Temporal displacement of environmental crime. Evidence from marine oil pollution*

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Abstract

The probability of conviction commonly varies across different circumstances due to imperfect monitoring. Evidence of whether and how offenders exploit gaps in monitoring provides insight into the process by which deterrence is produced. We present an empirical test of temporal displacement of illegal discharges of oil from shipping, a major source of ocean pollution, in response to a monitoring technology that features variation in the probability of conviction by time of day. After sunset and before sunrise, evidence collected using airborne radar day-round becomes contestable in court because the nature of an identified spot cannot be verified visually. Seasonal variation in time of sunset is used to distinguish daily routines on board from evasive behavior. Using data from surveillance flights above the Dutch part of the North Sea during 1992-2011, we provide evidence for substantial temporal displacement from the daytime to the first few hours after sunset.

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1. **Introduction**

Potential offenders often operate in an environment with a varying probability of detection. They may be less likely to get caught under certain circumstances, such as during the nighttime. A primary cause of the variation in the probability of detection are the particular characteristics of the monitoring technology used by law enforcement agencies. The human senses have their limitations and so do monitoring technologies.

When choosing a monitoring technology and the way it is deployed, law enforcement agencies face a dilemma that is more complicated than the standard case with a monitoring technology that produces a similar probability of detection across all circumstances (as in Becker 1968). In addition to the challenge of setting a probability of detection and penalty within one particular situation, say the daytime, an agency needs to choose a monitoring technology that produces a deterrent effect across a set of circumstances, say the daytime and the nighttime. Usually, none of the available technologies is equally effective under all circumstances. That is also not necessary because exploitation of gaps in enforcement is not a given. First, an offender will need to become familiar with gaps in monitoring. Potential offenders often have only a limited understanding of how law enforcement agencies go about their work. This explains why enforcement activity at a certain time and place has repeatedly been found to have a beneficial effect at other times and places as well (Clarke and Weisburd 1994). Second, the offender needs to devise an evasive strategy.[1] This is not without its costs and regularly requires the development of new knowledge and skills (Cook 1986, Cornish and Clarke 1987). In other words, not the possible but the *actual* displacement of illegal behavior to circumstances with a relatively low chance of getting caught is of importance in choosing a monitoring technology. Empirical evidence on whether and how offenders exploit variation in the chance of getting caught is of direct importance for an effective enforcement strategy.[2]

Evasive strategies may be particularly challenging in the context of the enforcement of environmental law. Legitimate business activities and activities that are in contravention of environmental law are often jointly produced, providing continuous pressure to engage in criminal behavior. For instance, as in the case discussed in this paper, an environmentally harmful substance may be generated as a by-product of a legal production process. With one way of illegal disposal of the substance closed off, the need to dispose of it is not diminished. If the legal alternative is sufficiently costly, then the potential offender may simply look for other ways of illegal disposal (Sigman 1998). Within the context of environmental crime there may be more of a 'lump of criminal activity' that seeks a way out than in other types of crime, even though the elasticity of environmental crime with respect to law enforcement activity has repeatedly proven to be negative rather than zero (Gray and Shimshack 2011).

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[1] Evasive strategies include displacement of illegal behavior to times or places where law enforcement is less effective; other forms are a change in target, tactics and offense type (Cornish and Clarke 1987).

[2] Inevitably, empirical evidence on evasive behavior provides a picture of one stage in a dynamic process. The interaction between law enforcement and affected parties can be characterized as a repeated game. The game may be cut short by effective counter-measures by law enforcement, but these measures may be undermined eventually. The adaptive behavior of both offenders and law enforcement is a cat-and-mouse game involving constant pursuit, near captures, and repeated escapes. In practice, the sequence of moves and counter-moves may be slow in unfolding; the point is that the chain of action and reaction is an integral part of the process underlying deterrence, and its study should improve our understanding of how deterrence works (McCrary 2010).

Temporal displacement of illegal behavior in response to law enforcement is thought to be a common evasive strategy – since it requires less from the potential offender compared to other strategies such as a change in tactics – but it is also one of the least studied (Guerette and Bowers 2009). In this paper, we study temporal displacement of illegal discharges of oily waste from shipping. Worldwide, the shipping industry is subject to regulation of the disposal of environmentally harmful substances, including oil and oily mixtures. Radar-guided surveillance by aircraft and satellite is a broadly used monitoring technology to detect illegal discharges, next to port state control. Actual detection of oil discharges still relies on visual inspection, however, since radar also picks up other anomalies on the water surface. In the jurisdiction under study, the Netherlands, the courts only accept evidence from observers who are trained to detect the particular rainbow sheen of oil on the water surface. As a consequence, the probability of conviction is negligible during low-visibility conditions. Disposal of oily substances can easily be postponed for a number of hours and the shipping industry has long been suspected of illegally disposing in the nighttime and during adverse weather conditions (Meetkundige Dienst 1981, Crist 2003, Carpenter 2007: 162, HELCOM 2011). Temporal displacement of illegal discharges in response to this variation in the probability of being convicted has never been studied however, primarily because in most countries surveillance effort during the nighttime is at too low a level to collect meaningful data. This is known to be the case for Belgium, Canada, Finland, France, Poland, Russia and Sweden, but could apply to other countries as well.

The Netherlands is unique in conducting relatively intensive nightly surveillance activities, allowing us to analyze temporal displacement.[3] The Dutch part of the North Sea provides a good area of study because it is one of the busiest navigated seas in the world and also one of the most polluted seas (Camphuysen and Vollaard 2015). The data collection is unaffected by visibility conditions because it relies on radar. We develop a test for the presence of temporal displacement. For nightly discharges to be strategic in nature, a necessary condition is that the timing is robust to seasonal variation in the time of sunset and sunrise. In December, the time window for illegal discharges starts at 4.30pm; in June only at 10pm. Variation in the timing of illegal oil discharges similar to variation in the time of darkness provides an indication for evasive behavior.

We use detailed data on radar-identified spots on the water surface and on the flight paths of all Coast Guard surveillance flights for the Dutch part of the North Sea for the period 1992-2011. We combine the geographical data with meteorological data on wind speed, water temperature and air temperature. The focus on hourly variation in the probability of radar-identified spots effectively eliminates measurement error from other substances that may also be picked up by radar but are not oil, including subsurface sand banks and algae blooms. All of the known sources of false positives do not vary with the time of day.

We find clear evidence for temporal displacement. The hour-by-hour upswings in the probability of detecting a spot – a sign of a surge in illegal oil discharges – only start after sunset, so not at some fixed time that may fit the schedule of the crew. Timing of illegal discharges, primarily during the watch of the chief engineer, vary with the seasons, in line with the variation in the time of sunset. This confirms the earlier suspicions of displacement to the nighttime. In absolute terms, the impact of temporal

[3] Apart from collecting statistics on illegal discharges for all hours of the day, nightly surveillance is mainly conducted to secure a rapid response in case of an emergency at sea and to enforce traffic regulations around the clock.

displacement is declining, together with the overall rate of oil discharges. We do not find that the tendency for temporal displacement has diminished in more recent years, however.

The context of oil pollution from shipping is particularly relevant because ocean pollution is a major source of environmental degradation. The legal discharge of oil and oily wastes is a standard part of operations of a large sea-going vessel, and these discharges are internationally regulated. Some vessel operators opt to discharge oily wastes illegally, and these discharges cumulatively are an important and chronic contributor to ocean pollution (National Research Council 2003). Oil spills can present a hazard by causing damage and death to birds and marine mammals and by exerting a toxic stress on subsurface organisms. Oil dissolved in the water can be taken up by organisms and affect their physiology, behavior, reproductive potential and survival. Oil may also be transferred to the sediment, where it might persist for many years, and impact on organisms on and in the sea bed. Marine oil pollution remains a great environmental concern globally (National Research Council 2003, Gullo 2011), even though the incidence of illegal oil discharges has been reported to have declined in some areas including the North Sea (Camphuysen 2010, Lagring et al. 2012), the Baltic Sea (HELCOM 2011) and the Pacific Ocean off the Canadian coast (Serra-Sogas et al. 2008). The policy relevance of the findings of this study extends beyond the confines of the Dutch part of the North Sea: many coastal countries in the western world use deterrence technology that is similar to the Netherlands, including the UK, the US, Germany, Belgium, Canada and France.

This paper contributes to the literature on the dynamics of criminal behavior. Empirical evidence on the interaction between law enforcement and potential offenders is scant, which also applies to evidence on temporal displacement of crime in response to law enforcement activity (McCrary 2010).[4] In a review of empirical evaluations of crime prevention initiatives, Guerette and Bowers (2009) found that positive or negative spillover effects from enforcement were only examined in half of all studies. Out of 574 evaluations that examined spillover effects, temporal displacement was analyzed in only 5 percent of cases. This is also typical for the literature on monitoring and enforcement of environmental regulations. In their review of this literature, Gray and Shimshack (2011) do not discuss any empirical evidence on evasive strategies other than falsification of self-reported violations of regulations, which Telle (2013) finds to be a common practice. Better insight into how and when evasive strategies are developed can have a high pay-off. Heyes (1994) shows theoretically that an increase in enforcement resources while leaving opportunities to evade punishment unchecked may actually *lower* overall compliance, which is confirmed empirically in a study into avoidance of import duties (Yang 2008). In addition, effectiveness of monitoring and enforcement may be lower than it seems when evasive actions are not taken into account, which is relevant for addressing the question of how to cost-effectively limit environmental degradation. Finally, we also contribute to the empirical literature on the effectiveness of measures to combat marine pollution from operational discharges. So far the evidence on what policies work in this area is limited.[5]

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[4] An exception is Jacob, Lefgren and Moretti (2007). They find evidence for temporal displacement of crime in response to weather shocks, which they explain by the presence of income effects for property crime and by decreasing marginal utility from violent crime in the amount of violent crime committed previously. For a review of the related literature on tax avoidance and tax evasion, see Slemrod and Yitzhaki (2002).

[5] Camphuysen (2010) finds that rates at which different types of beached seabirds are oiled are correlated with law enforcement activity in the habitats of these birds, suggesting a deterrent effect, but leaving open alternative explanations such as differences in shipping intensity. Lagring et al. (2012) correlate time-series data on possible oil spills from the Belgian Coast Guard with regulatory changes, and their findings suggest a

The remainder of the paper is structured as follows. The next two sections describe the regulations governing the management of oily waste from shipping, their enforcement and the rationale for temporal displacement. Section 4 discusses the data. In section 5, we present the empirical test for the presence of temporal displacement. Section 6 concludes.

2. Regulation of oily waste disposal and enforcement

Oily waste products from shipping are mainly generated by three processes. First, pre-treatment of high-viscosity bunker oil, which is often used as fuel in shipping, results in a relatively solid residue. This residue, called fuel oil sludge, consists of oil, water, and dirt. Second, in all ships, contaminated waste water, mainly from the engine room, gradually builds up at the bilge, the lowest space of the ship. This so-called bilge water contains a varying mixture of lube oil, fuel, water, solvents, detergents and other substances. Bilge water needs to be pumped out regularly to prevent the bilge wells from overflowing and to maintain stability of the ship. Third, the cleaning of cargo tanks of oil tankers creates oily slop.[6]

Up into the 1970s it was common and entirely legal to dispose the bilge water, the fuel oil sludge and the slop into the sea. Even though the spills are small compared to accidental oil spills – ranging from less than 100 liters for minor bilge water discharges to dozens of tons for tank washings – spill size is not necessarily a good predictor of environmental impact (Burger 1993). These smaller discharges can have large detrimental effects on marine life because they contribute cumulatively more to oil pollution input into the marine environmental than accidental spills, and are more likely to occur at the wrong place at the wrong time (National Research Council 2003, Camphuysen 2010). The pollution is chronic, putting continuous pressure on ecosystems in and close to major shipping lanes.

To limit environmental harm from shipping, a set of regulations was drafted in the 1973 International Convention for the Prevention of Pollution from Ships (MARPOL), organized under auspices of the International Maritime Organization (IMO). After some modifications, and after ratification in most of the countries participating in the IMO, the regulations that relate to oil pollution came into force in 1983. Close to all countries with some presence at sea are parties to the Convention. The regulations involve pollution standards, ship design standards, and mandatory self-reporting. The aim is to force the shipping industry to use alternatives to illegal discharges into the sea. Vessels have oil-water separation systems that remove the water component of waste products that build up during normal operations. Separated water should contain hydrocarbon concentrations of no more than 15 parts per million (15 mg per liter), which can be discharged legally while the vessel is at sea and underway. The oily slops that remain have to be stored for future disposal, which can occur legally in two ways. The first, most commonly used method of disposal is to incinerate oil sludge and other oily waste products

positive impact, but the influence of other factors cannot be excluded. O'Hara et al. (2013) model how aerial surveillance efforts are related to the number of observed spills in the Pacific Ocean. They find lower levels of illegal discharges than predicted by the model in the area closest to the airbase of the surveillance aircraft, suggesting a deterrent effect from aerial surveillance – at least on discharges during the day. Close to all of the literature on marine oil pollution focuses on the prevention of non-intentional oil spills. See Knapp and Franses (2009) on the effect of mandatory changes in ship design; Gawande and Bohara (2005) on the effect of Coast Guard inspections and penalties; Epple and Visscher (1984), Cohen (1986, 1987) and Viladrich Grau and Groves (1997) on the effect of Coast Guard surveillance on oil spills during oil transfer operations within the harbor.

[6] Currently, oil residues are mostly removed by spraying the tanks with pure oil (crude oil washing), rather than water. However, about twice a year a tanker is washed with water to be able to perform inspections and maintenance, resulting in some 6,000 m^3 of slop per tanker per year (Crist 2003: 12).

in shipboard incinerators, which are present on most large vessels.[7] The second method is to dispose sludge and slop at port reception facilities.

Under current pollution standards, all discharges of oil in the North Sea area are prohibited. Only substances contaminated with less than 15 parts per million oil can be legally discharged. Prior to the North Sea becoming a Special Area in 1999, discharges of up to 100 parts per million were allowed outside the 12 miles zone (approximately 22 kilometers). The ship design standards involve the fitting and proper functioning of an oil discharge monitoring and control system, an oily water separator, tanks for the storage of slop and sludge, and related piping and pumping arrangements. Shipping crews are also mandated to self-report how they handled oily waste products (and movement of cargo oil) in the Oil Record Book, which can be inspected by the authorities when visiting the harbor. Finally, incineration of cargo oil residues is prohibited. MARPOL regulations also require countries to provide legal alternatives in the form of port reception facilities for oily waste products.

The regulations are primarily enforced by aerial surveillance and port-side inspections. In this paper, we focus on aerial surveillance. All countries around the North Sea committed to aerial surveillance in 1994 through the Bonn Agreement. A similar agreement was reached between countries bordering the Baltic Sea. Coast Guard aircraft conduct surveillance flights above the Dutch Continental Shelf on a daily basis. Most of the flights occur during the day (70 percent). This has been the case for all of the years for which we have data. Radar on board of the aircraft detects possible oil spills through anomalies on the water surface. For about a third of the surveillance flights, satellite images are also used to guide the aircraft to potential oil spills. The combination of satellite and airborne remote sensing technology allows monitoring of vast sea areas at day and night, under all sky conditions and under most weather conditions.

All identified oil spots can be characterized as illegal, because oil spots containing less than 15 ppm are never detected by airborne radar; and oil spots containing less than 100 ppm are very unlikely to be detected (Dienst Noordzee 1992). The radar is fine-tuned to identify oil spots, but it is not perfectly accurate, particularly at very low and very high wind speeds. False positives occur when other phenomena produce similar anomalies on the water surface, including fresh water slicks, seaweed, algae blooms, and subsurface sand banks (Fingas and Brown 2012). Generally, after radar has detected a spot, the aircraft swerves back for a visual inspection and for an investigation of the size and thickness of the spot. The monitoring technology did not undergo fundamental changes since it was first used about 25 years ago. The number of flight hours gradually increased from 600 to 1,200 per year between 1990 and 1996 and has remained fairly constant since then.

The chance of being convicted for an illegal oil discharge is small. First, the Coast Guard aircraft are not in the air for 85 percent of time, and when in the air, it takes about five hours to cover all of the relevant area.[8] Oil spills may have disappeared for the radar before the area is surveyed. Generally, spills disappear or at least become undetectable 1 to 7 hours after the discharge, given prevailing wind speeds of 2 to 6 Beaufort (Helmers 2002). The exact duration depends on local weather conditions including wind speed and air and water temperature. The limited number of flight hours also means

[7] About half of ships that call into large ports are equipped with an onboard incinerator (De Langen and Nijdam 2008: 114).

[8] The chance that a discharge is detected is limited to the flight hours conducted. As discussed in the following section, reports by third parties or whistleblowers are exceedingly rare in the jurisdiction under study.

that shipping crews' chances of observing a Coast Guard aircraft or having radio contact with the aircraft are small.

Second, even when Coast Guard aircraft observe an oil spill, it is difficult to link the spill with a particular vessel in the busy shipping lanes of the North Sea. The data collected by the aerial observers show that in 9 out of 10 cases the offending vessel cannot be identified. In other words, the offender needs to be caught in the act or just after the act, and that rarely happens.

Third, on the off chance that an offender is detected, the case may still be dropped because of a lack of evidence. In the Netherlands, for a prosecutor to proceed with a case, an aerial observer needs to have confirmed the illegal nature of the substance based on visual inspection from the air.[9] The courts rely on the aerial observer's ability to identify the specific appearance of oil on the water surface. In other words, all of the advanced monitoring technology can only be used to guide the aerial observer to a potential oil spill for a visual inspection. This is useful in and of itself, however, because it improves the efficiency of aerial surveillance. Clearly, the standard of evidence has large implications for the chance of being convicted. In low-visibility conditions, including the hours between sunset and sunrise, fog as well as heavy precipitation, the probability of conviction drops to zero.

In the Netherlands, over the period 2006-2012, yearly some 10 to 15 vessels were identified as suspects of an illegal oil discharge. In about half of the cases, the prosecutor proceeded with the case. Cases tend to be settled out of court. The punishment is limited to fines. In the jurisdiction under study, the fines have always been rather low compared to countries like Belgium and France, generally less than 50,000 euros (Camphuysen and Vollaard 2015, Cedre 2010). In addition to the fine, the possible reputational damage may keep shipping companies from violating the regulations.

3. Evasive behavior

A low-cost and time-saving solution to handle the oily waste products is to discharge them into the sea rather than to dispose them at the harbor or to incinerate them on board. First of all, legal disposal of oily waste is expensive. Illegal disposal saves a vessel owner anywhere from 80,000 to 220,000 in 2015 US dollars per year, depending on the size of the ship, its age, number of days at sea, and how well it is maintained (Crist 2003). This is equal to some 5 to 12 percent of the ship's operating costs (*ibid*.). The costs are related to maintaining onboard waste processing machinery, including the oily water separator (see Olsen 2014), and disposal fees at ports (see De Langen and Nijdam 2008). Second, legal disposal at port is time-consuming, which is important because vessel operators limit time at port to the absolute minimum (Gullo 2011). Next to the expense and time, disposal at port was not always straightforward during the period of the analysis, because adequate port waste reception facilities were slow in coming. Only in 2004 Dutch law was brought in line EU Directive 2000/59/EC that stipulated the availability of proper reception facilities. It has been argued that better reception facilities were a major factor behind the sharp growth in legally disposed oily waste in the second half of the 2010s in the harbors of Antwerp and Rotterdam (Carpenter and MacGill 2001; De Langen and Nijdam 2008). For instance, in the harbor of Rotterdam, disposal of oily waste from commercial shipping almost doubled from 131,650 m^3 in 2004 to 227,569 m^3 in 2011 (Lagring et al. 2012: 645).

[9] In some nearby countries, the standard of evidence is even higher. For instance, in Denmark, it is also necessary to provide a sample of the substance, which is obtained from an oil sampling buoy.

Even though illegal disposal saves money and time and the chance of getting caught is low, the penalty may factor into decisions of vessel operators. First, the actual probability of getting caught is likely to be unknown to operators, which may result in overestimation of the expected penalty (Hjalmarsson 2009). Second, discharges happen in wide open areas – ships can be seen from a large distance at normal weather conditions – with lots of other ships passing by and civilian aircraft flying over. With discharges no longer being the norm during the period of the analysis, the disutility from social disapproval may have had a deterrent effect (Winter and May 2001). In addition, third parties may take the effort of reporting offenders to the authorities. The chance of that happening is remote – as can be learned from the data discussed in the next section – but vessel operators may not want to run this risk. Third, discharging in broad daylight may also make more crew members complicit, including those who are not directly involved. Cases of a whistle-blower reporting an illegal discharge to the authorities, not unheard of in the US (US Department of Justice 2004), seldomly occur in the Netherlands, but vessel operators may not want to run this risk either.

All of these chances can be lowered by simply disposing in the dark. Then, the chance of being prosecuted drops to zero, other ships and aircraft are not direct observers, and other crew members can at least pretend not to know what is going on. Temporal displacement to hours with no chance of being convicted is straightforward since disposal of oily substances can easily be postponed for a number of hours. Other low-visibility conditions such as very strong wind or heavy precipitation may also provide an opportunity to evade prosecution, but these conditions are obviously not always at hand, and much rarer and less predictable than the dark hours of the day.

As an alternative to temporal displacement, crews may decide to discharge the oily waste in areas with little chance of being detected, say somewhere on the Atlantic Ocean. This may not be an alternative for a substantial part of shipping traffic, however. Close to 50 percent of all goods handled in Dutch seaports are carried by coastal shipping (Netherlands Statistics 2016). These ships navigate along the coast and all European coastal waters are surveilled in a similar fashion (see also Section 2 on international coordination).[10] In addition, some part of deep sea shipping traffic may feel the urge to discharge in coastal waters since operational discharges cannot be postponed for too long a time. In short, at the very least, spatial displacement is not likely to fully substitute temporal displacement.

4. Data and descriptive statistics

Data on all radar-identified spots and the flight paths of all Coast Guard aircraft surveillance flights above the Dutch Continental Shelf during 1992-2011 were provided by the Netherlands Ministry of Infrastructure and the Environment. The data are part of the 'VluVerO'-database and are unique in covering a long period.[11] The original data are in GIS-format and have been transferred into a grid of 2.5 by 2.5 kilometer. The grid is based on UTM31N-coordinates. We assume the airborne radar to cover an area of 20 km to the right and 20 km the left of the aircraft. Unit of time is an hour.

[10] Surveillance may be more or less strict in other European jurisdictions. As far as we are aware, whether variation in the expected penalty between jurisdictions affects the tendency for illegal discharges has not been systematically studied.

[11] We exclude spots identified by satellite only since data on the frequency of orbit and which area was covered at what resolution could not be obtained.

For each grid cell we know when it was surveyed by airborne radar. We excluded grid cells in the very north of the Dutch Continental Shelf since it has very low shipping traffic intensity (this involves 2.6m cell-hour combinations). We also excluded grid cells where not a single spot was detected during 1992-2011 (this involves 13m cell-hour combinations). The resulting data set relates to an area of 17,450 km^2 – compared to 57,000 km^2 for the complete Dutch Continental Shelf. These restrictions make the data more tractable and do not affect our estimation results.[12] Within this area, on average each grid cell was surveyed 214 times per year during 1992-2011. Coverage varied between 1 and 510 times on average per year. Figure 1 shows the annual flight intensity.

[FIGURE 1]

All 6,610 spots that were identified during 1992-2011 were assigned to a grid cell. When matching spots to the grid, we allowed for a one-hour or two-hour difference between the time that a spot was detected and the time that the aircraft was noted to be crossing that grid cell. These differences could arise because aerial observers incidentally used Universal Time, the default in aviation, rather than local time in Amsterdam, the prescribed time standard for the database. The difference between the two is limited to two hours during daylight saving time and one hour otherwise. Further information on a spot, including the nature of the substance, its size and thickness, is incomplete, in particular during darkness, and not used in the analysis.

Figure 2 shows the trend in the number of detected spots per surveilled grid cell-hour and the trend in surveillance effort during 1992-2011. Clearly, the trend in the probability of detecting a spot by radar is downwards. In addition, our data indicate that the estimated volume of individual discharges has declined during this period (not shown). Given the relatively stable enforcement effort throughout the years – apart from the gradual growth up to 1996 and a major dip in 2007 due to technical problems with the aircraft – the number of detected spots per year closely tracks the trend shown in Figure 2. In the area under study, before 1999, about 300 spots were detected per year. After 1999, this dropped to about 100 spots per year. The drop in illegal oil discharges is confirmed in counts of beached seabirds that are oiled (Camphuysen 2010) and in the trend in radar-identified spots in the German and Belgian part of the North Sea (Carpenter 2007, Lagring et al. 2012). The decline has been attributed to a range of factors including changes in ship design, better facilities for legal disposal in the harbor, strengthened port state control and greater environmental awareness of shipping crews (*ibid.*). Shipping intensity remained roughly stable when measured by the number of sea-going vessels visiting the harbors of Rotterdam and Amsterdam (tonnage increased because of the trend towards larger vessels).[13]

[FIGURE 2]

[12] Given the similar flight paths followed by the aircraft throughout the years, the last restriction – dropping observations without one detected spot for all of the years of the analysis – does not affect our test for temporal displacement in Section 5.

[13] According to locally administered harbor statistics, the number of vessels visiting Rotterdam varied around 30,000 per year during 1992-2011; the number of ships visiting Amsterdam around 4,700 during 1992-2005 and around 5,400 during 2006-2011.

Figure 3 shows the incidence of radar-identified spots during 1992-2011 in the Dutch part of the North Sea. The areas with the highest incidence are concentrated in the three major shipping lanes along the coast and in the approaches towards the harbors of Antwerp, Rotterdam, Amsterdam and IJmuiden. This confirms that the data relate to discharges from shipping rather than oil from other sources, such as oil and gas exploration in the North Sea. Figure 3 shows that the area with the most oil and gas platforms, the southwestern part of the Friese Front (around coordinates 575000, 5900000) has a relatively low incidence of observed spots.

[FIGURE 3]

Figure 4 shows the probability of detecting a spot by hour of the day in the raw data. The time at which a spot was detected is usually not the time at which it was discharged (assuming that the spot is an illegal oil discharge). As discussed in Section 2, oil spills remain on the water surface for a limited time. This implies that a relatively high tendency to discharge at some hours will result in a build-up of discharges during these hours, and a gradual phase out after these hours. In other words: discharges that are concentrated in time accumulate because they do not disappear immediately. The line with the black dots in Figure 4 shows that the probability of detecting a spot strongly increases at 6pm and starts to decline after 11pm. This suggests a tendency to discharge between 6pm and 11pm. The line with the open dots in Figure 4 shows that most flights are conducted at times that the probability of detecting a spot is relatively low.

[FIGURE 4]

We match the geographical data discussed above with meteorological data. The meteorological data are provided by the Royal Netherlands Meteorological Institute (KNMI) and include air temperature and wind speed on an hourly basis. Measurements are taken at Lichteiland Goeree weather station, which is located 30 km off the coast, southwest from Hoek van Holland (the approach of Rotterdam harbor). The Ministry of Infrastructure and the Environment provided data on the water temperature at the Europlatform weather station, 60 km off the coast from Hoek van Holland. We exclude observations at wind speeds lower than 1.5 m/s (1 Beaufort) and higher than 20.8 m/s (9 Beaufort). In these weather conditions, the radar is ineffective (see Section 2). This affects about 2 percent of observations. We assume similar water and air temperatures and wind speeds across the Dutch part of the North Sea, which is a reasonable approximation for our purposes according to the KNMI. The KNMI also provided the time of sunset and sunrise at 52°00' northern latitude and 5°00 eastern longitude on a daily basis for 1992-2011. Table 1 presents the summary statistics.

[TABLE 1]

5. A test for temporal displacement

Oil discharges seem to be concentrated in the first hours of the night. That is what the raw data collected by the Coastguard aircraft suggest. This is not necessarily a sign of evasive behavior, however. A nightly routine may simply fit the schedule of the crew best. The crews operate on a rigid system of 4 or 6-hour watches; the ship is operational 24/7. A necessary condition for the hourly pattern in the raw data to reflect evasive behavior is that the timing should be robust to the wild swings in the time of sunset over the year. To identify whether the timing of discharges is the result of evasive behavior rather than considerations of other nature, we analyze whether the timing changes with the time of sunset.[14] Clearly, we cannot distinguish strategic from non-strategic behavior if the discharges are limited to the few hours that are dark regardless of the time of year. The raw data indicate that such is not the case: the increase in the probability of detecting a spot shown in Figure 4 mainly occurs at hours that are sometimes before and sometimes after sunset.

An increase in the probability of detecting a spot after sunset provides causal evidence for temporal displacement of oil discharges from shipping under the following five conditions.[15] First, other sources of detected spots, i.e. false positives, should not vary with the hour. This condition is met: all the known sources of false positives either do not vary with time (subsurface sand banks, seaweed, fresh water slicks) or vary at a much slower time scale (algae blooms) (see Section 2). The only exception could be other illegal discharges that shipping crews like to hide from the authorities such as environmentally harmful cargo residues. These discharges are very rarely observed by the Coast Guard aircraft however, as evidenced by the data used in this paper, and therefore cannot explain daily patterns.

Second, the technical feasibility of detecting an oil discharge should not vary with the hour. Observation by radar is unaffected by the absence of daylight and anecdotal evidence from experienced aerial observers suggests that spots are rarely identified by visual inspection only. In other words, false negatives are equally likely during the daytime and the nighttime.

Third, weather conditions affecting the duration that discharges are detectable for radar and that vary between day and night should be taken into account. We have data on the three factors that are known to affect this duration: water temperature, air temperature and wind speed (see Section 2). As can be deduced from our data, wind speed is on average about 10 percent higher during the night than during the day. Temperatures are on average 30 percent higher during the day than during the night. Water temperatures vary much less with time of day. We include weather conditions as covariates in our analysis.

Fourth, shipping intensity or the types of vessels present at sea should not differ between day and night. This condition is also met. Commercial shipping is a 24/7 business, and both shipping intensity and the mix of vessels are roughly stable over the course of the day. The relatively great presence of pleasure craft during the day is unlikely to lead to an estimation bias because they are responsible for only a tiny percentage of illegal oil discharges (about 1 percent, see Beco 2013: 6).

We specify a flexible event study framework that non-parametrically estimates how variation in the time of sunset relates to the diurnal pattern in radar-identified spots. We estimate the following linear probability model:[16]

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[14] When analyzing displacement to the nighttime, we focus on the time of sunset rather than the time of sunrise, given the increase in the probability of detecting a spot in the early hours of the night (Figure 4).
[15] We test for a general tendency for evasive behavior, allowing individual ships to diverge from the general pattern. Our data relate to aggregate behavior of all vessels navigating the North Sea after all.
[16] Our results are robust to estimating a logit rather than a linear probability model.

$$P(SPOT_{i,t}) = \sum_{\tau=-T}^{T} [\alpha_\tau W_\tau] + X_t \beta + \delta_i + \mu_j + \lambda_m + \varepsilon_{i,t} \quad (1)$$

The dependent variable $P(SPOT_{i,t})$ is the probability of detecting a spot with airborne radar at grid cell *i* and at hour *t*. The indicator variables W_τ denote the time relative to the hour of sunset. W_1 equals 1 for the first hour after sunset and is zero otherwise; W_2 equals 1 for the second hour after sunset and is zero otherwise, and so on. α_τ are the coefficients for each hour τ that are to be estimated.[17] The event time variable suffers from some random measurement error. Time in our data is truncated at the hour, which means that the difference between the time and the time of sunset can be off by almost an hour. This measurement error can be larger or smaller when aerial observers incidentally used Universal Time rather than local time (see Section 4). We return to this issue when presenting the results. We take a broad interval of six hours before and after sunset to identify signs of evasive behavior. The earliest time included in the analysis is 10am, six hours before sunset in December at 4.30pm; the latest time is 4am, six hours after sunset in June at 10pm. We abstract from any evasive behavior around the time of sunrise: within the above event time window, it is dark for all of the hours after sunset.

X_t is a vector of observable factors that are related to the probability of detecting a spot and to the hour of the day, including water temperature, air temperature and wind speed. We do not know the exact nature of the relation between weather conditions and the dependent variable, which is why we also include quadratic terms for each of these three covariates. δ_i represents area-fixed effects that are constant over time, for instance whether grid cell *i* is inside or outside a major shipping route. μ_j represents the year-fixed effects, which picks up general shocks to the chance of observing a spot, such as any effects of the increase in surveillance effort. The month-fixed effects λ_m capture any seasonal effects that are constant over time such as algae blooms in the spring. $\varepsilon_{i,t}$ is an error term, clustered at the level of grid cells.[18]

Figure 5 plots the estimated indicator coefficients α_τ from equation (1). Event time – the hour relative to the hour of sunset – is plotted on the horizontal axis. Event time 0 corresponds to observations for which the difference between the hour and the hour of sunset is 0. The coefficients are estimated relative to the last mostly 'clean' hour without sunsets, event time -2. Due to the measurement error discussed in above, event time -1 may also denote the hour of sunset, rather than event time 0 only. The plotted event time coefficients can be interpreted as the absolute difference in the probability of

[17] Darkness sets in slightly later than the time of sunset. At 52°00' northern latitude, twilight, the time between sunset and dusk, takes 35 to 50 minutes, depending on the time of year.

[18] The smaller surveillance effort during the night than during the day may be a source of measurement error in the probability of detecting a discharge. As worked out in O'Hara et al. (2013), the relationship between surveillance effort and detection probability may be s-shaped rather than linear. This is related to the fact that oil spots can be detected for only a limited number of hours after the discharge. At low (high) levels of surveillance effort, greater surveillance effort leads to a more-than-proportional (less-than-proportional) increase in the detection probability. Given the fact that oil spots tend to be on the water for some hours and the North Sea area is patrolled no more than once a day, our observations are likely to be at the left part of the s-shaped curve (for a discussion, see also Lagring et al. 2012 on the southern North Sea). In that case, the difference in the incidence of spots between the day and the night is even more pronounced than can be deduced from the data – in particular given a trend towards a greater share of small volume-discharges that disappear relatively quickly for the radar. Consequently, estimates of equation (1) may provide lower-bound estimates of the diurnal pattern.

observing a spot relative to 2 hours before sunset. The bands represent the 95 percent confidence intervals and show whether each point estimate is statistically different from 0.

[FIGURE 5]

Figure 5 shows that during the hours before sunset, the estimated event time coefficients are small and not statistically different from zero.[19] As soon as night falls, the probability of detecting a spot starts to increase. The increase starts at event time -1, which is the first hour with observations that are at or shortly after the time of sunset (recall the measurement error in event time). As of that time, all of the estimated event time coefficients are statistically significantly different from zero. As discussed in Section 4, if discharges are concentrated in time, then the spills on the water surface tend to accumulate, resulting in an increasing probability of observing a spot. The analysis suggests that the hours right after sunset are most popular for illegal oil discharges. That is during the watch of the chief engineer (6pm-12am and 6am-12pm for vessels on a 6 hour watch system or 8pm-12am and 8am-12pm for vessels on a 4-hour watch system). This is no coincidence: the chief engineer has repeatedly been found to be the organizer of the illegal discharges (US Department of Justice 2004). Figure 5 provides proof that discharges are timed strategically within the schedule of watches; the discharges do not simply start at the start of the watch of the chief engineer. The upward trend in detected spots is only discernable after sunset, and not at some fixed time regardless of visibility conditions. In other words, the timing of discharges is fine-tuned to avoid conviction.[20] Given an average incidence of detected spots (*1,000) in the early afternoon of 0.5, this rate goes up by 80 percent in the 6 hours after sunset. Given that oil spills tend to remain at the surface for many hours and that the average incidence in the early afternoon is also affected by other phenomena detected by radar, it is difficult to say which share of the discharges occurs at night. The results suggest that this share is substantial: it is at the least close to 50 percent (0.4 compared to a base rate of 0.5), but most likely much higher. Some 5 to 6 hours after sunset, the upward trend reverses, suggesting that at that time the rate at which oil spots disappear is greater than the rate at which oil spots are generated. The timing of the trend reversal is in line with the average duration that oil spots remain detectable for radar at prevailing weather conditions (see Section 2).

Just like the overall rate of discharges, the tendency to discharge at night may have altered during 1992-2011. Deterrence technology and surveillance tactics remained similar during this period and also enforcement effort did not vary greatly (see Sections 2 and 4), but a number of things changed. The regulations were tightened in 1999 when the North Sea became a MARPOL Special Area – reflecting the particular sensitivity of this marine environment to oil discharges because of its shallowness. Since then, ship companies had to comply with the most stringent oil discharge provisions when navigating in the North Sea. This could have both lowered illegal discharges and increased

[19] In addition, we find statistically significant effects of water temperature (negative), air temperature (positive) and wind speed (negative) on the probability of observing a spot.

[20] It could be that daily discharges are deterred and nightly discharges are not deterred. In that case, there is no temporal displacement of crime. This is not a plausible explanation for our findings, because oil discharges can be planned. It would imply that ships use legal and illegal alternatives interchangeably, which is implausible. For instance, the same ship that sails in the North Sea would put the oily waste in storage tanks during the day and dispose it at the harbor later (or incinerate the waste on board), but would illegally discharge oil at night. Clearly, if the option of an illegal discharge is in the choice set of the crew, it makes more sense to wait until after sunset rather than going through the effort of doing the right thing during the day.

displacement. In addition, as discussed in Section 2, doing the right thing became easier with better port reception facilities for disposal of oily waste that were developed in the 2000s. This is likely to have lowered the rate of illegal discharges, including those in the nighttime. To test the sensitivity of our results to these and other changes, we conduct the event time analysis for two sub-periods: before and after 1999. We cannot analyze the diurnal pattern for shorter periods because of the low incidence of detected spots.

[FIGURE 6]

Figure 6 shows the results. Given the drop in the overall rate of illegal discharges, we use separate vertical axes for the two periods. The pattern for the years until 1999 is similar to the estimates for the complete period shown in Figure 5. The increase after sunset is also statistically significantly different from zero. The event time coefficients for the years since 1999 are estimated with much less precision due to the sharp drop in the incidence of detected spots. The diurnal pattern remains similar though: a roughly stable rate before time of sunset and a clear increase after sunset. The reversal in the upward trend after sunset is earlier and more abrupt than in the first period. This is probably due to an increase in the share of low-volume oil discharges, because they disappear for the radar relatively quickly (see Section 4). Also during the second period, the increase after sunset is statistically significantly different from zero. Given an early afternoon base rate of detected spots (*1,000) of 0.86 for the first period compared to 0.26 for the second period, the relatively imprecisely estimated increase after sunset for the second period is certainly not lower than the increase for the first period. To conclude, the overall rate of oil discharges may have dropped in later years, but the tendency for temporal displacement has not diminished.

6. Conclusions

This paper illustrates the relevance of uncovering the dynamics of illegal behavior in response to imperfect monitoring and enforcement. For many years, the shipping industry has been suspected from shifting illegal oil discharges from the daytime to the nighttime. When it is dark, a possible oil spot detected on the water surface cannot be inspected visually. Consequently, a case will be dismissed over lack of evidence. This gap in enforcement is present in many jurisdictions, including the one under study. Whether vessel operators exploit this gap has not been put to the test before. With unique data collected by Coastguard aircraft for 20 years during both day and night we were able to empirically test for the presence of temporal displacement. The data cover the Dutch part of the North Sea, one of the busiest navigated seas in the world and also one of the most polluted seas. Side-looking airborne radar detects possible oil spills through anomalies on the water surface, regardless of whether it is day or night. The spots are concentrated in shipping lanes and approaches to harbors.

We find clear evidence that the timing of the illegal oil discharges moves back and forth with the time of sunset. As soon as sun sets, we identify a strong increase in the probability of detected spot on the water surface. No other phenomena picked up by radar such as seaweed and algae blooms can account for this diurnal pattern. We also find that the tendency for temporal displacement has not diminished since 2000. Our findings show that even a tiny chance of getting caught can have a major effect on illegal behavior. In this sense, we provide indirect evidence of a deterrent effect from aerial surveillance – even though the behavioral response includes temporal displacement.

Our findings are relevant to all coastal countries with shipping traffic along the coast. Marine oil pollution is a worldwide problem – and remains so even after a period of prolonged decline after regulations came in place in the beginning of the 1980s. Highly advanced remote sensing technologies based on airborne radar and satellite imagery that is employed in the Netherlands, but also in many other nations including the US, Canada and France, may have had a deterrent effect, prompting shipping companies to abandon illegal oil discharges all together, but leave gaps in enforcement during low-visibility conditions that invite evasive behavior.

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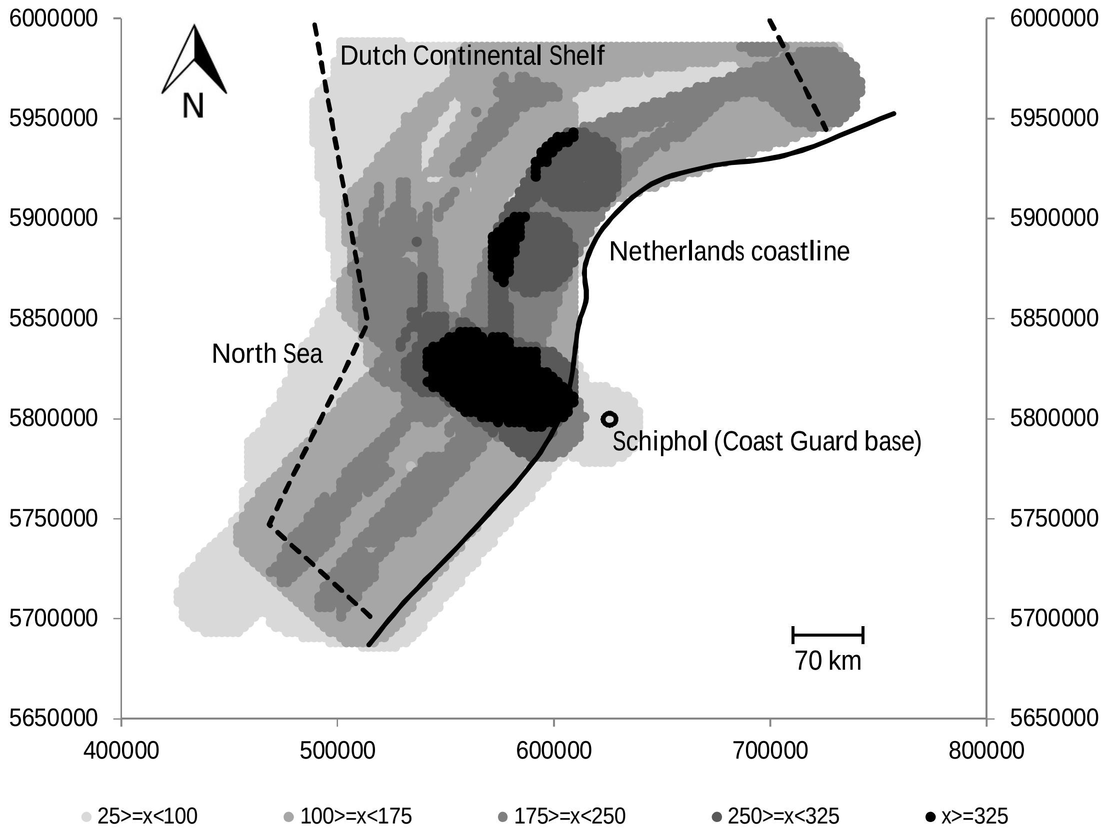
Table 1. Summary statistics

	Mean	Standard deviation	Min	Max
Spot (*1,000)	0.63	25.01	0	1
Darkness	0.32	0.47	0	1
Water temperature (ºC)	11.95	4.55	3.80	20.80
Air temperature (ºC)	11.05	5.33	-8.80	28.30
Wind speed (m/s)	8.05	3.49	2.00	20.6
Number of observations	10.759.697			

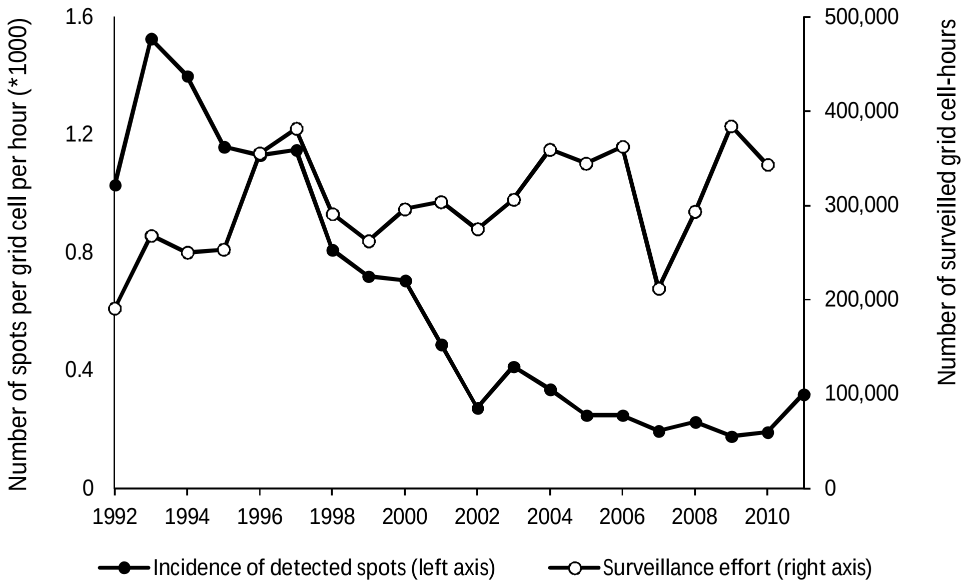
Note. Data by grid cell and hour for Dutch Continental Shelf, excluding grid cells not surveilled once during 1992-2011 and excluding grid cells without one detected spot during 1992-2011. Excluding observations at wind speeds of less than 1.5 m/s and more than 20.8 m/s.

Figure 1. Flight intensity above the Dutch Continental Shelf, 1992-2011



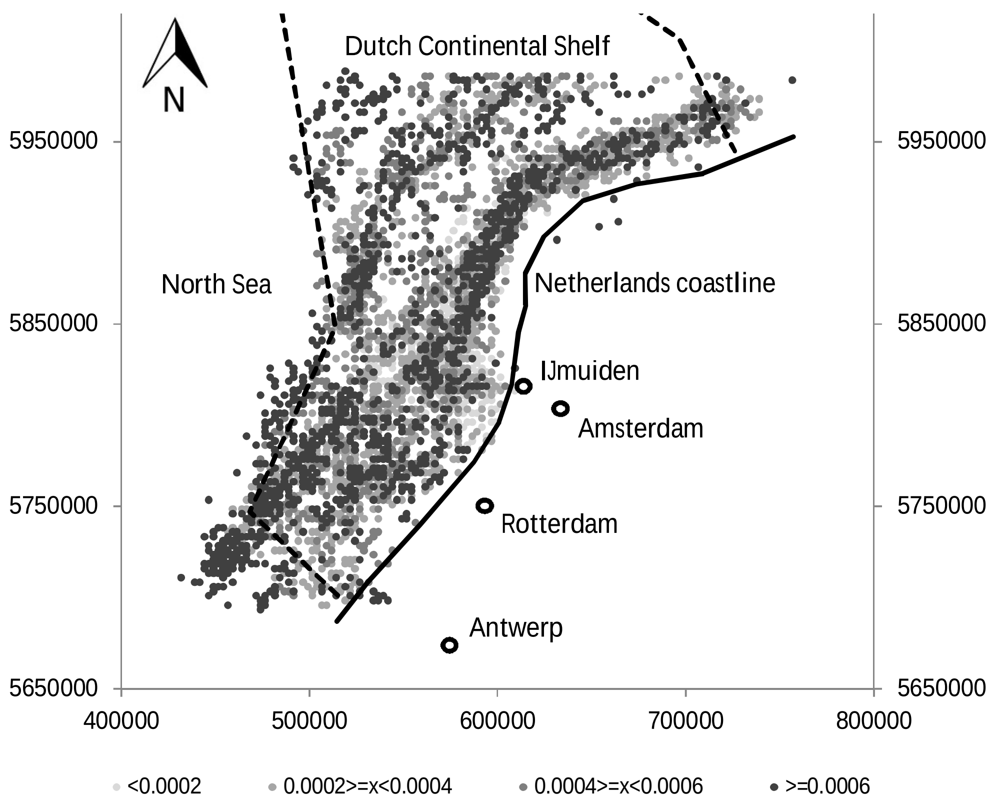
Note. Flight intensity is defined as the average number of times per year that a grid cell was patrolled during 1992-2011. DCS stands for Dutch Continental Shelf. On the axis are UTM31N-coordinates.

Figure 2. Radar-identified spots and surveillance effort, Dutch Continental Shelf, 1992-2011



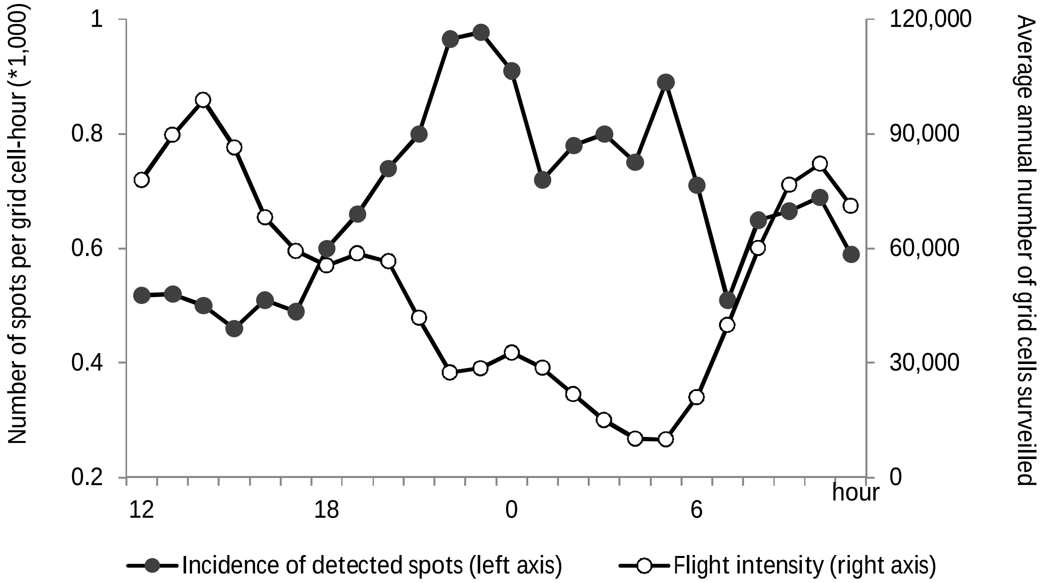
Note. Data for Dutch Continental Shelf, excluding grid cells without one detected spot during 1992-2011. Excluding observations featuring wind speeds of less than 1.5 m/s and more than 20.8 m/s.

Figure 3. Average yearly incidence of radar-identified spots, Dutch Continental Shelf, 1992-2011



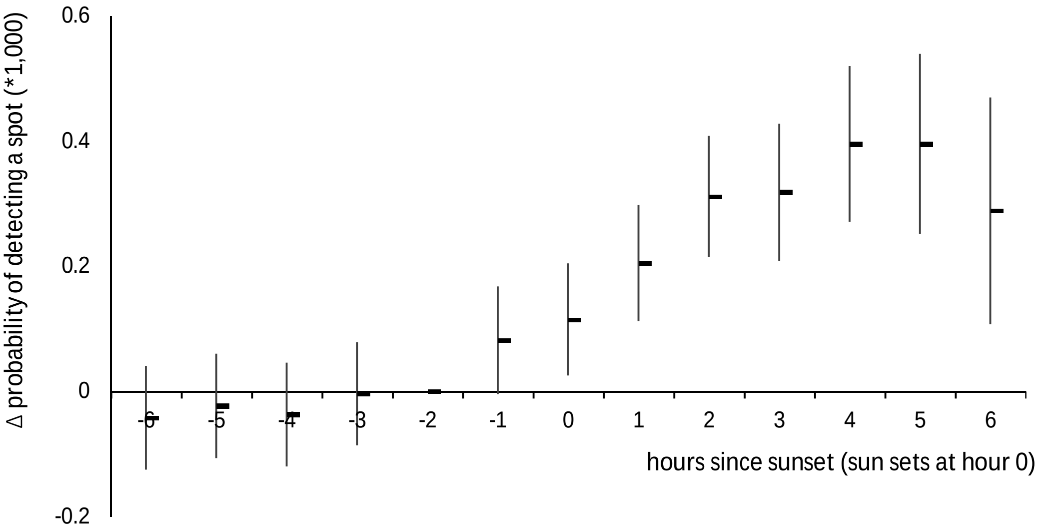
Note. Incidence is defined as the number of yearly identified spots per grid cell-hour. On the axis are UTM31N-coordinates.

Figure 4. Average incidence of detected spots and flight intensity, by hour of the day, Dutch Continental Shelf, 1992-2011



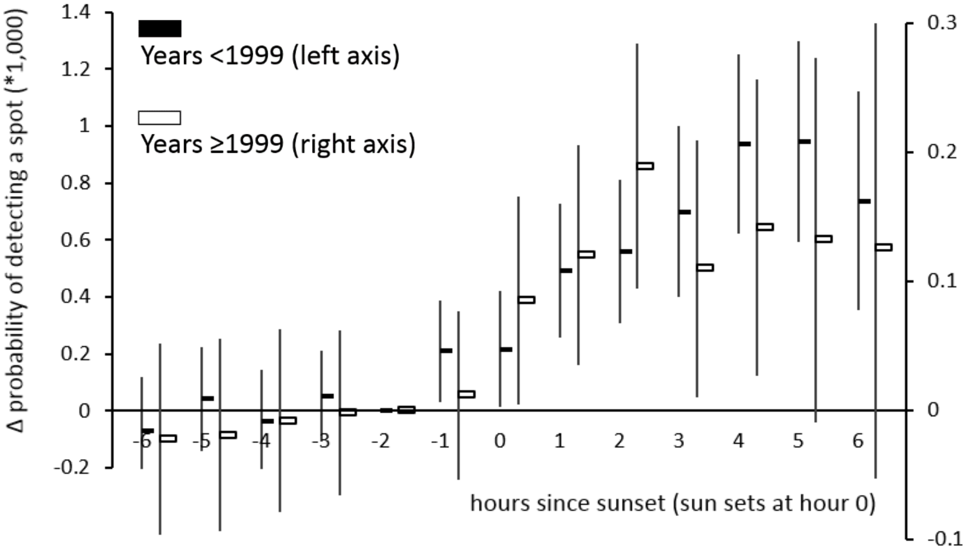
Note. Incidence is defined as the number of yearly identified spots per grid cell by hour of the day. Flight intensity is defined as the average yearly number of grid cells patrolled by hour of the day. Excluding grid cells without one detected spot during 1992-2011. Excluding observations featuring wind speeds of less than 1.5 m/s and more than 20.8 m/s.

Figure 5. Estimated probability of detecting a spot, relative to the last hour before sunset



Note. Graph plots coefficients α_τ from estimation equation (1). The bars show the 95% confidence interval based on standard errors clustered at the level of grid cells. Based on data by grid cell and hour for the Dutch Continental Shelf for 1992-2011. Excluding grid cells without one detected spot during 1992-2011. Excluding observations featuring wind speeds of less than 1.5 m/s and more than 20.8 m/s. Number of observations: 5,930,551.

Figure 6. Estimated probability of detecting a spot, relative to the last hour before sunset



Note. See Figure 5. Number of observations for years<1999: 1,990788; number of observations for years ≥1999: 3,939,763.