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INCORPORATION OF TROPICAL CYCLONE AVOIDANCE INTO AUTOMATED SHIP SCHEDULING

by

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June 2014

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The U.S. Navy's Combat Logistics Force (CLF) provides at-sea resupply to U.S. and allied vessels throughout the world. The CLF scheduling system anticipates demand and schedules 45 days in advance to meet that demand. Tropical cyclones (TCs) frequently disrupt these plans, requiring diversions and inefficient steaming speeds. We evaluate the impact of adding anticipated TC positions in an operational planning tool called the Replenishment At Sea Planner. Various scenarios are used to test the impact of different geographic representations of the TC obstacle in CLF operational planning. Open-ocean scenarios explore TC impact in ocean crossings, with no limitations caused by land masses, while near-shore scenarios examine the pinching effect of TC landfall. Shorter distances are traveled by CLF ships in the scenarios when the TC obstacle is "forecasted," but the present position is excluded. The recommended TC representation is the 24-hour advanced position, with no extended duration. This representation produces the shortest total travel distances for both the open-ocean and near-shore scenarios.

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INCORPORATION OF TROPICAL CYCLONE AVOIDANCE INTO AUTOMATED SHIP SCHEDULING

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ABSTRACT

The U.S. Navy's Combat Logistics Force (CLF) provides at-sea resupply to U.S. and allied vessels throughout the world. The CLF scheduling system anticipates demand and schedules 45 days in advance to meet that demand. Tropical cyclones (TCs) frequently disrupt these plans, requiring diversions and inefficient steaming speeds. We evaluate the impact of adding anticipated TC positions in an operational planning tool called the Replenishment At Sea Planner. Various scenarios are used to test the impact of different geographic representations of the TC obstacle in CLF operational planning. Open-ocean scenarios explore TC impact in ocean crossings, with no limitations caused by land masses, while near-shore scenarios examine the pinching effect of TC landfall. Shorter distances are traveled by CLF ships in the scenarios when the TC obstacle is "forecasted," but the present position is excluded. The recommended TC representation is the 24-hour advanced position, with no extended duration. This representation produces the shortest total travel distances for both the open-ocean and near-shore scenarios.

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LIST OF ACRONYMS AND ABBREVIATIONS

AME	USNS *Amelia Earhart*
AOR	Area of Responsibility
CLF	Combat Logistics Force
CTF	Commander Task Force
DDG	Guided Missile Destroyer
DTG	date time group
HLS	USS *Halsey*
JTWC	Joint Typhoon Warning Center
KML	Keyhole Markup Language
mph	miles per hour
NHC	National Hurricane Center
nm	nautical mile
OTSR	Optimum Track Ship Routing
PXT	USNS Patuxent
RAI	USNS Rainier
RASP	Replenishment At Sea Planner
SVP	Smart Voyage Planner
TC	Tropical Cyclone
U.S.	United States
USNS	United States Naval Ship
USS	United States Ship
UTC	Universal Time

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EXECUTIVE SUMMARY

Weather has always caused issues for transiting ships. Tropical Cyclones (TCs) can damage and even sink ships. Avoiding TCs adds to fuel costs and causes delays. In the private sector, commercial shipping uses automated routing services that include weather avoidance. The Navy has tools, such as the Smart Voyage Planner (SVP), for ship-by-ship optimal routing, with weather avoidance included. For many ships, operating in groups, which require coordination of both long- and short-term plans, the Navy uses scheduling tools like the Replenishment At Sea Planner (RASP), which is used by the Combat Logistics Force (CLF) to coordinate underway replenishments to support naval operations. As of June 2014, however, scheduling tools such as RASP do not yet incorporate weather. Ship scheduling by hand is very time-consuming. It would be valuable to find a way to incorporate a TC that may impact ship scheduling into automated scheduling tools. This thesis develops and tests a method of incorporating TCs into RASP in such a way that the solving algorithm routes ships around the area of adverse weather caused by the TC, while minimizing the distance traveled, thus also minimizing fuel usage. Several scenarios are examined to compare the effects of using different TC representations in RASP. A key focus is the impact of varying the duration and timing of the TC that is being included in RASP. This effort provides a recommendation for timing and duration of the TC for input that will both prevent damage to ships and provide effective routing.

The Joint Typhoon Warning Center (JTWC) provides the track forecasts for all TC activity in the northwest Pacific Ocean (http://www.usno.navy.mil/JTWC/products-and-services-notice) and historical TC data from JTWC is used to simulate TC forecasts. In RASP, the TCs are represented as land masses, and RASP treats these as an obstacle and routes CLF ships around them. To explore the impact of TCs in RASP, for each model day that RASP runs, an obstacle is created that covers a portion of the TC's life. In each scenario, RASP is run once for each simulated day. There is a trade-off between reducing the

size of the obstacle so that RASP can use efficient routes, and increasing the size to prevent frequent diversions when the TC moves into an area where transit was previously scheduled. The measure of performance is the total distance traveled by each CLF ship in each scenario.

The results indicate that a small representation of the TC is best (i.e., just one position), but delayed one day relative to the model time (equivalent to a 24-hour forecast). Including the present position in the TC obstacle provides no reference as to the direction of the translation of the TC, which lets RASP route ships directly in front of the TC's path and right into the TC. This occurred for both the open-ocean and the near-shore scenarios. A larger, three-day representation caused ships to travel farther than is required to keep clear of the storm.

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I. INTRODUCTION

Weather has always caused issues for ships transiting the oceans. Storms, fog, high winds, and large waves can delay, damage, and sink even larger ships. Tropical Cyclones (TCs) can generate high winds and large waves over hundreds of nautical miles (nm) and are a serious threat for transiting ships. Ships must be routed around TCs to prevent damage or loss to the ships and the cargo they are carrying. Satellite imagery, radar, and improvements in forecasting have enabled ships to avoid TC-impacted areas altogether.

Avoiding TCs does not come without a cost. Delaying departure or steaming around a TC results in more fuel being burned at a high cost, plus the cost due to the delay in arrival at the destination, and the associated mission impacts. Due to the rising cost of fuel, many companies are using optimal ship routing tools. Companies such as Weather Routing, Incorporated (http://www.wriwx.com/) and Applied Weather Technology, Incorporated (http://www.awtworldwide.com/) provide commercial shipping with routing services that include weather avoidance. The United States (U.S.) Navy, while not using these commercial tools, has tools such as the Smart Voyage Planner (SVP) for optimal routing (Miller, 2012).

An issue with these planning tools is they operate at the tactical level because they are designed for an individual ship and the route for that ship. This works well for commercial shipping that is moving cargo from port to port. The U.S. Navy schedules many ships that are operating in groups and they have to be coordinated to support both short- and long-term plans. Fleets are assigned an Area of Responsibility (AOR) within which they patrol to provide security or have a forward presence for deterrence. These patrols often do not have regularly scheduled ports for fueling and resupply because the U.S. Navy typically conducts replenishments underway. Such replenishment between warships and Combat Logistics Force (CLF) ships must also be coordinated by fleets on the operational level four to six weeks prior to the event.

A. RESEARCH

Commander Task Forces (CTFs) within the U.S. Navy have dedicated scheduling teams to ensure that all the moving parts come together in an efficient manner. Until recently, these teams planned schedules by hand, which took personnel many hours. Military Sealift Command sponsored the Naval Postgraduate School in the research and development of automated planning tools such as the Replenishment At Sea Planner (RASP) (Brown, Carlyle, & Burson, 2010).

While the RASP ship scheduling tool works well scheduling 10–40 ships over a four-to-six-week period, it has one major limitation: it does not incorporate weather. Weather events normally do not affect the resulting plans, but a TC event is an exception. The potential damaging effects of a TC may require ships to be diverted, sometimes for hundreds of miles. Since TCs have not been incorporated in the automated tools, schedulers are again forced to make the required adjustments by hand. Inclusion of TCs as an integral part of planning tools would allow standardization of the planning process.

B. OBJECTIVE

This thesis develops and tests a method of incorporating TCs into RASP in such a way that the solving algorithm routes ships around the area of adverse weather caused by the TC, while minimizing the distance traveled; thus minimizing fuel use. Several scenarios are examined to compare the effects of using different TC durations within RASP. Chapter V offers a recommendation for estimating the timing and duration of TCs for input that will both prevent damage to ships and provide effective routing.

II. BACKGROUND

TCs can dramatically impact naval warfare and operations because they are large and severe storms that can prohibit U.S. Navy operations over areas encompassing hundreds of miles of ocean. Routing ships around TCs to avoid damage has been the U.S. Navy's answer since technology has enabled them to do so.

A. TROPICAL CYCLONES

TC is the general term used to describe hurricanes, typhoons, and cyclones; these names vary by the region in which the TC forms. TCs form over tropical waters where the water temperature is 26 degrees Celsius or greater. Nearly two-thirds of TCs form between 5 degrees and 20 degrees of latitude (Ahrens, 2000), which represents a large area within which the U.S. Navy typically operates, and when a TC develops, all ships give way. In addition to the size of the TC, the translation speed of a TC, which can vary from 5 knots to as much as 50 knots (Ahrens, 2000), is another important consideration.

Once a TC has formed in the Atlantic or Eastern North Pacific, the National Hurricane Center (NHC) provides a forecast track warning every six hours (Pearman, 2011). For the Western North and South Pacific and Indian Oceans, the Joint Typhoon Warning Center (JTWC) provides the track forecasts for all TC activity (http://www.usno.navy.mil/JTWC/products-and-services-notice). The products of these weather centers form the key information that is passed to the fleet commands so that adjustments can be made to keep ship activities clear of the TC. Present satellite technology allows for storms to be tracked with considerable precision, and the intensity and size of the storm are also provided with the track forecast. The JTWC best track data site is http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/, with post analysis of every storm that forms in their AOR. This thesis uses this database for input and simulated forecasts. Normally, TC forecasts include probability rings (http://www.nhc.noaa.gov/refresh/graphics_ep3+shtml/203948.shtml?tswind120#content) for the 34-knot winds and adds a completely different complexity to what is being tested in this thesis. To simplify the process and narrow the focus of this thesis, actual TC historical data is used. Since the TC size and position are known with 100% accuracy, actual forecasts with probability are not used.

1. Admiral Halsey

The tragic impacts that TCs can have on U.S. Navy ships were illustrated during World War II (Drury & Clavin, 2007), when Admiral Fredrick “Bull” Halsey was maneuvering his Third Fleet and trying to refuel, while supporting General MacArthur’s invasion of the Philippines in 1944. Halsey, who was misinformed about the typhoon’s position, drove the 170 ships of the “Big Blue Fleet” right into the path of Typhoon Cobra. The ships had to endure wind gusts of 155 miles per hour (mph) and 90-foot seas for two days. Over 793 men died, over 80 were injured, three destroyers capsized, and 12 more ships were left inoperable, while 146 aircraft were either lost or damaged beyond repair (Drury & Clavin, 2007). While this is an extreme historical case, it illustrates the dangers of not considering TC tracks in ship scheduling.

2. Navy Policy

The U.S. Navy policy is to avoid such storms altogether by routing around the storm. The standard for adverse weather that determines how far to route around the center of a TC is the radius of gale-force winds (34 knots) and high seas (12-feet high). The “34-knot rule” is well established and can even be found on the NHC website under marine safety (http://www.nhc.noaa.gov/prepare/marine.php).

B. SCHEDULING AND ROUTING TOOLS

In recent years, the Navy has begun to incorporate weather into automated planning tools. The U.S. Navy has a planning tool, the SVP (Miller, 2012), to plan ships’ routing one ship at a time. The SVP uses the Optimum

Track Ship Routing (OTSR) algorithm and incorporates winds, waves, currents, and any other weather inputs to create the safest and most fuel-efficient route for a single ship. For the OTSR algorithm to work properly, it requires accurate short-range and medium-range weather predictions and accurate ship positions, including conditions for dead reckoning (Miller, 2012). These two inputs to OTSR are time-synchronized with the actual weather within the SVP model to calculate the optimum route (Miller, 2012). With U.S. Navy budget cuts and increases in fuel costs, optimal routing has become increasingly important.

Scheduling tools provide the timing of events for a group of ships operating over large areas for a number of weeks, rather than the precise routing for a single ship provided by planning tools. Scheduling tools presently do not include potential weather impacts. Weather is constantly changing and single ships, or groups traveling together, need the flexibility to make small routing corrections independently, taking into consideration local operating conditions and weather.

An added complexity of fleet operations is planning for the underway replenishment. It is the responsibility of the fleet CTF to ensure that combat ships have the appropriate levels of stores, goods, and fuel. These CLF ships are prepositioned throughout the fleet AOR and are scheduled to meet customer (combat) ships. Efforts to optimize both the planning process and the rendezvous of the combat and CLF ships resulted in the planning tool RASP (Brown et al., 2010). RASP is an example of a fleet operational-level scheduling tool that plans for transiting ships and underway replenishment in an effort to minimize fuel burned.

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III. INCORPORATING TROPICAL STORMS

As indicated above, ship scheduling by hand is very time-consuming. It would be valuable to find a way to incorporate a TC that may impact ship scheduling into automated scheduling tools. This thesis proposes a method to input TC data into the RASP scheduling tool, and explores the effect on total distance traveled by a CLF ship by varying the duration of the TC represented and the start time for the portion of the TC's track that is represented. A scenario consists of a CLF ship position, a customer ship position, a TC, and a choice of delay (between RASP time and storm time) and the duration of the TC represented. This chapter describes the method to input the TC into RASP and run a scenario in RASP.

A. REPLENISHMENT AT SEA PLANNER

RASP is a Microsoft Excel-based heuristic model used operationally to aid in scheduling CLF ships. RASP is owned by the U.S. Navy and is constantly being updated. Version 1.4 is used in this research. The user inputs the customer ships, available CLF ships, and all ship locations and the output is a replenishment schedule that takes into account the supply levels of all the ships and maintains the supplies above required levels. With the proper inputs, RASP completes the scheduling in a matter of seconds. As of June 2014, CTF 53 in the Middle East and CTF 73 in the Pacific use RASP for scheduling, but RASP does not incorporate TCs into the scheduling process.

RASP uses two Keyhole Markup Language (KML) files, one called the logic file, which is used as the database for obstacles to transiting ships, and one called the routing file, which is used for ship positions. Within the logic KML file are the locations of land masses, represented as closed paths (shown in red in Figure 1), and within the routing file are the ports used, straits, stations for rendezvous, and the ship positions (see Figure 2). The RASP algorithm treats the land masses as no-go areas and routes the ships around them. In this thesis, a TC is entered into the database as a no-go area, which RASP treats the same as land and around which it therefore routes the ship.

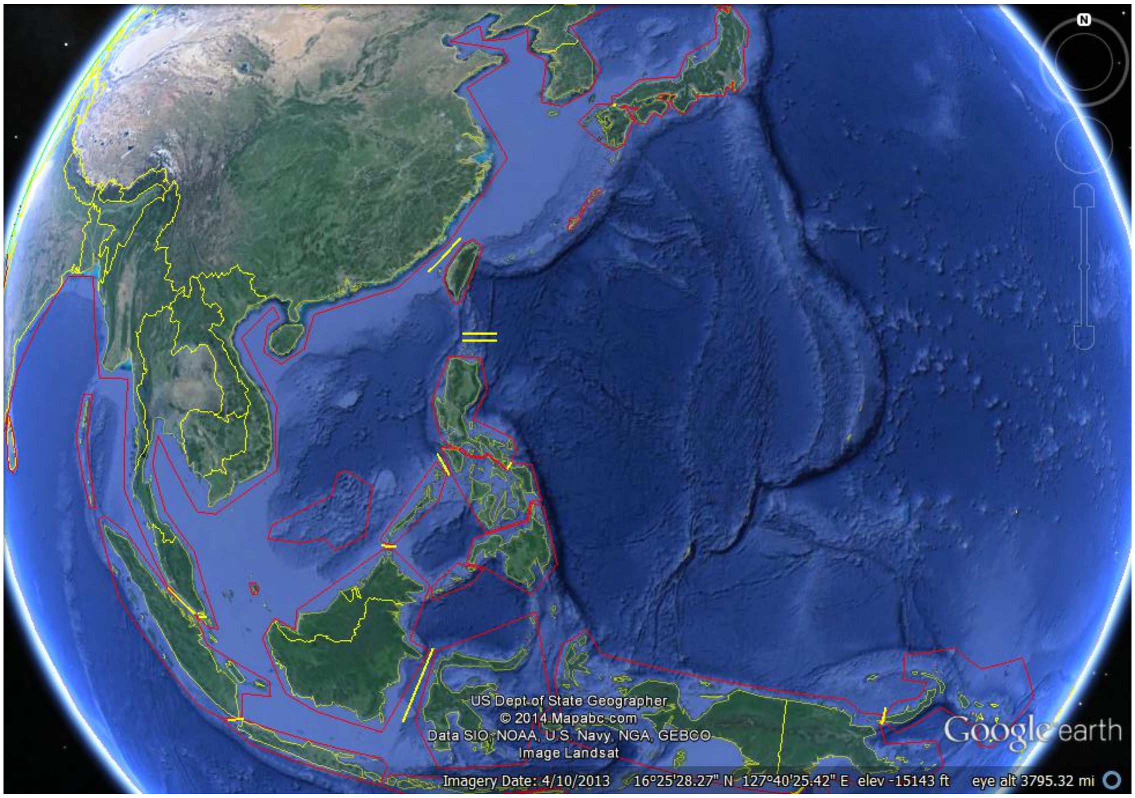

Figure 1. Illustration of the CTF-73 logic file showing the obstacles (red lines) surrounding land masses and straits (yellow lines) (from Google Earth, 2013).

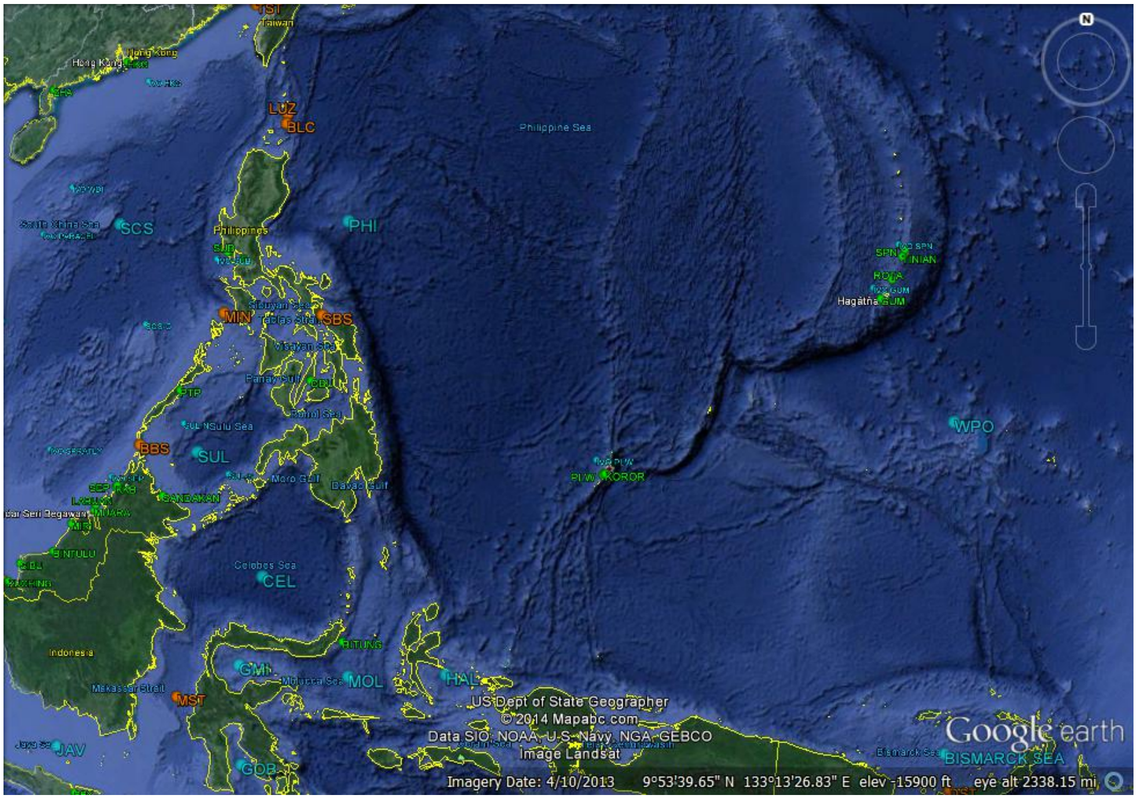

Figure 2. Example of a CTF-73 routing file showing ports in green, straits in orange, and rendezvous points in blue (from Google Earth, 2013).

These scenarios in RASP produce the daily schedules for the CLF ship(s) as well as the daily positions used from the routing KML. RASP produces a schedule for the transit of CLF ships and for replenishment events up to 45 days from the RASP start time. Land masses in RASP, however, cannot change over that planning horizon. To represent the motion of a TC over a period of days, RASP is run iteratively, with different logic files that incorporate different portions of the storm.

Scenarios are constructed in the RASP routing and logic files; they contain at least one customer ship, one CLF ship, and a TC placed in the operating area. Schedules in the Fleet are normally updated every 24 hours. A transit day in RASP is measured from 0800 to 0800. The dates used within RASP are arbitrary, but are necessary to the function of RASP (see Table 2). RASP time is denoted d, and measured in days. For consistency across all scenarios, 1 January 2014 is $d=1$ and 0800 on 1 January 2014 is $t=0$. As described below, the TC dates were adjusted such that the storms affect the relevant dates. Each scenario starts at day $d=1$ and RASP is run once for each subsequent day d with a 24-hour time step. To simulate TC movement, a new logic file, with a new TC obstacle, is used for each day according to the updated position of the TC for a given t and D.

For each scenario, RASP is run first with ship positions corresponding to 1 Jan 2014 at 0800 UTC, and an appropriate logic file including a portion of the TC, as discussed below. From the schedule produced by RASP, the ship positions at 0800 on 2 Jan 2014 ($d=2$) are extracted and used as the starting positions for a second run of RASP, with an updated logic file, representing a different portion of the TC, offset by one day. This process is repeated until the ship clears the storm and RASP schedules the ship to travel on a direct great-circle route to the customer ship. The total distance traveled by the ship is used as the measure of performance. For each d, $F(d)$ is defined as distance traveled by the CLF ship during the first 24 hours of the solution. A summation over d results in the total distance traveled by the CLF ship to complete a replenishment ($\sum_d F(d)$) for a given scenario. Fuel burn of the CLF ships varies from day to day, depending on the distance traveled, and since each ship is given the same amount of time to replenish the combat ship, minimizing the fuel burn instead of distance traveled would lead to the same result and is a level of detail not required to achieve quantifiable, valid results.

B. TROPICAL STORM DATA

In the test scenarios, historical TCs in the Western North Pacific Ocean are selected from the JTWC best-track database (http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/). This website includes data on TCs dating back to 1945. The data fields used are the date time group (DTG), latitude in degrees, longitude in degrees, and radius of 34-knot winds in nautical miles (nm) for each quadrant, all of which are given at six-hour intervals. The DTG is one number incorporating the four-digit year, two-digit month, two-digit day, and two-digit hour given in universal time (UTC) for each TC position.

These data are used to produce a polygon in KML using R (R Core Team, 2014). The TCs are represented as land masses and RASP routes CLF ships around the TC, thus avoiding the potential damage area of 34-knot winds. The next challenge is to determine how much of the TC track to use in creating an obstacle in RASP. If the entire track was used, the obstacle could cover a major portion of an ocean and block off a large area from routing. An obstacle is created that covers only a portion of the TC's life, duration D, which is measured in six-hour increments. For example, $D=5$ would indicate five six-hour positions, for a 24-hour duration (including both endpoints) represented with a polygon.

Moreover, we may not want to represent the current position of the TC in RASP. Depending on the speed and course of the TC, we may want to represent the TC positions after the delay, T, measured in six-hour increments, to reduce the size of the no-go area and allow for ships to route behind the storm. We anticipate that ships would not be positioned close to the storm and, therefore, the current position of the storm is not relevant to the schedule over the next several days. $T=0$ indicates that the TC position that most closely matches the current time of the RASP scenario is included in the TC polygon, while $T=1$ indicates that the TC position six hours after the current RASP time is included in each run of RASP and that the TC obstacle will extend through $D-1$ additional positions.

Each scenario is run in RASP without a TC ($D=0$) to establish a baseline for the measure of effectiveness. The six additional TC representations used for comparison are shown in Table 1. The duration D of the TC represented affects how large the associated no-go area is, and is varied from one six-hour period ($D=1$), to two days ($D=5$) and three days ($D=9$). This test simulates a forecasted track of a TC and is intended to prevent the ships from trying to cut in front of where the storm is moving.

		D (duration of TC represented, measured in six-hour increments)			
		1	3	5	9
T (delay, measured in six-hour increments)	0	×		×	×
	2		×		
	4	×		×	

Table 1. Scenario TC durations (D) and delays (T).

We anticipated that any duration longer than three days will result in a TC representation blocking off a large area and decreasing the probability to achieve efficient routing, and results confirmed that the total distance traveled increased from $D=5$ to $D=9$. The value of T affects the difference between RASP time and the timing of the portion of the TC represented. Delays of $T=0$, $T=2$, and $T=4$ correspond to no delay, a 12-hour delay, and a 24-hour delay between the RASP start time and the portion of the TC represented.

In order for the algorithm used in RASP to solve properly, the TC polygon must be converted to a closed path, similar to the obstacles in the logic file, and are represented such that the points are in clockwise order.

A polygon is created for a given TC start time $t=(d-1)*4+T$ and duration D as follows:

- For each six-hour period starting at the start time t and continuing for a given duration D, the gcDestination function in the package maptools (Bivand & Lewin-Koh, 2014) in R is given the latitude and longitude of the storm center and the maximum radius of 34-knot winds among the four quadrants for the corresponding DTG, which results in an octagon consisting of eight points at the

34-knot radius great-circle distance from the center for each position (see Figure 3). That is, the maximum 34-knot radius is considered the minimum safe distance for a ship, as recommended by the 34-knot rule.

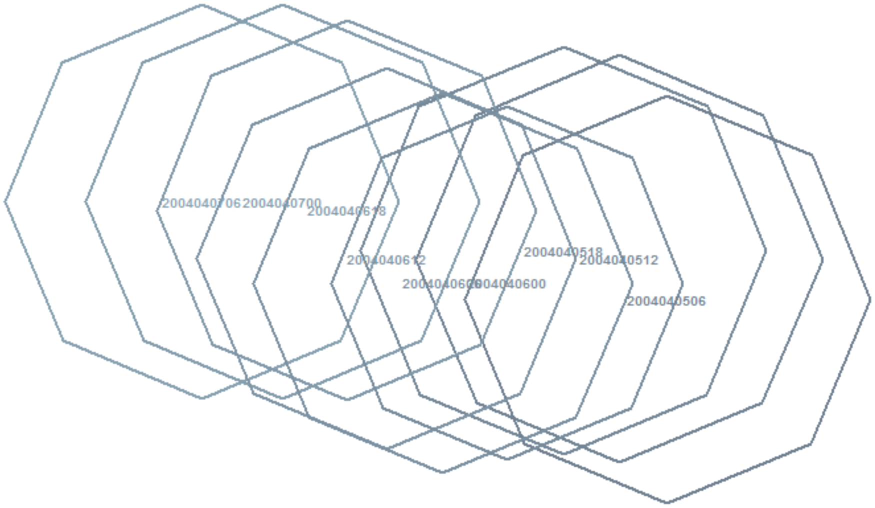

Figure 3. Sequence of octagons for sixhour positions starting at time t and continuing over duration $D=9$ (three-day period) using the gcDestination function in R.

- The unionSpatialPolygons function in the rgdal (Bivand, Keitt, & Rowlingson, 2014) R package is applied to the individual octagons and produces a polygon that is the union of the D octagons. The TC six-hour translation speed is relatively small compared to the speed necessary to reach the 34-knot radius, so the octagons will overlap and the union, as in Figure 4, results in a single polygon. This is visually verified for each polygon created.

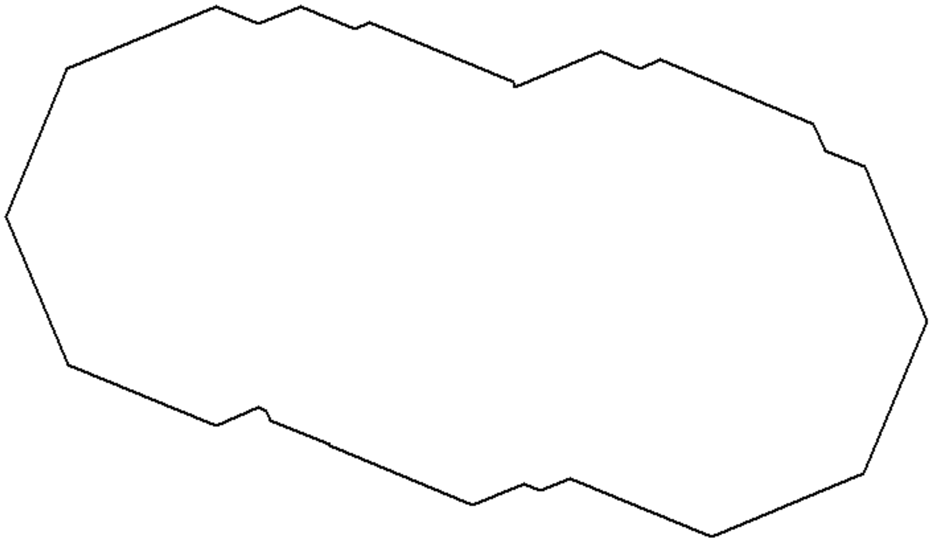

Figure 4. Union of octagons from Figure 3 created with the unionSpatialPolygons function in R.

- The writeOGR function in the rgdal (Bivand et al., 2014) R package writes the created single polygon into a KML file.
- The TC obstacle, now represented by a polygon in its own KML file, is changed to a closed path object using R, added to the obstacles in the RASP logic file (see Figure 1), and saved using Google Earth (see Figure 5). The new saved file becomes a new logic file for RASP.

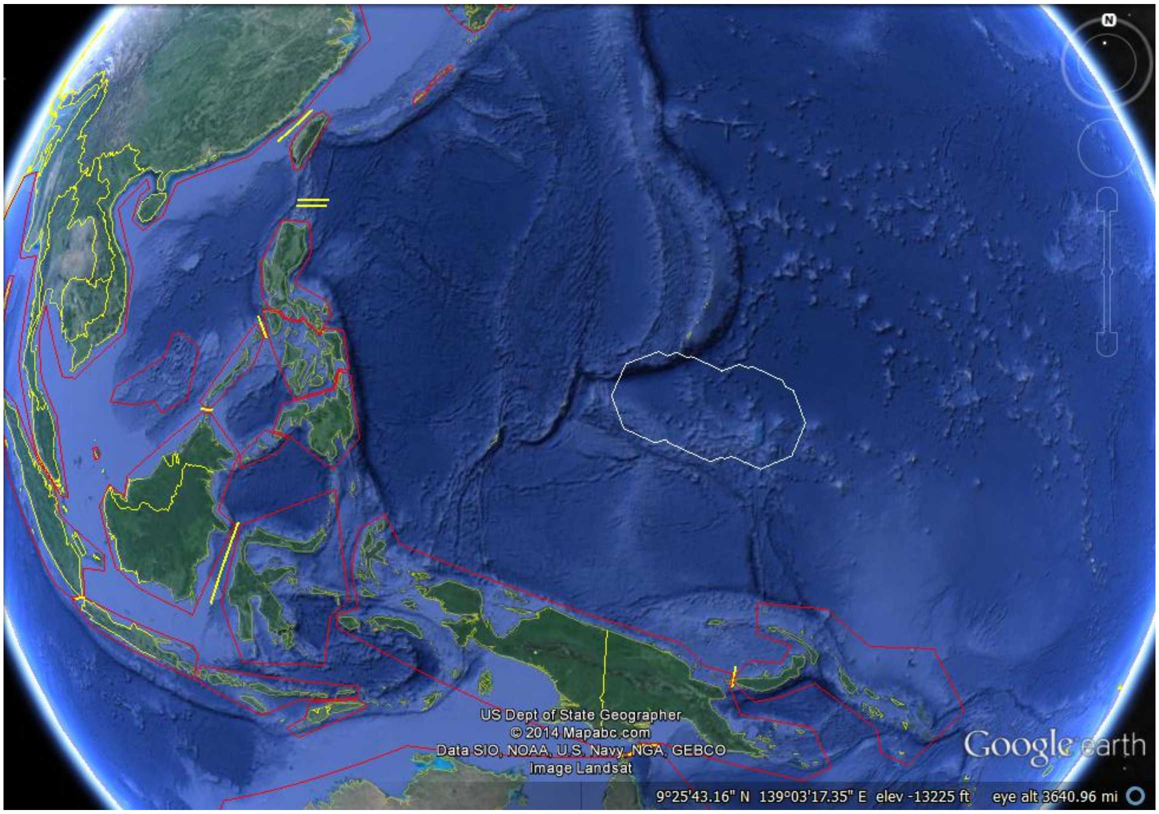

Figure 5. Logic file from Figure 1 with the TC obstacle created by the union of octagons from Figure 4 added (from Google Earth, 2013).

C. SCENARIOS

We ensure the slow-moving ships and the TC have sufficient time to interact for each scenario by running from the starting time and positions in the scenario to the arrival time of the CLF ship at the position of the customer ship. In some cases, the CLF ship reaches the customer ship before the end of the scenario, in which case it does not move any more. To make the scenarios more comparable, the ship's path is measured from the same starting and finishing point for a given scenario and given the same amount of time to transit to the customer. To guarantee a set total travel time, the CLF ship is hard-scheduled to be at the customer location on a specified day.

1. Open Ocean

The open-ocean scenarios are based in the Philippine Sea and are designed to evaluate TC effects when the ships are not constrained by land as they maneuver to avoid the TC. For these scenarios, the third TC during the 2004 season was selected from the JTWC database. The TC start time, to which we assign $t=0$, is 0600 UTC on the 5th of April. It is advanced at six-hour increments from there for each t to the last TC position of 1800 UTC on the 15th of April ($t=43$). The track of this TC cuts through prime routing areas in the Pacific, as it starts southeast of Guam and moves to the west before turning to northeast and passing through the Philippine Sea by Okinawa and south of Honshu before dissipating.

The Customer Ship is the Guided Missile Destroyer (DDG) United States Ship (USS) *Halsey* (97 HLS) with a location at 15 Degrees 59 Minutes North and 138 Degrees 52 Minutes East. For these scenarios, HLS does not move, but instead waits in that position for replenishment by the CLF ship. Three CLF ships are included in the open-ocean scenarios to conduct the replenishment at different starting distances from the TC (see Table 2). The three starting positions are used to test the effect that starting distance from the TC has on scheduling and the use of three ships allows all of the positions to be run together in RASP. For the scenarios, the CLF ships have to be assigned a replenishment date for the algorithm to move them to HLS.

CLF Ship	**Latitude**	**Longitude**	**Replenishment Date**
United States Naval Ship USNS *Amelia Earhart* (AME)	6° 21’ N	152° 10’ E	05 Jan 14
USNS *Patuxent* (PXT)	3° 42’ N	150° 05’ E	06 Jan 14
USNS *Rainer* (RAI)	0° 58’ N	148° 18’ E	07 Jan 14

Table 2. Three CLF starting ship positions and replenishment dates in the open-ocean scenario.

Each CLF ship is placed to cause interaction with the TC. A few calibration runs in RASP were used to position each CLF ship so that the $D=1$ and $T=0$ TC is directly in its path on the day before the ship reaches the TC track. Having the CLF ships at the different positions and distances provides the variation necessary for comparison across different scenarios. AME is less than one day from the track, PXT is between one and two days out, and RAI is between two and three days away from the TC track. Any ship added more than three days out from the TC would be too far away from the track for interaction. By the time a ship that far away arrived, the storm would have moved out of the area, so it is assumed that additional ships would not provide additional information.

We minimize the number of runs required by running all three CLF ships at the same time in RASP. The routing file is built containing all three ships and used with the logic file containing the TC for the specified d. Figure 6 reflects the starting positions for all the involved ships and the TC for $d=1$, $D=1$, and $T=0$. Each date in Table 2 (right column) is assigned to a CLF ship to give it enough time to interact with the TC without having to rush to make the replenishment traveling at 14 knots or less.

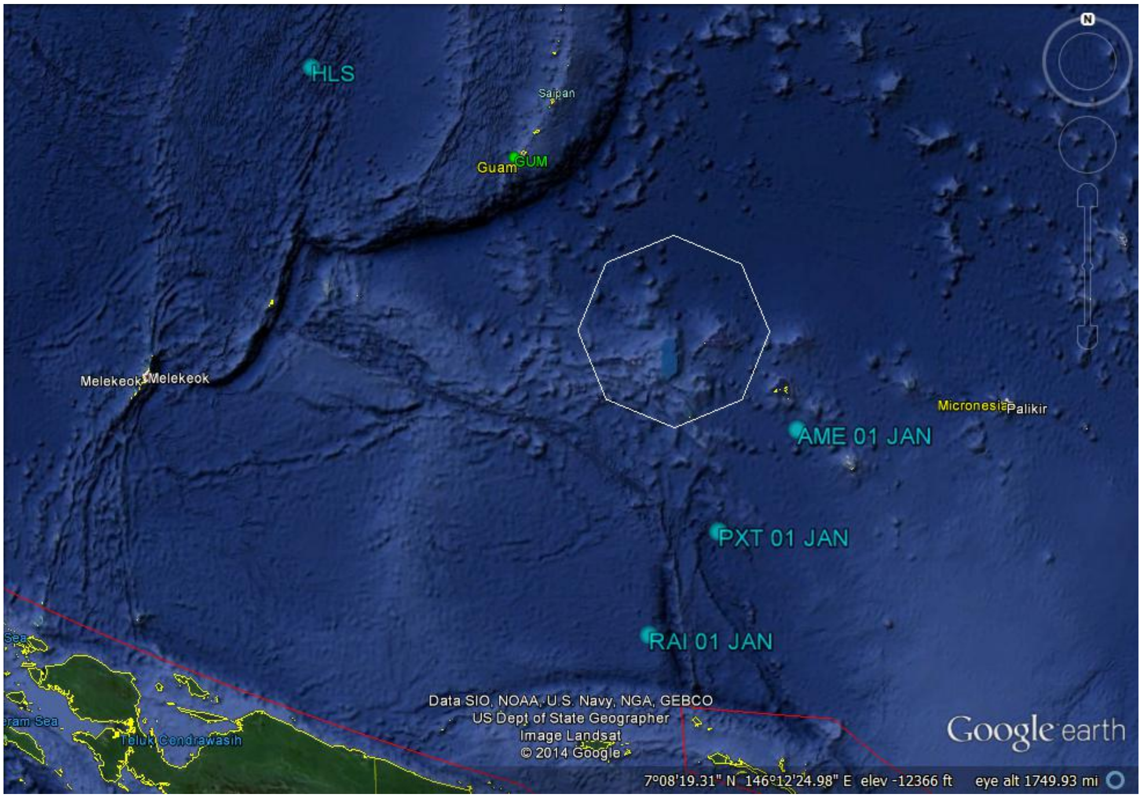

Figure 6. Final routing file and logic file, specifically for the open-ocean scenario $d = 1$, $D = 1$, and $T = 0$. The initial ship positions are indicated in blue (from Google Earth, 2013).

2. Near Shore

The near-shore scenarios are based in the vicinity of Taiwan, along the Chinese coast, and introduce land as a new obstacle. These scenarios are used to examine what happens when the TC is forecast to make landfall and thereby block prospective routes. For these scenarios, the thirteenth TC during 2005 is selected from the JTWC database. Time $t = 0$ is 0600 UTC on the 29th of August and is advanced as in the Open-Ocean TC, at six-hour increments to 1200 UTC on the 1st of September ($t = 13$). This TC develops in the northern Philippine Sea and moves westward, in an almost straight line, to pass directly over Taiwan and then dissipates over China.

The readOGR function in the rgdal (Bivand et al., 2014) R package extracts the land obstacles representing Taiwan and Europe/Asia from the logic file into R. These closed paths are then converted to polygons using R (R Core Team, 2014) and combined with the appropriate TC polygons using unionSpatialPolygons function in the rgdal (Bivand et al., 2014) to prevent overlap in RASP when the TC makes landfall. The combined object is written to KML using the writeOGR function in the rgdal (Bivand et al., 2014) R package, converted back to a closed path and then manually saved back into the appropriate logic file for the TC on day d .

The CLF and customer ships from the open-ocean scenario are used with starting positions given in Table 3. Once again, the HLS does not move for any of the scenarios and the three CLF ships conduct the replenishment at different starting distances from the TC (see Table 3). This time, the three starting positions for the CLF ships are used to test the effect of the TC pinching against land, with three CLF ships at different distances from the TC landfall. Calibration runs in RASP are again used to position each CLF ship to maximize the interaction with the TC. The CLF ships start a little farther away from the TC track than the open-ocean scenario. This gives the TC enough time to make contact with the land in front of the CLF ships and block their prospective routes. The CLF ship AME is between one and two days from the track, PXT is between two and three days out, and RAI is between three and four days away from the TC track. By the time a ship that starts more than four days away arrived, the storm would be completely over land and out of the way, so it is assumed that additional ships would not provide additional information.

CLF Ship	**Latitude**	**Longitude**	**Replenishment Date**
USNS Amelia Earhart (AME)	15° 36’ N	123° 32’ E	05 Jan 14
USNS Patuxent (PXT)	17° 12’ N	114° 44’ E	06 Jan 14
USNS Rainer (RAI)	16° 11’ N	109° 52’ E	07 Jan 14

Table 3. Three CLF starting ship positions and replenishment dates in the near-shore scenario.

The routing file is built as in the open-ocean case and again contains all three CLF ships and uses the logic file containing the TC for the specified d. Figure 7 reflects the starting positions for all the involved ships and the TC for $d = 1$, $D = 1$, and $T = 0$.

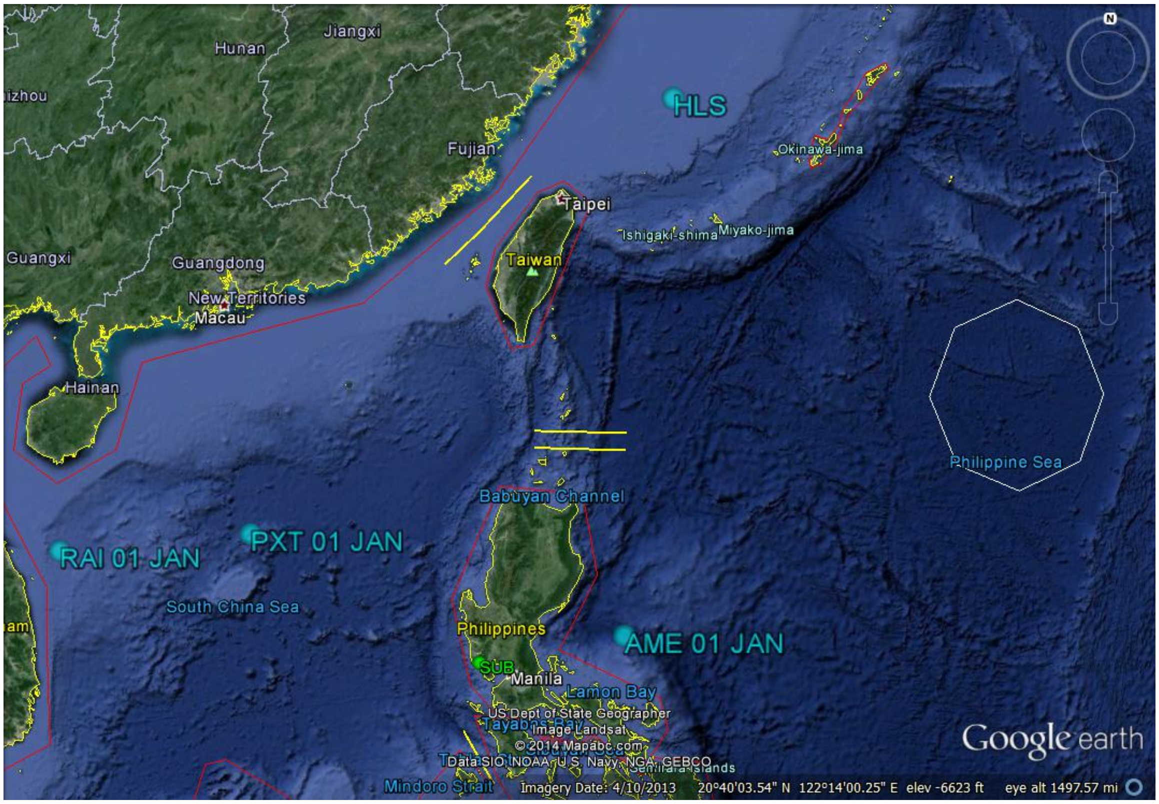

Figure 7. Final routing file and logic file, specifically for the near-shore scenario $d = 1$, $D = 1$, and $T = 0$. The initial ship positions are indicated in blue (from Google Earth, 2013).

IV. RESULTS

Each run of a scenario results in routes around the TC for each of the three CLF ships, shown in Figures 8–14 and 16–22, with tracks for AME shown in pink, PXT in green, and RAI in yellow. The day's starting position for the CLF ships is color coded with the TC position corresponding to that day. If a CLF ship ends up inside the next day's TC, RASP takes the shortest perpendicular path to travel out of the TC and then continues on course.

A. OPEN-OCEAN SCENARIOS

Figure 8 shows the baseline open-ocean scenario with resulting straight line tracks for the open-ocean scenario with no TC represented $(D = 0)$ and no obstacles between HLS and the CLF ships during all days of travel. AME travels 972 nm, PXT 989 nm, and RAI 1,057 nm.

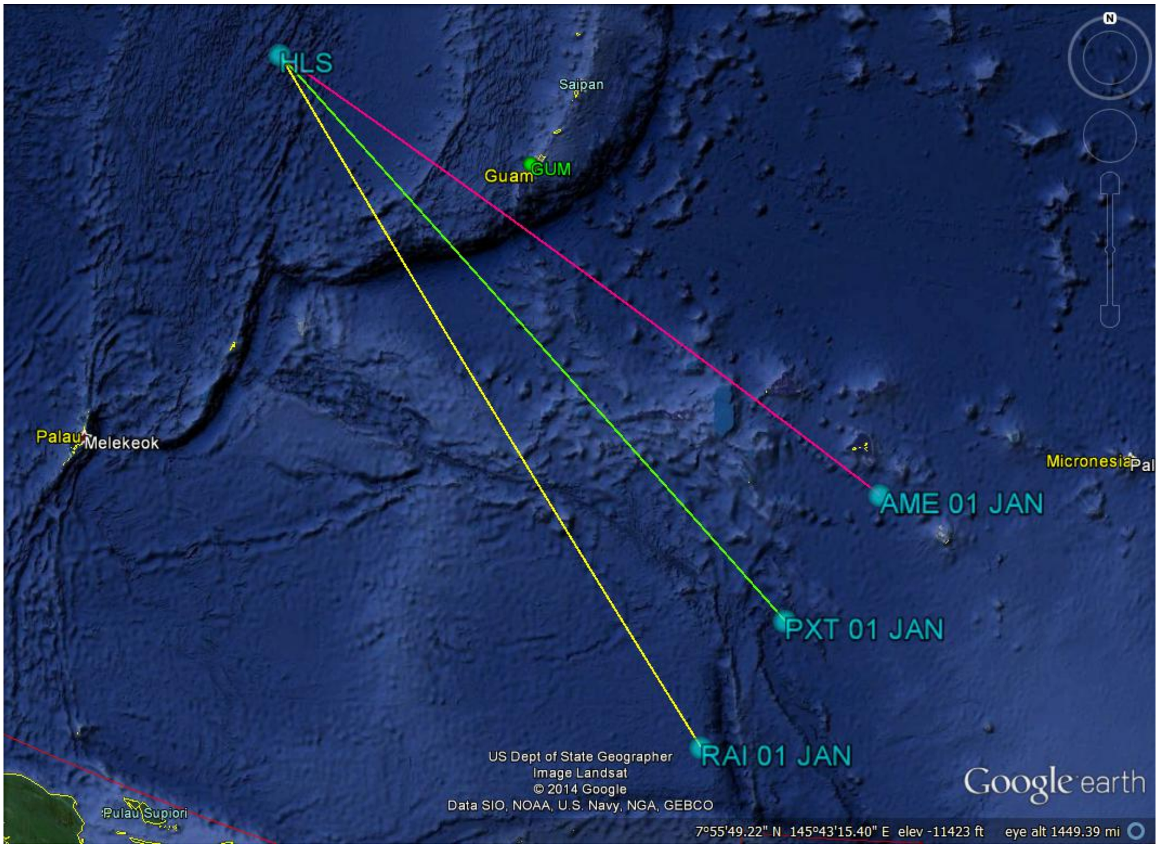

Figure 8. Tracks of the three CLF ships for the baseline of the open-ocean scenario (from Google Earth, 2013).

1. D=1 and T=0

When just the current TC position is represented ($D=1$ and $T=0$), the AME and PXT must make a lot of diversions, and even end up inside a represented TC (see Figure 9). Both ships repeatedly try to cut in front of the TC (whose future positions are not represented in these scenarios). On $d=2$, AME ends at a position that is inside the TC polygon for the following day ($d=3$ is shown in green). After getting out of the TC, AME tries to cut in front of the TC once more only to end up inside the TC again at the start of $d=4$. The total distance traveled by AME is 1,205 nm, which is longer than any other AME open-ocean scenario (see Figure 15). PXT starts on a direct course, but on $d=2$ also tries to cut in front of the TC. By $d=4$, PXT ends up inside the TC polygon as well, and travels a total of 1,235 nm—PXT's longest open-ocean distance (see

Figure 15). RAI is not affected by the TC until $d = 3$. Even though RAI tries to cut in front of the path of the TC, it is far enough away to remain clear. On $d = 4$ RAI routes around the back side of the TC and has a clear path at the start of $d = 5$, traveling a total distance of 1,098 nm.

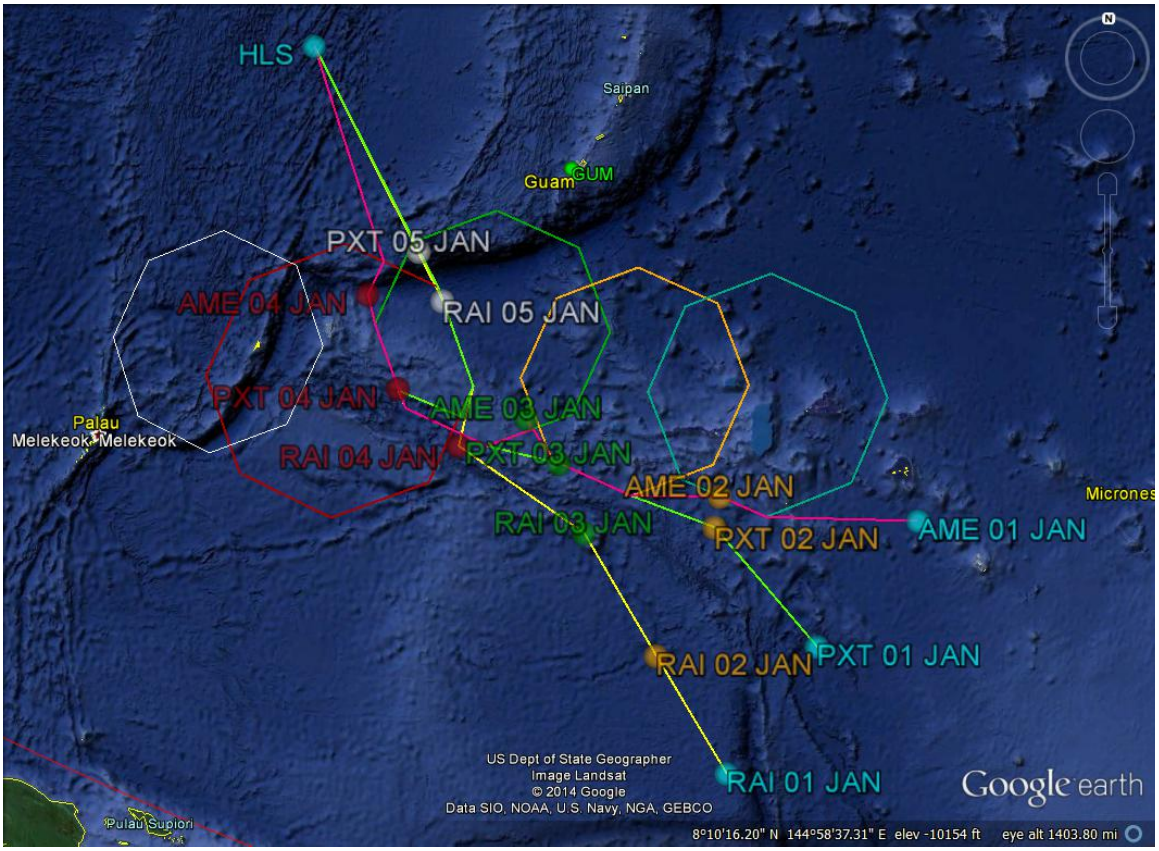

Figure 9. Tracks of the three CLF ships for $D = 1$ and $T = 0$ for the open-ocean scenario, with the represented TC for each day d (from Google Earth, 2013).

2. D=1 and T=4

$D = 1$ and $T = 4$ uses the next day "forecast" of the TC (see Figure 10) as the no-go area. Since the present TC was not represented, all CLF ship positions were visually confirmed to not enter the current-position TC area. On $d = 1$, AME routes around the back of the TC from the start and has a clear path to HLS by the start of $d = 2$, for a total distance traveled of 975 nm. The course of PXT starts by cutting in front of the TC on $d=1$, but then switches to routing behind on $d=2$, traveling a total of 1,010 nm. The course for RAI behaves similarly to PXT, but one day later, traveling a total distance of 1,066 nm.

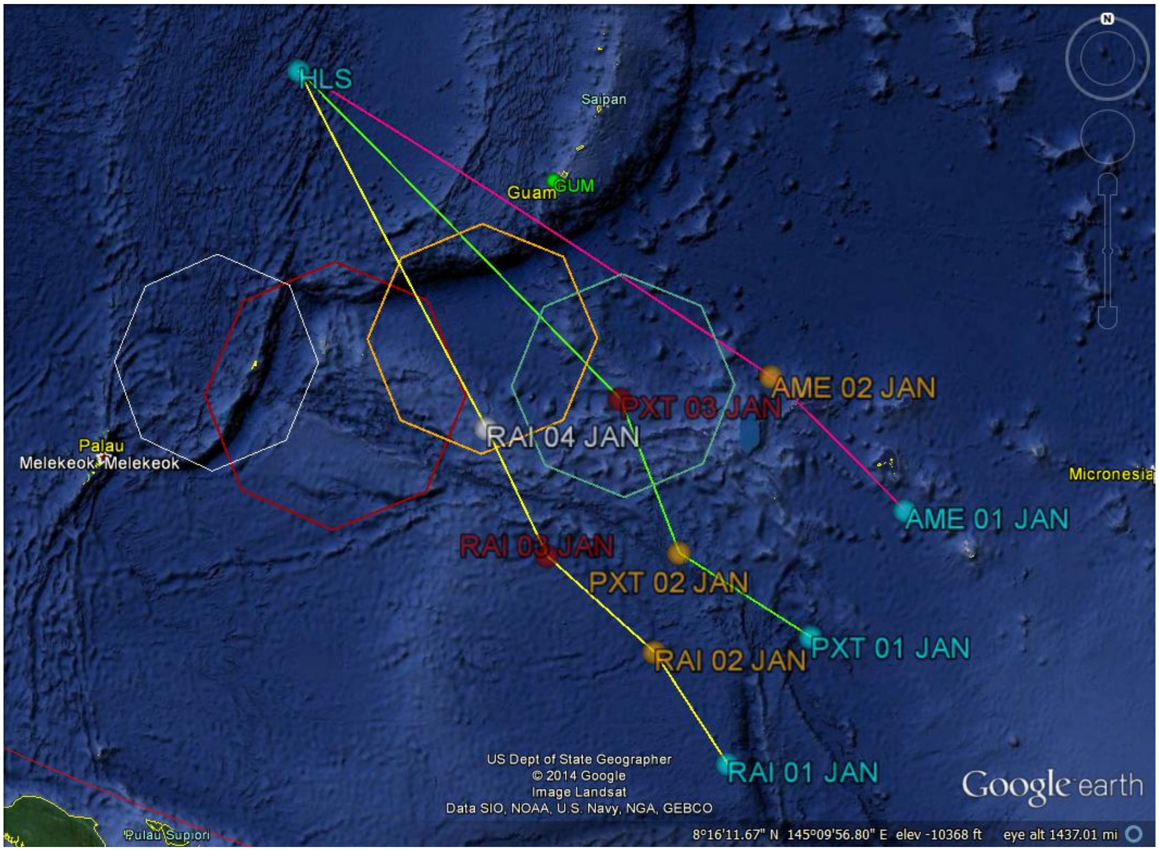

Figure 10. Tracks of the three CLF ships for $D=1$ and $T=4$ for the open-ocean scenario, with the represented TC for each day d (from Google Earth, 2013).

3. D=3 and T=2

For $D=3$ and $T=2$ (see Figure 11) AME routes behind the TC and has a straight path by $d=2$ and travels a distance of 1,000 nm. The courses for both PXT and RAI try to cut in front of the TC for two days and then route behind the TC on $d=3$. PXT, however, comes too close behind the TC and travels where the actual TC was at the time. PXT and RAI are clear of the represented TC on the start of $d=4$ and they travel a total of 1,050 nm and 1,080 nm, respectively.

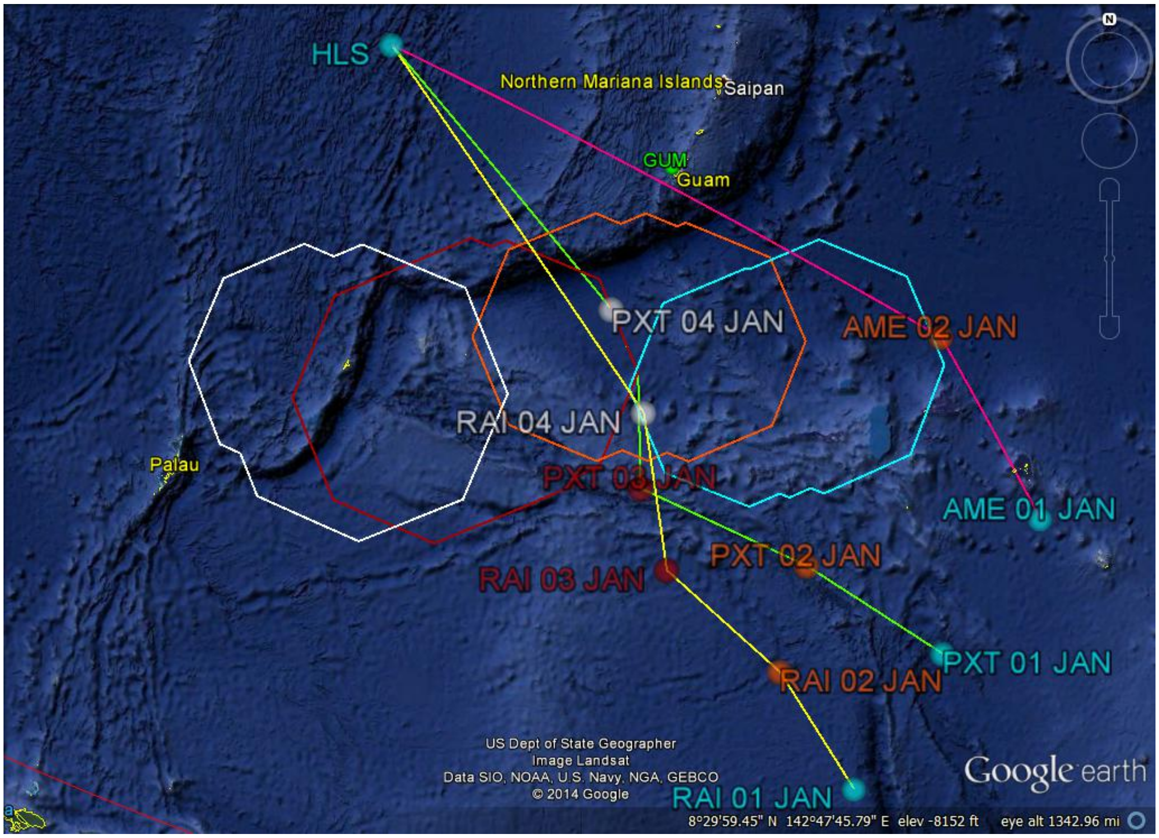

Figure 11. Tracks of the three CLF ships for $D=3$ and $T=2$ for the open-ocean scenario, with the represented TC for each day d (from Google Earth, 2013).

4. D=5 and T=0

Specifying $D=5$ and $T=0$ increases the size of the represented TC, and amplifies the course corrections made for the CLF ships (see Figure 12). On $d=1,$ AME routes behind the TC and is unobstructed to HLS on the start of $d=2,$ traveling a total distance of 1,030 nm. The course for PXT tries to route in front of the TC for two days and on $d=3$ cuts back to go behind the TC. At the start of $d=4,$ PXT has a straight path to HLS and travels a total distance of 1,152 nm. The course of RAI is unaffected on $d=1$, tries to cut in front of the TC on $d=2$, and then routes behind the TC on $d=3$. By $d=4,$ the route for RAI is clear and the total travel distance is 1,131 nm to reach HLS.

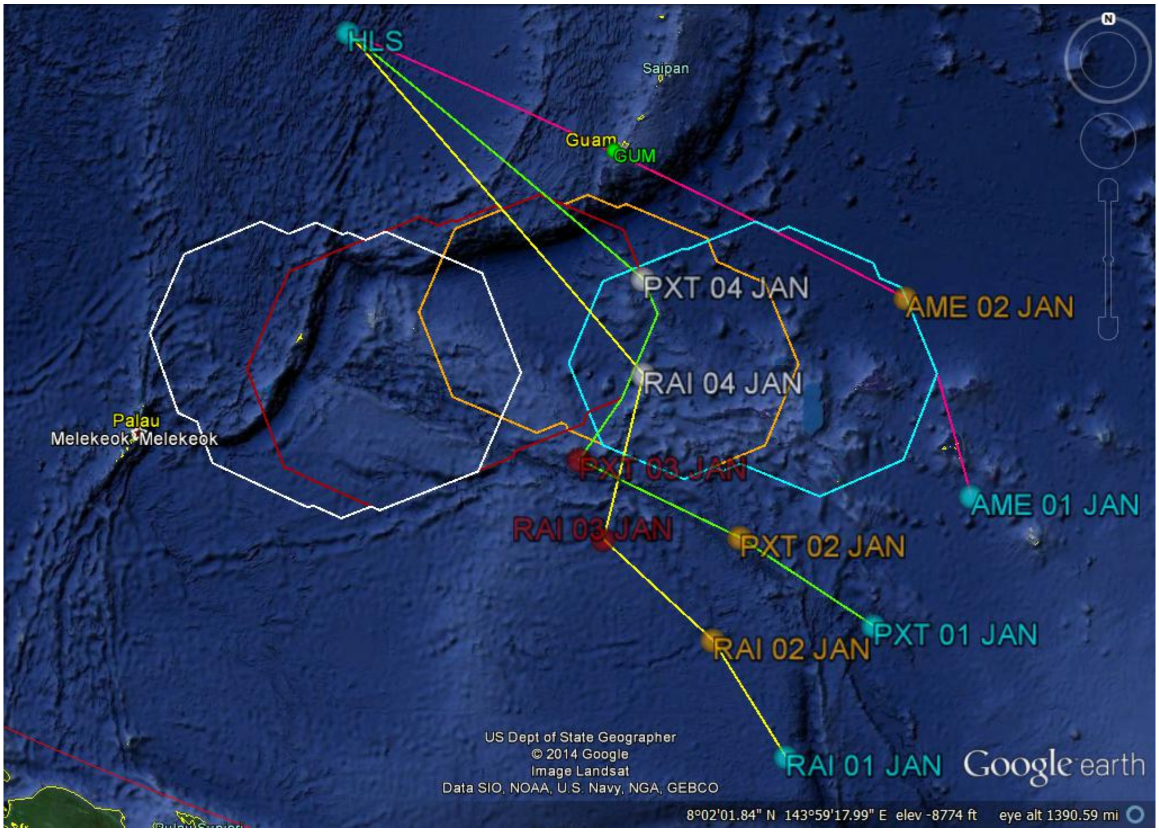

Figure 12. Tracks of the three CLF ships for $D=5$ and $T=0$ for the open-ocean scenario, with the represented TC for each day d (from Google Earth, 2013).

5. D=5 and T=4

Advancing the two-day TC in $D=5$ and $T=4$ (see Figure 13) causes AME to travel the exact same track as advancing the one-day TC (see Figure 10). The course for AME cuts behind the TC and travels a total distance of 975 nm. The route for PXT is behind the TC for $d=1$ and $d=2$. At the start of $d=3$, PXT has a clear path to HLS and travels a total distance of 1,014 nm. RAI, being farther away, first tries to route in front of the TC and then cuts behind the TC on $d=2$. On the start of $d=3$, RAI has an unobstructed path to HLS and the complete route is 1,081 nm.

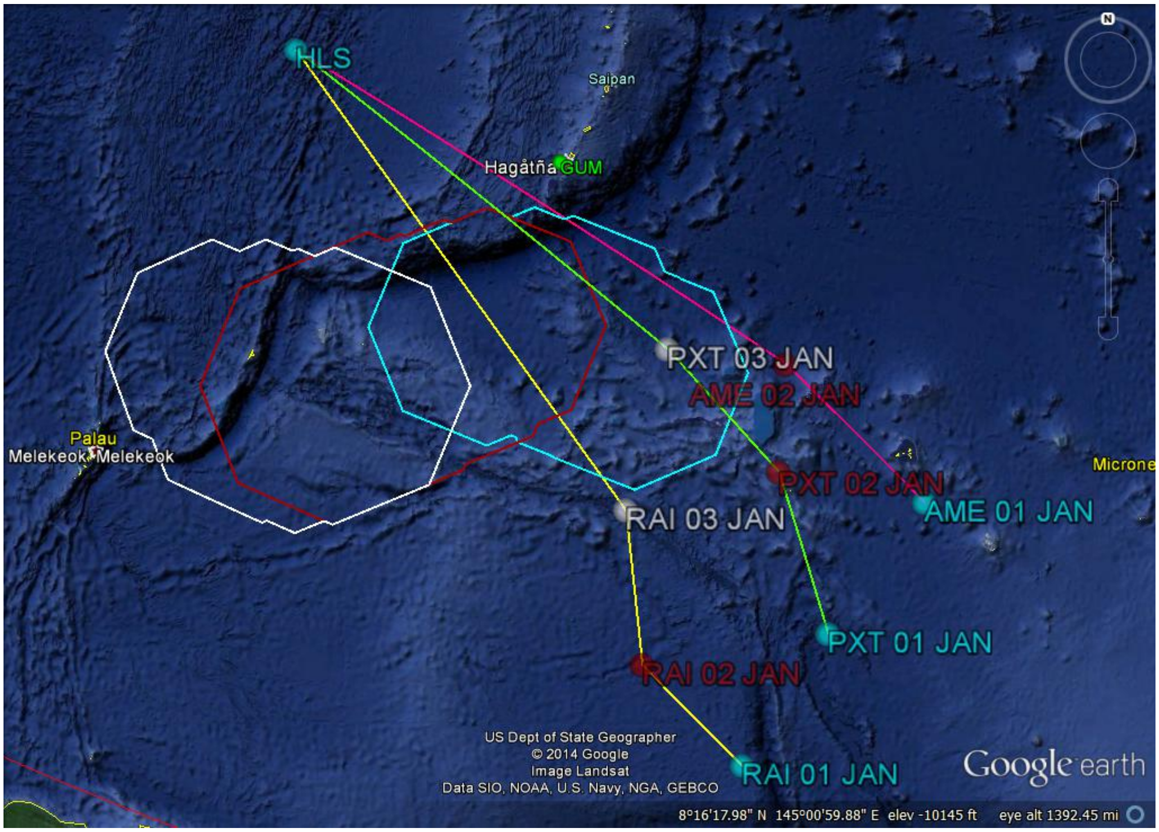

Figure 13. Tracks of the three CLF ships for $D=5$ and $T=4$ for the open-ocean scenario, with the represented TC for each day d (from Google Earth, 2013).

6. D=9 and T=0

$D=9$ and $T=0$ is the largest represented TC in the scenarios, which causes the most deviation in the CLF ships' routing (see Figure 14). AME routes behind the TC, just like in $D=5$ and $T=0$ (see Figure 12), and travels a total of 1,030 nm. On $d=1$, both PXT and RAI route in front of the TC and have to make a large cutback on $d=2$ to go behind the TC. By $d=3$, PXT has a straight path to HLS, while it takes until $d=4$ for RAI to be clear. PXT travel distance is 1,150 nm and RAI travels 1,165 nm. This is the farthest RAI travels in the runs of the open-ocean scenario.

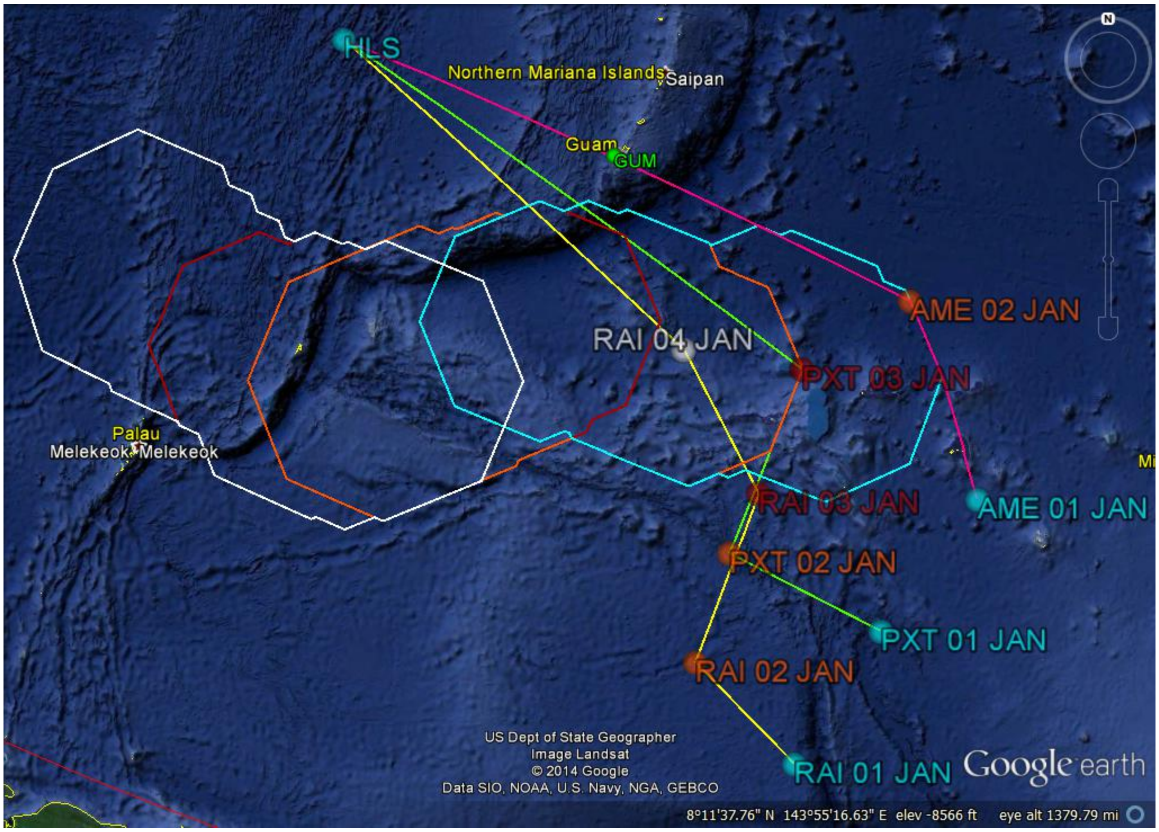

Figure 14. Tracks of the three CLF ships for $D=9$ and $T=0$ for the open-ocean scenario, with the represented TC for each day d (from Google Earth, 2013).

7. Summary of the Travel Distances of the Three CLF Ships

A side-by-side comparison of each run of the open-ocean scenario shows the variation of the distances the CLF ships had to travel (see Figure 15). The peaks for AME and PXT are from the runs $D=1$ and $T=0$. Not only did they travel long distances, but also routed in front of the TC and ended up inside the TC polygon the next day. Besides that spike, there is not a lot of variation in the distance traveled by AME across the different TCs represented. The variation in RAI travel distance seems slight across the different runs as well, with the farthest distance being for the largest TC, $D=9$. Most of the variation is with the total distances for PXT. Even with the spike for $D=1$ and $T=0$, the other runs vary almost 150 nm. With a ship speed of 14 knots, that is over 10 hours of travel time.

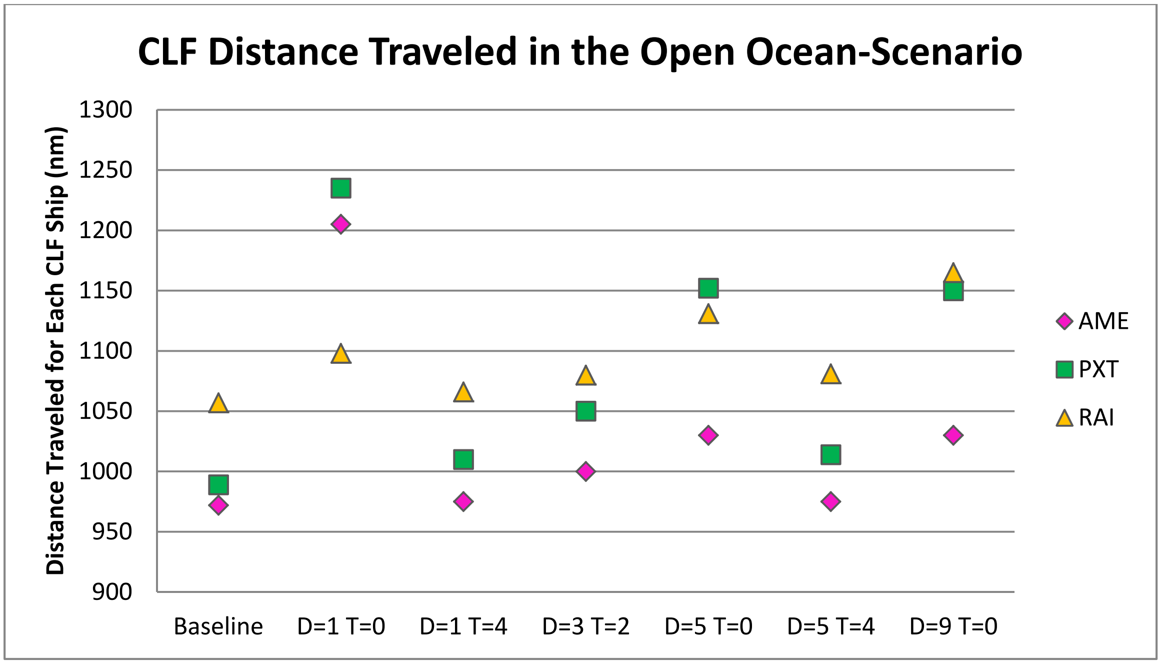

Figure 15. Summary of the distances traveled by each CLF ship over each run of the open-ocean scenario.

Note in Figure 15 that "forecast" TCs ($T > 0$) get the closest values to the baseline and are consistently shorter than the represented TC with the actual TC position included ($T = 0$). For all three CLF ships, the shortest distance traveled occurs in the scenario with $D = 1$ and $T = 4$ (excluding the baseline scenario). Compared to the baseline, AME travels an additional 3 nm, PXT an additional 11 nm, and RAI 9 nm.

B. NEAR-SHORE SCENARIO

For the near-shore scenario, the baseline has no TC represented and Taiwan is the only obstacle between HLS and the CLF ships (see Figure 16). The only CLF ship that is affected by Taiwan is PXT and it is routed around it on the Taiwan Strait side of the island, along with RAI. Figure 16 shows the resulting tracks, with AME traveling 713 nm, PXT 814 nm, and RAI 1,047 nm.

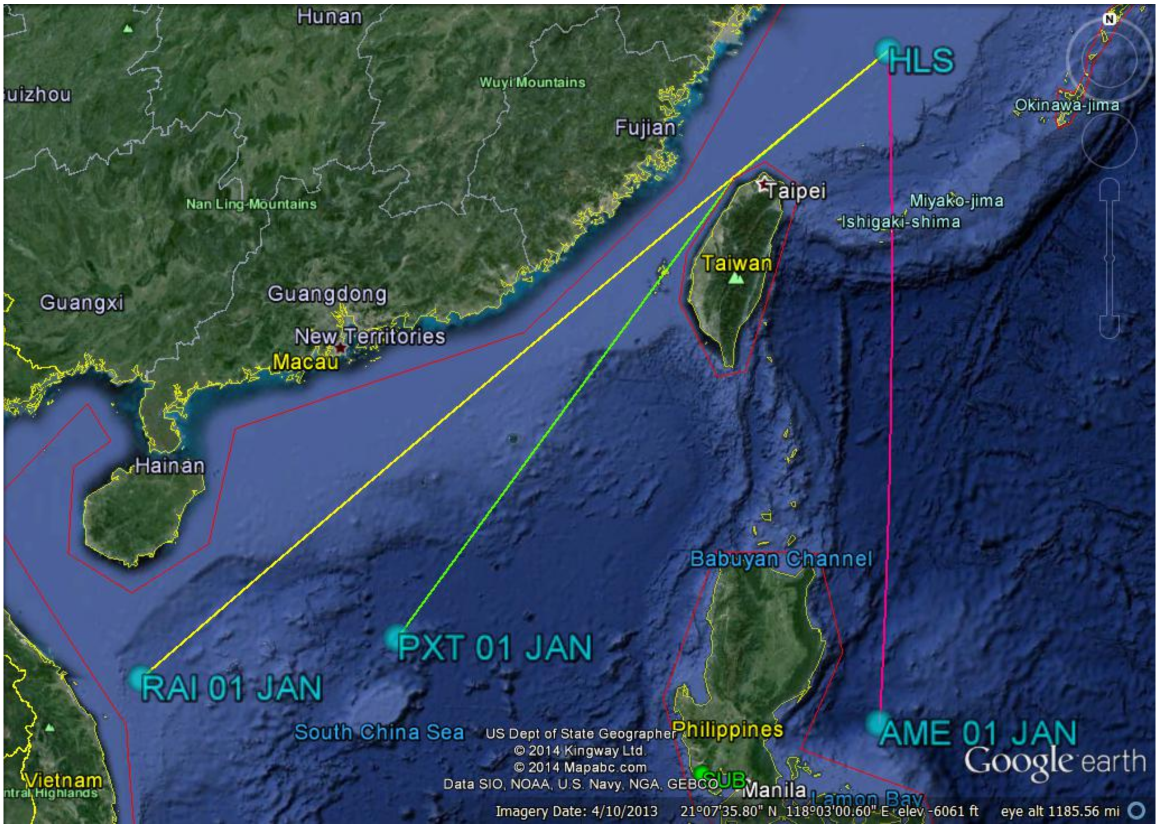

Figure 16. Tracks of the three CLF ships for the baseline of the near-shore scenario (from Google Earth, 2013).

1. D=1 and T=0

With the TC representation $D=1$ and $T=0$, the CLF ships do not interact with the storm until $d=3$ (see Figure 17).The course for AME is straight for HLS and right into the TC's path. On $d=3$, AME starts inside the TC polygon, has to backtrack to get out and then routes around the back side of the TC. By $d=4$, AME is clear of the TC and it travels a total distance of 936 nm. The routes for both PXT and RAI travel straight to HLS until $d=4$, where the TC blocks the Taiwan Strait. The PXT has to backtrack around Taiwan, where RAI just has a course deviation. On $d=5$, the TC is clear and PXT and RAI continue to HLS with only Taiwan as an obstacle. The total distance traveled by PXT is 1,030 nm and for RAI is 1,140 nm.

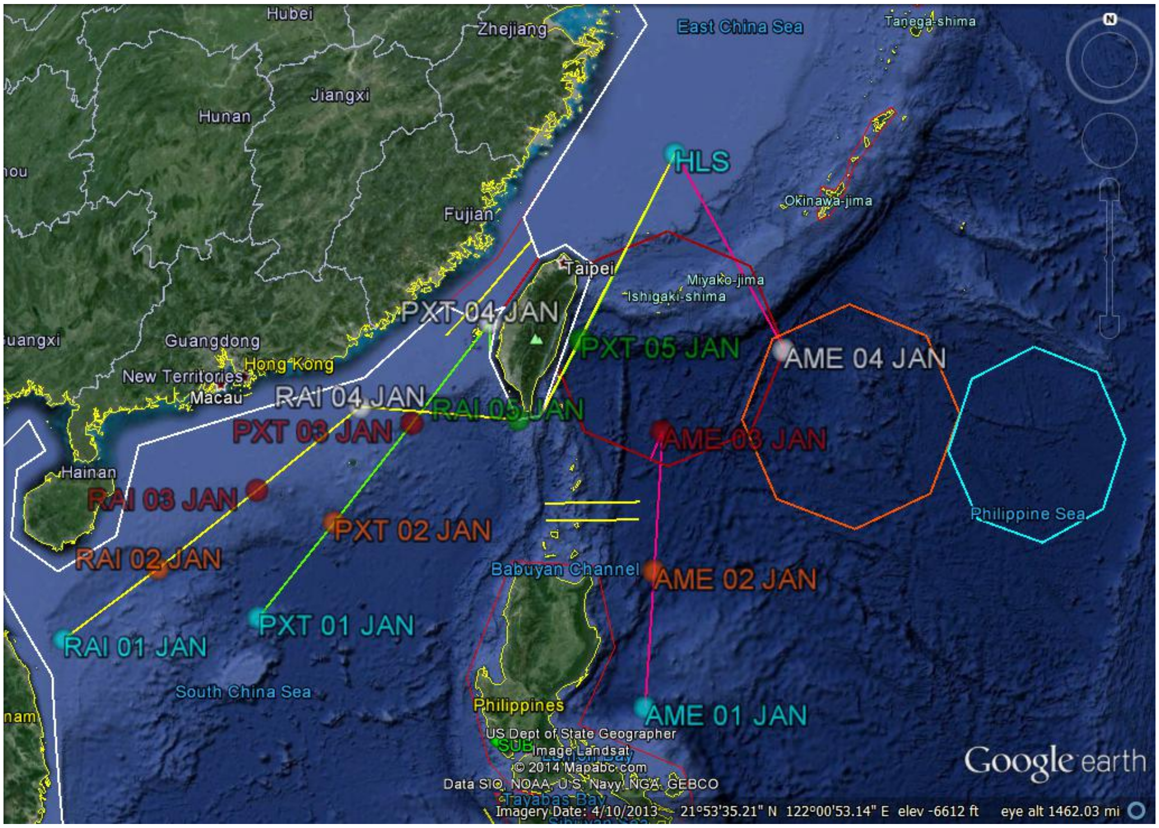

Figure 17. Tracks of the three CLF ships for $D=1$ and $T=0$ for the near-shore scenario, with the represented TC for each day d (from Google Earth, 2013).

2. D=1 and T=4

For the $D=1$ and $T=4$ representation the CLF ship AME is routed behind the TC on $d=2$ (see Figure 18). By doing so, AME routes to close behind the TC representation and ends up where the TC actually is. The TC is clear on $d=3$ and AME Travels straight to HLS for a total of 761 nm. PXT and RAI first interact with the TC on $d=3$, when it blocks the Taiwan Strait. PXT routes around Taiwan and then has a straight path to HLS, traveling a total distance of 870 nm. RAI cuts to go around Taiwan on $d=3$, but then routes back to the other side when the TC moves on $d=4$. The deviation in the route for RAI is only slight compared to the total path and the distance traveled is 1,076.

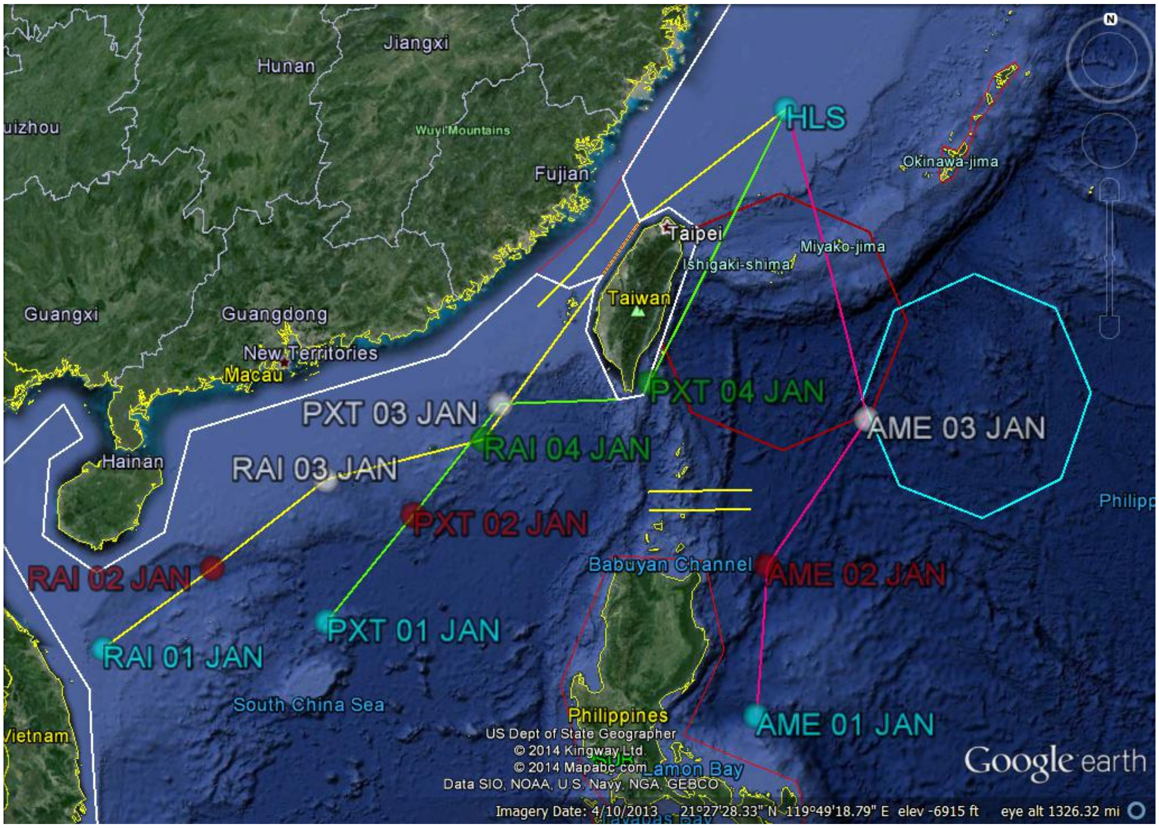

Figure 18. Tracks of the three CLF ships for $D=1$ and $T=4$ for the near-shore scenario, with the represented TC for each day d (from Google Earth, 2013).

3. D=3 and T=2

In $D=3$ and $T=2$ (see Figure 19), the TC overlaps with Taiwan on $d=2$ and AME is routed toward the Taiwan Strait. On $d=3$, the TC blocks the strait and all three CLF ships deviate to route around Taiwan on the other side. AME comes too close behind the TC representation and ends up traveling through where the actual TC is. AME and PXT are clear of the TC on $d=4$ and continue along course to HLS with AME traveling a total of 872 nm and PXT 894 nm. RAI routes back towards the Taiwan Strait, after the TC is clear on $d=4$, and travels a total of 1,084 nm.

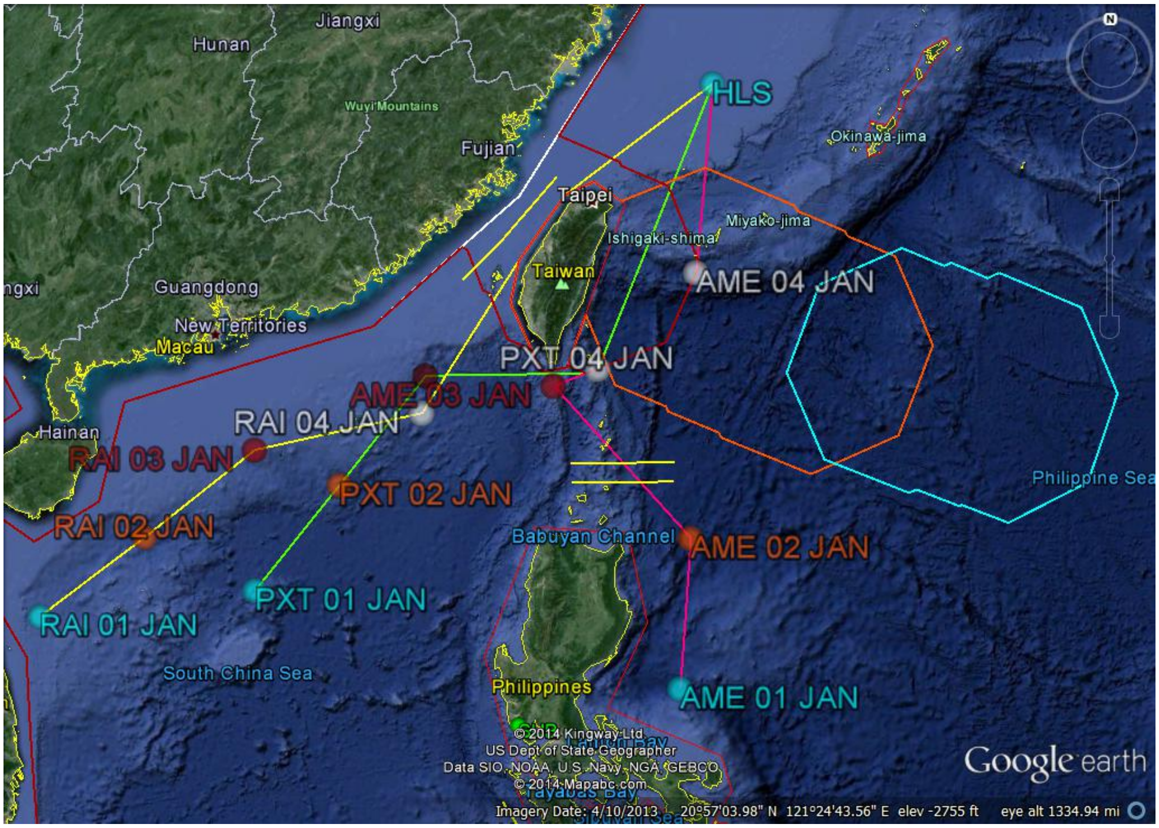

Figure 19. Tracks of the three CLF ships for $D=3$ and $T=2$ for the near-shore scenario, with the represented TC for each day d (from Google Earth, 2013).

4. D=5 and T=0

The two-day representation $D=5$ and $T=0$ leads to routes for all three CLF ships with large course deviations when interacting with land masses (see Figure 20). The route for AME deviates toward the Taiwan Strait on $d=2$ and cuts back to route around the back side of the TC on $d=3$. On $d=4$, AME is clear of the TC and travels unobstructed to HLS for a total distance of 1,096 nm. On $d=3$, the routes of both PXT and RAI make large course deviations to route behind the TC. On $d=4$, the TC has moved to block the Taiwan Strait and PXT and RAI route to HLS, with RAI having to go around the southern tip of Taiwan. PXT travels a total of 1,009 nm and RAI a total of 1,131 nm.

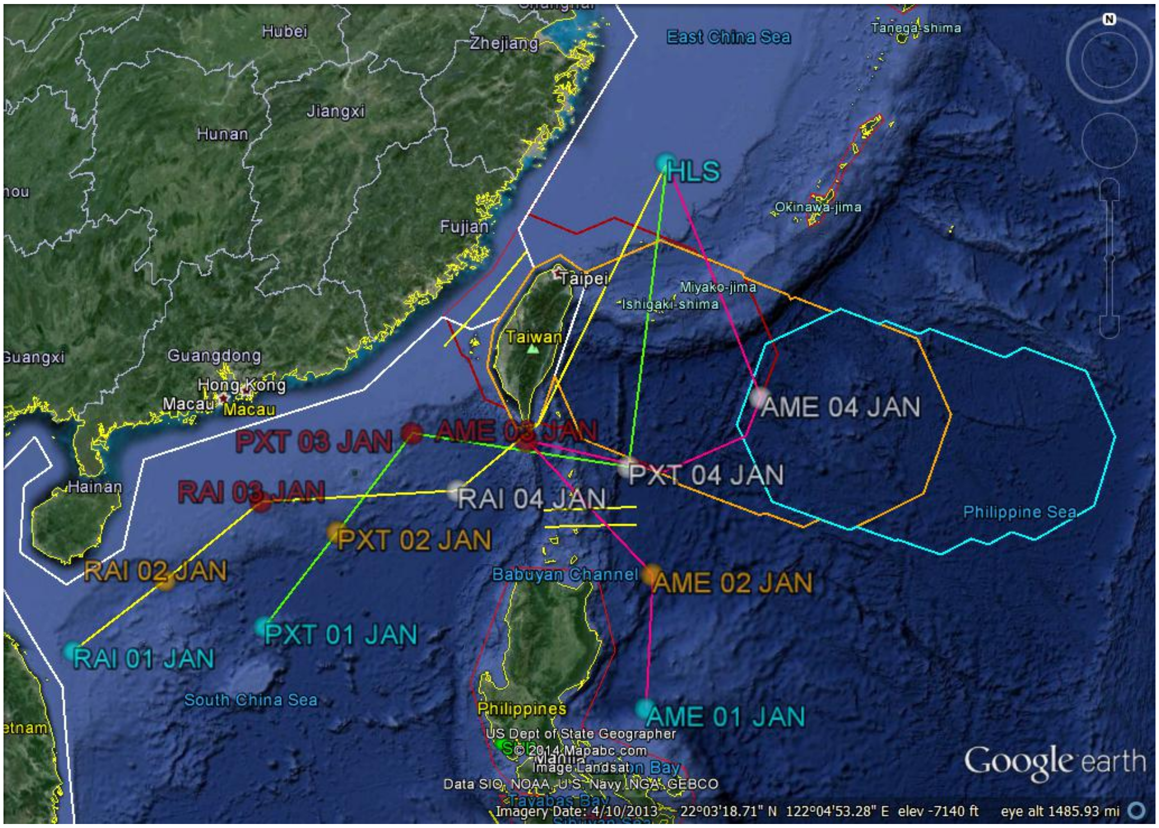

Figure 20. Tracks of the three CLF ships for $D=5$ and $T=0$ for the near-shore scenario, with the represented TC for each day d (from Google Earth, 2013).

5. D=5 and T=4

$D=5$ and $T=4$ leads to the CLF ships interacting earlier with the TC, making the course corrections to be less drastic (see Figure 21). Already on $d=2,$ the TC overlaps with Taiwan and AME routes for the Taiwan Strait, only to cut back behind the TC on $d=3$. By cutting too close behind the "forecast" TC representation, AME travels where the actual TC is. On $d=4,$ AME has a direct route to HLS and then travels a total distance of 821 nm. PXT and RAI route around Taiwan on $d=2,$ when the TC representation blocks the Taiwan Strait and it stays blocked on $d=3$. On $d=4,$ the TC has cleared the Taiwan Strait and PXT and RAI route towards HLS on the far side of Taiwan. PXT travels a total of 884 nm and RAI travels 1,113 nm.

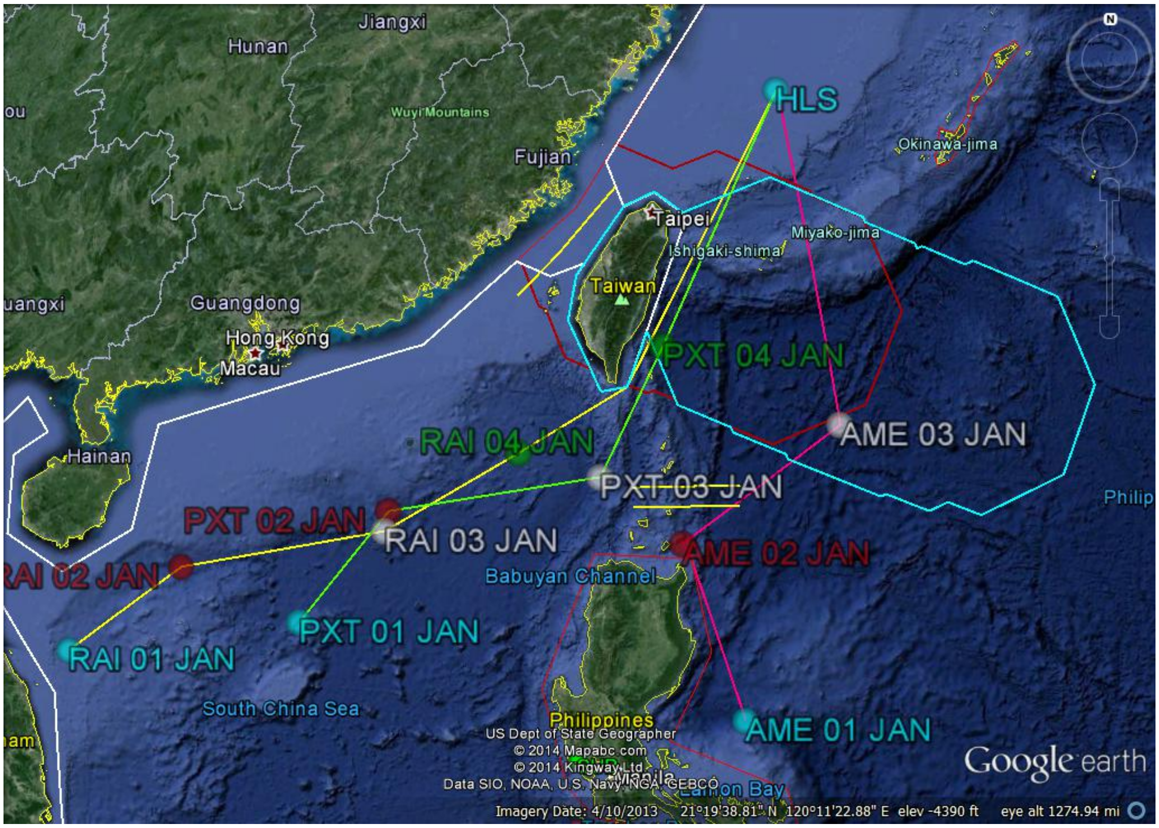

Figure 21. Tracks of the three CLF ships for $D = 5$ and $T = 4$ for the near-shore scenario, with the represented TC for each day d (from Google Earth, 2013).

6. D=9 and T=0

$D = 9$ and $T = 0$ (see Figure 22) is the largest TC representation and causes the longest routing distances than any other D and T combination used in the near-shore scenario (see Figure 23). On $d = 2,$ the TC has blocked off the Taiwan Strait and all three CLF ships over speed to route around the back side of the TC. On $d = 3,$ the TC is closer to shore and the CLF ships slow down, but continue around the back side of the TC. By $d = 4,$ only the Taiwan Strait is blocked and all three ships have a direct route to HLS on the east side of Taiwan. The total distances traveled are 1,290 nm for AME, 1,271 nm for PXT, and 1,391 nm for RAI.

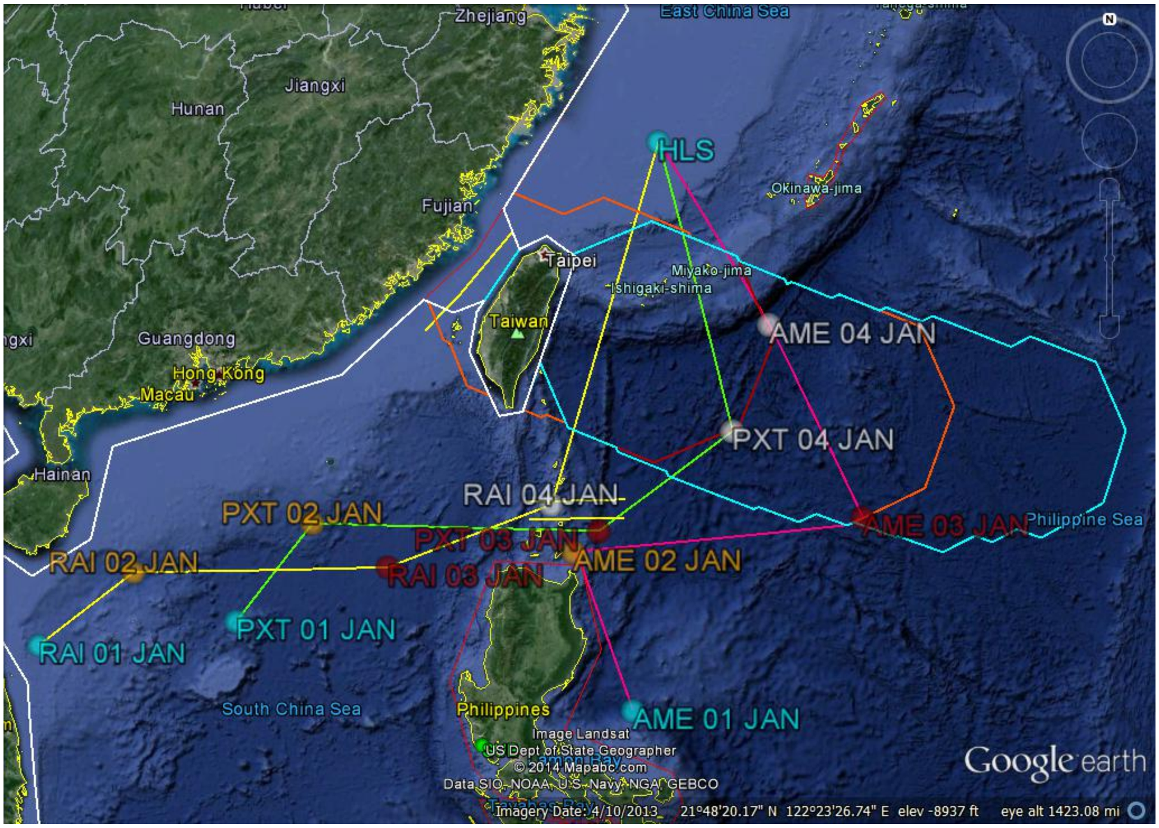

Figure 22. Tracks of the three CLF ships for $D = 9$ and $T = 0$ for the near-shore scenario, with the represented TC for each day d (from Google Earth, 2013).

7. Summary of the Travel Distances for the Three CLF Ships

A side-by-side comparison of the runs of the near-shore scenario shows the variation of the distances that each CLF ship had to travel (see Figure 23). The distances traveled for AME and PXT on the runs $D = 1$ and $T = 0$ are not as far as the open-ocean scenario, but AME routed in front of the TC and ended up inside the TC polygon the next day again. The largest travel distances for the near-shore scenario is $D = 9$ and $T = 0$. The large size of the TC representation cuts off the shore route very early, which requires all three CLF ships to be diverted to the east around the TC and travel much farther than necessary. Besides that spike, there is little variation in the distances traveled by RAI across the different TCs represented. The larger TC representations at $T = 0$ cause AME problems and it routes farther than PXT both times. With the effect of land in this scenario, the variation between runs is much greater than the open ocean. Even disregarding the spike for $D=9$ and $T=0$, the routes for AME still vary almost 400 nm.

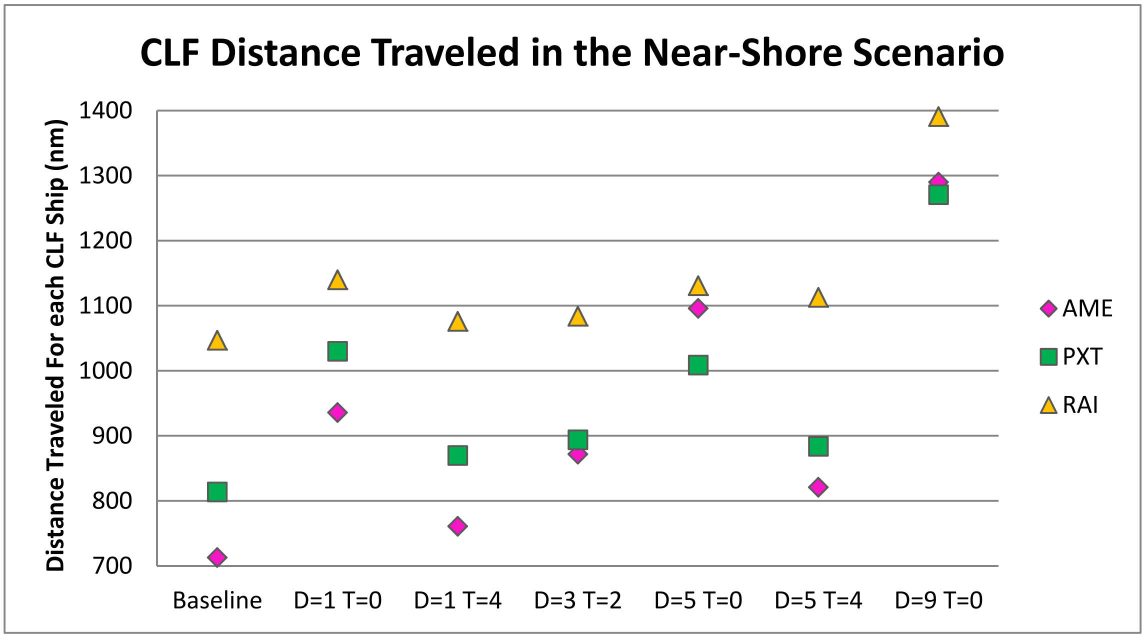

Figure 23. Summary of the distances traveled by each CLF ship over each run of the near-shore scenario.

As in the case of the open ocean, the summary in Figure 23 shows that the “forecast” TCs $(T>0)$ result in the travel distances closest to the baseline and are consistently lower than the represented TC with the actual TC position included $(T=0)$. The shortest distance traveled by all three CLF ships with a TC representation included is again the run $D=1$ and $T=4$. This time, however, the revised routing for AME cut too close behind the representation and AME ended up traveling into the TC’s actual location. The travel distances are not as close to the baseline as in the open-ocean scenario. Compared to the baseline, the routing for AME is an additional 58 nm, for PXT is an additional 56 nm, and for RAI is an additional 29 nm.

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V. CONCLUSIONS

Based on the scenarios described in this work, the clear recommendation is to represent just one TC position, at a 24-hour delay from the run-time of the RASP ($D=1$ and $T=4$), to minimize diversions and total travel distance for CLF ships in RASP schedules. The performance, measured in total travel distance, of routes generated with no TC is only slightly worse than the baseline scenario with no TC.

The scenarios ranged from using a duration of only one position to using TC positions over three days ($D=9$ and $T=0$). The present position representation provides no reference as to the direction of the translation of the TC. This allows ships to route in front of the TC's path and right into the TC. This occurred for both the open ocean and the near shore scenarios. In addition to risking experiencing TC conditions, routing in front of the TC adds to a ship's travel distance as the TC moves in the same direction and continues to block a direct route. On the other hand, the large size of the three-day representation causes ships to travel farther than is required to keep clear. This was particularly noticeable in the near-shore scenarios. Once the TC had overlap with land, the ships have to route behind the TC, avoiding the entire length of the representation. The distances traveled using $D=9$ and $T=0$ were 11% farther than the baseline in the open-ocean scenarios averaged over the three CLF ships. The effect was even more extreme in the near-shore scenarios. Averaged over the three CLF ships, the $D=9$ and $T=0$ scenarios required a 54% increase in distances traveled relative to the baseline. Once the TC had overlapped with land, the ships had to route behind the entire length of the representation.

The forecast representations with $T>0$ require CLF ships to travel shorter distances than routes with representations including the actual TC position, $T=0$. An issue with the forecast representations is that the actual TC position is not an obstacle, so there is nothing to keep a ship from routing into this position. Using $D = 3$ and $T = 2$ still produced this behavior. There is a trade-off between the routing of CLF ships for shorter distances ($T > 0$) and the risk of routing CLF ships into the actual TC position.

The CLF ships' starting distances from the TC track also have a large effect on the variation of the distances traveled. The closer ships, starting one and two days from the TC track, have three times the variance across all runs than ships that start three or more days out. The ships starting with a distance of three days out or greater have time to adjust with small course corrections that reduce the total distance traveled compared to ships starting only one or two days from the TC track.

The starting positions of the CLF ships do provide a variety of interaction with the TC. In the scenarios, ships were routed in front of the TC, behind the TC, had to backtrack around land, and entered the potential TC damage area, both in front of the current TC representation and behind the forecast TC representation.

A. RECOMMENDATIONS

The representation $D = 1$ and $T = 4$ had the lowest total distance traveled by all three CLF ships across both the open-ocean and near-shore scenarios. Accurate 24-hour forecasts are available from JTWC to support the use of these parameters on a daily basis in a scheduling tool. The five-year average forecast mean error from the 2012 JTWC Annual tropical cyclone report on 24-hour forecasts is only 60 nm (JTWC, 2012).

The representation $D = 5$ and $T = 0$ created the lowest risk schedule by routing zero CLF ships into the actual position of the TC. This reduction in risk increased the total distance traveled by all three CLF ships in both the open-ocean and near-shore scenarios by 14% over $D = 1$ and $T = 4$.

B. FUTURE WORK

1. Automating the Scenario Process to Test a Greater Number of D and T Combinations and CLF Ship Starting Positions

Due to the time required to update ship positions manually in Google Earth to create the RASP routing files for days $d > 1$, only 42 scenarios were run. Automating the creation of the routing files from the RASP output schedules would facilitate testing a large sample. Because the best TC representation fell in the middle of the experimental values for T, and it is not possible to represent a TC with $D < 1$, we expect that the recommendation that $D = 1$ and $T = 4$ is the best representation would not change. Before recommending operationalizing this method of including TCs in RASP, however, it would be worthwhile to test fleet schedules with multiple CLF and customer ships while varying D and T. An attempt was made to automate the process and, with more time, this could be done. The biggest challenge in the automating process is pulling the updated CLF ship position at the end of one day out of the RASP schedule in order to put it into the next day's run. In the longer term, if the fleet finds the value of incorporating TCs is high, but that the current approach to representing TCs as land masses is not ideal, it would be worth exploring the possibility of multiple daily runs of RASP with multiple TC representations, and selecting the best (a simulation approach) or developing a stochastic optimization algorithm for RASP.

2. Addition of Actual Forecasts

This thesis used past TC data to create the TC obstacles in RASP. The next step is to use actual forecasts of TCs to create the obstacles. Using actual forecasts adds uncertainty the position of the actual TC. The size of the forecast obstacle varies over the levels of this uncertainty and an important research question is the tradeoff between risk and the size of the TC representation. These forecasts are the only information that the fleet planners will have available to input obstacles in real time, which needs to be the standard for creating TC obstacles.

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