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Sinking microplastics in the water column: simulations in the Mediterranean Sea

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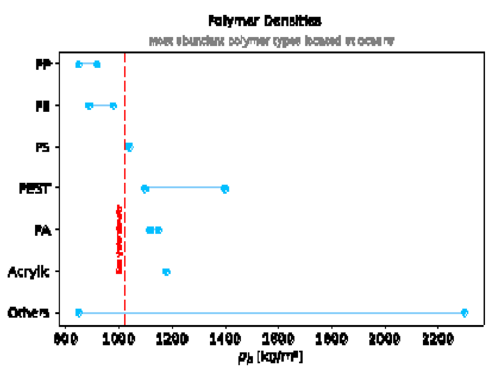
Motivation

- ■ Analyze vertical dispersion and distribution of negatively buoyant microplastics.
- ■ Equations of motion of idealized microplastics dynamics.
- ■ Physical effects.
- ■ Amount and vertical distribution of microplastic particles on the water column.

Model Setup

Physical properties of microplastics



- Negatively buoyant rigid particles (Increasing abundance with further decreasing size)
- Radius size, a = 0.05 mm
- Variable particle density

$$1025kg/m^3 < \rho_p < 1400kg/m^3$$

Dynamics

Simplified Maxey-Riley-Gatignol (MRG) equation

$$\frac{Dv}{dt} = \beta\frac{Du}{Dt} + \frac{u - v + v_s}{\tau_p}$$

$$\boxed{v = u + v_s}$$

Settling velocity, buoyancy, stokes times

$$v_s = (1-\beta)g\tau_p \qquad \beta = \frac{3\rho_f}{2\rho_p + \rho_f} \qquad \tau_p = \frac{a^2}{3\beta\nu}$$

Numerical procedure

- NEMO field data

3D velocity field from NEMO, with horizontal resolution of 1/12 degrees and 75s levels in the vertical. Data updated every 5 days

- Particle Integration

The Parcels Lagrangian framework (Delandmeter and van Sebille, 2019) is used to integrate particle trajectories.
Particles are released from 1m depth with uniform horizontal density over the whole Mediterranean.

Results

Range of validation

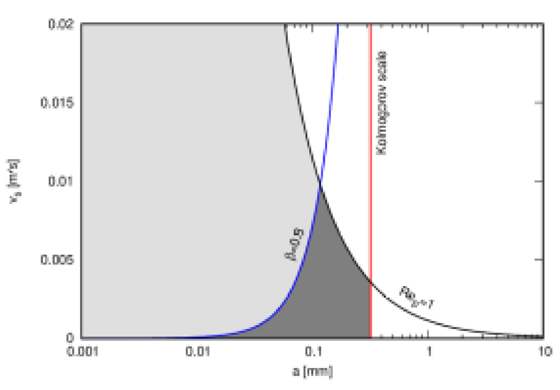
MRG equation represents an appropriate basis for qualitative estimations of the transport properties of negatively buoyant rigid microplastics

$$\frac{dv}{dt} = \beta\frac{Du}{Dt} + \frac{u - v + v_s}{\tau_p} \xrightarrow[St = \frac{\tau_p}{\tau_\mu} << 1]{} v = u + v_s + \tau_p(\beta - 1)\frac{Du}{Dt}$$

$$Re_p = \frac{a|v-u|}{\nu} \sim \frac{av_s}{\nu} << 1$$

$a << \eta$ (Kolmogorov scale of the flow at the ocean) $0.3mm < \eta < 2mm$

$$v = u + v_s + \tau_p(\beta - 1)\left(\frac{Du}{Dt} + 2\Omega \times u\right) + W$$



Typical plastic sizes and corresponind settling velocities for which equation is valid, with fluid density fixed at 1025kg/m³

$\rho_p \in [1025, 1400]kg/m^3 \longrightarrow \beta \in [0.8, 1]$

$v_s < 0.015m/s$
$a < 0.3mm$

Non-negligible terms?

$$\begin{cases} \boxed{(0) v = u + v_s} \\ (1) v = u + v_s(\rho_f) \\ (2) v = u + v_s + \tau_p(\beta - 1)\left(\frac{Du}{Dt} + 2\Omega \times u\right) \\ (3) v = u + v_s + W \end{cases}$$

Settling velocity uniformly distributed and fixed for each initial condition

$$v_s \in [1.776 \times 10^{-3}, 0)m/s$$

$$\beta \in [0.8, 1), a = 0.05mm$$

Relative effect on horizontal and vertical particle positions after 20 days of integrations from each pair (i),(j) of equations of motion, using the same release location and date

$$r^{(i,j)} = \frac{1}{N}|x_k^{(i)}(t) - x_k^{(j)}(t)|$$

Inertial and Coriolis terms
(Eq (0) and Eq (2))

Horizontal 0.26%
Vertical 0.005%

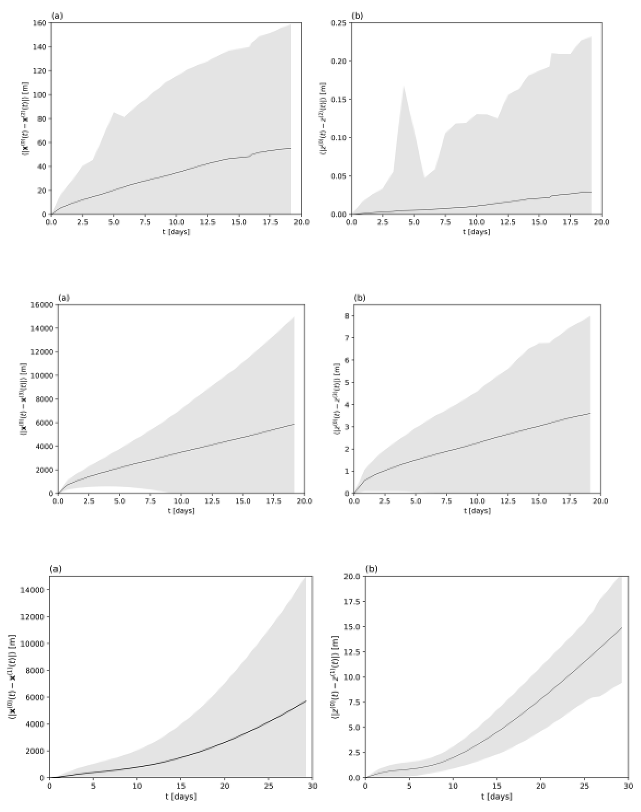
Unresolved small scales
(Eq (0) and Eq (3))

Horizontal 11.8%
Vertical 1.79%

Variable seawater density
(Eq (0) and Eq (1))

TEOS-10 equations, particle density 1041.5kg/m³

Horizontal 0.26%
Vertical 0.005%



Total mass of microplastics

Estimation of total mass of negatively buoyant rigid microplastics in the water column of the open Mediterranean sea assuming a uniform vertical distribution. We restrict the estimation to open sea microplastic input.

- 4000 t/year plastic release (Kaandorp et al. (2020)), 37% negatively buoyant and 6% of it comes from maritime activity
- We estimate the rate at which microplastic enter the water column in the open sea, r = 0.24 t/day
- Considering the mean depth of the Mediterranean, h = 1480m, and the total range of sinking velocities for microplastics 6.20 – 509.23 m/day, we estimate the residence time, i.e, the time of sinking of the microplastic particles

$$\tau = \frac{h}{v_s} = 3.1 - 255days$$

- Mean residence time, weighted by the proportion of each type of plastic

$$\bar{\tau} = 14days$$

Total amount of microplastics present in the water column at any given time

$$Q = r\bar{\tau} \approx 3.36t$$

Microplastic density in the Mediterranean
(considering the Mediterraenan volume of 4.39 x 10⁶ km³)

$$\rho_V \approx 7.7x10^{-11}kg/m^3$$

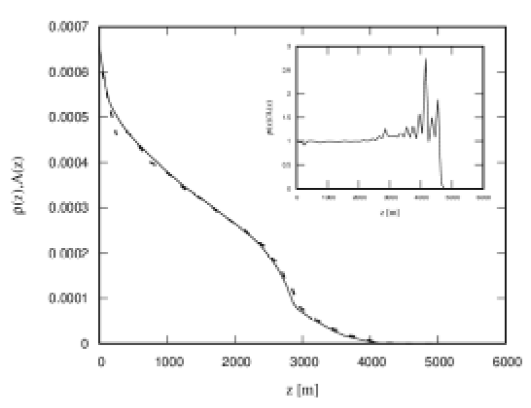
Vertical distribution

We look at all positions at all time steps for each release event. In particular, we fix buoyancy parameter at 0.8, which gives the fastest sinking velocity of typical plastic particles.

Uniform distribution of plastic in the water column

- Density of plastic particles per unit depth in the whole Mediterranean
- Horizontal area of the Mediterranean basin at each depth
- Both functions are normalized such the value of their integrals with respect to z is one

➔ The variation of the number of particles with depth is essentially due to the decrease in sea area with depth

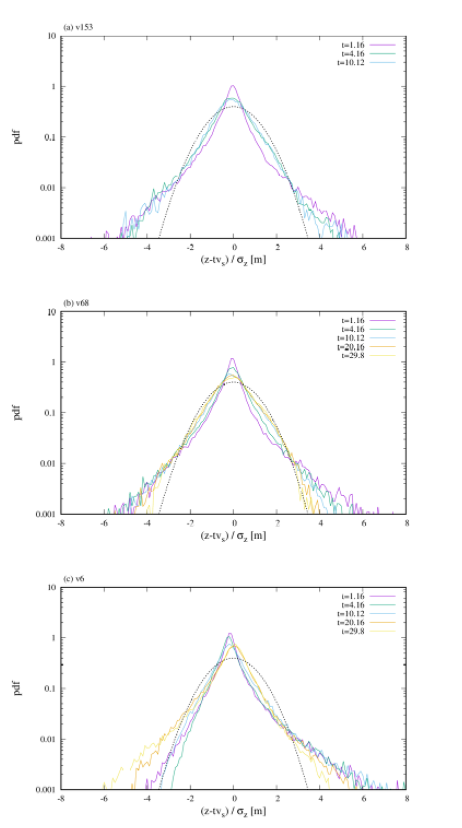


Transient evolution

$$\beta = 0.8\ (v_s = 153.48m/day)$$
$$\beta = 0.9\ (v_s = 68.21m/day)$$
$$\beta = 0.99\ (v_s = 6.20m/day)$$

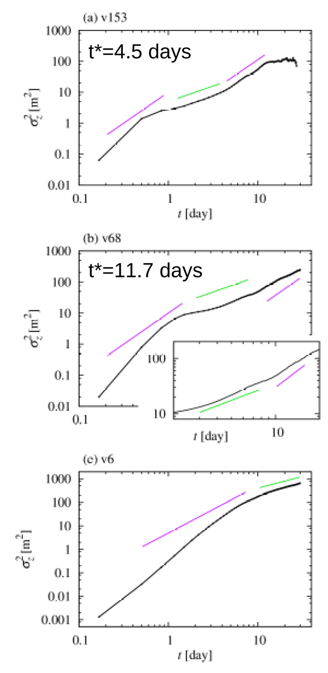
Probability density function of the rescaled variable

$$\bar{z} = \frac{z - tv_s}{\sigma_z} \qquad \sigma_z^2 \equiv \langle(z_i - \langle z_i\rangle)^2\rangle$$



➔ Deviations from Gaussianity for early times.
➔ The deviations in the tails may be related to anomalous diffusive behavior

How the variance of the vertical particle distribution evolves?
Exponent 1 (standard diffusion;green), Exponent 2 (ballistic dispersion;purple)



Dispersion appears to be governed by different laws in different regimes

$$\sigma_z^2 \sim t^\nu$$

V153, Fastest Sinking velocity
Crossover to ballistic dispersion (t*=4.5 days) resulting from different mean sinking velocity in diverse regions of the Mediterranean

$$z_i = \langle z_i\rangle + \bar{\omega}_i t + W_i \qquad \bar{W}_i^2 = D_i t$$

- Constant average velocity constribution
- Wiener process defining a diffusion coefficient

$$\langle\omega_i \bar{W}_i\rangle = 0 \longrightarrow \sigma_z^2 = \langle(z_i - \langle z_i\rangle)^2\rangle = \langle\bar{\omega}_i^2\rangle t^2 + \langle D_i\rangle t$$

Variance = Ballistic + Normal diffusive term

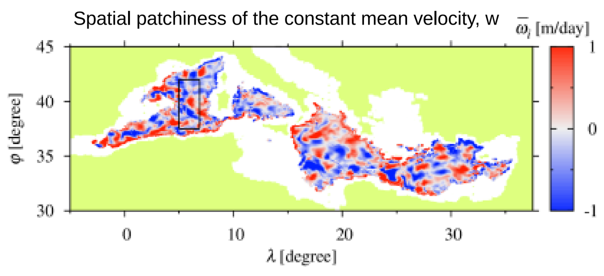
$D = \langle D_i\rangle$

Crossover between regimes $t^* = \frac{D}{\langle\bar{\omega}_i^2\rangle}$

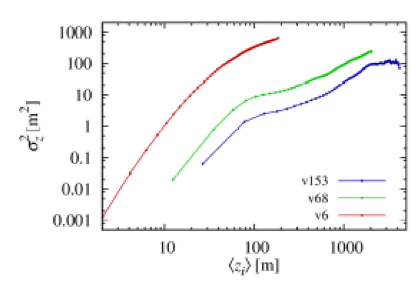
V68,Sinking velocity
Crossover to ballistic dispersion, t*=11.7 days.
Subdiffusive regime from the initial superdiffusion

V6,Sinking velocity
There is no subdiffusion regime. The decay of autocorrelation is faster for faster-sinking particles

Spatial patchiness of the constant mean velocity, w



Depth-dependent organization of the flow
(First transition takes place around 100m)



Conclusions

- ■ Simplified MRG equation approximates the dynamics of rigid microplastic particles with negative buoyancy sufficiently well for qualitative estimations.
- ■ Coriolis and inertial terms are negligible. Variable seawater density and small-scale effects are moderate but possibly non-negligible.
- ■ Nearly uniform steady distribution along the water column, except perhaps at lowest settling velocities.
- ■ Total amount of plastic present in the water column is close to 1% of the floating plastic mass, when restricted to open-ocean input.
- ■ Uniform vertical distribution, maybe linked to the weak vertical dispersion.
- ■ Transient vertical distribution with deviations from Gaussianity, which are related to anomalous diffusion. The different diffusive laws are related to the decay in the Lagrangian velocity autocorrelation.
- ■ This transition from initial superdiffusion to normal diffusion occurs around 100m depth.
- ■ Horizontal patchiness, resulting in a long-term ballistic dispersion. It returns to normal diffusion when horizontal mixing is developed.

CSIC Consejo Superior de Investigaciones Científicas

de la Fuente, R., Drótos, G., Hernández-García, E., López, C., and van Sebille, E.: Sinking microplastics in the water column: simulations in the Mediterranean Sea, Ocean Sci., 17, 43.
Monroy, P., Hernández-García, E., Rossi, V., and López, C.:Modeling the dynamical sinking of biogenic particles in oceanic flow, Nonlin. Processes Geophys., 24, 293–305, https://doi.org/10.5194/npg-24-293-2017, 2017.
Delandmeter, P. and van Sebille, E.: The Parcels v2.0 Lagrangian framework: new field interpolation schemes, Geosci. Model Dev., 12, 3571–3584, https://doi.org/10.5194/gmd-12-3571-2019, 2019.
Mikael L. A. Kaandorp, Henk A. Dijkstra, and Erik van Sebille Environmental Science & Technology 2020 54 (19), 11980-11989 DOI: 10.1021/acs.est.0c01984

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