Final Report

Satellite-Based Applications to Benefit Navy Tropical Cyclone Analysis and Numerical Model Forecasts

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Executive Summary

This 3-year research award (with a 1-year NCE) granted to the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison Space Science and Engineering Center (UW-SSEC) proposed to conduct applied research projects directed towards two main areas: 1) Advancing the use of satellite data and products in Tropical Cyclone (TC) analysis and forecasting, and 2) Improvements in the understanding and approaches to satellite data assimilation in numerical weather prediction (NWP) models. Both of these broad topics have relevance to the DoD mission and operations. In area 1), algorithms were created and enhanced that exploit inherent advantages from microwave imagers and sounders by virtue of their ability to see through non-raining clouds and thus monitor the TC 3-D environmental fields, and new methodologies were designed as advanced satellite sensors came on line. For area 2), the focus was on improving the existing strategies for assimilating satellite-derived winds into the Navy global NWP system. In both cases, our knowledge and expertise in satellite data and product development was employed to better understand how they can be applied to the focus areas and meet project goals. This understanding helped translate into enhanced algorithms and methodologies with a view toward evaluating the feasibility and practicality of proposed new solutions, and then determining their parameters after careful calibration and evaluation.

Brief Background

Recent studies have clearly indicated that space-based remote sensing must be employed to help fill meteorological data gaps over oceanic regions in order to provide more accurate forecasts for fleet operations. Advances in space-based technology are providing improved sensor capabilities with associated opportunities to better observe the 3-D atmosphere. In addition, progress in computer resources and numerical techniques have enabled the research community to expand the development of computer-based, automated algorithms capable of transforming real time measurements into useful information. Taking advantage of these emerging technologies has the potential to provide optimal satellite data coverage and quality. The resulting datasets, products and diagnostic derivatives can be used to enhance the forecasting capabilities of naval prediction centers and favorably impact global operations.

UW-CIMSS has pioneered the development of many new automated techniques designed to efficiently extract meteorological information from weather satellite measurements. Some of these methods were specifically developed for Naval applications, and under NRL support, leading to promising new data sets and capabilities. One such collaboration, a research program aimed at optimizing the extraction of atmospheric motion vectors (AMV) from sequential multi-channel geostationary satellite radiances, has demonstrated a positive impact on Navy numerical forecast models (Velden et al. 1998; Goerss et al. 1998; Berger et al. 2012). This set of algorithms has been transitioned into DoD operations. A primary benefit of these increased data will be realized through more effective assimilation (Pauley et al.

2012; Baker et al. 2012). The work under this grant, in collaboration with Rolf Langland at the Naval Research Laboratory (Monterey) further investigated the optimal assimilation of these satellite data, employing the new Navy NAVDAS/NAVGEM (which became operational in Feb 2013) global model system.

A significant portion of this grant research was aimed at the predictability of tropical cyclones (TCs). A research focus area involved the creation and enhancement of automated satellite-based TC analysis products and decision tools. The Joint Typhoon Warning Center (JTWC) relies heavily on satellite-based guidance for their TC analysis and forecast processes. Already, objective methods developed jointly by NRL and CIMSS to analyze TC intensity and structure are being demonstrated. These include the Advanced Dvorak technique (ADT, Olander and Velden 2012), an AMSU-based intensity estimation technique (Herndon and Velden, 2012), a consensus method (SATCON, Herndon et al. 2012), a microwave imager based total precipitable water (TPW) product (MIMIC-TPW, Wimmers and Velden, 2012b), and an objective center and structure diagnostic tool called ARCHER (Wimmers and Velden, 2012a). All of these techniques will benefit from the research performed under this grant, which included the incorporation of new science, adaptation to new sensors, and further validation/demonstration studies.

Scope of the Project

The completed research accomplished under this grant is broken down into two major task areas. The first area of directed research is in advancing the use of satellite data and products to enhance TC analysis. The resulting research and development will be summarized to include 1) upgrades to the CIMSS/NRL AMSU/SSMIS algorithm to objectively estimate TC intensity and its adaptation to new sensors, and 2) upgrades to new passive microwave imager-based products and algorithms, such as MIMIC-TPW and ARCHER. The CIMSS team worked closely with NRL-Monterey research partners to build, improve, test, and adapt the algorithms and methodologies, while at the same time interacting with JTWC forecasters as part of demonstration experiments to get feedback on product value.

The second area of directed research encompassed improvements in the understanding and approaches to satellite data assimilation towards realizing benefits in DoD NWP models. Working closely with expert scientists in the data assimilation and modeling groups at NRL-Monterey, research was focused toward better understanding the impact of assimilating AMVs, and to design numerical experiments and evaluate impacts.

Research Objectives and Summary of Accomplishments

Directed research area 1: Advancing the use of satellite data and products in Tropical Cyclone analysis and forecasting.

A. Refinements to the Advanced Dvorak Technique (ADT), an automated objective tropical cyclone intensity estimation algorithm using satellite data

Background: A prototype, computer-based, objective TC intensity estimation algorithm was developed and tested at UW-CIMSS under previous research grants from ONR/NRL (Velden et al. 1998; Olander and Velden 2007). The technique is based on objective IR cloud pattern recognition and statistical matching procedures, with enhancements from microwave inputs. The ADT is now an operational algorithm at

NOAA/NESDIS and is an integral part of the JTWC and NHC TC intensity estimation toolbox.

Approach/Accomplishments: Further algorithm modifications were necessary in order to correct for the deficiencies that still existed in the ADT algorithm. We refined the technique based on our performance analyses and user feedback from JTWC. A focus of this task was to adapt the ADT to operate more efficiently on systems designated as Sub-Tropical cyclones. ADT algorithm thresholds were modified to better perform on these cases to alleviate weak intensity estimation biases that emerged from the JTWC evaluation and validation studies. This ADT enhancement will be tested in a real-time trial during the upcoming 2017 TC season.

B. Furthered the exploration of satellite-based microwave information as tropical cyclone intensity estimation tools

Background: Passive microwave sensors offer a unique view of TC structure owing to their relatively low sensitivity to cloud contamination. Microwave sounders such as the NOAA Advanced Microwave Sounding Unit (AMSU) and the DMSP Special Sensor Microwave Imager Sounder (SSMIS) are good examples. Under previous NRL funding, microwave sounder information has been employed to exploit the relationship between measured warm core structures and tropical cyclone intensity (Brueske and Velden 2003; Herndon and Velden 2012).

In addition to the sounders, microwave imagers offer an important perspective on tropical cyclone structure and evolution. The signatures in passive microwave imagery from instruments such as the DMSP Special Sensor Microwave Imager (SSMI) and the

TRMM TMI have been used extensively in a qualitative mode by tropical cyclone satellite analysts to infer convective organization. CIMSS developed an algorithm ARCHER to objectively assess TC center-fix and structure information, which is now used to inform the sounder-based intensity estimates.

Approach/Accomplishments: The investigation of the AMSU warm core retrieval technique as a tropical cyclone intensity estimation algorithm continued by refining and adapting it to work with the SSMIS and ATMS scan geometry and antenna patterns. The resultant performance was characterized and documented. The effects of precipitation attenuation have been investigated, and the results of this work are now incorporated into the algorithm.

C. Refinements to the Morphed Integrated Microwave Imagery at CIMSS (MIMIC) Total Precipitable Water (TPW) product

Background. The MIMIC-TPW algorithm utilizes microwave retrievals of TPW to create seamless animations of the quantity, and the latest version is currently being demonstrated on the CIMSS tropical cyclone web site. The method is gaining weather community popularity in delineating analyses and trends in moisture from large-scale to TC-scales.

Approach/Accomplishments: Further work was needed to refine the algorithm as listed in the specific task accomplishments below. A new TPW retrieval method was successfully implemented. Upon successful demonstration of the advanced techniques, the algorithm packages will be available for implementation in operational environments.

D. Continued development and refinement of a consensus satellite-based tropical cyclone intensity estimation approach

Background: An ensemble approach to the problem of intensity estimation is being investigated by examining the properties and error characteristics of the available objective satellite-based methods and then creating a weighted consensus. By identifying the strengths and limitations of each approach, then intelligently combining the estimates, we are better able to diagnose the most representative picture of intensity trends over entire storm lifecycles (Herndon and Velden 2012). A latest version of such an objective algorithm (SATCON – SATellite CONsensus) is currently in test mode at CIMSS. Further work has been done to optimize the member weights, and add new members to the consensus as they are made available. The ultimate goal is to take advantage of the strengths of each independent method to develop an ensemble approach that yields superior collective intensity estimates.

Approach/Accomplishments: Further experiments have been performed to optimize the weighting of individual methods in the consensus approach in order to achieve reduced intensity estimation errors. We explored combining methods through information sharing (e.g., providing our AMSU technique with eye sizes from SSMI, ARCHER or ADT). The results of this study will be published, and the SATCON algorithm will be tested in a real-time trial with JTWC during the upcoming 2017 TC season. UW-CIMSS personnel will assist where necessary, and provide algorithm refinements as the needs are identified from the demo.

E. Development and application of a western North Pacific tropical cyclone validation dataset

Background. Since the discontinuance of recon flights into western North Pacific TCs in the mid-1980s, the development of satellite-based algorithms has had to rely primarily on validation campaigns in the Atlantic basin, with the assumption that these validation studies would be transferable to Pacific applications. Since there are identifiable differences in TC characteristics/behavior between the Pacific and Atlantic basins, it would be preferable to validate satellite algorithms applied in the Pacific with independent datasets collected in that basin. Although aircraft flights into western Pacific storms have been scarce since the mid-1980s, there have been a few research flights, and also many cases of storms making landfall at (or near) surface observation sites, and encounters with ships and ocean buoys. A thorough compilation of these data into a TC validation database would provide a very useful dataset for satellite algorithm evaluation, among other things.

Approach/Accomplishments. We have assembled in situ observations of western North Pacific TCs from multiple archive sources for a period dating back to 1995. Some of the observations collected were MSLP or wind only, and some were also not direct "hits" (eye passages). In these cases, we needed to explore wind/pressure relationships to estimate values from gradients, etc. The ultimate goal was to assemble a dataset sufficient to test and validate our satellite algorithms in the western North Pacific with direct in situ measurements of TC intensity. This collection is ongoing, with the sample now numbering in the hundreds.

Specific Proposal Task/Milestone Accomplishments

A. TC Intensity Analysis

i) Advance development of a CIMSS/NRL sounder-based algorithm to estimate TC intensity via microwave sounder observations. Specifically:

1) METOP-B, SSMIS and ATMS were added to the sounder intensity algorithm. Post-processing of passes was completed for storms with coincident aircraft ground truth data for calibration and tuning of the resulting sounder intensity estimates.

2) While ARCHER-based structure information has been updated and improved for the AMSU algorithm with good results, the position offset (bracketing) correction is still being evaluated. No statistically significant correlation with estimate error was found for the sensor field of view position offset for SSMIS or ATMS. This is likely due to the improved resolution of these sensors over AMSU and the mitigation of estimate error using the other bias corrections. In addition, the ARCHER position uncertainty begins to approach the position offset in many cases. The largest errors for this error source occur in the strongest storms with small eye diameters. However, ground truth for these types of storms has been lacking in the Atlantic in recent years, so more recent cases from 2015-2016 are being evaluated to determine if a more robust relationship between position offset and estimate bias can be determined by evaluating only the most extreme cases.

3) A rain scattering correction algorithm for SSMIS was investigated with the hope that it would improve intensity estimates. As with the bracketing correction, the estimate error from this source was determined to be small compared to other sources of error

(eye size, storm size, and ARCHER score). The scattering effect on the brightness temperatures in the environment is handled in the algorithm by computing the standard deviation of all temperatures in the ring used for the environment temperature and removing those that exceed 1 standard deviation.

ii) Continued development of an advanced passive microwave imager-based algorithm for TC center fixes (ARCHER).

1) The capabilities of ARCHER were enhanced to include probability distributions for position error and multi-platform assimilations of storm track. Extensive cal/val was reported in Wimmers and Velden (2016) for all satellite sensors, and is presented concisely in real-time on the ARCHER demonstration website as concentric rings of 50% and 95% probability locations.

B. Large-scale environmental moisture analysis (morphed MIMIC-TPW product)

1) We are now assimilating AMSU-B/MHS from NOAA-18/19, Metop-A/B, and Suomi ATMS using the MIRS retrieval to derive TPW over water, ice and land. Megha-Tropiques and AMSR-2 were not well suited to the scheme because they were not adequately calibrated to the other retrievals, and the five sources of MIRS retrievals are more than sufficient.

2) The original MIMIC-TPW Matlab code was replaced with Python for easier porting to potential operational platforms. The product is “MIMIC-TPW2”, which is shared on a separate website with more animation and data-access features. It performs a more advanced trajectory calculation on a separate processor, and lag time has been substantially reduced; processing time is now more than ten times faster.

3) The previous TPW retrieval method was computed locally and calibration was prone to drift over the course of several months. In our new version we use the MIRS retrieval, which is maintained by NOAA and is automatically adapted to channel degradation or loss. The most substantial adaptation that we undertook was to develop a post-processing correction to the MIRS product to reduce a “striping” artifact that resulted from AMSU-B sub-pixel sampling across a range of zenith angles.

Directed research area 2: Improvements in the understanding and approaches to satellite data assimilation towards realizing benefits in Navy numerical weather prediction (NWP) models.

Background: The potential for high-density wind observations derived from satellites (AMVs) to impact analysis and forecast operations has been demonstrated in previous research (Velden et al. 1998a; Goerss et al. 1998; Langland et al. 1999). Improved satellite-based instrumentation, evolved automated algorithms, and optimized processing/sampling strategies have led to better observations of the atmospheric state (Velden et al. 2005). This in turn has alleviated analysis deficiencies in many cases and resulted in a reduction of NWP forecast errors (Velden et al. 2017). While the positive impact of these data sets is encouraging, this impact is generally modest, and it is believed that additional impact can be realized with further understanding of the measurement errors and hence refinements to the data assimilation strategies.

The positive impact of AMVs on the NAVGEM analysis, as described by the adjoint-derived observation-impact (Langland and Baker 2004), is comparatively larger than that observed in other global analysis/forecast systems like the Environment Canada

DPS or the NASA GEOS-5 (Gelaro et al. 2010). This large AMV impact has often been assumed to be a positive aspect of the NAVDAS-AR's assimilation of AMVs, and other centers have made efforts to replicate it by experimenting with Navy-like assimilation (e.g. super-obs rather than thinned obs).

Early experiments in this project sought to further grow this observation-impact through adjustments to super-ob prism-size, adjustment of observation error, and other aspects of AMV assimilation, with no success. However, during experiments designed to investigate the impact of synthetic, high-quality pseudo-observation profiles from the ECMWF analysis, it was discovered that the NAVGEM analysis suffers from significant biases that may explain the large AMV observation-impact as an expression of this bias, rather than as an expression of superior assimilation.

Approach/Accomplishments:

1) Pseudo-Observation Experiments

NAVDAS-AR experiments consisted of assimilation of "pseudo-raob" profiles derived from analysis fields of the ECMWF Integrated Forecast System (IFS), made available through the THORPEX Integrated Grand Global Ensemble (TIGGE) archive. Analysis zonal wind (u), meridional wind (v), and temperature (T) grids are available every 0000 UTC and 1200 UTC at eight standard tropospheric pressure levels at one-degree resolution and were assimilated globally equatorward of 85 degrees latitude for a seasonal study from 20 April – 06 June 2013. Differences in the mean analysis between UVTOBS and Control show that assimilation of ECMWF analysis winds and temperatures in the form of pseudo-raobs produces a mean reduction of NAVGEM 500 hPa geopotential height globally, with largest height reductions in the southern hemisphere high latitudes (Fig. 1a) consistent with reduced mean temperatures in the low to mid troposphere (Fig. 1b). This represents a systemic difference between the ECMWF and NAVGEM analyses, corresponding to a systemic warm bias in the NAVGEM analysis that is most pronounced in the southern hemisphere polar latitudes.

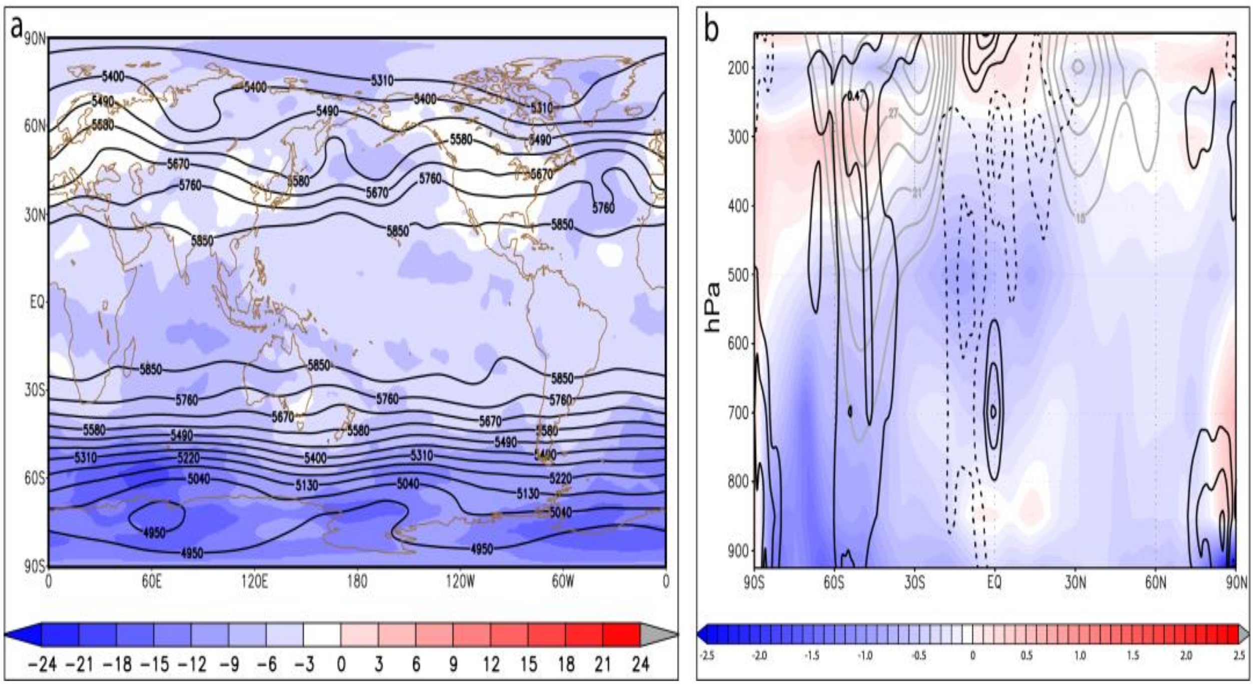

Figure 1. Mean analysis differences for all analyses (00Z, 06Z, 12Z, and 18Z) from 0000 UTC 20 April 2013 to 1200 UTC 6 June 2013. (a) Difference in 500 hPa geopotential heights shaded every 3 m (cool colors negative), with mean 500 hPa geopotential heights from the Control (black contours every 90 m). (b) Difference in zonal-mean temperature shaded every 0.1 K (cool colors negative), average zonal-mean wind speed from the Control (gray contours every 3 ms^{-1} starting at 15 ms^{-1}, and difference in zonal-mean wind (black contours every 0.2 ms^{-1}, negative contours dashed).

Removal of this bias in the NAVGEM analysis through assimilation of pseudo-raob profiles improved forecast skill scores for geopotential height RMSE in both hemispheres and tropical wind speed RMSE throughout the depth of the troposphere and through the entire 1-5 day forecast period, with statistical significance in the majority of these tests (not shown).

Assimilation of pseudo-raobs reduces the impact of all other observation types, with particularly large reductions in the impact of AMVs (Fig. 2).

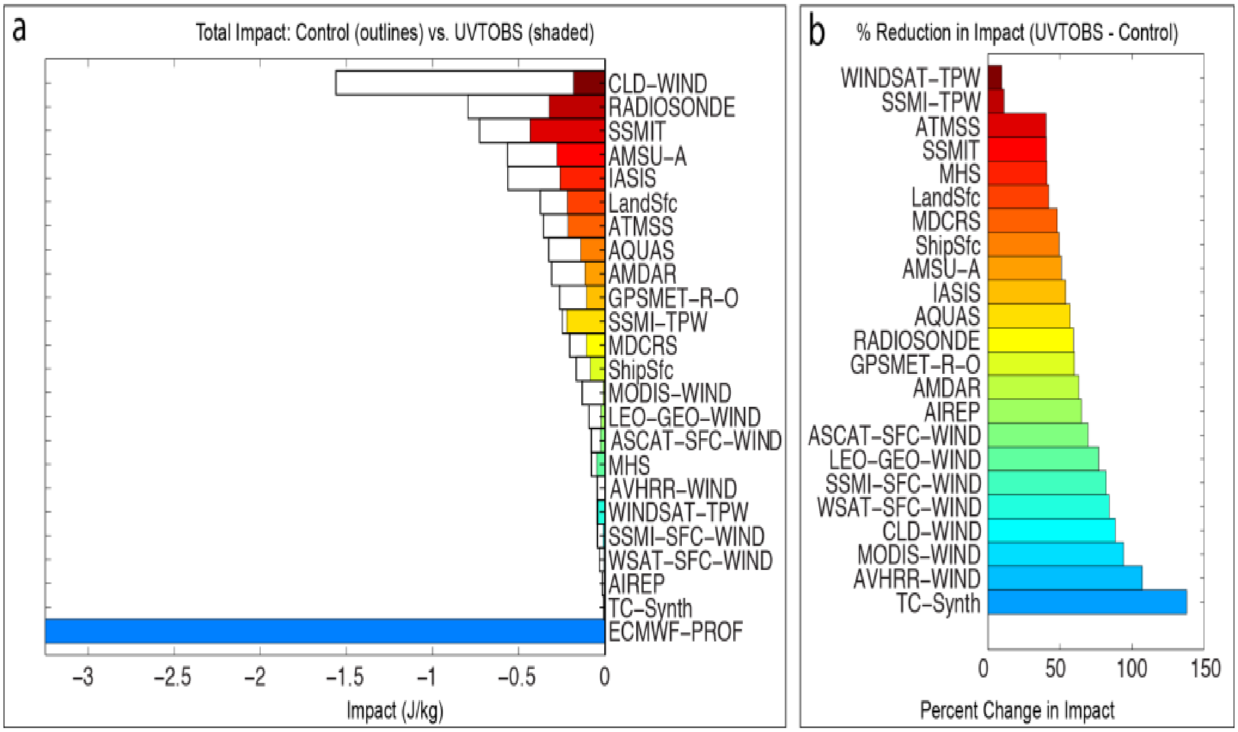

Figure 2. (a) Mean observation-impact (J kg^{-1}) summed over observation types for the Control (black outline of bars) and experiment (filled portion of bars). The impact of ECMWF pseudo-raobs is shown by the blue bar. Negative values indicate a reduction in 24 hr forecast error from assimilation of the observation type. (b) Percent change in observation-impact (experiment vs. Control) for observation categories. Values less than 100% indicate lower observation impact in the experiment. Mean impact is computed for all forecasts initialized 00Z, 06Z, 12Z, and 18Z between 0000 UTC 22 April 2013 – 1200 UTC 6 June 2013.

The severe reduction in AMV impact is an expression of the bias-correction provided by pseudo-raobs – at southern polar latitudes where the warm-bias is largest, the temperature observations available to correct the bias are mostly in the form of radiances, which are themselves bias-corrected against the model background, and as a result are incapable of correcting the bias already present in the background. Through thermal wind balance, the warm-bias is expressed as a slow-bias in the polar jet, where AMVs can constrain the analysis back toward reality through covariance between midlatitude wind errors and polar temperature errors, and this is the source of large AMV impacts. To confirm this hypothesis, a second experiment was run wherein only the pseudo-raob temperature observations were added to assimilation, and a similar reduction in warm-bias, forecast error, AMV impact - especially in the most poleward AMVs - was observed (not shown).

2. Radiance Bias Correction Experiments

Initial experiments were carried out to address the NAVGEM analysis warm-bias through radiance assimilation, by reducing the bias-correction against the model background used to adjust radiances. Bias coefficients from the pseudo-raob assimilation experiment were used in a new assimilation experiment containing no pseudo-raob assimilation, and the coefficients were kept constant on each analysis-cycle instead of allowing them to be updated through ob-minus-background statistics on each cycle. Early experiments confirmed that the resulting impact on the analysis is similar in-form to the assimilation of pseudo-raobs, with global reduction in mean 500 hPa geopotential heights, but distributed more equally across latitudes (Fig. 3).

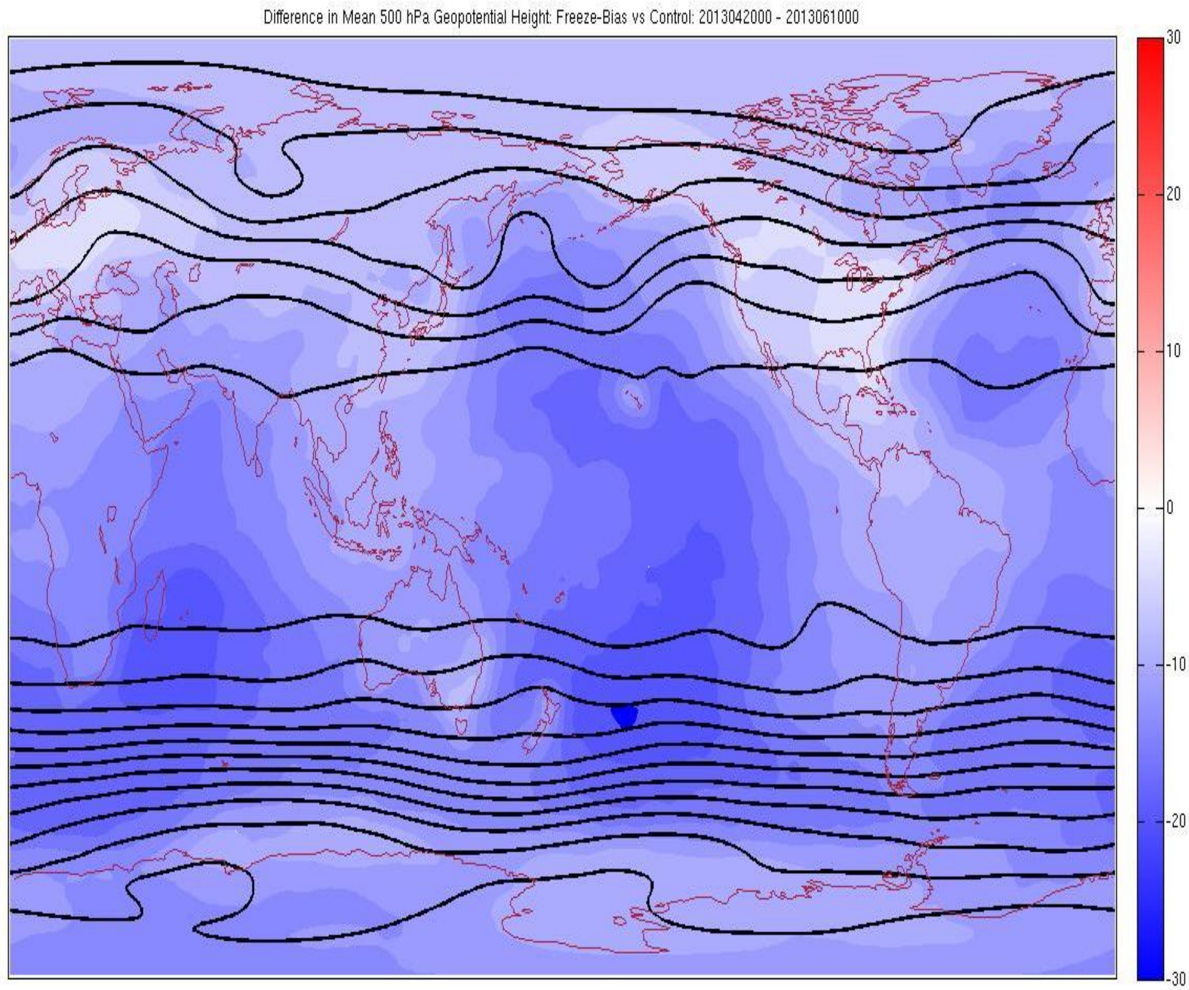

Figure 3. Mean 0000/1200 UTC analysis 500 hPa geopotential heights from the Control (contoured), and differences between Control and experiment with constant radiance bias-coefficients derived from the pseudo-raob assimilation experiment (shaded), for the period 0000 UTC 20 April – 0000 UTC 10 June 2013.

Initial experiments have yielded no significant forecast improvements, but new experiments designed to identify “anchor channels” with low observation-impact from bias correction are planned for the future under a new project.

Operational Implications and Transitions

As noted above, several of the objective algorithms developed and tested under this research initiative were made available for transition into operational environments. The ADT is now operational at the NOAA/NESDIS Satellite Analysis Branch. The TC intensity estimates are made available to Naval (and other) operational users through the Automated Tropical Cyclone Forecast (ATCF) conduit. The satellite-winds algorithm was ported to AFWA along with several significant upgrades. Other algorithms are set to be transitioned, such as the consensus intensity estimation method (SATCON), the TPW product (MIMIC-TPW), and the objective satellite-based TC center fix application (ARCHER).

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