Editor's Note: PIREP *is aviation shorthand for* pilot report. *It's a means for one pilot to pass on current, potentially useful information to other pilots. In the same fashion, we use this department to let readers know about items of interest.*

Optimizing the Effectiveness of Directed Energy Weapons with Specialized Weather Support

Maj De Leon C. Narcisse, USAF
Lt Col Steven T. Fiorino, USAF
Col Richard J. Bartell, USAFR*

When the thunderclap comes, there is no time to cover the ears.
—Sun Tzu

ACCURATE CHARACTERIZATION of the atmosphere is essential to maximizing the use of directed energy (DE) weapons. Developing, procuring, and sustaining such weapons has been and will continue to be difficult; therefore, it is imperative that they achieve optimum effect when employed. The atmosphere, a highly dynamic medium in which these systems must operate, can significantly impact their effectiveness, thus necessitating an understanding of this environment and a capability to predict it. DE systems, particularly high-energy lasers (HEL) employed at low altitudes, will exhibit significant variations in performance based on location, time of day, and time of year. Through the Air Force Weather Agency, the Air Force Weather (AFW) community provides centralized terrestrial and space weather support to the Joint Chiefs of Staff, Air Force, Army, unified commands, national intelligence community, and other agencies as directed.[1] This article outlines some of the unique atmospheric influences on DE weapons and the ways that specialized weather support can enhance the mission capability and efficacy of those weapons.

Anticipating the changing nature of warfare is part of the responsibility that AFW shares with other parts of the Department of Defense (DOD) after the terrorist attacks of 11 September 2001. AFW cannot afford to wait for DE weapons events to happen and then react. According to the *Quadrennial Defense Review Report* of 2006, "new capabilities [are] needed by Combatant Commanders to

*Major Narcisse is director of operations, 651st Electronic Systems Squadron, Hanscom AFB, Massachusetts. Lieutenant Colonel Fiorino is an assistant professor of atmospheric physics at the Air Force Institute of Technology (AFIT). Colonel Bartell is a research physicist at AFIT's Center for Directed Energy.

confront asymmetric threats."[2] Not all of the "new capabilities" are the weapons themselves; much of the advancing technology in the DE weapons realm involves the transition of high-fidelity modeling and simulation competencies into mission-planning tools. These decision aids, coupled with timely and accurate environmental assessments, would enable the DE weaponeer to optimize an employment strategy. AFW's ability to guide the employment of DE weapons in all environments—via accurate determination of how to exploit information on target-area weather conditions to best advantage—is essential to secure the battlespace of tomorrow. Identifying the optimum time of day, attack heading, and attack altitude for low-altitude employment of HELs serves as an example of such information exploitation.

Major Types of Directed Energy Weapons

This article addresses two types of DE systems: the HEL and the high-power microwave (HPM). Whereas HELs direct a beam of focused energy to a precise point on the target to damage or destroy it, HPMs do not physically destroy a target. Rather, they invade the electronics and disrupt the components, circuitry, and switches inside the device. Additionally, they can cause behavior-modifying sensations in living organisms. HPMs, which do not require the precise aiming necessary for HELs, can function as area weapons, depending on the frequency, field of view, range to the target, and selection of either a large or small footprint.[3]

These weapons complement each other, each having advantages and disadvantages. HPM weapons cannot focus on as small an area as can HEL weapons but have proven effective through clouds and fog since they experience about two orders of magnitude less extinction (i.e., loss of energy due to absorption and scattering) in those conditions than do HELs. HPMs generate high electric fields over the entire target, in sharp contrast to the intense energy delivered by a laser to a typically small and precisely selected target area.[4] Furthermore, they can affect enemy electrical systems regardless of whether those systems are on or off.[5] For example, HPMs can stop air-, land-, or seaborne systems in their tracks. Additionally, HEL and HPM systems can engage multiple targets nearly instantaneously since they propagate at the speed of light.[6] DE systems can have a "deep magazine," which means that their ability to fire is limited only by their capacity to recharge and cool themselves.[7] Because DE weapons only expend energy, the cost per shot represents the sole cost of powering the device. Electrically generated and free-electron lasers require nothing more than power sources, eliminating the need to transport, store, and load munitions, and minimizing the logistical footprint, compared to conventional weapons. The fact that the factory can directly resupply chemical lasers eliminates the need for long-term storage.[8] HEL weapons provide almost surgical precision, greatly minimizing the potential for collateral damage.

Issues with the Atmosphere

In a vacuum, electromagnetic energy travels unattenuated, reaching its target with the theoretical maximum energy available; however, Earth's atmosphere contains mitigating factors that affect the intensity of DE received at the target. These factors include linear and nonlinear processes in the atmosphere that can affect the propagation of DE systems or electromagnetic energy in general. Linear processes are those in which the DE beams do not modify the characteristics of the atmosphere—for example, scattering caused by molecules, aerosols, rain drops, or other particles. Nonlinear effects such as thermal blooming, a defocusing of the beam caused by heating of the beam path due to absorption, result from the presence and intensity of the DE beam itself.[9] Both linear and nonlinear effects combine to reduce intensity at the target.

Because the atmosphere decays exponentially with height, its effects on HEL/HPM propagation vary most dramatically in the vertical. Thus, a definition of the atmosphere's vertical structure is in order. For the purposes

of this article, the atmosphere consists of the boundary layer; lower, middle, and upper atmospheres; high altitude (as defined by the Air Force); and space regions (fig. 1).[10] The atmospheric zone where each DE system operates influences not only those systems' capabilities but also their support requirements.

Critical to the success of military weapon systems is understanding the conditions in which they must operate. Atmospheric differences can affect DE systems in various ways, depending on whether the weapon operates over water or land within the boundary layer or in the upper atmosphere (fig. 1). For example, although a system may operate in the boundary layer, many different climates exist within this area (e.g., desert, tropical, woodland), not to mention variations associated with the four seasons. The varied DE systems under development or planned for military use must account for the environments in which they are designed to function.

Directed Energy Weapon Systems and Environments

The armed forces will develop unique DE weapon systems tailored to their various missions. Land warfare dictates smaller engagement ranges than may be encountered through the air or via the seas. The Army, Air Force, Navy, and Marine Corps must adapt DE systems to their unique environments.

Army Systems and Their Anticipated Operating Environment

The Mobile Tactical High Energy Laser (MTHEL), a combined effort of the US Army and Israel, seeks to defeat rockets/artillery/mortars (RAM), cruise missiles, short-range ballistic missiles, and unmanned aerial vehicles in the boundary layer of the atmosphere.[11] In addition to defeating the RAM threat, the Army might also consider using DE solutions

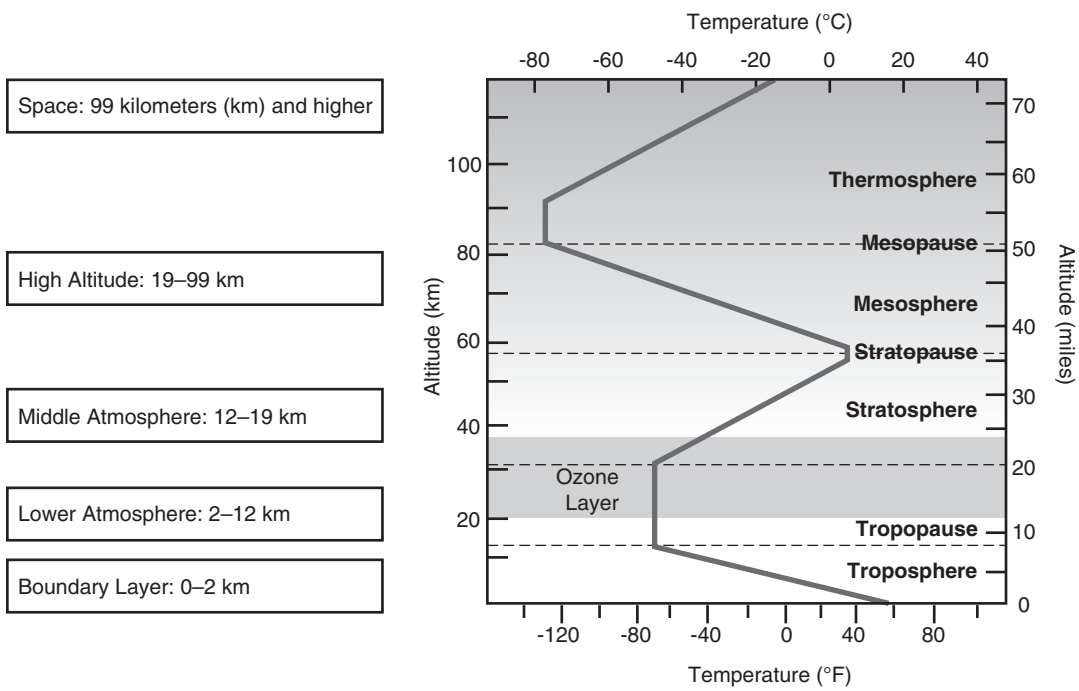

Figure 1. Structure of the atmosphere. (Adapted from "The Atmosphere," Directed Energy Professional Society, High-Energy Laser Weapon Systems Short Course, sec. 6, p. 50.)

to counter improvised explosive devices and man-portable air defense missiles.[12] Although not currently an active program, the MTHEL helped pave the way for other programs such as Skyguard, a land vehicle produced by Northrop Grumman that provides a laser-based air defense against short-range ballistic missiles, RAM, unmanned aerial vehicles, and cruise missiles.[13] Skyguard protects aircraft from man-portable air defense systems out to a range of roughly 20 km (12.4 miles); against harder RAM targets, it has an effective range of 5 km (3.1 miles).[14] Additionally, a laser ordnance-neutralization system integrated onto a Humvee, dubbed "Zeus," has seen action in Iraq for destruction of surface land mines and unexploded ordnance. Another descendant of the MTHEL, the High Energy Laser Rocket Artillery Mortar vehicle, developed by Northrop Grumman, is a truck-mounted HEL designed to defeat the RAM threat.[15]

In the future, Army DE systems may operate at ranges from tens of kilometers against larger weapons, to hundreds of meters against small-arms fire, primarily confined to long and nearly horizontal paths in the boundary layer. The potential to employ DE weapons on other Army platforms (e.g., tracked vehicles, wheeled vehicles, and helicopters) grows as DE weapons become modular and smaller. The precision and speed of HEL weapons raise the possibility of use in the countersniper or sniper mission. Due to the stealth of these systems (HELs emit no visible light beam and produce no sound), they may offer a level of tactical surprise not previously realized in warfare.[16]

The ground-based nature of potential Army HEL engagements will be strongly affected by the required long, oblique slant paths through the dense atmospheric boundary layer. Additionally, the most stressing effects of aerosols and optical turbulence, which create distortions within the atmosphere, will often occur near the aperture of the HEL, where any induced bending or spreading of the energy is more likely to reduce the weapon's effectiveness.[17] Thus, operational weather forecasting and tactical decision aids will likely play key roles in the employment of the Army's HEL weapons.

Air Force Systems and Their Anticipated Operating Environment

The Air Force manages the airborne laser (ABL), a modified Boeing 747-400 aircraft designed to carry a high-energy chemical oxygen-iodine laser (COIL) and shoot down enemy ballistic missiles during their boost phase. The ABL operates primarily at altitudes between 12 and 16 km, nearly ideal for a high-energy COIL because of the general absence of clouds, the vast reduction of water-vapor content, and pressure that amounts to only about 20 percent of that at sea level, which further reduces absorption. Here, the laser has an expected range of hundreds of kilometers. In January 2007, the ABL fired two solid-state illuminator lasers at the NC-135E "Big Crow" test aircraft, verifying the ability to track an airborne target and measure atmospheric turbulence.[18] On 8 September 2008, the ABL aircraft successfully fired its high-energy chemical laser for the first time during ground testing at Edwards AFB, California.[19] The ABL is scheduled to conduct its first intercept test against an in-flight ballistic missile in 2009.[20]

The Advanced Tactical Laser (ATL), a modified C-130 aircraft with an integrated COIL designed to support special operations, functions in and through the boundary layer with the laser primarily directed toward Earth's surface. Thus, the diurnal variation of aerosol effects, coupled with other manifestations of the dynamic nature of the lower and boundary layer of the atmosphere, is of extreme importance for the ATL, which has an expected range of tens of kilometers.

The degrading effects of the boundary layer on HEL propagation vary throughout any given day with changes in relative humidity (fig. 2). Furthermore, the thickness of the boundary layer and the strength of optical turbulence also vary diurnally. At times, high relative humidity can cause increased attenuation due to scattering, but a correspondingly thinner boundary layer or lower optical turbulence could offset this negative effect somewhat. Efforts to quantify these effects to optimize HEL engagement performance are likely to be of paramount importance.

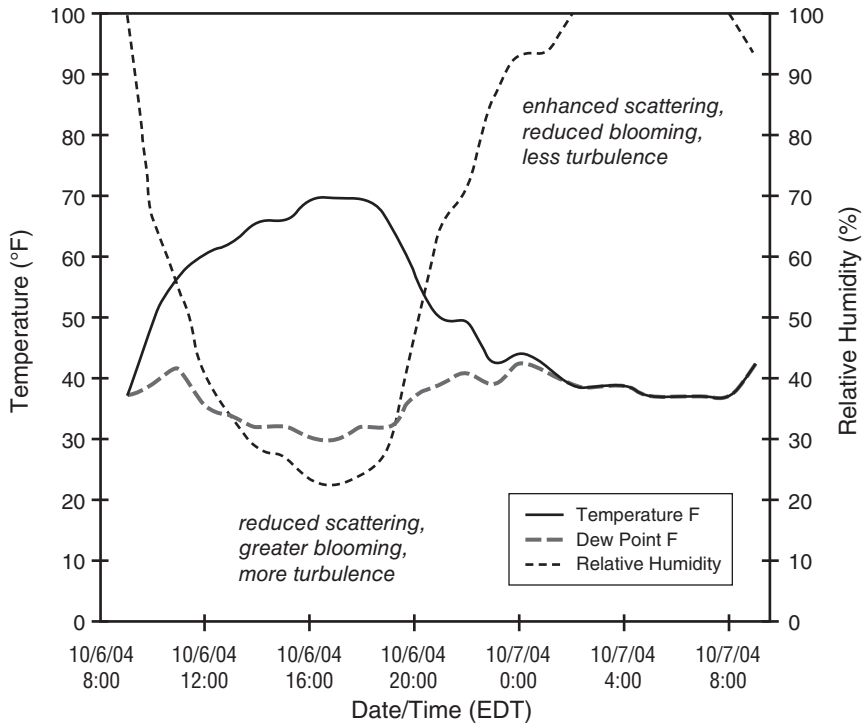

Figure 2. Variations in temperature, dew point, and relative humidity on a typical fair-weather day at a midlatitude site (Wright-Patterson AFB, Ohio, on 6–7 October 2004). Periods with lower (higher) relative humidity are noted as times with reduced (enhanced) aerosol scattering and thus greater (reduced) thermal-blooming effects. (Blooming is the effect that characterizes an intense laser beam passed through an absorbing medium [such as the air], causing the absorbed energy to produce density changes that can alter the intensity distribution of the beam and shift it away from the intended direction of propagation. Thermal blooming is an effect associated with heating the atmosphere. "The Atmosphere," Directed Energy Professional Society, High-Energy Laser Weapon Systems Short Course, sec. 6, p. 50.) Periods with greater solar heating and optical turbulence are also noted, primarily during afternoon/early evening hours.

The director of the ATL Advanced Concept Technology Demonstration program has indicated that Boeing is considering an array of potential fixed-wing platforms to carry the ATL. A COIL device was installed in a C-130H in late 2007, and during a test on 7 August 2008, the ATL aircraft fired its high-energy chemical laser through its beam-control system, which acquired a ground target and guided the laser beam to it, as directed by the ATL's battle-management system.[21]

The Air Force Research Laboratory (AFRL) has developed the Personnel Halting and Stimulation Response man-portable laser weapon, a nonlethal deterrent for protecting troops and controlling hostile crowds. The operating environment for this weapon includes the very lowest levels of the boundary layer. It uses laser light that temporarily impairs aggressors by illuminating or "dazzling" individuals, preventing them from seeing the laser source and areas near it.[22] Use of this weapon in rain, snow, or fog could have collateral, off-axis effects not yet fully quantified.

The Active Denial System (ADS), a nonlethal HPM DE weapon designed for use against per-

sonnel, uses focused millimeter-wave beams to produce an intolerable heating sensation on a person's skin. Mounted on a vehicle, the ADS operates over primarily horizontal paths in the boundary layer against ground targets. According to a media demonstration held at Moody AFB, Georgia, in January 2007, the vehicle's two-man crew located and affected targets more than 500 meters away. Full production should begin in 2010.[23] Further study is necessary to quantify the tactical impact of weather on ADS operations because many tropical locations can experience conditions that cause up to a 30 percent loss of ADS beam energy over a 1 km path. This is significant since it may force ADS operators to adjust power output based on humidity conditions.

Navy and Marine Systems and Their Anticipated Operating Environment

The Navy is focusing efforts on several requirements that DE might help to address, such as protecting the fleet. Efforts include mitigating air-sea cruise missiles, cigarette (fast-moving) boats, unmanned aircraft systems, rockets, floating mines, helicopters, fixed-wing aircraft, and other emerging threats.[24] Optimally, any system designed for use on Navy surface-warfare ships, which operate in a maritime environment heavily laden with moisture in the form of water vapor, should provide ship protection and indirect fire support to ground forces.[25] These systems direct fire from maritime surface vessels toward a land or an airborne target. If DE systems proliferate onto Navy and Marine aircraft that support ground forces or provide fleet defense, they too will often operate in the lowest, most attenuating reaches of the atmospheric boundary layer.

Marine Corps systems for large- and small-scale land engagements and close-quarters combat may prove similar to those used in tactical scenarios envisioned for the Army. Thus, some opportunities may present themselves for leveraging investments from the other services.

Weather-Support Considerations

Describing and predicting the weather may reach unprecedented levels for the proper employment of DE weapons. We cannot underestimate the need for a better understanding of the atmosphere as it relates to DE weapons. The work being done to address environmental issues must be leveraged, but much more is needed. We must also address weather requirements for DE weapons.

Accurate Characterization of the Atmosphere

DE weapons require an accurate characterization of the atmospheric path between sensor and target. The same holds true of traditional ordnance, but to a much lesser degree of accuracy since a bomb is not modified by the atmosphere at the molecular level along the path between the vehicle that transports it and the intended target. For example, wind can blow a bomb dropped from high altitude off course by a few hundred meters, but the bomb impacts somewhere on the ground. However, at every step along a DE weapon beam's intended propagation path, the atmosphere can modify its intensity, lethality, and overall effectiveness. Clearly, these types of weapons exemplify an unprecedented dependence on accurate weather characterization.

Laser weapons demand a more complete understanding of what happens to the beam along the potential engagement path than current predictive capabilities allow. Therefore, we cannot overemphasize the need for accurate characterization of a DE weapon's potential propagation path. Engagement distances and the changing environment create a need for more robust models and simulations than currently exist in the AFW inventory. Much of the present research addresses beam-control issues related to the ABL, which generally operates in the favorable environment of the middle and upper atmosphere. This same type of emphasis must occur in the boundary layer, where smaller-scale DE weapons operate. According to AFW's transformation guidance, we must "anticipate and manage

increasing model resolution, vertical domain from surface to near space, and physics requirements based on new weapon systems coming into the inventory (e.g., Airborne Laser)."[26] AFW has concerns about whether or not weather-support products are robust enough to meet anticipated requirements for the employment of DE weapons.

Leveraging the Work of Others

Army Materiel Command manages the Battlefield Environment Division, the lead DOD agency for research and development of boundary-layer weapons unique to the Army. AFW should be able to collaborate with the Army Research Laboratory to leverage the characterization of atmospheric effects on DE battlefield weapons used by the Army. This work not only could help AFW understand the effects of the atmosphere on these types of weapons, based on Army tactics, but also could help support the development of unique forecasting products for current or anticipated needs not currently being addressed.[27]

Readiness for the Operational Weather Requirements of Directed Energy Weapons

Tactics related to HEL and HPM systems will likely differ from those utilized for conventional weapon systems. What is generally considered "fair weather" for conventional weapons may not be favorable for DE weapons. Again, citing the example illustrated by figure 2, the time of day during fair weather can have a dramatic influence on the effectiveness of an engagement involving low-altitude DE weapons. A weather forecaster supporting such an engagement that includes low-altitude, tactical, high-energy, solid-state lasers would need to balance the counteracting effects of reduced aerosol extinction with greatly increased optical turbulence in the afternoon, as opposed to morning-hour conditions of relatively high aerosol extinction and much lower turbulence. Despite the quiescent weather suggested by figure 2, an accurate assessment of the dwell time necessary to produce the desired effect on an HEL engagement in the boundary layer could not be made without a high-fidelity forecast of the diurnally varying height of the boundary layer.[28] Such detailed forecasting in the apparent absence of "bad weather" differs significantly from traditional Air Force and Army weather support but is not completely unprecedented. The advent and later proliferation of infrared sensor and imaging systems in the 1970s and 1980s led to the development of electro-optical tactical decision aids for weather forecasters, based upon primitive radiative-transfer modeling algorithms used in research and development. Equipped with straightforward graphical user interfaces, they were repackaged as operational decision aids.[29] These aids saw use as, among other things, "thermal crossovers" for infrared targeting systems, helping distinguish targets by highlighting differences between hot and cold backgrounds. As HEL and HPM systems enter the inventory, we will need operational decision aids for DE weapons, based on today's sophisticated modeling, simulation, and research.

Recommendations

Various activities can be utilized right now as we begin to support DE weapons. AFW has many opportunities to tailor weather support. We must continue existing research and secure funding to help push atmospheric characterization forward. Beyond the research and funding, which are key, we must have support from the services at the highest levels.

Leveraging Current Air Force Weather Activities

AFW can begin by augmenting the education and training of new forecasters in the 335th Training Squadron at Keesler AFB, Mississippi, with a block of instruction on weather issues affecting the propagation of DE weapons. For example, a "For Your Information" document or Air Force Weather Agency Technical Note can help forecasters in the field. At most of its conferences and symposia, the Directed Energy Professional Society offers short courses in HEL propagation and HPMs taught by subject-matter experts.[30] Research modeling and simulation codes such as the High Energy Laser End-to-End Operational Simulation

(HELEEOS), developed and managed by the Center for Directed Energy at the Air Force Institute of Technology (AFIT), and the Directed Energy Environmental Simulation Tool (DEEST), managed by the AFRL's Space Vehicles directorate, provide opportunities for developing operational and tactical decision aids.[31] By attending briefings or short courses, senior leaders across the DOD can begin to understand the effects of weather. In summary, AFW can begin educating forecasters and those in leadership positions at senior levels both inside and outside the DOD. Educated leaders can help secure funding for research and development since they understand the problems associated with forecasting for DE weapons. Leveraging high-fidelity modeling codes such as HELEEOS and DEEST will assist with incorporating weather effects on DE propagation spanning from ultraviolet to radio frequencies. These available codes—candidates for decision-aid software used by the operational weather community—have been validated as modeling tools and have earned credibility in the research community.

Current Research Efforts

AFW must examine current programs sponsored by the High Energy Laser Joint Technology Office (HEL-JTO) to assess the relevance of the research in terms of assessment of atmospheric effects and prediction for operational DE weapons. Established in 2000 to manage a comprehensive approach to the development of HEL science and technology for DOD organizations, this office has had annual operating budgets in recent years in excess of $70 million, with programs sponsored across industry, academia, and government agencies.[32] Sponsored programs include research and development of the HELEEOS at AFIT and part of the DEEST development at the AFRL. Leveraging current efforts pursued by the AFRL's Directed Energy directorate (AFRL/RD), the Office of Naval Research, and the Army's Space and Missile Defense Command may also provide useful research that supports atmospheric propagation of HELs and HPMs.

Funding for Research

Funding would help support many areas of research. A key research topic would address whether today's meteorological observations support DE weapons to the degree required. We may need to develop new products, such as optical-turbulence maps, molecular and aerosol absorption maps, scattering maps, thermal-blooming maps, and others. These types of environmental inquiries will involve academia, private industry, and the DOD.

We must urge senior-level DOD and congressional leaders to understand the criticality of continuing support for research, development, and testing related to DE and environmental effects on DE weapons. Proper characterization and prediction of the environment are warranted in order to quantify environmental impacts. Benefits include speed-of-light engagement, precision strike to destroy, area strike to disable, low expended mass per engagement (deep magazine), and low cost per engagement.[33] Furthermore, US adversaries are rapidly moving ahead with the development of DE weapons (especially HELs).[34] A better understanding of how environment modifies the performance of such weapons would become an exploitable advantage even if the adversary has superior hardware.

Advocacy

AFW and the Air Force Weather Agency, through the Weather Requirements for Operational Capabilities Council, must continue to work with the acquisition community to anticipate and determine unique support needs.[35] New DE weapon-systems prediction information such as optical-turbulence forecasts, aerosol-concentration products, boundary-layer height forecasts, and so forth, will require policy support and coordination from the Air Force Weather Agency. Other products may be required to support the numerous systems under development.

Headquarters Air Force Materiel Command, Intelligence and Requirements (AFMC/A2/5) may be in the best position to address weather-acquisition concerns related to Air Force DE systems as they make the transition from the

labs to the war fighter. For the Air Force, AFMC could serve as lead command for this effort. Headquarters AFMC/A2/5 must account for these atmospheric-related concerns before any air or space system becomes operational. Close cooperation among AFRL/RD, Army Space and Missile Defense Command, Naval Sea Systems Command, acquisition professionals, and the operational community is essential.

Political considerations must become a part of this effort. Engaging the wrong target can have massive geo-political consequences, which can affect the acceptance and use of a new type of weapon that could change warfare.

Conclusions

With continued funding for research and focused advocacy by senior leaders, an already robust AFW community can transform itself into a superior support provider for DE weapons and an enhancer of employment. Funding from HEL-JTO, major military commands, and the Army can help answer how best to mitigate and/or, perhaps, ultimately exploit atmospheric effects in the employment of DE weapons. We need advocacy in various arenas as commands and agencies continue to battle for precious resources. Senior leaders must understand the potential consequences of not supporting these research and development efforts (e.g., DE weapon systems may not perform as expected due to unanticipated environmental effects), as well as the unintended strategic/political fallout that such a lack of support could have on future operations. We must encourage current research efforts that translate easily into operational decision aids for atmospheric characterization and assessment. Education and training in DE weapons are necessary for senior leaders and for people at all levels of the Air Force weather community to ensure weapons effectiveness against potential enemies. The United States' adversaries are not waiting for tomorrow; they are acting today.[36]

We anticipate no major changes in the organization of AFW. However, weather personnel may need to fill key positions in the HEL-JTO, AFRL/RD, or Naval Sea Systems Command to advocate and lead efforts to address atmospheric characterization. Collaboration with HEL-JTO, AFRL/RD, academia, and private industry is essential to keep abreast of advancements in areas related to military operations. AFIT and the AFRL should receive funding to continue the upgrading/improving of software codes such as HELEEOS and DEEST, and mission-level decision aids based on these research tools must be developed. In the current fiscal climate, increased manning is not a realistic expectation, so accurate characterization of the atmosphere through decision aids will likely be necessary—and might possibly represent the accepted solution. AFW can shape DE support and optimize DE performance for tomorrow by acting today. ❑

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36. Col M. D. Zettlemoyer, chief, Integration, Plans, and Requirements, to AF/A3O-WR/RP, MAJCOM A3Ws, letter, 12 February 2007.

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