Measuring the impact of natural environment representation on combat simulation outcomes

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ABSTRACT

Weather affects military operations, and simulated military operations should be similarly affected if these simulations are to deliver value to training, mission rehearsal, acquisition and other simulation-enabled communities across the DoD. Immersive simulations must derive human visibility with explicit or implicit assumptions about temperature, dew point and aerosol content in the space between player and target. Simulations of land, sea and air vehicles must make some set of assumptions about trafficability, wave heights, and turbulence or wind shear, even if the assumption is that these conditions are benign. The space environment, ionosphere and sensible weather (e.g., rain showers or thunderstorms) dramatically impact real command, control, communications, and computers (C4), and simulated C4 systems should be similarly, realistically affected. Achieving this level of fidelity in constructive simulations requires an authoritative representation of the natural environment driving a set of validated, calibrated behaviors within these simulations.

In this study, the Army OneSAF simulation system is used to revisit combat operations in the early days of Operation Iraqi Freedom during a severe and extended dust storm event (March 25-27, 2003). With the passage of a long, dry cold front through the region, sand and dust obscured visibility in the lower atmosphere in a wide swath down to the Arabian Gulf. This event limited ground, air and maritime operations and drove commanders in the field to operational and tactical improvisation. Using an authoritative representation of weather in southern Iraq, OneSAF simulation outcomes are examined and these results compared to known combat outcomes and mission limitations. These results provide insight and a starting point for improving model behaviors in OneSAF and other simulation systems.

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> This was the time of the Vietnam War, and the Army colonel and military historian Harry G. Summers, Jr., recounted a story that had circulated in 1969, as the Nixon administration was taking over. All the vast data on North Vietnam, from population and gross national product to number of tanks and size of its armed forces, had been fed into a computer. The computer was then asked, "When will we win?"
>
> The computer needed only a moment to answer: "You won in 1964."
>
> Thomas B. Allen, *Twilight Zone in the Pentagon*: **The Cold War**, 2005

INTRODUCTION

Military modeling and simulation (M&S) enables scientists, engineers, planners and warfighters to operate in a combat environment that is non-destructive, reproducible, and, ideally, realistic. Although the key performance parameters for each of these groups are somewhat different, the realism of the combat environment is a critical component to any meaningful outcome. Within the simulation domain, representing the natural environment—atmosphere, ocean, and terrain—is among the most challenging of tasks.

Numerical simulation of the weather is an active science with a long history; weather forecasting was among the first tasks given to the ENIAC computer in 1950 (Nebeker, 1995). Delivering model weather fields to combat and war-gaming simulations is a challenge, however, because the typical spatial and temporal resolutions for weather prediction (5 km at 1 hour) are often too fine or too coarse for the simulation physics models. The parameters of interest for weather prediction (e.g., temperature, humidity) often require transformation to physics-based environmental effects (e.g., transmissivity in the visible spectrum) to be useful within the simulation, and the computational cost of evaluating these effects at run time can be substantial (Shirkey & O'Brien, 2009). Finally, even if the correct parameters are delivered at the correct resolution, the myriad physical models inside of large simulations may not use these parameters effectively (Pfeiffer et al., 2013a).

The Modeling and Simulation Coordination Office (M&SCO), has guided a multi-year research and development effort to improve simulation outcomes across the Department of Defense with an integrated, authoritative natural environment representation. This effort, the Environmental Data Cube Support System (EDCSS), provides realistic weather and ocean data, and more importantly physics-based effects information, in a variety of simulation-ready formats. Providing a better environmental representation addresses a substantial part of the challenge, though an open question remains: Do DoD simulations effectively employ these representations?

The present work employs EDCSS generated scenarios under another M&SCO initiative, the Environmental Representation Testbed (ERTB), to conduct experiments with the Army OneSAF simulation system to explore how physical models within this simulation use the natural environment. For the experimental scenario, representative vignettes from the March 2003 Iraq dust storm (Anderson, 2004). This case represents both known, extreme weather and known weather impacts to land, sea and air operations in the opening days of the Second Gulf War. It is expected that OneSAF simulations of these vignettes without weather will show more—and unrealistic—success (e.g., sorties flown, targets collected) than simulations using realistic weather. These results offer insight not only to OneSAF but also to the broader family of DoD simulations that could be similarly investigated within the ERTB.

The rest of this paper is organized as follows. EDCSS is first briefly reviewed, and then previous research with DoD simulations and the natural environment are presented. This is followed by a brief overview of the ERTB. The experimental design for the present investigation is outlined, followed by a detailed discussion of results and analysis. The paper concludes with a summary of major findings and a discussion of the way ahead.

BACKGROUND

The Environmental Data Cube Support System (EDCSS)

EDCSS is the culmination of over a decade of DoD modeling and simulation initiatives focused on delivering an integrated natural environment to Defense simulation activities (Brents et al., 2011). The guiding design principle is to reduce or eliminate barriers to integration of the natural environment. The result is that EDCSS in its present form can produce simulation-ready packages of atmosphere, ocean and dynamic terrain information with correlated effects, for the parameters of interest at the temporal and spatial resolutions required by the simulation operator. These data can be delivered as a static package to the host simulation or exercise, or distributed machine-to-machine during simulation execution using the EDCSS Runtime Integration Module (RIM).

These atmosphere and ocean data are derived from long-term archives of global model data, made searchable through EDCSS technologies. Simulation operators and exercise controllers can identify natural environment scenarios that meet training, mission rehearsal or analysis goals, specifying mission-limiting weather by weapon system (e.g., red weather for Predator in southern Iraq) or specific environmental criteria (e.g., three days with temperature > 82°F). Just-in-time numerical modeling is used to downscale the archives (typically at 45 km, 6-hour resolution) to meet simulation operator or training requirements (typically at 5 km, 1-hour resolution). Use of numerical modeling also provides greater flexibility in developing atmospheric and ocean scenarios that both meet simulation goals and remain within the physics of the natural environmental (Holdzkom, 2010).

Prior Experiments with Natural Environment Representations

Using EDCSS environmental scenarios, Pfeiffer et al. (2013b) investigated natural environment representations and behaviors in the Air Force System Effectiveness Analysis Simulation (SEAS) to develop some quantitative insight in to the effect of a realistic natural environment on simulation outcomes and simulation runtime. SEAS is a constructive, agent-based simulation often used for mission rehearsal, studies, and analysis at the tactical and operational levels of engagement (Gonzalez et al., 2001). These experiments demonstrated that increasing the fidelity of the natural environment improved realism at a noticeable increase in runtime. In particular, comparing a no-weather case to the highest resolution representation (cloud cover at 1-degree resolution with hourly updates) improved realism for successful targets collected, falling from 100% to a more realistic 23%, at the cost of about an order of magnitude in runtime over the no-weather case.

The SEAS system offers a domain-specific language with good flexibility (see, for example, Miller & Honabarger, 2006) though the source code is not readily available for inspection. In a subsequent investigation, Pfeiffer et al. (2014) worked with the open-source flight simulator framework OpenEaagles, with access to source code and fully compiled simulation components to investigate the representation and use of the natural environment. OpenEaagles is a community version of the Air Force Extensible Architecture for the Analysis and Generation of Linked Simulations (EAAGLES) system (Hodson et al., 2006). This collection of interoperable C++ components can be tailored and assembled to form simulation entities from general models of sensors, communications and navigation systems, weapons, and other components geared to aerospace systems.

The natural environment representation in OpenEaagles is not integrated across models, so that the sensor models use transmissivity values for electro-optical and infrared (EO/IR) sensors that are uncorrelated with atmospheric thermodynamic data used in the flight dynamics. Further, only the three-dimensional wind field can be specified as a real-time weather input to a running simulation. In Pfeiffer et al. (2014), code modifications were made to the OpenEaagles v13 baseline to permit introduction of realistic atmospheric thermodynamic data from EDCSS for the flight dynamics models. Using this modified baseline, experiments were conducted with a flight model of the Cessna C-310 to assess the impact of realistic air temperature, humidity and wind on simulated flight dynamics. Warmer temperatures should affect both model engine performance and lift, though even an extreme lower atmosphere sampled from Baghdad demonstrated only minimal effect on fuel burn and flight time in these experiments. More dramatic impact was demonstrated in trials with a strong but physically realistic 80-kt head wind, where the simulated flight from Norfolk, VA, to Boston, MA, at flight level 5000 feet, required an additional 62.5% in flight time over the no-weather (no wind) case, with a correlated dangerously high fuel burn rate.

Although both the SEAS and OpenEaagles studies demonstrated impacts by improving the realism of the natural environment representation, the physical models and experimental scenarios were not comprehensive, with quantitative results giving more insight in to the direction rather than magnitude of the relationship—more realism in means more realism out. Useful quantitative results require more rigorous and controlled experimentation with a richer set of physical models and clearer comparisons to physical reality.

Environmental Representation Testbed (ERTB)

The Environmental Representation Testbed (ERTB) offers a venue for rigorous and controlled experimentation with natural environment representations, with the objective of improving the fidelity of simulation behaviors through the demonstrated use of higher resolution data and dynamic effects. The ERTB is an FY14 M&SCO initiative to create and maintain a persistent research and development platform for the objective evaluation of simulation outcomes.

Figure 1 depicts the ERTB concept. The testbed includes a foundation of Common Environmental Representation, spanning physical domains and providing both data and effects. This layer is fed by existing technologies such as EDCSS and OneSAF terrain (Dukstein et al., 2007). Although the focus is on delivering simulation-ready datasets, the Environmental Data Visualization tools provide a means to view this low-level data to support debugging.

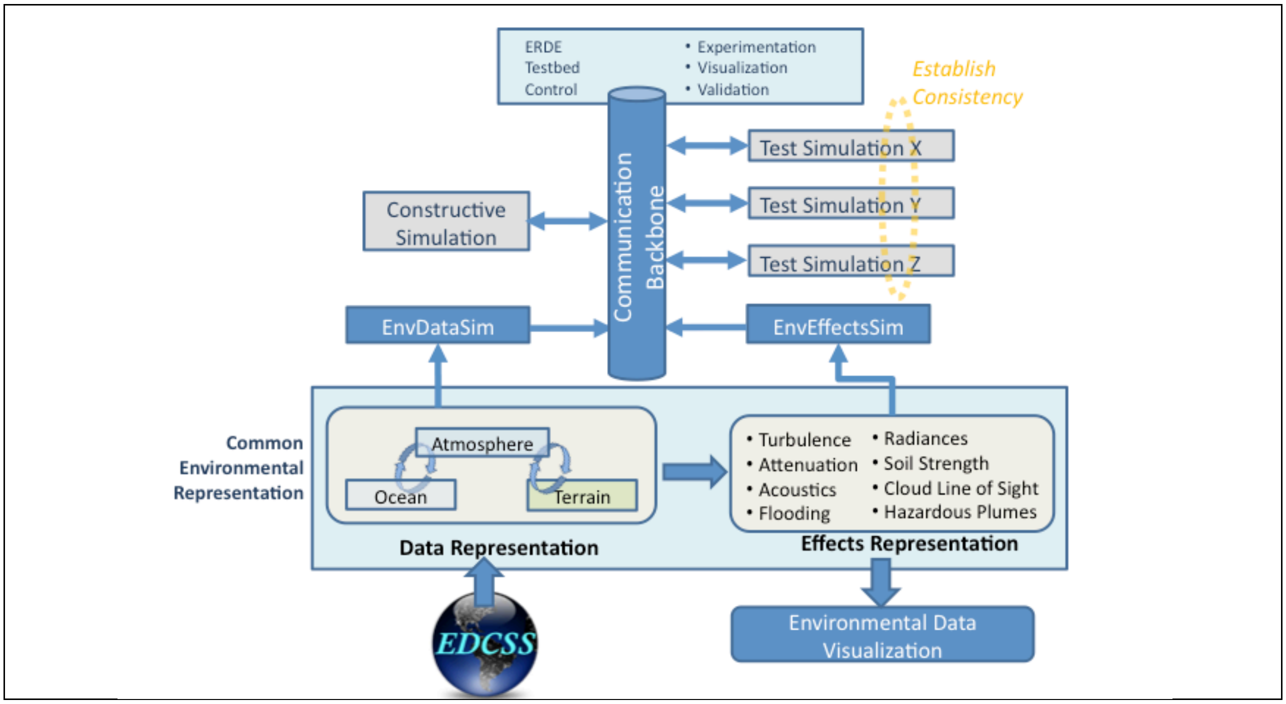

Figure 1. The ERTB Concept

In practice, the testbed comes to life when populated with a constructive (computer generated forces) simulation to provide simulation context, as well as some number of test simulations that provide the basis of a given experiment. The EnvDataSim and EnvEffectsSim components facilitate meaningful environment representation usage by the testbed simulations. The EnvDataSim component helps bridge the resolution gap, if any, between the environment representations provided by EDCSS and the representations required by entity-level simulations (often on the order of meters and seconds). The EnvEffectsSim provides meaningful and efficient access to EDCSS hypercubes, which are pre-computed effects products designed to reduce the computational burden on M&S applications. Hypercubes offer quick access to EO/IR transmissivity, ground mobility and soil strength, target thermal characteristics, and other physical parameters computed from the natural environment; the availability of hypercubes should minimize the need for individual simulations to compute these effects. These testbed components together present environmental data and effects tailored to the needs of component simulations (e.g., AWSIM, OneSAF, JCATS) under experimentation. This architecture enables rigorous, repeatable processes in experimentation, and ensures the external validity of experimental results—findings on the testbed provide immediate insight in to improvements for fielded simulation programs.

EDCSS technologies implemented on the ERTB enable more thorough investigation of the ideas motivated by previous studies (Pfeiffer et al. 2013b, 2014). Next is discussed the experimental design for the present work.

EXPERIMENTAL DESIGN

Controlled experimentation gives insight in to the relationship between independent and dependent variables, and ideally gives quantitative measures not only of the direction of this relationship but also the magnitude. In prior work the authors have shown that the (independent) natural environment representation has some measurable impact on (dependent) simulation outcomes for a limited set of DoD simulations.

In the present study the authors explore a more complex and operationally relevant, constructive simulation, OneSAF, using real weather vignettes from the Second Gulf War, developed using EDCSS technologies and delivered under the ERTB. The intent of these experiments is to develop more insight in to the physics-based models within OneSAF and their application of a given natural environment representation. By employing a more robust weather scenario, simulation outcomes can be more easily compared to known, historic operational limitations and to subject matter expertise regarding platforms and sensors.

This section provides a brief background on OneSAF and its Environmental Runtime Component. The weather scenario to be used for this study is then described. The section concludes with a discussion of the working hypothesis, and dependent and independent variables, and controls.

Simulation Under Study: Army OneSAF

The Army One Semi-Automated Forces (OneSAF) simulation serves research and development, analysis, mission rehearsal and training communities across the Joint forces (Wittman & Courtemanche, 2002). An Environmental Data Model (EDM) specifies the range of terrain, atmosphere, ocean and space (AOS) information that can be used within OneSAF. The Environmental Runtime Component (ERC) connects providers of these data to an executing OneSAF simulation (Dukstein et al., 2007). The term environment in ERC refers to the larger battle space in which simulated action occurs. In addition to the natural environment, the ERC also helps manage those parts of the environment that have been altered as part of simulated action (e.g., detonation craters, chemical weapons clouds) or are part of the human-altered terrain (e.g., ultra-high resolution buildings or UHRBs).

Atmosphere and ocean parameters available to OneSAF through the ERC are well documented (see, for example, Dukstein et al., 2013). Table 1 depicts the two and three-dimensional atmospheric parameters of interest.

Table 1. Surface and vertical natural environment parameters available to OneSAF.

Surface Parameter	Unit
Cloud Ceiling	meters
Cloud Type	enumeration
Fog	fraction
Illumination	millilux
Mean sea-level pressure	millibars
Precipitation Phase	enumeration
Precipitation Rate	mm H_2O
Total Cloud Cover	percentage
Visibility	kilometers

Vertical Parameter	Unit
Pressure	millibars
Relative Humidity	percentage
Temperature	Celsius
Wind U-component	m/s
Wind V-component	m/s

The Environmental Runtime Component and AOS API within the OneSAF Objective System provide a clear path to deliver an integrated atmosphere and ocean representation to the component models. A review of the source code of these models suggests that this path may be used unevenly within OneSAF. Among the source code and components there are circumstances where environmental data are assumed constant or benign, and circumstances where the data are pulled at runtime through the AosApi; resulting inconsistent or uneven behaviors should be identifiable in simulation outcomes. This source code analysis helps motivate our experimental trials to examine the behavior of a full OneSAF simulation with a realistic natural environment stimulating these component models.

EDCSS directly supports OneSAF through the ERC and the EDCSS Runtime Integration Module, and this support will be part of the OneSAF v8 baseline. The experiments in the present study used OneSAF v7 on the ERTB with the v7 code modified to reflect the v8 EDCSS support.

Scenario: Operation IRAQI FREEDOM March 25-27 2003

A late winter shamal in March 2003 drove a deep and persistent dust storm through the opening military operations across Southwest Asia in the Second Gulf War. Hinz (2004) documents the impacts to maritime operations, largely in the realm of naval aviation, while Anderson (2004) discusses impacts to coalition air and ground operations. This case is particularly interesting because the storm was reasonably well forecast by military weather personnel, with enough advance warning to planners at the Combined Air Operations Center (CAOC) such that significant adjustments were made to the air tasking order (ATO) to account for the severe visibility issues (Anderson, 2004).

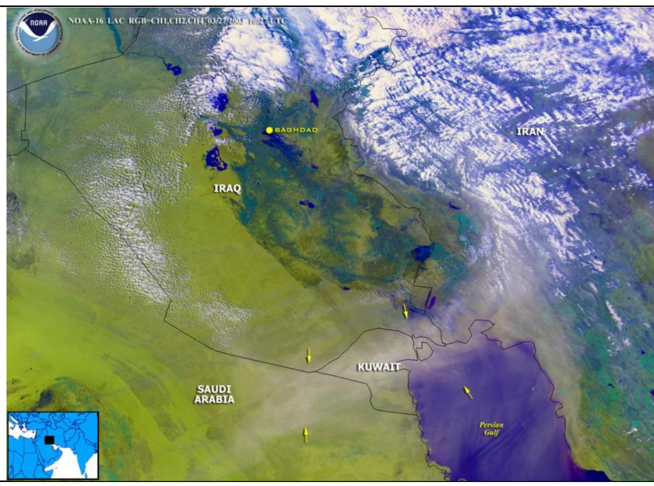

Figure 2. NOAA-16 Satellite image from 1027 UTC 27 Mar 2003 showing the dust plume extending from western Iran through southern Iraq and across Kuwait and northeast Saudi Arabia. Yellow arrows highlight the plume.

These changes to the theater air operations included front-loading airlift missions early in the period to pre-position materiel prior to the onset of the storm. To continue strike and close air support missions during the storm passage, planners shifted away from infrared (IR) and laser-guided weapons to global positioning system (GPS) guided munitions. For ground operations, surface guns were refitted with heat-detecting guns sights to “see” through the dust (Anderson, 2004). Naval aviation was similarly affected with changes in weapons load and schedules to better meet the weather restrictions (Hinz, 2004).

Despite efforts to anticipate and exploit the weather in this situation, there were still interruptions to the coalition effort, and the ground attack on Baghdad was delayed by five days because of these impacts.

Experimental Plan

Documented impacts to air and ground operations make the March 2003 dust storm rich for investigation with the ERTB and with OneSAF. Although there were strong winds and thunderstorms with this event, the primary impact was to visibility and transmissivity, parameters both treated within many of the OneSAF physics-based models.

The working hypothesis for these experiments is that improving the available natural environment representation will produce more realistic simulation outcomes in OneSAF. Specifically, the independent variable is treated as ordinal, describing the quality of the environmental representation. To better quantify the idea of more realistic simulation outcomes, the dependent variables are the measures of success for two mission areas: air support, and ground convoy operations (Table 2). Using operationally realistic vignettes for rotary wing and ground operations, OneSAF was executed in a series of trials to collect data across both levels of the independent variable.

Table 2. Experiment Matrix

Dependent Variables	Independent Variable		
	Level I **Default Weather**	**Level II** **Mar 2003 Weather without dust**	**Level III** **Mar 2003 Weather with dust**
Successful Air Missions	**Ia**	**IIa**	**IIIa**
Convoy Execution Time	**Ib**	**IIb**	**IIIb**

Using the experiment matrix (Table 2) a more precise hypothesis can be specified. The levels of the independent variable (natural environment representation) represent a static (default) weather case (Level I); and two realistic weather representation using simulated weather from Iraq in the period Mar 25-27 2003 (Levels II and III). In Level II, the weather representation included realistic atmospheric parameters but no explicit impact from dust. In Level III, the weather representation included explicit impacts on visibility, temperature and other parameters from the dust in the region. The variables **Ia**, **IIa** and **IIIa** represent numbers from the OneSAF after actions reporting and are quantifiable measures of mission success for the rotary wing vignette. Similarly, **Ib**, **IIb** and **IIIb** represent mission success for the ground vignette. The working hypothesis is that:

Ia > IIa > IIIa

Ib > IIb > IIIb

That is, success rates should decrease with more realistic (visibility restricted) weather. This is consistent with reality and similar to known mission outcomes (Anderson, 2004). The use of two realistic weather scenarios, with Level III (with dust) more realistic than Level II (without dust), offers additional insight in to the incremental impact of the environmental representation.

The OneSAF scenario was created with several air and ground units moving toward the center of Baghdad. One set is moving in from the south and another from the west. In the south, an Armed Cavalry Troop with M2A3 (Bradley fighting vehicle), M1A2 (Abrams tank), and Infantry elements moves along roadways towards Baghdad while a flight of eight AH64D (Apache helicopters) reconnoiters along the route, then provide support during the movement.

Traveling along the roadways from the west is a Platoon of M2A2s with Infantry Fighting Vehicles. Supporting them in the air are four AH64Ds and five UH60L (Blackhawk helicopters). Each mission is designed so that the air support elements will be in close proximity to the ground units to provide air cover as needed.

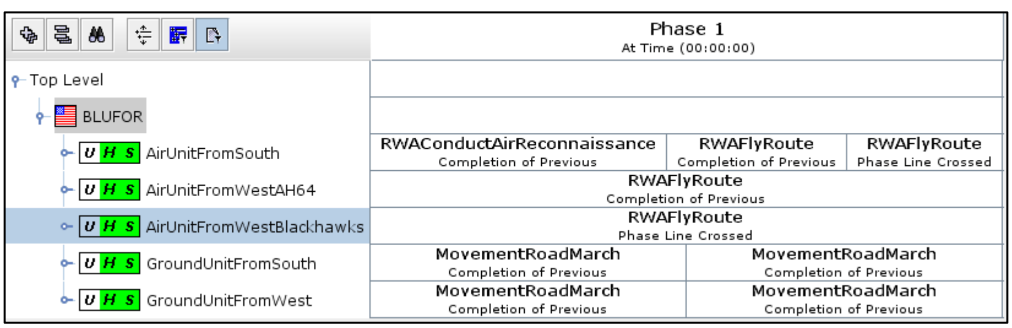

Figure 3. OneSAF Mission Table

Missions for each unit are depicted in Figure 3. Each ground unit executes two Movement Road March missions. Each is divided based on challenging spots in the road network in the Baghdad terrain database. This database is not production quality, and therefore has several un-resolved issues such as the connectivity of the simulated roadway network. The missions kick off as soon as the scenario is executed. Two of the air missions kick off when the ground units are about halfway to their goal in order to provide support coverage along the entire length of the ground route. Next, the quantitative and qualitative outcomes of these experiments are discussed.

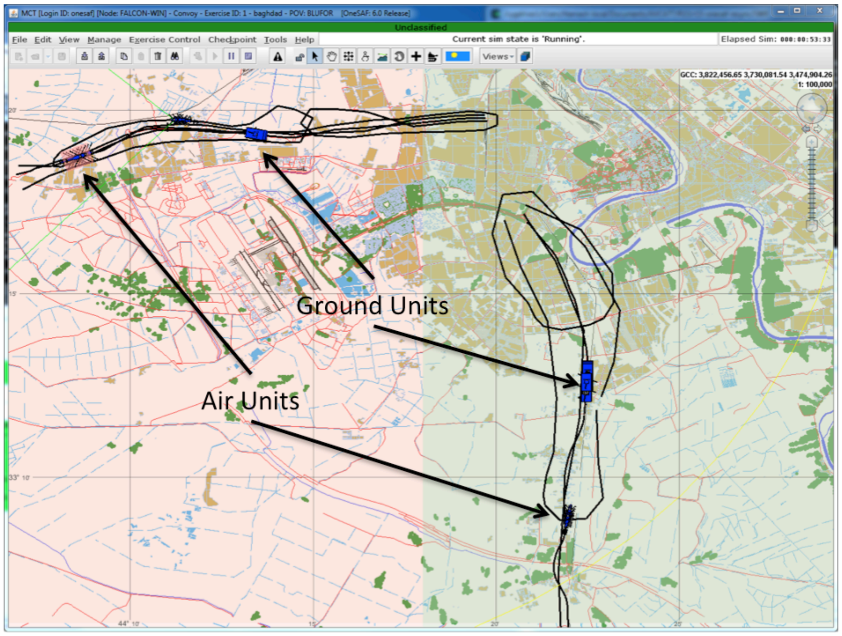

Figure 4. OneSAF Operating Area

RESULTS AND ANALYSIS

The OneSAF scenario was executed for each of the levels of the independent variable (Table 2) using weather data for 27 Mar 2003 in Levels II and III, generated through EDCSS and delivered at runtime on the ERTB. The line-of-sight visibility parameter in the Level III dataset included explicit effects from blowing dust, consistent with the actual weather and weather effects in southern Iraq during this event. The Level I (default weather) case used a static spring scenario consistent with Southwest Asia.

Ordered and actual speed for the convoy and ordered and actual speed and altitude for the helicopters were tracked at 10-minute intervals. The simulation clock time rounded to the nearest 30 seconds was used as an overall measure of success across the levels of the independent variable, with a summary of these times in Table 2.

Table 3. Summary of Experimental Results in Terms of Mission Execution Time.

	Simulation Time (hh:mm:ss)		
	Level I Default Weather	Level II Mar 2003 Weather No Dust	Level III Mar 2003 Weather With Dust
Unit Movements			
Air Unit South Recon	21:30	1:02:00	1:20:00
Air Unit South Fly One	26:00	Never executed	Never executed
Air Unit South Fly Two	52:00	1:35:00	1:57:00
Ground Unit South Movement One	23:30	0:58:00	1:18:00
Ground Unit South Movement Two	42:00	1:25:00	1:48:00
Ground Unit West Movement One	16:00	0:29:00	0:44:00
Ground Unit West Movement Two	56:00	1:21:00	1:45:00
Air Unit West AH64D Movement	29:00	1:36:00	1:56:00
Air Unit West UH60L Movement	38:30	1:34:00	1:55:00

The results in Table 3 support the hypothesis that a more realistic natural environment does affect simulated air and ground movements in OneSAF, with significant increase in execution time for individual movements between the "default weather" (Level I) and "realistic weather" (Level II) runs. A quick analysis of the air and ground movements shows simulated delays on the order of one hour under the more realistic natural environment representation.

Because of the phased nature of the ground and air missions, in the realistic weather cases (Levels II and III) the first air support mission (Air Unit South Fly One) does not execute (Table 3). These Air Units are still engaged in reconnaissance when the Ground Units cross the phase line. This outcome is physically consistent with reduced visibility and operationally realistic based on the historical vignette. This outcome also supports our hypothesis that enhanced environmental realism produces significantly different—and more realistic—outcomes. A screen shot (Figure 5) from one of these OneSAF runs depicts the lag between air and ground units.

Air and ground units to the west show more impact in terms of time lag than movements to the south, consistent as well with the historical scenario. The weather moved in to the area from north and west over the three-day event (27-29 Mar 2003). In the OneSAF scenario, both Air Unit West movements show nearly an hour of delay in execution while waiting for the convoys they supported.

Although not shown, the visibilities reflected in the Level III dataset more closely resemble the military weather observations from the Mar 27-29 2003 period. OneSAF internal models use the horizontal visibility (Table 1) frequently and in the realistic weather datasets (Levels II and III) these restricted visibilities do appear to show operational impact on both ground and air operations. In comparing Levels II and III, air and ground unit delays are noticeably longer under the with-dust representation, typically on the order of 20 minutes. While this is still somewhat different from the observed impacts on the order of several hours (Anderson, 2004), the additional realism in Level III does bring us closer to the operational outcomes.

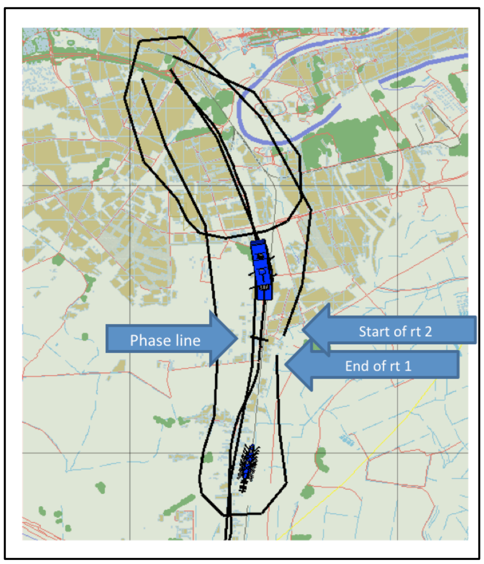

Figure 5. In this screen shot from a Level II run (weather with no dust), the ground unit crosses the phase line to kick off the air unit's final Fly Route order.

CONCLUSIONS AND FUTURE WORK

Using the Environment Representation Testbed and a realistic weather scenario from the Second Gulf War, this research demonstrated significant and operationally relevant differences in simulation outcome for ground and air operations. Improved realism of the horizontal visibility based on weather and aerosol content triggered these differences and improved the realism of simulated mission outcomes. Quantitative measures in mission execution time give some sense of both the direction and magnitude of this relationship.

For this effort, the differences observed between levels of the independent variable give confidence that the natural environment representation is being applied within OneSAF with some fidelity. Further investigation is required to understand the detailed level of fidelity, and if this fidelity is similarly applied across all parameters in the OneSAF inventory (Table 1). Although the horizontal visibility appears to restrict operations in the simulation and in the historical vignette, further study of other parameters of interest aligned to other known operational outcomes could help better validate and calibrate these behaviors.

In this effort the authors have used OneSAF as the simulation platform because of its current integration within the ERTB, though future studies will examine other simulations with a similar experimental approach. In particular, the Joint Semi-Automated Forces (JSAF) simulation will be examined in future work in a Horn of Africa scenario, and compared in performance and outcomes to a weather-identical scenario in OneSAF. Future studies may also examine the Army Warfighters' Simulation (WARSIM) and Air Force Air Warfare Simulation (AWSIM), as well as simulations with more comprehensive out-the-window (OTW) rendering of the natural environment. Every DoD M&S platform has some sense of the natural environment, and the focus of research on the ERTB is to investigate, understand and—where needed—improve this representation, ultimately improving the fidelity and value of M&S to the analyst, planner and warfighter.

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