Summary of Research
University Of Wisconsin-Madison

Project Title:	**Investigation of mesoscale flow fields in severe storm environments enabled by the development and multiple-application of high-resolution (space and time), research-quality Atmospheric Motion Vector fields derived from GOES-R multi-spectral imagery**
Award Number:	**NNX15AR61G (ROSES-2014 / Severe Storms Research)**
UW Internal IDs:	**MSN184900 / AAA4745**
For the Period of:	**7/31/2015 through 7/30/2018**
Principal Investigator:	**Christopher Velden**
Collaborators:	**Robert Rabin, NOAA/National Severe Storms Laboratory** **John Mecikalski, University of Alabama in Huntsville** **Kristopher Bedka, NASA/Langley Research Center** **Jason Otkin, University of Wisconsin** **Daniel Cecil, NASA/Marshall Space Flight Center** **Thomas Jones, OU-Cooperative Institute for Mesoscale Meteorological Studies** **Timothy Lang, NASA/Marshall Space Flight Center**
Date Submitted:	**7/13/2018**
Location:	**University of Wisconsin - Madison** **Space Science and Engineering Center** **1225 West Dayton Street** **Madison, WI 53706**
Reports will be sent to:	**Technical Officer: Ramesh Kakar** **Ramesh.k.kakar@nasa.gov** **Grants Office: NSSC-Grant-Report@mail.nasa.gov** **New Technology Office: hq-ntsr@lists.nasa.gov** **STIO/CASI: eft_ftp@sti.nasa.gov** **Closeout: NSSC-closeout@mail.nasa.gov**

SSEC Number (Internal) ***1457***

Inventions Report:

☒ No Inventions resulted from this award
☐ Yes

Inventory Report:

☒ No federally owned equipment is in the custody of the PI
☐ Yes

Publications:

Griffin, S., K. M. Bedka, and C. S. Velden, 2016: A Method for Calculating the Height of Overshooting Convective Cloud Tops Using Satellite-Based IR Imager and *CloudSat* Cloud Profiling Radar Observations. Journal of Applied Meteorology and Climatology 2016 55:2, 479-491.

Velden, C., W.E. Lewis, W. Bresky, D. Stettner, J. Daniels, and S. Wanzong, 2017: Assimilation of High-Resolution Satellite-Derived Atmospheric Motion Vectors: Impact on HWRF Forecasts of Tropical Cyclone Track and Intensity. *Mon. Wea. Rev.,* **145**, 1107–1125, https://doi.org/10.1175/MWR-D-16-0229.1

Zhang, S., Z. Pu, and C. Velden, 2018: Impact of Enhanced Atmospheric Motion Vectors on HWRF Hurricane Analyses and Forecasts with Different Data Assimilation Configurations. *Mon. Wea. Rev.,* **146**, 1549–1569, https://doi.org/10.1175/MWR-D-17-0136.1

Recent Conference Presentations:

Apke, J., J. Mecikalski and C. Jewett, 2018: Utilization of Atmospheric Motion Vectors for Deep Convection Cloud-Top Flow Analysis Using GOES-16 Imagery. Amer. Meteor. Soc. Annual Mtg.

Stettner, D., and C. Velden, 2018: Telescoping Down to the Convective Scales: Development and Application of AMVs. 14th International Winds Workshop.

Velden, C., and D. Stettner, 2018: Improved Monitoring of the Evolving Upper-Tropospheric Wind Fields Over the Core of Tropical Cyclones Aided by High Spatiotemporal Resolution GOES-16 Atmospheric Motion Vectors. 33rd AMS Conf. on Hurricanes.

Summary of Technical Effort:

The work plan for the 3-year effort supported under this project consisted of two major goals/milestones:

1) Participate in field campaign feasibility study team
   -- Technical report outlining feasibility and strategies of potential NASA-led severe weather field campaign was submitted.

2) Using simulated and real GOES-R/16 image datasets, conduct research and development of meso-AMV processing and sampling strategies for analyses of severe weather events
   -- Development and tuning of existing and new AMV algorithms/methodologies to provide high-density and quality AMV fields/products for impacting severe weather applications has been demonstrated.

With regards to Task/Milestone 1, the PI directly participated in workshops held to discuss and report on the feasibility of a NASA-led severe weather field campaign. The proposed project collaboration team, led by Dr. Amber Emory, delivered a final report with our findings and recommendations to Dr. Kakar. This report was later combined with a second team's report. Briefly summarizing the reports, the teams crafted a field campaign feasibility study that emphasizes the synergistic use of ground-based, airborne, and high-resolution GOES-R (now GOES-16) measurements to develop an improved three-dimensional understanding of the evolution of tornadic storms and their manifestation in GOES-R/16 products. Several experimental design and flight scenario options are described. The proposed campaign has the capability to improve the understanding of storm processes and provides an opportunity for NASA to play a role in basic and applied research using a spaceborne asset (GOES-R/16) that it played a leading role in developing. PI Velden was also on the GOES-R/16 team recently awarded the prestigious 2017 NASA Agency Honor Award.

Regarding the second milestone, our research team actively collaborated with Prof. John Mecikalski's group at the University of Alabama-Huntsville, Dr. Kris Bedka at NASA-Langley, and Dr. Robert Rabin at NOAA/NESDIS/NSSL. The Bedka collaboration resulted in a publication which examines a new and improved method to estimate overshooting cloud top heights in strong convective systems. In collaboration with Mecikalski, we explored advanced methods to derive high-resolution atmospheric motion vectors (AMVs) that can also be used to diagnose the cloud-top structure evolution in severe weather events. Structures in the anvil cirrus canopy can be tracked in super rapid scan imagery (which is routinely available with GOES-R/16) to deduce features such as cloud-top kinematic features, ageostrophic motions, developing blocked flow, and canopy-level divergence and vorticity trends. Collaborator Mecikalski and associate Apke have done preliminary diagnostic studies relating some of these features to severe weather occurrences using heritage tracking methods. Examples were shown in the interim reports. The AMV fields are now optimized to capture all of the flow features pertinent to the storm meso scales.

We continue to investigate this application using novel AMV derivation approaches being developed in collaborations with the GOES Risk Reduction program. These new methods are exploratory, and the effort now is to evaluate algorithm processing trade-offs, tuning of parameters that can affect the vector quality, and careful validation studies with the end goal of providing high-quality, meso-AMV datasets to the mix of observations for the proposed field campaign in 2019 or 2020. One proposed new method is the feasibility of using an optical flow technique to obtain AMVs at the top of thunderstorms, and this is has been tested using imagery from the GOES-14 satellite (SRSOR mode), and from GOES-16 Mesoscale sectors operating in 1-minute mode. Wind vectors are estimated using a "Classical Variational Optical Flow algorithm" obtained courtesy of the Computer Vision Group, Feiburg, Germany. The algorithm is derived from that described in *High accuracy optical flow estimation based on a theory for warping* by T. Brox, A. Bruhn, N. Papenberg, J. Weickert. *T. Pajdla and J. Matas (Eds.), European Conference on Computer Vision (ECCV) Prague, Czech Republic, Springer, LNCS, Vol. 3024, 25-36, May 2004.* Visible image pairs of 1 minute time separation have been utilized in this approach. The images have been remapped to equal latitude longitude grids before applying the algorithm. In the case of GOES-16 band 2 (visible) data, the grid spacing is .005 deg, approximately 0.5km. For GOES-14 band 1 data, the grid spacing is .01deg (1km). Wind vectors are derived at each grid point from the computed displacement along the eastward and southward directions between images.

This alternative approach to heritage AMV pattern matching is optical flow (Horn and Schunk 1981), which uses a fixed image neighborhood to derive motion. Assuming an object with constant brightness I is located at x, y with time t, then, with motion (u and v)

$$I(x, y, t) = I(x + u, y + v, t + 1) \qquad (1)$$

With a Taylor series approximation used on (1), we get:

$$-\frac{\partial I}{\partial t} = u\frac{\partial I}{\partial x} + v\frac{\partial I}{\partial y} \qquad (2)$$

Constraint 1 (and eq. 2) can be calculated at any image pixel box, however, the equation for one pixel is underdetermined, so only flow in the direction of the gradient can be resolved (aperture problem). The aperture problem is solved by applying (1), among other possible constraints, to an image neighborhood (rectangular group of pixels) and finding u and v in the field that minimizes a cost function (e.g. Lucas and Kanade 1981; Bresky and Daniels 2005). With GOES-16 60-sec data, optical flow cloud-tracking and AMV derivation is tractable.

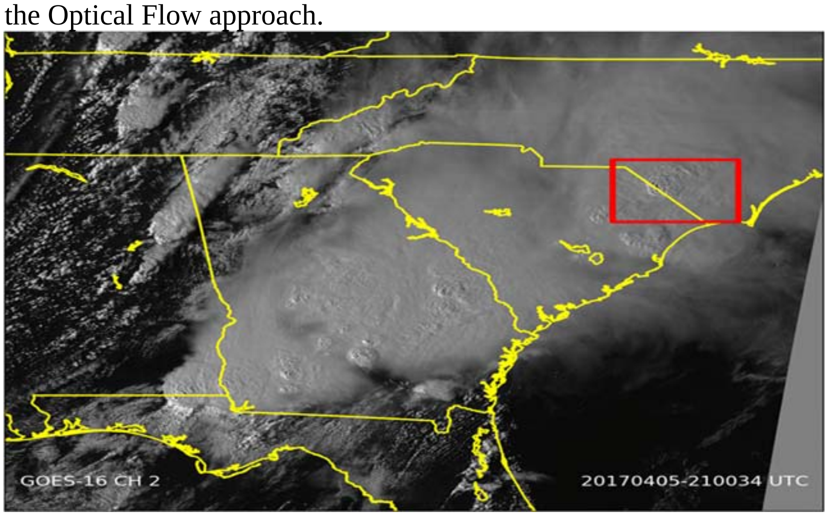
Cloud top pressure estimates are assigned to the AMVs at each grid point using the CLAVR-x (Clouds from AVHRR Extended) product. We have assessed the spatial characteristics of the cloud top/height pressure in the vicinity of thunderstorm anvils and overshooting tops for selected cases. Dave Stettner and Steve Wanzong (UW-CIMSS) have provided valuable support and guidance for this application.

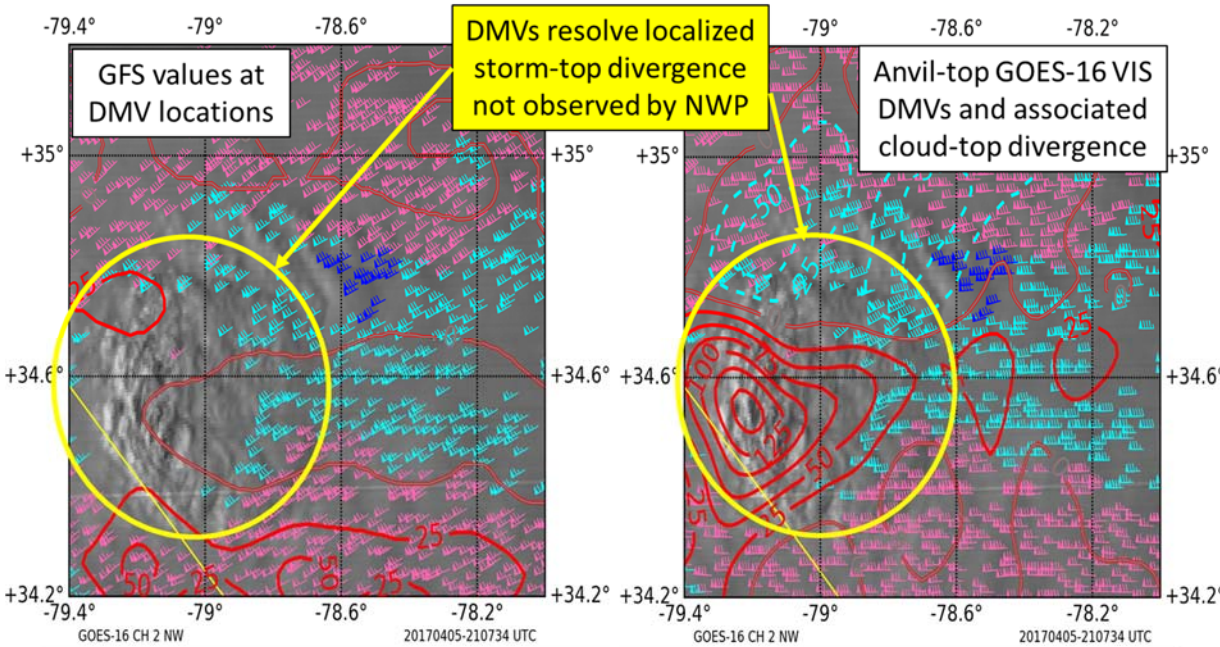
The modified strategy for mesoscale AMV processing to obtain enhanced coverage in severe weather environments (vs. routine full-disk processing) is the following:

- Increase AMV target density
  - Reduce target spacing and search box size
  - Reduce minimum gradient required for target identification
  - Disable coherency requirements
- Employ image triplets with higher spatiotemporal resolution
  - Full-res Vis (0.5km) and IR (2km)
  - Utilize 1-min. images (available from GOES-16 MESO scans)
- Utilize VIS to produce high-level cloud-top AMVs
  - Normally, VIS only used for low-level cloud tracking
- Relax QC constraints
  - Modify required Quality Indicators (QI) in some cases (band dependent thresholds, reduce/eliminate model agreement checks)

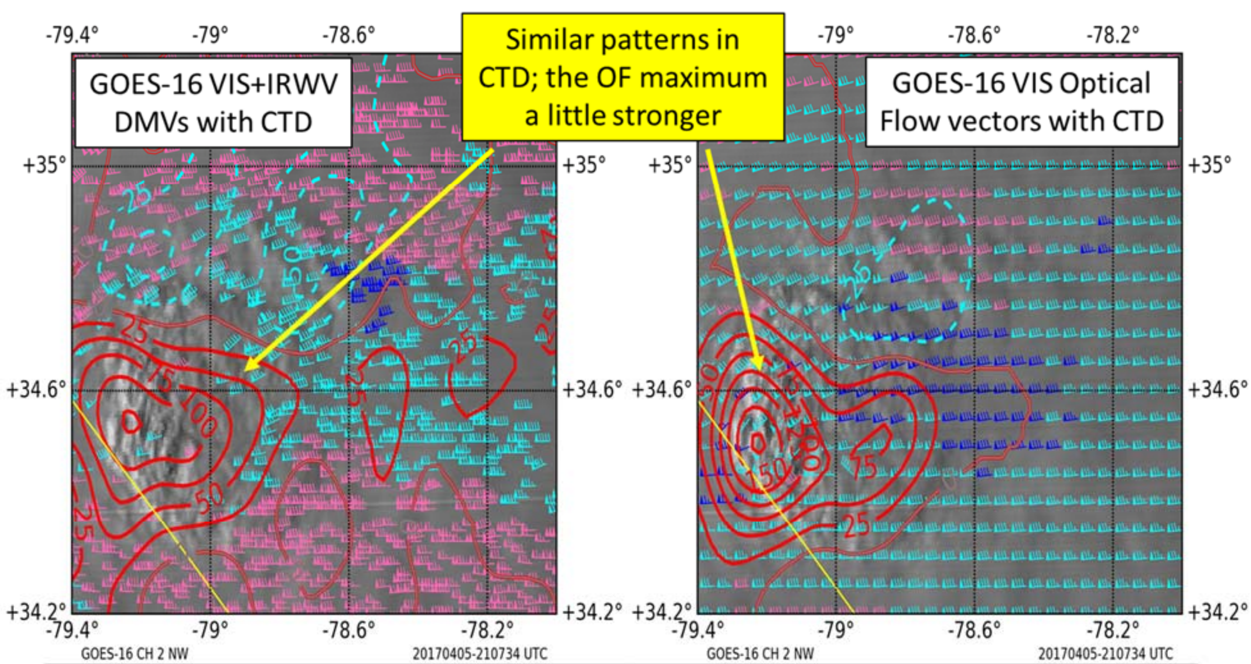
Several cases were processed with this strategy and methodology employed. From the analysis of a few supercell storms, cloud-top high speed winds were observed to develop rapidly downwind of overshooting tops within minutes of tornado formation. The high speed winds downwind of those regions may be indicative of strong outflow above the equilibrium level of intense updrafts. The strength of these winds may signal the intensity of the updrafts as they penetrate into the stratosphere and divergence flow intensifies. Ultimately, this information could be combined with GLM-enhanced lightning flash rate and 3-dimensional winds from weather surveillance Doppler radars to provide a multi-sensor analysis product.

An example is illustrated in the figures below. The case involved a severe weather outbreak over the southeastern US on 5 April 2017. Multiple supercells and reports of tornados and severe winds were observed. GOES-16 was not yet operational, but was in beta test mode and providing 1-min. meso sector scans over this region. AMVs were processed over the tornadic supercell (red box) using two methods: 1) Derived Motion Vectors (DMVs) from enhanced processing using the legacy NESDIS algorithm, and 2) the Optical Flow approach.



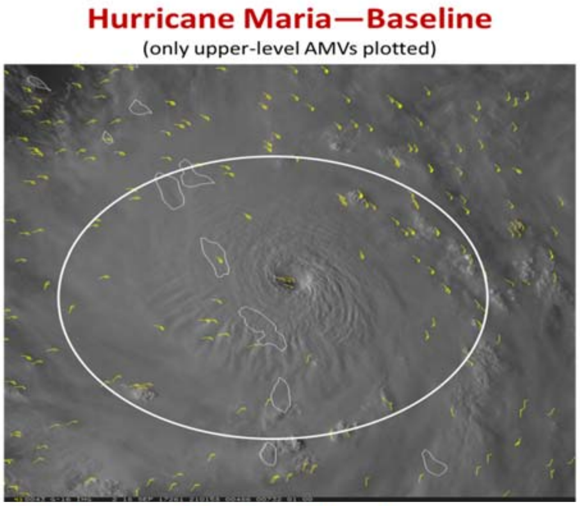


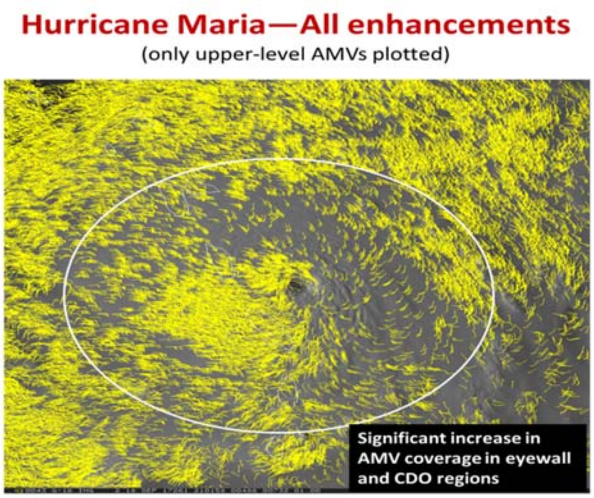
GOES-16 channel 2 VIS imagery of a storm over North Carolina on 5 April 2017 shown with GFS 6- hr forecast winds and associated calculated cloud-top divergence (*Left*) ,and derived GOES-16 VIS DMVs with divergence field (*Right*). The cloud-top divergence (CTD) is contoured with positive (negative) values in red (blue dash) every 25x10^{-5} s^{-1}, and vectors are colored by pressure, with pink representing vectors at pressure (p) 300 hPa > p ≥ 200 hPa , cyan at 200 hPa ≥ p > 175 hPa, and blue at 175 hPa ≥ p > 150 hPa.

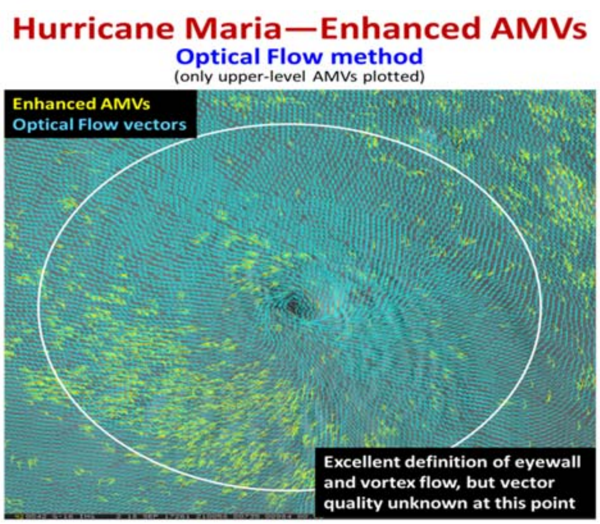


GOES-16 channel 2 VIS imagery of a storm over North Carolina on 5 April 2017 shown with GOES-16 VIS, IR and CTWV DMVs and associated CTD analysis (*Left*) and VIS Optical Flow vectors with CTD (*Right*). CTD is contoured with positive (negative) values in red (blue dash) every 25x10^{-5} s^{-1}, and vectors are colored by pressure, with pink representing vectors at pressure (p) 300 hPa > p ≥ 200 hPa , cyan at 200 hPa ≥ p > 175 hPa, and blue at 175 hPa ≥ p > 150 hPa.

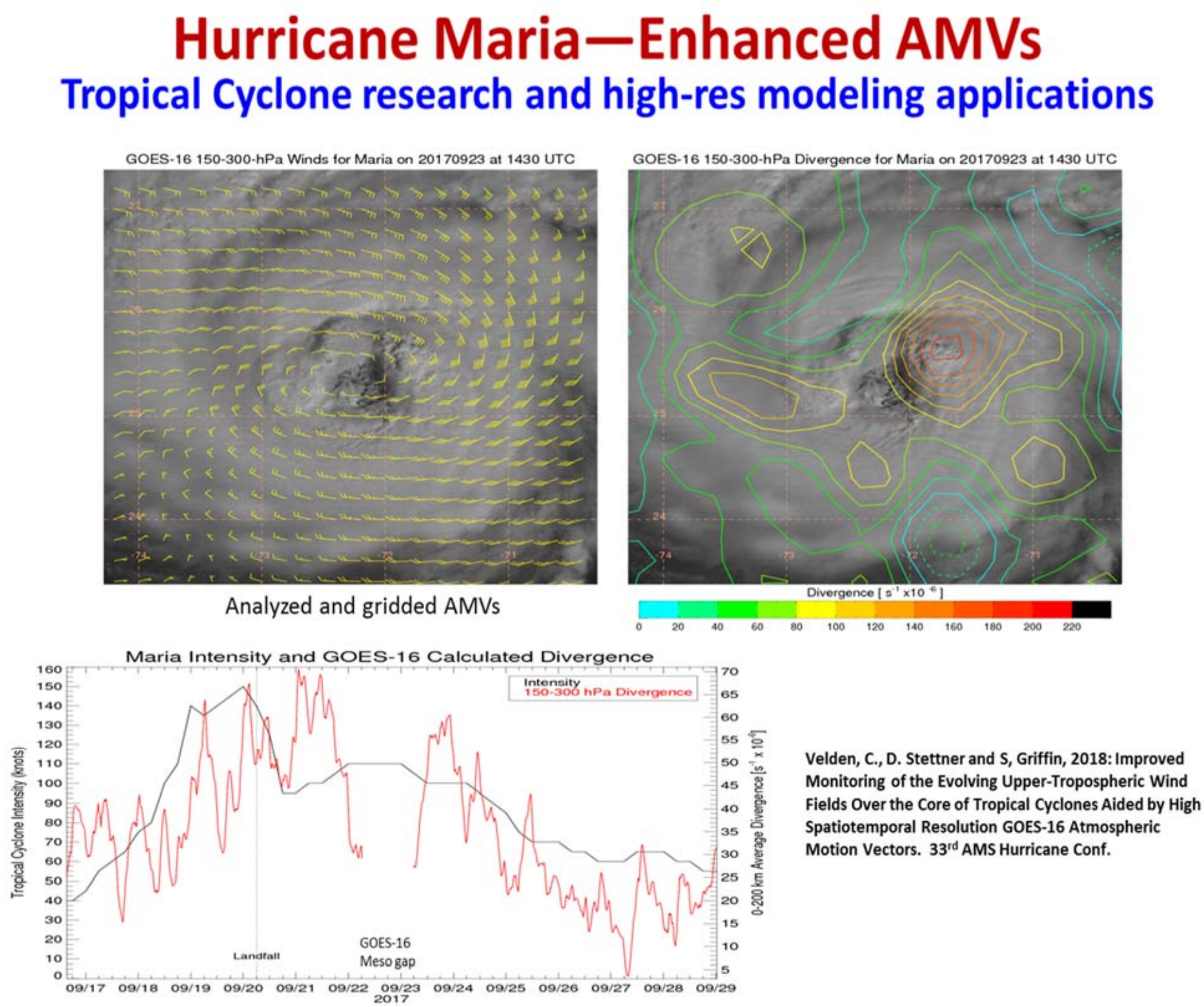
Another good candidate for the potential applications of the meso AMV processing strategies is hurricanes. As an example, Hurricane Maria in 2017 was tracked by the GOES-R/16 meso sectors for much of its lifetime. AMVs were processed utilizing both methods outlined above, at 15-minute dataset intervals and using the 1-min. meso scan imagery. An example of how the AMV coverage can be greatly enhanced over routine processing is illustrated below.







These AMV fields can be used for diagnostic purposes. For example:



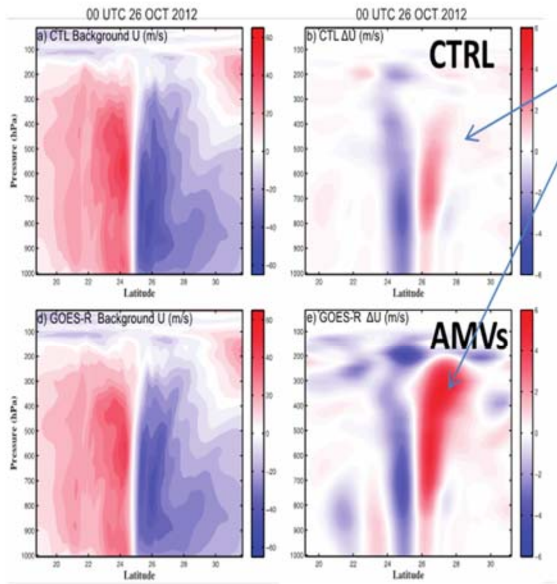
As shown above, upper-level flow fields over the TC core region are generally divergent, as expected, but localized regions of more intense divergence are also identifiable, likely associated with intense eyewall convective bursts.

The datasets can also be assimilated into high-resolution hurricane models to assess forecast impact and improve the initial analysis of the hurricane structure. For example:

Hurricane Maria—Enhanced AMVs

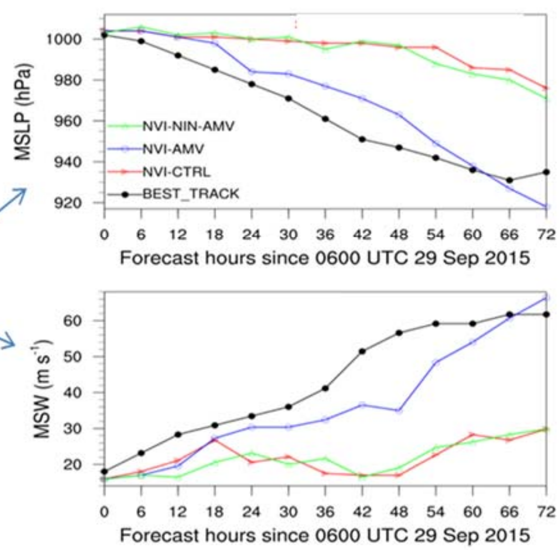
Tropical Cyclone research and high-res modeling applications

Two recent studies using enhanced AMVs in the Hurricane WRF (HWRF) model



Velden, C., W.E. Lewis, W. Bresky, D. Stettner, J. Daniels, and S. Wanzong, 2017: Assimilation of High-Resolution Satellite-Derived Atmospheric Motion Vectors: Impact on HWRF Forecasts of Tropical Cyclone Track and Intensity. *Mon. Wea. Rev.*, 145, 1107–1125.

Zhang, S., Z. Pu and C. Velden, 2018: Impact of Enhanced Atmospheric Motion Vectors on HWRF Hurricane Analyses and Forecasts with Different Data Assimilation Configurations. Accepted in Mon. Wea. Rev.



Top: Assimilated enhanced AMVs lead to stronger vortex zonal wind component increments in the HWRF cycle during Hurricane Joaquin (2014), and subsequently improved intensity forecasts. Bottom: Assimilating enhanced AMVs in all HWRF nested domains including the inner vortex region yields better Hurricane Joaquin intensity forecast impacts (blue) vs. CTRL (no enh AMVs, red) and assimilation of AMVs only in the outer HWRF domains (green).

Overall project summary and findings:

- Retrieving AMVs in mesoscale flow environments offers unique challenges, but these are often important dynamic regions associated with hazardous weather events
- Regional (e.g., mesoscale/hurricane) weather forecast models and their associated data assimilation systems are now becoming convective-scale, demanding observations on these scales
- Advanced and recently-available satellite imagers that offer increased spatiotemporal sampling and solid navigation/co-registration, along with customized AMV processing, can help meet these challenges
- Tracking of cloud motions with modified processing strategies to produce enhanced AMVs using high spatiotemporal imagery such as from the GOES-16 meso sector scans can allow for detailed diagnoses of deep convection cloud-top flow kinematics
- The optical flow method produces more vectors over turbulent deep convection tops and results in stronger divergent flow than the legacy method, but the validity of these winds needs to be confirmed through more extensive radar and aircraft comparisons, etc.
- Work is underway (Apke et al.; Velden et al.) to experiment with finer detail analyses of the meso AMVs (down to ~5 km features will be resolved)