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Real-Time Prediction of Shut-in Production From Hurricanes in the Gulf of Mexico

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Abstract

Accurate prediction of damage to petroleum production infrastructure from hurricane winds, waves, and storm surges has numerous applications to facility design, production planning, and the financial markets, among others. Here we describe a system for the estimation of damage, repair time, and shut in production using a numerical hurricane model and damage models for various infrastructure components. The system was designed and pilot-tested using data from Hurricane Ivan (2004) and prior storms, and validated operationally in forecast mode during the 2005 hurricane season. The petroleum extraction and distribution systems in the Gulf of Mexico as of 1 May 2005 were stored in a geographic information system. Damage to that infrastructure, consisting of over 50,000 elements, was computed using a three-dimensional physics hurricane model driven by forecast track and intensity data. The resulting damage statistics were then used to derive shut in production predictions for the Katrina and Rita landfalls, the results of which were posted on a web site in real time. The performance of the real time forecast system has been compared to reported statistics and found to accurately predict shut in production, especially using 24 hour forecasts through immediate post storm meteorological data. The validated shut in production prediction model was then applied using the 155 years of existing historical data to produce estimates of the magnitude and frequency with which significant production disruption would have been expected from the Gulf of Mexico facilities, given the present distribution of platforms and on-shore facilities. These frequencies indicate that significant disruptions of production on the order of magnitude seen in 2005 would be relatively common occurrences, given the performance of the infrastructure in recent events and historical hurricane activity. This implies that both design criteria and management of the petroleum production and distribution infrastructure should be revised.

1. Introduction

Hurricanes Katrina and Rita in 2005 dramatized the vulnerability of the oil and gas production and refining infrastructure in the Gulf of Mexico (GoM) and adjacent coastal areas. While a few previous storms, notably Hurricane Ivan, also caused significant disruption to production, the period of development of the GoM and especially the Outer Continental Shelf (OCS) fields coincided with a lull in intense storms¹. While the cause of this lull is a subject of debate (see Goldenberger² and Emanuel^{3,4} for example), the net effect is that the GoM petroleum extraction and processing infrastructure has not experienced a sustained period of frequent and intense hurricane activity until very recently.

Estimating the frequency and magnitude of production disruptions from hurricanes is a complex problem, involving climatology and meteorology, engineering, and statistics. One approach, taken by Kaiser and Pulsipher⁵, is to analyze recent production history and apply simple regression models to the relatively short production record in an attempt to predict production impacts. Here we present a fundamentally different approach using a physics based computer simulation of every hurricane since 1851 and engineering models of oil and gas infrastructure. While Kaiser and Pulsipher concluded that “Hurricanes Katrina and Rita appear as exceptional cases”, we found that Katrina scale disruptions would be relatively common, occurring on the order of once every 20 years. We should expect no production impact from hurricanes in only 10% of years, using all 155 years of available history as a guide.

In this paper we start by describing the methodology used to forecast the impact of individual storms. Next we describe our verification process, followed by an assessment of the performance of the system in real time forecasting during the 2005 season. The results of simulating all storms since 1851 are discussed, followed by the potential for seasonal forecasts of GoM risks using climate signals such as the El Niño/Southern Oscillation. We conclude with a discussion of the implications of our analyses for infrastructure design and resource management.

2. Modeling single events

2.1 Model design and structure

The basic building block in a system to predict the disruption to oil and gas infrastructure from storms is the ability to predict the impact from a single event. Our approach is similar to that used in the insurance risk industry (Watson and Johnson⁶). In summary, these complex models consist of input data bases of the exposure at risk, the physical environment (topography, land cover, bathymetry, and so forth), details of the specific storm to be simulated, a model of the damage producing phenomena (in the case of a hurricane, a wind, wave, and storm surge model), a model of how the phenomena impacts the exposure (the damage function), and a cost estimation function (here a repair time and production loss model). Figure 1 is a block diagram of the single event model.

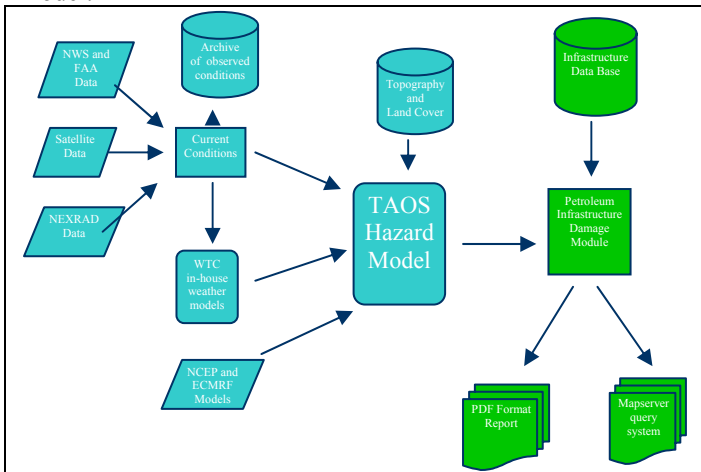


Figure 1: Oil/Gas Production Model Configuration

One of the most important components of any damage model is a data base of the infrastructure at risk. Known in insurance circles as the exposure data base, the data base created for our study consists of rigs, platforms, refineries, pipelines and terminals. We used the May 1, 2005 configuration of the GoM production environment as our baseline, using data from the Minerals Management Service (MMS) supplemented with satellite data (Figure 2). The components of interest were identified and organized into a data base of approximately 50,000 elements, each with location (latitude and longitude) and pertinent characteristics related to potential damage impacts (height above sea level for platforms and mobile rigs, age of platform, pipeline depth and capacity, and so forth). The components of the infrastructure interact in the sense that damage to critical pipelines can disrupt the production from connected yet undamaged platforms. These interrelationships are thus considered in estimating production disruption.

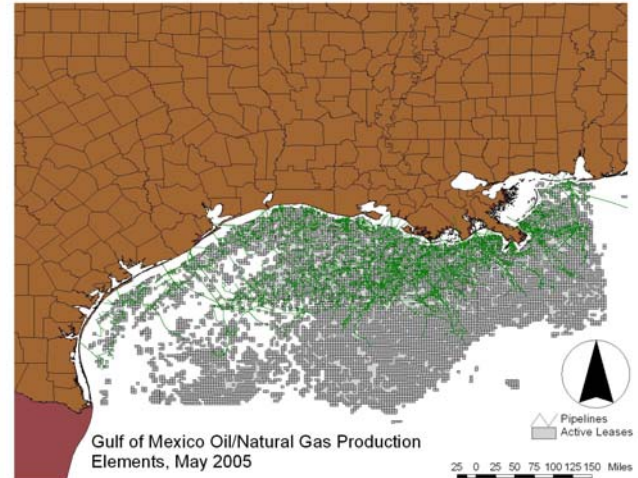


Figure 2: GoM Production Elements, May 2005

The process for simulating an event is, as follows: A full physics hurricane model (the TAOS model developed by Watson⁷) computes the wind, waves, and storm surge experienced by each element based on input storm track and intensity. These values are then used to drive engineering based damage models that translate the wind, waves, and storm surge computed at a structure into damage and repair time estimates. Direct damage from a storm and the time it takes to assess and repair it is only one source of disruption. A hurricane that will potentially enter the Gulf or a tropical cyclone that forms in the Gulf also disrupts oil and gas production due to precautionary evacuations. Thus, a module to simulate the decision making process of safety managers is also included to factor in these disruptions. As noted in section six, shut-in production due to evacuations for events which did not eventually produce damage can be significant.

2.2 Model verification

Initial verification of the model was performed using Hurricane Ivan. Figure 3 shows the wind swath of the storm, while Figure 4 shows a plot of the predicted shut-in oil production as compared to MMS reports.

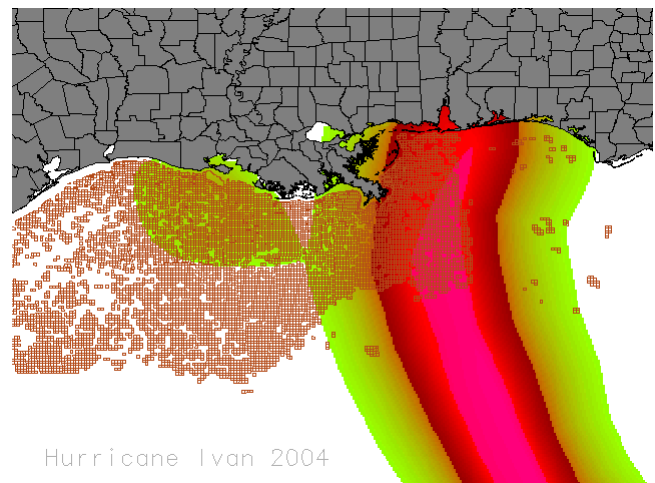


Figure 3: Hurricane Ivan wind swath and GoM Leases.

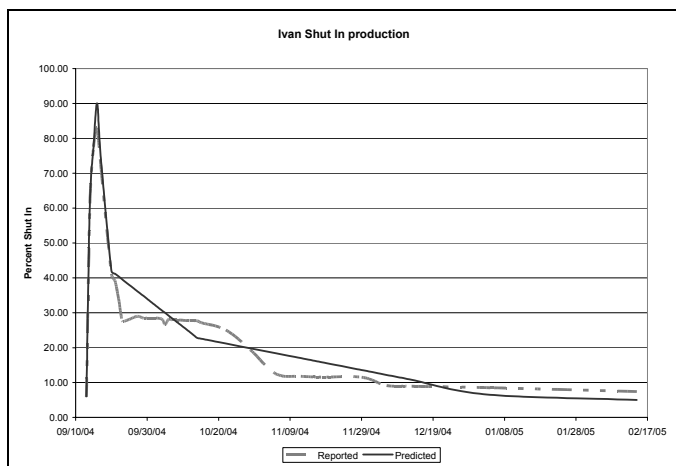


Figure 4: Predicted vs. reported percent shut in oil production for Hurricane Ivan.

The basic model developed with Ivan was improved in several ways prior to the 2005 season. In particular, the damage and repair functions were refined to include the influence the size of the owning company on repair time. Larger firms with greater “in-house” repair capacity can restore operations faster than smaller organizations that must contract out and compete for repair services. The impact of evacuations of on-shore infrastructure was also improved. Finally, an additional factor for major storms is a phenomenon known in the insurance industry as demand surge. Demand surge is the increase in costs and repair times due to limited resources available after a major catastrophe. In the case of the petroleum industry, two limiting factors are the resources needed to repair heavily damaged platforms, and the limited ability to replace destroyed structures given the globally limited capacity to manufacture heavy industrial equipment in general and drilling platforms in particular.

3. Forecasting single events

Forecasting an event, as opposed to hindcasting, presents additional challenges. Key among the challenges is uncertainty in both the future track of the storm and the intensity of the storm on arrival. While a full discussion of these issues is beyond the scope of this paper, the impact of track and intensity errors can be considerable⁸. Figure 5 shows reported shut-in oil production along with estimates based on the 72 hour official National Hurricane Center (NHC) forecast, as well as the best objective computer track model at that time (72 hours prior to OCS passage). In most cases, the objective track guidance provides more accurate impact estimates in the 48 to 120 hour forecast range, largely due to the NHC tracks primary purpose being coastal watch and warnings, and evacuation guidance. Offshore resource managers would do well to consider this factor in their planning process. Often official tracks linger near the Florida coastline well after the objective guidance has shifted over the Gulf, due to NHC’s concern that the population in these areas may relax prematurely.

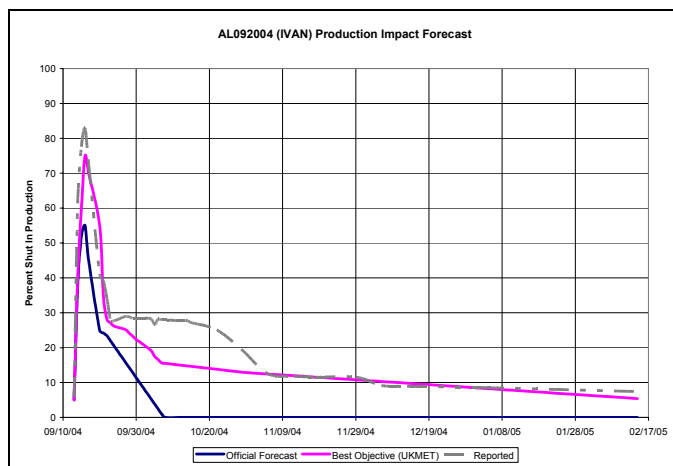


Figure 5: 72 hour forecasts for Ivan

4. Forecasting the cumulative impact of multiple events

The events of the 2005 hurricane season provided an intense test of our modeling techniques, especially in light of the fact that we decided to make our forecasts available on-line in real time on our web site (<http://hurricane.methaz.org>). Foremost among the challenges was the interaction among events. This introduced numerous complications, including:

- lack of up-to-date data, since damage assessments for the first storm had not been completed before the next storm arrived;
- demand surge well above previously experienced levels;
- damage to on-shore support infrastructure;
- additional evacuations interrupting repairs in progress; and,
- damage to already weakened structures.

After Katrina, when it was apparent that there could be additional storms impacting the GoM, we added a module to carry over damage from one event to the next. As seen in the following sequence of figures (6, 7, and 8), the system was able to generate reasonably accurate estimates of shut-in production.

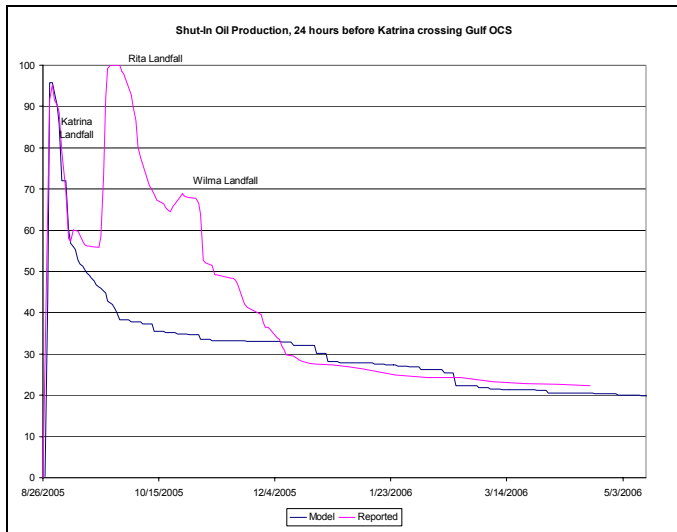


Figure 6: Forecast Shut-In Oil Production, 24 hours before Katrina OCS Crossing

Figures 6 and 7 are the real time forecasts for the 2006 storms, using the best objective forecast track, 24 hours prior to the storm crossing the GoM OCS production areas. Figure 8 shows the immediate post-Wilma forecast. The Rita forecast is especially interesting, in that it used the estimated damages from Katrina to initialize the model, since accurate post-Katrina damage estimates were still unavailable.

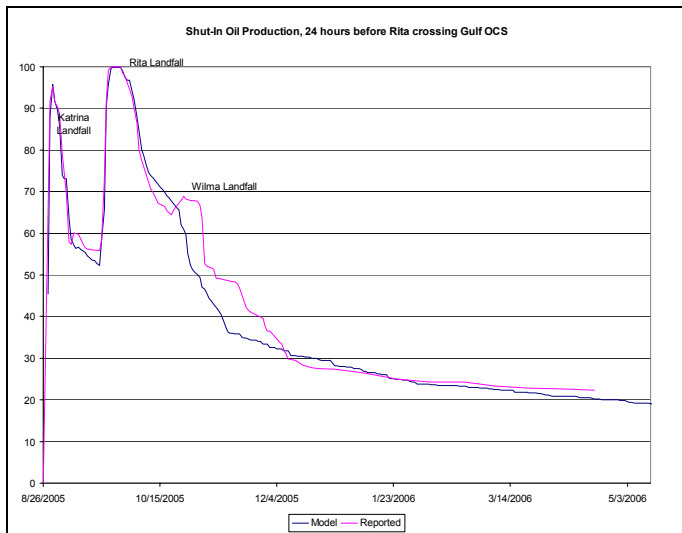


Figure 7: Forecast 24 hours before Rita OCS crossing.

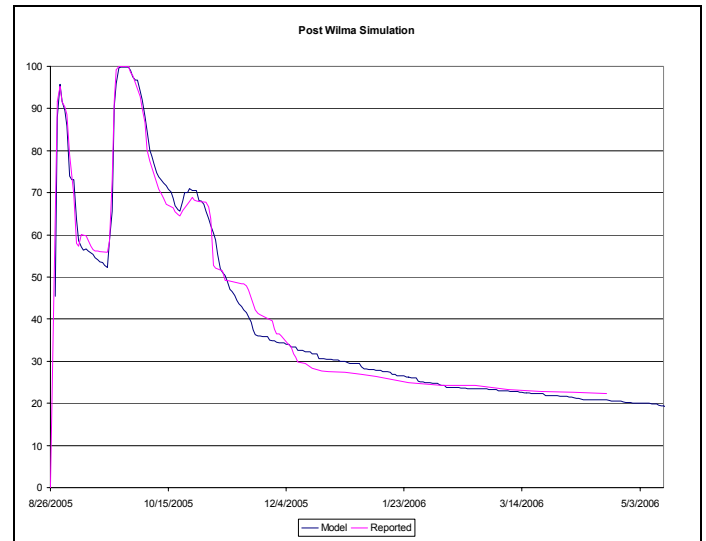


Figure 8: Results after Wilma landfall.

5. Historical Analysis

Having demonstrated the ability of the system to simulate the impacts of both single events and the cumulative impact of multiple events during a season, we were prepared to analyze the historical record to assess the long term risks in the Gulf. The Gulf of Mexico production environment as of May 2005 is designated as the baseline exposure, as this date predates the extensive damage from the 2005 season. Every historical hurricane from 1851 – 2005 was simulated, thus allowing us to estimate what would have happened in each of those years had the current infrastructure been present using methods originally developed to forecast impacts on Caribbean infrastructure⁹. The results of these simulations for oil production are detailed below. Results for natural gas production are similar, but differ slightly due to the different spatial distribution of infrastructure.

No losses were sustained in only 10% of years. The average annual shut in production due to storms was 47 million barrels. Sixty percent of years suffered the equivalent of at least one week shut-in production loss, half of the time (30% of total years) solely due to evacuations from storms that failed to ultimately produce actual damage. Our evacuation decision model was based on how managers handled the Opal, Ivan, Katrina, and Rita events. An interesting topic for future research would be to assess in detail how evacuation and shut down decisions are made and find ways of reducing the frequency of unnecessary evacuations. Cumulative losses of the order of magnitude experience from Katrina and Rita should be expected once in 20 years. The peak loss, not surprisingly, was experienced in 1900 due to the Galveston hurricane, although Hurricane Carla (1960) and storms in 1886, 1893, and 1915 would have also caused extensive damage to the present distribution of infrastructure. Figure 9 shows the expected return period for various levels of production loss expressed in terms of the percent of annual pre-Katrina production (1.5 million barrels of oil per day). Note that for many intense events, shut-in production carries over into the next calendar year. Thus a Katrina level event

might cause the loss of the equivalent of 50% of annual production, but it would be spread over two years.

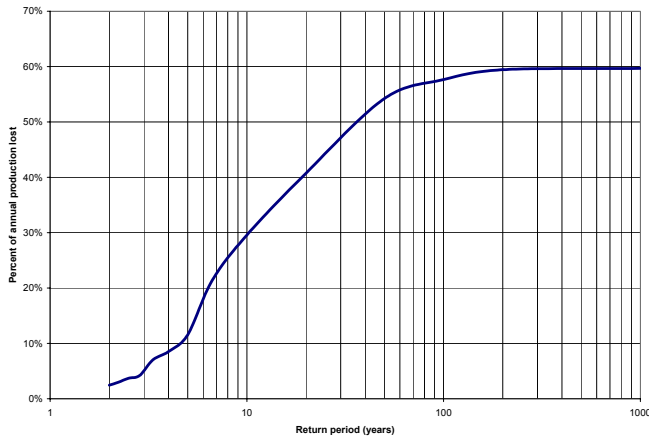


Figure 9: Return periods for annual shut in production

6. Seasonal forecast

The average yearly disruption over the 155 years of simulated storm seasons provides a simple baseline for assessing typical hurricane disruption. Further insight is achievable by considering partitions of the historical record into well defined strata corresponding to clearly defined and observable phenomena¹⁰. Through experience we have found that the ENSO (El Niño/Southern Oscillation) signal related to Pacific sea surface temperatures (SST) is useful in refining forecasts for individual seasons. Figure 10 provides a graphical display of oil shut in production for la Niña, el Niño and neutral years. The la Niña years yield more shut in production overall than the other two categories, and is particularly different than neutral (normal) years.

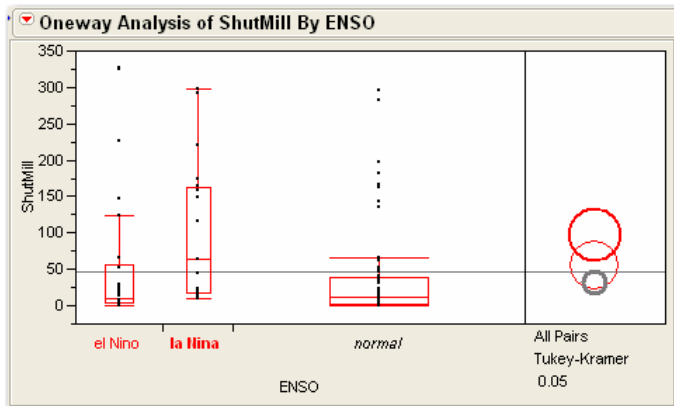


Figure 10: Comparisons for the Three ENSO Possibilities

Another depiction of the same data is provided by the cumulative distribution function plots given in Figure 11.

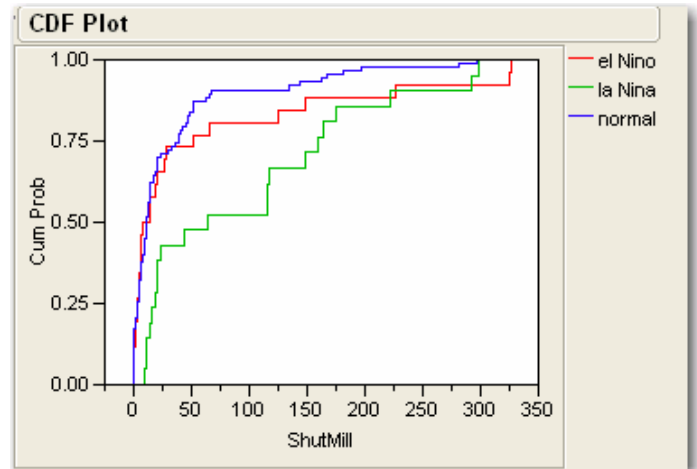


Figure 11: Empirical Distribution Functions for the Three ENSO Possibilities

The la Niña curve is generally to the right of the other two curves (except for massive shut in values around 225 million barrels). Some catastrophic seasons have occurred for each of the three regimes, but aside from these extremes, la Niña presents the worst scenario (at least stochastically), and el Niño the most favorable.

The striking differences among the three SST conditions suggest that it is prudent for seasonal forecasts to take this into consideration. As of 1 April 2006 the Pacific SST region 4 (the basis of our classification) was in a la Niña condition. Summary statistics for those historical la Niña years are:

- Minimum shut-in production: 10 million barrels
- Average shut-in production: 98 million barrels
- Median shut-in production: 64 million barrels

Every historical la Niña would have experienced production disruption. Hurricanes entering the Gulf through the Florida Strait usually induce a phased evacuation of platforms which in turn forces shut in. The distribution of shut-in production is quite skewed. Although the sample size (21) is small, the 90th percentile is 278 million barrels which is about half of the annual Gulf of Mexico production.

Although the SST conditions in the Pacific as of April 1, 2006 corresponded to la Niña, subsequent observations suggested that temperatures were rising (some models in fact were forecasting this trend) and thus the in season conditions could reflect a neutral condition rather than la Niña. If these warming forecasts are borne out, then the year 2006 could eventually be classified as a “transition” year from la Niña to neutral. Selecting comparable transition years in the 155 year record provides the shut in values summarized in Figure 11.

Quantiles		Moments		
100.0%	maximum	166.64	Mean	26.794377
99.5%		166.64	Std Dev	40.861508
97.5%		166.64	Std Err Mean	10.215377
90.0%		86.34	upper 95% Mean	48.567937
75.0%	quartile	42.00	lower 95% Mean	5.0208162
50.0%	median	10.20	N	16
25.0%	quartile	6.29	Sum Wgt	16
10.0%		3.99	Sum	428.71003
2.5%		2.38	Variance	1669.6628
0.5%		2.38	Skewness	2.9949046
0.0%	minimum	2.38	Kurtosis	10.04288
			CV	152.50031
			N Missing	0

Figure 11: Transitional Years

The implications of a transition are less severe (median 10 and mean 27), yet every transition year would have generated some disruption. Therefore, it is likely that 2006 will see at least some disruption of GoM production.

These techniques can be used in a number of petroleum industry decision making roles. We previously investigated (Watson and Johnson¹¹) seasonal forecasts in conjunction with the temporary storage of a drilling platform en route from the North Sea to Venezuela. Several sites were considered, including Curaçao. As Curaçao is located at 10°-12° N. latitude, near the southern extremities of hurricane activity in the Atlantic basin, traditional risk analyses based on circular neighborhoods were inappropriate. However, using a simulation approach combined with the recognition of the ENSO signal led to a sound determination of platform location for the season.

7. Implications for infrastructure design and management

The components in the GoM petroleum infrastructure are interrelated and thus, the overall risk of petroleum disruption is not a simple function of the risks associated with the individual components. Even if each component is built to withstand the 50 year event, there may be significant damage or disruptions on a more regular basis (every few years perhaps) owing to spatial variation in the risks and the common cause failures to infrastructure from large events. Individual sites should experience the appropriate frequency of return periods but the GoM region as a whole will likely experience isolated pulses of activity which might seem to be more common than expected with the return period notion. The Curaçao risk analysis mentioned in the previous section was a site specific risk. Multiple sites spanning the Gulf of Mexico production and refining region can experience varying activity which can be taken into account by means of developing a system level disruption return period assessment.

Even small performance enhancements can dramatically improve the performance of the system. For example, suppose we improve the wind resistance of each individual component in the system by 5 knots (in other words, a 120 knot wind would only cause as much damage as a 115 knot wind). The average annual production loss would drop from 47 million barrels to 40 million barrels. Figure 12 shows the return period curves for the existing infrastructure and the same infrastructure with a 5 knot wind resistance improvement. The benefits of this hypothetical hardening of the components is rather negligible at the low end (years of weak storms) owing to evacuation policies in place for all types of infrastructures in the GoM.

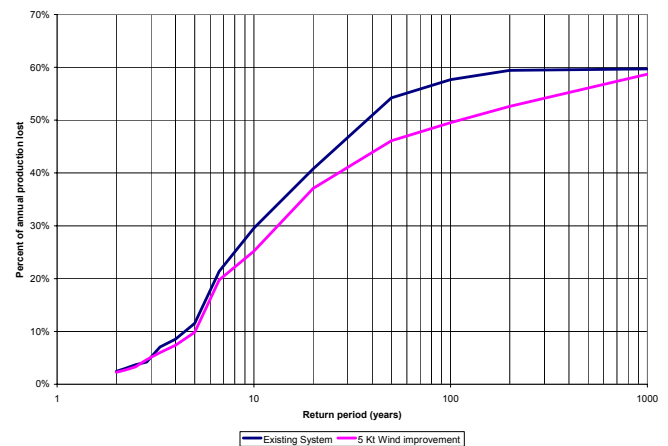


Figure 12: Return period for improved infrastructure.

The seasonal forecasts for petroleum disruption that we have made for the 2006 season reflect ENSO conditions as of April 1, 2006. Even if the la Niña conditions transition to a neutral state, all of the years in either condition in the historical record (as gleaned from the simulation approach) would have experienced as least 1 week of disruption (47 of 47 years). Thus it would seem prudent for distribution managers to keep this in mind during the season, and for Federal officials to encumber at least one week's additional petroleum supplies in the strategic petroleum reserve to account for this likely eventuality.

In summary, our research shows that given the current distribution and performance of infrastructure in the Gulf, significant disruptions due to hurricanes would be relatively frequent events. There is a strong correlation with springtime global climate patterns such as ENSO, which contain significant predictive ability which in turn can be used for strategic resource management decisions.

References

1. Blake, E., J. Jarrell, E. Rappaport, and C. Landsea, 2005. The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2005, NOAA Technical Memorandum NWS NHC-31.
2. Goldenberg, S.B., C.W. Landsea, A.M. Mestas-Nuñez, and W.M. Gray, 2001: The Recent Increase in Atlantic Hurricane Activity. Causes and Implications, *Science*, 293, 474-479 (2001).

3. Emanuel, K., 2005: Increasing Destructiveness of Tropical Cyclones Over the Past 30 Years, *Nature*, 43, 686-688.
4. Mann, M. E. and Emanuel, K., 2006: Atlantic Hurricane Trends Linked to Climate Change, *EOS, Transactions, American Geophysical Union*, 87, 233-244.
5. Kaiser, M., and A. Pulsipher, 2006. Analysis of Extreme Weather Events Shows Vulnerability of Gulf of Mexico Production, *Oil and Gas Journal*, Vol. 104.17.
6. Watson, C. Jr., and Johnson, M., 2004: Hurricane Loss Estimation Models, Opportunities for Improving the State of the Art, *Bulletin of the American Meteorological Society*, 85, 1713-1726.
7. Watson, C., Jr., 1995: The Arbiter Of Storms: a High Resolution, GIS Based Storm Hazard Model, *National Weather Digest*, 20, 2-9.
8. Iman, R. L., M. E. Johnson and C. Watson, Jr., 2006: Statistical Aspects of Forecasting and Planning for Hurricanes, *The American Statistician*, 60, 105-121.
9. Johnson, M. E., 1997: Caribbean Storm Surge Return Periods, Organization of American States Caribbean Disaster Mitigation Project Workshop, Kingston, Jamaica, October 31, 1997.
10. Watson, C., Jr., 2002b: Implications of climate change for modeling coastal hazards, Solutions for Coastal Disaster '02 Conference Proceedings, American Society of Civil Engineers, Reston, VA.
11. Watson, C., Jr. and Johnson, M. E., 2000: Risk Analysis for a Drilling Platform, WTC internal report.