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Weather the Storms? Hurricanes, Technology and Oil Production

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Abstract

Do technological improvements mitigate the potential damages from extreme weather events? We address this question using oil production and hurricane data from the Gulf of Mexico. We show that hurricane activity lowers well production and that stronger storms have larger impacts that persist for months after impact. Hurricanes also significantly increase the probability that oil assets are stranded, particularly when the hurricanes pass within 50km of an oil rig's location. Regulations enacted in 1980 that required improved construction standards for rigs in the Gulf only modestly mitigated the short-run production losses caused by hurricanes. The 1980 regulatory reforms also modestly decreased the probability that leases permanently exited production.

Topics: Business fluctuations and cycles, Climate change, Potential output
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Everyone has a plan until they get punched in the mouth. — Mike Tyson

1 Introduction

In the coming decades, changing climatic conditions are expected to transform the Earth's habitats through rising seas, changing currents and stronger, and possibly more frequent, storms. Some mitigation efforts, such as the Paris Climate Accord, are designed to limit the growth in the forcing variables most commonly identified as the root causes of the changing climate. A complementary approach to mitigate the costs of the changing climate is to strengthen the resilience of new and/or existing infrastructure. At present, little is known about the viability and general effectiveness of this latter approach (Fankhauser 2017). In this paper, we focus on one aspect of climate — extreme weather events — and ask whether resilience efforts can mitigate damages from these events.

To address this question, we use oil production data from the Gulf of Mexico (Gulf) and changes in the regulations governing oil rig construction enacted in the 1980s to investigate the feasibility and efficacy of resilience efforts. We map hurricane trajectories and identify hurricanes that impact oil leases in the Gulf of Mexico. Our first contribution is to identify production losses associated with extreme storms. We find in general that major hurricanes that pass within 50 km of an oil platform cause a near total decline in production one month after the hurricane and that losses persisted for months, particularly for major hurricanes. We find qualitatively similar outcomes if we expand the range to within 250 km of a rig's location. We use changes in the regulatory standards for newly built offshore rigs in 1980 and 1988 to estimate the efficacy of new technological standards for platform construction to help withstand hurricanes. We find modest evidence that the changes in regulatory standards mitigated damages from hurricanes. One caveat to this is that these results are specific to a particular industry and location, offshore oil in the Gulf of Mexico, and to a specific aspect of climate, extreme weather events. Whether these conclusions generalize to other industries and locations is uncertain. However, they do suggest that caution may be warranted over assumptions about the efficacy of technology for mitigating climate-related damage.

Our empirical approach combines production and facility data for oil leases in the Gulf of Mexico from the Bureau of Ocean Energy Management and hurricane tracking data from the National Oceanic and Atmospheric Administration's National Hurricane Center to map hurricane paths to oil facility locations. Our sample is monthly from 1980 to 2018 and includes 2,447 oil well locations. To determine rigs that are hit directly by the maximum wind and waves of a hurricane, we use a radius of 50 km that corresponds to the radius of the eyewall of a typical hurricane, where wind speeds are highest. We estimate the hurricane effect on production up to eight months from impact using hurricane ratings on the Saffir-Simpson scale. Since two possible regulatory reforms may have impacted platform resilience to hurricanes, we consider both in our empirical specifications. Using interaction terms based on the earliest year of rig installation at a lease location, we estimate the effect of both the 1980 and 1988 regulatory changes on production losses from hurricanes.

Our results suggest that hurricanes that are Category 3 or higher on the Saffir-Simpson scale that pass within 50 km of a lease lower oil production by roughly 90 percent one month after impact. The effects of hurricane hits are also persistent and the persistence depends on the hurricane strength. For Category 4 storms, production remained 44 percent below pre-storm production eight months after impact. The production impact of a hurricane appears mitigated by its distance from the lease location although there is little evidence that distances up to 250 km matter for the largest (Category 5) hurricanes which are generally catastrophic. In general, our estimates suggest that the production losses from hurricanes are non-linear. Our results suggest that the increased standards imposed by the 1980 regulatory changes generally had significant effects on the production lost from hurricanes, although, in level terms, the effects are generally small in the first months after impact. We also find some evidence that the 1988 regulatory reforms may have actually increased production losses.

We next investigate the effect of hurricanes on the extensive margin of oil lease production. For each producing lease in our sample, we construct a dummy variable equal to 1 if that rig exits our sample prior to the end of our sample, December 2018. We estimate a logit model using the history of hurricane hits in our data to determine whether hurricane activity leads to a termination of oil production for a lease. Our estimates imply that hurricanes of Category 2 or higher significantly increase the odds that a lease stops production. Having established that hurricanes affect lease survival, we next ask whether the regulatory reforms affected the probability that a lease exits after a hurricane. Identifying the causal effect of the regulatory reforms is challenging because, ideally, we want to compare the exit probabilities of a lease built according to the reforms with a lease built prior to 1980 that are hit by a hurricane of the same magnitude. We propose a nearest neighbour matching model to estimate whether the regulatory changes in 1980 and 1988 affected the probability of lease exit where we match leases exactly according the category of the last hurricane to hit the platform. Our estimates suggest that the regulatory changes significantly lowered the probability of lease exit, by roughly 12 to 18 percent, when matched on recent hurricane activity. To provide some qualitative measure of the cost of exit, we estimate an exponential decline model and find that most leases that exit the sample are individually relatively small in terms of the oil not recovered, but that the aggregate loss may be close to 70 million barrels. We find that the 1980 regulations may have saved roughly 9 million barrels from being stranded.

We are not the first to examine the impact of hurricanes on economic activity. Stobl (2011) examines the impact on county-level growth of hurricanes and finds that they lower economic growth by roughly 0.45 percentage points (see also Hsiang and Jina (2014)). Belasen and Polachek (2008), Gallagher and Hartley (2017) and Deryugina (2017) study the impact of hurricanes on employment, household finance and government transfers, respectively, and find evidence that the direct effect of hurricanes are costly, though the distribution of those costs between private and public actors may depend on private and public insurance. Elliott, Strobl, and Sun (2015) examine the damages from typhoons in China and find short-run persistent effects on local production as proxied by nightlight intensity data.

Compared with other studies of climate damages, our study's use of oil production data to assess the costs of hurricane damage and the potential for technological investment to mitigate damages has three advantages. First, production is recorded monthly, which means that the timing of a production disruption from a hurricane is more easily identified. Unlike, for example, agricultural yields, which are complex functions of soil, sunlight, precipitation and time (Dell, Jones, and Olken 2014), oil production is determined mainly by non-climate factors such as field size, age and pressure. Second, oil leases produce oil and producers cannot adapt by changing production to another commodity (e.g. from canola to soy) using the same resource. Agricultural yields can be affected by the seeding decisions of farmers even within the same basic staple crop. Third, as noted above, capital investment can potentially mitigate the losses from hurricanes for oil production. While some aspects of agricultural production are capital intensive, the effects of weather events on soil quality cannot easily be mitigated by capital investment. The same is not necessarily true for oil production, which is more capital intensive. One limitation of this study is that we are unable to measure the capital cost of hurricane damage to rigs because of a lack of data. Thus, we are unable to estimate the expected rate of return to investment in mitigating technologies. However, our estimates provide suggestive evidence that these rates of return are likely to be low.

Our results also highlight how difficult climate change policy-making may be, at least for mitigating the effects of extreme weather. It would appear either that efforts to make rigs resilient to major hurricanes are bordering on the futile or that regulators may not be capable of determining or detecting compliance with such standards (perhaps because there are few, or no, examples of success as templates). Such climate policies may unintentionally lead to inefficient allocations of capital and thus increase the costs of economic transitions in the face of climate change. One implication from our study is that to minimize inefficiencies, regulators should review the evidence on whether a particular mitigation policy is effective after some specified period of time since it may be *a priori* unknown whether the intended mitigation is even feasible.

The non-linearity in hurricane impacts that we document may be particularly relevant in coming decades. Although forecasting how long-term climate trends will affect hurricane activity is challenging, the general consensus is that hurricanes will increase in strength and perhaps in frequency, particularly in the Atlantic region. Emanuel (2021) examines a high-resolution but simplified coupled atmosphere–ocean tropical cyclone model (from the sixth-generation Coupled Climate Model Intercomparison Project) and finds that global tropical cyclone activity is expected to increase in strength and frequency, particularly in the Atlantic and Northern hemisphere regions. Yamaguchi, Chan, Moon, Yoshida, and Mizuta (2020) use a model similar to the fifth-generation Coupled Climate Model to investigate hurricane translation speed and find that hurricanes near the tropics are unlikely to change their speed over ground in coming decades. Bruyère, Rasmussen, Gutmann, Done, Tye, Jaye, Prein, Mooney, Ge, Fredrick, Friis-Hansen, Garrè, Veldore, and Niesel (2017) use the Weather Research and Forecasting model (Skamarock, Klemp, Dudhia, Gill, Barker, Wang, and Powers 2008) and find that hurricane activity in the Gulf of Mexico may decrease in frequency but that the proportion of Category 3 or higher hurricanes will increase. Our results suggest that production loss from such hurricanes is much larger than for Category 1 or 2 storms and so the coming climate trends appear to portend significant production losses. Our results also suggest that regulatory improvements and investment in rig resilience are unlikely to substantially mitigate these anticipated losses.

2 Oil production and hurricanes in the Gulf of Mexico

Oil exploration and production in the Gulf expanded after World War II for a number of reasons, related to both demand (the automobile age) and supply (the surplus military equipment and engineering experience gained during the war). The late 1940s and 1950s also coincided with a period of relatively infrequent hurricane activity that influenced platform design. Early oil production platforms, located in Gulf waters that were shallow despite being miles from shore, were built to withstand modest wave heights and wind speeds. The 1960s saw a return of hurricane activity to the Gulf of Mexico with four named storms — Carla (1961), Hilda (1964), Betsy(1965) and Camille (1969) — that impacted oil production.[1] The oil industry responded to the changing climatic conditions by establishing the annual Offshore Technology Conference in 1969, which brought together platform engineers to discuss and revise design standards. One of the lessons learned from the 1960s hurricanes, particularly Camille, was that the waves produced during such storms could be much higher than previously believed possible. Shell recorded wave heights of 70–75 feet at its platforms, which shocked experts who had previously declared that wave heights would "seldom, if ever, exceed 20 feet."[2] Such findings led to design changes and, in 1972, the issuance of standards and guidelines for mobile drilling units by Lloyd's Register of Ships and the American Bureau of Shipping. These guidelines were then incorporated into the US Coast Guard's regulatory requirements (OCS Order No. 2), as these mobile units were classified as ships and fell under the US Coast Guard's authority.[3] Mobile drilling units in this era were used primarily for exploratory drilling, and, if oil reserves were found, platforms were constructed at the well site for extraction.

Offshore oil leases on the Gulf of Mexico Outer Continental Shelf (OCS) are administered by the US Fed-

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[1] For example, losses from Hilda reached $100 million on facilities valued at $350 million prior to the storm, see Austin, Priest, Penney, Pratt, Pulsipher, Abel, and Taylor (2008).

[2] See Austin, Priest, Penney, Pratt, Pulsipher, Abel, and Taylor (2008), page 141.

[3] We thank Tyler Priest for outlining this history to us. In some cases, the mobile units were, in fact, ships that had drilling units installed on their decks. In other cases, the mobile units were more similar to barges that could be towed to locations. Because the technology to hold mobile units in place was still evolving, some units would be fixed in place using cables during drilling operations. Modern deepwater rigs use thrusters to maintain position.

eral Government. Between the 1970s and the present, responsibility for the OCS passed from the Geological Survey (USGS) to the Minerals Management Service (MMS), in 1982, which was subsequently split into three new US government agencies in 2011, including the Bureau of Ocean Energy Management (BOEM). These agencies develop and administer the regulations governing oil platforms. Perhaps spurred by the re-emergence of hurricane activity in the Gulf in the 1960s, the USGS introduced regulations in November 1979 (effective January 1, 1980) that required new oil rigs to be built to a standard that would withstand the forces generated by anticipated extreme weather, including waves and subsea soil instability. These regulations were first proposed in August, 1977, and the intervening period allowed for comments by interested parties. One of the key regulatory requirements is in OCS Order No. 8, Section 3.2.1.4 (b) Structural Information, which relates to the Platform Verification Program. The final wording of this paragraph requires leasees to provide for approval "[d]esign loading and criteria which consist of a summary description of the design load conditions and design load combinations taking into consideration the worst environmental and operational conditions anticipated over the service life of the platform or structure" (Fed. Reg. Vol. 44, No. 247, 76248). These regulations appear to have been salient to the industry, as the preamble discussion and replies to comments for OCS Order No. 8 totalled roughly 4 pages whereas the regulations themselves were 2.5 pages. One point to note about OCS Order No. 8 is that while the wording in some cases appears clear (i.e. "worst environmental and operational conditions"), in others it appears open to interpretation (i.e. "anticipated over the service life"). OCS Order No. 8 does not clarify how expectations should be determined.

As oil exploration in the Gulf ventured into deeper waters during the 1980s, the MMS introduced additional language to the regulations for newly installed rigs as part of an overall proposal to streamline the regulatory progress in March, 1986 (Fed. Reg. Vol. 51, No. 52, 9333). Perusal of the comments and discussion in the preamble to the final version of the regulations published in April, 1988, shows that these regulations were also salient to the industry. Several comments suggested cancelling the Platform Verification Program entirely and others argued that its scope should be reduced to rigs built in 600 feet of water or more. The responses from the MMS were categorical: they felt numerous platforms had benefited from the program since its start in 1980 and the program would be kept. The Federal Register 30 CFR 250.900 section 250.134 outlined the new engineering standards that replaced OCS Order No 8 as of May 31, 1988. In many respects, the language in 250.134 is very similar to that in OCS Order No. 8; however, the ambiguity in terms of "worst" and "anticipated" appears to have been resolved. Paragraph 250.134(c)(2)(iv) states:

> In general, the recurrence period chosen for the events specified in paragraphs (c)(2)(ii)(A) and (C) of this section shall primarily be based on the design service live of the platform. For platforms designed for a service life of 20 years, the recurrence period chosen for the determination of these events shall not be less than 100 years. For other service lives, the design event recurrence interval

> shall generally be adjusted to provide for a risk of occurrence which does not exceed the risk of occurrence for the 20-year/100-year combination. (Federal Register: 53 Fed. Reg. 9 Apr. 1 1988)

This regulation clarifies that expectations of the worst environmental conditions for the anticipated service live are evaluated by requiring all new platforms covered by the regulations to be built to withstand 100 year storms. In the Gulf, a 100-year storm is typically interpreted as a Category 4 hurricane, which features winds over 130 miles per hour (209 kilometres per hour [kph]). While such wind speeds are capable of enormous damage, at sea, winds are coupled with waves whose heights can approach 80 feet or more. Such waves can do serious damage to rigs with platforms below this level. The effects of these waves are not confined to the surface: large waves can also induce seafloor instability and damage platform supports and moorings. However, whether the wording of 1988 regulations led to design requirements that were substantively different than those of the 1980 regulations is unclear. What is clear is that the 1988 regulations were claimed to have had their intended affect. After hurricanes Katrina and Rita swept through the Gulf in 2005, eventually being credited with the destruction of 115 rigs, Secretary of the Interior Gale Norton testified before Congress to their effectiveness: "Those offshore facilities that withstood the storms best were those constructed to the 1988 MMS upgraded design standards."[4]

2.1 Geocoded lease production and hurricane data

We obtain monthly lease production data for offshore oil leases in the Gulf of Mexico from the US Bureau of Ocean Energy Management (BOEM). We also obtain information on the production structures, such as their latitude and longitude, water depth and dates of installation and removal (if applicable) from the BOEM.[5] We merge both data together using the lease number where available. Not all observations in the production structures data include the lease number. Using this method, we are able to match 2,650 leases of which 2,447 produced oil or condensate at some point in our sample with their location in latitude and longitude. We choose to sum both oil and condensate production by lease location as this appears to be the standard measure reported by the Energy Information Administration (EIA). We note that single leases often have multiple rig locations. Typically, these rig locations are very close together and in some cases are physically connected. Of the 2,447 producing leases, 1,830 were installed after the 1980 regulatory change and 1,266 were installed subsequent to the 1988 regulatory changes.

We obtain hurricane track data from the National Oceanic and Atmospheric Administration's National Hurricane Center, which tracks hurricanes and their maximum wind speeds on a six hourly basis (Landsea and Franklin 2013). We map hurricane tracks to the latitude and longitude of the lease platform locations

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[4] See testimony by Interior Secretary Gale Norton to Congress on October 4, 2005: `https://www.doi.gov/sites/doi.gov/files/archive/news/archive/05_News_Releases/051005.htm` and `https://www.bsee.gov/what-we-do/research/tap/tap-categories/hurricane-katrina-and-rita.htm`

[5] Both datasets were downloaded from `https://www.data.boem.gov/Main/RawData.aspx` in December, 2020.

using Haversine distances based on the latitude and longitude of the platform locations and the hurricane locations. Because the hurricanes in our data are only observed periodically, we infer a linear path between the observed points and also measure the minimum distance on this path to the platform locations.

Hurricanes also vary in size and so we use two distance measures: 50 km and 250 km.[6] Of the leases we examine, only 164 (6.7 percent of the sample) have not had a single hurricane of Category 1 or higher pass within 250 km (roughly the radius of a typical hurricane). Roughly one quarter of our sample have had five hurricanes pass within 250 km. However, not every hurricane that passes within a 250 km radius of a well is likely to damage production facilities. Small hurricanes have hurricane-force wind fields that have a radius of roughly 40 km from the eye. Large hurricanes can have wind field radii of around 250 km. Thus, we consider a range of possible distance measures to illustrate how distance and storm strength impact oil production and resiliency. Since a hurricane's wind speed often changes over its path, we use the maximum recorded wind speed when the hurricane is within the distance measure of a lease location (we use the maximum of either vertex when interpolating between observations). Thus, for example, the same hurricane can be recorded as a Category 4 hurricane for some leases and a Category 3 hurricane for others. A hurricane can also change between category ratings for the same lease location if the hurricane's speed over ground is such that it is within the distance measure for multiple observations and its average wind speed changes.

Because our production data is reported by lease, we cannot attribute production to separate rigs. We assume that lease production is complementary so that a hurricane affecting any of the structures on the lease will potentially affect production. This "weakest link" assumption implies that our estimates of the effects of hurricanes on production should be interpreted as a lower bound for damages since our sample of rigs hit by a hurricane may include platforms that are not essential for production.

For our analysis, we set the sample period from 1980 to 2018, although both the hurricane data and the production data extend as far back as 1947. We choose to restrict our sample to the period 1980–2018 because we are concerned that production responses to the oil price shocks of the early 1970s (including the creation of the Organization of the Petroleum Exporting Countries) and the regulatory and institutional changes in the US during this period (including the Energy Policy and Conservation Act of 1975 and the creation of the Department of Energy in 1977) may confound our estimates for this period. We are also concerned that changes in how hurricane paths were recorded prior to the introduction of satellite monitoring technology in the 1960s could spuriously affect our estimates. Given the nearly 40-year period of our sample, we are not concerned that this sample truncation will affect our results. Our sample truncation does not directly affect the distribution of rig ages because we include any rig that produces between 1980 and 2018 in our sample regardless of the date it begins production.

Our final sample includes 2,447 separate oil-producing leases for the period 1980–2018. Table 1 illustrates

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[6] For robustness, we also consider 25 km and 100 km radii but choose not to report these in the paper as they generally do not provide any additional insights regarding hurricane damages.

how the choice of distance affects whether a rig is classified as affected or not. For example, 1,753 leases had at least one hurricane of Category 1 on the Saffir-Simpson scale (SS1) or higher pass within 50 km during this period while 936 had at least one hurricane of Category 3 (SS3) or higher pass within this distance. Thus, while hurricanes are relatively rare events occurring in roughly 3 percent of the observations using our largest distance measure of 250 km (16,883 hurricane events out of 502,808 observations), they are nevertheless broadly distributed across leases. Indeed, roughly 94 percent of all leases had at least one hurricane of level 1 or higher pass within 250 km in our sample.

Table 1: Affected oil leases and hurricane events by proximity

Distance (km)	Leases: SS1-5	Leases: SS3-5	Hurricane events
50	1,753	936	3,551
250	2,289	1,969	16,883

Note: Columns 2 and 3 display the number of leases that were within the indicated distance to a hurricane at least one time during 1980–2018. Column 4 displays the total number hurricane-month observations. SS1-5 stands for hurricanes of Categories 1 to 5 on the Saffir-Simpson scale; SS3-5 stands for hurricanes of Categories 3 to 5 on the Saffir-Simpson scale.

3 Methodology

We estimate the effect of hurricanes on oil production using a Jordá (2005) panel local projection approach. Oil production flows from existing wells typically decline over time as well-head pressure declines from the depleted oil reserves. Changing the flow rate of production requires engineering investment to change the pressure, which is costly; so oil production is typically invariant to the oil price (Anderson, Kellogg, and Salant 2018).[7] Because oil production can be zero, we transform production flows using an inverse hyperbolic sine (IHS) transformation, $sinh^{-1}(x) = \ln(x + \sqrt{1 + x^2})$, to construct our dependent variable, $q_{i,t}$, where i is the lease ID and t is the period. Our baseline estimating equations for $h = \{1, 2, ..., 7, 8\}$ are:

$$q_{i,t+h} = \alpha_i + \delta_m + \delta_y + \sum_{k=1}^{3} \rho_k q_{i,t-k} + \mu(\text{Well Age})_{i,t} + \sum_{j=1}^{5} \beta_h^j H_{i,t}^j + \sum_{j=1}^{5} \gamma_h^j H_{i,t}^j \times Reg_i + e_{i,t}, \qquad (1)$$

where α_i is the lease fixed effect; δ_m and δ_y are month and year dummies to reflect normal seasonal operating patterns and trend changes in technology; $q_{i,t-k}$ is lease production lagged $k = \{1, 2, 3\}$ months;[8] Well Age

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[7] New rig investment and installation is, however, sensitive to oil prices.

[8] Including the lagged dependent variable introduces a bias that is scaled by $1/T$ (Nickell 1981). This bias is likely to be small in our application, as the average T for our panel is roughly 200. Similarly, Montiel Olea and Plagborg-Møller (2021) suggest that including lagged dependent variables controls for serial correlation. Including the lagged production also controls for normal production declines, previous production declines from storms and also any anticipatory declines in production. We do not find that our estimates of the effects of hurricanes are sensitive to lag lengths greater than 3.

measures the number of months since production began on the lease; $H^j_{i,t-h}$ is a dummy variable equal to 1 if the eye of a hurricane of level j on the Saffir-Simpson scale passed within the specified distance (50 or 250 km) of the lease location i in period t; Reg_i is a dummy variable equal to 1 if the first rig on the lease was installed after the 1980 regulatory reforms were imposed (we consider the 1980 and 1988 reforms separately). We note that Reg_i is, itself, subsumed in the rig fixed effect α_i. We focus on the 50 km distance measure for our baseline results and then consider how the estimates change for the 250 km distance. Intuitively, being closer to the eyewall of a hurricane is likely to cause more damage, and indeed this is generally what we find albeit with some exceptions, which we discuss below.

The estimated β^j_h coefficients measure the impact of a hurricane of level j, h periods after impact on the IHS of oil production. Because oil production levels are typically in thousands of barrels, the IHS is roughly equivalent to a logarithmic transformation; so $e^{\beta^j_h} - 1$ is the approximate percentage production decline from a hurricane (Bellemare and Wichman 2020). Similarly, $e^{\gamma^j_h}$ measures the effectiveness of the regulatory policy introduced at mitigating hurricane damage, with $e^{\beta^j_h + \gamma^j_h} - 1$ measuring the percentage production decline for rigs built after the regulatory reform.

The focus of this paper is to examine the direct effect of hurricanes on oil rig production and whether damages can be mitigated by investment in capital structures. However, oil rig production is also affected by the anticipation of hurricane activity. There are two potential channels for expectations. The first is that producers may schedule production and routine maintenance for periods of the year when hurricanes are expected. We capture such expectations using month and year dummies. The month and year dummies capture seasonal patterns or annual climate trends (such as El Niño years) that may affect rig activity. The second channel is that, for reasons of personnel and environment safety, oil rigs are typically shut-in when producers expect hurricanes to pass nearby. Although precise times to shut down oil rigs and to evacuate crews varies by rig for reasons such as age, size and distance from shore, the typical process involves several phases and can take over a week. Hurricane forecasting at horizons greater than one week, while improving, remains relatively imprecise in terms of category strength and direction; as a result, some shut-in rigs are not directly affected by hurricanes. Because our focus is on production losses caused by hurricane *damages*, we do not focus on the production losses during the same month as the hurricane activity.

4 Hurricanes' effects on oil production

We focus first on our baseline regression estimates for the 50 km distance specification. The final sample encompasses 2,441 leases and 494,926 observations for $h = 1$ (six leases do not produce any oil during the period 1980–2018) and declines to 2,247 leases and 481,491 observations once $h = 8$. The decline in the number of leases over the sample appears to reflect permanently damaged rigs. We investigate the role of hurricanes for stranded oil assets below.

We begin chronologically and consider first the impact of the 1980 regulations on oil production on leases that are within 50 km of the eye of a hurricane. For brevity, in the main text we focus only on the estimates of β_h^j and the joint estimate $\beta_h^j + \gamma_h^j$ — the full regression results are reported in Table 6 in the Appendix. Panel (a) of Figure 1 presents the estimated coefficients, $\hat{\beta}_h^j$, and whisker bars for the 95 percent confidence intervals for the 50 km distance sample. (For all specifications, unless otherwise noted, we cluster our standard errors by lease location.) We remind readers that no hurricane that passed within 50 km of a rig had wind speeds rated Category 5. Hurricanes of Category 3 or 4 significantly lower oil production at impacted leases and do so for at least eight months (left panel Figure 2). For example, Category 4 storms lowered production by approximately 97 percent ($e^{-3.49} - 1$) one month after impact and production remained approximately 50 percent below pre-storm production eight months after impact. A similar pattern is observed for the Category 3 storms. In contrast, there is less impact from Category 1 or 2 hurricanes, although Category 2 hurricanes cause a sharp contemporaneous decline in oil production of nearly 80 percent in the first month after impact. Any impact from Category 2 hurricanes largely disappears by the fourth month after impact and, indeed, production appears to increase after six months. Interestingly, declines in production after Category 1 hurricanes appear to be persistent, which may suggest that producers do not repair minor damages from hurricanes. The baseline 50 km estimates suggest that hurricanes, particularly strong ones that pass near oil-producing rigs, cause significant production losses.

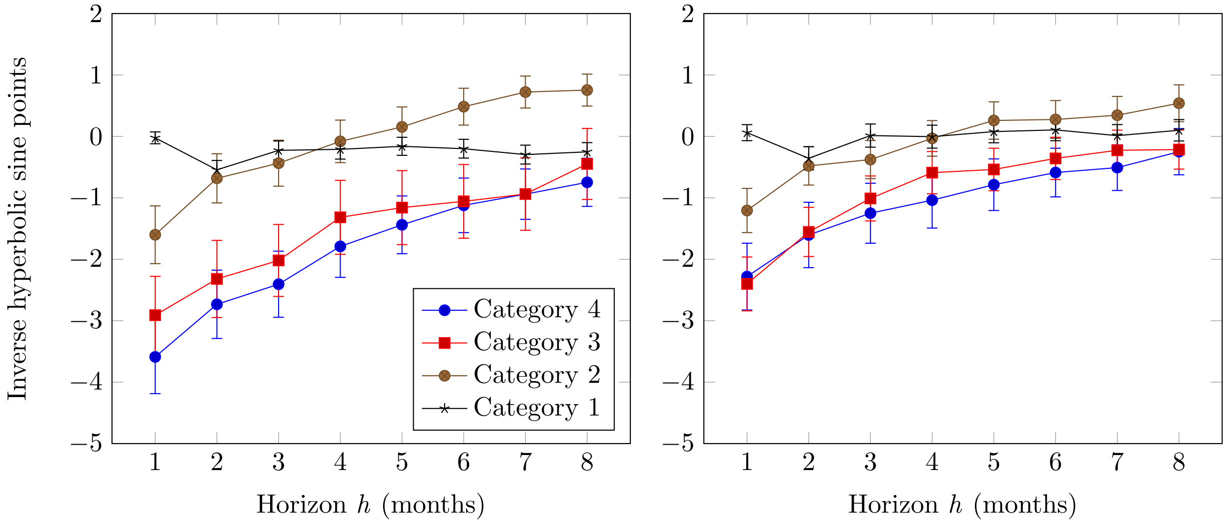
Panel (b) of Figure 1 presents the estimates for rigs installed after 1980. There is evidence that the enhanced engineering requirements significantly mitigated hurricane impacts for Category 3 and 4 hurricanes as the estimates $\beta_h^j + \gamma_h^j$ are less negative than those in the left panel for these storms. Panel (c) presents the estimates of the regulatory effect, γ_h^j, which are close to 1 for storms of Category 3 and 4. We caution that although these estimates are statistically different at the 5 percent level of significance for almost the entire horizon considered, the magnitude of these differences in level terms are not particularly large to start but become larger over months. For example, both Category 3 and 4 hurricanes lower production by roughly 92 percent in the first month after impact compared with 97 percent and 95 percent, respectively, for rigs built prior to the 1980 regulations. Similarly, there is little difference in the hurricane impact of Category 2 storms. However, the effects of the regulations appear to grow in level terms over the horizon. Five months after a Category 4 storm, production at rigs built before 1980 remains 76 percent lower, while rigs built after 1980 are 54 percent lower. The 1980 regulations do not appear to have had any impact on production after Category 1 or 2 hurricanes for a period of at least four months. The effects of the regulations also appear to diminish over the horizon considered, although there is some evidence that rigs built after 1980 returned to their usual levels of production sooner than rigs built after 1980, particularly for Category 3 storms. The overall picture suggests that hurricanes, particularly major hurricanes of Category 3 or higher, cause significant and persistent production losses at oil platforms within 50 km of the storm's eye. They also suggest that the regulatory reforms enacted in 1980 lessened these losses, although the majority of the benefits appear to accrue over time rather than immediately after impact.

We next consider the role of the 1988 regulatory reforms for oil production in the Gulf. As noted in the introduction, the 1988 reforms both streamlined and clarified the existing guidelines and it is possible that these refinements affected the efficacy of these regulations. We re-estimate our baseline regression specification including an additional regulatory reform dummy equal to 1 for any lease with a platform built on or after June 1988. We label the coefficient on this dummy variable τ_h^j for hurricane Category j and horizon h. Figure 2 presents the estimated coefficients, $\hat{\beta}_h^j$, $\hat{\tau}_h^j$ and $\hat{\gamma}_h^j$ and whisker bars for the 95 percent confidence intervals for the 50 km distance sample (see also Table 7 in the Appendix). The estimated impact of hurricanes on rig production in panel (a) is similar to that presented in panel (a) of Figure 1. Hurricanes of Category 3 or 4 significantly lower oil production at impacted leases and do so for at least eight months. In contrast, there is less long-term impact from Category 1 or 2 hurricanes, although Category 2 hurricanes cause a sharp contemporaneous decline in oil production of roughly 75 percent in the first month after impact. This effect largely disappears by the fourth month after impact. The baseline 50 km estimates suggest that hurricanes that pass near oil-producing rigs cause lasting damage. The estimated impact on production for rigs built after the regulatory reforms in 1980 and 1988 is shown in panel (b) of Figure 2. The estimated impacts are again similar to those presented in panel (b) of Figure 1 and suggest some evidence that the regulatory reforms lessened the production losses from Category 3 and 4 hurricanes.

Panels (c) and (d) of Figure 2 present the coefficient estimates for the regulatory reforms in 1980 and 1988, respectively. There is almost no evidence that the 1988 regulatory reforms significantly mitigated hurricane impacts for any category of hurricane at the 5 percent level of significance. The sole exception is $\hat{\tau}_5^2$, which, given the lack of any other evidence of efficacy, may be an anomaly. There is also little evidence that the 1988 regulatory reforms lowered the production losses for rigs affected by Category 3 or 4 hurricanes. In fact, these point estimates are negative for the first three months after hurricane impact, although only $\hat{\tau}_1^3$ is different from zero at the 5 percent level of significance. Somewhat interestingly, the estimates in panel (d) suggest that Category 1 hurricanes were more damaging for rigs built after 1988. We discuss why this might be the case below when we investigate the role of oceanography for hurricane damages. Overall, there is no evidence that the 1988 change in engineering standards mitigated storm damage, particularly from Category 3 or higher hurricanes. This suggests that the additional clarity regarding how to determine the expected worst environmental conditions was not particularly salient for platform design.

To further investigate the difference between the 1980 and 1988 regulatory reforms, we conduct a hypothetical test to examine the marginal impacts of the 1988 regulatory statutes. While the estimates presented in Figure 2 suggest little benefit from the 1988 regulatory reforms, our specification of the dummy variables is such that all rigs built after 1980 are coded $Reg_i = 1$. This reflects the fact that the 1988 regulatory

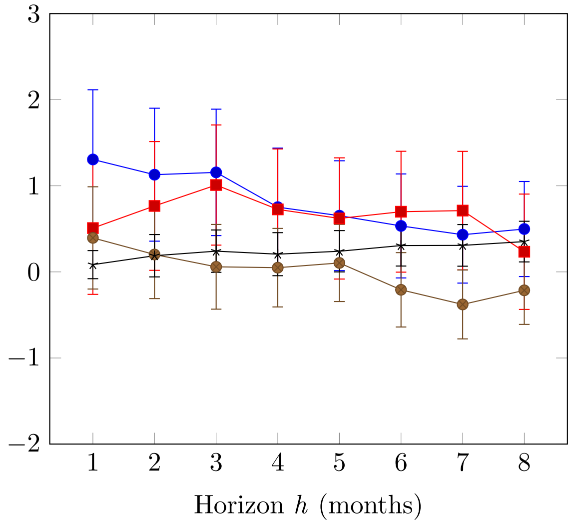
Figure 1: Effect of hurricanes on oil production flows (50 km distance), 1980 regulatory change



(a) $\hat{\beta}_h^j$

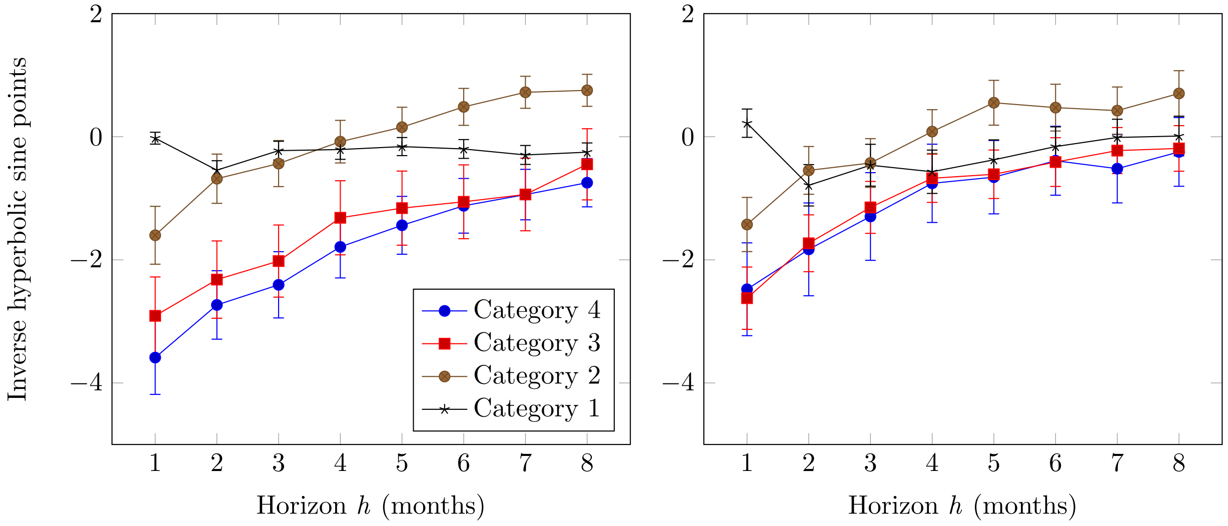
(b) $\hat{\beta}_h^j + \hat{\gamma}_h^j$

(c) $\hat{\gamma}_h^j$



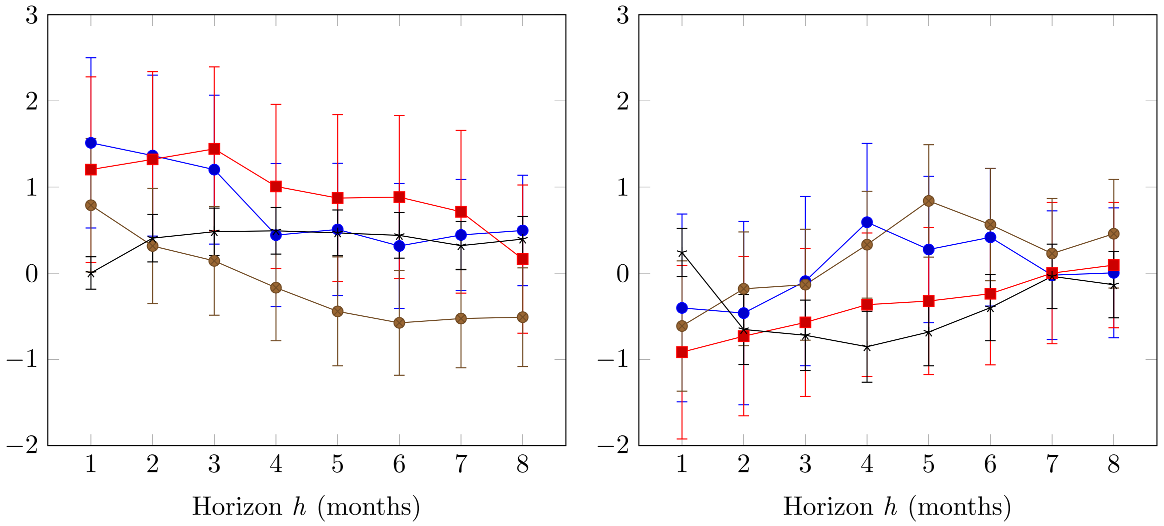
Notes: The figure shows estimated effects of hurricanes on oil production flows, Equation (1). The dependent variable is the inverse hyperbolic sine of oil production. $\hat{\beta}_h^j$ is the estimated base effect of hurricane of Category j on the Saffir-Simpson scale at month h after the hit, $\hat{\beta}_h^j + \hat{\gamma}_h^j$ is the estimated effect for rigs constructed after 1980, and $\hat{\gamma}_h^j$ is the estimated benefit of the 1980 regulatory changes. Markers represent point estimates; whiskers indicate 95% confidence intervals using robust standard errors clustered by lease. The sample period is 1980 to 2018.

Figure 2: Effect of hurricanes on oil production flows (50 km distance), 1980 and 1988 regulatory changes



(a) $\hat{\beta}^j_h$

(b) $\hat{\beta}^j_h + \hat{\gamma}^j_h + \hat{\tau}^j_h$

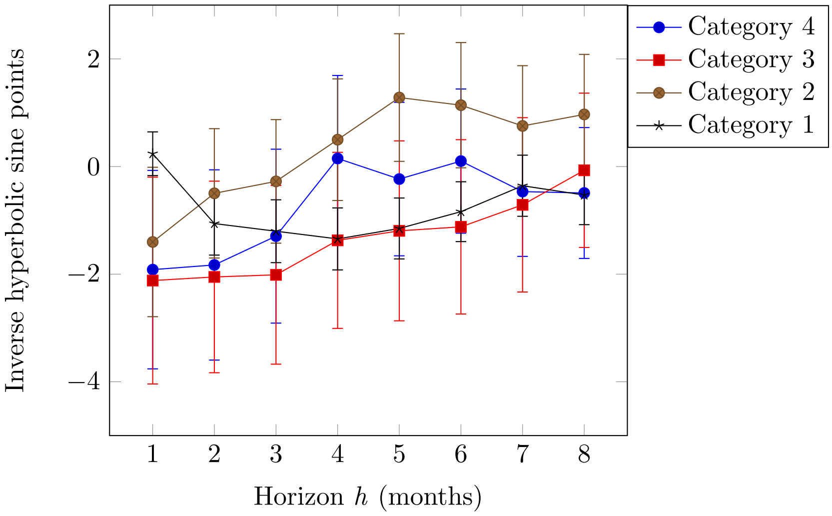


(c) $\hat{\gamma}^j_h$

(d) $\hat{\tau}^j_h$

Notes: The figure shows estimated effects of hurricanes on oil production flows, Equation (1). The dependent variable is the inverse hyperbolic sine of oil production. $\hat{\beta}^j_h$ is the estimated base effect of hurricane of Category j on the Saffir-Simpson scale at month h after the hit, $\hat{\gamma}^j_h$ is the estimated effect of the 1980 regulatory change, $\hat{\tau}^j_h$ is the estimated effect for the 1988 regulatory change and $\hat{\beta}^j_h + \hat{\gamma}^j_h + \hat{\tau}^j_h$ is the estimated total effect for rigs constructed after 1988. Markers represent point estimates; whiskers indicate 95% confidence intervals using robust standard errors clustered by lease. The sample period is 1980 to 2018.

Figure 3: Marginal regulatory effect (50 km distance), $\hat{\tau}_h^j - \hat{\gamma}_h^j$



Notes: The figure shows estimated effects of $\hat{\tau}_h^j - \hat{\gamma}_h^j$. Markers represent point estimates; whiskers indicate 95% confidence intervals using robust standard errors. The sample period underlying the estimates is 1980 to 2018.

reforms largely streamlined the 1980 regulations and did not substantially change their intent. To isolate the marginal contribution of the 1988 reforms, we estimate the effect: $\hat{\tau}_h^j - \hat{\gamma}_h^j$. One interpretation of $\hat{\tau}_h^j - \hat{\gamma}_h^j$ is that it estimates the effect of the elements of the 1988 regulations that are not common to the 1980 regulations. Figure 3 presents the estimates of $\hat{\tau}_h^j - \hat{\gamma}_h^j$ for hurricanes of Category j at horizons indexed by h. For hurricanes of Category 3 and 4, the estimates are negative and significant for horizons of up to two and three months respectively. They are also negative and significant at the one-month horizon for Category 2 hurricanes. Finally, the estimates are negative and significant for horizons of two to eight months for Category 1 hurricanes. The remaining point estimates are not significantly different from zero. Overall, the estimates of $\hat{\tau}_h^j - \hat{\gamma}_h^j$ suggest that the 1988 regulatory changes may have negatively impacted oil production after hurricanes.

4.1 Hurricane size, strength and distance to rig locations

Our choice of a 50 km distance is arbitrary because there is not a precise threshold at which hurricanes are no longer a danger to an oil rig. We chose to focus on the 50 km distance measure for our baseline results because the eyewall of a hurricane can have a radius of around 30 km and a hurricane's greatest wind speeds are usually along the circumference of the eyewall. A 50 km distance measure therefore will capture events where hurricanes pass over rigs with wind speeds close to their maximum force. It is perhaps not surprising that major hurricanes of Category 3 or higher cause such significant production declines using a 50 km distance measure because the extreme forces associated with the intense winds and large waves may simply be too strong to be survivable, at least without substantial damage. As an analogy, safety devices in automobiles may prevent fatalities at reasonable speeds, but at very excessive speeds, no airbag or seatbelt will protect a driver from serious harm or death. To continue our analogy, it may be that we are examining the effectiveness of safety devices in automobiles by comparing outcomes for drivers going 250 kph or more with those going less. Finding that safety devices do not prevent catastrophic outcomes for the former does not imply that safety devices provide no protection in accidents at speeds of, say, 100 kph or less.

Hurricane wind speeds generally decline with the distance from the eyewall, and hurricane damage is usually proportional to wind speed. Thus, $\hat{\beta}_h^j$ should be expected to decline if the distance measure is increased because the treated group will include locations that, while affected, are less severely affected than those within 50 km. The opposite is true if the distance measure is decreased.[9] It is also plausible that the heightened engineering standards required after 1980 were designed to be effective in situations where rigs were not directly in a hurricane path but were nevertheless close enough to be impacted by rising seas and winds. We next consider a specification in which we specify the dummy variables $H_{i,t}^j$ for a 250 km distance in the regression equation (1).

Figure 4 presents the estimates from our 250 km distance measure (full regression estimates are in Table 8 in the Appendix). As expected, the estimated impact of hurricanes is mostly lower conditional on hurricane strength. It remains the case that hurricanes of Categories 3 and 4 impact production significantly more than Category 1 hurricanes. One aspect of using the wider distance measure is that some rigs are affected by Category 5 hurricanes. (One Category 5 hurricane in our sample, Katrina, affected 220 leases in 2005 and a second Category 5 hurricane, Michael, in 2018 affected 9 leases.) The estimated production losses from Category 5 hurricanes are effectively catastrophic, especially for rigs built prior to the 1980s. Category 5 storms lead to an estimated fall of essentially 99 percent in oil production for two months after impact and production remained roughly 60 percent lower 8 months after impact for these rigs. However, rigs installed after 1980 fare significantly better over the first three months that follow a Category 5 hurricane. This experience is also true, even if harder to discern in panel (c), for Category 4 storms. There is, however, no evidence that the 1980 regulatory changes significantly impacted production losses after hurricanes at other horizons or hurricane categories.

The estimates in Figure 4 do appear surprising in at least one respect: the production disruptions from Category 2 and 3 hurricanes are estimated to be greater for rigs installed after the regulatory changes in 1988. Panel (d) presents the estimated effect of the 1988 regulatory dummy variable, and the point estimates for Category 2 and 3 hurricanes are negative and significant for horizons of three months and one month, respectively. Indeed, the estimated impact of the 1988 regulatory reforms appear to explain the difference between panels (a) and (b) for hurricanes of Categories 2 and 3. And, for these rigs, the production losses

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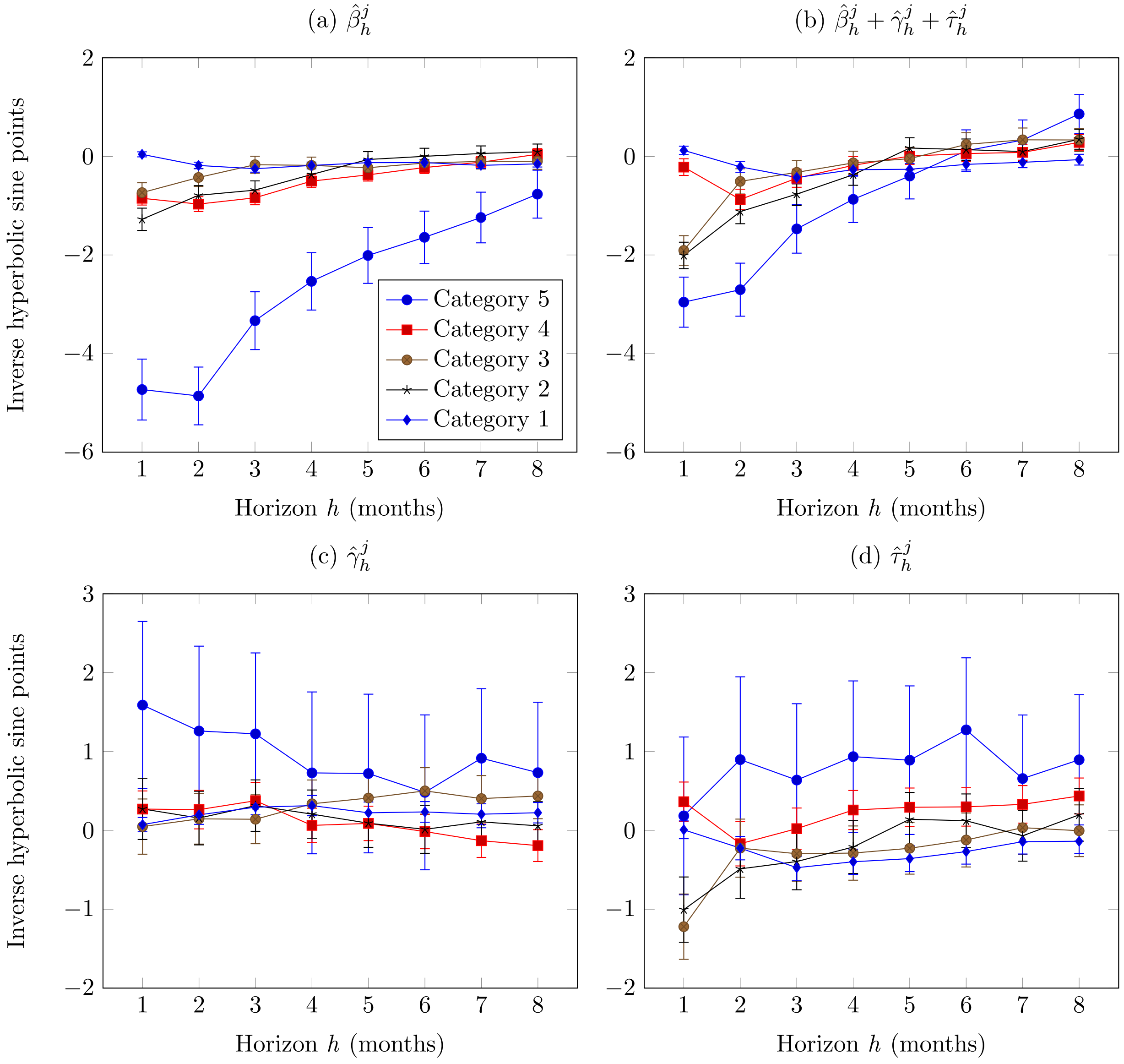
[9] This is indeed what we find when we consider 25 km and 100 km radii. These results are available upon request.

Figure 4: Effect of hurricanes on oil production flows (250 km distance), 1980 and 1988 regulatory changes



(a) $\hat{\beta}_h^j$

(b) $\hat{\beta}_h^j + \hat{\gamma}_h^j + \hat{\tau}_h^j$

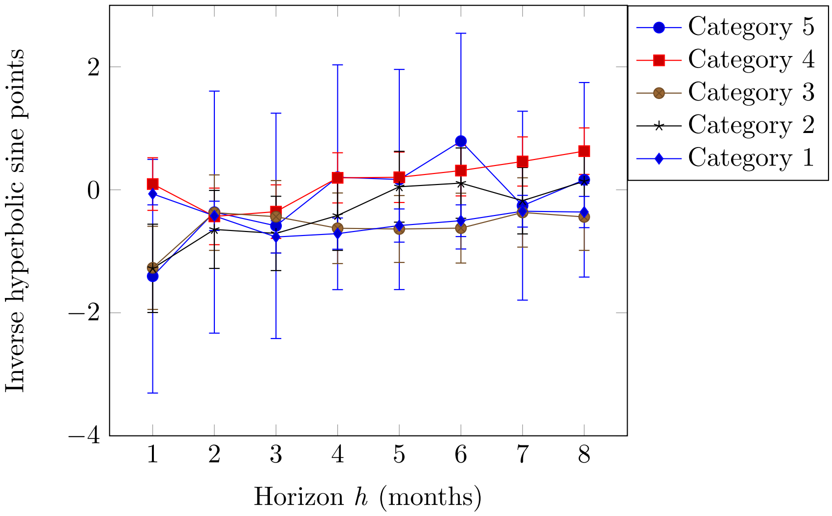
(c) $\hat{\gamma}_h^j$

(d) $\hat{\tau}_h^j$

Notes: The figure shows estimated effects of hurricanes on oil production flows, Equation (1). The dependent variable is the inverse hyperbolic sine of oil production. $\hat{\beta}_h^j$ is the estimated base effect of hurricane of Category j on the Saffir-Simpson scale at month h after the hit, $\hat{\gamma}_h^j$ is the estimated effect of the 1980 regulatory change, $\hat{\tau}_h^j$ is the estimated effect for rigs built after 1970 and $\hat{\beta}_h^j + \hat{\gamma}_h^j + \hat{\tau}_h^j$ is the estimated total effect for rigs constructed after 1970 and to the standards imposed by the 1980 regulatory reforms. Markers represent point estimates; whiskers indicate 95% confidence intervals using robust standard errors clustered by lease. The sample period is 1980 to 2018.

from Category 2 and 3 storms appears to be greater, at least initially, than for Category 4 storms. Given that the wind speeds and wave heights of a Category 2 or 3 storm are typically lower that those of a Category 4 storm, the $\hat{\beta}_h^j + \hat{\gamma}_h^j + \hat{\tau}_h^j$ estimates may appear implausible. The increased magnitude of these coefficient estimates appear to reflect the Category 2 hurricanes Ike and Gustav in September 2008 and the Category 3 hurricane Rita in September 2005. Roughly 70 percent of all Category 2 hurricane hits within 250 km occurred in September 2008, and almost 60 percent of all Category 3 hurricane hits occurred in September 2005. Compared with typical hurricanes in the Gulf of Mexico, Hurricane Ike had an usually large wind field with hurricane wind speeds up to 115 miles (185 km) from its eye. (The maximum wind speeds were also only 1.6 kph below the level of a Category 3 hurricane.) Hurricane Ike was preceded by roughly 10 days by hurricane Gustav, which was also a Category 2 hurricane with wind speeds near the upper bound of the Category 2 range and, unusually, no obvious eye. Similarly, hurricane Rita arrived only weeks after hurricane Katrina, and the two storm tracks were remarkably close offshore before diverging. Rigs built after 1980 are typically further from shore and in deeper water. Both factors can influence the damage from hurricanes because wave heights are proportional to water depth, and hurricane strength typically moderates close to land. We interpret these results as indicative that the Saffir-Simpson hurricane category classifications may not perfectly align with the potential damage to oil rigs because of distance and water-depth differences. The estimates also indicate that the interpretation of the estimates is sensitive to the assignment to treatment decision and that assignment to treatment may vary non-linearly with hurricane strength.[10]

Figure 5: Marginal regulatory effect (250 km distance), $\hat{\tau}_h^j - \hat{\gamma}_h^j$



Notes: The figure shows estimated effects of $\hat{\tau}_h^j - \hat{\gamma}_h^j$. Markers represent point estimates; whiskers indicate 95% confidence intervals using robust standard errors clustered by lease. The sample period underlying the estimates is 1980 to 2018.

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[10] The lower estimates of $\hat{\beta}_h^2$ for the 50 km distance reflects the fact that many leases outside the 50 km distance were also affected by hurricanes Gustav and Ike.

We next examine the marginal impact of the 1988 regulations for the 250 km distance measure. Figure 5 presents the estimated difference $\hat{\tau}_h^j - \hat{\gamma}_h^j$, which we argue above captures the marginal effect of the 1988 regulatory changes. The estimated differences are insignificantly different from zero at all horizons for Category 4 and 5 hurricanes. However, the estimated marginal effect of the 1988 regulations is negative and significant for the first three months and for the first month for Category 2 and 3 hurricanes, respectively. The estimates are also negative and significant for the two to eight month horizon for Category 1 hurricanes. Similar to the marginal estimates for the smaller distance measure of 50 km, there is no evidence that the 1988 regulatory changes lessened production losses after hurricanes of any category. Instead, there is some evidence that the regulatory changes introduced in 1988 made production losses slightly larger.

5 Oceanography and hurricane damage

The physical location of rigs may affect how damaging a hurricane impact is on the rig. While the wind speeds of a hurricane are damaging themselves, at sea, high winds can produce extreme wave heights (potentially in excess of 80 feet) which can exacerbate damages or cause damage themselves even if structures are resilient to the winds. The damage from waves is a complicated function of many factors, including wave speed. Wave speeds slow when the wave contacts the sea bed because of the increase in friction (which is why waves break near shores as the bottom of the wave is moving slower than the crest). Wave depth is roughly one-half of the wave length (the distance between peaks) and wave length is generally a few hundred feet; so a depth of around 150 feet is approximately when a wave might encounter the sea bed and begin to slow. We define a shallow water rig dummy (shallow) for those located in less than 150 feet of water.[11] It is also possible that rigs located closer to shore repair facilities may be repaired more quickly than those at locations further out to sea.

Identifying the effect of water depth or distance to shore on hurricane damage to lease production is challenging because the average depth of leases is increasing over time as is the average distance to shore. Thus, water depth and distance to shore are negatively correlated with the age of the lease and positively correlated with the 1980 rig dummy. To isolate the effect of water depth and distance in a regression equation similar to Equation (1) would require multiple interaction terms, effectively a quadruple difference specification. Because the water depth and location of a particular lease are invariant over time, deeper water leases are also newer which implies a selection effect for the hurricane shock in terms of water depth since climate research suggests that storms are becoming stronger over time.

To approach the issue of water depth and distance to shore, we focus on one particular set of events that impacted the majority of oil leases in our sample: hurricanes Gustav and Ike in September 2008. In our sample for 2008, 1,300 out of the 1,341 leases were hit by either Gustav or Ike using the 250 km measure

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[11] We also considered a depth of 100 feet without change to our results.

because of the large wind fields of these storms. Of the 1,300 leases, 1,264 were producing in 2008 or 2009. Of these, 827 (64 percent) are classified as shallow using our threshold of 150 feet and 612 (48 percent) are classified as near to shore (less than 30 miles, roughly 50 km).[12] Roughly one-third of the sample was installed after the 1980 regulatory reform. Since all 1,300 leases were directly affected by either Gustav and/or Ike, we use period dummies interacting with the shallow dummy and the 1980 rig dummy to trace out the average treatment effect on the treated. We limit the sample to the years 2008 and 2009 to avoid contamination from other hurricanes (the only hurricanes in 2009 were Category 1 hurricanes in the oil lease sample). We report results only for regressions including the 1980 rig dummy variables; this is because the evidence thus far suggests only modest effects from the 1988 regulatory reforms and, for expository reasons, we do not wish to include too many series in our figure.[13] Our estimating specification is:

$$q_{i,t} = \alpha_i + \rho q_{i,t-12} + \mu \Delta \bar{q}_{i,t-12} + \gamma_t + \gamma_t^s \times shallow_i + \gamma_t^d \times nearshore_i + \gamma_t^{80} \times Reg_i + e_{i,t}, \tag{2}$$

where $shallow_i = 1$ if the water depth of lease i is less than 150 feet and $nearshore_i = 1$ if the oil platform hit by Gustav or Ike is 30 miles or less from the shore. Figure 6 presents the estimates of γ_t and the interaction terms γ_t^s, γ_t^d and γ_t^{80}.[14] There is no apparent pre-trend prior to the arrival of hurricanes Gustav and Ike and the effect of hurricanes Gustav and Ike is apparent given that production essentially shuts down entirely at the time of impact and for months afterwards. There is no evidence that leases developed after 1980 weathered the hurricanes better than leases built prior to 1980 conditional on the distance to shore and water depth variables. The estimates of γ_t^{80} are insignificantly different from zero at the 5 percent level of significance at every horizon. The same is not true, however, for leases located in shallow water or leases located closer to shore by our measures. Leases that are 30 miles or less from shore are less affected than leases farther from shore and this advantage is statistically significant for the 10-month horizon we consider. The point estimates peak at around 2.3 one month after impact, which translates into roughly a 3 percentage point increase in lease production given the estimate of γ_t. Shallow water leases are also significantly less affected for five months after impact, with a peak estimate of roughly 1 three months after impact, which translates into a 2 percentage point increase. The effect of shallow water is statistically significant for five months after impact. This is suggestive evidence that hurricane damages are mitigated for rigs by oceanographic features. Although we control for fixed attributes of the rigs using α_i, which includes rig age, it is possible that these results reflect a selection effect because less durable rigs may have exited production as a result of earlier hurricanes. This selection effect would bias our estimates of γ_t^{80} towards zero because older rigs built before 1980 that were more durable would be more likely to weather Gustav and Ike. Thus, one should be cautious

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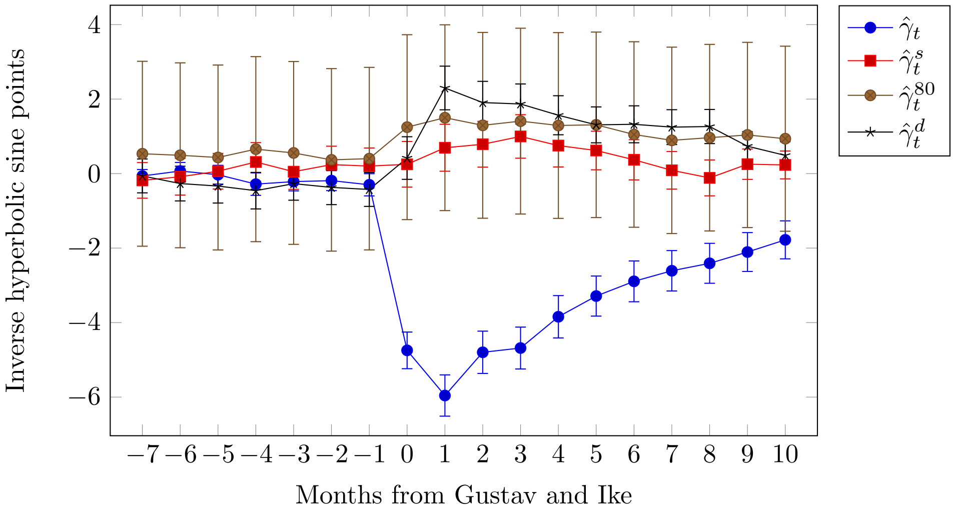
[12] The raw BOEM data reports distances in miles and we follow their convention for this measure.

[13] We have, however, estimated the model including both regulatory dummies, and qualitatively the results are unchanged. The quantitative differences are also small for the estimates we present in Figure 6.

[14] Figure 6 presents all the coefficient estimates, apart from the fixed effects, so we do not report the coefficient estimates separately in a table. However, these results are available from the authors upon request.

Figure 6: Effect of hurricanes Gustav and Ike for different water depths and distances to shore (250 km distance)



Notes: The figure shows estimated effects of hurricanes Gustav and Ike on oil production flows, Equation (2). The dependent variable is the inverse hyperbolic sine of oil production. t refers to the month from the event, $\hat{\gamma}_t$ is the estimated base effect, $\hat{\gamma}_t^s$ is the estimated coefficient for a dummy representing water depths less than 150 feet, $\hat{\gamma}_t^{80}$ is the estimated coefficient for a dummy representing post-1980 rigs, and $\hat{\gamma}_t^d$ is the estimated coefficient for a dummy representing rigs that are 30 miles or less from the shore. Markers represent point estimates; whiskers indicate 95% confidence intervals using robust standard errors. The sample period is 2008–2009.

about over-generalizing these results.

It is also the case in our sample that oil production is positively correlated with the water depth and distance from shore of a lease. Table 2 reports the median, mean, maximum and standard deviation in the monthly production of oil from the 1,264 leases considered in Figure 6. Every measure is higher for leases not classified as shallow and for leases farther from shore. The mean production of a lease not in shallow water is 5.2 times that of a shallow lease and the mean production of a lease more than 30 miles from shore is 2.7 times the production of leases closer to shore. These differences reflect a trend towards larger projects in deeper waters that characterize the offshore oil industry in the Gulf of Mexico. Thus, the share of deepwater in total oil and condensate production in the Gulf of Mexico rose from below 10 percent in the 1980s to about 90 percent in 2018.[15] Much of the trend can be traced back to projects with water depths of over 1,000 meters, which accounted for more than 70 percent of total production in 2018. To the extent that oil exploration is pushing into deeper depths and farther from the coast in the Gulf of Mexico, the production losses from hurricanes may be expected to increase.

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[15] Rystad Energy, UCube Database, `https://www.rystadenergy.com/energy-themes/oil--gas/upstream/u-cube/`, accessed October 2021.

Table 2: Production by water depth and distance to shore

	Median	Mean	Max	Std dev
Shallow (< 150 feet)	477	6,326	263,105	17,723
Not shallow (> 150 feet)	3,563	32,928	2,139,162	147,082
Near shore (< 30 miles)	702	8,476	263,105	21,141
Offshore (> 30 miles)	1,507	22,848	2,139,162	123,066

Note: Average monthly production in barrels for different types of leases, January–July 2008.

6 The extensive margin of hurricane damage

While there is some modest evidence that regulatory reforms may help to mitigate production losses from hurricane hits on rigs, the overarching conclusion is that hurricane hits, particularly Category 3 or higher, lead to persistent production losses and that the regulatory reforms had modest impacts in terms of mitigating these losses. One may naturally wonder whether some persistent production losses become permanent. If the expected profit of the remaining oil at a lease is below the replacement cost of a damaged or destroyed rig, then hurricane hits could lead to permanent losses and stranded oil assets. It is plausible that the regulatory reforms in 1980, and 1988, made platforms more resilient to permanent destruction even if they had less effect in the immediate aftermath of a hurricane hit.

Our sample includes 2,447 leases that have ever reported oil production. In December 2018, there were 558 leases that reported oil production.[16] For each lease in our sample, we determine its last reporting date and label this the exit date for that lease. We choose the last reporting date instead of the date of removal of lease platforms as our measure of exit because abandoned rigs remain on many leases that no longer produce. For each lease, we also calculate the total number of hurricanes hits of each category for the 50 km and 250 km distance measures and, the category and number of months from the exit date of the last hurricane hit for each platform.

Our interest is to determine whether the regulatory reforms of 1980 and 1988 had any effect on the probability that a rig will exit our sample after being hit by a hurricane. Ideally, we want to compare the exit probabilities of a lease built according to the reforms with those of a lease built prior to 1980 when both are hit by a hurricane of the same magnitude. Using an event study approach is problematic because, as we have noted, hurricane strength can vary over time. Thus, comparing lease exit rates for one particular hurricane risks confounding changes in hurricane strength. A second complicating factor is determining whether a rig exits because of a hurricane or whether other factors are at play.

We proceed in two steps. First we estimate a logistic regression to establish that hurricanes affect the

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[16] Because leases enter and exit production over the period of our sample, it is not the case that 2,447 leases existed in January 1980, so calculating the exit rate is not possible using just these data points.

likelihood that a platform exits our sample. Our logistic regression is:

$$P(Exit_i) = \mathcal{S}(\alpha + \sum_{h=1}^{5} \beta^h H_i^h + X_i \Gamma + e_i), \tag{3}$$

where $P(Exit_i)$ stands for the probability that lease i will exit the sample and $\mathcal{S}(A)$ is a logit transformation on A; H_i^h is an index of the last category of hurricane, h, to hit rig i prior to its exit or the end of the sample; and X_i is a vector of controls for each lease i. X_i includes: the maximum oil production for each lease, its average production, the total number of months a lease is in the reporting data, whether it is a shallow lease, its distance from shore and dummy variables for rigs constructed after the 1980 and 1988 regulatory changes.

Table 3: Extensive margin of hurricane damage (50 km distance and 250 km distance)

	50 km distance			250 km distance		
	Estimate	SE	Odds ratio	Estimate	SE	Odds ratio
Shore	-0.157	0.180	0.854	-0.338	0.162	0.713
Shallow	0.362	0.163	1.436	0.495	0.167	1.640
Maximum production	-0.0274	0.0981	0.973	0.058	0.102	1.059
Average production	-0.503	0.0678	0.605	-0.504	0.0710	0.604
Lease age	-0.0175	0.0012	0.983	-0.015	0.0011	0.985
Rig80	-0.615	0.198	0.541	-0.568	0.207	0.567
Rig88	-2.738	0.263	0.065	-2.692	0.260	0.068
β^1	1.040	0.266	2.830	0.321	0.393	1.378
β^2	1.476	0.288	4.373	1.798	0.422	6.037
β^3	1.349	0.271	3.854	0.480	0.509	1.616
β^4	1.602	0.293	4.964	0.986	0.398	2.681
β^5				1.764	0.786	5.833
Constant	10.37	0.803		9.057	0.760	
Observations	2447			2447		

Notes: The figure shows estimated effects on lease exits with robust standard errors (SE) and associated odds ratio based on the logit regression described in Equation (3). We omit reporting the odds ratio for the constant because interpreting its value is complicated. This is because the observation of zero values for the remaining covariates is not feasible for any lease. The sample period is 1980 to 2018.

Table 3 presents the coefficient estimates, standard errors and odds ratios for those estimates from the logistic regression specification for the β^h and the control variables. Hurricanes increase the odds that a lease exits our sample. These estimates are significant at the 1 percent level for every hurricane category for the 50 km distance measure (columns 2–4). Hurricanes of Categories 2, 3 and 4 that pass within 50 km of a lease platform increase the likelihood of exit by a factor of roughly 4. Category 1 hurricanes increase the odds of exit by roughly a factor of 3. For the 250 km distance measure, hurricanes of Categories 2 and 4 significantly increase the odds of exit by factors of roughly 5 and 3 at the 5 percent level of significance. The point estimate for Category 5 hurricanes implies an odds ratio of exit of 6, but the point estimate is only marginally significant at the 10 percent level. Although these hurricanes increase the probability of exit, the odds ratios are not strictly increasing in hurricane strength, particularly for the 250 km distance measure. While perhaps counter intuitive, this may reflect how we measure hurricane strength for each affected rig. Our measure of hurricane category is based on the wind speed at the time the last hurricane hits a given rig. Thus, for example, the Category 5 hurricane Katrina was followed by hurricane Rita, which was recorded as a Category 3 hurricane for many of the rigs in our data. Thus, the exit due to damage from Katrina of some rigs that were also hit by hurricane Rita would be attributed solely to hurricane Rita using the 250 km distance measure. What does appear clear is that hurricanes tend to increase the likelihood of lease exit, particularly when they pass within 50 km of a platform.

The control variables are generally significantly different from zero for either distance measure. The estimates for the regulatory dummies suggest that these reforms reduced the likelihood of platform exit even controlling for the age of the lease and the average production levels. Shallow rigs also appear more likely to exit the sample, which may reflect the fact that the shallow water areas of the Gulf were among the first explored.

We next turn to the question of whether the regulatory reforms increased the likelihood that rigs did not exit after hurricanes. To address this question, we specify a nearest neighbour matching estimator to estimate a linear probability model and the effect of the regulatory reforms for the probability of exit. This matching estimator compares the difference in the linear probability of exit between rigs built prior to the regulatory reforms and those installed after conditional on the platforms having similar characteristics. In particular, we exactly match rigs according to the category of the last hurricane to hit the platform in addition to other conditioning variables.

The dependent variable for our matching estimator, $P_i = \{0, 1\}$, measures whether lease i stops reporting before the end of our sample, $P_i = 1$, or not, $P_i = 0$. We match lease platforms using a Mahalanobis distance measure based on several covariates: the maximum oil production for each lease; its average production; the total number of months the lease is in the reporting data (lease age); whether it is a shallow lease; whether is near the shore; the total number of hurricanes of each category that have hit a platform at the 50 km and 250 km distances; and the category of the last hurricane to hit the platform at the 50 km and 250 km distances. As noted above, we specify that the matching algorithm exactly match on the category of the last hurricane to hit the platform. We consider exact matches for the 50 km and 250 km distances separately because we cannot match all observations exactly on both.[17] Because the standard errors for matching estimators can have a bias when matched on continuous covariates, we adjust the standard errors for the (potentially) continuous variables of lease age, the maximum production and the average production as recommended by Abadie and Imbens (2011).

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[17] We are able to match exactly for the full sample of 2,447 platforms for the 250 km distance measure but are unable to exactly match 18 leases for the 50 km distance measure. These unmatched leases are dropped from the estimation sample. We use the STATA command teffects nnmatch to compute these estimates.

Table 4: Regulatory reform and lease exit

	50 km distance exact match		250 km distance exact match	
	Estimate	SE	Estimate	SE
1980 Regulatory Reform	-0.116	0.0147	-0.142	0.0147
1988 Regulatory Reform	-0.160	0.0220	-0.178	0.0176

Notes: SE refers to bias adjusted standard errors corrected for lease age, the maximum production, the average production, and the number of months since the last hurricane hit for either the 50 km or 250 km distance measure. Columns 2 and 3 present the estimated effect of the regulatory reform for lease exit matching rigs exactly by the category of the last hurricane to hit the platform for 50 km distance measure. Columns 4 and 5 present the analogous estimates for the 250 km distance measure. The sample size for the exact match for the 250 km measure is 2,447 and the sample size for the 50 km measure is 2,429 because some rigs do not have exact matches at this distance.

Table (4) presents the estimated regulatory effect of the 1980 and 1988 reforms for the linear probability of lease exit conditional on the leases' hurricane history. Both the 1980 and 1988 regulatory reforms decreased the probability of lease exit. The 1980 regulatory reforms reduced the probability of exit by roughly 12 and 14 percentage points for rigs matched exactly at the 50 km and 250 km distance measures, respectively. The 1988 regulatory reform dummy shows a reduction of 16 and 18 percentage points, respectively, which given the estimates for the 1980 regulatory reforms suggests that the 1988 reforms may have modestly increased the probability of not exiting. In general, these estimates do suggest that the regulatory reforms were successful in reducing the extensive margin of lease exit after a hurricane.

To give some idea of the value of oil production lost from lease exit, and the potential benefits of the regulatory reforms, we estimate a simple exponential decline curve for oil production at leases in our sample:[18]

$$q_{i,\tau_i} = \kappa q_{i,0} + \nu \tau_i + \epsilon_{i,\tau_i}, \forall \tau_i > 0, \tag{4}$$

where $q_{i,0}$ is the log of maximum oil production at lease i at a (re)normalized date $\tau_i = 0$, where τ_i is the number of months since the date of maximum production at lease i and where ϵ_{i,τ_i} are regression errors.[19] We use our estimates of $\hat{\kappa} = 0.77$ and $\hat{\nu} = -0.009$ to estimate the oil production expected for leases that exit our sample at the month of exit. While these estimates appear to give a reasonable insample fit, as one would expect, they tend to overestimate production for the bottom quartile and tend to underestimate production for the top quartile. We interpret our estimates of lost production cautiously and the discussion which follows is more qualitative than quantitative.

Table 5 presents the mean and median of $\hat{q}_{i,t}$ conditional on h_i and $Exit_i$ for leases according to the hurricanes of Category $h_i = \{2, 3, 4\}$ and $Exit_i = \{0, 1\}$, and the number of observations for the distance

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[18] See Arps (1945).

[19] For simplicity, we do not include additional controls, such as hurricane hits. Our presumption here is that such hurricane hits are effectively randomly allocated in terms of τ_i. While this may or may not be exactly accurate, we do not observe much difference in our estimates of ν by including additional controls. Including additional controls does, however, affect our estimates of κ mostly by introducing lease specific intercepts, which in turn complicates our estimates of oil production lost.

measure of 50 km. If $Exit_i = 0$, then the estimated oil production is the production expected at the end of our sample period. In general, there appears to be only modest differences in the mean or median size of leases that exit or do not for each category of hurricane hit. The mean and median affected lease produces less than 1,000 barrels per month, which suggests that many affected leases are relatively small producers.

One feature of exponential decline functions is that the stock of oil remaining is relative straightforward to calculate. The total remaining barrels in a lease, assuming production decline to zero, is $Q_i = \frac{e^{\hat{q}_{i,t}}}{|\hat{\nu}|}$. The last column of Table 5 presents estimates of the stock of oil remaining for the median lease hit by hurricane of Category h. Those that exit leave between $43,938$ and $84,165$ barrels of oil unexploited. Simple back of envelope calculations suggest that, if we assume all rigs that exit after a hurricane do so because of the hurricane hit, then $(482 \times 43,938) + (233 \times 84,165) + (267 \times 66,206) + (138 \times 79263) = 69,403,857$ barrels of oil may be left stranded by hurricane hits. Although this number may appear too large to be believable — at $70 per barrel this is worth roughly $4.9 billion — the relative dispersion in the geographic locations of the stranded assets and their relatively small median size may provide the explanation. The value of the median stranded lease is, at $70 per barrel, between $4 and $6 million, which is likely below the cost of recovering the oil, at least at present.

We next consider the regulatory reforms and how they may affect the valuation of the stranded assets. Since our estimates of the extensive margin effect of the regulations was not conditioned on the hurricane category, we assume that the probability of not exiting is identical across all categories. This assumption is unlikely to be true so our results here are mainly illustrative. If we further assume that the regulatory reforms applied to all rigs that exited our sample then the number of barrels that would have been stranded without the regulatory reforms would have been: $(\frac{482}{0.88} \times 43,938) + (\frac{233}{0.88} \times 84,165) + (\frac{267}{0.88} \times 66,206) + (\frac{138}{0.88} \times 79263) = 78,868,019$. This implies that the regulatory reforms would have prevented $9,464,162$ barrels from being stranded. At $70 per barrel, this translates into $662 million dollars.

7 Conclusion

Our results suggest that hurricanes that are Category 3 or higher on the Saffir-Simpson scale that pass within 50 km of a lease effectively shut down oil production one month after impact. The effects of hurricane hits are also persistent, and the persistence depends on the hurricane strength. The increased standards imposed by the 1980 regulatory change generally had modest effects on the production lost from hurricanes except for Category 5 storms with the 250 km distance measure. We do find some evidence that shallow water leases were less affected by Gustav and Ike in 2008, although in level terms the difference is small.

When we consider how hurricanes affect the extensive margin of oil lease exploitation, we observe that hurricanes lead to significantly higher probabilities of lease exit, particular when they pass within 50 km of a platform's location. We also find evidence that the regulatory reforms did affect the extensive margin

Table 5: Estimates of production lost from lease exit

Category	*Exit*	Median	Mean	Number	Median Q
$h = 1$	0	6.84	6.82	177	103,832
	1	5.98	5.77	482	43,938
$h = 2$	0	6.78	6.59	108	97,785
	1	6.63	6.30	233	84,165
$h = 3$	0	6.84	6.64	120	103,832
	1	6.39	6.17	267	66,206
$h = 4$	0	6.77	6.86	81	96,812
	1	6.57	6.40	138	79,263

Notes: Production of leases that exited ($Exit = 1$) and did not exit ($Exit = 0$). Category h refers to the strength of the hurricane on the Saffir-Simpson scale. Median and Mean refer to log values in production, respectively. *Number* refers to the number of leases. Median Q refers to the estimated remaining recoverable barrels of oil and condensate in a lease, assuming production declines to zero. The sample period is 1980 to 2018.

of lease exit, lowering the probability of lease exit by roughly 12–18 percentage points. Simple back of the envelope calculations suggest that the costs of stranded oil assets are generally small individually but relatively sizeable in the aggregate. For oil production at least, this appears to be a feature of weather-related disruptions — the aggregate value of the stranded oil can be sizeable even if the individual losses are relatively small. However, we note that these estimates of the extensive margin costs of hurricane hits do not account for the capital depreciation costs on oil rigs, which are, themselves, likely to be sizeable.

Finally, we acknowledge that the regulatory changes may have made it less expensive to rebuild damaged production facilities. However, at present, we do not have capital expenditure data available by lease and cannot assess such considerations. Overall, our results suggest that future climate scenarios are likely to imply increasing volatility and persistence and that regulatory reforms and investment in resilience may have only modest mitigating effects, at least for oil production.

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8 Appendix

Table 6: Local projection: baseline regression

Dependent variable	Horizon h							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.Arcsinh(barrels of oil produced)	0.576***	0.500***	0.442***	0.392***	0.359***	0.325***	0.300***	0.281***
	[0.004]	[0.005]	[0.004]	[0.004]	[0.004]	[0.005]	[0.005]	[0.005]
L2.Arcsinh(barrels of oil produced)	0.104***	0.102***	0.095***	0.097***	0.086***	0.084***	0.083***	0.071***
	[0.004]	[0.004]	[0.003]	[0.004]	[0.003]	[0.003]	[0.003]	[0.003]
L3.Arcsinh(barrels of oil produced)	0.096***	0.106***	0.116***	0.115***	0.119***	0.118***	0.113***	0.118***
	[0.003]	[0.003]	[0.003]	[0.003]	[0.004]	[0.004]	[0.004]	[0.004]
Age of well	-0.001***	-0.001***	-0.001***	-0.001***	-0.002***	-0.002***	-0.002***	-0.002***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Category 4, 50 km	-3.589***	-2.733***	-2.406***	-1.790***	-1.439***	-1.122***	-0.940***	-0.747***
	[0.299]	[0.278]	[0.269]	[0.252]	[0.235]	[0.222]	[0.205]	[0.196]
Category 3, 50 km	-2.910***	-2.320***	-2.019***	-1.317***	-1.159***	-1.057***	-0.938**	-0.448
	[0.316]	[0.314]	[0.293]	[0.301]	[0.301]	[0.300]	[0.295]	[0.289]
Category 2, 50 km	-1.601***	-0.682***	-0.436*	-0.081	0.155	0.484**	0.722***	0.754***
	[0.235]	[0.200]	[0.187]	[0.173]	[0.162]	[0.150]	[0.130]	[0.130]
Category 1, 50 km	-0.023	-0.544***	-0.227**	-0.210**	-0.161*	-0.200**	-0.296***	-0.251***
	[0.048]	[0.076]	[0.076]	[0.080]	[0.073]	[0.076]	[0.077]	[0.075]
Post-1980 x Cat. 4, 50 km	1.306**	1.129**	1.156**	0.752*	0.653*	0.534	0.432	0.498
	[0.405]	[0.386]	[0.367]	[0.343]	[0.319]	[0.302]	[0.281]	[0.276]
Post-1980 x Cat. 3, 50 km	0.509	0.766*	1.009**	0.726*	0.621	0.699*	0.712*	0.234
	[0.385]	[0.374]	[0.349]	[0.351]	[0.352]	[0.351]	[0.344]	[0.335]
Post-1980 x Cat. 2, 50 km	0.395	0.202	0.059	0.049	0.104	-0.208	-0.378	-0.214
	[0.297]	[0.256]	[0.246]	[0.228]	[0.224]	[0.216]	[0.200]	[0.198]
Post-1980 x Cat. 1, 50 km	0.084	0.188	0.241	0.206	0.240*	0.306*	0.308*	0.352**
	[0.082]	[0.123]	[0.123]	[0.125]	[0.120]	[0.119]	[0.121]	[0.118]
R^2	0.603	0.516	0.453	0.405	0.369	0.340	0.316	0.297
Fixed effects	Rig, Month, Year							
Number of rigs	2441	2441	2441	2439	2435	2431	2431	2427
Average observations per rig	202.755	201.953	201.163	200.539	200.082	199.626	198.842	198.389
Observations	494926	492968	491038	489114	487200	485290	483386	481491

Notes: The table shows estimation by local projection. Robust standard errors clustered by rig are in parentheses. ***, **, * indicate estimates are significantly different from 0 at the 0.1%, 1% and 5% levels of significance.

Table 7: Local projection: 1980 and 1988 regulatory changes, 50km distance

Dependent variable	Horizon h							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.Arcsinh(barrels of oil produced)	0.576***	0.500***	0.441***	0.392***	0.359***	0.325***	0.300***	0.281***
	[0.004]	[0.005]	[0.004]	[0.004]	[0.004]	[0.005]	[0.005]	[0.005]
L2.Arcsinh(barrels of oil produced)	0.104***	0.102***	0.095***	0.097***	0.086***	0.084***	0.083***	0.071***
	[0.004]	[0.004]	[0.003]	[0.004]	[0.003]	[0.003]	[0.003]	[0.003]
L3.Arcsinh(barrels of oil produced)	0.096***	0.106***	0.116***	0.115***	0.119***	0.118***	0.113***	0.118***
	[0.003]	[0.003]	[0.003]	[0.003]	[0.004]	[0.004]	[0.004]	[0.004]
Age of well	-0.001***	-0.001***	-0.001***	-0.001***	-0.002***	-0.002***	-0.002***	-0.002***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Category 4, 50 km	-3.588***	-2.733***	-2.406***	-1.790***	-1.439***	-1.122***	-0.940***	-0.747***
	[0.299]	[0.278]	[0.269]	[0.252]	[0.235]	[0.222]	[0.205]	[0.196]
Category 3, 50 km	-2.910***	-2.321***	-2.020***	-1.317***	-1.160***	-1.057***	-0.938**	-0.448
	[0.316]	[0.314]	[0.293]	[0.301]	[0.301]	[0.300]	[0.295]	[0.289]
Category 2, 50 km	-1.601***	-0.682***	-0.436*	-0.080	0.155	0.485**	0.722***	0.754***
	[0.235]	[0.200]	[0.187]	[0.173]	[0.162]	[0.150]	[0.130]	[0.130]
Category 1, 50 km	-0.024	-0.543***	-0.226**	-0.208**	-0.160*	-0.199**	-0.296***	-0.251***
	[0.048]	[0.076]	[0.076]	[0.080]	[0.074]	[0.076]	[0.077]	[0.075]
Post-1980 x Cat. 4, 50 km	1.513**	1.365**	1.202**	0.442	0.508	0.316	0.444	0.496
	[0.494]	[0.467]	[0.432]	[0.415]	[0.384]	[0.362]	[0.322]	[0.321]
Post-1980 x Cat. 3, 50 km	1.203*	1.321**	1.443**	1.007*	0.872	0.883	0.713	0.164
	[0.538]	[0.509]	[0.476]	[0.476]	[0.484]	[0.473]	[0.472]	[0.430]
Post-1980 x Cat. 2, 50 km	0.789*	0.316	0.143	-0.168	-0.443	-0.576	-0.526	-0.510
	[0.387]	[0.334]	[0.315]	[0.308]	[0.316]	[0.304]	[0.286]	[0.286]
Post-1980 x Cat. 1, 50 km	0.003	0.407**	0.482***	0.492***	0.468***	0.439***	0.320*	0.396**
	[0.094]	[0.138]	[0.137]	[0.135]	[0.133]	[0.132]	[0.140]	[0.131]
Post-1988 x Cat. 4, 50 km	-0.403	-0.463	-0.092	0.592	0.275	0.417	-0.022	0.004
	[0.545]	[0.532]	[0.491]	[0.457]	[0.425]	[0.399]	[0.373]	[0.377]
Post-1988 x Cat. 3, 50 km	-0.916	-0.731	-0.571	-0.365	-0.323	-0.238	0.001	0.094
	[0.504]	[0.462]	[0.429]	[0.416]	[0.426]	[0.413]	[0.410]	[0.364]
Post-1988 x Cat. 2, 50 km	-0.613	-0.181	-0.133	0.331	0.839*	0.564	0.228	0.458
	[0.378]	[0.330]	[0.322]	[0.310]	[0.326]	[0.326]	[0.319]	[0.315]
Post-1988 x Cat. 1, 50 km	0.241	-0.653**	-0.720***	-0.853***	-0.683***	-0.400*	-0.036	-0.134
	[0.140]	[0.203]	[0.204]	[0.206]	[0.196]	[0.192]	[0.187]	[0.192]
R^2	0.603	0.516	0.453	0.405	0.369	0.340	0.316	0.297
Fixed effects	Rig, Month, Year							
Number of rigs	2441.000	2441.000	2441.000	2439.000	2435.000	2431.000	2431.000	2427.000
Average observations per rig	202.755	201.953	201.163	200.539	200.082	199.626	198.842	198.389
Observations	494926	492968	491038	489114	487200	485290	483386	481491

Notes: The table shows estimation by local projection. Robust standard errors clustered by rig are in parentheses. ***, **, * indicate estimates are significantly different from 0 at the 0.1%, 1% and 5% levels of significance.

Table 8: Local projection: 1980 and 1988 regulatory changes, 250km distance

Dependent variable	Horizon h							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
L.Arcsinh(barrels of oil produced)	0.577***	0.501***	0.442***	0.393***	0.359***	0.325***	0.300***	0.281***
	[0.004]	[0.005]	[0.004]	[0.004]	[0.004]	[0.005]	[0.005]	[0.005]
L2.Arcsinh(barrels of oil produced)	0.105***	0.103***	0.095***	0.097***	0.086***	0.085***	0.084***	0.071***
	[0.004]	[0.004]	[0.003]	[0.004]	[0.003]	[0.003]	[0.003]	[0.003]
L3.Arcsinh(barrels of oil produced)	0.096***	0.105***	0.115***	0.114***	0.118***	0.118***	0.113***	0.118***
	[0.003]	[0.003]	[0.003]	[0.003]	[0.004]	[0.004]	[0.004]	[0.004]
Age of well	-0.001***	-0.001***	-0.001***	-0.001***	-0.002***	-0.002***	-0.002***	-0.002***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
Category 5, 250 km	-4.730***	-4.860***	-3.333***	-2.535***	-2.010***	-1.642***	-1.240***	-0.766**
	[0.309]	[0.293]	[0.293]	[0.291]	[0.283]	[0.266]	[0.257]	[0.243]
Category 4, 250 km	-0.850***	-0.968***	-0.840***	-0.502***	-0.375***	-0.226***	-0.118*	0.041
	[0.069]	[0.076]	[0.071]	[0.066]	[0.063]	[0.060]	[0.060]	[0.058]
Category 3, 250 km	-0.735***	-0.428***	-0.169	-0.182*	-0.230**	-0.135	-0.101	-0.099
	[0.100]	[0.091]	[0.086]	[0.084]	[0.080]	[0.079]	[0.078]	[0.082]
Category 2, 250 km	-1.276***	-0.789***	-0.685***	-0.368***	-0.063	0.001	0.059	0.092
	[0.113]	[0.098]	[0.094]	[0.087]	[0.080]	[0.082]	[0.077]	[0.079]
Category 1, 250 km	0.041	-0.184***	-0.250***	-0.184***	-0.127***	-0.126***	-0.182***	-0.152***
	[0.025]	[0.033]	[0.035]	[0.034]	[0.033]	[0.032]	[0.032]	[0.032]
Post-1980 x Cat. 5, 250 km	1.589**	1.260*	1.224*	0.729	0.721	0.482	0.915*	0.732
	[0.530]	[0.538]	[0.513]	[0.513]	[0.503]	[0.491]	[0.441]	[0.446]
Post-1980 x Cat. 4, 250 km	0.270*	0.263*	0.376**	0.063	0.088	-0.015	-0.131	-0.193
	[0.115]	[0.122]	[0.116]	[0.109]	[0.109]	[0.109]	[0.106]	[0.101]
Post-1980 x Cat. 3, 250km	0.048	0.146	0.141	0.337*	0.410**	0.501***	0.403**	0.436**
	[0.175]	[0.160]	[0.155]	[0.151]	[0.143]	[0.147]	[0.146]	[0.144]
Post-1980 x Cat. 2, 250 km	0.272	0.156	0.314	0.206	0.091	0.013	0.108	0.058
	[0.194]	[0.170]	[0.163]	[0.153]	[0.153]	[0.152]	[0.144]	[0.153]
Post-1980 x Cat. 1, 250 km	0.073	0.197**	0.294***	0.314***	0.223**	0.234***	0.205**	0.224***
	[0.045]	[0.060]	[0.066]	[0.064]	[0.068]	[0.065]	[0.066]	[0.065]
Post-1988 x Cat. 5, 250 km	0.184	0.897	0.638	0.935	0.890	1.274**	0.657	0.895*
	[0.500]	[0.525]	[0.484]	[0.480]	[0.471]	[0.457]	[0.403]	[0.413]
Post-1988 x Cat. 4, 250 km	0.363**	-0.169	0.022	0.258*	0.293*	0.298*	0.330**	0.436***
	[0.125]	[0.141]	[0.131]	[0.124]	[0.122]	[0.122]	[0.119]	[0.114]
Post-1988 x Cat. 3, 250 km	-1.221***	-0.225	-0.296	-0.288	-0.227	-0.122	0.034	-0.005
	[0.207]	[0.184]	[0.174]	[0.172]	[0.164]	[0.171]	[0.171]	[0.164]
Post-1988 x Cat. 2, 250 km	-1.005***	-0.488**	-0.395*	-0.211	0.141	0.122	-0.069	0.197
	[0.207]	[0.187]	[0.179]	[0.168]	[0.170]	[0.170]	[0.161]	[0.167]
Post-1988 x Cat. 1, 250 km	0.007	-0.225**	-0.473***	-0.398***	-0.358***	-0.269***	-0.143	-0.138
	[0.056]	[0.074]	[0.082]	[0.080]	[0.083]	[0.079]	[0.078]	[0.077]
R^2	0.605	0.519	0.454	0.406	0.369	0.340	0.316	0.297
Fixed effects	Rig, Month, Year							
Number of rigs	2441.000	2441.000	2441.000	2439.000	2435.000	2431.000	2431.000	2427.000
Average observations per rig	202.755	201.953	201.163	200.539	200.082	199.626	198.842	198.389
Observations	494926	492968	491038	489114	487200	485290	483386	481491

Notes: The table shows estimation by local projection. Robust standard errors clustered by rig are in parentheses. ***, **, * indicate estimates are significantly different from 0 at the 0.1%, 1% and 5% levels of significance.