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Improved EM Tactical Applications through UAS-Enhanced High-Resolution Mesoscale Data Assimilation and Modeling

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LONG-TERM GOALS

The long-term goal of this project is to develop new and emerging analysis and forecast capabilities via improvements to environmental inputs to electro-magnetic (EM) tactical applications through Unmanned Aerial Systems (UAS) enhanced high-resolution mesoscale data assimilation and modeling. These capabilities will be achieved through the formulation, testing, evaluation, and demonstration of an environmental data assimilation and prediction system designed to quantify the UAS observation parameters, characteristics (e.g., vertical resolution), measurement strategies and assimilation approaches that provide the greatest benefit for high-resolution (grid increment of 5-km or less) atmospheric tactical-scale environmental forecasts. The goal is to focus on EM tactical applications and metrics in evaluating the performance of the system. This development will leverage current and emerging capabilities for: i) environmental data assimilation, ii) adjoint-based sensitivity and observation impact, iii) air-ocean coupled modeling, and iv) EM tactical decision aid systems. Observational results from field programs such as Trident Warrior 2013 (TW13) will also be leveraged to build, test, and transition the prototype end-to-end (observation to tactical decision aid (TDA)) demonstration system. All meteorological inputs to the demonstration system will come from UAS platforms and sensors consistent with the present state-of-the-art; however, no specific operational UAS system will be targeted, transitioned or modified as part of this effort.

OBJECTIVE

The objective is to develop, validate, and transition new METOC capabilities within a high-resolution modeling system using advanced data assimilation of UAS data in order to achieve superior short and medium term forecasts of high-impact weather and EM-related parameters. We will use three crucial model components: i) the coupled atmospheric and oceanic components of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®[1]), ii) the 3D-variational (3DVAR) analysis schemes NAVDAS (NRL Atmospheric Variational Data Assimilation System) for the atmosphere and NCODA (Navy Coupled Ocean Data Assimilation) for the ocean and wave models, and iii) the COAMPS Adjoint observation impact system. COAMPS-OS®[1] will be used as the software interface for configuring COAMPS and the other system components to facilitate high-resolution coupled mesoscale forecasts. The COAMPS system includes an ocean circulation model, the Navy

[1] COAMPS® and COAMPS-OS® are registered trademarks of the Naval Research Laboratory.

Coastal Ocean Model (NCOM), which fully interacts with the nonhydrostatic atmospheric module. In addition, two different wave models are currently being implemented and tested: Simulating Waves Nearshore (SWAN) and Wavewatch III (WWIII), which will also be available for testing. NAVDAS is the Navy's state-of-the-art analyses system. The adjoint of the COAMPS forecast model and NAVDAS data assimilation systems have already been developed and linked together to provide a quantitative measure of the impact of individual observation types (e.g., radiosonde, aircraft, UAS, etc.) on the COAMPS forecast error. This observation impact capability has only recently become available for COAMPS and is one of the first such observation impact capabilities for a mesoscale modeling system developed anywhere.

Several key scientific objectives are identified in relation to the impact of the environment on EM propagation characteristics, particularly in the coastal marine atmospheric boundary layer (MABL): i) the time-varying 3-D structure of the MABL and its interaction and impact on EM propagation characteristics and ducting of EM energy, ii) the response of the MABL to the structure of the underlying SST, including SST gradients, and the impact on evaporative duct height calculations, on MABL refractive layers, and on larger-scale surface and MABL ducting phenomena, and iii) the most effective UAS observing strategies from an atmospheric model data assimilation perspective in order to accurately predict mesoscale weather and EM propagation conditions.

APPROACH

Our approach is to leverage prior investments in NRL-developed NAVDAS (including aircraft data assimilation), COAMPS and its adjoint system, and EM TDA technologies to produce a UAS-enabled, integrated, and automated on-scene system to support ASW, ASuW, and ISR mission planning and execution. Significant collaborations with other investigators developing and integrating UAS-based data and tools will be also leveraged. Collaborations with Scripps Institute of Oceanography (SIO), NSWC-Dahlgren, and other PMW-120 EM investigators will be pursued and help guide our sampling strategies, assure the UAS observations taken are in accord with NRL goals, and enhance synergistic development of UAS-based TDAs. Six specific technologies that will be developed, tested, and integrated in this project are i) tactical-scale data assimilation, ii) adjoint-based observation impact, iii) air-ocean coupled modeling, iv) EM tactical decision aid systems, v) software infrastructure, and vi) validation and verification of the end-to-end system.

WORK COMPLETED

Completed work includes: (i) efforts toward merging the UAS data assimilation (DA)-enabled NAVDAS software branch with the main NAVDAS branch in preparation for operational UAS data streams, (ii) enhancements to the 4D data assimilation system COAMPS/NAVDAS Accelerated Representer (COAMPS-AR) and the adjoint model-based observation impact system plus experimental tests, (iii) new COAMPS® model performance assessments from the Trident Warrior 2013 (TW-13) dataset, (iv) application of the combined NAVDAS 3-DVar UAS DA system and COAMPS model evaluation to the New Zealand Sea Breeze Trail (NZSBT) experiments and (v) production of a comprehensive report of measurements and investigations in the Trident Warrior 2013 campaign as a Technical Memorandum for NRL.

i) *Preparation for operational UAS data streams*
Merging of the private NAVDAS code branch, constructed in support of UAS DA investigations, with the mainstream (beta) NAVDAS branch was initiated. The First-Guess-At-Appropriate-Time (FGAT) algorithm of the UAS DA branch was integrated successfully. Also in support of operational UAS DA, substantial efforts focused on the coordination of processing, formatting and transfer of the U.S. Air Force 557th Weather Wing (*f.k.a.,* AFWA) Predator UAS data.

ii) *Enhancements to and testing of COAMPS-AR and the Observation Impact System*
Updates to COAMPS-AR codes were completed and transferred for testing within COAMPS-OS. Capability for UAS DA was successfully integrated into COAMPS-AR, permitting performance tests with the TW-13 dataset. New error metrics were developed and incorporated in the 4D-Var observation impact system. Functionality of the enhanced observation impact system was subsequently confirmed with real atmosphere test cases. Additional system assessment included testing with AirDat TAMDAR observations to identify relative impact versus existing assimilated datasets.

iii) *Mining the Trident Warrior 2013 Dataset for new Model Performance Assessments:*
New analyses of COAMPS model forecasts from the Trident Warrior 2013 (TW-13) dataset evaluated multiple aspects of model performance with respect to UAS DA. New COAMPS model runs with NAVDAS 3D-Var following the TW-13 configuration concentrated on isolating the relative impact of individual DA sources (a.k.a. "data denial tests"). Additional evaluation of existing runs from the TW-13 dataset investigated the potential role of cloud cover prediction in yielding the broad forecast error reduction due to UAS DA identified in FY14, as well as the impact of UAS DA on boundary layer height prediction and EM signal propagation loss

iv) *Application of the End-to-End System to the New Zealand Sea Breeze Trial Experiments:*
The NAVDAS UAS DA branch developed and implemented for TW-13 investigations was applied to the New Zealand Sea Breeze Trail (NZSBT) Experiments 2009 field campaign for assessment of the UAS impact on forecasts and relevant EM environment quantities. UAS DA branch component settings were modified to coordinate with NZSBT UAS data, including the observation decoder and averaging routine. Benchmark COAMPS runs were executed.

v) *Comprehensive Report on the Trident Warrior 2013 scientific campaign:*
The first draft of a technical report detailing the scientific measurements and subsequent investigations of the Trident Warrior 2013 field campaign was completed. Project principal investigators (13 in total, representing seven research institutions) were solicited for written summaries of their efforts toward the TW-13 campaign, including preparation, execution, post-processing and evaluation of measurements as well as modeling investigations. Written contributions were assimilated into a common report framework. The report (216 p.) was cleared for public release and subsequently disseminated to project co-authors with a request for review.

RESULTS

i. Preparation for operational UAS data streams
Sample dataset assessment confirmed viability of Predator UAS measurements as data sources for use by FNMOC in NAVDAS (N.B., the Predator UAS data and all derived products are Classified). The on-going implementation of Predator UAS measurements into NAVDAS DA is the first case of UAS

METOC data applied to operational forecasting. This emerging capability coupled with the incorporation of the NAVDAS DA UAS branch into the mainstream NAVDAS branch represent critical steps forward in applying future systematic data streams of UAS measurements to operational forecasts.

ii. Enhancements to and testing of COAMPS-AR and the Observation Impact System

The new implementation of UAS DA capability within COAMPS-AR permits comparison between COAMPS-AR (using 4D-Var DA) and COAMPS coupled to the NAVDAS 3D-Var UAS DA branch. It also allows a quantification of UAS impact within a 4D-Var DA system. COAMPS-AR was run using the TW-13 COAMPS configuration for identical test cases: UAS data included (*UAS4d*) and UAS data excluded (*noUAS4d*). Comparison of these two cases shows a net reduction of forecast error (measured through the root-mean-squared error (RMSE) statistic) of generally similar magnitude to that seen in the comparison of the equivalent 3D-Var cases (*UAS*, *noUAS*). This supports the result found in FY14. Forecast error was verified against the TW-13 campaign radiosondes. Comparison of cases *noUAS4d* and *noUAS* (Figure 1) reveals a net reduction in model error due to 4D-Var DA usage broadly over the vertical range of ScanEagle UAS flight paths (< 1550 m ASL), particularly in the vicinity of the top of the atmospheric boundary layer (h_{ABL}) and for prediction of moisture (shown using dew point temperature here). These two quantities are among the most important components to forecasts of modified refractivity vertical profiles and EM signal propagation loss modeling. Initial results show little change in model forecast performance between case UAS4d and case UAS; error covariance matrices for the UAS in 4D-Var DA remain under investigation

A new error metric added to the 4D-Var observation impact system permits calculation of the forecast error with respect to actual observations as opposed to the analysis field. This metric facilitates comparisons between observation impacts calculated with 3 and 4D-Var systems, quantifying impacts by data source and DA system. The 4D-Var observation impact system was tested using forecasts of Hurricane Eduardo (2014) (Figure 2). This tool was employed also for evaluation of the relative impact of AirDat TAMDAR observations (comparable to UAS METOC measurements) on forecast error reduction using moist energy and modified refractivity metrics. On a per-observation basis, the TAMDAR observations were found to be among the most important observations using the moist energy (4th) (Figure 3) and modified refractivity (3rd) metrics. In a data-denied tactical scenario, TAMDAR was the most important observation source on a per-observation basis, and third most-important overall behind SSMI-PRH and AMVs, respectively (Figure 4).

iii. Mining the Trident Warrior 2013 Dataset for new Model Performance Assessments

In an effort to further diagnosis the relative impact of UAS DA on COAMPS model forecast performance, four experimental model runs (Table 1) with systematic omission of input data streams were executed following the TW-13 model configuration using NAVDAS 3D-Var DA. These four experiments are labelled *tw13n1* through *tw13n4*. These data omission (denial) experiments were combined with the existing case *noUAS* and case *UAS* experiments to investigate the relative contribution of ScanEagle UAS and other data sources. COAMPS performance was gauged using an RMSE score assessment of the 0-12 hour lead time forecasts in the vertical region of UAS sampling (< 1550m ASL) compared against TW-13 radiosonde measurements. Results show relatively high RMSE scores for temperature in case *tw13n1* (ScanEagle UAS, U.S. satellite and foreign satellite data only) and a noticeable RMSE increase at longer forecast lead times when ScanEagle UAS data is the sole DA source (case *tw13n3*). The denial of data sources from the NAVDAS 3D-Var DA system reveals a

predictable but limited net gain in RMSE overall, with particular sensitivity to the inclusion [exclusion] of foreign satellite data (Figure 5a, Figure 5b) [(Figure 5c, Figure 5d)]. The use of ScanEagle UAS data as the sole data source to the DA system showed increasing RMSE with increasing forecast lead time.

A comparison of model cloud cover forecasts during TW-13 was conducted to identify the extent to which cloud placement influenced model forecast error reduction given UAS DA. Model forecasts of cloud liquid water path and cloud base height were compared against radiosonde measurements, ScanEagle measurements, satellite imagery and land-based WMO station observations for verification. Four instances of false cloud prediction at the radiosonde sites were identified over the 4 day campaign. Removal of these instances yielded a small overall improvement to dew point temperature forecasts (locally up to 1°C RMSE reduction) but limited in vertical space and time. The finding indicates that change in predicted cloud presence/absence in model forecasts does not substantially account for the improvement to model forecast performance seen as a result of UAS DA.

Investigation of results from the Navy's Advanced Refractive Effects Prediction System (AREPS) applied to the TW-13 campaign environment using COAMPS forecasts (cases *UAS* and *noUAS*) reveals complex impacts of UAS DA on EM signal propagation loss modeling. Use of UAS DA reduced the RMSE of signal propagation loss prediction by 3 dB overall during TW-13. Model performance against individual radiosondes varied during the campaign, however (Figure 6). Although UAS DA improved M-profile prediction (FY14), propagation loss prediction was found to be acutely sensitive to the local vertical gradient of M, predicted inversion height, and model vertical resolution.

iv. Application of the End-to-End System to the New Zealand Sea Breeze Trial Experiments
Preliminary COAMPS model runs of the NZSBT campaign period indicate reduced model forecast error due to UAS DA. The use of UAS DA is attributed to an overall 1.25 M-unit RMSE reduction in modified refractivity prediction. These runs for the NZSBT campaign demonstrate the portability of the NAVDAS UAS DA branch to different field campaigns and environments.

IMPACT/APPLICATIONS

Comprehensive Report on the Trident Warrior 2013 scientific campaign :
The TW-13 scientific campaign demonstrated COAMPS model forecast error reduction in key fields of relevance to EM propagation interests due to the incorporation of UAS METOC measurements into a coupled data assimilation system. Understanding of the potential utility of broader implementations of UAS METOC data collection is currently in its initial stages. This report on TW-13 will serve as a centralized resource for all aspects of the campaign, including instrumentation, measurements and modeling studies. It will serve as valuable, unified reference for on-going and future studies involving TW-13 as well as future UAS METOC measurement impact investigations. A final draft is in progress pending receipt of co-author revisions and will be submitted as an NRL Technical Memorandum.

RELATED PROJECTS

The EM environment verification (EMver) software developed for the SPAWAR-funded 6.4 *COAMPS-EM* project serves as a tactical decision aid for EM duct prediction and can be enhanced to incorporate operational UAS METOC observations if such data streams become available. Joint

efforts continue with the NRL-Base funded 6.2 *Boundary Layer Characterization for EM Propagation Predictions* (BLEMP) project to investigate M-profile blending techniques for improved prediction of surface ducts and evaporation ducts. Modeling investigations with UAS and additional measurements from the NZSBT dataset are on-going using COAMPS with the NAVDAS 3D-Var UAS DA capability implemented in this project.

HONORS/AWARDS/PRIZES

The investigation of UAS impacts on numerical weather prediction during Trident Warrior 2013 was selected for inclusion in the 2014 issue of the NRL Review:

- Doyle JD, Holt T, Flagg DD, Amerault C, Cook J, Geiszler D, Haack T, Nachamkin J, Pauley P, Tyndall D, Melville WK, Lenain L, Reineman B. 2015. UAS Impact on Marine Atmospheric Boundary Layer Forecasts. NRL Review 2014.

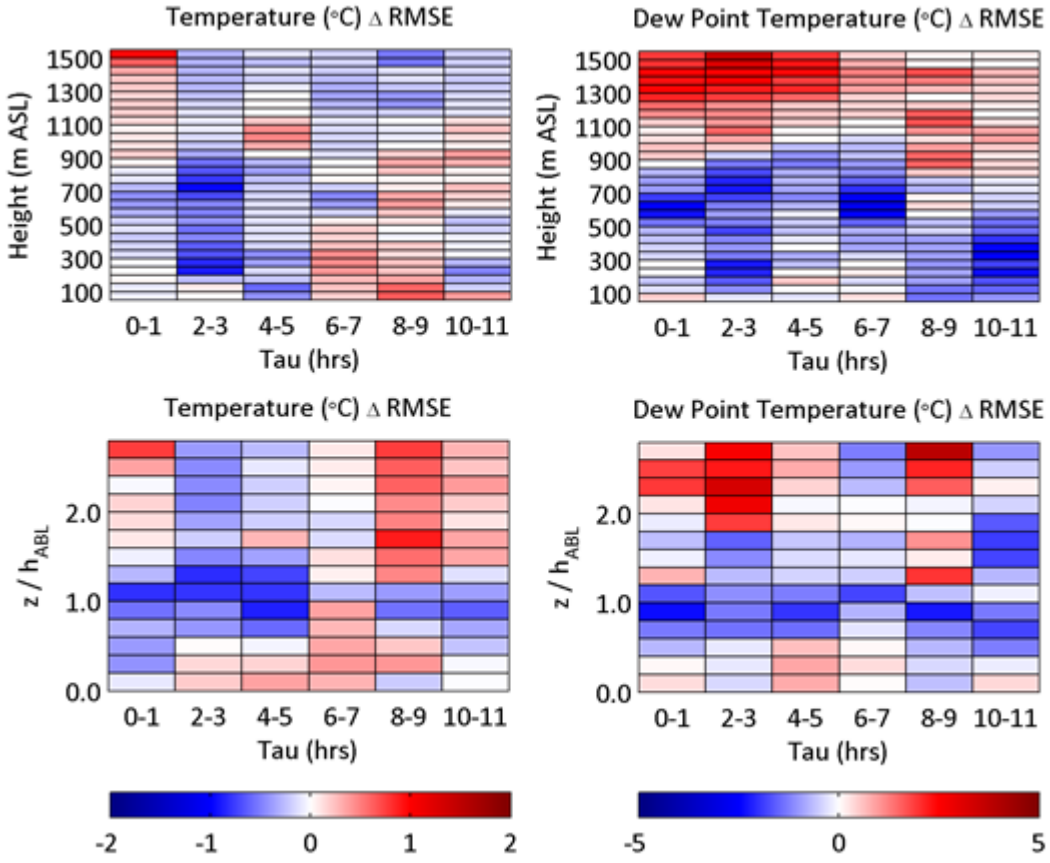

Figure 1. Difference in root-mean-squared-error (RMSE) of temperature (left) and dew point temperature (right) in case noUAS4d versus case noUAS using height as a vertical coordinate (top) and geometric height scaled by model-estimated boundary layer depth (bottom). Blue (red) shades indicate decreased (increased) model error. Model error is measured according to radiosondes launched during TW-13. The abscissa is forecast lead time in hours, grouped into two hour bins.

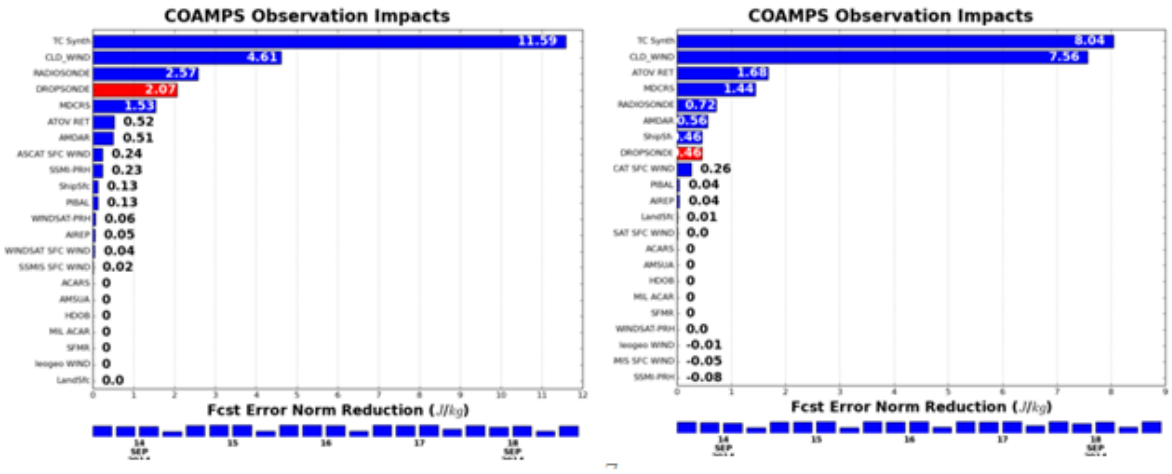

Figure 2. Observation impacts for 4D (left) and 3D-Var (right) experiments for Hurricane Eduardo (13-18 September 2014). The impacts are calculated with respect to each experiment's respective analysis. The impacts from measurements taken from the Global Hawk platform are highlighted by the red bars. The error shown is calculated with respect to each experiment's respective analysis.

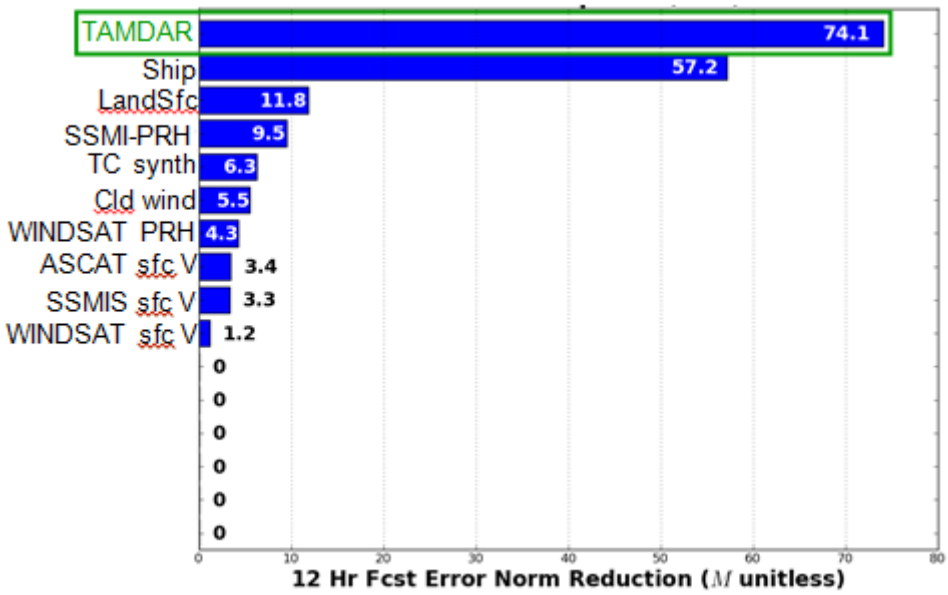

Figure 3. COAMPS per-observation impact (10^{-5}) for assimilated data streams for the San Diego AirDat TAMDAR Region during September 2012 using a modified refractivity metric with AMDAR, AIREP and radiosonde data streams omitted. The impact of AirDat TAMDAR observation is outlined in green.

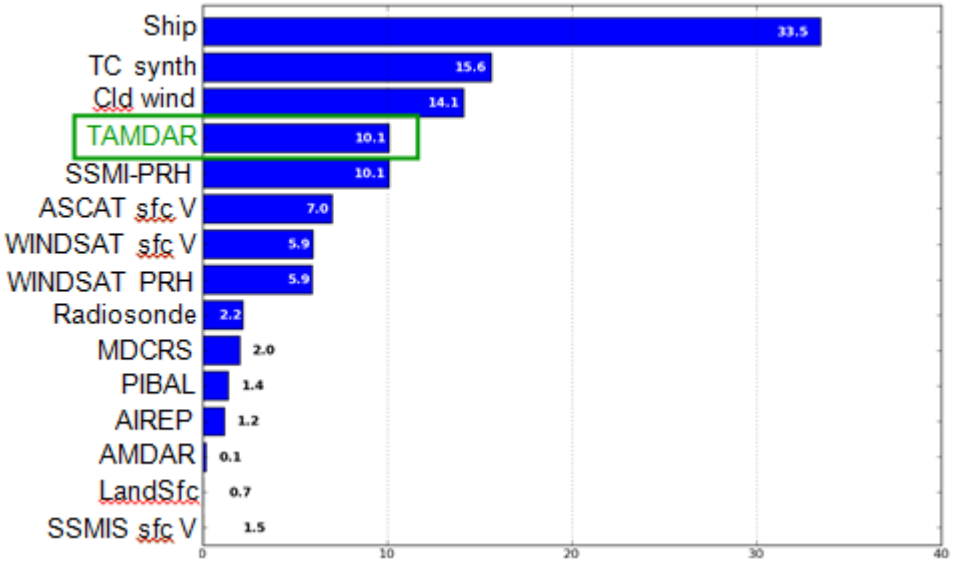

Figure 4. COAMPS per-observation impact (10^{-5}) for assimilated data streams for the San Diego AirDat TAMDAR Region during September 2012 using a moist energy metric. The impact of AirDat TAMDAR observation is outlined in green.

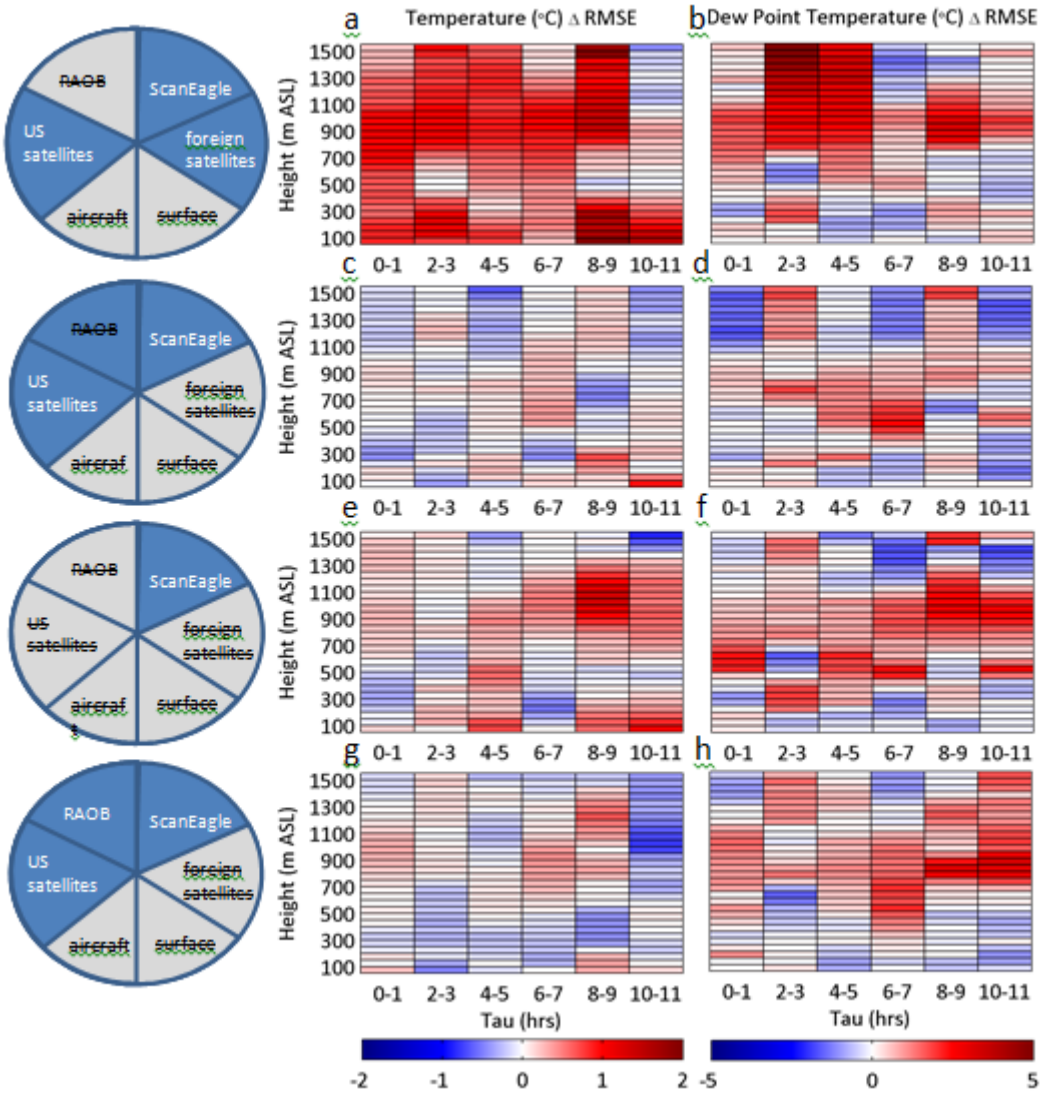

Figure 5. Change in root-mean-squared-error (RMSE) of temperature (a, c, e, g) and dew point temperature (b, d, f, h) due to the denial of selected data sources from the NAVDAS 3D-Var DA system. Data sources withheld (retained) are indicated by gray (blue) shading in the left column. RMSE is calculated from all available model-radiosonde measurement comparisons within vertical bins representing geometric height above sea level. The forecast lead times (Tau) are merged together into two-hour bins and are labelled along the abscissa of each subplot.

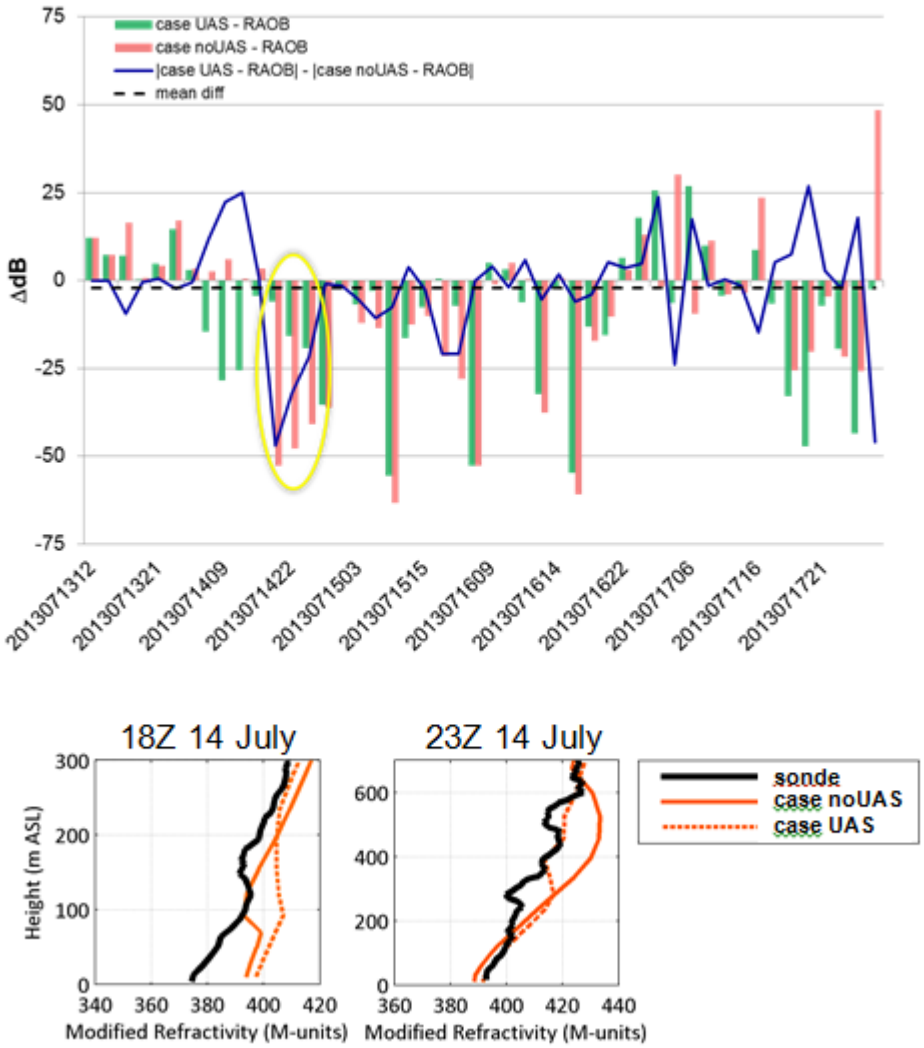

Figure 6. (top) Difference in AREPS-computed EM signal propagation loss between COAMPS forecasts for Trident Warrior 2013 case UAS (green), case noUAS (salmon) and campaign radiosonde observations (RAOB). The change in absolute value of model error is shown in blue with the campaign time-mean in black (dashed). Shown at the bottom are the profiles of modified refractivity derived from Trident Warrior 2013 test cases and campaign radiosondes, for two times during the period highlighted in yellow in (a) where UAS data assimilation yields much reduced forecast error of signal propagation loss

Table 1. Data assimilation sources used in NAVDAS 3D-Var DA with COAMPS forecasts in the data denial experiments conducted using the Trident Warrior 2013 dataset. Blue-shaded cells denote inclusion of a data source in the experiment indicated in the left column; gray-shaded cells denote exclusion therefrom.

Experiment	Data Sources Included in NAVDAS 3D-Var Data Assimilation					
	ScanEagle UAS	US Satellites	Foreign Satellites	Radiosondes	Aircraft	Surface
tw13n1						
tw13n2						
tw13n3						
tw13n4						
noUAS						
UAS						