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Spreading pathways of Pilgrim Nuclear Power Station wastewater in and around Cape Cod Bay: Estimates from ocean drifter observations

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A B S T R A C T

Near-surface drifter observations were used to study the spreading pathways in and around the Cape Cod Bay from a source region located just offshore of the Pilgrim Nuclear Power Station. The study was motivated by the recent closing of the power plant and a possible release of accumulated wastewater. The investigation applies several different techniques to the drifter data set to estimate and quantify various aspects of the circulation and spreading. Our goal was two-fold: first, to better understand and predict the fate of the Pilgrim wastewater should it be released; and second, to review, compare, and contrast several useful techniques that can be applied to drifter datasets in other parts of the global ocean. Our analysis suggests weaker spreading of the wastewater plume inside the Bay than outside, and sensitivity of the advection pathways to the location of the release. Statistical techniques predicted that part of the plume would likely be advected cyclonically around the inner coastline of the Bay towards the more quiescent eastern regions, while another part of the plume would likely pass close to the tip of Cape Cod and the beaches of the Outer Cape. For the soluble radionuclides, the levels observed in our statistical model offshore of Provincetown and Dennis/Brewster will be at least 100 times smaller than the initial concentrations.

1. Introduction

Pilgrim Nuclear Power Station (PNPS) is located in Plymouth, MA on the US east coast facing Cape Cod Bay and south of Boston. It was built in 1972, decommissioned in 2019, and bought by Holtec International. About four million liters (or, equivalently, one million gallons) of radioactive wastewater used to cool the reactor were left at the site after the closing of PNPS (Fraser, 2022; Junker, 2022). The wastewater likely contains several types of radionuclides, including cesium-137, strontium-90, cobalt-60, tritium, and the isotopes of plutonium, whose half-lives range from order ten to tens of thousands of years (Buesseler, 2020). However, the exact composition of the wastewater and the exact concentrations of different radionuclides are either not known or have not been made public (Flanary, 2022). Four possible wastewater disposal options include release of wastewater into the ocean offshore of PNPS, evaporation of the wastewater into the atmosphere, transportation of wastewater to an appropriately equipped storage facility, or keeping wastewater on site to reduce radioactivity via natural radioactive decay. Each option comes with its own costs, risks, and challenges. Release into the ocean might pollute the Bay. Evaporation might increase the risk of inhalation of radionuclides. The main objection to transportation is the risk of an accident during the transportation process. Keeping wastewater on site for several decades comes with an inherent risk of storage in a populated area and, while significantly decreasing the radioactivity levels for shorter-lived radionuclides such as tritium (half-life of 12.3 years), would do little for isotopes with longer half-lives. Holtec appears to favor the release of the wastewater into the ocean in its public statements (Damiano, 2022; see also the Information Sheet For Pilgrim Station Stakeholders available at https://holtecinternational.com/wp-content/uploads/2022/01/Info-Sheet-for-Stakeholder-Water-Disposal-Final.pdf), but the other three options are still on the table as of this writing (although options 2 and 3 are more costly).

Not surprisingly, the proposed release of potentially harmful radioactive wastewater into Cape Cod Bay concerns local residents, who have become increasingly worried about the health and safety of the Bay and impacts on tourism and fisheries industries (see, for example, local news articles on this topic available at https://www.capecodtimes.com 〉 story

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⟩ news ⟩ 2022/06/17, or https://www.capecod.com/newscenter/noaa-official-expresses-concern-over-potential-pilgrim-discharge-plans/, or https://www.wbur.org/news/2022/07/26/pilgrim-nuclear-power-plant-holtec-wastewater, among many others). This concern led to a sequence of public events and rallies (such as https://www.patriotledger.com/story/news/2022/04/10/hundreds-rally-plymouth-prevent-dumping-radioactive-water-into-cape-cod-bay/9509862002/) against the release, and motivated this study, where we apply a scientific approach to better understand the potential fate of a PNPS wastewater release in terms of its spreading pathways in and around Cape Cod Bay. The aim is to provide a solid foundation of scientific understanding for a more informed decision. Note that without knowing the exact content of the wastewater, it is not possible to predict resulting concentrations of radionuclides in the ocean water, sediments, or beaches nor their impacts on the health and safety of humans and animals. Therefore, here we only focus on the dynamical aspect of the oceanographic problem, i.e., how contaminants would be transported and spread through movement of ocean waters, without considering their chemical or biological fates. In this case, movement by currents and dilution would be the only physical processes to consider. For this investigation we use surface drifters.

Drifting ocean buoys, or drifters, that are carried by the oceanic currents are perhaps one of the oldest forms of oceanographic instrumentation. Ancient drifters were as simple as bottles with messages about their release locations. When such a drifter was fished out or picked up onshore, it provided two points of reference: where it came from and where it eventually arrived. Modern day drifters consist of a surface floating buoy, which provides buoyancy, and a drogue, i.e., an underwater sail that allows the drifter to closely follow the currents at the depth of the sail. Modern drifters are also equipped with GPS devices that transmit their position at fixed intervals of time and thus provide information about the entire drifter trajectory, rather than just the start and end points. Drifter data are especially appealing for the studies of transport and spreading because drifters are Lagrangian by nature and their trajectories naturally depict the water pathways. A variety of drifter datasets with both global and regional coverage are publicly available on-line (e.g., NEFSC, 2022; GDP, 2022; or SPLASH drifter dataset available at https://data.gulfresearchinitiative.org/data/R4.x265.000:0074), making drifter data a commonly used resource for many oceanographic applications.

2. Methods

We apply a variety of techniques, from widely used conventional methods to more recently developed approaches, to available drifter data to investigate various aspects of the proposed PNPS wastewater release. Each technique highlights different aspects of the problem, but the results agree and reinforce each other, so that together they tell a coherent story about the likely fate of the dissolved components of the PNPS wastewater. We start with the classic binned-and-averaged velocity field approach to investigate the spreading pathways associated with the regional mean ocean circulation. Next, we apply two statistical methods to produce probabilistic maps of spreading pathways and transit times in and around the Cape Cod Bay. We then look at quantitative estimates of dispersion as a means of characterizing the intensity and character of spreading. Finally, we apply a state-of-the-art spectral clustering method to identify the most connected coherent regions within the drifter dataset.

For our analysis we use the dataset entitled “Drifter Tracks from the NE US Shelf and Beyond”, which is available from the ERDDAP server maintained by NOAA (https://comet.nefsc.noaa.gov/erddap/tabledap/drifters.html). The dataset contains trajectories of Coastal Ocean Dynamic Experiment (CODE)-type surface drifters that were deployed over more than 30 years (1989–2021) as part of numerous scientific and educational programs. CODE drifters were originally developed by Dr. R. Davis of Scripps Institute of Oceanography and consist of one or several small surface buoys equipped with a GPS devise and a substantial cross-shaped subsurface drogue that allows the drifter to closely follow the movement of surrounding water (Davis, 1985a,b). Drifters of this design are widely used by the U.S. Coast Guard for search and rescue operations and by the physical oceanographic scientific community for studying surface and near-surface oceanic currents (see, for example, Rypina et al., 2014, 2016, 2021a; 2021b; Manning et al., 2009; Chen et al., 2014; D’Asaro et al., 2020). While the entire drifter dataset encompasses a broad region of the Northeast Atlantic, our field of study is defined as 70.8–69.9°W and 41.6–42.5°N, which includes waters in and to the north and east of Cape Cod Bay. There are 417 drifters in our domain. Most drifters transmitted their positions every hour and measured currents approximately 1 m below the surface, but some drifters (about 15% of those used) had deeper drogues and/or a less frequent transmission schedule of 2–6 h.

2.1. Binned-and-averaged mean velocities (BAMV)

This technique produces a long-term mean velocity field on a predefined grid, regular 0.025° by 0.025° grid in our case, by averaging together velocity estimates from all available drifters within each grid bin. Drifter velocities were defined by finite differencing the consecutive GPS positions. A variant of BAMV with the variable bin size is also possible (Koszalka et al., 2011) but here we use the conventional BAMV with a regular grid, as in Rypina et al. (2009). For the conventional BAMV, bin size is a user-defined parameter and is generally chosen as a compromise between precision (larger bins contain more data and yield more robust mean velocity estimates) and resolution (smaller bins provide improved spatial resolution). Varying the bin size over a range of 0.01°–0.03° produced similar results. The resulting mean field is useful for understanding the overall geometry of the flow in and around Cape Cod Bay.

2.2. Simulated trajectory estimation (STE)

This method allows investigation of the mean spreading pathways of PNPS discharge waters caused by the mean oceanic currents. Specifically, simulated trajectories of water parcels advected by the drifter-based mean velocities were estimated using a 4th order variable-step Runge-Kutta velocity integration (ode45 function in Matlab®) with bilinear interpolation in space between neighboring grid points. The same technique has been used in most of our prior studies of oceanic transport (Rypina et al., 2011, 2014, 2021b). Simulations for three release box sizes (small – 0.02° square, medium – 0.05° square, and large – 0.2° square) have been performed, with 1000 water parcels released within each box on a uniform grid and integrated forward in time for 3 weeks. Note that because of the non-zero convergence of currents present in the BAMV field, integrating over time intervals longer than 3 weeks resulted in a nearly identical pathways as most trajectories by this time had been attracted into the convergence regions, reached land, or left the domain.

2.3. Single-particle dispersion tensor and diffusivity (SDTD)

Time evolving ocean currents can redistribute biogeochemical tracers in nontrivial ways. The resulting tracer transport has often been simplistically represented as a diffusive process similar to molecular diffusion, but with increased intensity, i.e., increased diffusivity. Diffusivity can be estimated by computing a single-particle dispersion tensor for an ensemble of Lagrangian particles relative to their center of mass (LaCasce 2008; Rypina et al., 2012, 2016; Kamenkovich et al., 2015). In essence, one fits an ellipse (dispersion ellipse) to the growing distribution of particles released near a given location, and the rate at which this ellipse grows in time defines the diffusivity. The diffusivity is by its nature a local measure. When computed at each location within the domain, the resulting map quantifies the intensity of local tracer transfer. In the context of drifters, we are forced to group drifters into finite boxes (we used 0.025°) when estimating diffusivity, thus relaxing the locality assumption.

When *actual* drifter displacements are used to estimate the best-fit ellipse, dispersion is due to the action of the *full* flow (i.e., time-mean plus eddies), and diffusivities quantify the cumulative effect of both the mean and eddy fields on particle spreading. If the displacement caused by the mean is removed at each time step following each trajectory, so that one uses the cumulative *eddy-induced* displacements instead of the full displacements, then the dispersion and diffusivity quantify the action of eddies only. Note that the eddy field is defined as the deviation from the long-term mean and so includes tides, seasonal and inter-annual variability, as well as all other time-dependent flow features. Overall, diffusivity provides an easy way to both quantify the spread of a tracer released at any given location and characterize the importance of mean currents vs. eddies on the resulting tracer spreading.

2.4. Transit matrix approach to tracer spreading (TM)

The transit matrix approach (van Sebille et al., 2012, 2015; Maximenko et al., 2012; Lumpkin et al., 2016) allows visualization and quantification of probable pathways for the spread of the PNPS discharge waters, based on the information about drifter trajectories. TM uses short segments of trajectories to construct a transit matrix P^{TM}, characterizing the probability that a drifter would travel from bin i to bin j over some fixed transit time interval $T_{transit}$. For a known P^{TM}, the distribution of a tracer with a given initial concentration $n(\vec{x}, t_0)$ after time $T_{transit}$ can be estimated by applying the transit matrix operation to the initial concentration, $n(\vec{x}, t_0 + T_{transit}) = \int nP^{TM} d\vec{x}$, and the distribution after time $N * T_{transit}$ results from repeating the application of the transit matrix P^{TM} to the initial concentration N times. The transit time is chosen to be much shorter than the average drifter lifetime (we use $T_{transit} = 6$ hours), and the box size is chosen to be much smaller than the study domain (we use 0.01° bins).

2.5. Multi-iteration approach to tracer spreading (MI)

This approach makes use of a simple iterative procedure to construct a statistical probability map P showing the likelihood that a tracer released at a given source location would visit different geographical regions, along with the associated expected travel time map T. The method (specifically, formulas for P and T) is described in detail in Rypina et al. (2017). Simply speaking, we start with those trajectories that go through a predefined source region to construct the first iteration of P_1 and T_1, then append to these 1st iteration maps those trajectories that go through all the non-zero bins of P_1 to get improved 2nd iteration maps P_2 and T_2. The procedure is repeated until all the drifter data have been used and/or until the maps converge (i.e., stop changing with further iterations). We use the regular 0.01° grid size (as for TM – our other statistical method). We iterate until the maps have converged, in this case 6 times. Similar to the transit matrix, the multi-iteration probability and travel time maps allow quantification of where and when PNPS discharge waters would be expected to show up throughout the Cape Cod Bay and its surroundings. The MI calculation is based on analysis of superimposed buoy data over a long period of time, so the resulting map envelopes all possible routes and assigns probability to each one.

2.6. Spectral clustering method (SC)

The optimized-parameter spectral clustering (Filippi et al., 2021 and references therein) splits the domain of interest into coherent regions with qualitatively different Lagrangian behavior, i.e., regions that have qualitatively different characteristics of transport and spreading. In the conventional application of this method, drifters are released at the same time, yielding fully-material Lagrangian coherent sets. In our case, however, the number of drifters available at any given time is limited. Therefore, to obtain adequate coverage we must use all available drifter trajectories at once, regardless of when they were released. By doing so, we combine trajectories released in different years, different seasons, different phases of the tide, and during periods of different wind and weather conditions, just as we did for all other methods. The resulting spectral clusters highlight regions where trajectories *on average* spread and evolve in a manner that is similar within each cluster and different between the various clusters. Thus, the method allows for the division of the domain into clusters with qualitatively different, in a statistical sense, transport and spreading pathways.

3. Results

Within the domain of interest there exist 417 drifters, whose pathways (i.e., trajectories) we use for our analysis (Fig. 1a). The first data point was obtained in 1989 and the last in 2019. Trajectories with gaps of more than 12 h are split into segments, and each segment is then treated as an independent trajectory. The average lifetime of a trajectory segment in our dataset is about 2 days. When binned into 0.025° bins, the number of GPS position pings per bin is > 10 for nearly all bins, and >40 for most bins (Fig. 1b). (The higher number of observations in the southeastern corner of the bay was associated with a study of turtle strandings in that area (Liu et al., 2019).)

3.1. BAMV

The binned and averaged ocean currents (Fig. 1c) suggest that the wide southward flow coming from the north splits into several branches as it approaches Cape Cod and the Bay. Part of the flow diverts offshore prior to entering the Bay, hugs Race Point located at the northern tip of Cape Cod and forms a strong southward current along the outer Cape. This outer-Cape flow is a component of the shelf current system that flows southward along the US east coast. We will refer to this current as the offshore branch. The magnitude of the offshore branch just to the north-northeast of Race Point exceeds 25 cm/s (or just under half a knot). The remainder of the wide southward flow proceeds into the Cape Cod Bay. As these waters try to penetrate further into the Bay, strips of the current peel away, curving towards Race Point to merge with the offshore branch. Thus, the current flowing southward into the Bay offshore of the PNPS weakens as it penetrates further into the Bay, decaying in magnitude to O(5 cm/s) as it reaches the eastern part of the Bay. Note that while the small-scale details of the mean velocity field, such as exact locations and shapes of small-scale recirculation features within Cape Cod Bay and areas of the strongest convergence, depend on the grid size used to bin the drifters, the overall geometry and magnitude of the mean currents are robust and insensitive to bin size (varying bin size from 0.01° to 0.03° yielded the same geometry and similar intensity of the dominant currents within the domain as described above). The geometry of the mean currents identified from the drifter data is schematically shown in Fig. 1e and agrees with the findings by Liu et al. (2019) and Manning et al. (2009). The eddy kinetic energy map (Fig. 1d) shows a maximum just north of the tip of Cape Cod and suggests that the time-dependent component of the currents is at least twice as large as the mean at most locations throughout our study domain. This is to be expected for a geographical region with strong tidal, seasonal, and wind-driven current variability.

3.2. STE

The PNPS is located in a dynamically sensitive region near the splitting point, where waters that head southward into the Bay separate from waters that peel off curving towards Race Point to merge with the offshore branch. This is confirmed by the simulated PNPS wastewater release (Fig. 1f), where mean advection by the binned and averaged

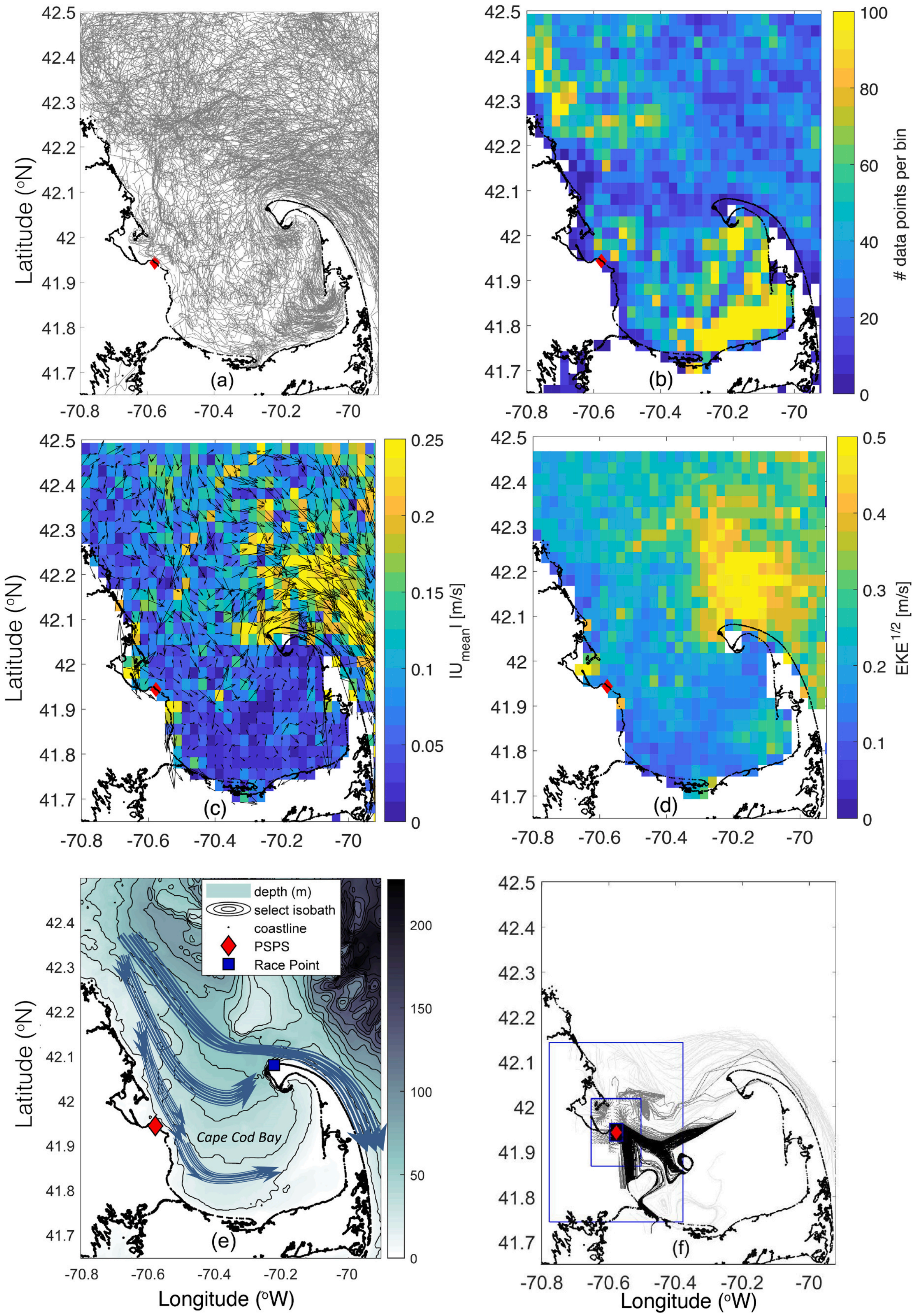

Fig. 1. For the drifter dataset used, spaghetti diagram showing trajectories of all available drifters (417 in total) deployed between 1989 and 2019 (a), number of data points per bin (b), mean velocity (c), eddy kinetic energy (d), schematic diagram showing the geometry of the flow in and around the Cape Cod Bay (e), and simulated trajectories advected by the mean field (f). In (f), black/dark grey/light grey trajectories start within the small/intermediate/large release boxes (blue

rectangles) around the PNPS (red diamond). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

ocean currents (Fig. 1c) causes wastewater released just south of the PNPS to penetrate into the Bay, and wastewater released to the north and/or slightly further offshore of PNPS (i.e., trajectories starting in the northeastern corner of the release boxes in Fig. 1f) to head towards Race Point. Note however, that some of the simulated water parcels that try to make it around the tip of Cape Cod end up on the beaches of the inner or outer cape adjacent to Race Point. Trajectories released further north/northeast of PNPS (i.e., trajectories starting in the northeastern corner of the largest release box) are more likely to successfully clear the tip of Cape Cod and its outer beaches. In STE, trajectories were advected by the coarse grain mean field and beaching is likely, at least partially, due to the unresolved details of the small-scale circulation around coastlines. In the real ocean, it usually requires a significant wind event to cause an ocean drifter to strand on the beach.

3.3. SDTD

The full-flow diffusivity ellipses (Fig. 2a) are significantly smaller within the Bay than everywhere outside of it, with the smallest values in the coastal regions (and slightly larger values toward the center of the Bay). This pattern suggests that the expected spreading of the PNPS wastewater released directly into Cape Cod Bay offshore off PNPS would be significantly weaker than for wastewater released outside the Bay. The ellipses are large in front of Race Point, with large values also extending along the coastal areas of the Outer Cape. This indicates that the spreading of the wastewater plume would be enhanced for the part of the plume that is able to successfully clear (i.e., curve around) Race Point. Diffusivity is strongly anisotropic almost everywhere, and ellipses generally align well with the mean currents in most locations, suggesting that the mean velocity shear is important. The eddy-induced diffusivities (Fig. 2b) are smaller in magnitude but share many properties with the full-flow diffusivities, i.e., the ellipses are still small within the Bay, large in front of Race Point, and strongly elongated at most locations. The 50% decrease in magnitude between the full-flow and eddy-induced estimates suggests approximately the same contribution from the mean flow and the eddy field to the spread of a wastewater plume.

3.4. TM

The transit matrix approach (Fig. 3) suggests that a wastewater plume released as a pulse in front of the PNPS will initially spread in all offshore directions – north, south, and east. The southward-heading portion of the plume proceeds into the Bay, turns east following the coastline of the inner Cape, and reaches the more quiescent eastern bay in about 1 week. The distribution within the eastern/southeastern bay during the 2nd week is similar to what it was after 10 days, suggesting that it would take a long time for this wastewater to leave the confines of the Bay. The portion of the plume that initially heads northward from PNPS reaches the maximum latitude of 42.3°N, at which point it turns to the southeast towards Race Point, merging with the offshore branch of the current (seen in the schematic diagram in Fig. 1e). After about 3 days, the leading edge of this feature approaches Race Point, and the trailing edge passes by Race Point after about 10 days. After 10 days, a roughly diagonal boundary extending to the southwest from Race Point separates the southeastern Bay, where the wastewater is still present, from the white wastewater-free areas to the northwest. Note also that a portion of the plume passes in close proximity to Race Point and the nearby beaches of the outer cape during days 3–15, suggesting the potential for radionuclide penetration and longer-term storage in the sediment/clay and beaches of these coastal regions after the main plume passes. Recent studies have shown that accumulation of radioactive cesium in beach sands can be a long-term source back to the ocean via tidal exchange with water within the beach sands (Sanial et al., 2017). Note that the pathways depicted in Fig. 3 (TM calculation) are more widespread than those in Fig. 1f (STE method). The difference between the STE and TM approaches is that the former accounts only for the transport caused by the time-mean currents (and thus depict the mean spreading pathways caused by the mean field in the absence of eddies), whereas the latter includes the influences of both the mean and the eddies (because it is based on real un-filtered drifter trajectories which

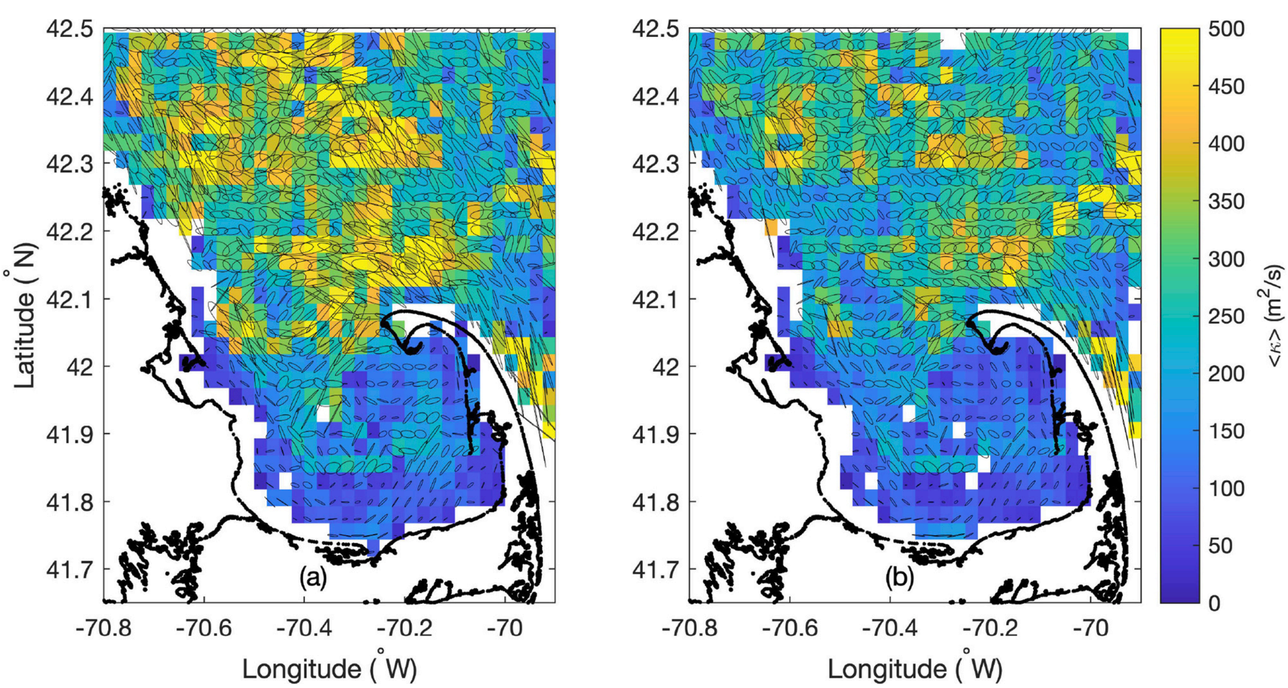

Fig. 2. Full-flow (a) and eddy-induced diffusivity (b).

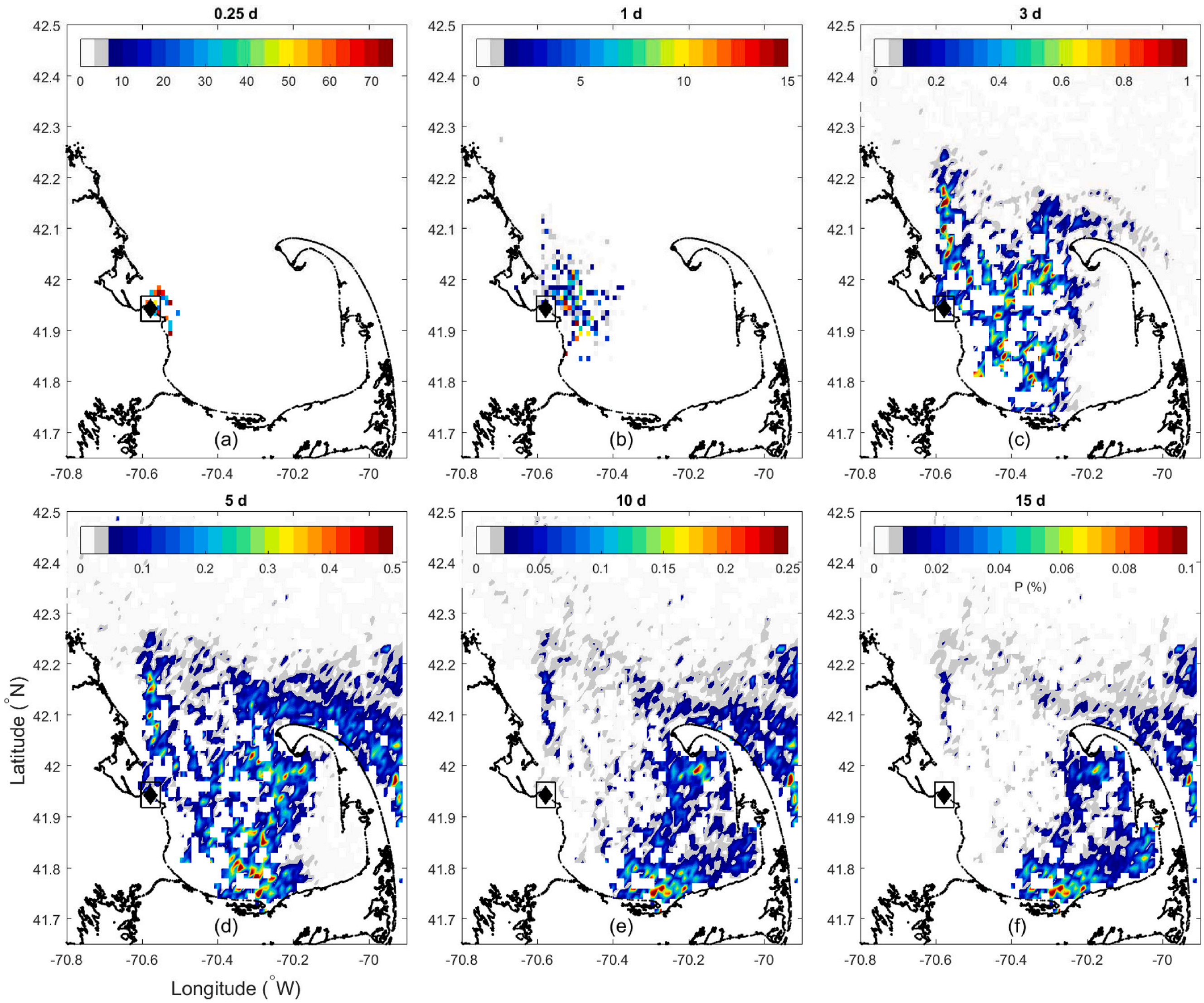

Fig. 3. Evolution of the wastewater plume computed using the transit matrix approach. (a–f) Percentage (P in %) of the initial wastewater concentration per bin after 0.5, 1, 3, 5, 10, and 15 days since release. Black rectangle around PNPS (black diamond) shows the release domain.

are advected by the full velocity field). We have already seen in the SDTD calculations that the eddies play an important role, and contribute as much as the mean, to the overall plume spreading. Thus, it comes as no surprise that the spread of the plume in the TM calculation is more widespread than in the STE approach. A similar comment also applies to the comparison between the MI and STE calculations.

3.5. MI

The multi-iteration probability map (Fig. 4) shares many features in common with the transit-matrix-based predictions. Just like Fig. 3 (TM), Fig. 4 suggests that initially the wastewater plume begins spreading in all directions from PNPS, i.e., north, south and offshore (east). Note that, similar to the TM method, MI is based on the un-filtered and un-averaged drifter trajectories, which are advected by the full velocity field and thus include the influences of both the mean and the eddies. Thus, by contrasting the MI with the STE, one can evaluate the overall influence of eddies. Specifically, comparing Fig. 4 with Fig. 1f shows that, unlike the southward and eastward routes, which are consistent with the mean current map, the northern route is not present in the mean, suggesting that it is of transient nature and must be caused by the time-dependent currents (could be seasonal, wind-driven, tidal etc.). The southward flowing component makes its way into the southeastern bay in approximately 7–10 days; the offshore flowing portion reaches Race Point in 3–6 days, hugs the tip of Cape Cod and merges with the coastal current along the Outer Cape; and the northward-flowing component proceeds north for about 1 day before turning to the southeast and heading towards Race Point to join the current flowing southward along the Outer Cape. The probability map shows a distinct location of higher accumulation (yellow/orange) in the Bay near 70.2°W, as well as elevated probability in the vicinity of Race Point and near the Outer Cape beaches.

3.6. SC

The foliation of the domain produced by the spectral clustering method consists of 4 clusters (Fig. 5b): i) a blue cluster encompassing the entirety of Cape Cod Bay to the south of Race Point (~42°N) (and including the southward flow along the Outer Cape), ii) a yellow cluster adjacent to a blue cluster that extends from Race Point to the west and to the north and contains trajectories that approach/pass close to Race Point, iii) a cyan cluster in the northwest, and iv) a red cluster in the northeast. The latter two contain trajectories that neither come close to Race Point nor penetrate far into Cape Cod Bay. The PNPS is located

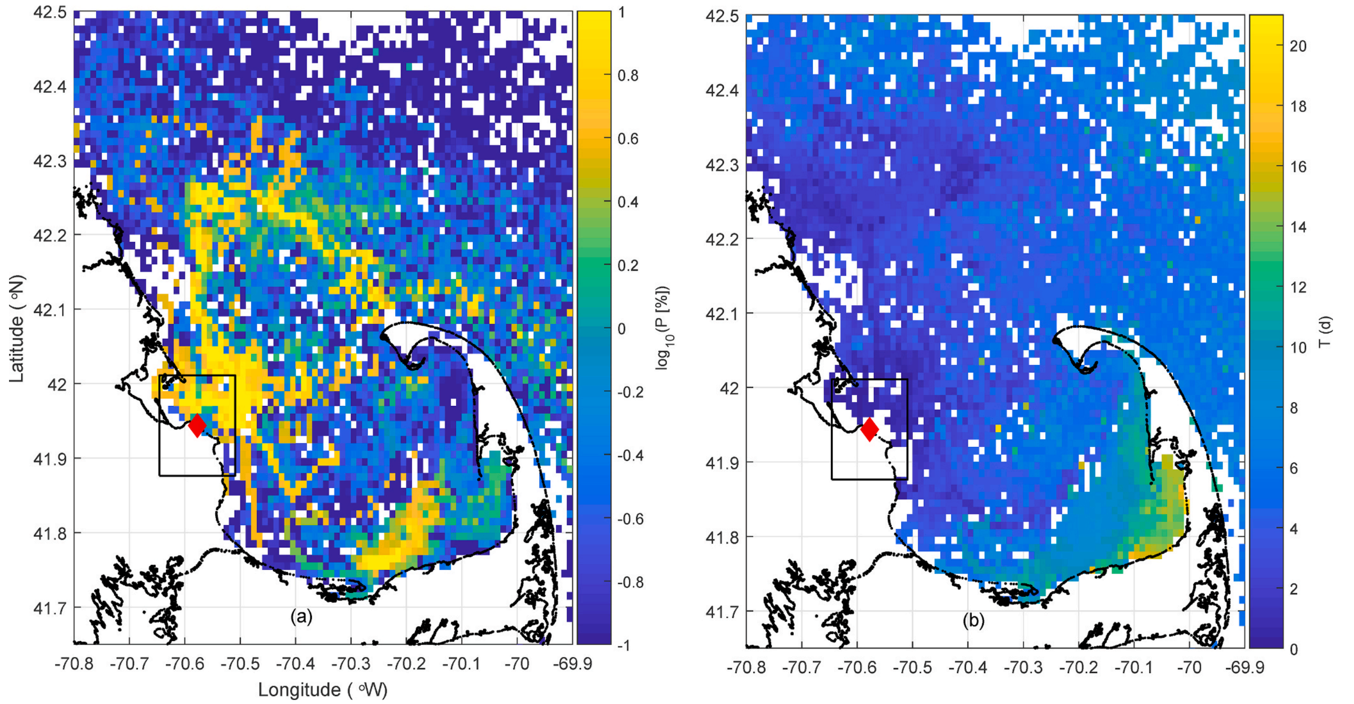

Fig. 4. (a) Probability (on a logarithmic scale for visibility) and (b) travel time (in days) maps computed using the multi-iteration method. Black rectangle around the PNPS (red diamond) marks the release box. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

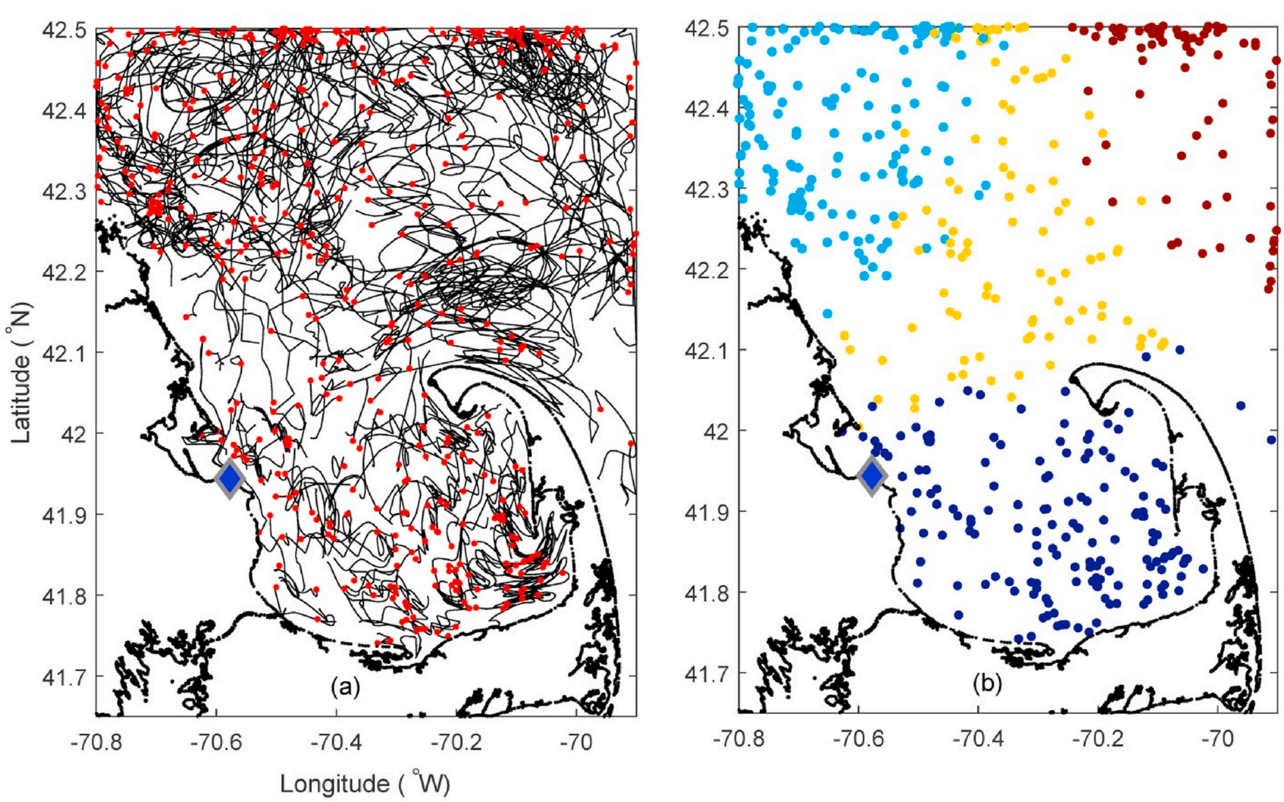

Fig. 5. (a) 1-day long segments of trajectories (red dot is the start) and (b) the corresponding spectral clusters (colors indicate different clusters). PNPS is shown with blue diamond. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

within the blue cluster (i) very close to its boundary with the yellow cluster (ii). One inference from this result is that PNPS wastewaters would be "most connected" to waters in the Bay, but that any part of the release that gets into the yellow region will be destined to flow towards Race Point and then along the Outer Cape and its beaches.

4. Discussion

We have looked at the available drifter trajectories in and around Cape Cod Bay to better understand the fate of the PNPS wastewater, were it to be released into the ocean. We have used a variety of techniques, each providing a piece of information about the geometry of the flow, the importance of transient currents vs. mean currents, the spreading intensity throughout the region, the spreading pathways and barriers, and the likely path of the wastewater plume.

In agreement with the prior knowledge of the geometry of the currents in this area (Liu et al., 2019), our results indicate that, in the mean, the flow coming into the domain from the north splits into two main branches as it impinges on the topographic barrier presented by Cape Cod Bay. The offshore branch curves to hug Race Point and then forms a strong southward current along the Outer Cape, or NE shoreline of Cape Cod. The in-shore branch, which proceeds southward into the Bay in front of PNPS, weakens as it penetrates the Bay, with strips of water peeling off the current and curving towards Race Point to merge with the offshore branch. The remaining flow proceeds counterclockwise around the Bay all the way to its more quiescent eastern elbow where residence times are longer than elsewhere in our domain. The spreading is significantly weaker inside the Bay than outside, with the time-dependent currents being as important as the mean. Both probabilistic approaches suggested that the wastewater plume originating in the vicinity of PNPS will initially spread from PNPS in all directions – north, east, and south. The southward flow will circulate around the Bay, reaching the eastern edge in about 1 week and has the potential to remain within the confines of the Bay for longer than 15 days. The eastward part of the plume will reach Race Point in about 2–3 days, curve around the tip of Cape Cod and flow southward along the Outer Cape. The part of the plume that originally heads north will take a sharp turn to the southeast after about a day, flow towards Race Point and then along the Outer Cape. The fact that the northern route is absent in the picture of mean currents suggests that it is generated by the transient currents, therefore, the timing of the release will likely affect the fate of the contamination.

Overall, the simulations suggest a high likelihood for the wastewaters to enter the Bay, with one area of elevated probabilities in the coastal region near 70.25°W, as well as near Race Point and the beaches of the Outer Cape. As the plume is advected and dispersed by the oceanic currents, the wastewater becomes diluted, so for a pulse release of the soluble radionuclides like tritium, the levels observed in our statistical model off Race Point and offshore of Dennis/Brewster at the time when the plume is passing by, are at least 100 times smaller than the initial concentrations at the time of the pulse release. Although the plume will be significantly diluted, the passing of the plume in close proximity to the coast has the potential to lead to the accumulation of some radionuclides into sediments (Sanial et al., 2017), and the long flushing times of the southern/eastern Bay further enhances this concern.

All 5 methods employed in our investigation required several user-defined parameter choices, such as bin sizes, the size of the wastewater release box in the two probabilistic approaches, and the duration of trajectory segments used in the spectral clustering method. We have varied all these parameters within reasonable limits and have determined that our results are relatively insensitive to the choices. Specifically, the mean velocity showed the same qualitative geometry and same velocity magnitudes for bin sizes from 0.01° to 0.03°. The probability and travel time maps stayed qualitatively similar when the wastewater release domain was made slightly larger or slightly smaller. Specifically, the same three pathways – northward, southward, and eastward from the assumed release region centered just offshore of PNPS – were still present and their associated travel times did not change significantly. The location of the probability hot spot within the Bay also remained the same. One difference between simulations with the larger/smaller release domain was in the relative importance of the northward-heading branch, which became less pronounced than the other 2 branches for the smaller release box simulations. This result further supports the inferences made from other methods that the exact location (s) and timing chosen for release are extremely important to the fate of the contaminants. The two most important spectral clusters (blue and yellow) stayed nearly the same when the duration of trajectory segments was varied from 0.5 days to 5 days. The main difference was that with 5 days, the number of available trajectories decreased so the clusters had fewer trajectories, and the exact location of the boundaries between the clusters became less well resolved.

With many different drifter datasets available both globally and regionally, the analysis presented in this paper is easily relocatable to other geographical regions. The 5 techniques that we have used seem to work well in tandem, complementing each other and highlighting different aspects of the problem. However, this list of techniques is by no means exhaustive as many other useful methods are available for untangling the complex transport processes at work in oceanic flows (see, for example, Hadjighasem et al., 2017; Haller, 2015; Balasuriya et al., 2018; Rypina et al., 2022; Serra et al., 2020; Froyland and Junge, 2018).

One of the most severe shortcomings of drifters is that they are restricted to two dimensions in space measuring the near-surface circulation and transport only. Another shortcoming, as mentioned previously, is that only fairly coarse spatial and no temporal resolution is achievable with the available drifter dataset. Were there more available trajectories, then seasonal and inter-annual variability, as well as the dependence of the spreading pathways on weather and wind conditions, could have been investigated by selecting the drifters by season, year, or wind direction/strength and repeating the analysis. With only 417 drifters, however, any such subsampling is challenging and would likely return statistically non-robust results due to a small sample size. Other means, such as numerical ocean circulation models, would be better suited to study temporal variability, three-dimensional aspects, small-scale details of the circulation patterns and spreading pathways, and, most importantly, sensitivity to the exact location of the outfall of the release pipe and the timing of the release. There are at least four regional ocean circulation models that cover Cape Cod Bay at spatial resolutions of 1–7 km and O(1 h) temporal resolution over multiple years (FVCOM, see Chen et al., 2012; DOPPIO, see López et al., 2020; GOMOFS, see Yang et al., 2019; NESS, see Wang et al., 2022 and references therein), which can potentially be used to address these issues in more detail. Satellite altimeters provide another type of data that is commonly employed in the studies of transport and mixing (see, for example, Rypina et al., 2011, 2012). However, with an area of only about 1500 km^2, Cape Cod Bay is too small to be reliably resolved in most satellite-based products such as altimetry-based geostrophic current maps.

Our analysis of the transport and dilution of PNPS wastewater would hold only for soluble, or so-called conservative, contaminants. However, many elements generated at nuclear facilities have strong affinities for binding with seafloor sediments and/or uptake by marine biota. As such, their fate is different than for a conservative element. Tritium – a radioactive form of hydrogen – is considered a conservative element that will track water, since it has similar chemistry to the hydrogen atom in water, H_2O. That being said, even tritium can exist in organically bound forms, which are more persistent in the biosphere (Eyrolle et al., 2018). For the non-tritium radionuclides, the affinities for seafloor sediments can be much higher than for tritium, for example 300,000 times higher for cobalt-60, and 4000 times higher for radioactive forms of cesium (ICRP publication 119, 2010). Release of such isotopes would result in accumulation of some fraction in muddy, organic rich coastal sediments near an outfall pipe. Radiocesium is also >100 times more likely to be incorporated into the muscle tissue of fish than tritium (ICRP publication 119, 2010; Buesseler, 2020). Likewise, strontium-90 is a common product of NPP activities, and it behaves in a geochemically similar fashion to calcium, so would end up preferentially in carbonate shells of shellfish and the bones of fish. In addition, the non-tritium radionuclides have higher potential health effects (higher dose coefficients; ICRP publication 119, 2010). Local retention in seafloor sediments and higher rates of uptake by marine organisms would be of greater concern for possible human health effects. One of the concerns with the PNPS situation is that there is no detailed accounting of what is in the PNPS waters proposed for discharge, and there are only vague assurances that the non-tritium isotopes will be removed prior to discharge. As explained above, the fates and transport in the ocean will differ for various radioactive contaminants (see Buesseler, 2020). Thus the wastewater transport studied here is just one part of the story, and the non-tritium isotopes would need to be considered in a more complete radiological assessment of potential releases from PNPS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The "Drifter Tracks from the NE US Shelf and beyond" dataset that was used in this paper is available from https://comet.nefsc.noaa.gov/erddap/tabledap/drifters.html or http://studentdrifters.org/drift.dat.

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