On simulating cold stunned turtle strandings on Cape Cod

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Abstract

Kemp's ridley turtles were on the verge of extinction in the 1960s. While they have slowly recovered, they are still endangered. In the last few years, the number of strandings on Cape Cod Massachusetts beaches has increased by nearly an order of magnitude relative to preceding decades. This study uses a combination of ocean observations and models to investigate the causes and transport of cold-stunned animals in Cape Cod Bay. The Finite Volume Community Ocean Model (FVCOM) is used here as an example of a well-respected high resolution model. First, using data from satellite-tracked drifters and local temperature moorings, the FVCOM ocean model was validated. The model was used to simulate the ocean currents in the Cape Cod Bay during periods of anomalous strandings and to explain stranding locations as observed by volunteers. Nearby observations and model estimates of water temperature and wind are used to document the forcing mechanisms associated with strandings at particular times and places. Finally, the origin of the stranding turtles was estimated by backtracking through modelled flow fields.

Key words: Kemp's ridley turtles; FVCOM model; ocean current; particle tracking

Introduction

Kemp's ridley is the smallest and the most endangered sea turtle in the world and shows little sign of recovery [1,2]. Their perilous situation is attributed primarily to the over-harvesting of their eggs during the last century. In 1970, it was listed by the U.S. Fish and Wildlife Service [3] as “endangered throughout its range” and it has received Federal protection under the U.S. Endangered Species Act of 1973 ever since [2].

During the past 18 years, Padre Island National Seashore (PAIS) has been using satellite telemetry to understand migratory patterns and habitat of adult Kemp's ridleys [4,5,6]. Kemp's ridley adults are primarily found in the Gulf of Mexico [7-8]. Juveniles are also found along the eastern seaboard of the United States as far north as Nova Scotia, Canada [9]. The adult Kemp's ridley turtles are mainly active in coastal waters less than 165 feet deep, and the smallest juveniles Kemp's ridley are found in shallow waters, often foraging in less than 3 feet of water [10]. Young sea turtles have ventured up the Northeast Coast, leaving warm seas to feed on crabs and other prey.

Sea turtles on the East Coast of the US swim to warmer waters to spend the winter. For example, turtles in the vicinity of Virginia, tend to migrate south in late fall each year [11,12,13]. However, even in Florida, significant mortalities have been reported [14] as a result of being caught in some water bodies/estuaries. In laboratory experiments, Schwartz [15] demonstrated that Kemp's ridleys become inactive at temperatures below 10°C, although they are somewhat more resistant than other species. If a sea turtle becomes cold stunned there is little chance of survival without assistance. Morreale, et al. [16] studied cold stunned stranding events in the late 1980s on Long Island, NY. Burke et al [17] specifically addressed the causes of these events and found one year, in particular, when fewer strandings occurred. They attributed this inter-annual variability to slight changes in the prevalent wind direction at the critical time of year when the water temperature fell below 10°C. As documented by Still et al, 2005, when Kemp's ridley's inside Cape Cod Bay are late in heading south and the water temperature gets below 10.4^{o}, they become "cold stunned" [18].

Kemp ridleys in Cape Cod Bay are unable to move south due to the presence of the Cape Cod landmass. These turtles, typically 2 to 3 years old, are sized between a dinner plate and a serving platter [19]. They are so small that we can not easily use the

satellite telemetry devices typically used to track adult turtles in Gulf of Mexico to track their position. In recent years, a large number of cold stunned Kemp's ridley turtles have been stranding on the shores of Cape Cod Bay on the eastern coast of the United States in late Fall. These turtles are extremely weak, often wash ashore, and need to be rescued by dozens of trained volunteers each fall. Since 1979, Wellfleet Bay Wildlife Sanctuary staff and volunteers have patrolled the beaches of Cape Cod, on the lookout for cold-stunned turtles, which are rapidly transported to the New England Aquarium for evaluation and rehabilitation. In the last few years, the number of strandings has increased by nearly an order of magnitude relative to the strandings in the preceding decades.

This paper explores the transport of cold stunned Kemp's ridleys using the Finite Volume Community Ocean Model (FVCOM), a numerical ocean model well-suited to simulating coastal ocean processes. First, we attempt to validate FVCOM by using drifter data and mooring data from the region. Secondly, we look at the number of sea turtles stranded in various towns along the shore of Cape Cod Bay from 2012 to 2015 and try to explain these distributions based on FVCOM-derived simulated particle tracks, wind records, and observations of water temperature.

Methods

FVCOM model

FVCOM is a prognostic, unstructured-grid, Finite-Volume, free-surface, three-dimensional (3-D) primitive equations Community Ocean Model developed originally by Chen et al [20]. FVCOM is solved numerically by a second-order accurate discrete flux calculation in the integral form of the governing equations over an unstructured

triangular grid. This approach combines the best features of finite-element methods (grid flexibility) and finite-difference methods (numerical efficiency and code simplicity) and provides a much better numerical representation of both local and global momentum, mass, salt, heat, and tracer conservation. The ability of FVCOM to accurately solve scalar conservation equations in addition to the topological flexibility provided by unstructured meshes and the simplicity of the coding structure has made FVCOM ideally suited for many coastal and interdisciplinary scientific applications [21].

FVCOM model has been run on several grids spanning the Northeast Continental Shelf of the US and is still evolving. The third generation grid (GOM3) was used in this experiment covering Gulf of Maine and Georges Bank waters and hourly flow fields are available from 1978 to 2015. The GOM3 grid was developed primarily for the prediction of coastal ocean dynamics, with horizontal grid resolution ranging from 20 meters to 15 kilometers and includes tides. The vertical domain was divided into 45 s-coordinate levels [22]. We also experimented on finer-resolution "MassBay" grid that had hourly flow fields available from 2011-2014.

Drifter observations

The surface drifters used in this study track the top meter of the water column [23]. This type is typically referred to as the "Davis-style" or "CODE" drifter first developed by Russ Davis for the Coastal Ocean Dynamics Experiment in the early 1980s (Fig 1) [24]. Our version of this drifter typically has a metal-frame and four fabric sails measuring 91 cm long and 48 cm wide. These units were deployed in the vicinity of Cape Cod from 1978 to 2010 with tracks archived for public access. More

than a thousand of these student-built drifters have been deployed off the New England coast in the past few decades [25].

Fig 1. Schematic of standard surface drifter from Poulain [24] (left) and photo of surface drifter used in this report being recovered after stranding in Barnstable MA (right).

Moored temperature observations

There are at least three different sets of moored ocean temperature observations available in the Northeast US. The Northeastern Regional Association of Coastal Ocean Observing System (NERACOOS) typically has several mooring sites in the Gulf of Maine [26]. In 2017, they added a mooring (CDIP) inside Cape Cod Bay. The NERACOOS Mooring A location is shown in Fig 2. The Environmental Monitors on Lobster Trap Project (eMOLT) [27] comprises another collection of moorings with 18+ years of hourly bottom temperatures from dozens of locations off the New England coast include several within Cape Cod Bay. Finally, the Mass Division of Marine Fisheries (DMF) maintains several diver-serviced bottom temperature times series at a set of shipwrecks off the Massachusetts coast.

Fig 2. Locations of moored observations used in this report including two NERACOOS moorings (blue triangles), five eMOLT moorings (red circles) and four Massachusetts Division of Marine of Fisheries moorings (green squares).

On using models and observations

Forward tracks through modeled flow compared with drifter tracks

Surface drifter tracks from 2012 to 2015 are used to quantify the difference between FVCOM model currents and observed Lagrangian currents. We limited drifter data to those with sample intervals less than 2.5 hours. This resulted in 55 drifter tracks in Cape Cod Bay that had a total of 1365 days. We also compared the model track to the drifter track by restarting the comparison every 3 days for a total of 454 comparisons. When the drifter trajectory is compared with the model trajectory, the "separation distance" and "distance ratio" are often used as two measures of accuracy. They are defined as the distance between the drifter point and the modeled track point at the same time and the ratio of separation distance to the drifter's total distance traveled, respectively.

Backtracking turtle trajectories

We would like to estimate the origin of stranded turtles based on backtracking particles through numerical models. However, we first need to get the simulated turtle off the beach in order to begin moving it backward through the water. The process of selecting a "short distance off the beach" is not easy. We experimented with multiple methods (simple to complex) to solve this problem. For the purpose of this study, we chose the simplest method which involves a) finding the nearest point on the model-based coastline to the stranding location, b) calculating the line from the specified stranding to that point, and c) then extending the line ***X*** km out to sea. After experimenting with several values, we chose to set "***X*** =1.5 km". The backward tracking is conducted by moving the simulated turtle with speed and direction as prescribed by the model at the nearest grid nodes with hourly time steps. The tracking is terminated when the estimated water temperature exceeds the cold-stunned level. For reasons discussed below, we chose this to be 10.5 ^{0}C.

Binned averaged current and wind to help explain strandings

The model data used is the hourly output of the FVCOM model as described in section 2.1 above. Even before looking at particle tracks, we first averaged the observed current, modeled current, and wind stress on 0.05 ° bins. The "observed current" is derived from averaging the first differences of the near-hourly drifter fixes within each bin. The "modeled current" in each grid cell is the average velocities of all nodes within each bin whenever drifters were present in the bin. While technically different types of current velocity (Lagrangian vs Eulerian), we assume they are the same. After removing the tidal effects by sequentially averaging over the solar (24 hour) and lunar (24.841) periods, we calculated the average surface current of each bin. The wind stress was derived from the same weather model that drives the FVCOM ocean model.

Turtle stranding data

The Kemp's ridley turtle data used in this experiment was provided by Mass Audubon's Wellfleet Bay Wildlife Sanctuary. These data include information on date and location of stranding for each cold-stunned Kemp's ridley Sea turtle from 1991 to 2015. Hundreds of trained volunteers have been participating in this project since 1978. Beach walkers cover the coastline each fall to document strandings and report their findings.

Sea-surface temperature observations

In addition to the modeled sea-surface temperature (SST) estimates available hourly, we also have observations of SST from satellite. While clear images are only available a few times per month in this region, they provide another snapshot

realization of the conditions in Cape Cod Bay. For the purpose of this report, we accessed the raw data prepared by the University of Delaware and posted via the MARACOOS.org website.

Results

Kemp's ridley strandings on Cape Cod

Fig 3 shows the number of Kemp's ridleys stranded on the shores of Cape Cod Bay from 1991 to 2015 (with some years 1994-1998 not available). As shown, the number of strandings vary from year to year but have increased dramatically in recent years.

Fig 3. 1991-2015 Cape Cod Bay turtle strandings.

Turtles were recovered in several towns each year between 2012 and 2015 (Figs 4 and 5). The towns with the largest numbers of strandings between 2012-2015 were located on the mid to outer Cape (Table 1). Among them, each town reported strandings in more than one year of the study period, and strandings were reported every year in Wellfleet and Brewster. While most stranding events occur on the Outer Cape, some occur Mid Cape. Our hypothesis is that year-to-year changes of stranding locations are primarily due to small changes in the surface current.

Fig 4. Total turtle strandings per town from 2012-2015. Most of the "Outer Cape" towns (green dots) had >400 strandings while some of the "Mid Cape" towns (purple) had ~200.

Fig 5. Chart of the number of strandings by town between 2012 - 2015 showing most in the first three Outer Cape towns.

Table 1. The top four towns with the largest number of strandings from 2012 to 2015

Years	1st	2nd	3rd	4th
2012	Dennis	Barnstable	Brewster	Wellfleet
2013	Brewster	Eastham	Dennis	Wellfleet
2014	Eastham	Truro	Wellfleet	Brewster
2015	Wellfleet	Truro	Eastham	Brewster

Verifying FVCOM model

After describing the distribution of strandings in different years and towns, we now turn to verifying the FVCOM model before using it to simulate turtle advection. Before any particle tracking is conducted, we first examine the bin-averaged current and wind. The current averaging is conducted for both the drifter observations and the model output and shown in Fig 6.

Fig 6. Surface current derived from all drifters (a) and FVCOM model (b), number of drifter observations prior to 2018 (c), and contoured bathymetry in meters (d). It is clear from panel c that there are relatively few drifter observations inside Cape Cod Bay compared to other parts of Mass Bay and the ocean side of Cape Cod.

If we derive the mean field from drifters whenever there was GOM3 model data available (<2015), we get the vector plot Fig 6a and compare it to the model-derived field in Fig 6b. In a mean-flow sense, the model does well to estimate the flow of the coastal waters in this region. While there are some areas of discrepancies in, for example, the middle of the bay, most of the region is resolved by the model. When we

calculate the overall mean differences (observed-mean), we find values of X and Y for the eastward and northward flows, respectively. The variability of the flow is less resolved with the mean standard deviations of these means being 0.07m/s and 0.09m/s, respectively. Given additional drifter deployments in Cape Cod Bay providing more observations of current (Fig 6c) especially in recent years (2016-2017), we derived a new mean field in Fig 6d showing very small subtidal mean flow field.

We next compare observed and modeled drifter tracks directly. The results are shown in Fig 7. The 3-day "separation distances" (defined earlier) are mainly distributed around 20 km, the minimum value is close to 0km and the maximum is 80 km or more; while the "distance ratios" are distributed around 0.2, the minimum value is close to 0 and the maximum value is above 1.0. Based on these comparisons, we estimate that the FVCOM model can be used to simulate particle pathways with an uncertainty of 200 m per kilometer of trackline.

Fig 7. The 3-day separation distance and the distance ratio between observed and modeled drifter track.

Taking 2012 and 2013 as an example, we compared the surface temperature monitored by a mooring and the temperature simulated by the nearest FVCOM model grid cell (less than 1km away). As shown in Fig 8a and Fig 8b and Table 2, the surface temperature monitored by NERACOOS mooring A is close (<0.4 ^{o}C) from the temperature simulated by FVCOM. We also compared the bottom temperature monitored by a nearby (again <1km from model grid node) eMOLT station and the temperature simulated by the FVCOM model, as shown in Fig 8c and Fig 8d. FVCOM bottom temperatures were less accurate near the bottom but still within 0.6 ^{o}C of the observed.

Fig 8. Observed (NERACOOS Mooring A) vs modeled (FVCOM) surface (2 meters) temperatures in 2012 (a) and 2013 (b). Observed (eMOLT RM04) vs modelled (FVCOM) bottom temperatures in 2012 (c) and 2013 (d).

Table 2. Observed minus modeled temperatures where NERACOOS "Mooring A" is observed at the surface and eMOLT "RM04" is observed at the bottom.

Time	index	Surface temperature	Bottom temperature
		NERACOOS-FVCOM	eMOLT-FVCOM
2012	mean	-0.385	-0.540
	std	0.334	0.517
2013	mean	-0.220	-0.600
	std	0.267	0.500
2014	mean	-0.087	NA
	std	0.270	NA

Examining binned current and wind

Despite recent efforts to survey the bay from both ships and planes, we do not know the exact location of the cold stunned turtles in the bay or in the water column. However, considering that the cold-stunned turtles are not capable of swimming, we assume they generally follow the surface currents with some effects by the wind and waves. It is expected that more skillful predictions of stranding positions may be made using observed ocean surface currents and wind stress to numerically advect water parcels forward. Fig 9 shows the number of turtles stranded on the shores of Cape Cod Bay per day in late 2014 with most occurring the week of November 21st. Fig 10 maps the mean current and the mean wind stress from November 18 – 23, 2014, and the distribution of the stranded sea turtles for these six days.

Fig 9. The number of turtles stranded on Cape Cod Bay beaches in Nov-Dec 2014.

Fig 10. November 18-23, 2014 mean wind (black arrows) with November 3, 2014 sea surface temperature (a), Mass Bay grid simulation of mean ocean surface currents (black arrows) during that time overlaid on surface current variance ellipses (pink) (b), and distribution of turtle strandings by town with November 19, 2014 sea surface temperature (c) , and mean wind for the entire month of November 2014 with December 26, 2014 sea surface temperature (d). The legends are posted on the land mast on the western side of the charts. The largest red dot in panel c denotes 260 turtles stranded in Eastham during the period 18-23 November 2014.

From November 18, 2014 to November 23, 2014, as depicted on the turtle stranding map (Fig 10c), Truro, Wellfleet, and Eastham had the most strandings (253, 225, and 260, respectively), and their positions are consistent with the oceanic currents and winds shown by the simulated current and wind maps (Fig 10a and 10b), distributed in the area where currents and wind stress are most intense, and in their direction. It can be seen that the combination of ocean current and wind calculated by FVCOM model can be used to explain the general distribution of strandings. Comparing the mean wind for one week in mid-November 2014 (Fig 10a) to the mean wind for the entire month of November 2014 (Fig 10d), we see the intensity of the mid-November period explains the unusually high rate of strandings on the Outer Cape. The intensity of these events is best described in the form of time series plots below. In the future turtle rescue work, FVCOM 3 day forecast model can be used to simulate stranding events and help volunteer beach walkers focus their efforts.

As previous studies have found, when the water temperature of the Cape Cod Bay is less than 50F (10℃), the metabolism of Kemp's ridley turtle will slow to the point where they are unable to move and are at the mercy of the wind, waves, and currents [18]. As shown in Fig 11, we set up 10 temperature detection points and 10 wind stress monitoring points across Cape Cod Bay and Mass Bay to extract the temperature and wind stress simulated by the model. In the following plots (Figs 12-14), we examine the relationship between wind stress and strandings especially when the ocean temperature is below 10.5 ^{o}C.

Fig 11. Ten modeled wind stress points (green dots) and ten modeled surface temperature points (green).

Fig 12. 2012: Top panel shows wind stress (Pa) direction shown in green vectors (north up) and magnitude in purple. Bottom panel shows Mid-Cape strandings (blue bars) the Outer-Cape strandings (red bars), modeled surface temperature (green line), and observed bottom temperature (blueline) in 2012.

Fig 13. 2013: Top panel: Wind stress with direction shown in green vectors (north up) and magnitude in purple. Bottom panel: Mid-Cape (blue bars) and Outer-Cape (red bars) strandings, modeled surface temperature (green line), and observed bottom temperature (blueline) in 2013.

Fig 14. 2014: Top panel: Wind stress with direction shown in green vectors (north up) and magnitude in purple. Bottom panel: Mid-Cape strandings (blue bars), Outer-Cape strandings (red bars), modeled surface temperature (green line), and observed bottom temperature (blueline) in 2014.

Figs 12-14 show the relationship between the wind stress (top panels), and the number of strandings in "Outer Cape" and "Mid-Cape" (bottom panels) towns in 2012, 2013, and 2014, respectively. The average of the surface temperature simulated by all the FVCOM model points (specific model sites shown in Fig 11) and the average of the bottom temperature observed in Cape Cod Bay (specific observation sites shown in Fig 2) are also plotted in the bottom panels. The wind stress vector is the average simulated by FVCOM model points (sites shown in Fig 11). When the temperature is less than 10.5 ^{o}C and the wind stress from a particular direction is greater than ~0.4 Pa, the strandings generally increase but both conditions must be met. In the case of 2012 (Fig 12), for example, the strong wind in early November resulted in near-zero strandings since the water temperature was still above 11°C. In the case of 2013 (Fig 13), there was a pair of events with strong northwesterly wind

events at the end of November that coincided with a drop in temperatures resulting in peaks in strandings around 26 November and 1 December. Note the strong winds (>0.4Pa) in mid-December 2013 resulted in very few strandings presumably due to the turtles having fled or already stranded by that time. In the case of 2014 (Fig 14), the wind in mid-to-late November was not strong but it was persistently from the west over many days with a drop in both surface and bottom temperature of a few degrees which evidently resulted in historically high amounts of strandings.

In order to quantify the relationship between wind stress and the number of strandings, we calculated the correlation between wind stress and the number of strandings when the temperature was below 10.5^{o}C. As noted above, it is not only the strength of the wind that may be important but the persistence of the wind over time. For this reason, we chose to calculate the "3-day sum of the windstress components" . Fig 15 (left hand panels) shows the correlation between the number of turtle strandings in "Outer Cape" towns and the 3-day sum of the **eastward** wind stress in 2012, 2013, 2014 and mean respectively. Fig 15 (right hand panels) show the correlation between the number of turtles strandings in "Mid Cape" towns and the **southward** wind stress in 2012, 2013, 2014, and mean respectively. In most cases, the correlation is greater than 90% and exceeds 95% in several cases. Wind stress and the number of strandings per three days show a linear correlation.

Fig 15. Linear correlations between eastward (left) and southward (right) components of the wind stress and number of strandings (summed over 3 days) in 2012 , 2013 ,2014 and mean (2012-2014) for Outer Cape (left) and Mid Cape (right) towns.

In all of the above cases (2012-2014), it is clear that water temperature is important as well as the wind so it is necessary to understand the change of ocean temperature before estimating the origin of stranded turtles. Time series of surface temperature are extracted from 10 FVCOM grid nodes across Cape Cod Bay (Fig 16). The temperature across the 10 nodes is similar, dropping to 10.7 ^{o}C on November 17 in both years. As is shown in this figure, there is very little spatial variability in the surface temperature across the bay and any one monitoring site could potential work as a marker of change. If one site has cold stun conditions, they all do.

Fig 16. Simulation of surface temperature for Cape Cod Bay and its adjacent waters in 2012 (a) and 2013 (b). The locations a-j are plotted in Fig 11.

We backtracked turtles for 2012 and 2013[1]. Using the hourly currents from FVCOM model, we selected the 167 turtle strandings in these years who's simulated trajectory stayed off the beach. In other words, we focus on only those 167 cases where the backtracking generated origins within the bay (Fig 17). We also looked at the estimate of temperature along their track (Fig 18). In these time series we see that a) many of the stranded turtles were exposed to <10.5 ^{o}C water in mid-to-late November and b) there were more December stranding events in 2012.

Fig 17. The backtracked positions of the turtles in 2012 and 2013. Red dots show landing locations in November and December. Blue and green dots show estimated locations of back-tracked turtles that stranded in November and December, respectively, when they first encountered <10.5^{0}C. water. This assumes passive (non-swimming) turtles were only transported by the current when the modeled surface temperature is less than 10.5 ^{0}C. The blue

[11] Note: Since there were evidently issues with 2014 model hindcast, we chose to focus only on the previous two years in this analysis.

line is one example of backtracking a turtle that landed just south of Boston Harbor in December. According to the model, that turtle was first cold-stunned off Gloucester, MA.

We might ask where were the turtles that stranded in November located when they were first exposed to <10.5 ^{o}C surface waters? Our results show that turtles stranded in November 2012 and 2013 may be cold stunned at a variety of locations (blue dots in Fig 17) primarily in Cape Cod Bay but some in Massachusetts Bay. Turtles stranded in December 2012 and 2013 (green dots in Fig 17) may originate even further away, some as far as northern Massachusetts Bay. After first being exposed to <10.5 ^{o}C surface waters, the turtles are evidently in temperatures that vary considerably but gradually decrease by a few degrees at most before stranding (Fig 18).

Fig 18. Modelled temperature of backtracked surface particles in 2012 (top panel) and 2013 (bottom panel).

Discussion

Although the state-of-the-art coastal ocean models like FVCOM can help simulate cold stunned turtle pathways, there are a variety of issues to consider: First, uncertainty in the numerically simulated drifter tracks result in differences of up to several kilometers per day relative to the observed satellite-tracked drifter tracks. Obviously, there is significant uncertainty in the backtracking results shown in Fig 17. The 200-meter-per-kilometer difference in modeled vs observed trajectory shown earlier grows over long distances and time so that the numerical circulation models

and particle tracking routines will need to be improved considerably before these particle tracking tools can be used confidently and operationally.

Simulated trajectories might also differ from actual trajectories due wind and waves influencing cold stun turtle trajectories. There is a growing body of literature on surface wave effects on the transport of surface particles. Much of this research comes from the coast guard search and rescue operations [28]. Methods have been devised to add the effects of multiples forces including direct wind effect, breaking waves [29], and Stokes drift [30] and these will need to be considered in future work.

Additional uncertainties are introduced with the tracking methodology near the boundary of the model grid (i.e. in shallow waters near the shoreline). We need to further explore algorithms for forward and backward particle tracking near the coast. Hence, it will be necessary to improve the accuracy of both the circulation models like FVCOM with more data assimilation but we also need to improve our particle tracking models with both the effects of wind and waves and processes near the coast.

Despite these limitations, models like FVCOM are improving every year particularly with increasing grid resolution, incorporation of more realistic bathymetry, and more observations to assimilate. In order to examine the effect of different grid resolution, for example, we conducted a sensitivity study comparing particle tracks on the "GOM3" vs "MassBay" grid (Fig 19). It can be seen here that the particles released on the GOM3 grid stranded on the Cape Cod beaches faster than those released on the MassBay. While the final stranding locations would likely be similar, the particles on the latter grid were not yet stranded at the end of the week-long simulation.

Fig 19. Comparing particle tracks on the GOM3 (left) and MassBay (right) grid during the week of 18-25 Nov 2014.

Still more observations are needed to monitor in-situ conditions throughout Cape Cod Bay including more realizations of the deeper currents not depicted by the standard surface drifters used here. There is uncertainty in both the deeper currents and the depth at which the turtles generally reside during this critical time in the fall.

As the frequency of extreme weather events is apparently on the increase [31], the chances of turtles being suddenly surprised by wind and temperature changes will increase. As more tropical species migrate north with warming conditions, will we see a larger sea turtle population in Cape Cod Bay in the future and will that result in larger strandings?

Conclusion

With some specified degree of uncertainty, the ocean current and temperatures simulated by the FVCOM ocean model is similar to that observed by satellite-tracked drifters and moored observations. The model can help predict the strandings of the Kemp's ridley turtle on the shores of Cape Cod and also be used to backtrack their source. In the forward prediction runs, the FVCOM model helped explain the anomalously large stranding event that occurred on Outer Cape Cod between November 18 – 23, 2014. In general, the geographic distribution of standings is consistent with the model simulation of ocean current and wind. Given these findings, coastal ocean models such as FVCOM can help explain the general locations of strandings and may help volunteers to rescue turtles in the future.

In the backtracking experiments, the FVCOM model was used to estimate the origination of stranded Kemp's ridley turtles in 2012 and 2013, showing with a specified degree of uncertainty that most turtles stranded in November were originally located in a variety of locations in both Cape Cod Bay and Massachusetts Bay when

they were first exposed to cold-stun temperatures (<10.5 ^{o}C). The turtles stranded in December may have originated well outside Cape Cod Bay just a few weeks earlier.

There are still many uncertainties as to when the turtles are cold-stunned but a simple regression of different components of the wind stress (with water temperatures below the 10.5^{o}C threshold) vs number of strandings indicate that values greater than 0.4 Pa will induce more stranding events (r^2=95). As expected, strong winds out of the west will result in Outer Cape strandings and strong winds out of the north will result in Mid-Cape strandings.

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References

1. Plotkin, PT. National Marine Fisheries Service and U. S. Fish and Wildlife Service Status Reviews for Sea Turtles Listed under the Endangered Species Act of 1973. National Marine Fisheries Service, Silver Spring, Maryland, 2009. 109-116.
2. National Marine Fisheries Service, U.S. Fish and Wildlife Service, and Secretaría de Medio Ambiente y Recursos Naturales . Bi-national Recovery Plan for the Kemp's ridley Sea Turtle (Lepidochelys kempii). Second Revision. 2011. National Marine Fisheries Service, Silver Spring, Maryland, USA.
3. U.S. Fish and Wildlife Service. List of endangered foreign fish and wildlife. Federal Register 1970;35:18319−18322.
4. McClellan, CM, Read AJ, Cluse WM, and Godfrey MH. Using telemetry to mitigate the bycatch of long-lived marine vertebrates. Ecological Applications 2009;19(6):1660-1671.
5. Putman, NF and Mansfield KL. 2015. Direct evidence of swimming demonstrates active dispersal in the sea turtle “lost years.” Current Biology 25:1-7.
6. Shaver, DJ, Hart KM, Fujisaki I, Rubio C, Sartain AR, Pena J, et al Foraging area fidelity for Kemp's ridleys in the Gulf of Mexico. Ecology and Evolution 2013;3(7):2002-2012.
7. Shaver, DJ, Schroeder BA, Byles RA, Burchfield PM, Peña J, Márquez R, et al. Movements and home ranges of adult male Kemp's ridley sea turtles (Lepidochelys kempii) in the Gulf of Mexico investigated by satellite telemetry. Chelonian Conserv. Biol. 2005;4:817–827.

8. Shaver, DJ, Rubio C. Post-nesting movement of wild and head-started Kemp's ridley sea turtles (Lepidochelys kempii) in the Gulf of Mexico. Endanger. Species Res. 2008;4:43–55.

9. Bleakney, JS. Four records of the Atlantic ridley turtle, Lepidochelys kempi, from Nova Scotia. Copeia 1955;2:137.

10. Kemp's ridley Sea Turtle. Lepidochelys kempi. URL: http://www.docin.com/p-984318341.html.

11. Bianca SS, David MK, Marjorie A.M., Susan GB, Katherine LM, James PM. Consequences of drift and carcass decomposition for estimating sea turtle mortality hotspots. 2017;Ecological Indicators,84:391-396.

12. Keinath, JA, Musick JA, Byles RA. 1987. Aspects of the biology of Virginia's sea turtles: 1979-1986. Virginia J. Sci. 38(4):329-336.

13. Byles, RA 1988. Behavior and ecology of sea turtles from Chesapeake Bay, Virginia. Ph.D. dissertation, College of William and Mary, Virginia Institute of Marine Science, Gloucester, VA.

14. Blair EW, Ehrhart LM. Hypothermic Stunning and Mortality of Marine Turtles in the Indian River Lagoon System, Florida. American Society of Ichthyologists and Herpetologists. 1989;3:696-703.

15. Schwartz FJ. Behavioral and tolerance responses to cold water temperatures by three species of seaturtles (Reptilia,Chelonidae) in North Carolina. Fla Mar Res Publ.1978;33:16-18 .

16. Morreale SJ, Meylan AB, Sadove SS, Standora EA, et al. Annual Occurrence and Winter Mortality of Marine Turtles in New York Waters. Journal of Herpetology, 1992;26(3):301–308. JSTOR, www.jstor.org/stable/1564885.

17. Burke VJ, Standora EA, Morreale SJ. Factors Affecting Strandings of Cold-Stunned Juvenile Kemp's ridley and Loggerhead Sea Turtles in Long Island, New York. Copeia, 1991;4:1136–1138. www.jstor.org/stable/1446115.9.

18. Still BM, Griffin CR, Prescott R. Climatic and oceanographic factors affecting daily patterns of juvenile sea turtle cold-stunning in Cape Cod Bay, Massachusetts. Chelonian Conserv Biol. 2005; 4: 883–89 0

19. Gorman J. A Surge of Stranded Turtles. The New York Times. URL: https://www.nytimes.com/2014/12/13/science/a-cape-cod-mystery-hundreds-of-sea-turtles-stranded-on-beaches.html. 2014.

20. Chen C, Liu H., Beardsley RC. An unstructured, finite-volume, three-dimensional, primitive equation ocean model: application to coastal ocean and estuaries. J. Atm.&Oceanic Tech., 2003a;20: 159-186.

21. Chen C, Beardsley RC, Cowles G, Qi J, Lai Z, Gao G, et al. An Unstructured Grid, Finite-Volume Coastal Ocean Model FVCOM User Manual. 2011. SMAST/UMASSD-11-1101.

22. The unstructured Grid Finite Volume Community Ocean Model (FVCOM). 2014. URL: http://fvcom.smast.umassd.edu/2014/01/17/1-research-gulf-model-domain/

23. Lynch DR, Greenberg DA, Bilgili A , McGillicuddy DJ, Manning JP, Aretxabaleta AL . Particles in the Coastal Ocean Theory and Applications. Cambridge University Press, America. 2015, pp. 20-21

24. Poulain P. Drifter observations of surface circulation in the Adriatic Sea between December 1994 and March 1996. Journal of Marine Systems, 1999;20: 231-253.

25. Manning JP, McGillicuddy DJ, Pettigrew N, Churchill JH, Incze L. Drifter Observations of Maine Coastal Current Drift. Continental Shelf Res. 2009;doi:10.1016/j.csr.2008.12.008.

26. The GoMOOS Moored Buoy Design. URL: http://gyre.umeoce.maine.edu/GoMoos/oceans2003.pdf.

27. Manning JP, Pelletier E. Environmental Monitors on Lobster Traps: longterm temperature observations from New England's bottom waters. Jour. of Operational Oceanography. 2009;2:25-33.

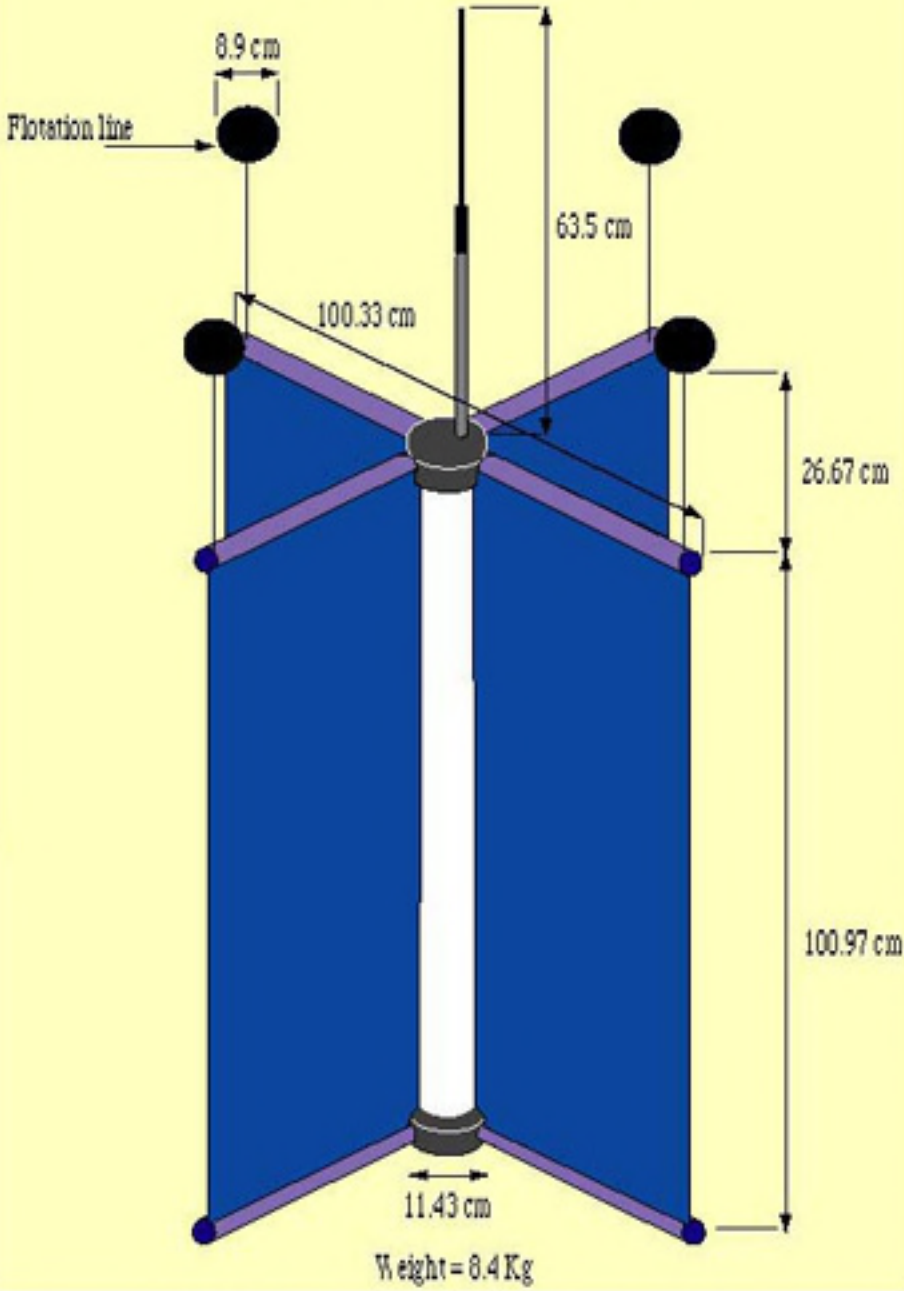
28. Breivik Ø, Allen AA, Maisondieu C and Roth JC. Wind-induced drift of objects at sea: the leeway field method. 2011 doi:10.1016/j.apor.2011.01.005

29. Carniel S, Warner JC, Chiggiato J, and Sclavo M. Investigating the impact of surface wave breaking on modeling the trajectories of drifters in the Northern Adriatic Sea during a wind-storm event. Ocean Modelling. 2009;30:225-239.

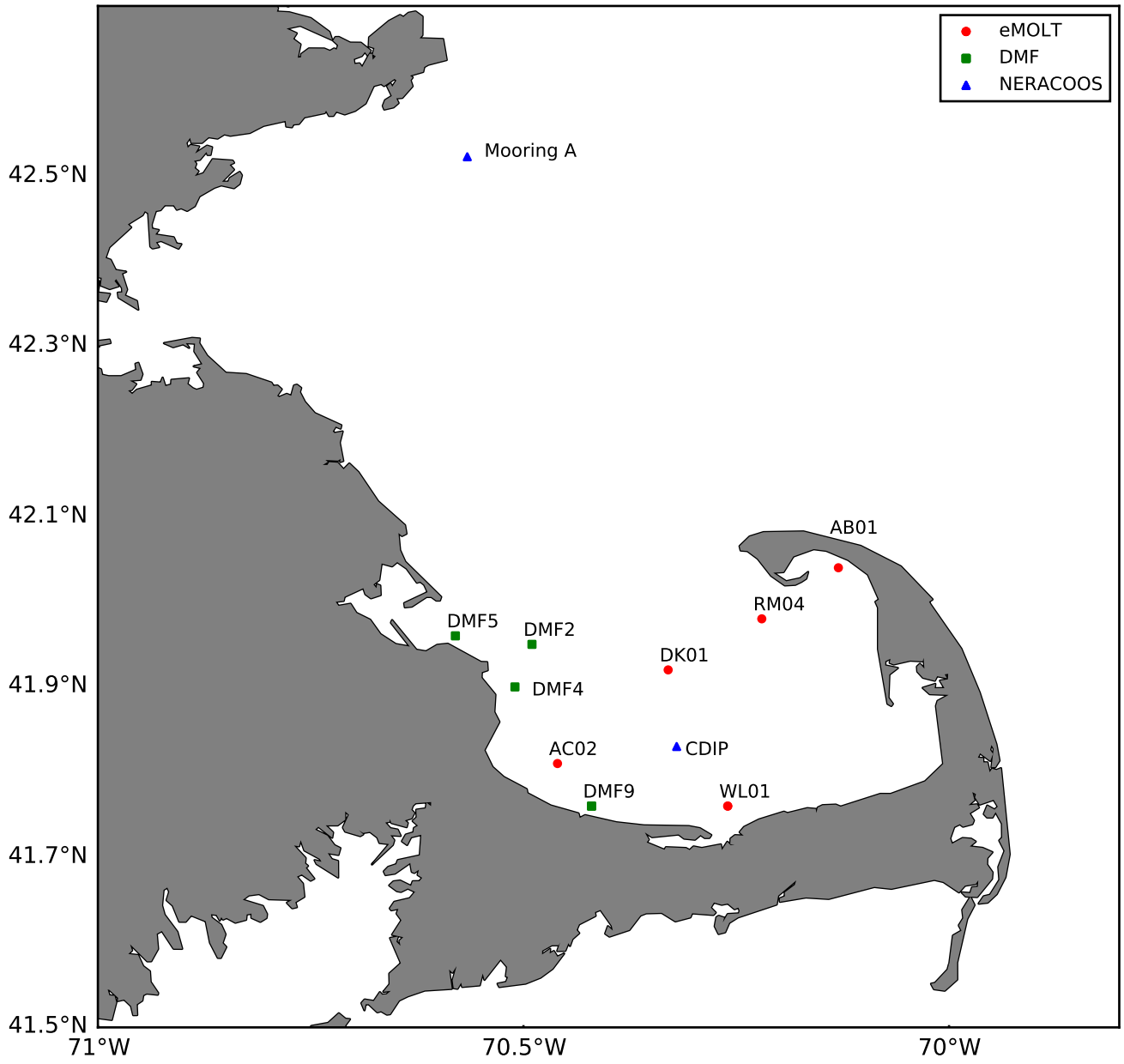
30. Röhrs J, Christensen, KH, Hole, LR, et al. Observation-based evaluation of surface wave effects on currents and trajectory forecasts. Ocean Dynamics 2012;62: 1519-1533.

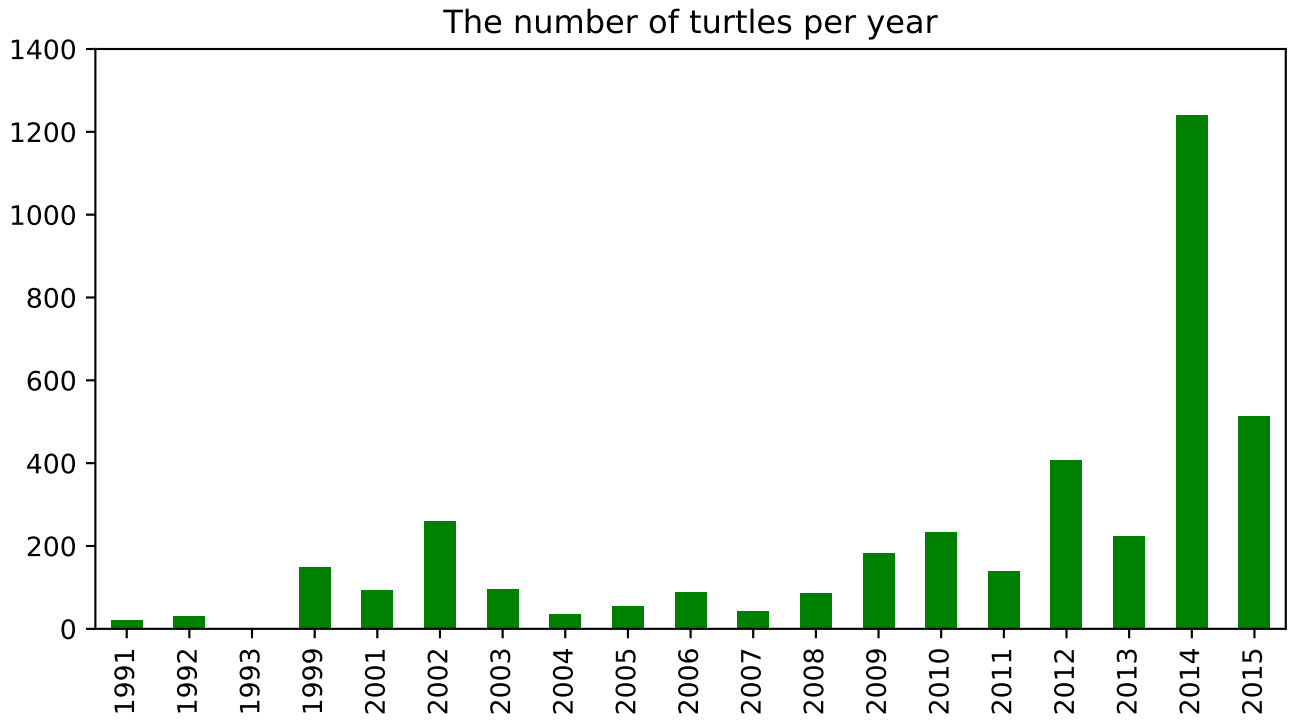
31. Vose, RS. and Coauthors. Monitoring and understanding changes in extremes: Extratropical storms, winds, and waves. *Bull. Amer. Meteor. Soc.* 2014;**95**:377–386. doi:https://doi.org/10.1175/BAMS-D-12-00162.1.

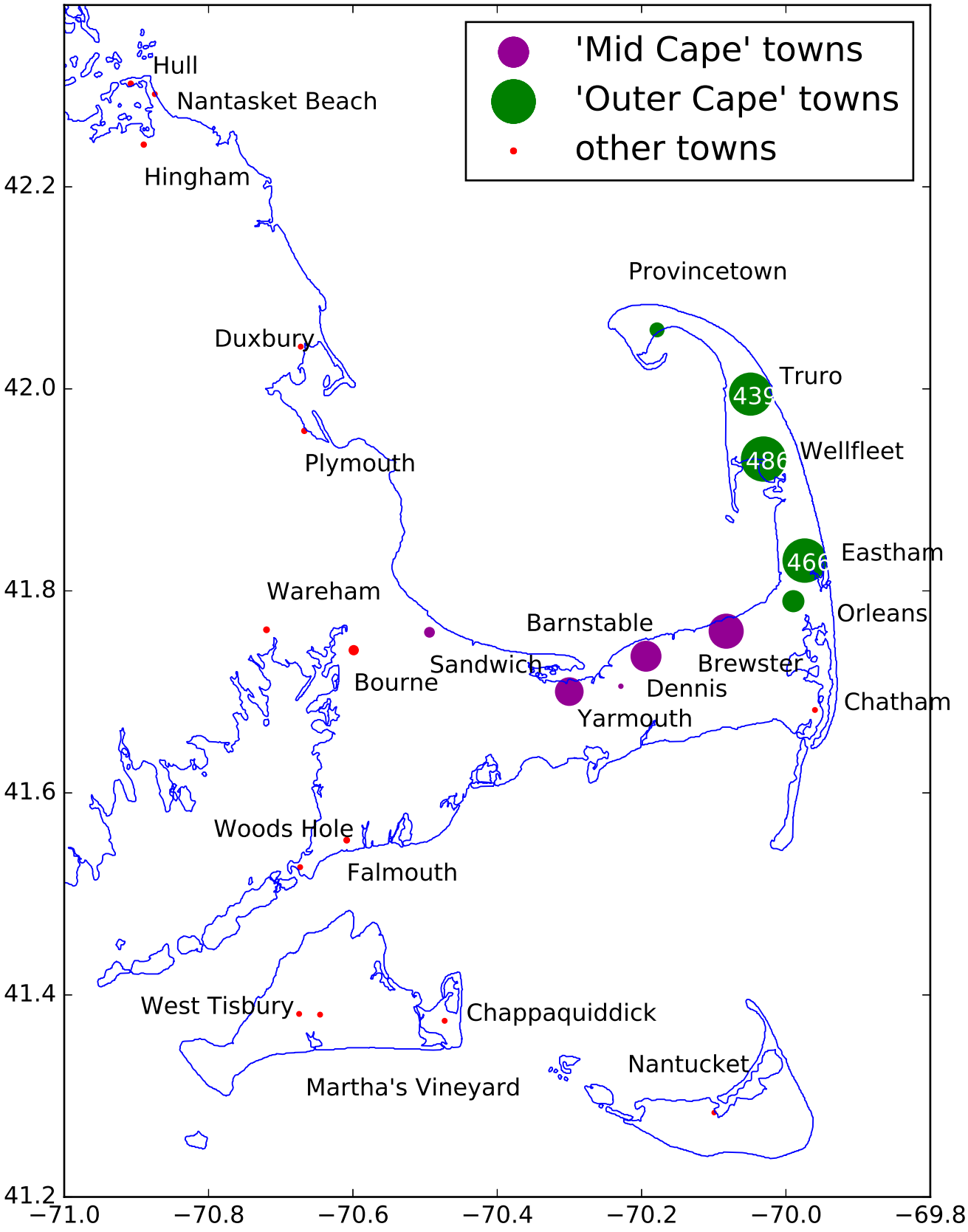
CODE SURFACE DRIFTER

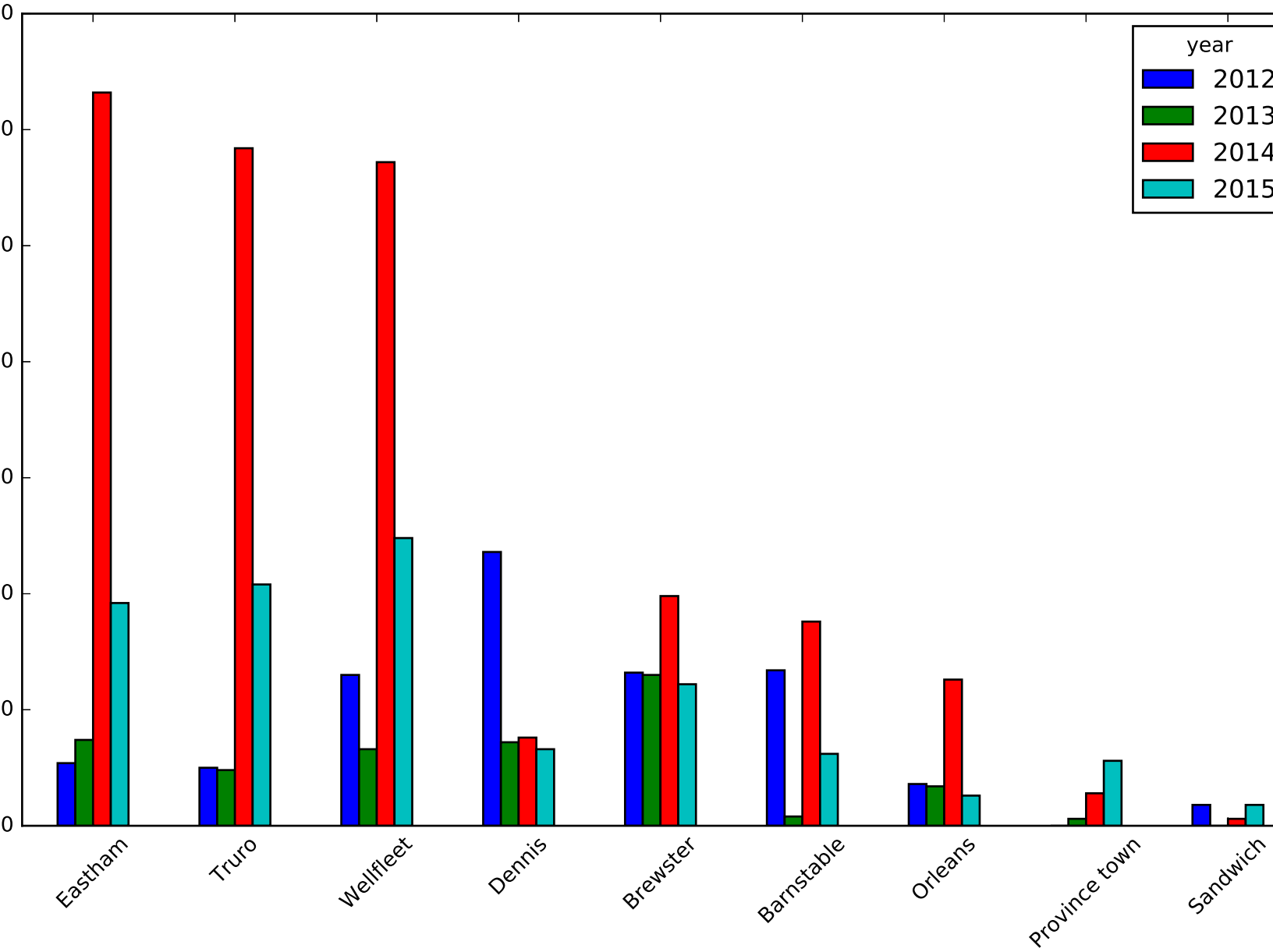


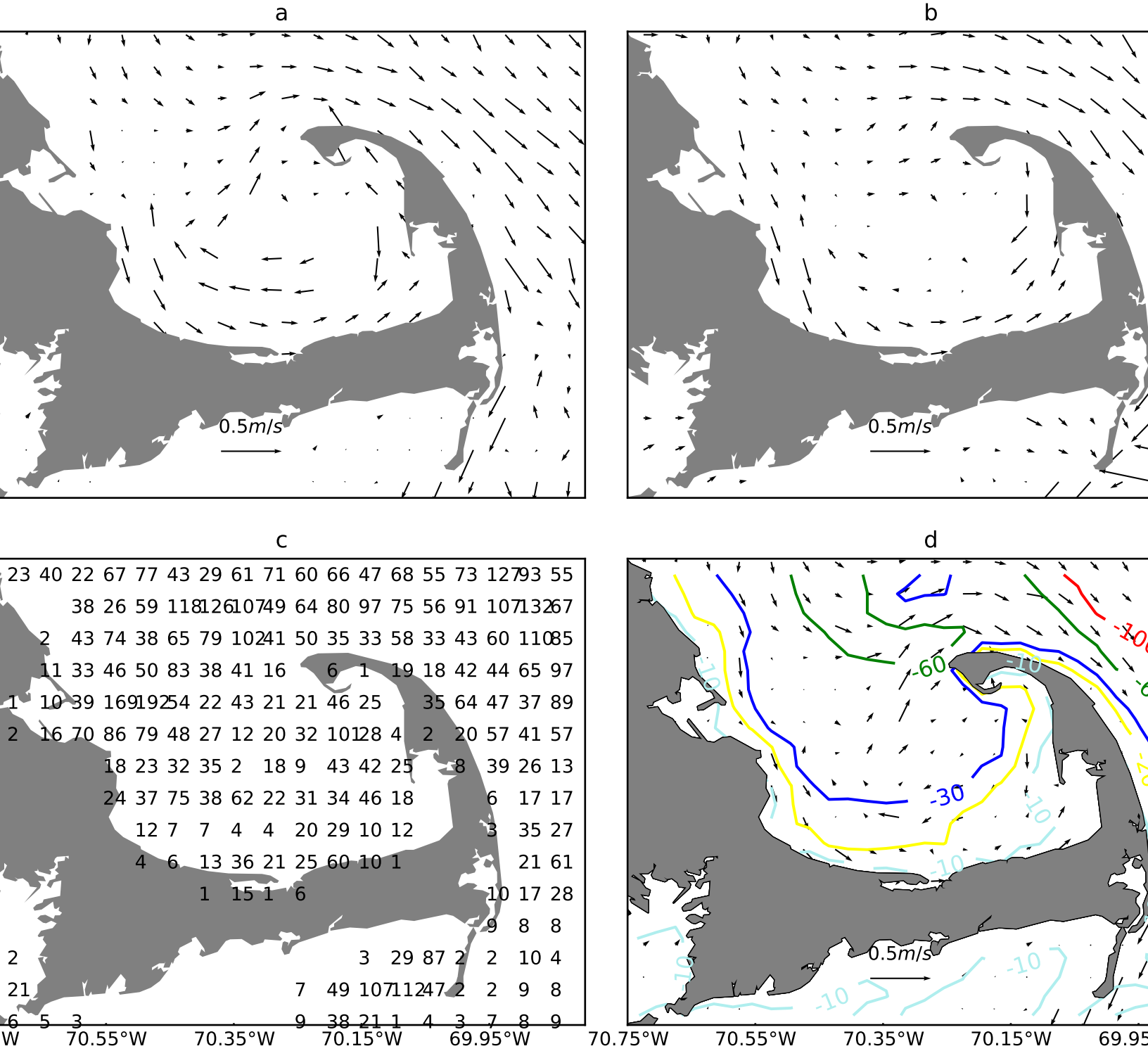
2615
NAUSET
DRIFTER
PROJECT

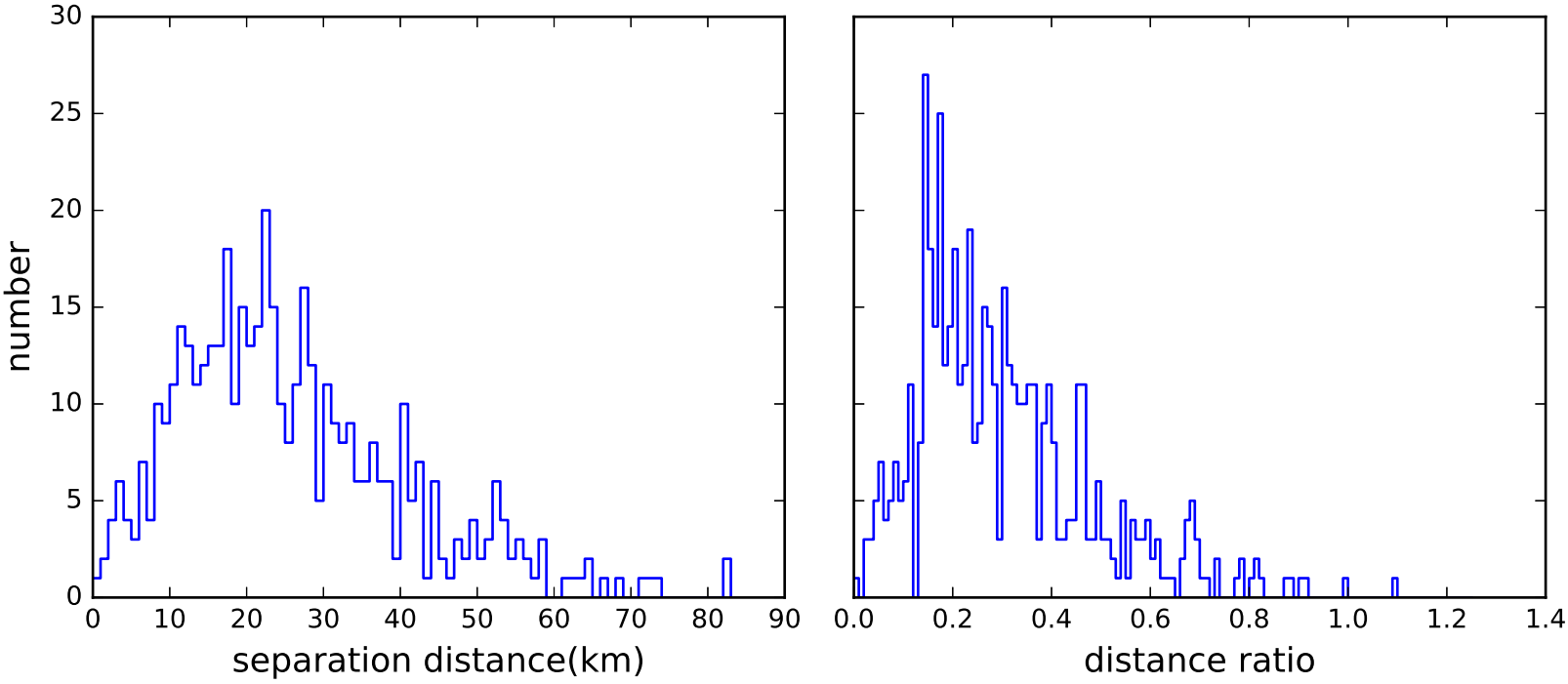

eMOLT
DMF
NERACOOS
Mooring A
AB01
RM04
DMF5
DMF2
DK01
DMF4
AC02
CDIP
DMF9
WL01
42.5°N
42.3°N
42.1°N
41.9°N
41.7°N
41.5°N
71°W
70.5°W
70°W

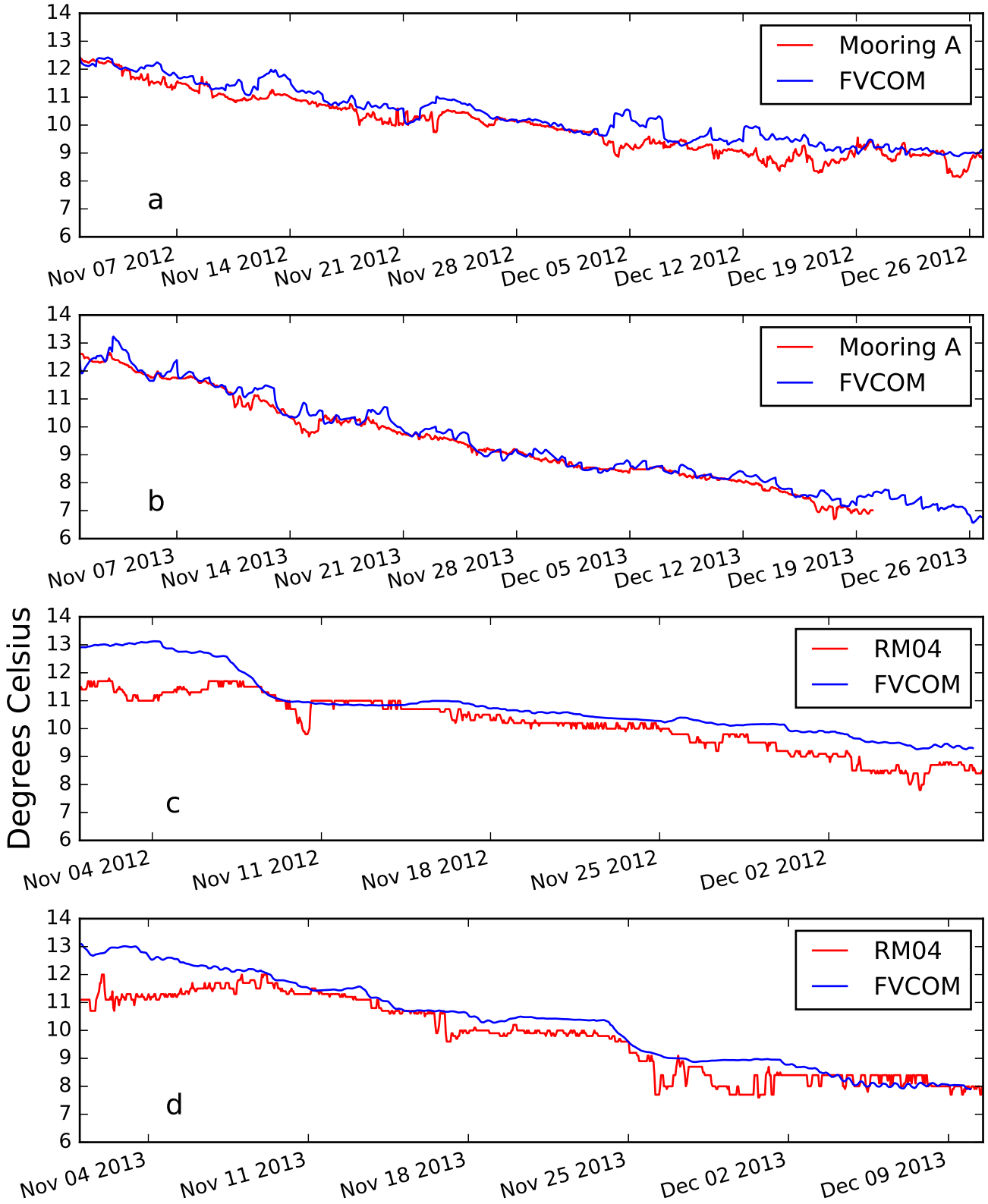

The number of turtles per year
1400
1200
1000
800
600
400
200
0
1991
1992
1993
1999
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015

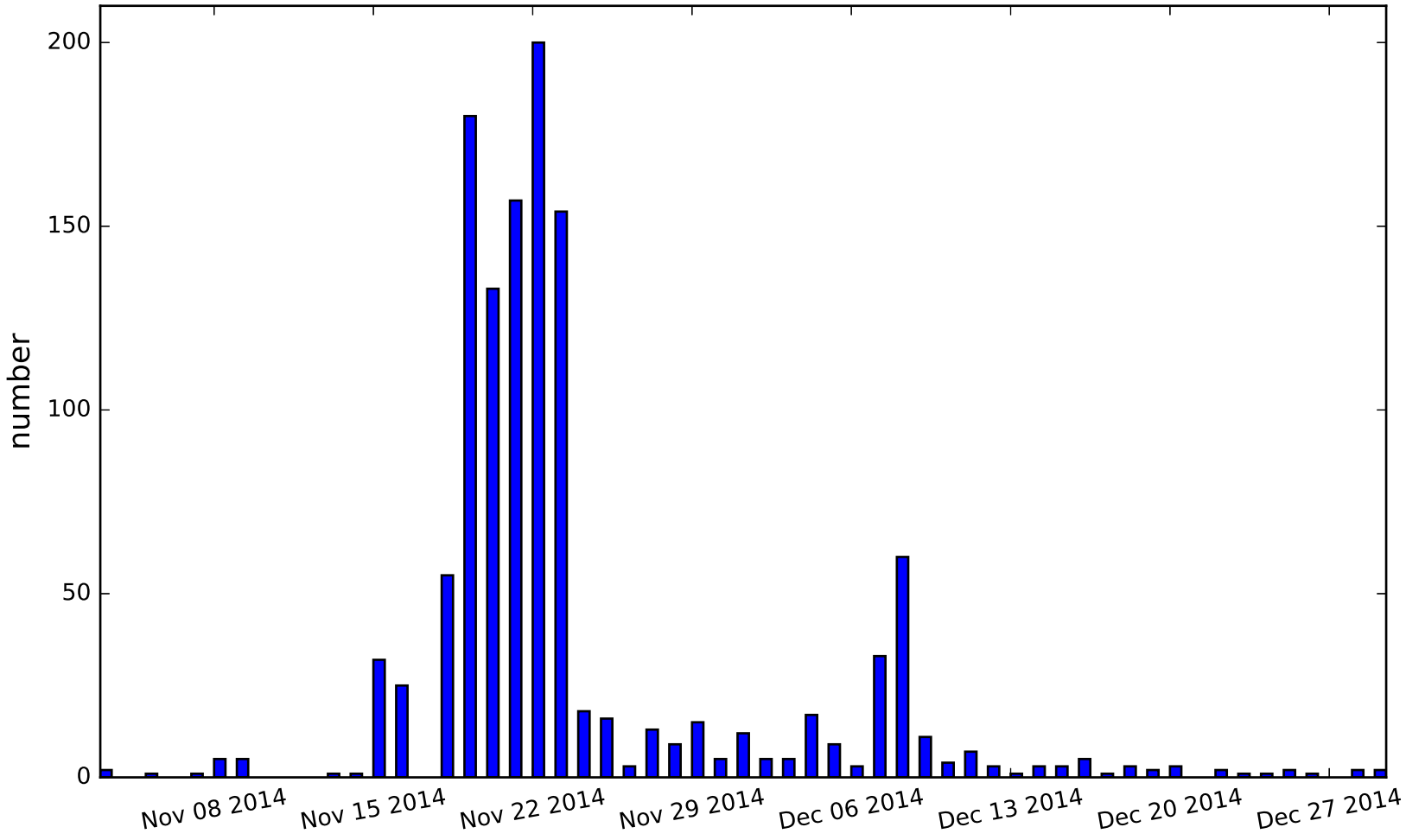

'Mid Cape' towns
'Outer Cape' towns
other towns
Hull
Nantasket Beach
Hingham
Provincetown
Duxbury
Truro
439
Wellfleet
486
Plymouth
Eastham
466
Wareham
Orleans
Barnstable
Sandwich
Brewster
Bourne
Dennis
Chatham
Yarmouth
Woods Hole
Falmouth
West Tisbury
Chappaquiddick
Nantucket
Martha's Vineyard
42.2
42.0
41.8
41.6
41.4
41.2
−71.0
−70.8
−70.6
−70.4
−70.2
−70.0
−69.8

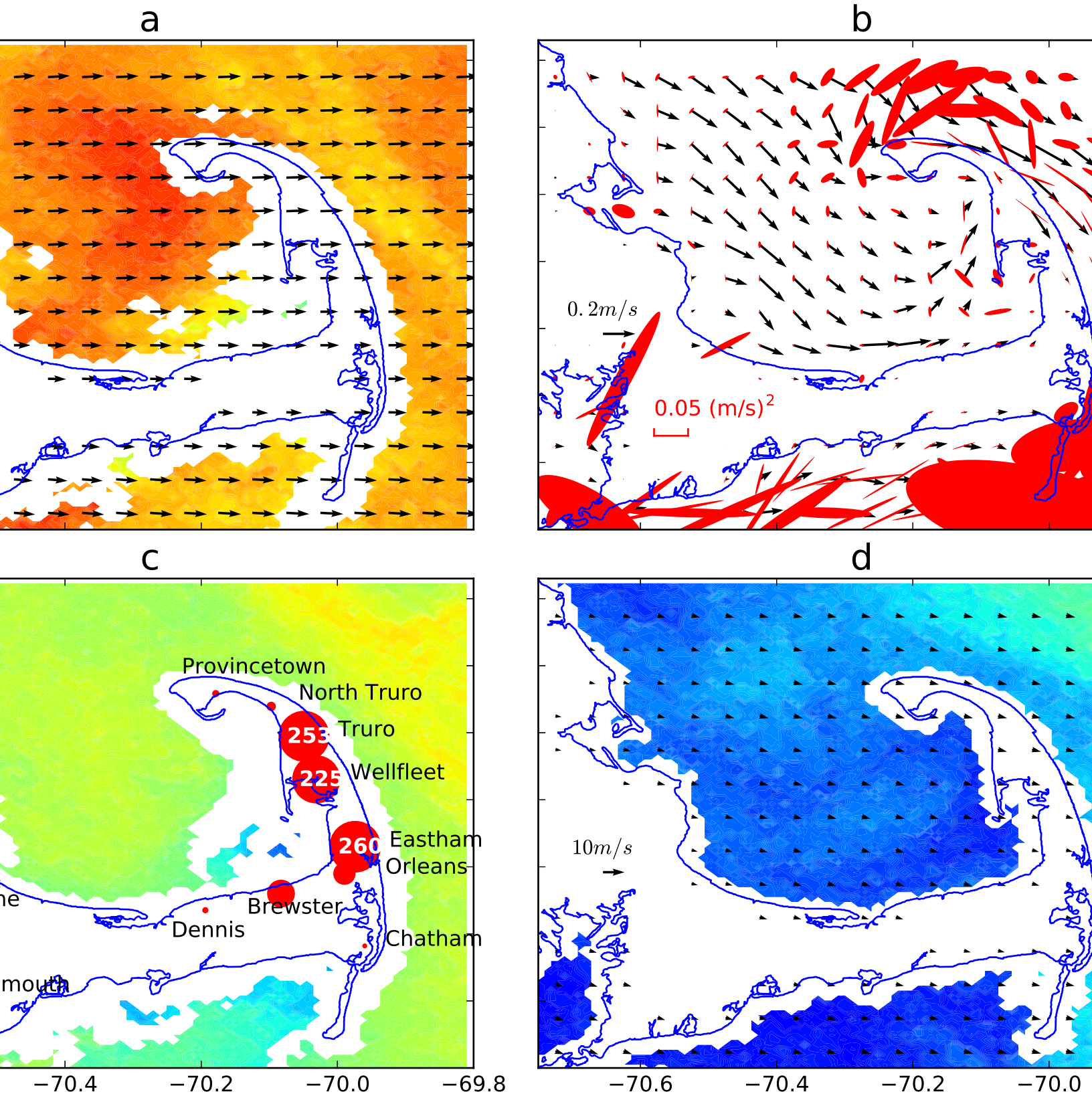

year
2012
2013
2014
2015
Eastham
Truro
Wellfleet
Dennis
Brewster
Barnstable
Orleans
Province town
Sandwich

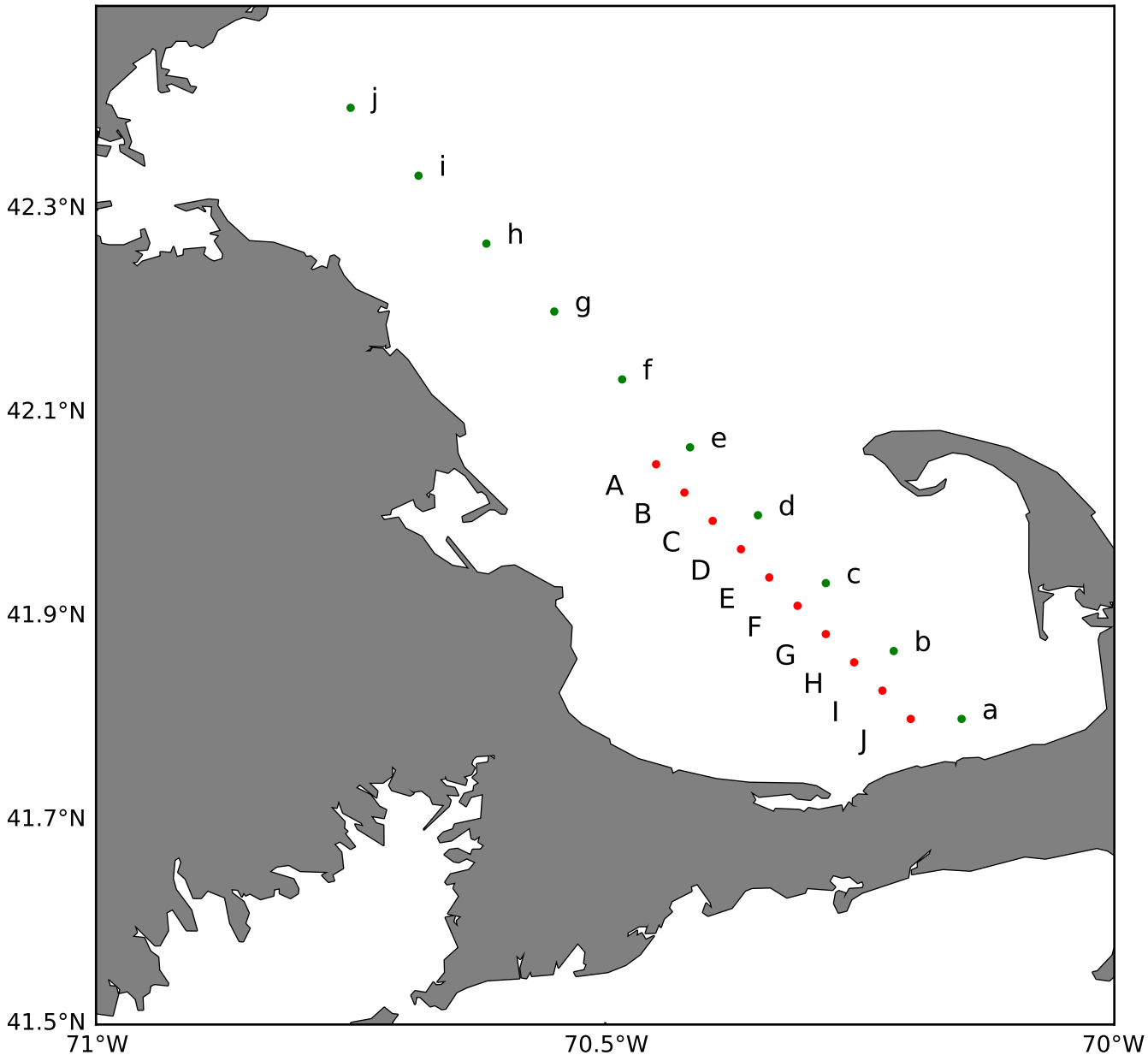

a
b
c
d
0.5m/s
0.5m/s
0.5m/s
-60
-30
-10
70.55°W
70.35°W
70.15°W
69.95°W
70.75°W
70.55°W
70.35°W
70.15°W

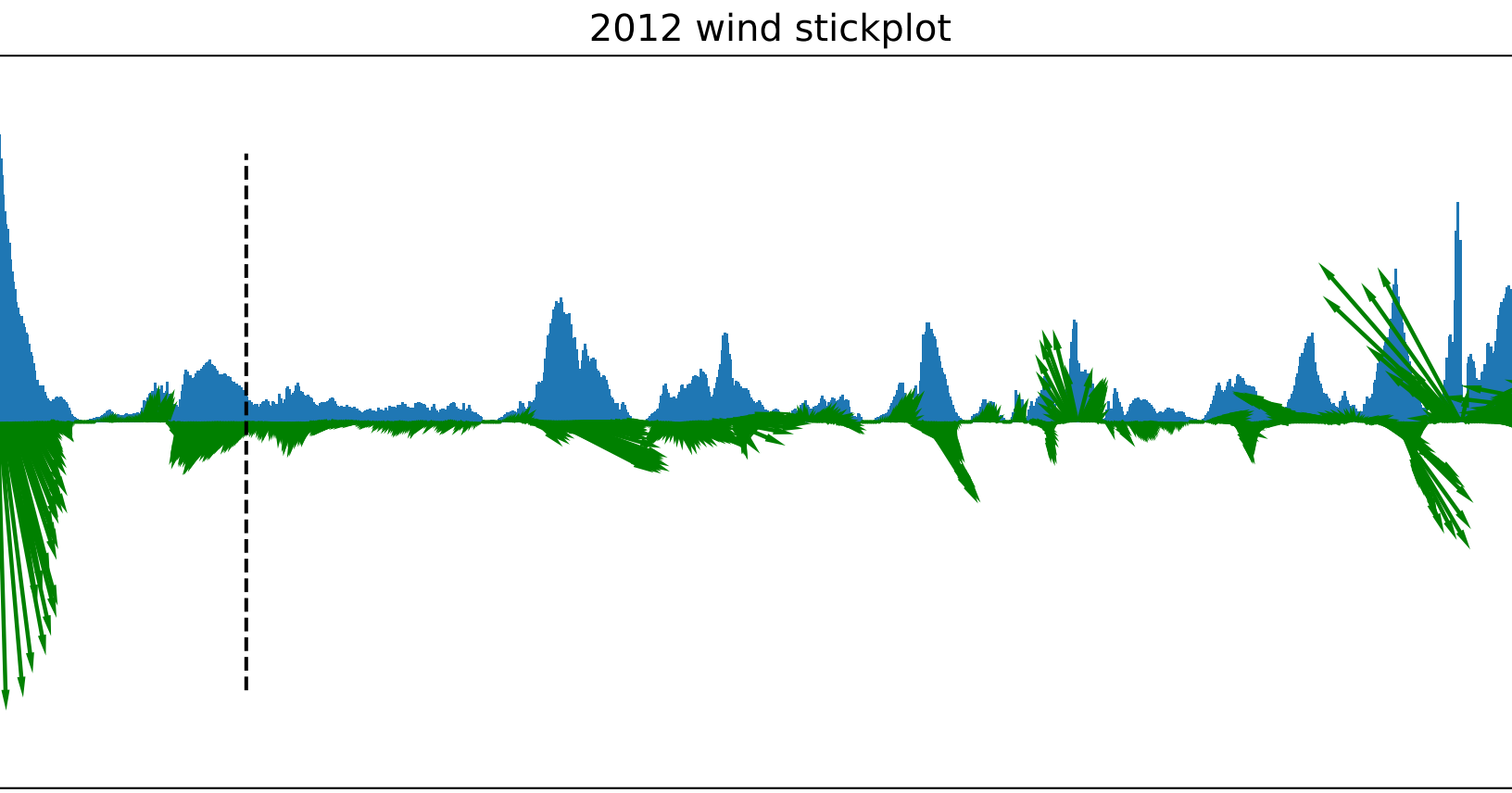

number
separation distance(km)
distance ratio
0
5
10
15
20
25
30
0
10
20
30
40
50
60
70
80
90
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4


Degrees Celsius
Mooring A
FVCOM
a
Nov 07 2012
Nov 14 2012
Nov 21 2012
Nov 28 2012
Dec 05 2012
Dec 12 2012
Dec 19 2012
Dec 26 2012
Mooring A
FVCOM
b
Nov 07 2013
Nov 14 2013
Nov 21 2013
Nov 28 2013
Dec 05 2013
Dec 12 2013
Dec 19 2013
Dec 26 2013
RM04
FVCOM
c
Nov 04 2012
Nov 11 2012
Nov 18 2012
Nov 25 2012
Dec 02 2012
RM04
FVCOM
d
Nov 04 2013
Nov 11 2013
Nov 18 2013
Nov 25 2013
Dec 02 2013
Dec 09 2013

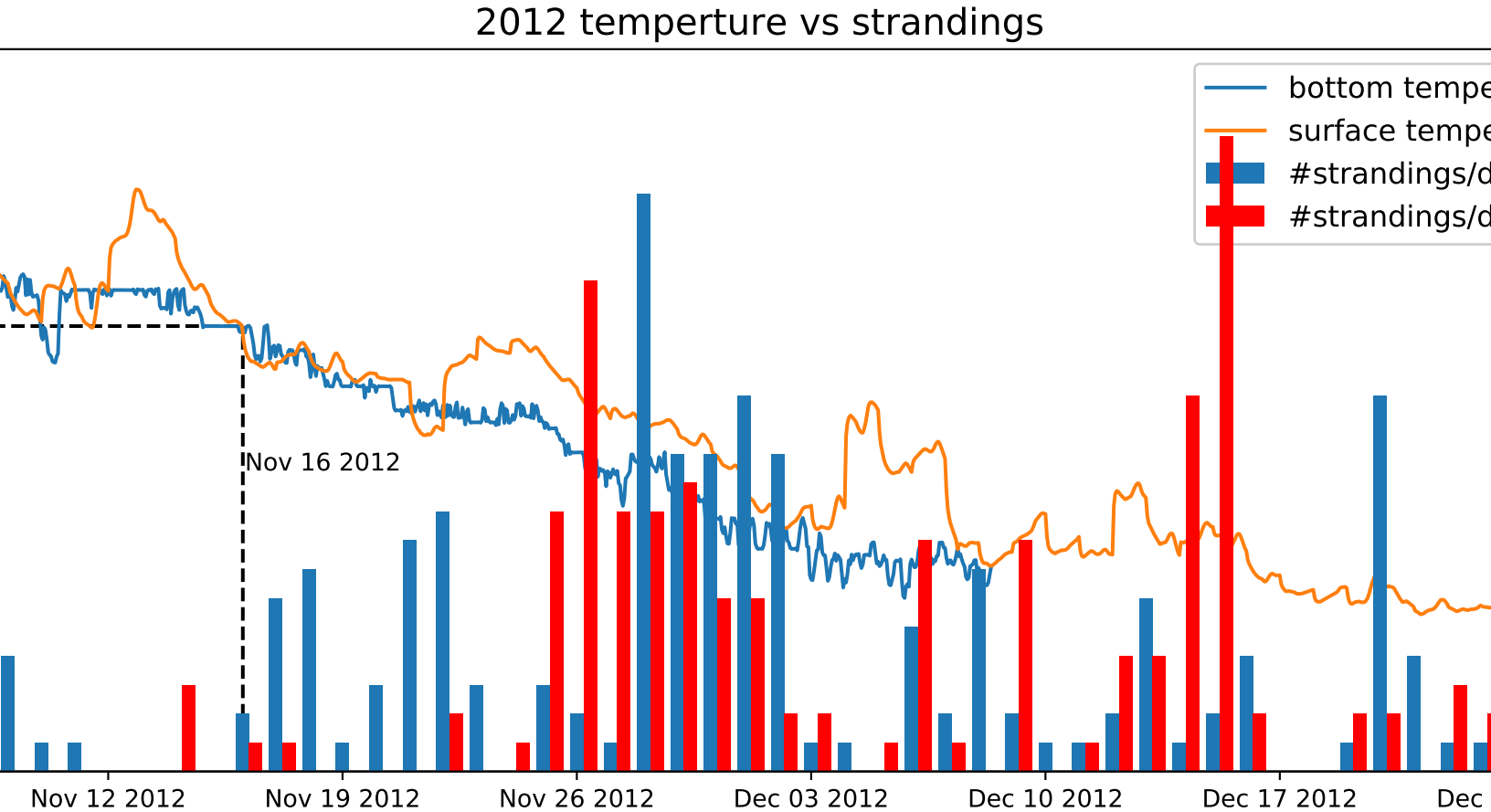

number
200
150
100
50
0
Nov 08 2014
Nov 15 2014
Nov 22 2014
Nov 29 2014
Dec 06 2014
Dec 13 2014
Dec 20 2014
Dec 27 2014


a
b
0.2m/s
0.05 (m/s)2
c
Provincetown
North Truro
Truro
253
Wellfleet
225
Eastham
260
Orleans
Brewster
Dennis
Chatham
d
10m/s
−70.4
−70.2
−70.0
−69.8
−70.6
−70.4
−70.2
−70.0

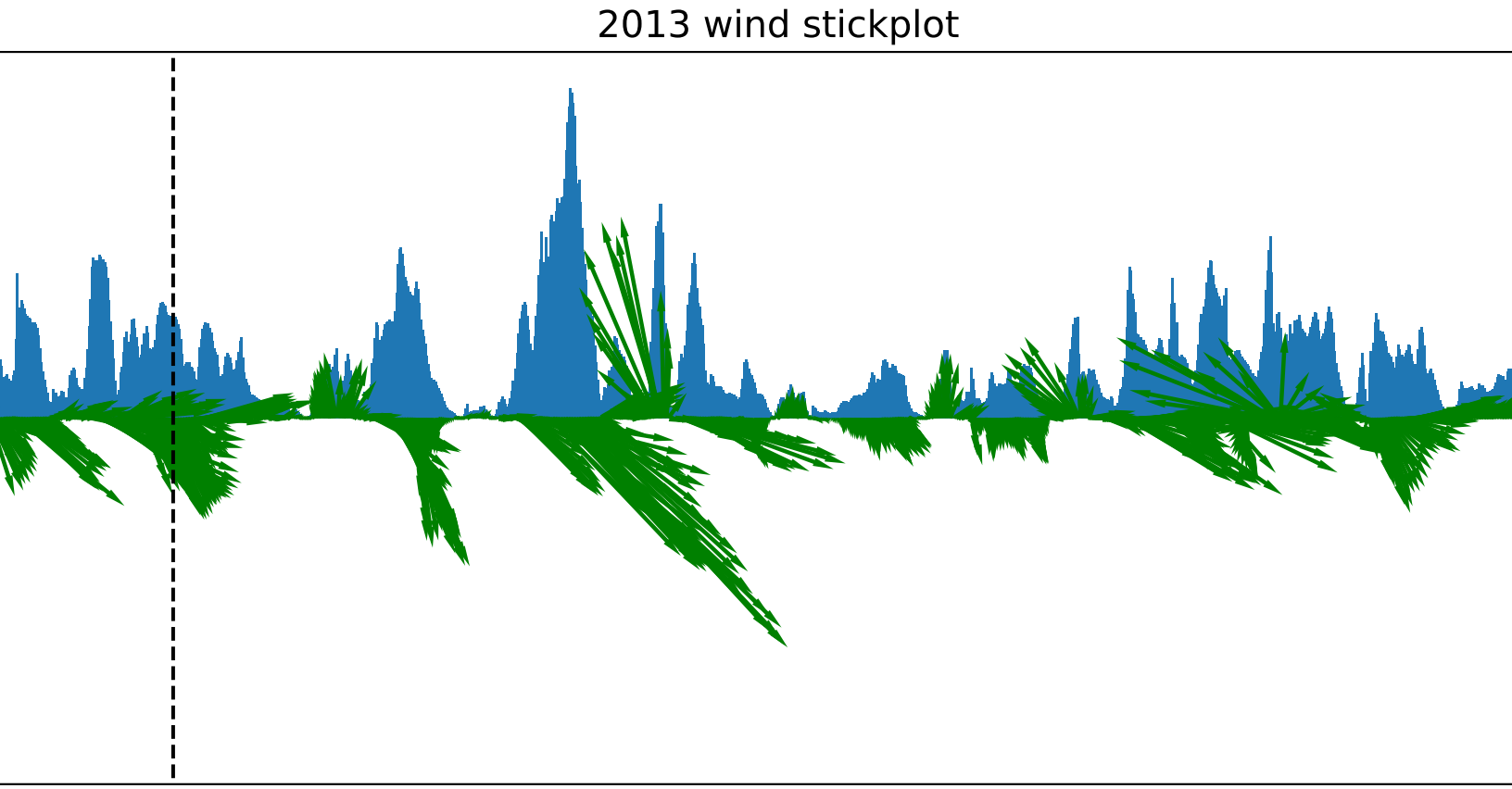

j
i
h
g
f
e
d
c
b
a
A
B
C
D
E
F
G
H
I
J
42.3°N
42.1°N
41.9°N
41.7°N
41.5°N
71°W
70.5°W
70°W


2012 wind stickplot

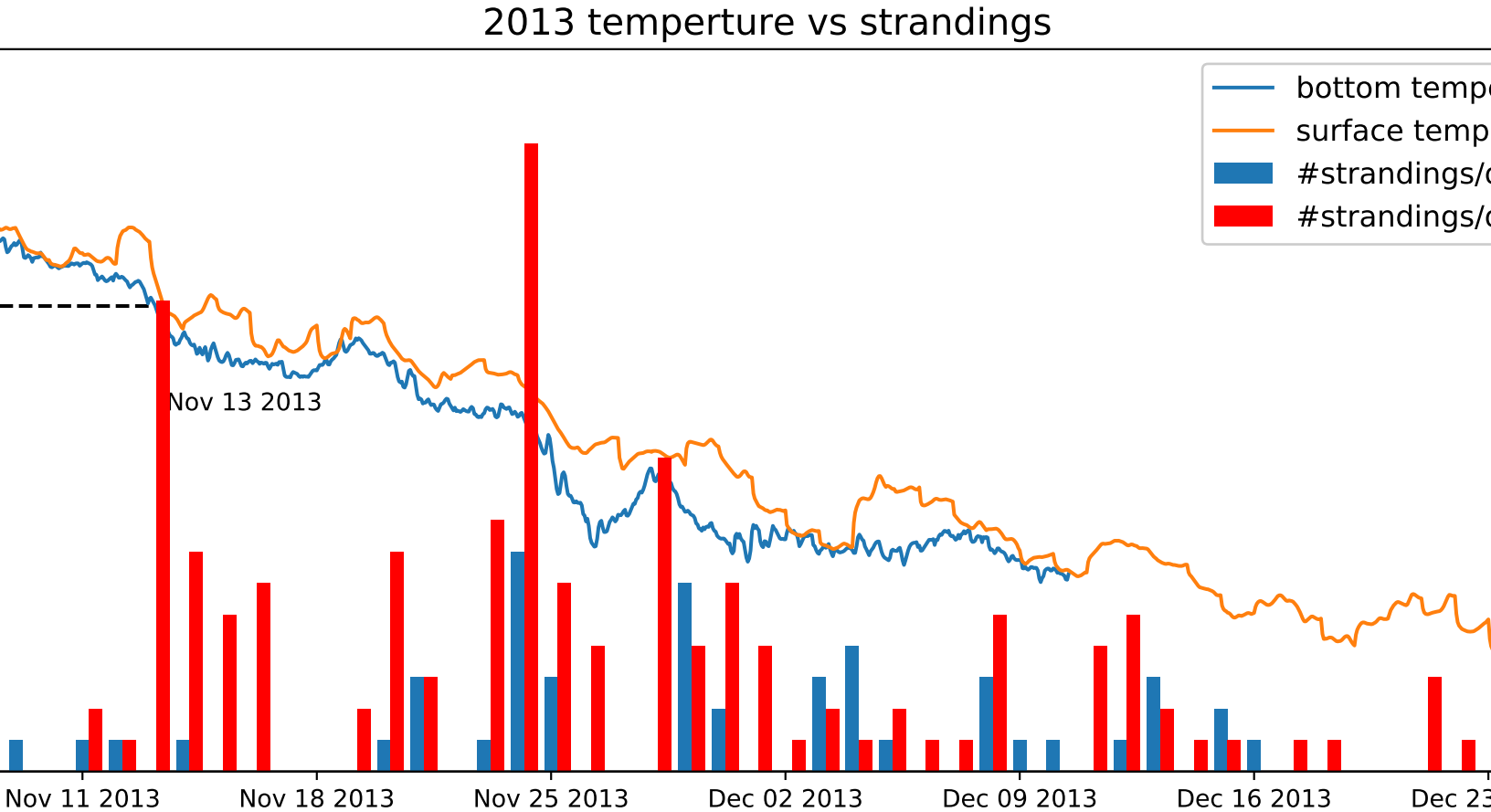
a


2012 temperture vs strandings
bottom tempe
surface tempe
#strandings/d
#strandings/d
Nov 16 2012
Nov 12 2012
Nov 19 2012
Nov 26 2012
Dec 03 2012
Dec 10 2012
Dec 17 2012
Dec

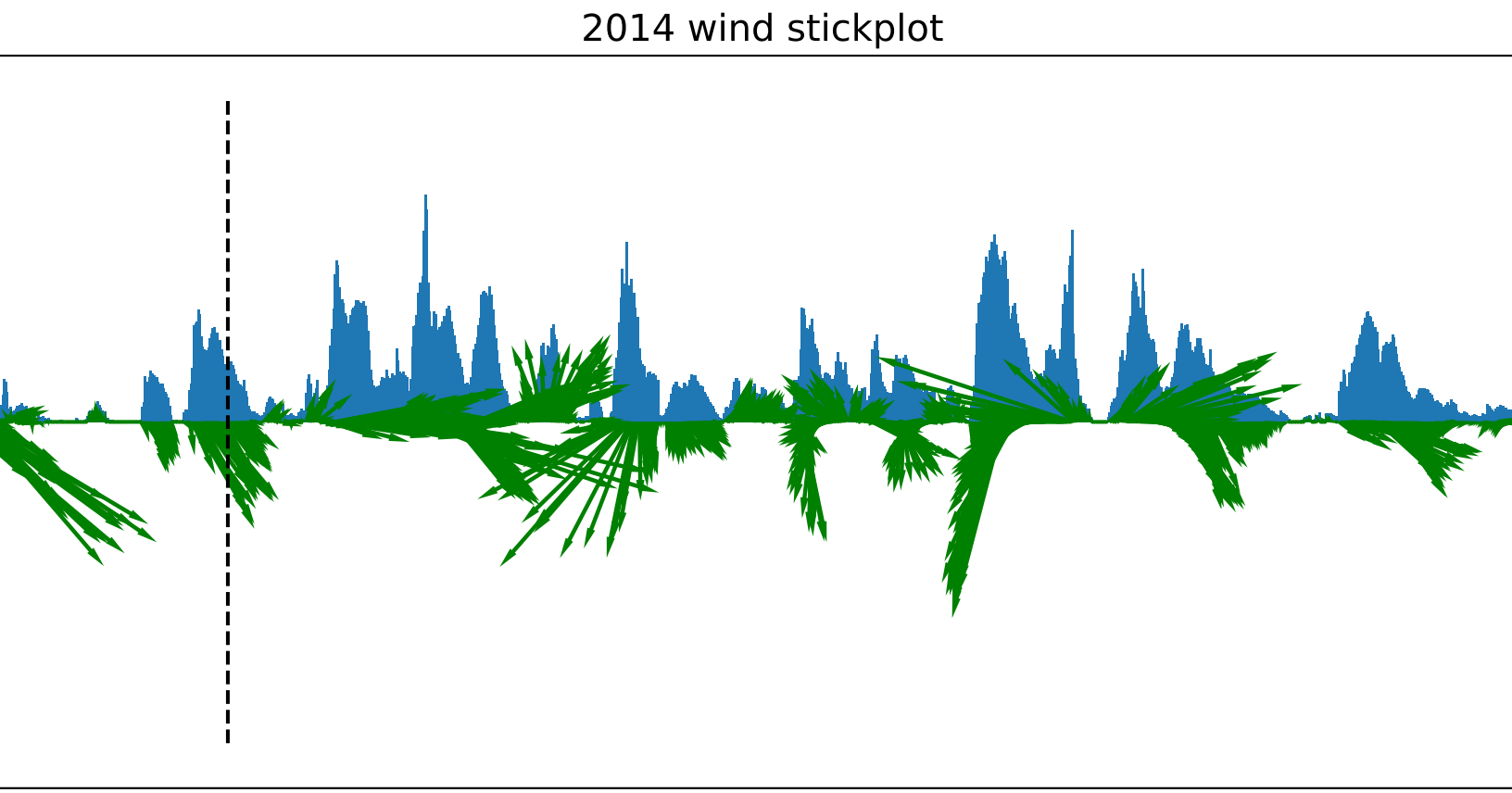
b


2013 wind stickplot

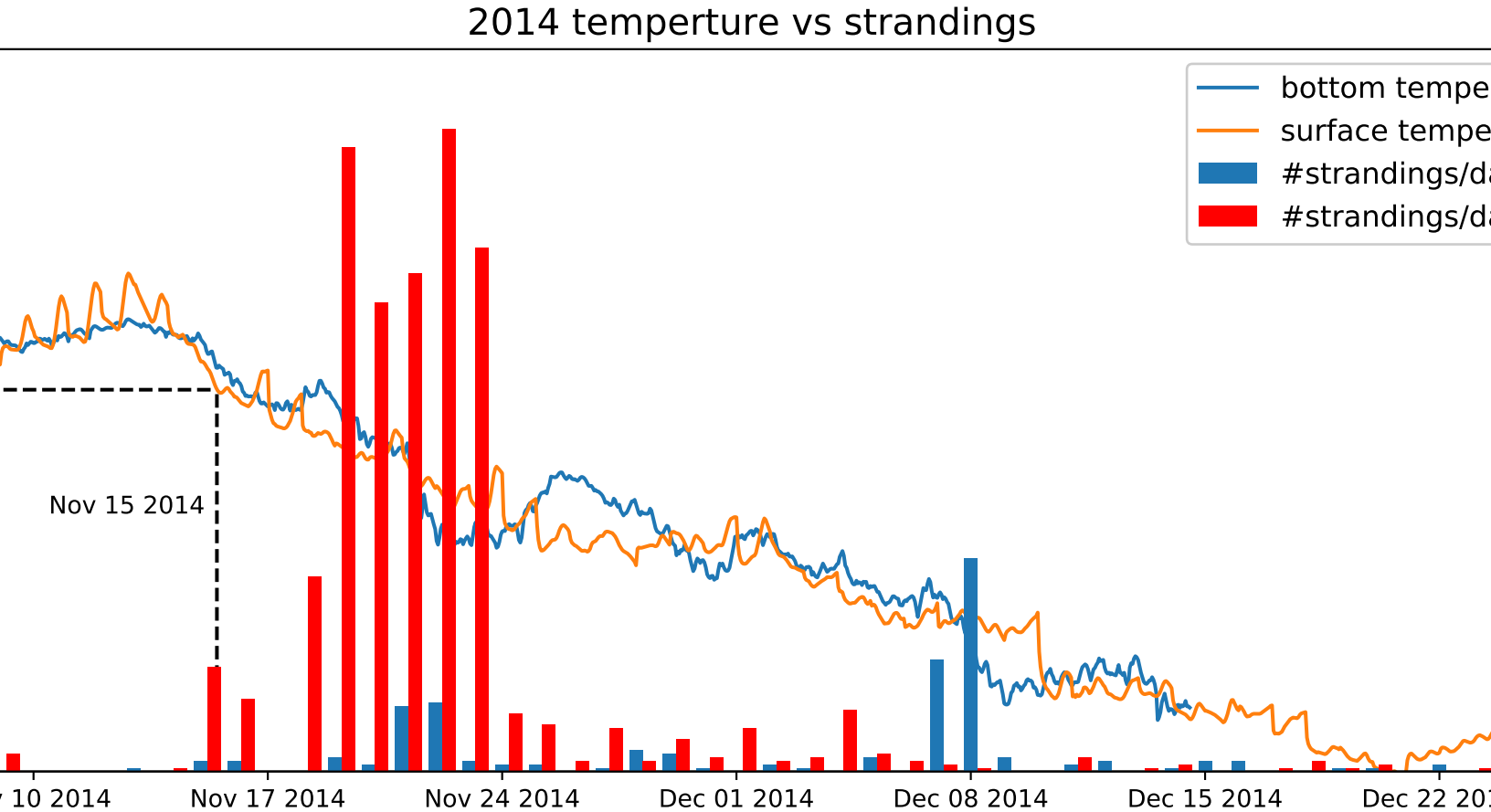
a


2013 temperture vs strandings
bottom tempe
surface temp
#strandings/d
#strandings/d
Nov 13 2013
Nov 11 2013
Nov 18 2013
Nov 25 2013
Dec 02 2013
Dec 09 2013
Dec 16 2013
Dec 23

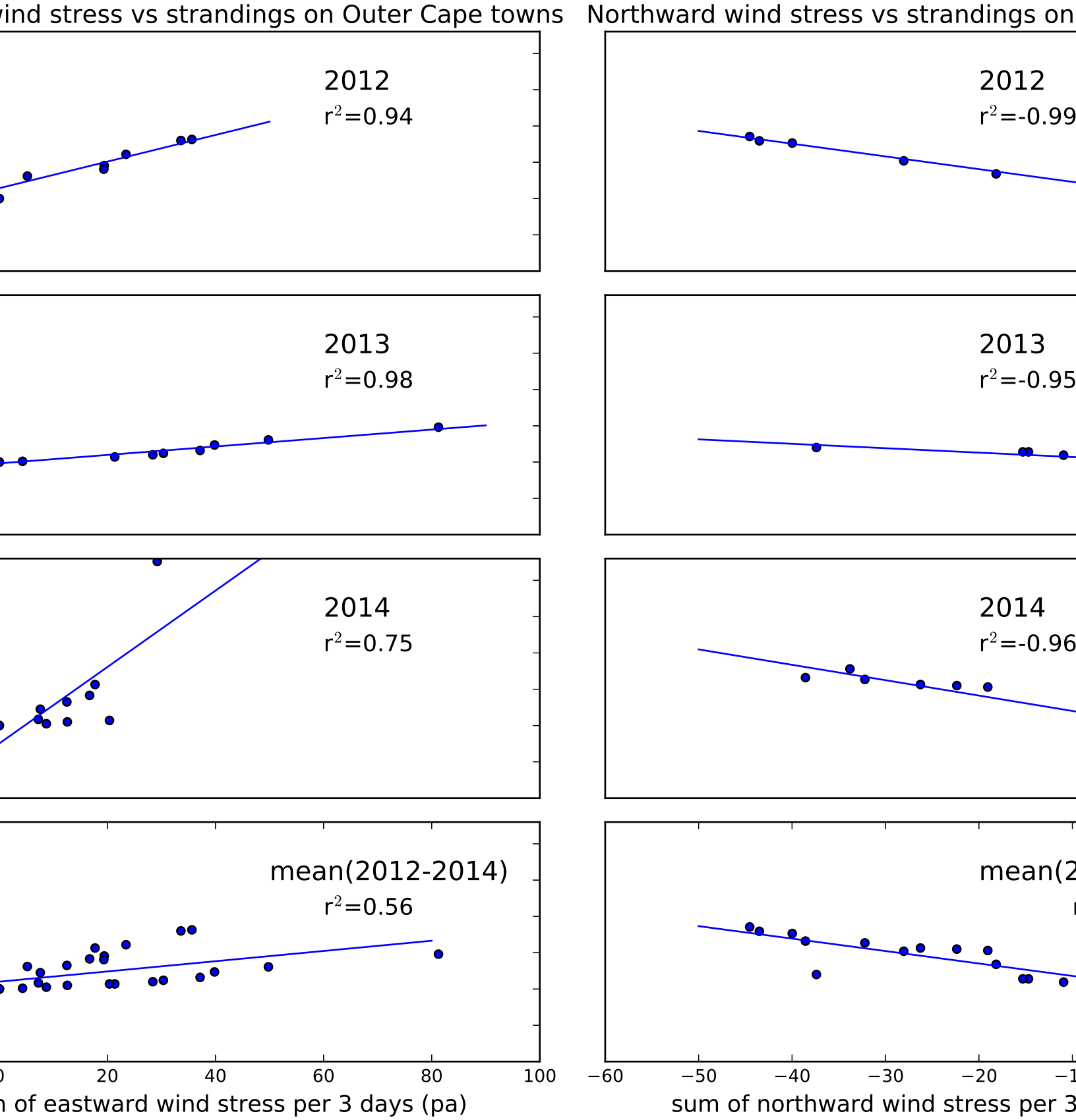
b

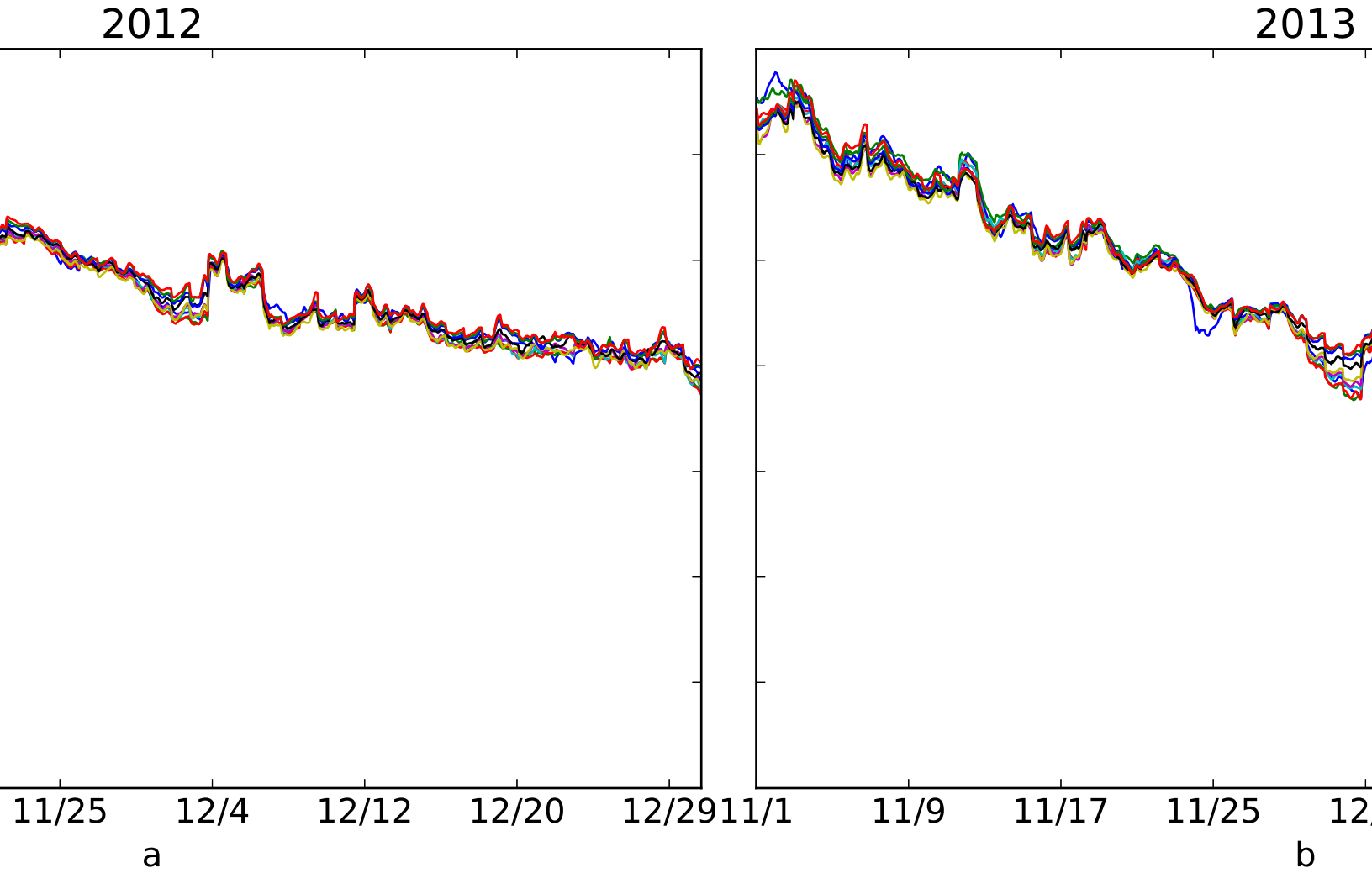

2014 wind stickplot

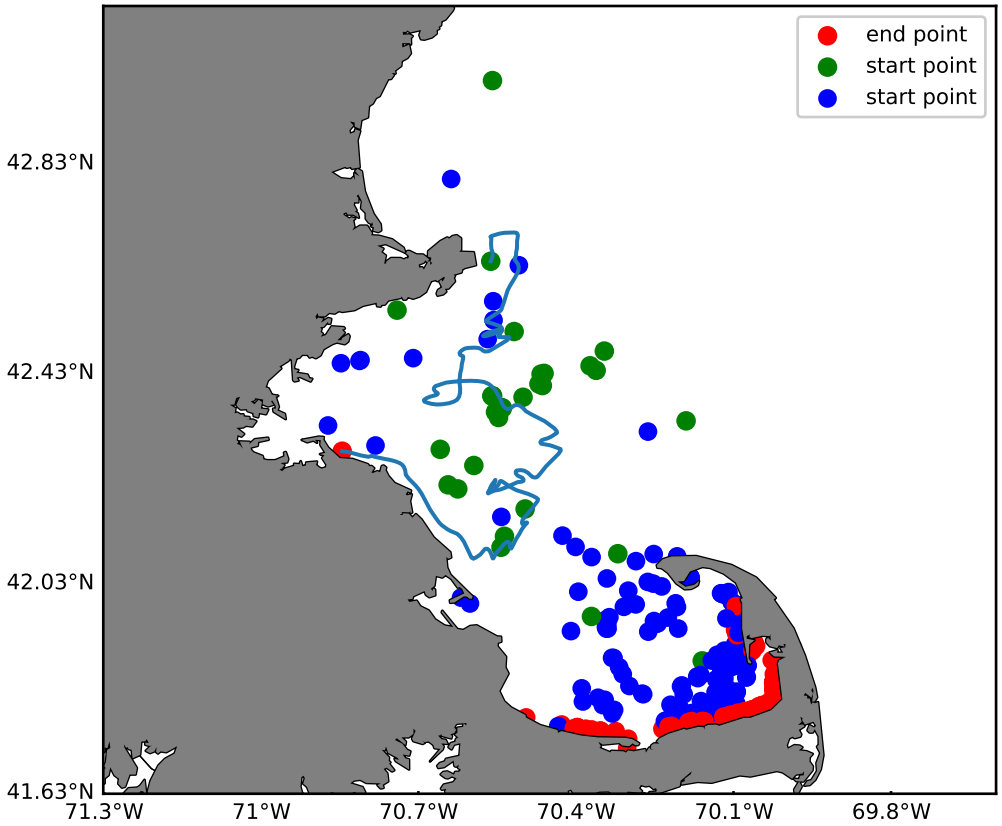
a

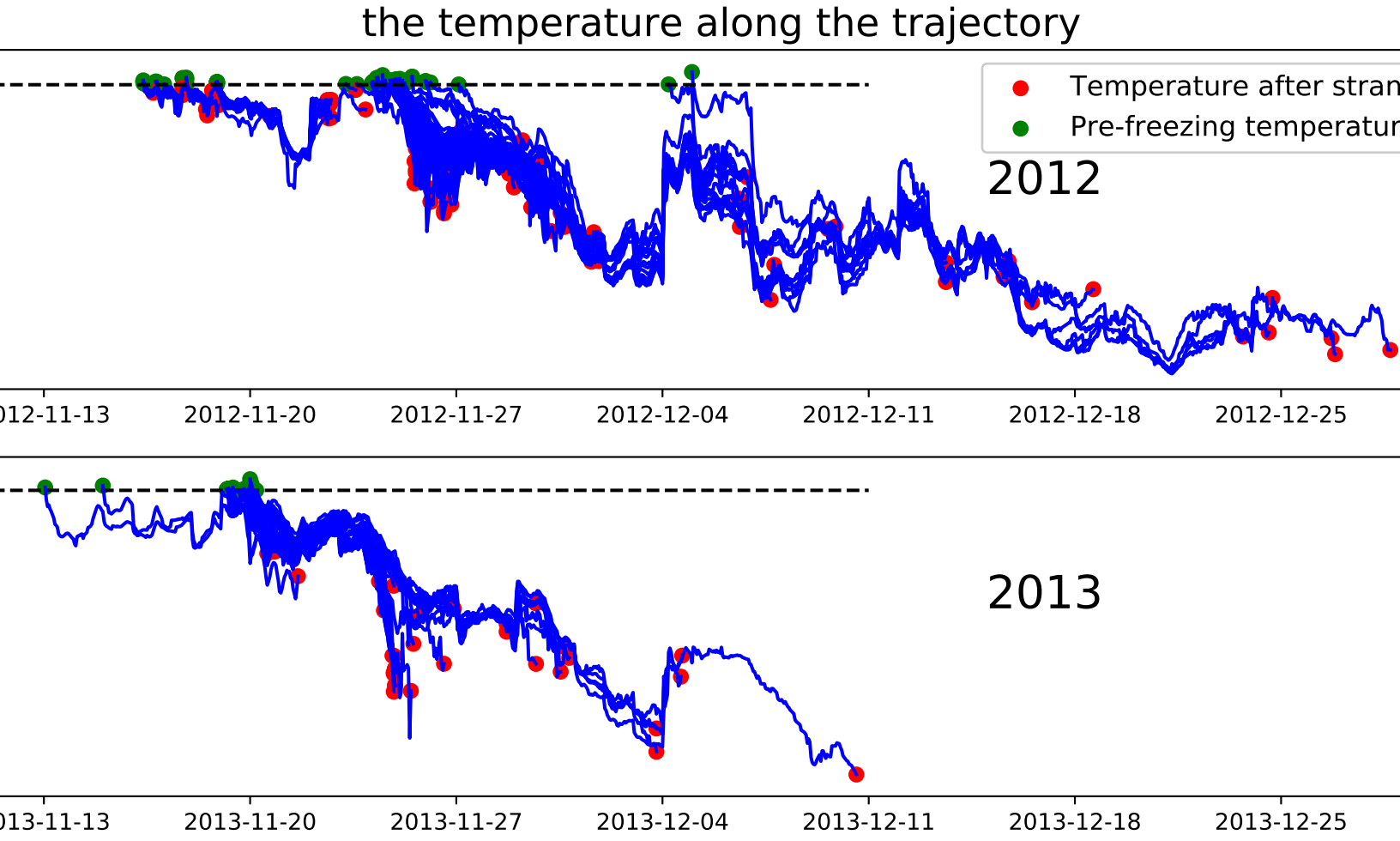

2014 temperture vs strandings
bottom tempe
surface tempe
#strandings/da
#strandings/da
Nov 15 2014
10 2014
Nov 17 2014
Nov 24 2014
Dec 01 2014
Dec 08 2014
Dec 15 2014
Dec 22 201

b


wind stress vs strandings on Outer Cape towns
Northward wind stress vs strandings on
2012
r²=0.94
2012
r²=-0.99
2013
r²=0.98
2013
r²=-0.95
2014
r²=0.75
2014
r²=-0.96
mean(2012-2014)
r²=0.56
mean(2
0
20
40
60
80
100
−60
−50
−40
−30
−20
−1
n of eastward wind stress per 3 days (pa)
sum of northward wind stress per 3


2012
2013
11/25
12/4
12/12
12/20
12/29
11/1
11/9
11/17
11/25
a
b


end point
start point
start point
42.83°N
42.43°N
42.03°N
41.63°N
71.3°W
71°W
70.7°W
70.4°W
70.1°W
69.8°W


the temperature along the trajectory
Temperature after stran
Pre-freezing temperatur
2012
2013
012-11-13
2012-11-20
2012-11-27
2012-12-04
2012-12-11
2012-12-18
2012-12-25
013-11-13
2013-11-20
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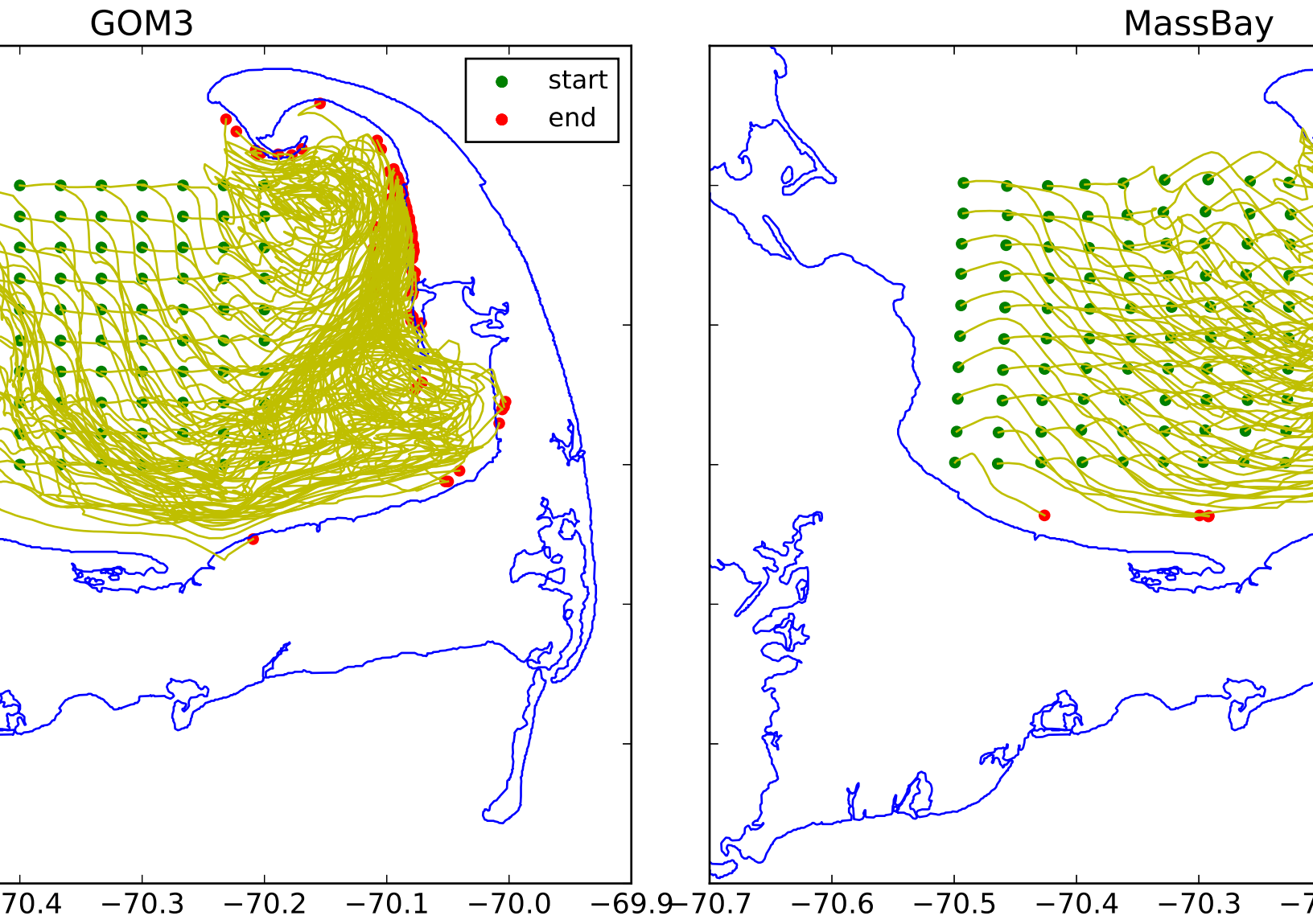
2013-12-11
2013-12-18
2013-12-25


GOM3
start
end
−70.4
−70.3
−70.2
−70.1
−70.0
−69.9
MassBay
−70.7
−70.6
−70.5
−70.4
−70.3