# A Lagrangian study of the Canary coastal upwelling: Supplementary text and figures

### Lagrangian experiment details

We conduct quantitative then qualitative experiments with ARIANE. In the quantitative experiment, particles are released on a strip defined by a bathymetry criterion based on the onshore water flow volume into the coastal region. Each particle is tagged with the corresponding initial transport that is assumed to follow it for the remainder of the experiment. In this quantitative experiment, the particles are tracked until they reach they leave the coastal region again, at which point they are discarded. In the event of a recirculation that brings that same water mass back into the coastal domain, this will be associated with a new particle release. By the end of the quantitative experiment, therefore, for each particle, we have obtained the location and time of release, associated water volume and time of exiting the coastal region. A qualitative ARIANE experiment is then run on the initial conditions set by the quantitative experiment to track the particle trajectories and their along-path nitrogen concentrations by setting the maximum duration of tracking uniformly as 720 days for each particle (since day of release). The qualitative experiment is not limited by the coastal control box and tracks particles throughout the simulation's domain.

If a particle leaves the coastal domain without upwelling, it is simply ignored (Figure 3). In the quantitative experiment, a water mass that enters and leaves the coastal domain and returns back to the coast will have prompted two particle releases: first particle released at the water's first entry to the coast and discarded when the water leaves the coast and a second particle released as the water reenters the coast. But in the qualitative experiment, two separate particles will be initialized at the initial conditions of these two particles and each tracked throughout their trajectories, much of which will be overlapping. Therefore, if a particle upwells and leaves the coastal region and returns into the coastal domain to re-upwell, its trajectory after re-upwelling is cut out since this second upwelling will have been associated with another particle that was introduced when this same water mass reentered the coast (Figure 2).

Some particles also exit the experiment domain early: around 4.2% and 0.37% of the particles released in the southern and central subregions leave the domain at the southward limit within one year of their release while virtually no particle that upwells in the northern subregion leaves the domain southward or northward. The early exit of particles therefore bias offshore transport to a certain degree, particularly in the southern subregion.

In our analyses, we define the offshore/downward transport of water (resp. nitrogen) by upwelling particles at their first arrival to a given offshore distance/depth as the total water volume (resp. nitrogen mass) associated with upwelling particles when they first reach that distance/depth (see Fig. 6). We define the net offshore/downward transport of water (resp. nitrogen) by upwelling particles at a given distance/depth from the coast as the fraction of water (resp. nitrogen) associated with upwelling that remains offshore/at-depth of that distance/depth by the end of the experiment. For water, the difference between first-arrival transport and net transport is the amount of water transported offshore/downward that recirculates back onshore/upward (Fig. 6). Finally, we define total offshore/downward transport of water (resp. nitrogen) at a given distance/depth as the total water volume (resp. nitrogen) carried by particles when they cross this distance/depth throughout our experiment. For water, total offshore/downward transport is equal to transport at particles' first arrival.

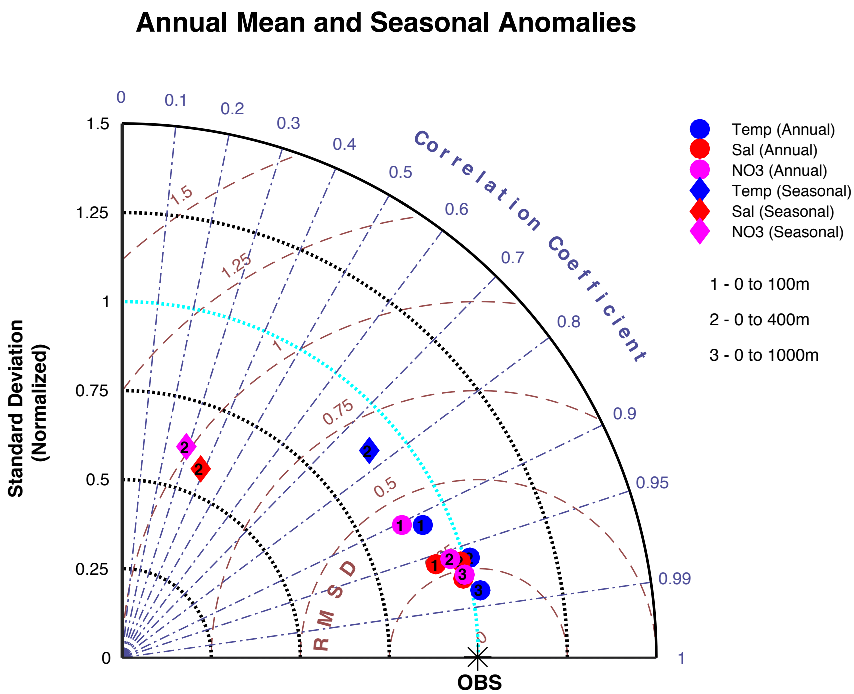


**Figure 1.** Taylor diagrams displaying statistical comparisons of modeled and observed annual mean (circular) and seasonal anomaly (diamond) estimates of temperature (blue), salinity (red) and $NO_3^-$ (pink) in the top 100 m (data points labeled "1"), top 400 m (data points labeled "2") and top 1000 m (data points labeled "3"). The reference point of the Taylor diagram corresponds to AVHRR data for temperature, world ocean database (WOD) 2013 for salinity and nitrate.

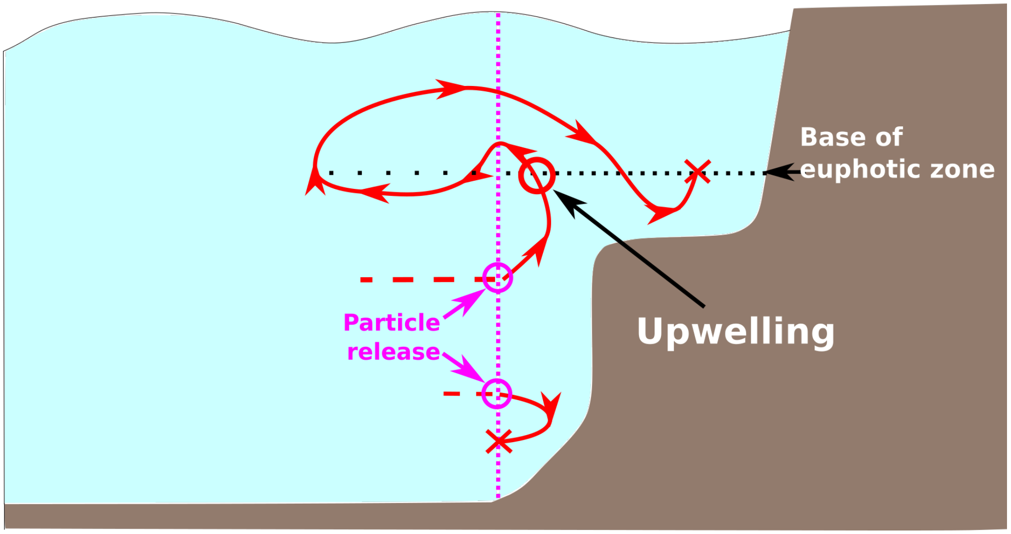


**Figure 2.** Schematic of experiment setup. Sample particle paths are the directional solid red curves (dotted line being hypothetical path before release) until they are discarded (represented by an 'X'). The bottom trajectory demonstrates a particles that enters and leaves the coastal control box without upwelling. The top trajectory represents a particle that enters the coastal region, upwells and leaves the coastal region but returns again to upwell, at which point it is discarded.

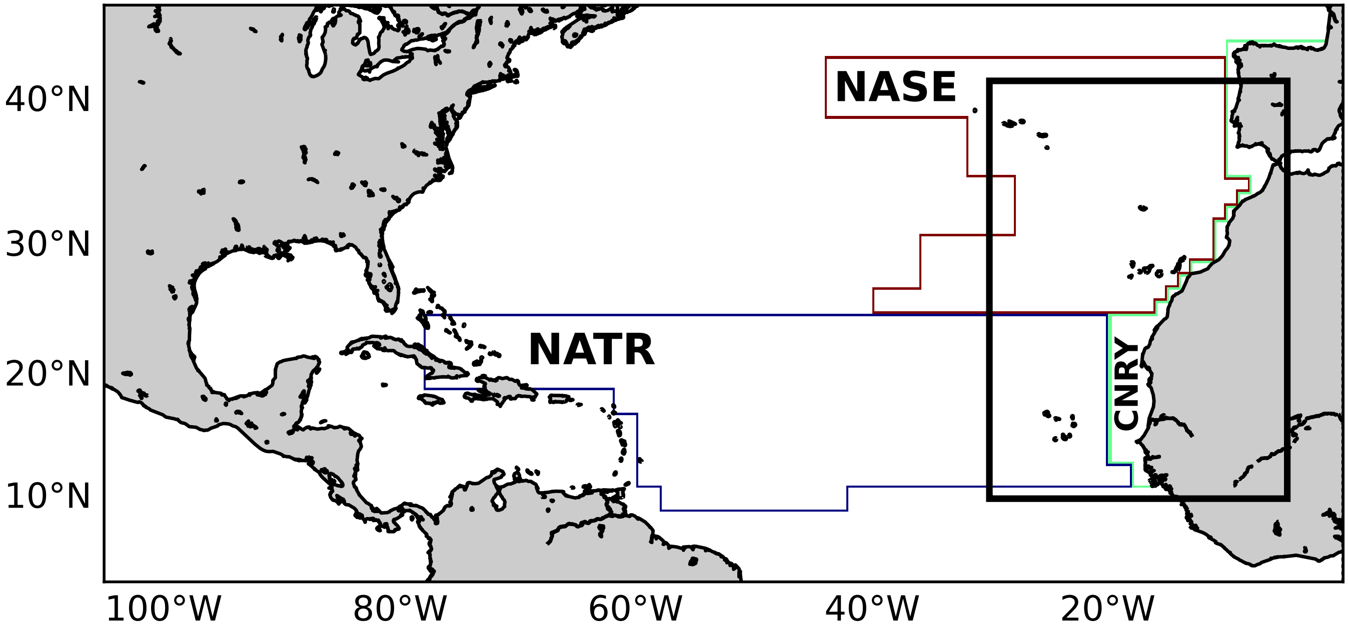


**Figure 3.** Geographical limits of the CNRY (green), NATR (blue) and NASE (red) Longhurst provinces. The black box shows the regional limit of our ROMS model domain. The total surface areas of the NATR and NASE are 8.2 and 4.4 million $km^2$, respectively.

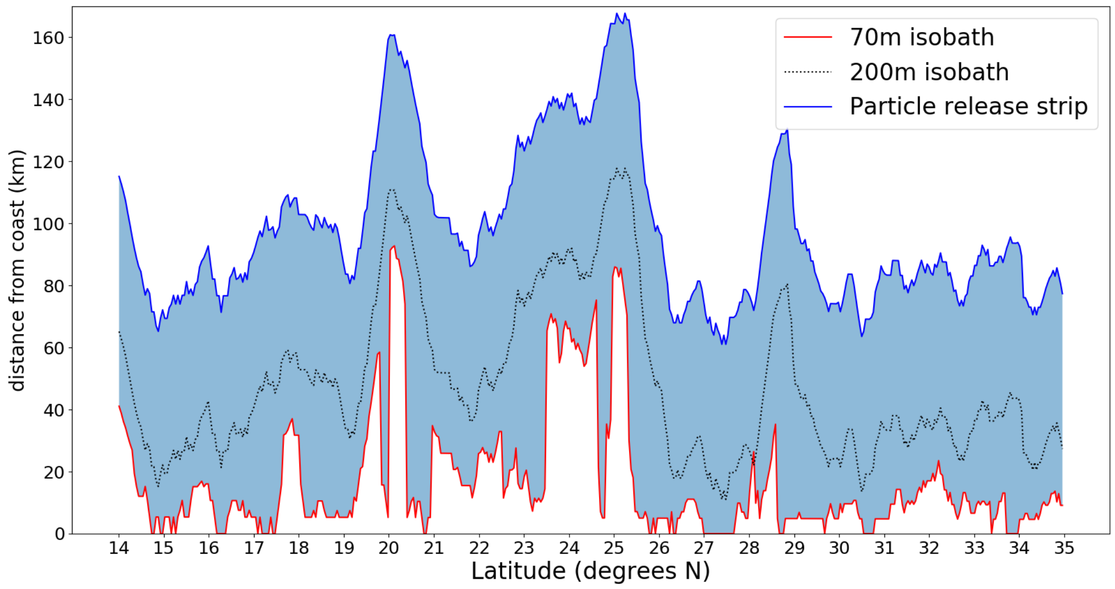


**Figure 4.** The distance from coast of the 70m isobath, 200m isobath and the particle release strip. The particle release strip uniformly lies 50km west of the 200m isobath. In our tracking experiment, particles that upwell between the 70m isobath and the particle release strip (in the blue shaded area) are considered.

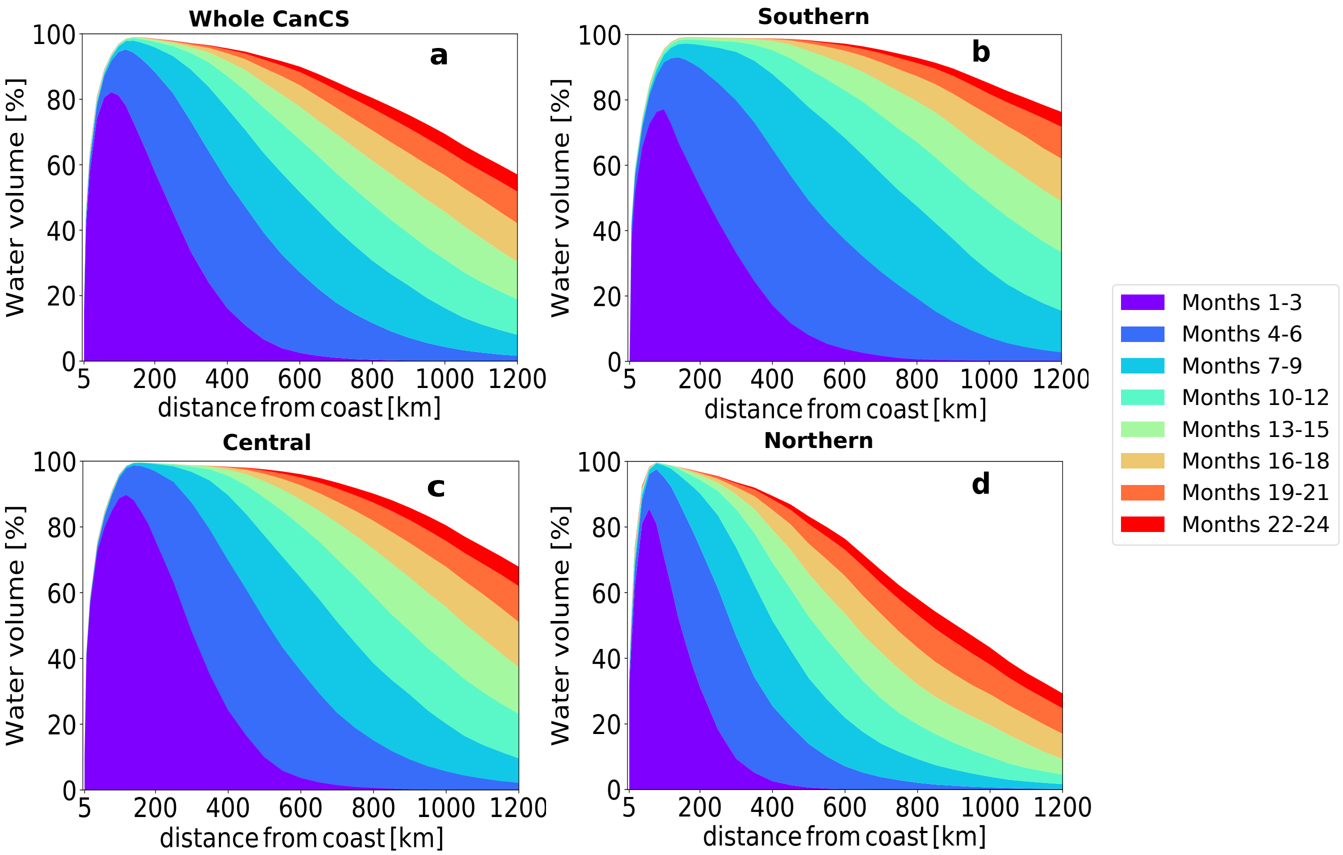


**Figure 5.** Upwelling water volume that first reaches each distance in each 3-month period of the total 2-year trajectories for the three subregions and the entire CanCS region in our experiment.

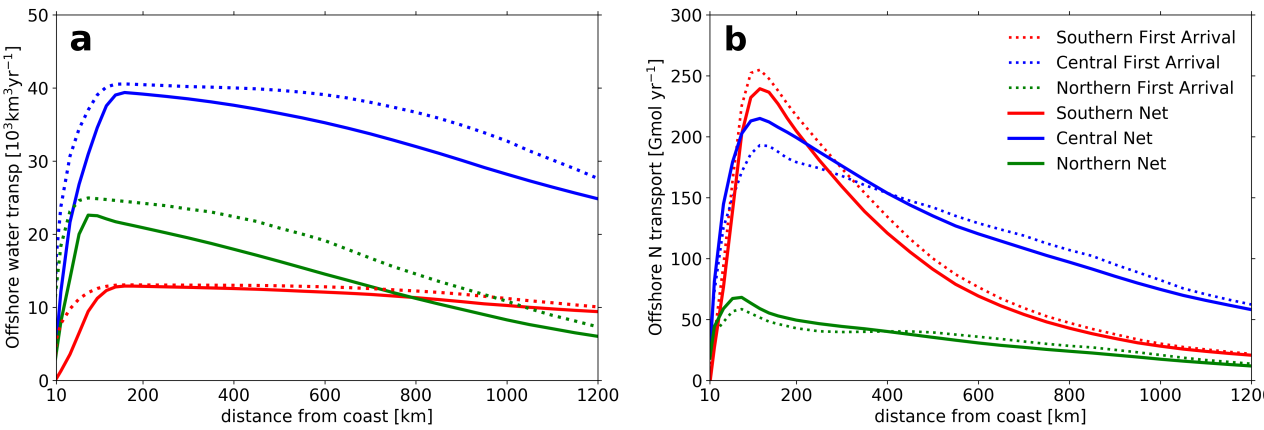


**Figure 6.** The annual average (a) water and (b) nitrogen carried to each distance by upwelled particles at their first arrival (dashed lines) and as net transport (solid lines) in each subregion. First arrival volume to a given distance is equal to total transport (net transport + net recirculation), thus exceeding net transport, for water while it may be higher or lower than net transport for nitrogen.

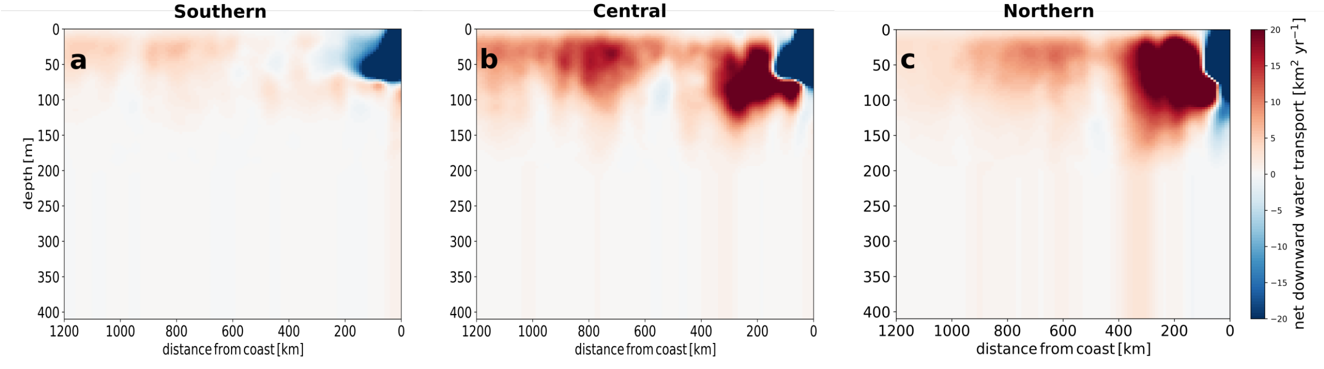


**Figure 7.** Meridionally integrated net downward transport of water in the (a) southern, (b) central and (c) northern subregions. All values are in km$^3$ of water per km of offshore distance per year.

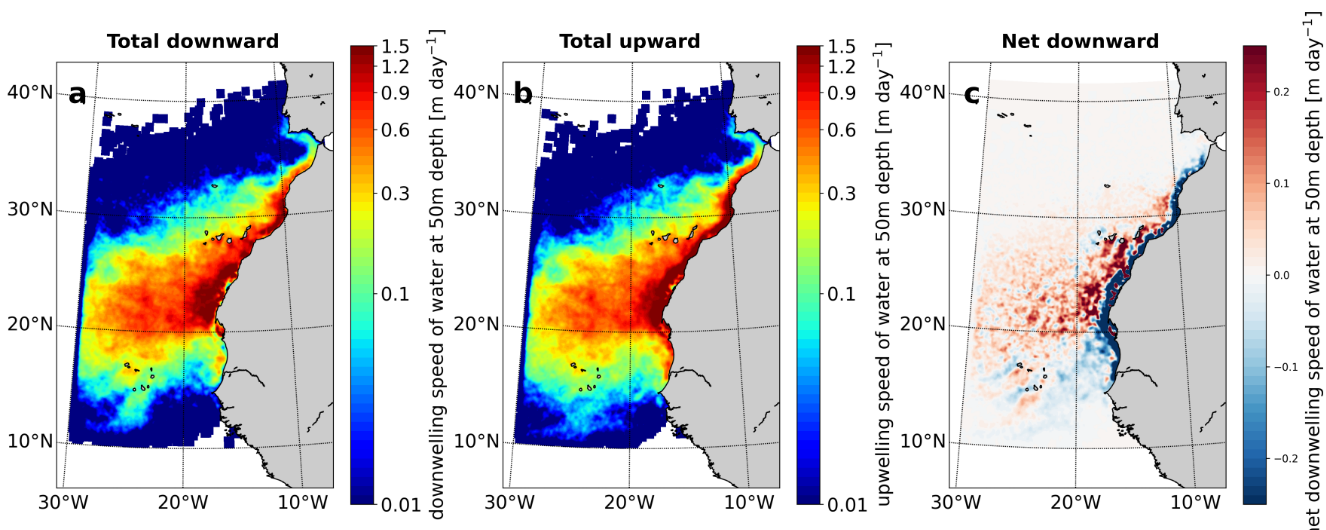


**Figure 8.** Horizontal distribution of vertical transport of water at 50m depth in the entire domain. (a) Total downward transport speed. (b) Total upward transport speed. (c) Net downward transport speed.

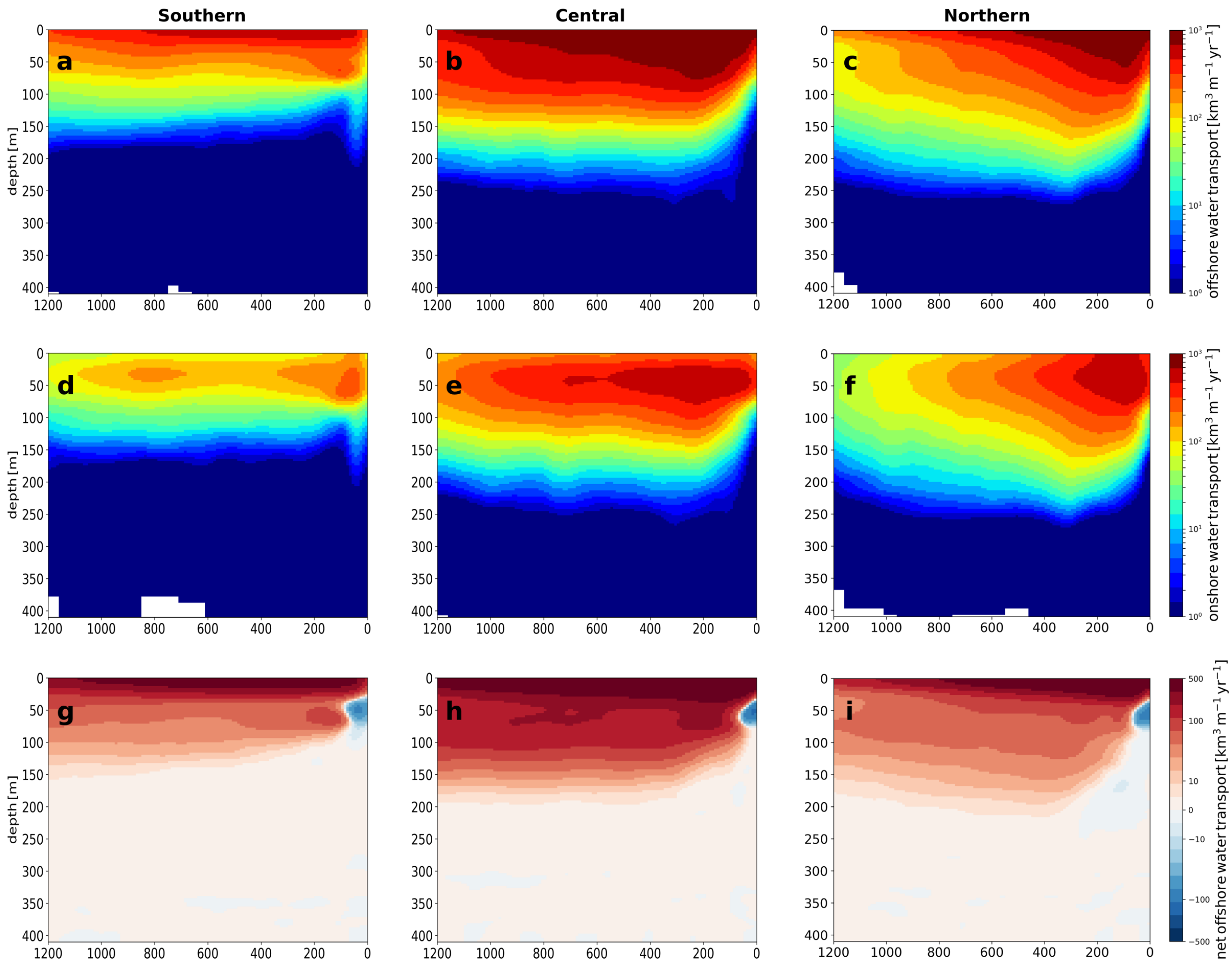


**Figure 9.** Meridionally integrated offshore transport of water. All values are in km$^3$ of water per a meter of depth per year. The columns (left to right) show the southern, central and northern subregions while the rows (top to bottom) show total offshore transport, total onshore transport and net offshore transport, all in logarithmic scales.

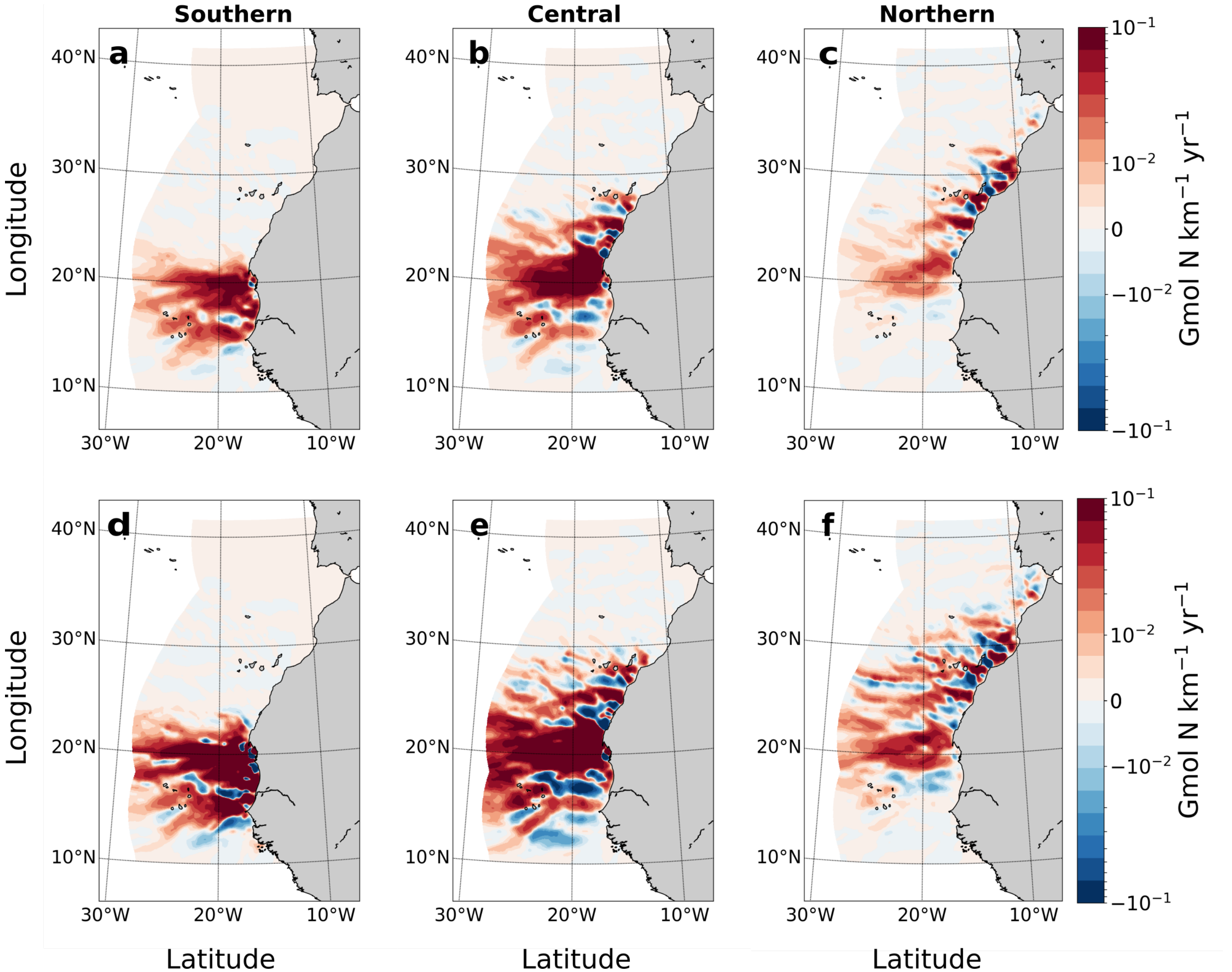


**Figure 10.** Horizontal distribution of vertically integrated offshore transport of organic (top) and inorganic (bottom) nitrogen in the three subregions.

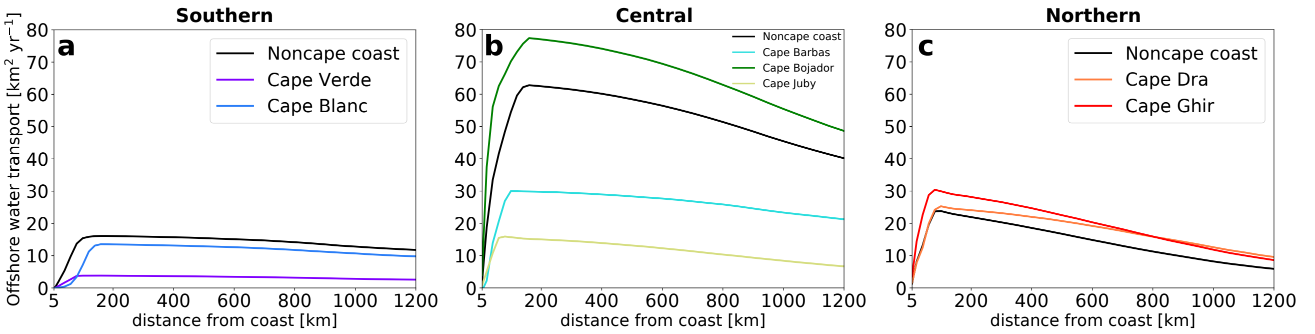


**Figure 11.** Net offshore transport of water by particles upwelling locally in each cape or non-cape coast in (a) the southern, (b) the central and (c) the northern CanCS. Note that the transport is normalized by coastal length (divided by the length of the coast at the respective cape or non-cape).

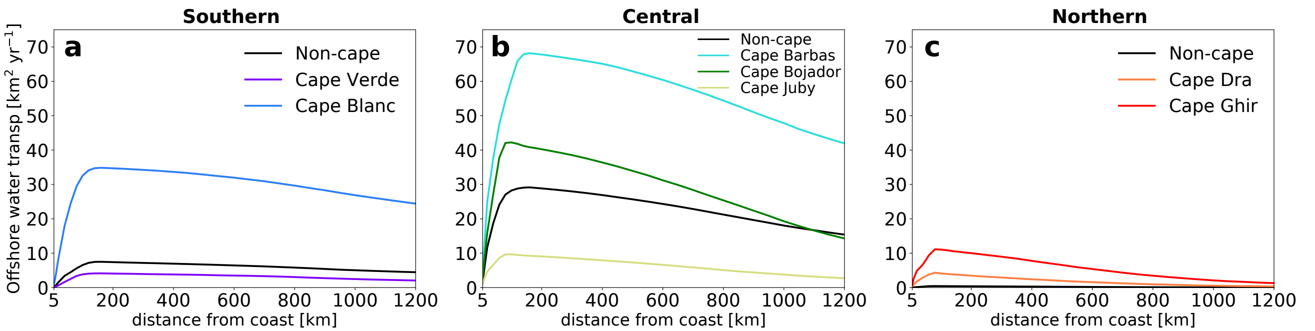


**Figure 12.** Net offshore transport of water by particles that leave the coastal upwelling region at each cape or non-cape area but upwell remotely in (a) the southern, (b) the central and (c) the northern CanCS. Note that the transport is normalized by coastal length (divided by the length of the coast at the respective cape/non-cape).

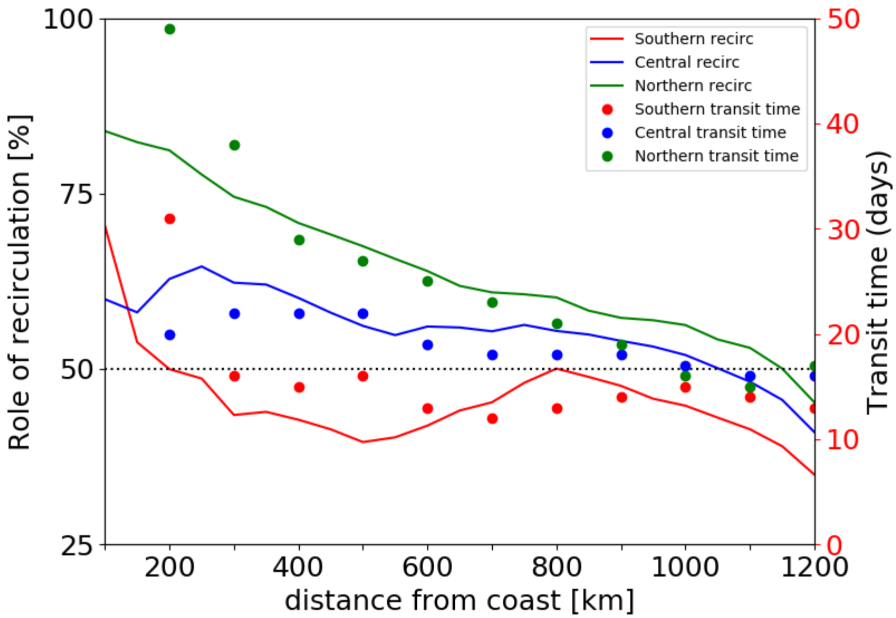


**Figure 13.** Total water recirculation (indirect transport + net recirculation) (filled circles) and median transit times (solid lines) at different offshore distances for the southern (red), the central (blue) and the northern (green) CanCS. Median transit times at each offshore distance is the median time particles take to cross the 100 km that precedes the given distance.

| | 200km | 400km | 600km | 800km | 1000km | 1200km |
|---|---|---|---|---|---|---|
| Southern | 84 | 146 | 208 | 268 | 332 | 385 |
| Central | 59 | 131 | 214 | 298 | 369 | 430 |
| Northern | 126 | 252 | 361 | 434 | 473 | 517 |
| Whole CanCS | 83 | 169 | 254 | 329 | 391 | 443 |

**Table 1.** The median residence time (days) of particles between upwelling and reaching each distance for the three subregions as well as the entire CanCS region in our experiment.

| | Latitude range (°N) | Coast length (km) |
|---|---|---|
| C. Verde | 14.5-15.5 | 192 |
| C. Blanc | 20-21 | 195 |
| C. Barbas | 22-22.75 | 112 |
| C. Bojador | 25-26.5 | 210 |
| C. Juby | 27.5-28.5 | 238 |
| C. Dra | 28.5-29.5 | 169 |
| C. Ghir | 30-31 | 139 |

**Table 2.** Latitudinal range of major capes and their coastal length (in km).

| | Our results | Lovecchio et al. (2017) |
|---|---|---|
| 100 km | 12.3 | 18.8 |
| 500 km | 6.9 | 8.2 |
| 1,000 km | 2.5 | 4.6 |

**Table 3.** Comparison of net offshore export of organic carbon (in Tg C $yr^{-1}$) by upwelling particles at different distances from the coast between our experiment and estimates based on Lovecchio et al. (2017).

**Table 4.** Estimates of annual mean offshore transport of nitrogen (in Gmol N $yr^{-1}$) in the California and Benguela upwelling systems from previous studies. Organic nitrogen is considered in both particulate organic nitrogen (PON) and dissolved organic nitrogen (DON) forms.

| Prvious study | Latitude | Longitude (offshore dist.) | Depth | Form | Offshore transport |
|---|---|---|---|---|---|
| Gutknecht et al., 2013 | 18°S-35°S | 10°E | 0m-50m | PON | 340 ± 144.5 |
| | - | - | - | DON | 93.5 ± 42.5 |
| | - | - | - | $NO_3 + NO_2 + NH_4$ | 289 ± 144.5 |
| Frischknecht et al., 2018 | 34°N-41°N | 100km | 0m-100m | PON + DON | 160 |
| | - | - | - | $NO_3 + NH_4$ | 187 |
| | 32°N-41°N | 500km | - | PON + DON | 90 |
| | - | - | - | $NO_3 + NH_4$ | 78 |