Benefits to Maritime Commerce from Ocean Surface Vector Wind Observations and Forecasts

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Summary

Severe wind and wave conditions associated with extratropical storms in the North Pacific and North Atlantic impose costs on maritime commerce by delaying and sometimes damaging vessels that encounter these storms. In particular, container ship traffic in these regions is at increased risk of losing containers overboard in severe weather conditions; and dry bulk ships carrying grain (Pacific and Atlantic) and coal (Pacific) face increased risk of structural damage from these conditions.

We estimate that average expected annual losses to container shipping (lost containers and associated damage to vessels) in the absence of good information about extratropical storm conditions would be on the order of $250 million/year in the North Pacific and $120 million/year in the North Atlantic; and we estimate average expected annual losses to bulk shipping operations from extratropical storm exposure in these regions to be on the order of $150 million/year.

A significant fraction of this risk can be avoided with ocean surface vector wind observations and forecasts. We model the change in storm conditions exposure that becomes possible with nowcasts and forecasts of ocean surface vector wind fields under information scenarios representing the present QuikSCAT data, the European ASCAT radar, and a hypothetical Extended Ocean Vector Wind Mission (XOVWM) instrument. Model results suggest that the present QuikSCAT information and associated forecasts enable a reduction in annual exposure for shipping traffic in the North Atlantic and North Pacific of about 44%, with total annual net savings of $135 million. This is due mostly to avoided losses in the container ship trades, with $77 million/year in net avoided losses on the Pacific and $47 million/year on the Atlantic. The combined estimate of net annual benefits to shipping operations from ASCAT is $58 million, and hypothetical net benefits from XOVWM are $207 million. A perfect long-term forecast (not feasible with present technology) could deliver expected annual benefits of $520 million from all shipping by allowing for the virtual elimination of storm conditions exposure with no significant increase in operating costs.

Approach

We develop and apply a computer model to simulate the storm exposure of commercial ship transits of the North Atlantic (between the US East Coast and the Atlantic coast of Europe) and North Pacific (between the US and Central American West Coast and Southeast Asia/Japan) during months when extratropical storms are known to occur (September – May). The model includes a simple decision process by which the ship adjusts its course and speed in response to information about storm conditions. By modeling transits under different sets of information about ocean surface vector winds, we can compare transit duration and storm exposure for a range of nowcast/forecast scenarios.

We model extratropical storms as moving and transient geographic regions in which severe wind/wave conditions exist. The model treats storminess as a binary condition: the weather at a given location is characterized by severe winds and waves, or it is not. When a ship is geographically within an active storm region, it is forced to slow its speed (in the model) to 10 knots. Ships are assumed to travel on great circle routes, except when they deviate to avoid storm exposure.

Satellite-Based Vector Wind Data Sources

Ocean vector wind nowcasts and forecasts are improved by satellite-based observations of surface vector winds. Satellite-based instruments that presently provide scatterometry data useful for this purpose include NASA's Quick Scatterometer (QuikSCAT, launched in 1999; Chang and Jelenak 2006) and the Advanced Scatterometer (ASCAT, on the European MetOp-A satellite, launched in 2006; Sienkiewicz *et al.* 2008). A next-generation ocean vector wind measurement (Extended Ocean Vector Wind Mission, XOVWM) instrument has been defined at the conceptual level (Jelenak and Chang 2008; Rodriguez and Gaston 2008). Table 1 summarizes some of the key features of surface wind data obtained from these instruments; for details, please see the references listed in this paragraph.

Instrument	Coverage	Resolution	Accuracy
QuikSCAT (Ku-band radar)	90% daily coverage 18 hour revisit 30 km land mask	12.5/25 km horizontal 100 kts max. speed	+/- 2 m/s or 10% degraded by rain
ASCAT (C-band radar, 5.255 GHz)	54% daily coverage	25/50 km horizontal	less sensitive to rain
XOVWM (two satellites)	100% daily coverage 6 hour revisit <5 km land mask	<5 km horizontal 165 kts max. speed	+/- 1 m/s
Ships & buoys	minimal	single point observations	

Table 1: Alternatives instrument systems for acquisition of ocean surface vector wind data.

Observing system simulation experiments to determine the contribution of different data sources to quality of extratropical ocean storm condition forecasts have been conducted only for a few limited cases designed to compare QuikSCAT and XOVWM (Jelenak and Chang 2008). However, the instances in which hurricane-force extratropical storm conditions were observed by NOAA's Ocean Prediction Center in the North Atlantic and North Pacific each year increased from fewer than 10 prior to QuikSCAT to more than 100 using QuikSCAT data at 12.5 km horizontal resolution with advanced wind algorithms and rain impact analysis (Jelenak and Chang 2008). Comparisons of ASCAT and QuikSCAT data suggest that only 10 to 20% of the extratropical hurricane-force storm events observed by QuikSCAT can be reliably identified using ASCAT data (Sienkiewicz *et al.* 2008). XOVWM data would improve on QuikSCAT by improved observation of cyclone development and intensity, and evolution of wind fields (more frequent observations at finer resolution), better nearshore data, and avoidance of rain degradation (Jelenak and Chang 2008).

We consider seven information scenarios, each with particular implications for ship routing decisions:

Blind

In the "Blind" scenario, the ship has no information other than what is observed on board (it is either in storm conditions, or it is not). The ship slows when conditions require this, but does not change course.

Historical Pattern

In the "Historical pattern" scenario, the ship has little or no information about specific storm events other than what is observed on board the ship, but knows the historical distribution of storms and can choose a route other than the shortest distance great circle to avoid historically stormy regions. This is an approximation of a simple routing procedure that might be followed in the absence of ocean surface vector wind observations, other than those from buoys and ships of opportunity, if ships put a high premium on avoiding storm conditions.

Nowcast

In the "Nowcast" scenario, the ship receives nowcasts of observed storm conditions at specified intervals (6 hours) and with specified time delay (1 hour), and can choose to modify its course to avoid a specific stormy area that may be in its path. With two or more consecutive nowcasts, the ship also can generate a primitive forecast of which areas may see storm conditions in the future (assuming the weather system continues to move/evolve as suggested by past observations), and can take this into account.

Figure 1 illustrates one possible set of course decisions taken by a vessel travelling from left to right that finds itself inside or in the path of a stormy area, and has nowcast information about the area's size (diameter) and the location of its center.

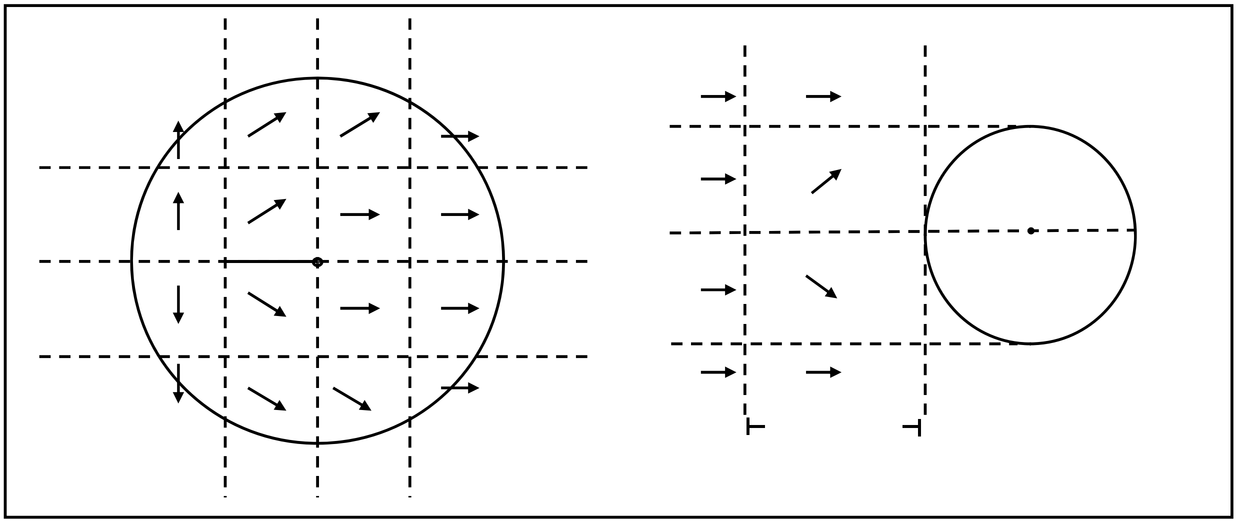

Figure 1: Nowcast scenario course decisions. Arrows indicate the course (direction) chosen by the vessel depending on its location within (left) or in the path of (right) the stormy area (designated by the circle).

XOVWM

In the XOVWM scenario, we assume that forecast and routing services observe nearly all significant extratropical storm activity, and are able to generate forecasts that are accurate for 24 hours and 75% accurate for 48 hours. These forecasts are transmitted to the ship at 6 hour intervals. The ship uses nowcast, observations, and forecasts to adjust its course.

QuikSCAT

The QuikSCAT scenario is similar to XOVWM, but only 80% of extratropical storm conditions are observed, and forecasts are 75% accurate for 24 hours and 60% accurate for 48 hours, reflecting the less detailed, timely, and complete nature of QuikSCAT data as compared to that from XOVWM. The ship receives the nowcasts and forecast at 6 hour intervals, and uses nowcast, observations, and these forecasts to adjust its course.

ASCAT

The ASCAT scenario is similar to QuikSCAT, but only 30% of extratropical storm events are observed.

Perfect Forecast

In the "Perfect Forecast" scenario, the ship has a perfect forecast at the outset of the voyage for its entire duration, and can plan an optimal route to avoid all stormy areas. This is unrealistic given present technology and modeling capability, and is included only to illustrate the upper bound on hypothetical forecast value.

Traffic and Storm Loss Data

Container and dry bulk ships are the major commercial maritime users of North Atlantic and North Pacific transoceanic routes.

Container Ships

Large containerships are rarely lost at sea, unlike dry bulkers and smaller general cargo vessels (IMO MSC 2003). However, storm exposure implies a risk of cargo loss and/or damage to the vessel. Globally, some 10,000 containers are lost annually at sea, often with some associated damage to the vessels, and largely due to severe wind and wave conditions (American Institute of Marine Underwriters). Perhaps half of these losses are associated with extratropical storm events, and half of those losses occur in the Pacific: estimate 2,500 containers lost/year in the Pacific.

Estimates of costs to the shipping industry per lost container range from $50,000 to more than $200,000. We assume for the purpose of this analysis an average economic loss of $100,000/lost container.

Large container ships typically operate at speeds between 15 and 20 knots. Slowing in a storm or deviating from shortest great circle route implies increased operating time for the voyage. We use in this analysis a daily cost for large container vessels of $50,000/day (US Army Corps of Engineers).

Dry Bulk Ships

The primary dry bulk commodities on routes traversing the northern Pacific are grain and coal. Grain cargos move from ports along the west coast of North America and from Central America (Panama Canal) to Asia; coal cargos move primarily from northern South America (Colombia) to Asia. Approximately 500 grain shipments (mainly Panamax vessels) and 1,000 coal shipments (mainly Capesize vessels) cross the Pacifc annually (Kite-Powell 2001, adjusted).

The primary dry bulk commodity traversing the northern Atlantic is grain moving from the Gulf of Mexico to western Europe. Approximately 500 such shipments take place each year (Kite-Powell 2001, adjusted).

In combination, these bulk trades account for about 10 percent of global transoceanic bulk shipments. Historically, the global dry bulk fleet loses about 16 vessels per year at sea, primarily due to structural failures exacerbated by severe weather conditions (IMO MSC 2003). If we assume that the North Atlantic and North Pacific trades are representative of the global risk level facing the dry bulk trades, this suggests an expected loss of one or two dry bulk vessels per year on those routes.

A representative price for a dry bulk vessel on these trades is $50 million (US Army Corps of Engineers); and loss of life and cargo may amount to another $50 million, for total loss of $100 million per dry bulk vessel.

Dry bulk carriers typically operate at speeds around 12 to 15 knots. Operating delays are assumed in our analysis to result in costs of $20,000/day (US Army Corps of Engineers, various years).

Results

Tables 1 through 4 summarize the results of model simulations of container ship and dry bulk carrier transits on typical North Pacific and North Atlantic routes.

Container Vessels, Pacific Routes

We model container vessel traffic through the northern Pacific on a great circle route between San Francisco and Hong Kong. There are approximately 6,000 large container ship movements across the North Pacific each year (Kite-Powell 2001, adjusted). Table 2 shows results for expected annual storm exposure and cost implications under different information scenarios.

Information scenario	Average hours/transit	Total storm exposure (hours/year)	Avoided losses relative to Blind ($ million/year)	Additional voyage costs relative to Blind ($ million/yr)
Blind	300	1,800	---	---
Historical pattern	305 – 310	1,200	80	60 – 120
Nowcast	300.5	1,500	40	6
ASCAT	301	1,470	46	11
QuikSCAT	302.5	1,030	107	30
XOVWM	303	700	153	36
Perfect Forecast	299.7	[0]	250	(minimal)

Table 2: Model results for container vessels, North Pacific, 6,000 transits/year. See pages 3-4 for descriptions of information scenarios.

Container Vessels, Atlantic Routes

We model container vessel traffic through the northern Atlantic on a great circle route between New York and Rotterdam. There are approximately 4,000 large container ship movements across the North Atlantic each year (Kite-Powell 2001, adjusted). Table 3 shows results for expected annual storm exposure and cost implications under different information scenarios.

Information scenario	Average hours/transit	Total storm exposure (hours/year)	Avoided losses relative to Blind ($ million/year)	Additional voyage costs relative to Blind ($ million/yr)
Blind	110	860	---	---
Historical pattern	115	650	29	38
Nowcast	110.2	810	7	2
ASCAT	110.5	690	23	5
QuikSCAT	111	470	55	8
XOVWM	111.2	300	78	10
Perfect Forecast	109.5	[0]	120	(minimal)

Table 3: Model results for container vessel, North Atlantic, 4,000 transits/year. See pages 3-4 for descriptions of information scenarios.

Dry Bulk Vessels, Pacific Routes

We model dry bulk carrier traffic across the northern Pacific on a great circle route between southern Central America and South Korea. There are approximately 3,000 dry bulk vessel movements across the North Pacific each year (1,500 loaded shipments and 1,500 return voyages). Table 4 shows results for expected annual storm exposure and cost implications under different information scenarios.

Information scenario	Average hours/transit	Total storm exposure (hours/year)	Avoided losses relative to Blind ($ million/year)	Additional voyage costs relative to Blind ($ million/yr)
Blind	500	1,500	---	---
Historical pattern	550	1,100	29	125
Nowcast	502.5	1,450	4	6
ASCAT	505	1,290	15	13
QuikSCAT	512.5	1,010	36	32
XOVWM	515	800	51	40
Perfect Forecast	499	[0]	110	(minimal)

Table 4: Model results for dry bulk vessels, North Pacific, 3,000 transits/year. See pages 3-4 for descriptions of information scenarios.

Dry Bulk Vessels, Atlantic Routes

We model dry bulk carrier traffic across the northern Pacific on a great circle route between Miami and Rotterdam. There are approximately 1,000 dry bulk vessel movements across the North Atlantic each year (500 loaded shipments and 500 return voyages). Table 5 shows results for expected annual storm exposure and cost implications under different information scenarios.

Information scenario	Average hours/transit	Total storm exposure (hours/year)	Avoided losses relative to Blind ($ million/year)	Additional voyage costs relative to Blind ($ million/yr)
Blind	180	240	---	---
Historical pattern	200	180	10	17
Nowcast	181	210	5	1
ASCAT	182	210	5	2
QuikSCAT	184.5	170	11.5	5
XOVWM	185.5	140	17	6
Perfect Forecast	179	[0]	40	(minimal)

Table 5: Model results for dry bulk vessels, North Atlantic, 1,000 transits/year. See pages 3-4 for descriptions of information scenarios.

Table 6 summarizes the main results in terms of storm exposure reduction and net economic benefit to shipping operations.

Information scenario	Reduction in storm exposure relative to Blind	Total net benefit to shipping ($ million/year)	Net benefit to container shipping ($ million/year)	Net benefit to dry bulk shipping ($ million/yr)
ASCAT	18 %	**58**	53	5
QuikSCAT	44 %	**135**	124	11
XOVWM	63 %	**207**	185	22

Table 5: Summary of model results for Atlantic and Pacific traffic. See pages 3-4 for descriptions of information scenarios.

Discussion

The "Historical pattern" scenario – storm condition avoidance based primarily on annual storm patterns as opposed to specific observations and forecasts – generates little or no net benefit for either container ships or bulk carriers because the increased operating costs due to longer routes counteract the effect of reduced storm exposure.

As the coverage (instances of storm conditions observed) and forecast quality of information scenarios improves, net benefits to ship operations increase. In general, better information results in slight increases in voyage length as ships take measures to avoid storm conditions, and in decreases in exposure. The avoided losses from reduced exposure must be reduced by the additional cost due to longer voyages to obtain the net benefits from each information scenario. Container ships are better able to make use of short-term forecast information to avoid storm exposure because of their higher operating speed; and so the net value of better information is greater for container ships than for bulk carriers.

For container ships, the present QuikSCAT information scenario allows for the reduction of storm condition exposure by an estimated 44 percent over the Blind scenario, and delivers expected annual benefits of an estimated $124 million in avoided losses, net of increased operating costs. This compares to a possible 63 percent reduction in exposure with the hypothetical XOVWM information, at a net value of $185 million/year; and a reduction of 18 percent (value of $53 million/year) under ASCAT. About two thirds of the value generated by this kind of information for the container trades is generated on the Pacific. The Perfect Forecast delivers expected annual benefits of $370 million by allowing for the virtual elimination of storm condition exposure with no significant increase in operating costs.

Compared to container vessels, bulk carriers operate at lower speeds and are less easily able to move out of the way of stormy regions in their path, and course deviations tend to take longer and therefore be relatively more expensive. This reduces the value of nowcasts and short-term forecasts to bulk vessels. The present QuikSCAT scenario generates an estimated $11 million in annual benefits, net of increased operating costs. In comparison, the hypothetical XOVWM information would produce $22 million and the ASCAT scenario $5 million in annual net benefits. The Perfect Forecast could deliver expected annual benefits of $150 million ($110 million on the Pacific and $40 million on the Atlantic) by allowing for the virtual elimination of exposure with no significant increase in operating costs.

The combined estimate of net annual benefits to shipping operations from QuikSCAT information is $135 million, compared to estimates of $58 million for ASCAT and $207 million for XOVWM.

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Appendix: Storm Conditions Submodel

Atlantic

Likelihood of storm starting on a given day in…

January	0.26
February	0.25
March	0.02
April	0.01
May	0.02
…	
September	0.05
October	0.07
November	0.09
December	0.15

Starting latitude:

Normally distributed between 15N and 69N

Starting longitude:

Normally distributed between [check]

Starting diameter:

Initial: uniform over [100 – 500] nm

Change per hour: uniform over [-10 – 10] nm

Starting velocity :

Initial: uniform over [20 – 30] knots

Change per hour: normally distributed around mean 0 and std. dev. 2.3

Starting heading:

Initial: uniform over 0 – 360 deg

Change per hour: normally distributed around mean 0 and std. dev. 9

Duration:

Hours	likelihood
6	0.15
12	0.15
18	0.13
24	0.10
30	0.09
36	0.06
42	0.02
48	0.01
54	0.05
60	0.04
66	0.03
72	0.05
78	0.05

Pacific

Likelihood of storm starting on a given day in…

January	0.20
February	0.13
March	0.10
April	0.03
May	0.01
…	
September	0.04
October	0.11
November	0.11
December	0.24

Starting latitude:

Normally distributed between 18N and 63N

Starting longitude:

Between longitude	likelihood
140 – 150	0.04
150 – 160	0.12
160 – 170	0.17
170 – 180	0.19
180 – -170	0.14
-170 – -160	0.09
-160 – -150	0.08
-150 – -140	0.10
-140 – -130	0.07

Starting diameter:

Initial: uniform over [200 – 300] nm

Change per hour: uniform over [-10 – 10] nm

Starting velocity :

Initial: uniform over [20 – 30] knots

Change per hour: normally distributed around mean 0 and std. dev. 2.3

Starting heading:

Initial: uniform over 0 – 360 deg

Change per hour: normally distributed around mean 0 and std. dev. 9

Duration:

Hours	likelihood
6	0.18
12	0.22
18	0.18
24	0.20
30	0.10
36	0.06
42	0.03
48	0.02
54	0.01