPACTs are  
286 separated by less than 400m, they show a remarkable difference in salinity both during the  
287 rain (despite appearing to experience relatively similar amounts of rainfall) and afterwards.  
288 Until 14:00 GMT (event A shown on the bottom panel of Figure 3 on SURPACT-S), the two  
289 SURPACTs show similar evolution of T and S. However, whereas T and S continue to drop  
290 on SURPACT-N towards event B at 14:11 GMT, they remain much higher on SURPACT-S.  
291 After event B, there is a large regular increase in salinity observed by SURPACT-N, whereas  
292 SURPACT-S salinity shows a plateau, followed by a large decrease reached at 15:07 GMT  
293 (event C). At 15:05 GMT, high-frequency wave spectral energy (and hence likely wind

294 speed) is slightly larger on SURPACT-N compared to SURPACT-S, which might have  
295 contributed to the relative difference in salinity tendency between the two floats. This salinity  
296 difference could also be attributed to advection of the fresher surface water flushing past  
297 drifter SURPACT-S (the drogue extends deeper than the fresh layer). This suggests that  
298 advection of freshwater past the buoy might have also happened earlier during the rain event,  
299 which could have contributed to the lack of strong relation between salinity changes and the  
300 fast rainfall and wind changes. Both SURPACTs then record T and S increases as the wind  
301 intensifies after 15:10 GMT, mixing away the freshwater deposited by the rain. T and S both  
302 continued to increase after 15:30 GMT (not shown).

303 During the 30 to 40 minute period with rainfall, there is no close correspondence between the  
304 fluctuations of rainfall or wind with the changes in T or S. However, for drifter SURPACT-S,  
305 periods of slightly lower 0.75 s waves (i.e., wind) appear to coincide with minima in T and S  
306 (e.g., at 14:00, 14:15, 14:20 GMT). There is also a tendency for peaks in rainfall estimated  
307 from the sound record to precede or correspond to local minima in T and S (e.g., at 14:00,  
308 14:25 GMT). This relation between T and S and rainfall is also apparent in the SURPACT-N  
309 measurements. Following the rain, there are still large oscillations in T and S with periods as  
310 short as 5 minutes: for example, on SURPACT-S between 14:20 and 14:55 GMT (typical  
311 amplitude  $0.1^{\circ}\text{C}/0.7$  psu in T/S). These do not seem closely related to changes in wind waves.

312 As seen on Figure 3, the temperature and salinity records for a particular SURPACT are well  
313 correlated at all scales. This can be better visualized on a T-S diagram color-coded as a  
314 function of time (Fig. 4). The T- S data tend to be aligned at a given time, but with an increase  
315 in slope with time (notice also on fig. 4 how well correlated the changes in density are related  
316 at a given time to the changes in salinity). Until  $\sim 1$  hour after the rain starts, the slope of the  
317 diagram is on the order of  $1.5^{\circ}\text{C}/10$  psu. This ratio tends to slightly increase in time,  
318 particularly after the rain stops and later, when wind-induced mixing results in increasing T  
319 and S. This can be explained by the fact that due to the strong vertical stratification (cf density  
320 changes on Fig. 4), heat loss gets trapped in a shallow surface layer, even after the rain stops,  
321 resulting in a net decrease of T relative to changes in S (Reverdin et al., 2012; Bellenger et al.,  
322 2017). We hypothesize that this effect will be more pronounced in areas with stronger,  
323 shallower stratification.

324 There are also significant differences between the SSP T and S time series and that from the  
325 SURPACT. Starting around 14:33 GMT, there are large fluctuations in T and S from the SSP

326 not seen by either SURPACT (Figure 3). At this time, the SSP was being towed through a  
327 rain-formed fresh pool, though local rain rate measured at the ship was zero at that time,  
328 indicating that the rain had fallen earlier. It appears that these fluctuations indicate variability  
329 on scales of one hundred meters to a few hundred meters. At the top panel of Fig. 3, we  
330 identify and label four fluctuations seen both in T and S. Note that fluctuation 1 is fairly close  
331 to drifter S (1 km), but SSP measures 0.6°C and 5 psu smaller T and S than the SURPACT-S.  
332 When looking at a time zoom over the period with fluctuations, we more clearly identify the  
333 temporal structures (Fig. 5). Fluctuations 1, 2 and 3 have salinity drops of more than 2 psu,  
334 which last more than 90 seconds and thus are close to 200-m wide. Fluctuation 4, which also  
335 features salinity drops, presents similar amplitude but appears to be much narrower in time  
336 and space (~50-m wide). There is a tendency for the low T and low S periods to happen near  
337 lows in the wind, based on the high-frequency wind record of the ship's meteorological  
338 station (at least for fluctuations 1, 3 and 4, whereas 2 occurs between a low and a high of the  
339 wind speed). Fluctuation 1 is also associated with a weak local rain shower (0.03 cm of total  
340 rain), but this would cause a salinity drop at most of 0.2 psu at 5-cm depth: much smaller than  
341 the 2 psu drop observed. This suggests that the S fluctuation was influenced by nearby rainfall  
342 in addition to local rainfall.

### 343 3.3 Vertical stratification

344 Figure 5b,c show the T and S records at the different depths on the SSP keel in addition to the  
345 snake data. There is a very high correspondence between T and S at the different levels. These  
346 data indicate stratification trapped close to the surface, with little T or S changes observed at  
347 54 cm (except for small decreases observed near filament 1). Even at 23 cm depth, there are  
348 periods between fluctuations 1 and 3 when the fresh and cool signature of the filaments is not  
349 observed, indicating that the 23-cm depth sensor is below the near-surface stratification. In  
350 other words, stratification is trapped very near the surface at times, but slightly deeper at  
351 fluctuations 1 and 3. Starting at fluctuation 4, wind speed increases and S in the upper 15 cm  
352 becomes homogenous, forming in effect a very shallow mixed layer. This homogenous layer  
353 then mixes downwards to 23 cm by 14:54 GMT. Throughout the time series shown in Figure  
354 5, fluctuations are seen at small scales, most obvious in T (or S) at 12 cm between 14:33 and  
355 14:39, corresponding to a distance between successive local maxima and local minima on the  
356 order of 100 m. This length scale is suggestive of oscillatory behavior due to internal gravity  
357 waves. Internal wave-like features have been previously observed in stratified near-surface  
358 open ocean conditions (Hodges and Fratantoni, 2017; Asher et al., 2019). It is tempting to



359 associate those spatial oscillations to the T and S time variability (at 5-minutes period)  
360 observed on SURPACT- S, which was then less than 1 km from the SSP to its north-  
361 northwest. This will be further discussed in the discussion section. On the other hand, we do  
362 not observe such intense fast oscillations in T and S on the SSP during the rain period (e.g.,  
363 13:50 to 14:30 GMT) at 12-cm depth or deeper (not shown).

364 We will now investigate the freshwater and heat content changes (we take a constant heat  
365 capacity so that heat content is being proportional to temperature content with an error of less  
366 than 2% in this salinity range). The freshwater content is expressed as the height of excess  
367 freshwater (precipitation minus evaporation; however, evaporation over these timescales is  
368 very small) that results in the observed salinity decrease with respect to conditions before the  
369 rain, taking into account the small change in seawater density. Profiles of the salinity and  
370 temperature anomaly are defined by subtracting the T and S measured at 13:45 GMT, which  
371 occurred during the initial unstratified period.

372 The anomaly profiles are constructed from the discrete measurements by assuming that the  
373 vertical profile varies linearly between successive instrumented depths, until we reach an  
374 instrumented depth ( $z_i$ ) with no anomaly. In that case, we first extrapolate linearly the vertical  
375 gradient between the previous pair of instrumented depths ( $z_{i-2}$  and  $z_{i-1}$ ) until T/S reaches the  
376 initial value (no anomaly) found at a depth  $z_0$ . If  $z_0$  is shallower than  $z_i$ , we adopt that linear  
377 profile with no anomaly below  $z_0$ , whereas if  $z_0$  is deeper than  $z_i$ , we adopt a steeper linear  
378 profile between instrumented depths  $z_{i-1}$  and  $z_i$ . If there is still freshening/cooling at the  
379 deepest instrumented level, we extend the profile deeper by extrapolating the gradient above it  
380 and down to the level of zero anomaly. A running average over 1 minute is then performed on  
381 the temperature and salinity anomaly time series at each depth. We assume that T and S are  
382 well mixed above the uppermost measurement at 5-cm depth, which is supported by  
383 laboratory measurements (Ho et al., 2004; Zappa et al., 2009) showing that rain drops mix the  
384 upper 5-10 cm of the water column. We also neglect the effect of anomalies in the surface  
385 skin layer of thickness of a few mm (Yu, 2010; Wurl et al., 2018).

386 The interpolated anomaly profiles are constructed separately for both the drifter data and the  
387 SSP data. For the drifters, we combine the 5-cm data from the SURPACTs with the  
388 temperature data at 18 cm and 36 cm from the SC40 drifter. We assume a linear relationship  
389 between T and S and extrapolate temperature to estimate a salinity profile (starting from the  
390 observed surface salinity value) every 5 minutes. There is no well-defined model of the

391 vertical salinity profile within a fresh layer; however, comparisons with the SSP data at 5, 12,  
392 and 23 cm suggest that the error caused by interpolating linearly between 5 cm and 18 cm on  
393 the drifters is likely small. The interpolation between the 23 and 54 cm depth SSP  
394 measurements, and below 36 cm on the drifters, is much less certain, so we assume a 20%  
395 uncertainty in the vertically integrated temperature and salinity anomaly.

396 A ratio, referred to as a penetration depth proxy, is defined as the depth-integrated salinity or  
397 temperature anomaly normalized by the surface anomaly. It is a proxy for the depth of the  
398 fresh surface layer: larger ratios indicate that the rainwater penetrated deeper into the water  
399 column. However, due to the relatively coarse vertical sampling and lack of deeper  
400 measurements, more refined estimates of the exact thickness and depth of the fresh layer are  
401 not possible. We first comment on the penetration scale proxy before presenting the  
402 freshwater anomalies and commenting on the heat content anomalies.

403 As the penetration scale proxies derived from the temperature and salinity data are very  
404 similar, we will only comment on the salinity penetration scale proxy. First, we notice, in a  
405 similar way as for surface records, more variability in the penetration scale proxy with the  
406 SSP than with the surface SURPACT records (Fig. 6a). On the other hand, we find rather  
407 similar-looking penetration scale proxies for the two SURPACT records, despite very  
408 different surface variations. For the drifters and for the SSP, there is an initial gradual increase  
409 of the penetration depth proxy during the rain, indicating that the fresh layer thickens with  
410 time. This trend is consistent with the initial time at which freshening and cooling starts at  
411 different levels. For example, the drifters show freshening/cooling at 5 cm at 13:50 GMT as  
412 soon as the rain starts (Fig. 6), then at 18 cm around 13:55 GMT, and after 14:00 GMT at 36  
413 cm (not shown). Similarly, the SSP shows freshening at 5 cm that is well correlated with an  
414 increase in penetration scale proxy.

415 The immediate response to rain at the top level on the SSP and SURPACT is consistent with  
416 rain drops penetrating at least to 5 cm. The lack of immediate response at 12 cm (SSP) or 18  
417 cm (drifter) (not shown) indicates that water from the rain drops does not immediately  
418 penetrate to 12 cm. The progressive vertical penetration of the freshening/cold signal from the  
419 rain is thus probably a result of vertical mixing induced by the heavy rain rate and the  
420 associated input in the ocean of momentum in vertical and horizontal direction, the latter of  
421 which contributes to vertical shear of the horizontal ocean current. For the SURPACTs, the

422 increase in penetration depth proxy lasts until 14:15 GMT (after event B on SURPACT-N;  
423 Figure 3), when it exceeds 30 cm (a little larger for SURPACT-S than for SURPACT-N).

424 There is then little change in the proxy until the rain stops, followed by a gradual decrease of  
425 the penetration scale proxy to <20 cm at 15:10 GMT (larger decrease for SURPACT-S than  
426 for SURPACT-N). The similarity of the decrease in penetration depth proxy between 14:30  
427 and 15:10 GMT for the two SURPACTS, and the progressive disappearance of the freshening  
428 signal at 36 cm during that period (not shown), is suggestive either of relative advection of the  
429 initial fresh pool past the drifters or of horizontal divergence in the fresh pool layer causing a  
430 vertical thinning of the fresh and cool layer. Notice, however, that the penetration depth proxy  
431 estimated by the SSP also thins after 14:30 GMT, when the SSP crosses fluctuation 1, and  
432 remains relatively small (~15 cm) until the wind speed intensifies at 14:50 GMT. On SSP, the  
433 penetration depth proxy for the period of the fluctuations (14:30 to 14:45 GMT) (top panel of  
434 Fig. 6) does not show much variability at the smaller 1-minute scale of the near-surface  
435 oscillations in T and S between 14:33 and 14:39 GMT. However, insufficient vertical  
436 resolution and uncertainties preclude interpreting the relationship between penetration depth  
437 proxy variability and variability in T or S.

438 After 15:15 GMT, the wind intensifies and penetration depth increases to >40 cm, likely due  
439 to wind-induced vertical mixing.

440 The freshwater content, as expected, shows an initial increase during the rain event, followed  
441 by a decrease starting at 14:15 GMT, with a stronger signal observed at drifter-N (Fig. 6b).  
442 For drifter-S, there is much less decrease in freshwater content following the initial increase,  
443 despite large changes in penetration depth proxy and surface salinity (Fig. 6a). Maximum  
444 values of freshwater content exceed 4 cm for the two SURPACTs and the SSP. For the SSP,  
445 freshwater content exceeds 4 cm only briefly, during the crossing of filament 1. Maxima in  
446 freshwater content are observed on drifter-N and drifter-S at the end of the heavy rain, with  
447 values of 8.3 and 4.5 cm, respectively. These maxima do not coincide with the lowest salinity,  
448 which happens ~5-10 minutes earlier (Fig. 6a).

449 It is interesting to compare these freshwater content estimates with gridded radar rain rates  
450 estimated every five minutes and the rain rates we calculated along the SURPACT trajectories  
451 (Fig. 6c). For both drifters, this radar estimate of total rain accumulation is on the order of 5  
452 cm. This has a similar magnitude to the observed total freshwater input estimated from the  
453 drifters (evaporation effects can be neglected on these times scales). In comparison, the rain

454 measured on the ship only integrates to 1.3 cm. Though flow distortion could be an issue, this  
455 value is significantly lower than the 5 cm observed very nearby by the ship's radar. The 1.3  
456 cm rain accumulation value measured by the ship gauge is close to the lower bound of the  
457 freshwater content observed with salinity by the SSP (~2 cm), but less than the peak values of  
458 freshwater content observed with salinity by the SSP (Figure 6b).

459 We will now comment on the near-surface heat content changes measured by the drifters and  
460 the SSP (Fig. 7). We first estimate the contribution to the heat content changes of the 'no-rain  
461 surface heat flux', which is the net surface heat flux but without the contribution of cooling  
462 caused by the input in the surface layer of the colder rain drops. We assume that the average  
463 flux experienced by the drifters is the one estimated at the ship. Until 14:30 GMT, the 'no-  
464 rain surface heat flux' contributes little to the upper ocean heat content change (which reaches  
465  $-0.2^{\circ}\text{C}\cdot\text{m}$ ), and most of the observed heat content drop measured with the SURPACTs (or the  
466 SSP) is not explained by them. The most likely candidate for the difference between heat  
467 content change and the 'no-rain surface heat flux' is the contribution of the cooling effect of  
468 rain drops mixing into the upper ocean. We use the estimated change in freshwater content to  
469 estimate the raindrop temperature that would explain the part of the heat content change not  
470 explained by the 'no-rain surface heat flux'. This yields a raindrop temperature on the order of  
471  $24^{\circ}\text{C}$  (Fig. 7): given the 10-m air temperature on the order of  $25^{\circ}\text{C}$  at 95% saturation  
472 observed from R/V Revelle during the rain, this value of raindrop temperature is low but in  
473 the possible range (Gosnell et al., 1995).

474 The change in heat content observed after the end of the rain has to be related to either heat  
475 fluxes or relative advection. As the heat content coherently co-varies with freshwater content,  
476 and based on the small heat fluxes estimated from R/V Revelle and the relatively small  
477 changes in the T-S diagram (Fig. 4), it is likely that a large contribution to the observed  
478 changes in heat content after the rain originates from relative advection of the surface water  
479 with respect to the drifting platforms during that period. At 15:10 GMT, when the wind  
480 increases, vertical mixing with the warmer deeper water becomes a dominant contribution to  
481 the increase in heat content near the surface.

482

#### 4834. Discussion

484 The radar data suggest that ~5 cm of rain fell near the center of the surveyed area over about  
485 90 min in a location where the SURPACTs drifted (Fig. 8). This series of events is also

486 shown by observed temperature and salinity records (Fig. 6). Surprisingly, in situ sensors  
487 located on the R/V Revelle only measured 1.3 cm of rain accumulation despite being less than  
488 2 km away from the drifters during the rain event (Fig. 6c). There are also very large  
489 differences in T and S between the two drifters, which were roughly 400 m apart, both during  
490 the last 30 minutes of rainfall (after event A) and during the 40 minutes afterwards (Fig. 3).  
491 SSP data from the R/V Revelle also show large spatial variability, suggesting filaments and  
492 inhomogeneities on scales of a hundred to a few hundred meters during the period with low  
493 wind that follows the rain events. Thus, we have two sets of questions to address:

494. How does rain and/or wind heterogeneity at those short time and space scales contribute to  
495 the spatial heterogeneity in the ocean?

496. What is the contribution of oceanic processes involved in the spreading or mixing of the  
497 surface freshwater pool?

498 We will first discuss (1). Because of the lack of data concerning spatial heterogeneity of the  
499 wind over the study area, it is difficult to assess this aspect. However, we hypothesize that  
500 wind variability likely happens at the scales involved with the heterogeneity of rain events,  
501 both in time and space. We thus only assess the impact of rain variability on ocean salinity.  
502 To examine this, we consider the SEA-POL radar rain data during the approximately 90  
503 minutes when rain cells were in the study area (the higher-resolution X-band rain retrievals  
504 were not available during this survey). The SEA-POL rain rate product is calculated on a 1-  
505 km grid, and shows intense isolated rain events happening on just one grid box (including a  
506 grid box located over the drifters). In addition, the radar samples for two minutes every five  
507 minutes, introducing uncertainties in local integrated rain amounts due to the intermittency of  
508 rainfall that is witnessed in the rainfall estimates from the sound records of the two  
509 SURPACTs. There is thus likely significant sub-grid variability in the rain field not captured  
510 by the SEA-POL dataset, even though radar-to-rain gauge comparisons show that the radar  
511 estimates are still very accurate over relatively short (minutes to hours) time scales and small  
512 spatial scales of a kilometer. For instance, when rain accumulation is integrated over the  
513 whole duration of the rain events, rain accumulation from SEA-POL data showed a similar  
514 magnitude as that estimated from the salinity records of the drifters (5 cm; Fig. 6); thus some  
515 of these resolution/sampling caveats might compensate when cumulated over time.

516

517 The integrated effect of the rain heterogeneity is illustrated by integrating rainfall on  
518 simulated particle trajectories (all having the horizontal velocity of the deployed drifters).  
519 1000 simulated particles were released at 13:40 GMT in a 10-km x 10-km square box  
520 centered on the circle sampled by R/V Revelle. This is used in order to develop a statistical  
521 characterization, but does not take into account the likely spreading of particle trajectories.  
522 Because the ship superstructure prevents SEA-POL from measuring rain aft of the ship, some  
523 regions with rain over the particles are not seen by the radar part of the time. Thus, the overall  
524 statistics are skewed towards lower accumulated rain (Fig. 8). On the other hand, when  
525 selecting areas which were covered at least 75% of the time by the radar, we get an almost  
526 Gaussian distribution of rain accumulation centered near 2.5 cm, and no rain amount larger  
527 than 6 cm.

528 The time distribution is rather similar whether we use all simulated particles or only the ones  
529 with 75% time coverage, and peaks near 14:00 GMT, a little earlier than what was observed  
530 with the two real drifters and the R/V Revelle. This slightly earlier peak in rain observed with  
531 the radar is because regions towards the southern/ southeastern part of the domain  
532 experienced rainfall earlier than at the ship's location (Fig. 8). The distribution of rainfall  
533 suggests that it rained in a large part of the domain, even though individual rain cells were  
534 very small (a few kilometers across). Within the region measured by the radar more than 75%  
535 of the time, there is a clear structure, with heavier rainfall near the 'real' drifters and in the  
536 southeast quadrant of the circle, with 1-3 km wide patches of heavy rainfall amounts. The plot  
537 with all simulated drifters suggests that there was at least another area with large total rainfall  
538 amount in the southwest, but we cannot assess the accuracy of these rain rates because of  
539 insufficient temporal sampling in the radar dataset.

540 (2) We will now discuss the contribution of oceanic processes to the fresh pools spreading  
541 and mixing. The large changes in T and S observed by the drifters (in particular drifter S)  
542 after the end of the rain between 14:30 and 15:20 GMT are likely not induced solely by  
543 vertical mixing from wind input, as indicated by the shallowing of the penetration depth of the  
544 temperature and salinity anomalies (Fig. 6a). This lack of vertical mixing is also supported by  
545 the lack of cooling/freshening at the deepest levels of the SSP before the wind picks up at  
546 14:50 GMT along the R/V Revelle track.

547 Thus, the large T and S changes seen by the drifters until the wind picks up are likely  
548 associated with horizontal advection of surface waters relative to the drifters. As noted earlier,

549 the drogue depth and the drifting characteristics of the drifters are probably more  
550 characteristic of the drift below 25 cm depth than above, and thus do not properly track the  
551 flow in the top freshest layer, which is confined to the upper 25 cm.

552 There are multiple factors which would explain why the seawater velocity would be different  
553 in this top layer. First, raindrops deposit horizontal momentum in this layer. During the rain  
554 event, the horizontal wind and thus the drops' horizontal momentum could easily be on the  
555 order of 1 m/s or more. For 5 cm of total rainfall, drops having this momentum deposited into  
556 a 25-cm penetration depth would generate a 20 cm/s current in the upper 25 cm. In an hour,  
557 this would induce more than 700 m of displacement of the freshwater lens relative to the  
558 drifters, which might be around half the scale of the rain cells. In addition, the spatial  
559 heterogeneity of rainfall (Fig. 8) can induce large horizontal gradients in surface density, and  
560 thus in pressure with its associated horizontal acceleration  $[-1/\rho \text{ grad}(P)]$  after the fast, but  
561 very small barotropic dynamic adjustment. Assuming a 3-cm gradient of rain accumulation  
562 over a 1-km horizontal scale, as seems possible from Figure 8 is associated with an  
563 acceleration of  $10^{-5} \text{ m s}^{-2}$ . Horizontal surface convergence/divergence induced by the spatial  
564 heterogeneity in the momentum input of rain and wind in the stratified surface layer will also  
565 generate horizontal pressure gradients.

566 In linear theory, the surface-trapped pressure gradients will generate surface-trapped gravity  
567 waves in this highly stratified surface layer at periods set by the spatial and temporal scales of  
568 the forcing, as well as their dispersion relation (internal gravity wave period cut off is at a  
569 period of 30-s or less). The 5-cm total rain amount at the drifter site produces a relative  
570 density anomaly of  $7.0 \times 10^{-3} \text{ kg m}^{-3}$  over 25 cm, which corresponds to phase speeds on the  
571 order of 10-15 cm/s. Surface gravitational currents generated by the density gradients, as well  
572 as the sheared background currents and the currents associated with large amplitude internal  
573 waves have similar magnitude to this phase speed, thus non-linear effects are expected to be  
574 large (Soloviev et al., 2002, 2015), and fronts could form. Nonetheless, oscillations in surface  
575 currents at periods of a few minutes and longer are also likely to be associated with internal  
576 waves, both as the boundary of the fresh pool evolves and due to the observed intermittency  
577 of the rain and hence the momentum input. Initially, these oscillatory horizontal surface  
578 currents will be surface-trapped.

579 The oscillations in surface salinity over time that were observed for SURPACT-S during the  
580 half hour following the rain and preceding the period of minimum surface salinity (Fig. 3)

581 might result from relative horizontal advection by these internal wave currents in the presence  
582 of large horizontal gradients of surface salinity. Similar waves are also likely to have been  
583 crossed by the SSP towed by the R/V Revelle (14:33 to 14:39 GMT) (Fig. 4), which was  
584 spatially rather close to SURPACT-S (less than 1-km). As we do not know the directional  
585 propagation speed of the waves at SURPACT-S and cannot fully assess whether it is the same  
586 wave packet crossed by the SSP, as the distance to SURPACT-S could be a large multiple of  
587 the wave length, it is not possible to directly assess the directional wave propagation speed,  
588 and how they affect the fluctuations that were seen on the SSP records. The structures are not  
589 stationary during the SSP survey, which could result in distortion of the wave pattern, but by  
590 less than 10% with the expected internal wave speeds of 10-15 cm/s. Interestingly, on SSP,  
591 the oscillations are witnessed after crossing the pool with lowest salinity (event 1) in the  
592 south-east part of the survey, whereas on SURPACT-S they are seen as S decreases, maybe  
593 on the eastern front of the freshest water which was initially probably to its north based on  
594 SURPACT-N record. On the other hand, the very fresh water of SSP event (1) is to the south-  
595 east of SURPACT-S. This suggests either multiple fresh pools, or the possibility that the fresh  
596 water pool fronts might have started to be associated with filaments, which are crossed in  
597 different instances by the SSP (events (1) to (4), for example).

598 Currents associated with the gravity waves, the displacements of the fresh water pool fronts  
599 and its filaments will result in spreading the fresh/cool pool: typically by ~400 m over an  
600 hour, based on the density anomaly and linear wave theory. Such spreading is associated with  
601 a shallowing of the pool: for an initial fresh pool 1- km wide, the shallowing is by a factor of  
602 two in 1 hour. This is not far to what we observe on the two drifters, before wind-induced  
603 mixing sets in (Fig. 6a). Obviously, however, because of the heterogeneity of rainfall  
604 conditions in this surveyed area, we would need much more in situ estimates to be able to  
605 quantify precisely the spreading rate. Also, it is possible that some mixing happens near the  
606 density fronts, in particular if the weak winds opposed its propagation resulting in density  
607 overturns (Soloviev et al., 2002).

## 6085. Conclusions

609 The area surveyed on November 9 during the 2017 SPURS-2 cruise on R/V Revelle in the  
610 equatorial Pacific was less than 10 km<sup>2</sup>. This survey, which was characterized by intense rain  
611 events over 90 minutes, experienced huge spatial and temporal variability in its surface  
612 temperature and salinity during the rainfall periods and also for more than 30 minutes



613 afterwards. During that period, spatial heterogeneity in salinity appeared to reach more than 5  
614 psu, although the sampling in only three places makes it difficult to quantify the magnitude  
615 and spatial scales of the variability. Even at locations separated by only 400 m, surface  
616 salinity presented very different time evolution, with differences between sampling points  
617 often exceeding 4 psu, even more than 30 min following the rainfall. The weak wind  
618 conditions and highly heterogeneous and intermittent rain events witnessed are key elements  
619 in generating this strong surface salinity variability. Interestingly, point-measuring  
620 precipitation gauges mounted on the R/V Revelle measured only a total of 1.3 cm of rain, but  
621 the integrated freshwater measured by the SSP suggested that the survey crossed areas which  
622 had experienced more than 3 cm of rain. Similarly, the integrated freshwater measured with  
623 the drifters suggested that more than 5 cm of rain fell, a large variability over a scale of a few  
624 kms. A particularly unusual characteristic of this event is that the fresh pool thinned vertically  
625 after the end of the rain, which may have been related to its horizontal spreading, a result of  
626 ocean dynamics. The thinning suggests a very small contribution of vertical diffusion (which  
627 tends to thicken rain layers), consistent with the weak winds. We also suggest that horizontal  
628 advection of the surface fresh pools relative to slightly deeper waters, and ocean dynamics  
629 (internal waves, fronts, filaments) associated with the fresh pools have largely modified the  
630 spatial distribution of fresh water and contributed to the evolution of surface salinity in the  
631 hour following the rain when wind was still weak.

632 This survey did not resolve all the relevant spatial scales of the strong variability. For rainfall,  
633 this is the case both in time (rainfall intermittency happens at timescales of hundreds of  
634 seconds) and in space (rainfall appears to vary on scales smaller than 1 km). The SEA-POL  
635 radar data provide broad spatial coverage, but the rain rate estimates are averaged over 2  
636 minutes every 5 minutes so it is not possible to observe the intermittency at timescales shorter  
637 than a few minutes. We also cannot fully separate surface T and S variability that is locally  
638 forced by variability in rainfall from that which is due to ocean dynamics. For example, the  
639 large difference in maximum freshwater content and minimum surface salinity between  
640 drifters SURPACT-N and SURPACT-S (Fig. 6b) may be related to differences in rainfall, to  
641 subtle differences in the momentum input from the rain and wind, or to the inhomogeneity of  
642 the spreading of the fresh pools. The latter effects could have induced a local convergence at  
643 SURPACT-N of the freshwater, which probably would also reduce the vertical mixing. The  
644 surveys also suggest that internal gravity waves or other ocean dynamics with periods on the

645 order of 5 minutes or less may induce large T/S surface variability, as well as fronts and  
646 filaments associated with the rain-induced fresh pools. This is a topic for further research.

647 This strong variability limits our ability to accurately determine the relation between local  
648 observations of T and S near the surface and local wind and rain conditions in such extreme  
649 events, whether they are sampled by drifters, sea snakes, or other surface devices (such as the  
650 probes at the bow of the ships used during COARE) (Boutin et al., 2016). Strong rain events  
651 such as observed here generating anomalies having almost 10 psu and 1.5°C maximum  
652 amplitudes, can be trapped so close to the surface that they would be missed by measurements  
653 made at depths of 1 m (and greater). This is significant when interpreting S/T data from  
654 platforms such as Argo floats, ship-mounted thermosalinographs, or even the salinity drifters  
655 that measure at ~40-50 cm depth (Reverdin et al., 2012 ; Centurioni et al., 2015; Dong et al.,  
656 2017; Volkov et al., 2019). On the other hand, the rain-generated cooling would be sensed by  
657 the hull temperature sensor at 18 cm depth on SVP drifters.

658 How common are decreases in SST and SSS close to 1.5°C and 10 psu such as we found? We  
659 are anecdotally aware of two other documented (though not published) occurrences of very  
660 large SST and SSS decreases, one during the SPURS-2 cruise in 2016 and one from a drifter  
661 of the same type as used here (but drogued at 15 m) in the tropical Atlantic ITCZ region. Such  
662 strong surface cooling and freshening requires very low winds during rain to minimize  
663 vertical mixing induced by the wind stress and momentum input by the drops (Asher et al.,  
664 2014). These conditions are uncommon, as intense tropical convection is often associated  
665 with downdrafts reaching the surface under or near the rain cells. However, the ITCZ is  
666 known to be a weak wind area due to horizontal convergence of the trade winds. What is  
667 special in the observations of this paper is the relatively long duration of the period of very  
668 weak winds, which lasted at the drifters over forty minutes after the end of the rain. These  
669 low-wind conditions are very common in the ITCZ, hence why they are referred to as the  
670 Doldrums.

671 Even if such low-wind rain events are not frequent (a tail in the distribution of rain events),  
672 they could have an impact in the overall oceanic freshwater budget: a missed surface  
673 freshwater component in budgets based on in situ measurements collected most of the time at  
674 1 m or more (for example, Yu, 2011). In rainy regions, such as near the ITCZ, one could also  
675 expect that strong rain events with weak winds will modify the relationship derived from  
676 satellite data between rain rate and SSS changes at scales typically of 50 km or more (Supply

677 et al., 2018, 2019). In such regions, it could also impact the overall satellite reconstruction of  
678 SST, as SST is not measured in or near areas of intense rain. This particular event has also  
679 been shown to strongly influence surface pCO<sub>2</sub> and air-sea gas exchange (D. Ho, pers. Comm.  
680 2018). From an atmospheric point of view, it would be interesting to better understand the  
681 atmospheric dynamical context in which such rain cells develop, and whether there is some  
682 local feedback from the cold pool formed by the rain deposition on the organization of the  
683 rain cells.

684

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692 POL radar and data analysis was provided by S. A. Rutledge at Colorado State University.  
693 The data are archived on NASA PO.DDAC as part of the SPURS-2 dataset, and will soon be  
694 all accessible there. The SSP data are at <http://dx.doi.org/10.5067/SPURS2-SSP00> and the  
695 ship's meteorological data are at <http://dx.doi.org/10.5067/SPURS2-MET00>. Advice and  
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820 Figure captions

821 Figure 1: Track of R/V Revelle (red) and of the towed SSP (color-coded with measured SSS)  
822 during the survey on November 9 as well as the tracks of the two drifters (also color-coded  
823 for SSS from their deployment at 13:30 until 15:30 GMT; drifters moving towards the  
824 east/south-east). Key events are mentioned on the R/V Revelle track. Step 1 corresponds to  
825 the first big rain events in the center of the domain; step 2 with the time of maximum rainfall;  
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829 on figure)

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833 Figure 3: Time series of upper level (at 5 cm for SSP and for the drifters) T (green) and S(red)  
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835 (N) and (S) (3b, 3c). For the drifters, “rain rate” is an unscaled indicator based on the  
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843

844 Figure 4: SST-SSS scatter diagram from the two drifters with overlaid density contours  
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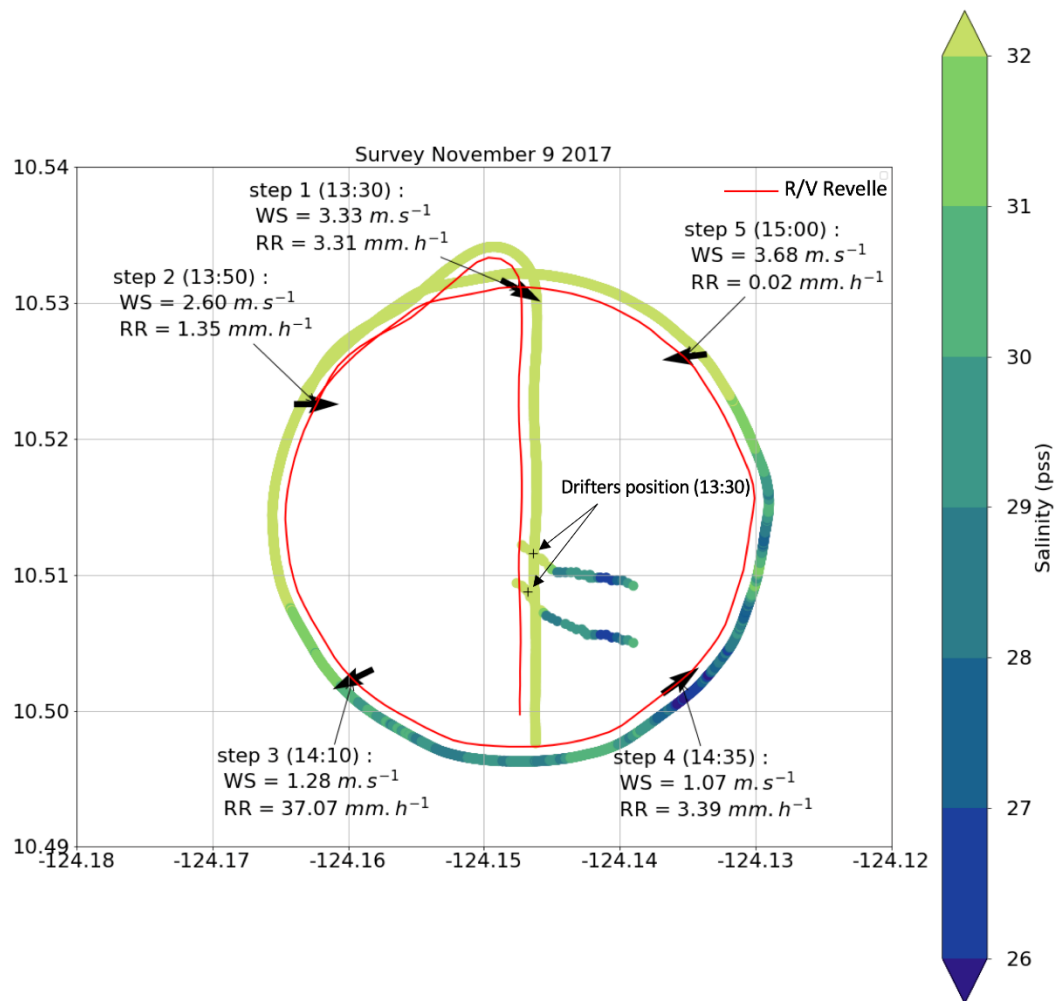
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862 Figure 7: Vertically integrated temperature anomaly budget at SURPACT-S. The heat content  
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867 Figure 8: Statistics of rainfall at 1000 virtual drifters in a 10-km x 10-km square box. The  
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870 averaged positions; black line indicates the track of R/V Revelle during this time period,;  
871 magenta and red lines the trajectories of the two drifters; Top, right) accumulated rainfall only  
872 for the 368 virtual drifters for which the SEA-POL radar provides rain rate information more  
873 than 75% of the time; Bottom, left) Averaged time series of rain rate measured by virtual  
874 drifters (blue, all drifters; orange, drifters with more than 75% of time coverage by the radar);  
875 Bottom, right) histogram of accumulated rainfall among all the drifters (blue) and among the  
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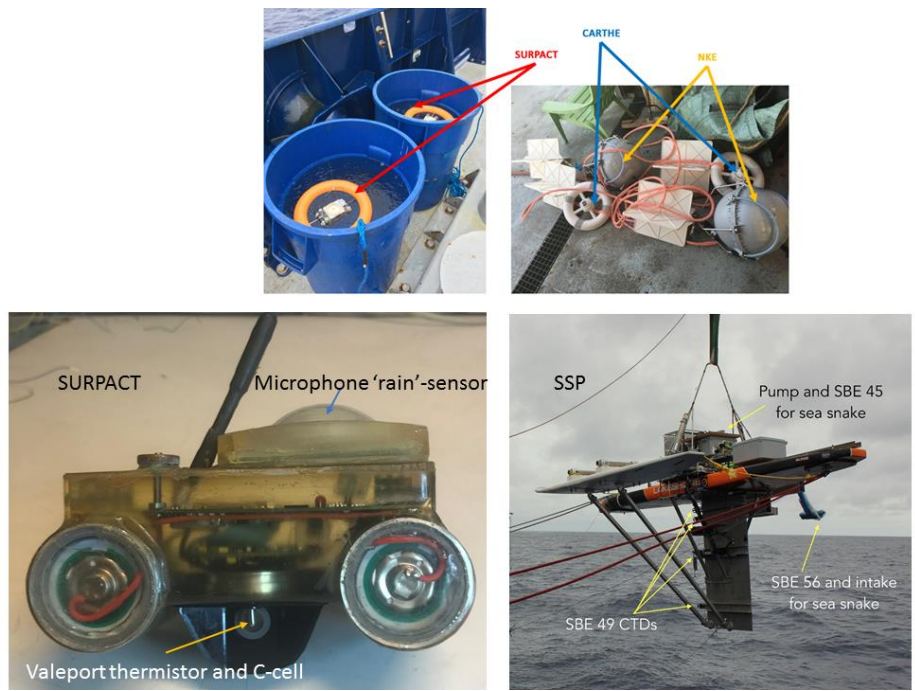
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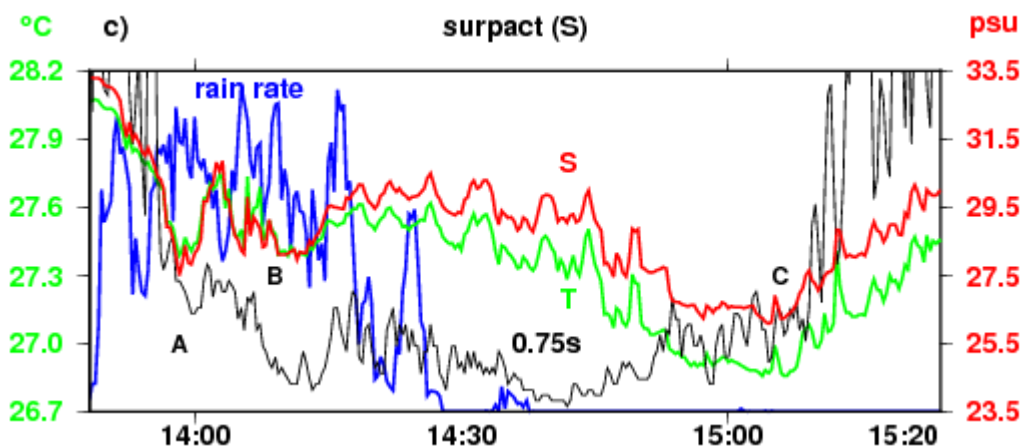
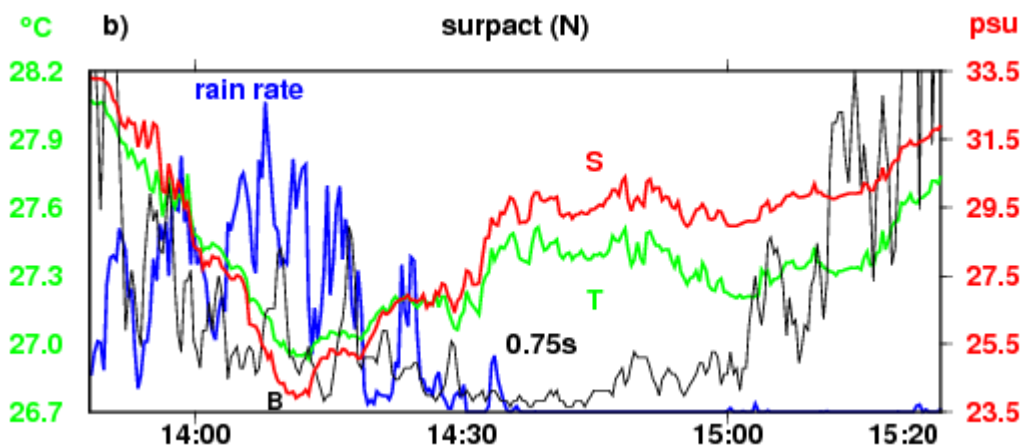
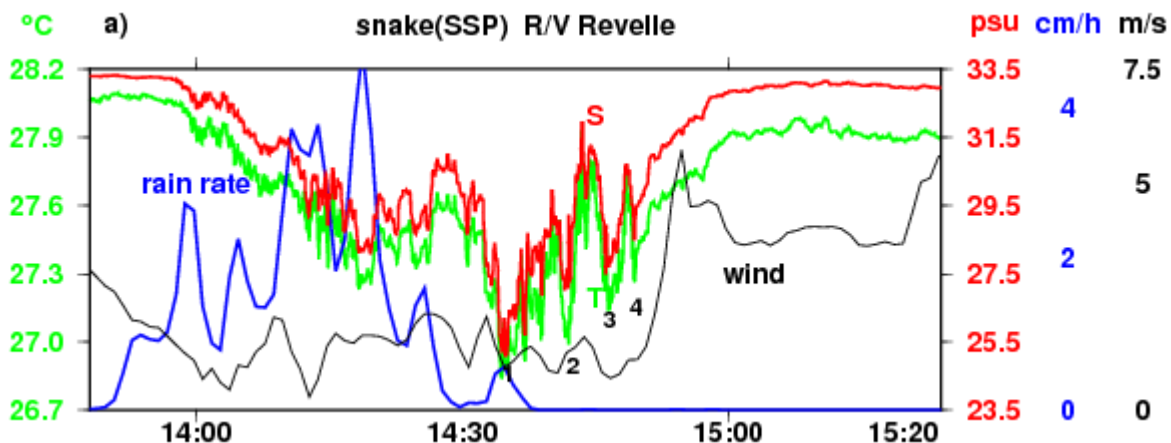
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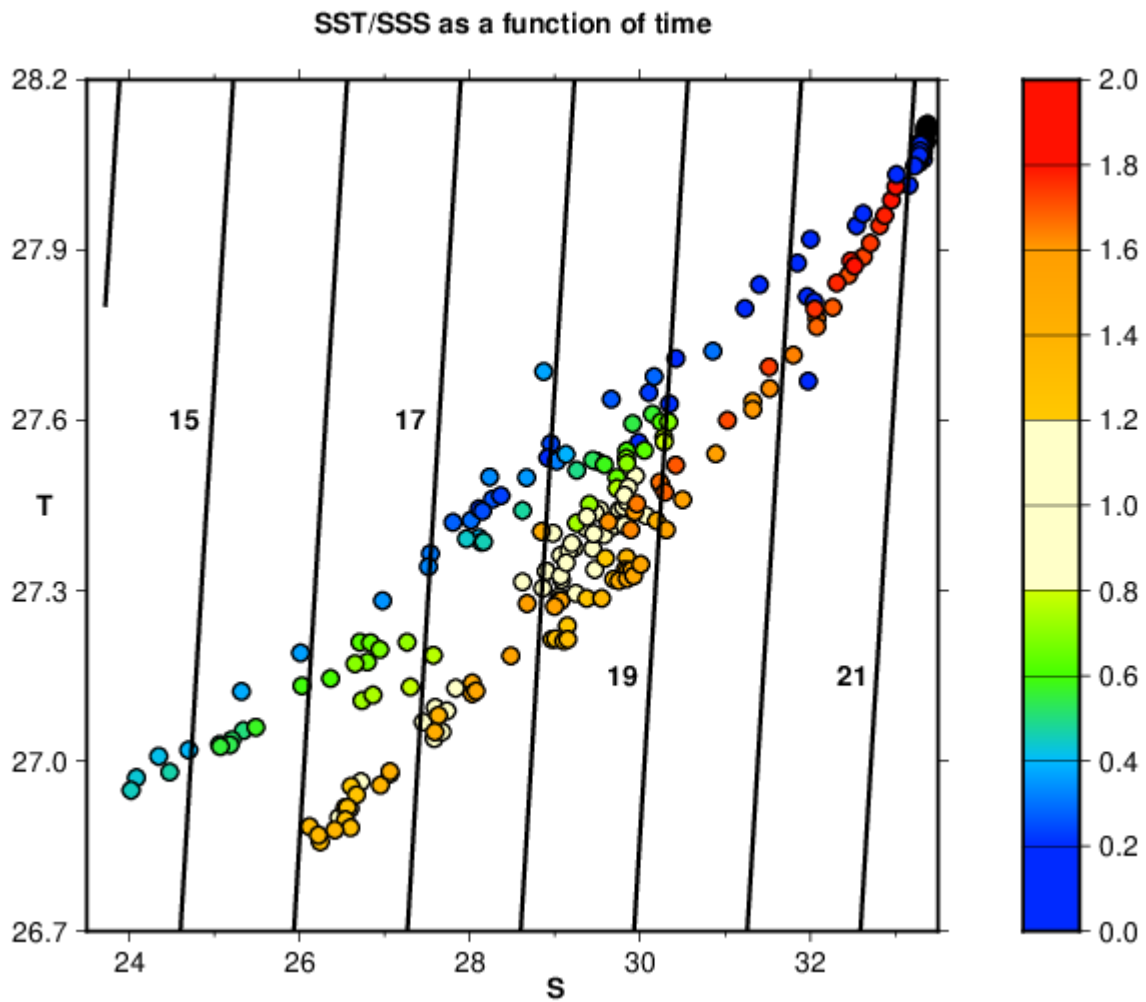
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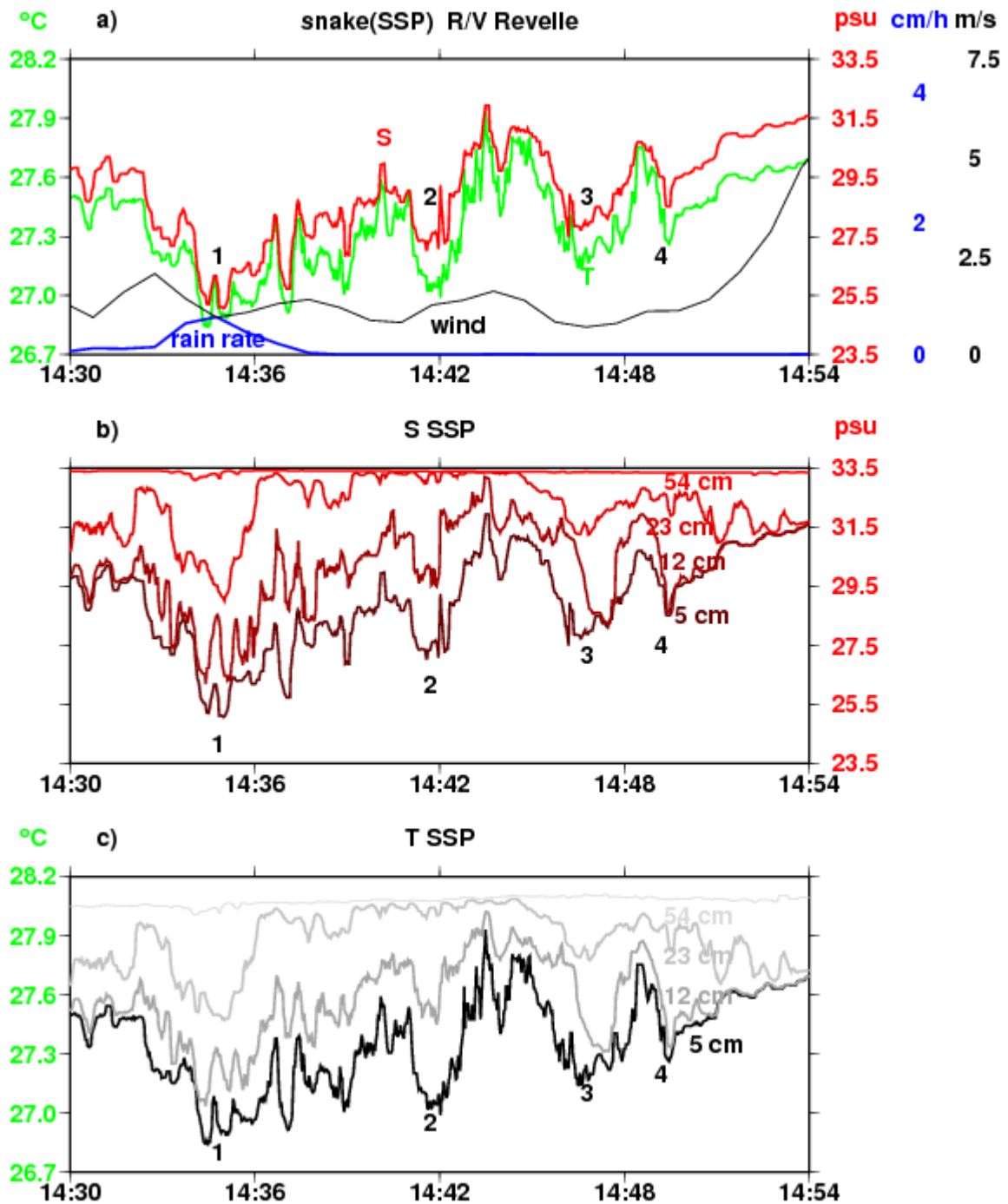
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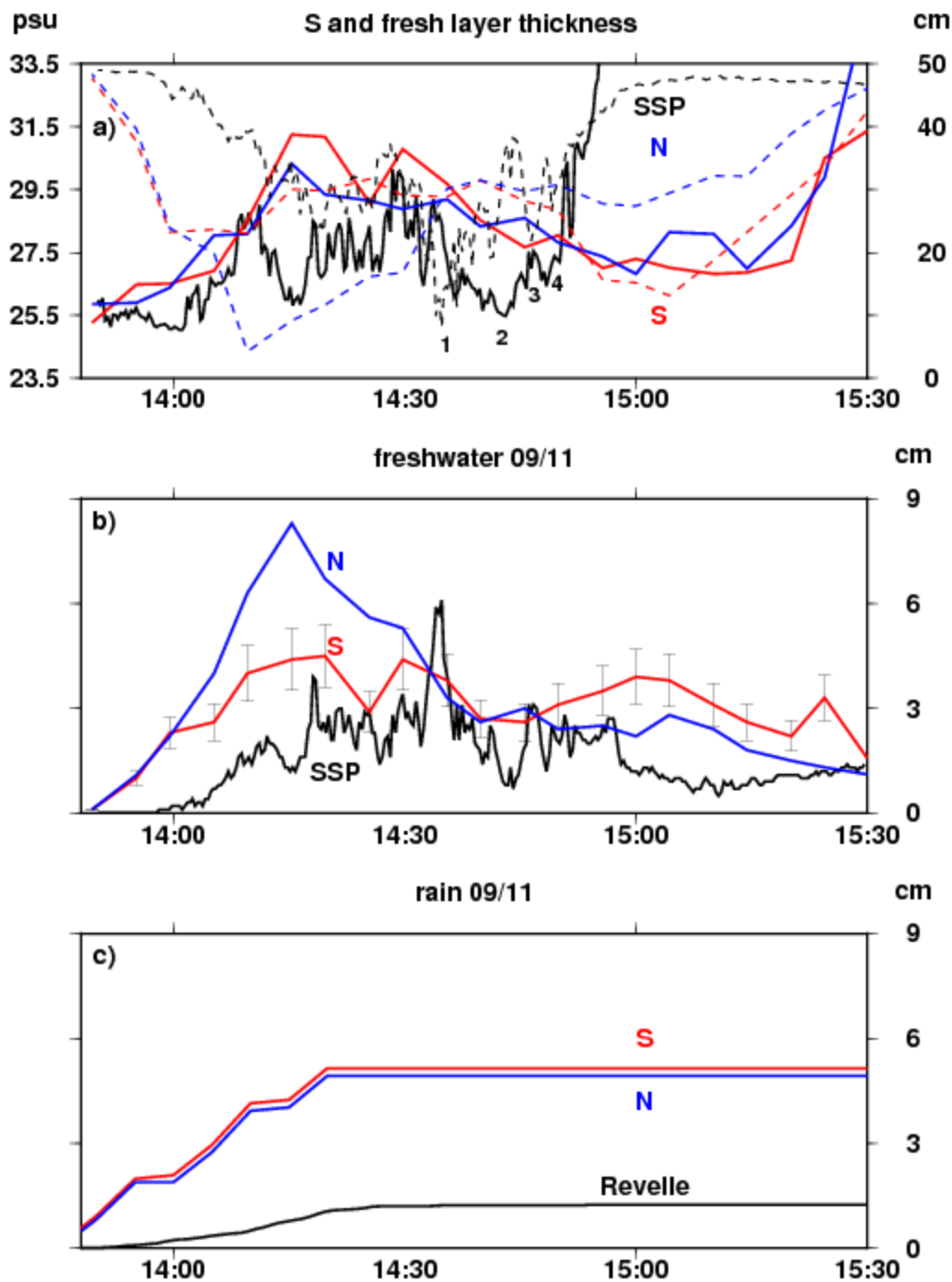
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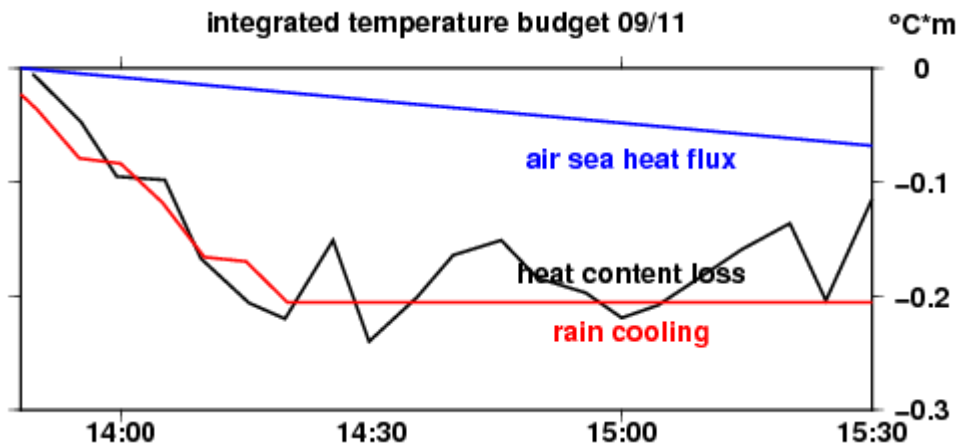


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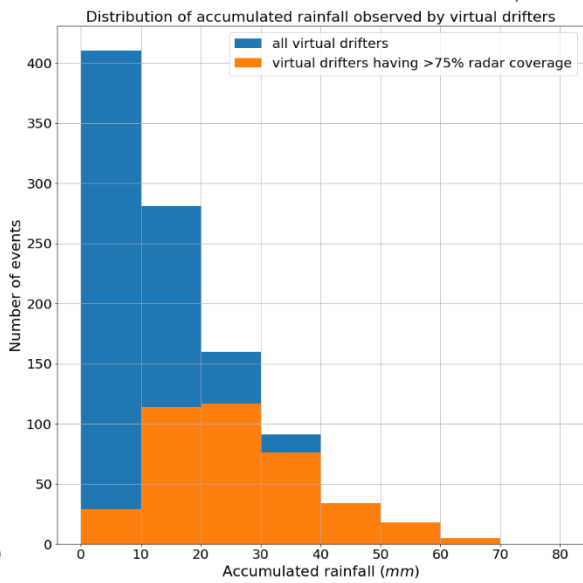
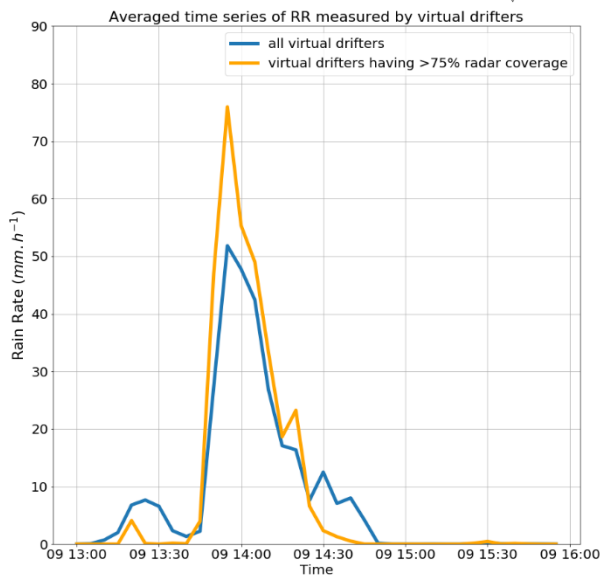
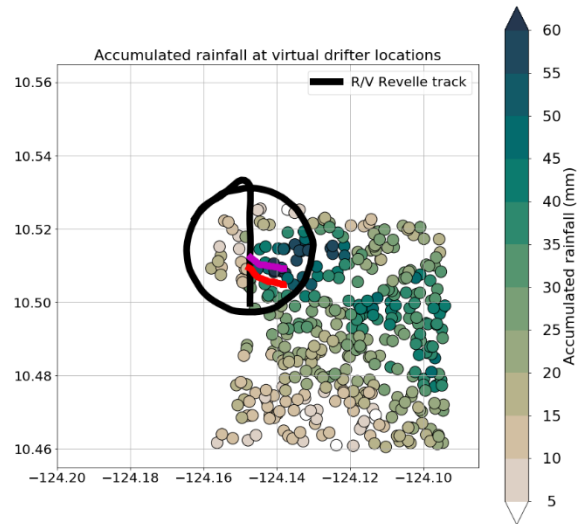
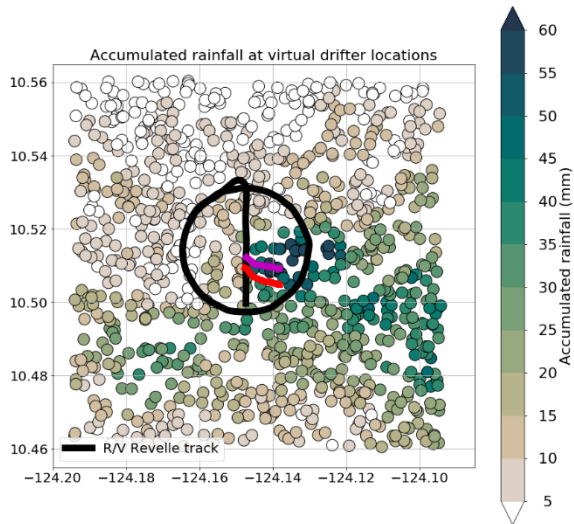


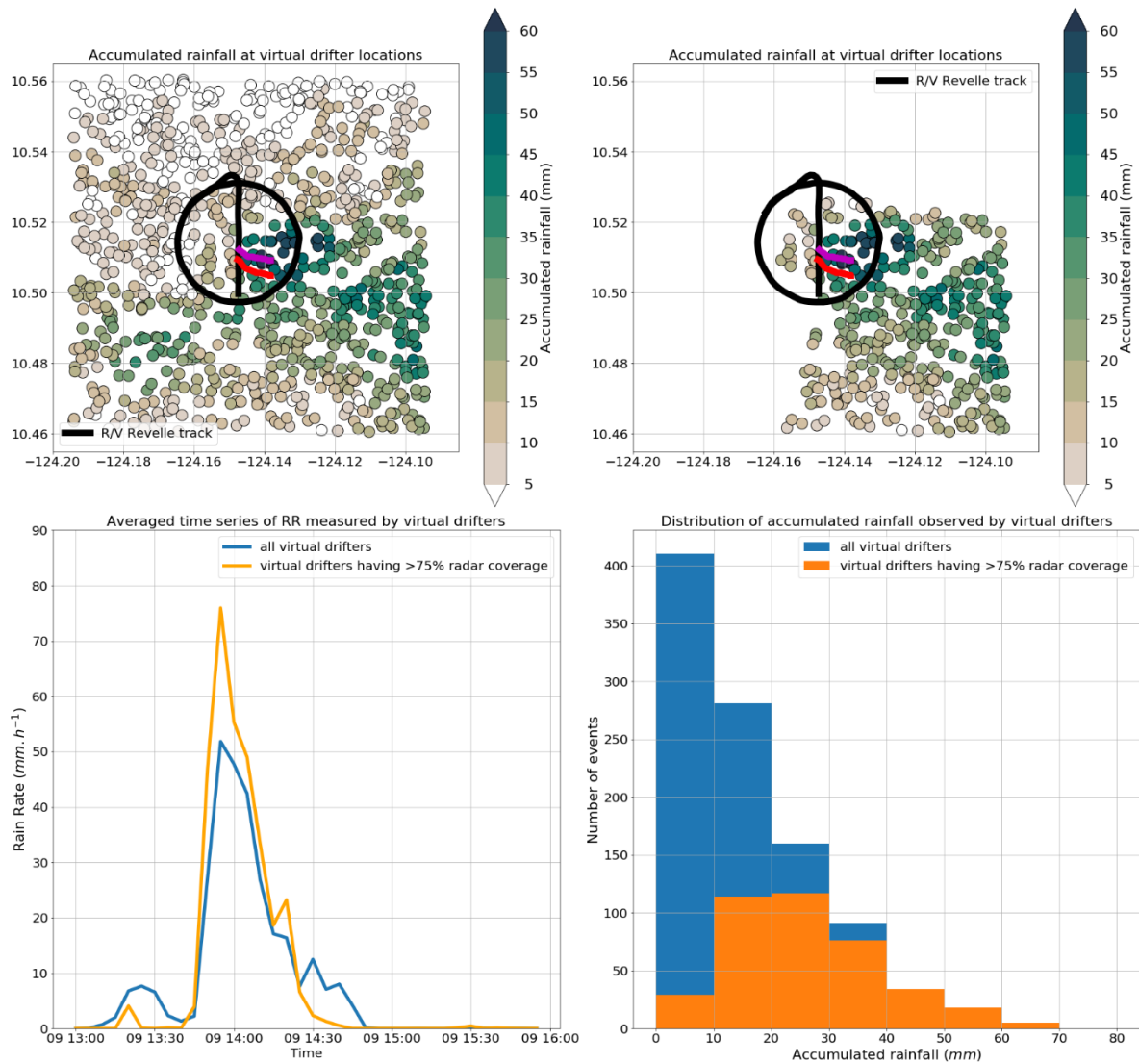


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 944 rate estimations between 13:30 and 14:45 UTC : Top, left) accumulated rainfall at the drifter  
 945 averaged positions; black line indicates the track of R/V Revelle during this time period;  
 946 magenta and red lines the trajectories of the two drifters; Top, right) accumulated rainfall only  
 947 for the 368 virtual drifters for which the SEA-POL radar provides rain rate information more  
 948 than 75% of the time; Bottom, left) Averaged time series of rain rate measured by virtual  
 949 drifters (blue, all drifters; orange, drifters with more than 75% of time coverage by the radar);  
 950 Bottom, right) histogram of accumulated rainfall among all the drifters (blue) and among the  
 951 drifters with more than 75% of time coverage by the radar (orange).