Virtual Natural Environments for the 21st Century

David Whitney, Dana Z. Sherer, Robert Reynolds, Peter Dailey, Chuck Medler*

*35 Argilla Road
Andover, MA 01810
dawhitney@earthlink.net

TASC
55 Walkers Brook Drive
Reading, MA 01867
dzsherer@tasc.com

ABSTRACT. *Technology to provide realistic virtual natural environments (atmosphere, ocean, and space) for distributed simulations is a relatively recent development that will have a wide-ranging impact on the next generation of constructive, manned trainer, and analysis simulations. Significant recent research has laid the groundwork for expanding growth in this area and the introduction of these new levels of environmental realism in operational simulations. This paper describes a vision of how these emerging technologies will form a unified framework for creating, managing, modifying, and distributing environmental data and effects. Technologies to enable this vision will be discussed, including: desktop numerical weather prediction models for user-controlled weather scenario pre-exercise generation; interactive run-time modification of the environmental state to support exercise control; production of exercise meteorological and oceanographic chart products that reflect imperfect forecasting or data acquisition capabilities; and architectural options for enabling environmental effects computations to meet different simulation requirements. The state of the art in these areas, as well ongoing research that will lead to twenty-first-century system implementations, is presented.*

BIOGRAPHY OF DAVID WHITNEY. Mr. Whitney, currently working as a consultant to TASC, was recently a Senior Principal Researcher at TASC and director of Environmental Modeling and Simulation Programs. He served as Principal Investigator for several DARPA-sponsored R&D efforts, including the development of the TAOS (Total Atmosphere Ocean Space) environmental services system for STOW, and the ASTT-MRA program that is researching environmental representation and modeling issues in the context of interacting simulations operating at differing model resolution levels. He was project lead for the enhancement of TAOS with space-regime data and its integration with the PSM (Portable Space Model) simulation for USSPACECOM. He has been involved in the development of atmosphere-ocean representations for SEDRIS, and with the development of architectural options for the integration of TAOS with the JSIMS infrastructure. He has conceived and directed several internal R&D projects in the area of distributed environmental simulation, and developed and taught a course in distributed simulation technology. He is a Senior Member of IEEE, has served on the SISO Paper Review Panel for the Synthetic Natural Environment Forum, and has published more than 25 technical papers, most of them in the area of advanced distributed simulation.

1. INTRODUCTION

1.1 New Realism for Virtual Environments

Natural environments are those physical states, features, and effects that make up the ocean, atmosphere, and space regimes of earth and near-space. Ocean currents, intervisibility due to haze and particulates, and total electron count are examples of such environmental elements. The definition can be broadened to include man-made or cultural elements that become part of these environments, such as smoke plumes that mix with the ambient atmosphere. *Virtual Natural Environments (VNE)* are the representation of these natural elements in modeling and simulation systems. These representations can be constructed using current live data, representative historical data, or forecast data. The representations used must strike a balance between the scientific fidelity/realism of the virtual natural environment, what is needed by the particular simulation models to meet their operational goals, and the computational (network bandwidth and local processing loads) constraints.

A critical objective of the next generation of simulation systems is the integration of these natural environment (atmosphere-ocean-space) data and effects across heterogeneous simulations to provide new levels of realism, consistency, and interoperability. A goal of ADS (Advanced Distributed Simulation) is to develop and implement portable technologies enabling the integration into a common synthetic battlespace of war-fighting through virtual and constructive simulation models, ranging from individual combatants to Joint Task Force Levels, operating in geographically distributed locations and on heterogeneous computing platforms. These interoperability requirements demand that simulation entities operate in consistent natural environments that ensure equivalent behaviors of simulations. This requirement has led to the development of several breakthrough technologies for VNEs, and provided the impetus for several areas of ongoing research that will lead to the next generation of VNE simulation systems.

2. STATE OF THE ART 1998

2.1 Introducing "Dirty" Environments

Until fairly recently, most mainstream simulation systems for training and analysis used little information about the natural environment (with the exception of sophisticated terrain data) and its effects on operations and employed very simple VNE representations. Simulations generally operated with "blue skies and flat oceans", with justifiable emphasis on first developing models for simulation objects, sensors, and behaviors. That has changed today, and can have a significant impact on simulations and exercises (Ref. 1).

2.2 Constructive Simulations

A major advancement in the representations of natural environments was achieved by DARPA's Synthetic Theatre of War Program (STOW) and the STOW-97 exercise for USACOM (United States Atlantic Command), a sponsor of the STOW Advanced Concept Technology Demonstration. A new environmental services system, Total Atmosphere Ocean Space (TAOS), was developed and successfully implemented the VNE database construction process and real-time network VNE data management, control, and distribution to simulations. High resolution, 3-D gridded, temporally and spatially varying environmental data was provided for the first time to a large-scale network of constructive simulations. Examples of atmosphere-ocean-littoral zone parameters provided during the STOW ACTD include: wind vectors; temperature; precipitation; cloud type, base, and top; fog; wave spectra; tide levels; and currents. TAOS supported HLA/RTI (High-Level Architecture / Run-time Infrastructure) protocols, and provided consistent VNE data during the exercise to over 300 networked simulation workstations (Ref. 2).

The ModSAF computer-generated forces system served as the basis for the constructive simulations in STOW, and was enhanced to use the TAOS data to model a greatly expanded set of environmental effects, such as optical and infrared intervisibility as a function of haze and precipitation, clouds, smoke plumes that respond to wind, and sun/moon illumination that is impacted by clouds and precipitation. Ocean and land mobility due to the VNE (trafficability due to precipitation and wave-induced ship motions) were also modeled. Authoritative models, such as CSSM (Cloud Scene Simulation System), COMBIC and LOWTRAN were adapted for real-time use. The VNE data was also used to drive a stealth "magic carpet" viewer with consistent environmental data.

Earlier constructive simulations that employ environmental data (*e.g.,* THUNDER) generally have used spatially-uniform VNE data that does not vary over time, or representations that provide a coarse quantization of the environment (*e.g.,* a small set of discrete cloud levels).

2.3 Manned Simulators

In the early 1980's, uniform horizontal weather profiles and a small set of temperature-dependent vertical profiles based on standard atmosphere models was typically used in USAF flight simulators. Today the VNE capabilities have evolved to allow spatially *varying* horizontal weather profiles and vertical profiles, providing pressure, temperature, wind, turbulence, and humidity, and sea state derived from wind data. Atmospheric attenuation in electro-optical and infrared bands could be provided by LOWTRAN. Data is still largely time-invariant. Visualization systems generally represent a small number of cloud layers, and ground fog and snow can be visualized. These simulators have not been generally part of a distributed network.

3. A Vision for VNE

The following synopsis provides a vision of how VNEs might be used in twenty-first-century warfighter training.

Word has come down that the next joint training simulation exercise will take place in the Persian Gulf (PG) region and begin next month, November 2002. It will start with NEO (Noncombatant Evacuation Operations) operations in two major cities, followed by a combined land-air-sea operation including an amphibious assault by an MEF (Marine Expeditionary Force). The JTF (Joint Task Force) commander wants to train against moderately harsh weather conditions in a winter timeline. The exercise will involve both command-level training that uses constructive simulations, as well as two squadron's of A-10s and F-18s manned simulators that will be linked in from the DMT (Distributed Mission Training) network. The constructive simulations will model the amphibious and air assaults at the individual entity level, and employ aggregate land-warfare models that represent tank platoons and company units.

The METOC (Meteorology Oceanography)officer sits down in front of his central VNE MetStation, where he will exercise the process diagrammed in Figure 1.

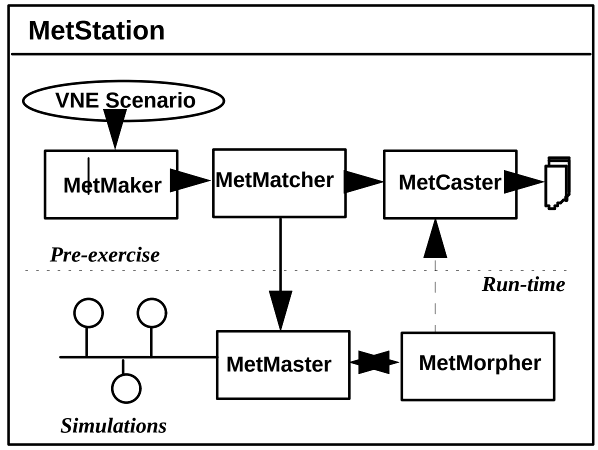

Figure 1: Conceptual VNE MetStation Functions

He calls up his web browser and reviews the climatological data summaries for the PG region in winter that are available from DoD data archives in SEDRIS (Synthetic Environment Data Representation and Interchange Specification) format. He identifies a set of wind, precipitation, cloud cover, cloud type, visibility conditions, sea state, and space weather conditions, such as scintillation, that reflect "25^{th} percentile historical weather". He reviews the order of battle, feeding both the list of platforms and sensors and the environmental conditions into his platform-effects-database analysis applet. The applet provides him a list of the platforms and sensors that will be in the exercise and the impacts that the environmental conditions would have on each platform and sensor.

He next reviews a time-chart of the planned warfighting scenario and the summary of the detailed exercise objectives, to assess the constraints that put on the environmental scenario. He notes that the NEO operation is planned for completion one day after STARTEX (Start of Exercise), and weather is not to be a factor in that training segment. Air operations preceding the amphibious landing are to have only limited ability to use the latest set of smart weapons – the commander wants the trainees to have a "refresher" in the use of more conventional munitions. The METOC officer notes that humidity and high clouds impact the weapon system performance. The amphibious operations are a key part of the training exercise, so sea-state must be kept to less than three to prevent a weather-abort of the landing. The commander wants to train with degraded GPS availability during the latter half of the assault, and the METOC officer notes that increased scintillation levels could be used to disrupt satellite downlinks.

The METOC officer makes some annotations on the exercise scenario time charts that reflect the set of environmental constraints to include in his VNE. This constraint information is automatically linked to the input files for MetMaker, his desktop numerical environmental modeling system — he will run a mesoscale numerical model for the atmospheric components. MetMaker has already linked to the appropriate terrain files for the PG exercise region and historical climatological data grids for initialization. MetMaker runs a set of iterative calculations that produce a set of high-resolution, volumetric gridded numerical model environmental data that matches the scenario constraints the METOC officer has defined.

Since he will need to provide a consistent environmental representation for simulations operating at different resolutions (constructive entity-level and unit-level, as well as manned simulators), he calls up his MetMatcher module. This links to the metadata for his models contained in his MSRR (Modeling and Simulation Resource Repository) and identifies the individual model resolution and representation requirements. MetMatcher performs a set of transformations of the high-resolution data that convert it to the required multiple-resolution representations. MetMatcher flags those cases where the knowledge base indicates there may be less than complete consistency in model behaviors due to differences in the METOC representations. The METOC officer could now use MetMatcher to run some Monte-Carlo simulations on a "mini-federation" of the models in question to study the issue further, but he reviews the degrees of degraded consistency between models and determines they are acceptable for the range of METOC conditions in this exercise. He then clicks the "create databases" button and generates the appropriate set of pre-exercise METOC databases.

One more pre-exercise data generation step: he needs to generate the set of electronic weather charts that will be distributed to the trainees each day during the exercise for their planning, used for ATO (Air Tasking Order) development, and other mission specific purposes. These METOC (Meteorology and Oceanography) charts are also used during the exercise to brief the commanders. He calls up the MetCaster module, which generates standard-format operational weather charts from the gridded numerical data MetMaker has generated and sends them to his internal exercise web site where they are made available to the METOC staff officers, exercise controllers and planners. He notes that his scenario calls for space-weather conditions that will degrade satellite communications during the latter part of the exercise. He employs the "adjust skill" controls in MetCaster, and MetCaster degrades the weather satellite images at the appropriate times to account for those data dropouts that will occur and so produces degraded, but realistic, operational forecast data.

A week has passed and the exercise is underway. The MetMaster module is controlling the run-time distribution of environmental data across the HLA network for all the simulations and the local, distributed execution of environmental effects models. He monitors 3-D interactive images of the environmental data being distributed, and tweaks the network data distribution controls when the environmental loading rate on the network briefly peaks over its allocated share of bandwidth. During the exercise, a message comes down from the white controllers that at the rate the exercise is unfolding, blue tank forces are moving too rapidly and will not get the chance to engage red forces, as called for by the training plan — what could METOC do to alter the tempo of the exercise? He proposes a three-hour localized sandstorm, which he can blend in over the next six hours. That is approved, and the METOC officer calls up the MetMorpher module, which allows him to make specific localized changes to the surface wind field to produce a sandstorm. He gradually cranks up the wind to provide a natural transition to the storm, and modifies the near-field vertical wind field as well for consistency. He transfers the new data to MetMaster, re-runs some new forecast charts with MetCaster, and sits back to watch the rest of the exercise unfold. . .

4. Enabling Technologies

While the vision presented above for the VNE of the future may seem far from the capabilities of tools widely available to the M&S (Modeling & Simulation) community today, realization of the vision is closer than one might at first think. Many of the key core technologies needed to implement the vision are now being developed in a variety of R&D programs, and selected technology components are already migrating to operational M&S systems, such as JSIMS (Joint Simulation System) and the Portable Space Model (PSM).

4.1 Archived Data Access

DMSO (Defense Modeling & Simulation Office) has been sponsoring a significant effort to develop the MEL (Master Environmental Library), a central clearinghouse for authoritative environmental data. MEL provides web access to a large set of DoD environmental model data, through user searches of archives or subscriptions to current and future data sets. MEL is a "virtual" library — it does not actually maintain the data sources, but accesses the data on demand from a set of regional sites, *e.g.*, FNMOC (Fleet Numerical Meteorology and Oceanography Center), AFWA (Air Force Weather Agency), or NGDC (National Geophysical Data Center). MEL provides data format translation services as well, delivering the data to users in standardized formats, such as GRIB (Gridded Binary) or BUFR (Binary Un-Formatted Records). The MEL homepage is located at mel.dmso.mil.

4.2 Integrating and Distributing Environmental Data

The TAOS system was a major product of the STOW program. TAOS provides consistent, tactically-significant, high-fidelity environmental data on demand to distributed simulation federations. TAOS environmental data service provides a consistent, detailed, dynamic description of the combined atmosphere-ocean-littoral-space natural environment, using 4-D grids (three spatial dimensions plus time – see Figure 2) to provide a common representation of the environmental base fields and embedded features. Base fields describe the ambient conditions, such as a temperature or wind field, while embedded features are fine-scale localized processes, such as clouds or dust storms. TAOS provides links to a wide variety of external data sources, ranging from authoritative gridded forecast products provided by DMSO's MEL, to live observations from operational sources (*e.g.,* AWN, Automated Weather Network, and commercial weather radar feeds) or public Internet sites.

Data scenarios can be predistributed or the latest data sets can be accessed in real-time during a simulation exercise. Data from different sources can be integrated and distributed to simulation clients in a variety of user-selected formats, using DIS (Distributed Interactive Simulation) or HLA/RTI protocols. New protocols for packaging and distributing large gridded data objects, *e.g.,* a Gridded Data PDU (Ref 1.), have been developed and implemented in TAOS to meet some of the unique requirements for delivering high-fidelity environmental data.

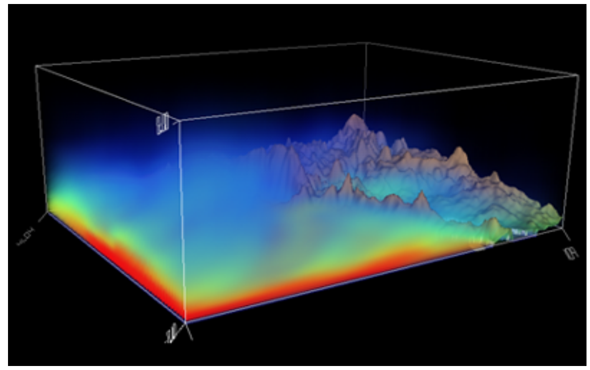

Figure 2: 3-D Time-Varying High-Resolution VNE

The TAOS model integration and local services (client) framework has evolved under the sponsorship of USAF and USSPACECOM to more fully support environmental feature and effects models that can be accessed via a query-response API (Application Programmers Interface). For example, a simulation model might pass a target/sensor location pair and wavelength of interest to TAOS via the API. TAOS then collects environmental data (*e.g.,* humidity) from its database and runs an internal propagation model, such as MODTRAN, and returns to the simulation via the API a value for atmospheric transmission loss along the specified path. Such models are being implemented in support of environmental upgrades to the Portable Space Model satellite navigation and warning functions. The TAOS technology has been adopted to provide the VNE for programs such as JSIMS and PSM, and is under evaluation by several other programs and applications, such as JWARS (Joint Warfighting Analysis System), for technology transition

4.3 Consistent Multiresolution VNE Representations

Historically, most interoperating simulations have been working at the same model level (*e.g.,* both entity-level representations of individual tanks or both unit-level (company) representations. Previous analysis of multiresolution VNE issues has focussed primarily on impacts of differences in terrain resolution on outputs of a single simulation (Refs. 7, 8). Federations of the future are expected to include interacting simulation models that will have fundamentally different representations of simulation objects. For example, a simulation with the "smallest" unit being a tank company will need to interoperate with another simulation that models individual tanks only. In addition, the VNEs of the future now extend beyond terrain alone, and include the whole atmosphere-ocean-space volume, a new set of regimes, which have not been evaluated before in the multiresolution context.

DARPA's ASTT (Advanced Simulation Technology Thrust) program is addressing several research questions related to multiresolution VNE representations and use. ASTT-MRA (Multiresolution Analysis) is looking at the VNE representations for federations of the near future and asking fundamental questions relating to: what should be measured; where in the archetypal simulation model should such measurements be made; what mathematical/statistical measures of consistency should be applied; how the significance of differences be determined. Through a combination of analysis of abstracted models and Monte Carlo simulation, ASTT-MRA will look at the combined influences of the VNE elements (*e.g.,* terrain and atmosphere effects on intervisibility) for different VNE representations, and for different simulation models which may use the same VNE data in different ways (Ref. 3). Analysis of a multiresolution land-warfare scenario experiment using combined atmosphere-terrain data and influences is currently underway.

4.4 Building Specific VNEs on the Desktop

Once exposed to the use of high-fidelity VNEs in their simulations, most VNE users become very interested in specifying what the details of the VNE scenario should be. The use of archived data sources can serve many needs, but it is limited by what is available to the exercise planner — he can only use weather that actually occurred sometime in the past. Programs such as MEL's Weather Scenario Generator (WSG), sponsored by DMSO's Modeling & Simulation Executive Agents (MSEAs) for Air & Space, are developing efficient search mechanisms for matching a specified set of environmental constraints to historical data, yet the fundamental limitations of available historical data remain.

Recent advances in desktop computing hardware are opening up a new option for exercise planners – creation, on-demand, of environmental scenarios at their desktop. Numerical weather prediction models that once required supercomputers can now be effectively run on mid-range workstations. The ratio of wall clock time needed to generate a time history of gridded environmental data to the number of hours of data has now reached levels that make on-demand model runs practical. For example the MM5 mesoscale numerical weather prediction model of NCAR (National Center for Atmospheric Research) is such a model.

Once the hurdle of computational feasibility is passed, the next step is automating the process of running the environmental models to support their use by non-experts. These models are complex, and have elaborate input data preparation that is often specified in a text file in "card deck" format, reminiscent of the mainframe and supercomputers they once ran on. Examples of key considerations for configuring such models to run in an automated mode are:

- Choice of domain (land boundaries, surface terrain elevation, land-use categories)
- Initialization of the model for stability
- Consistent and appropriate control parameter settings (derivation of parameters from grid, time step, and resolution settings, *e.g.,* choice of map projection).

Significant knowledge of environmental science and the numerical models must be embedded in such a system. However, the fact that such models are run several times daily in "production mode" in support of operational users (*e.g.,* at FNMOC) indicate that the processes for running and validating such models have already been extensively studied and codified.

The next key step in building user-specified VNEs on the desktop is to be able to drive the model outputs to meet a set of specified constraints. For example, "low clouds on day one followed by heavy rain on day three". One of the more effective and sophisticated modern techniques for this is the use of an adjoint model for a numerical model defined by a set of differential equations. The adjoint can be thought of as a (linearized) numerical model running "in reverse". It allows the set of initial conditions which will produce a specified end condition be (approximately) determined. Through the combination of this method and others, the numerical model can be driven to meet a set of desired constraint conditions, while preserving the basic internal physical consistency of the model.

TASC has undertaken an internal R&D project that is demonstrating these approaches to building specific VNEs on the desktop. The MetMaker system under development uses the established MM5 model from NCAR (National Center for Atmospheric Research) as the core numerical model. GUIs that streamline the model setup and control procedure are being developed, automation of the model setup and control is being developed, and adjoint methods for providing VNEs that meet specific constraints are being evaluated (Ref. 4). j

It is anticipated that a prototype of the MetMaker system will be demonstrated at I/ITSEC98.

4.5 Run-time VNE Modification

MetMaker technology can build a specific VNE scenario that matches known constraints that exist pre-exercise. However, the exercise control group may, during the evolution of an exercise, decide to modify or steer the course of action through user changes in the natural environment. Such changes cannot be anticipated before the exercise starts, and require run-time editing of the environmental scenario.

Basic Modification Technology — The TAOS system gives the user the capability to perform run-time editing or modification of any of the data in its database. It supplies a range of temporal and spatial data editors controlled through GUIs:

- Gridded (3-D) Variable Editor
- Uniform Weather Variable Editor
- Uniform Sea (NetSea) Variable Editor
- Time Playback Control.

The first three spatial editors allow the user to modify the value of any variable in the TAOS database in order to change environmental events, or introduce new ones. These editors are completely manual — the user is responsible for assuring realism and consistency of any changes made. For example, an increase in surface wind speed over water made with the Gridded Variable Editor should be matched by a corresponding increase in wave height made using the NetSea Variable Editor. The Time Playback Control gives the user the ability to play back an environmental scenario at faster or slower than its historical time, to move forward or backward in the data set, or to jump to a specific, tagged environmental event of interest.

Developing Modification Technology — As part of the DARPA ASTT program, a more sophisticated set of tools for run-time data modification are being developed under the ASTT-JETS program. The JETS (JSIMS Environmental Tailoring System) program is developing a collection of tools for insertion and physically consistent blending of specified environmental conditions into a pre-existing gridded data set (Ref. 5). Spatial and temporal smoothing and time evolution of phenomenon are being evaluated, along with measures to characterize the validity of the (necessarily) approximate resulting modified data set. A range of tailoring solutions will be developed to support real-time modification of a VNE. Simpler techniques include merging and blending existing scenarios while maintaining some measure of physical consistency. More complex methods involve the use of NWP (Numerical Weather Prediction) models for tailoring, including wave-based alteration techniques.

4.6 Realistic Operational METOC Charts

Now that the technology for delivering numerical VNE data directly to simulations exists, the data that will be sent "over the wire" to simulations must be consistent with the charts that exercise participants and controllers are accustomed to looking at for exercise planning and execution. The TAOS Chart Assistant provides a capability to deliver such charts in electronic format (TIFF, GIF, or PS) and hardcopy.

The Chart Assistant products match exactly the "ground truth" environmental conditions that make up the VNE supplied to simulations. However, in the operational world, forecast data and charts are seldom that good. Technology exists (Ref. 6) for degrading the accuracy of the certain environmental data presented in the charts to reflect either:

- Ranges of human forecaster skill level
- Degraded forecasts due to data dropouts or processing delays / constraints

Such "imperfect" chart data can be provided to exercise participants to more accurately reflect the insights they would gain from forecast data in an operational environment, and so increase the realism of the training experience along this dimension.

Figure 3 provides one view of the maturity of key technologies for realizing the VNE vision, with major development activities indicated on the bars.

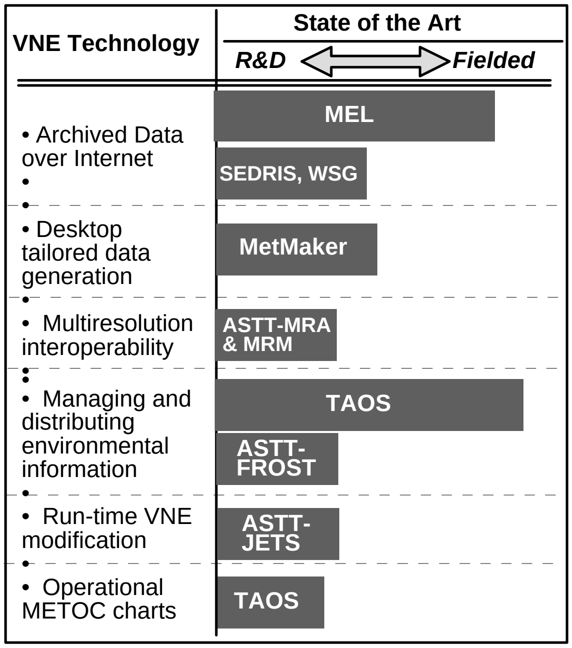

Figure 3 Characterization of Enabling Technologies

5. Research Issues

There are a variety of research challenges that need to be addressed to bring the enabling technology for twenty-first-century VNEs to maturity. These include:

- Developing precise concepts, metrics, and tools for assessing environmental interoperability of federated simulations modeling at different resolution levels.
- Understanding how to consistently identify and relate abstract environmental features, such as “a thunderstorm”, to the base 3-D grid of multiple correlated parameters that is also a representation of the storm.
- Encapsulating sufficient meteorological knowledge in systems so that they can be effectively and correctly used by non-METOC experts (like simulation engineers and exercise planners).
- Providing flexible environmental data delivery systems that can provide consistent data and services, both locally and centrally, to networked heterogeneous simulations.
- Specifying environmental representations that can provide the right levels of consistency between simulations operating with different time and space scales, *e.g.,* a real-time manned simulator and a faster-than-real-time unit-level planing simulation.
- Assessing the impact of post-hoc run-time modifications of different types on the overall integrity of the VNE, and providing authoritative guidance on the use of such methods.
- Defining the proper form of metadata and its derivation for archived data sets that captures not only statistical summaries of variables, but also identifies abstract features of interest.
- Expanding capabilities to model the impact of forecaster skill, data availability and processing on forecast products for all major environmental simulation variables.

6. SUMMARY

This paper has described a vision of what the VNEs of the twenty-first-century might look like, and the elements that will be part of the process for creating, managing, and controlling these environments to meet specific simulation needs. The vision evolves from an assessment of where VNE technology stands today, what research is currently ongoing, and identifies several research hurdles that need to be overcome in reaching that vision.

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