Demonstrations in Satellite Product-Infused Dense Optical Flow Winds and Motions for Earth and Atmospheric Sciences

Jason Apke, Steven Miller, Matthew Rogers, Yoo-Jeong Noh, Kyle Hilburn, Yoonjin Lee [1], Bill Line[2], and Kristopher Bedka[3]

[1] Cooperative Institute for Research in the Atmosphere (CIRA), Fort Collins, CO

[2] NOAA/NESDIS/STAR/Regional and Mesoscale Meteorology Branch, Fort Collins, CO

[3] NASA Langley Research Center, Hampton, Virginia

Introduction

- **Optical Flow Definition:**
  "The distribution of apparent velocities of movement of brightness patterns in an image" (Horn and Schunck 1981)
- "Dense" optical flow (DOF): Motion from EVERY image pixel
  - ➢ Retrieval enabled for cloud/water-vapor motions by rapid scanning (≤ 5 min) on new generation geostationary satellites
- When navigated & height assigned, DOF demarcates tropospheric winds
- Wind obs. inform on cloud-processes, aerosol and pollutant transport, and the global circulation, and routinely improve NWP model initial states

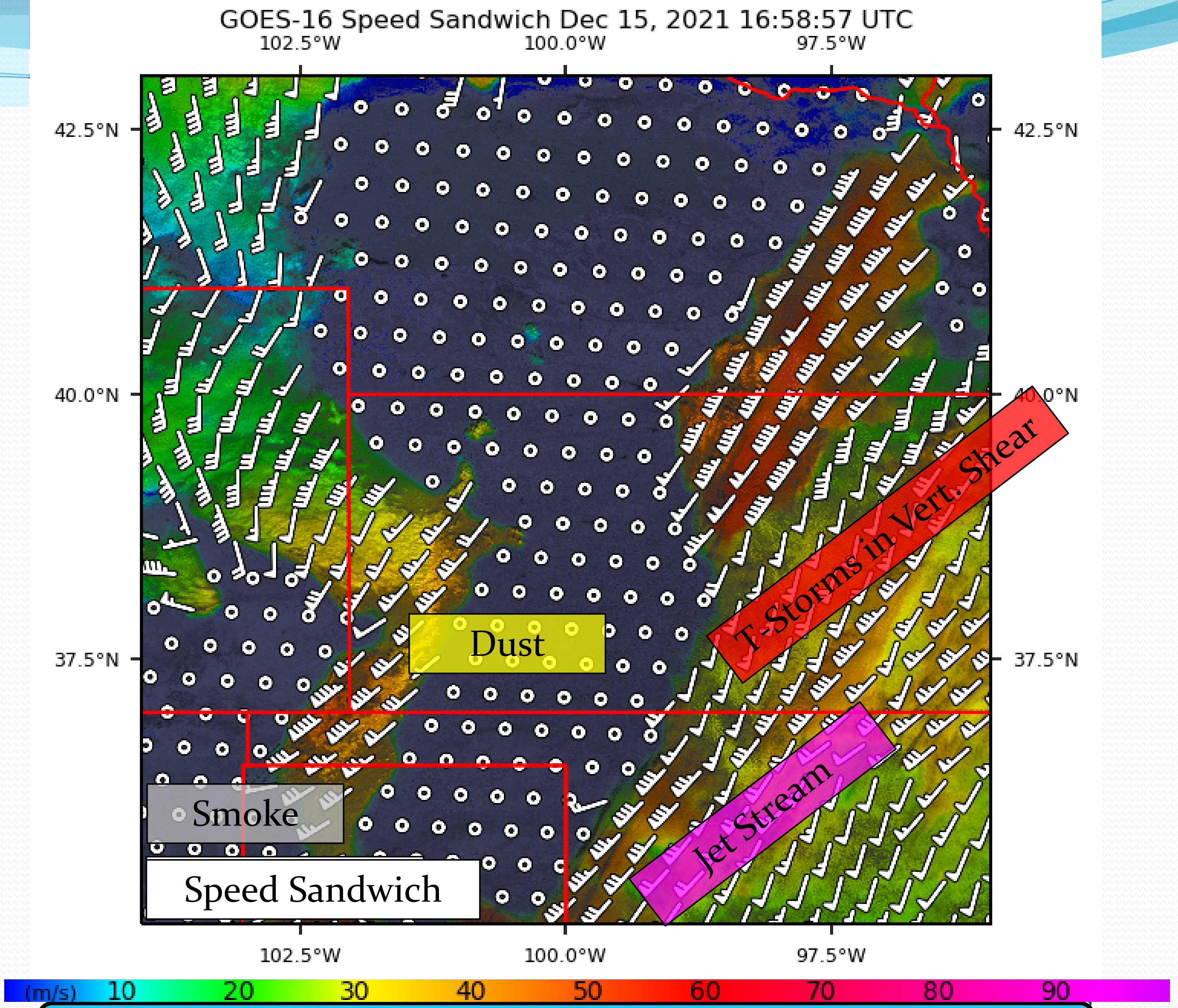


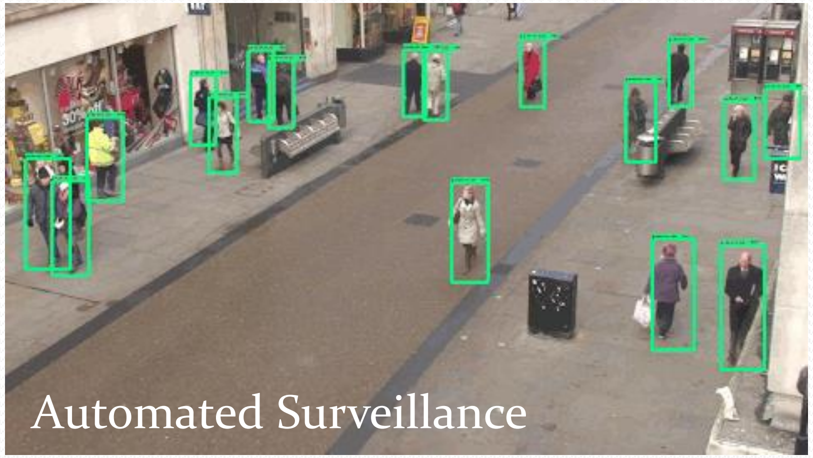
Figure 1. GOES-16 Ch-02 0.64 μm imagery plotted with optical flow winds (white barbs) and the speed sandwich product over a strong low-pressure system in the Central Great Plains.

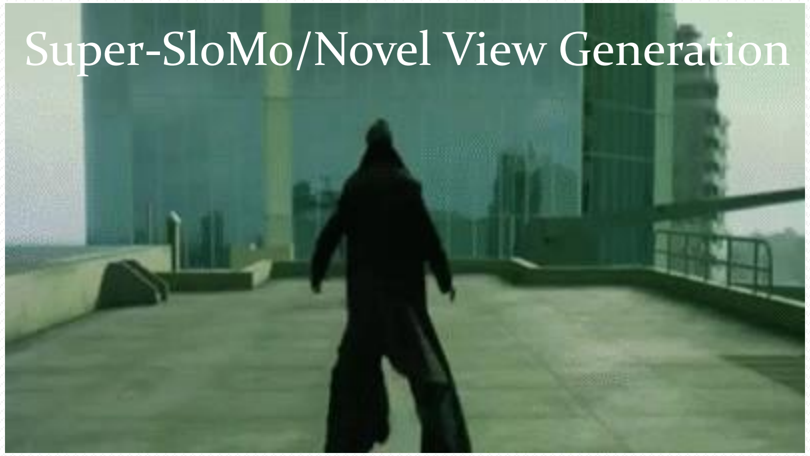
OCTANE Research at CIRA

- "***Dense Optical Flow Derivation Development and Applications for Fine-Temporal Resolution Satellite Imagery***" (NASA-NIP; PI: J. Apke, CIRA)
  1. "Explore approaches and capabilities of novel Dense Optical Flow algorithms tailored to motion derivation from new-generation satellite imagery sequences"
  2. "Produce and validate satellite-derived Dense Optical Flow applications"
- ***Advanced-Concepts Enabling Situational and Hazards Awareness, via Imagery*** (ACES-HAI; NOAA/GOES-R; PI: S. Miller, CIRA)
  1. "Deliver advanced multispectral imaging capabilities for ABI…" (including products from Dense Optical Flow)"…leveraging a versatile multi-dimensional blending technique"
- "***Using JPSS for New Understanding of Multilayer Water Vapor Transport***" (NOAA/JPSS; PI: J. Forsythe, CIRA), "***Night Research and Innovation from the Day/Night-Band for Environmental Remote Sensing***" (Night RIDER; NOAA/JPSS; PI: S. Miller)

What is OF used for?

Outside of Satellite Remote Sensing, OF has been developed for 40 years in support of applications such as…

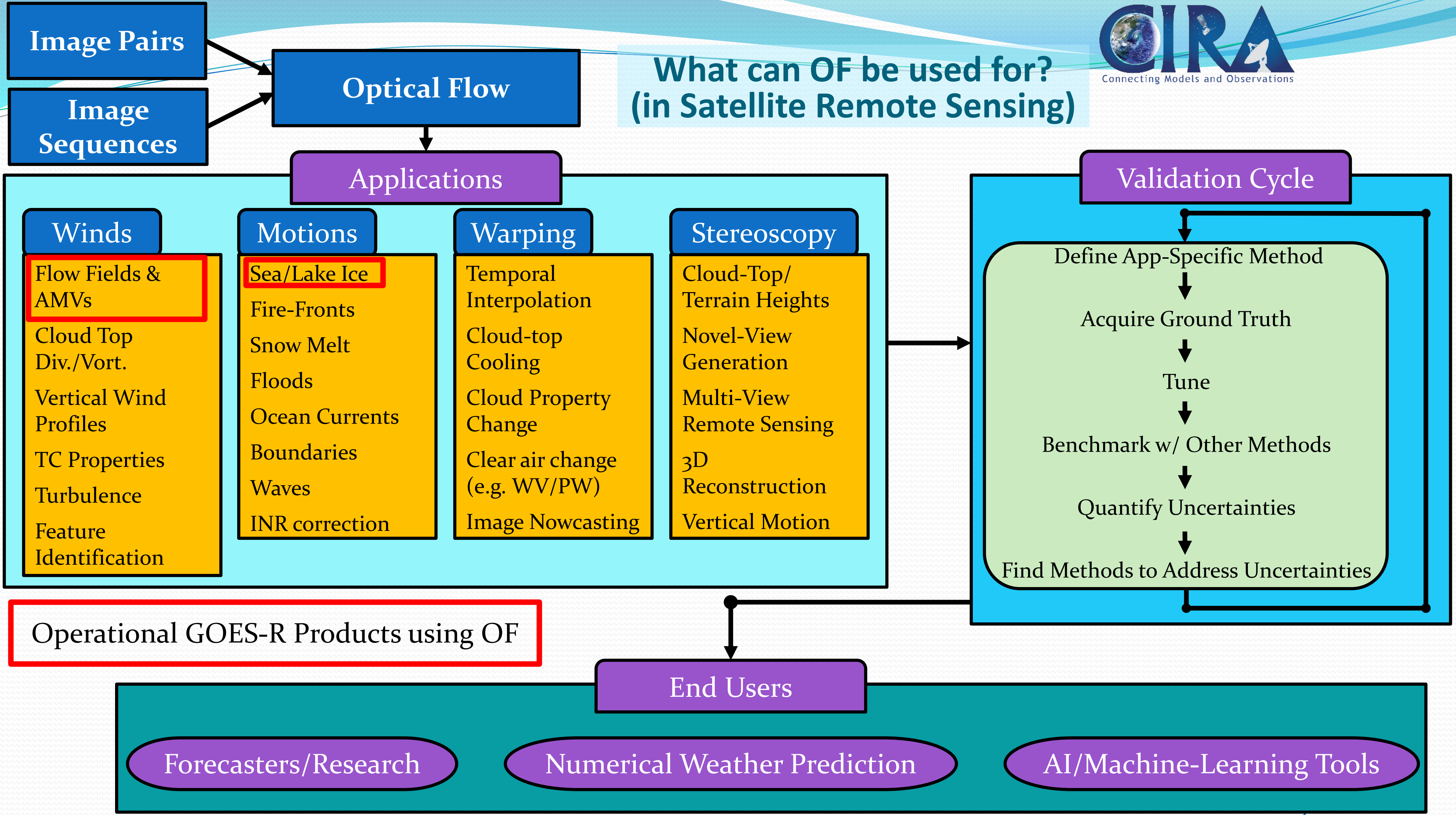




Sources (top left to bottom right): media.giphy.com, medium.com, androidpolice.com, Tao et al. (2012), metro.co.uk, gifs.com (The Matrix; 1999)

What can OF be used for?
(in Satellite Remote Sensing)

Connecting Models and Observations

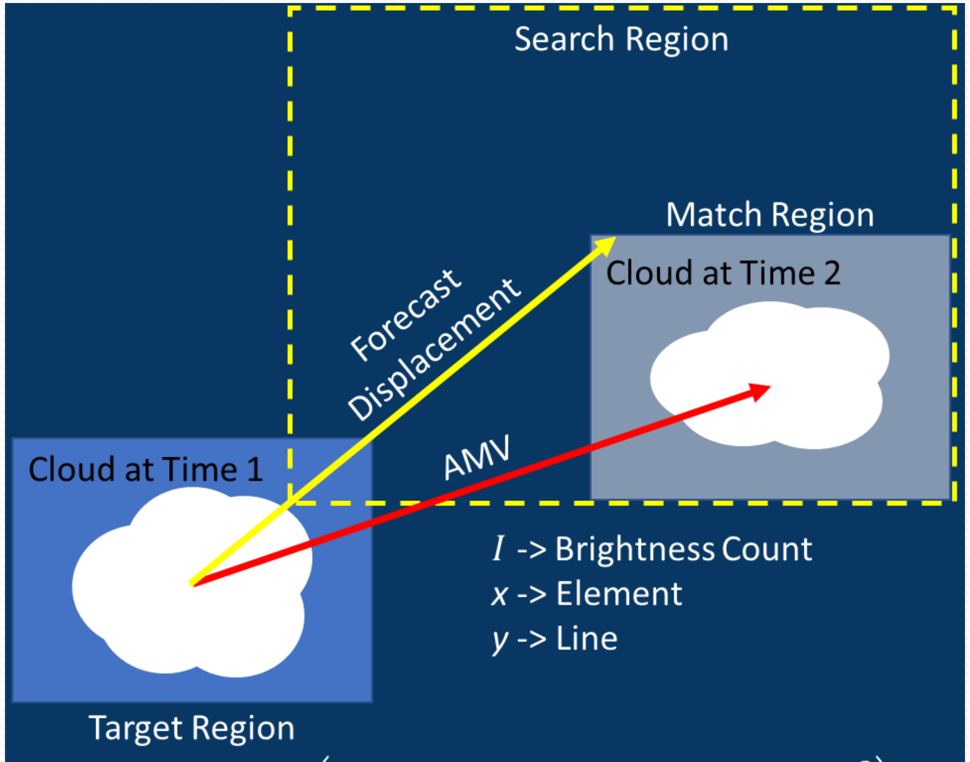


Optical Flow in GOES-R

Connecting Models and Observations

Atmospheric Motion Vectors (AMVs) use a 4-step "Patch Matching" retrieval method

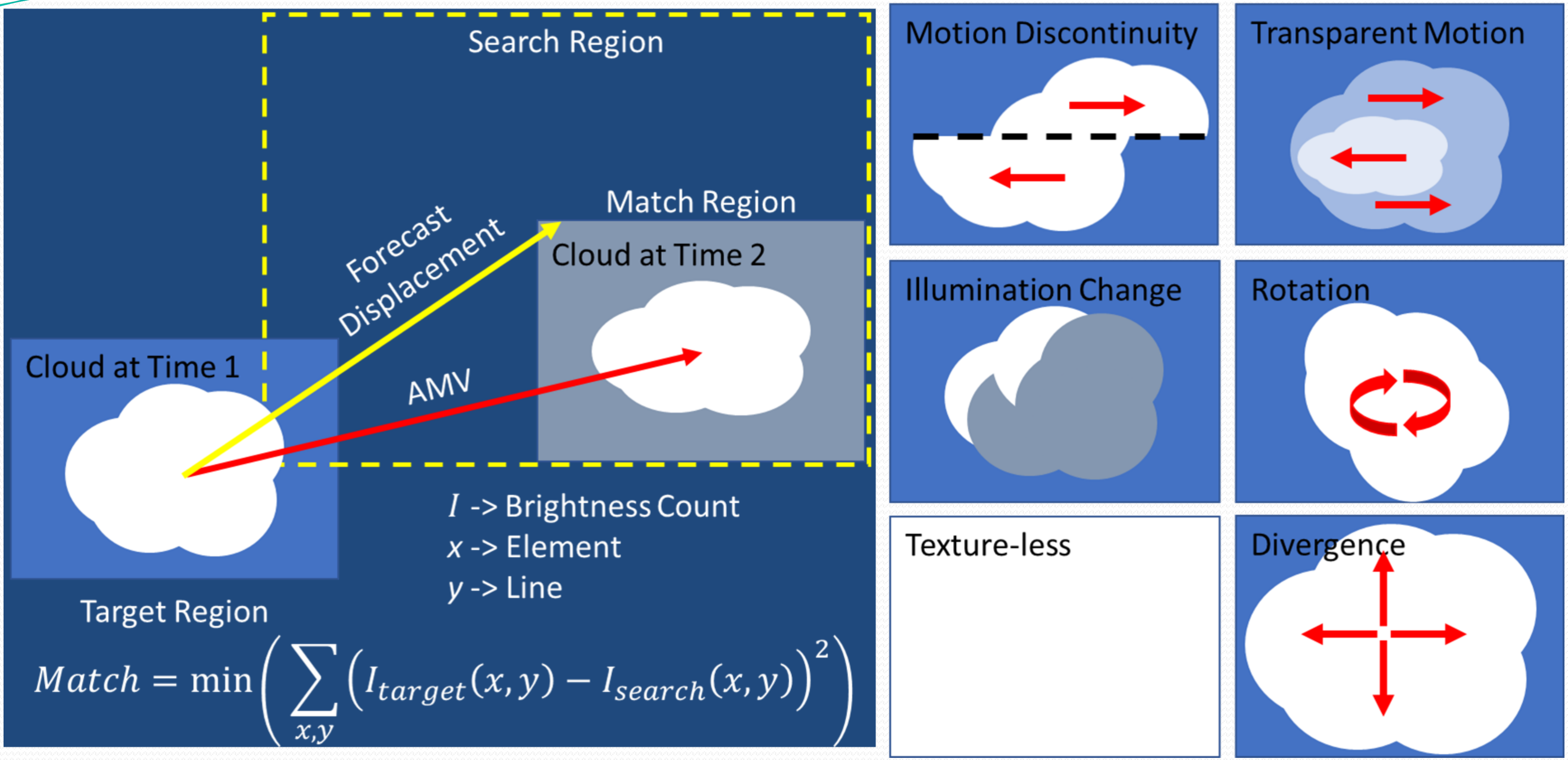
1. Identify target in VIS/IR/WV imagery
2. Height assign target with Numerical Weather Prediction (NWP) fields, and estimate forecast displacement with background wind
3. Identify the target in next image w/ least-squares/cross-correlation (the "optical flow" step)
   - GOES-R algorithm clusters tracked results over a larger target area
4. (Optional) Implement quality control to prune results, required because…



$$Match = \min\left(\sum_{x,y}\left(I_{target}(x,y) - I_{search}(x,y)\right)^2\right)$$

Figure 2. Schematic of Atmospheric Motion Vector optical flow derivation. In practice, this is performed twice, forwards (like that shown above) and backwards in time, and the two AMVs are used for quality control and then averaged to produce a final motion estimate (Adapted from Bresky et al. 2012).

Optical Flow in GOES-R



$$Match = \min\left(\sum_{x,y}\left(I_{target}(x,y) - I_{search}(x,y)\right)^2\right)$$

...this approach fails if → Any one of these happen

*Operational AMVs are VERY GOOD at pruning bad targets, and are thus considered a “Sparse” optical flow algorithm

Advancements in OF Retrieval

- New OF retrieval techniques relax inherent assumptions in operational OF techniques
- Variational OF retrieval, for example, works by minimizing a penalty function E over every image pixel Ω at once, so:

$$E(I_1, I_2, u(\boldsymbol{x}), v(\boldsymbol{x})) = \int_{\Omega} Data(I_1, I_2, u, v) + Smooth(u, v)\, d\boldsymbol{x}$$

- $Data$ is smaller when u,v tracks consistent features (e.g. brightness, gradients)
- $Smooth$ is larger when motion estimate u,v is inconsistent in some way with it's neighbors (note, w/ no texture, Smooth can dictate the solution!)
- Returns u, v at every pixel, makes no assumptions on local flow shape, can be designed to preserve motion discontinuities and properly handle flow deformations, illumination changes and texture-less scenes (Black and Anandan 1996, Corpetti et al. 2000, Brox et al. 2004, Zimmer et al. 2011, Sun et al. 2014)
- Accurate minimizations ordinarily require small displacements and predictable feature evolution (no condensation/evaporation), which is why these techniques are enabled by the resolutions of instruments like the GOES-R Advanced Baseline Imager

OCTANE

- CIRA developed the Optical Flow Toolkit for Atmospheric and Earth Sciences (OCTANE) for use on satellite imagery sequences (MURI/ONR "RAM-HORNS"; PI: Steve Miller) (also see Apke et al. 2020)
- Contains several GPU-accelerated variational OF retrieval algorithms, (e.g. Zimmer et al. 2011):

$$E(u(\boldsymbol{x}), v(\boldsymbol{x})) = \iint_{\Omega} \rho_d(BC + \gamma\, GC) + \alpha\, \rho_s(SC) d\boldsymbol{x}$$

BC = Brightness Constancy -> $C_1\, |I(\boldsymbol{x}+\boldsymbol{U}, t+\Delta t) - I(\boldsymbol{x}, t)|^2$

GC = Gradient Constancy -> $|C_2(I_x(\boldsymbol{x}+\boldsymbol{U}, t+\Delta t) - I_x(\boldsymbol{x}, t))|^2 + |C_3(I_y(\boldsymbol{x}+\boldsymbol{U}, t+\Delta t) - I_y(\boldsymbol{x}, t))|^2$, γ = weight of GC

SC = Smoothness Constraint -> $|\nabla u|^2 + |\nabla v|^2$, α = weight of SC

The $\rho_d(x^2) = \rho_s(x^2) = \sqrt{x^2 + \varepsilon^2}$ are "Robust Functions", and $C_1 = \frac{1}{|\nabla I|^2 + \epsilon}$ and $C_2 = \frac{1}{|\nabla I_x|^2 + \epsilon}$ and $C_3 = \frac{1}{|\nabla I_y|^2 + \epsilon}$

Mitigates motion caused by illumination changes & preserves discontinuities

- These constraints can be modified within OCTANE to take advantage of advanced satellite products which help identify specific motions
  - Modified Smoothness Constraint: The flow of any given pixel is close to that of surrounding pixels with similar cloud-top heights / classifications (cloud/snow)
  - Modified Brightness (Gradient) Constancy: The brightness (gradient) from multiple channels on an imager remains constant with time
- Product infusion can happen before, during, or after optical flow computation
- GPU acceleration enables practical real time computation

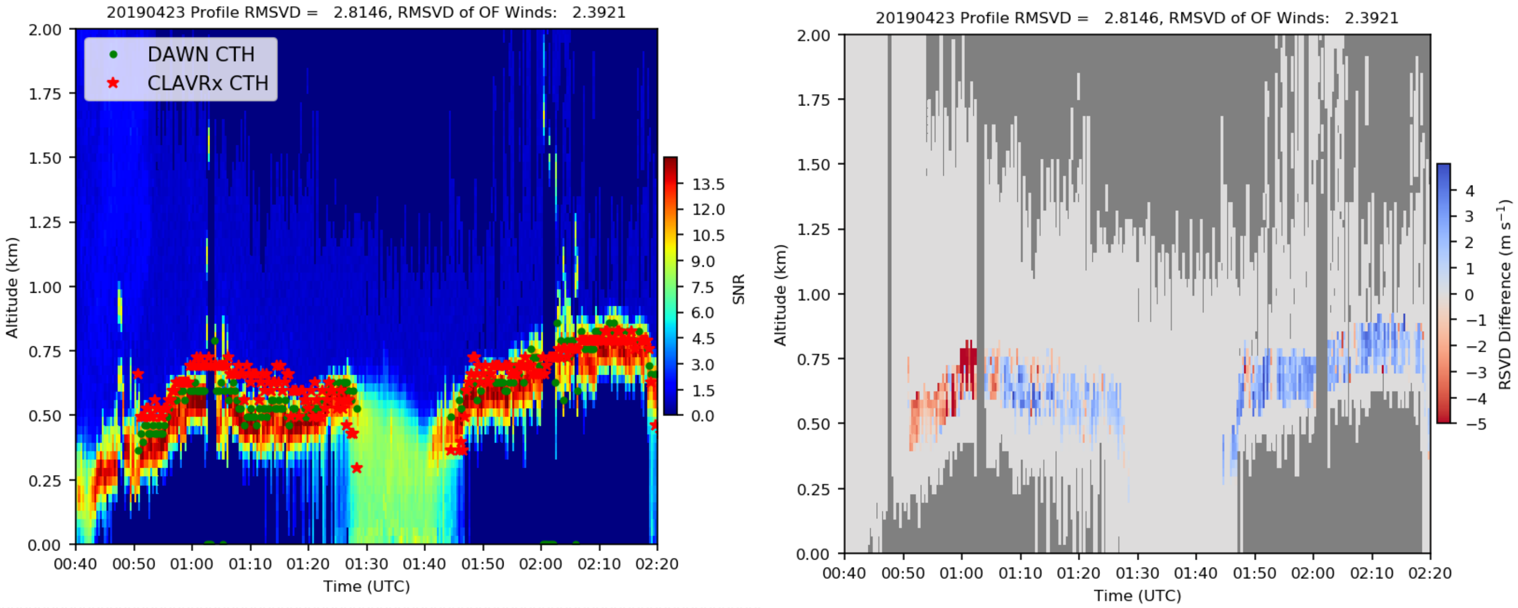
Apps Under Development

1. OF Winds
   - OF displacements in visible/IR are navigated to m/s
   - Can be combined w/ cloud-top height assignment from ECTH or used for RGBs
   - Validated & Tune w/ ancillary ground truth (i.e. Rawinsondes, Wind Profilers)
2. Cloud-Top Cooling
   - OF Displacements used to track visible features through time
   - Cooling in 10.3 μm over 5-min period returned (for tasks like CI nowcasting)
   - Not sensitive to merging/splitting like segmentation-based cooling algorithms
3. Temporal Sharpening
   - OF motions are used on 5-min imagery to approximate intermediate scans (Baker et al. 2011)
   - Good for subjective interpretation of motions & OF validation
4. Cloud Object Nowcasting
   - OF motions are used to nowcast cloud locations

OF Tuning

- Winds are tuned/validated by filling wind columns along the Lidar track with estimates from DOF products
  - Challenges both tracking AND height assignment!
  - Encourages dense multi-layer winds solutions
  - Benchmarks techniques with one clean score (Root mean square vector difference)
- In general, DOF winds validate within ~3-4 m/s RMSVD

Figure 3. (*Left*) Wind profiling Lidar (DAWN) Signal-to-noise ratio and cloud-top heights (shading/green circles) compared to DOF/NOAA Enterprise cloud-top heights (CLAVRx) along the track of the NASA DC-8. (*Right*) DOF wind estimate improvement (m s^{-1}) over a model background guess of the wind profile, with improvements (deteriorations) shown in blue (red).



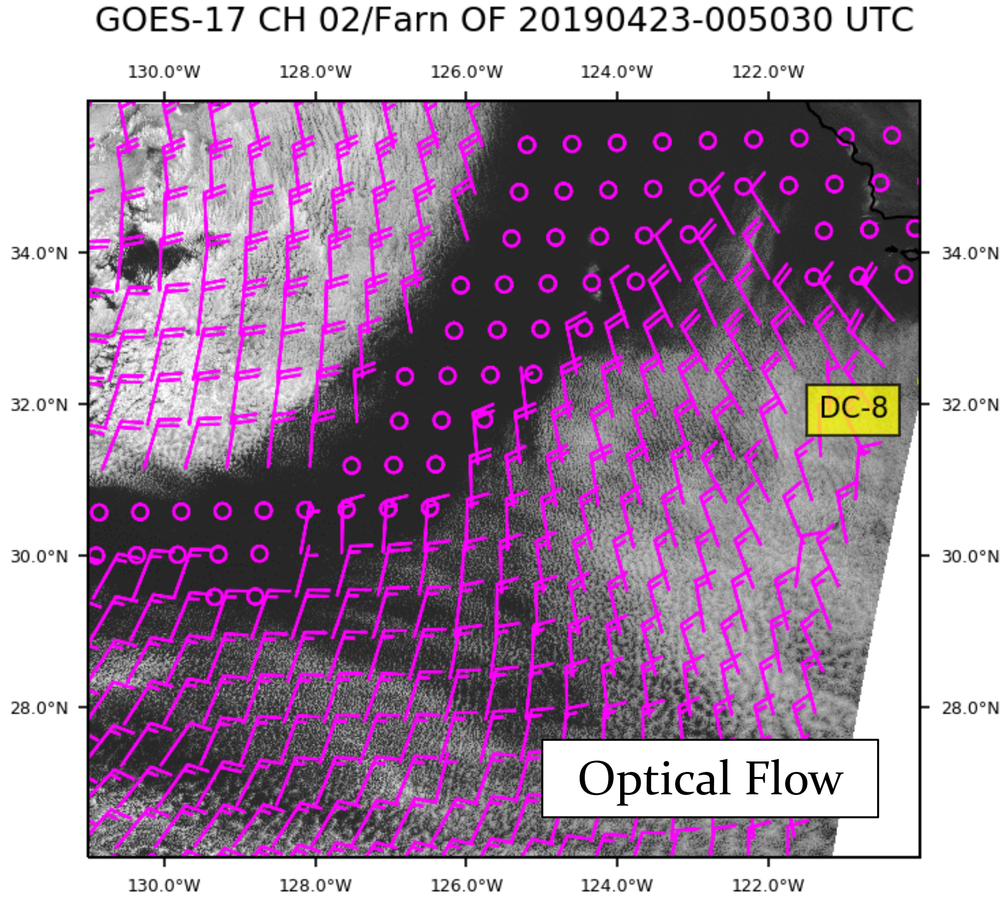
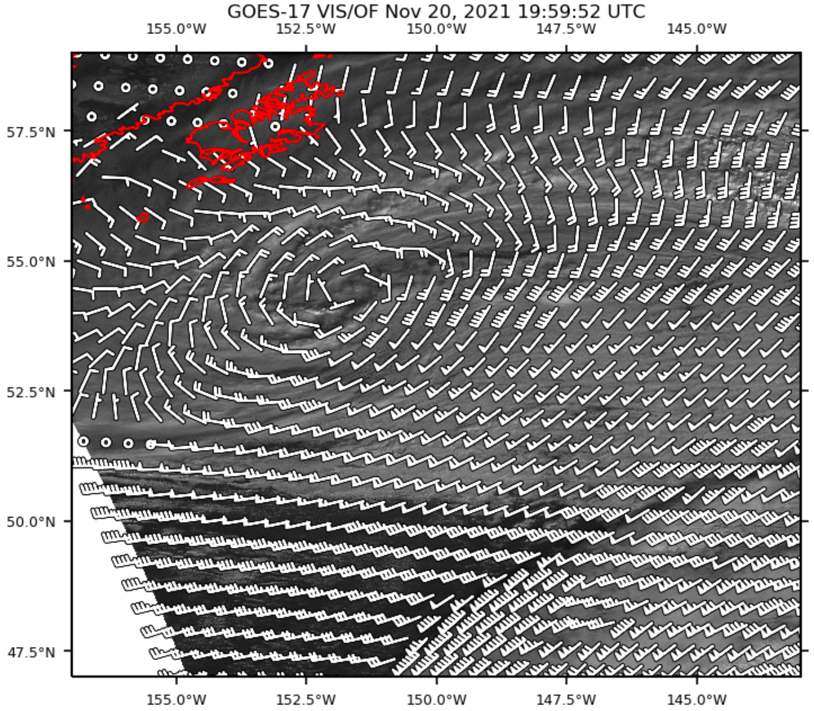


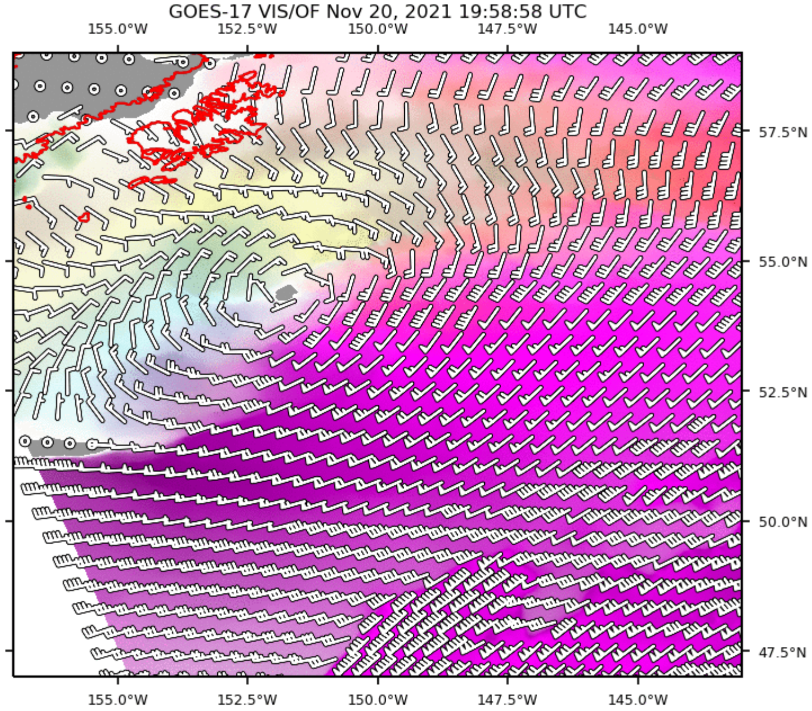
Figure 4. GOES-17 Ch-02 0.64 μm imagery plotted with 1-min DOF, shown with the track of the NASA DC-8 carrying the DAWN wind profiler.

OF Plotting

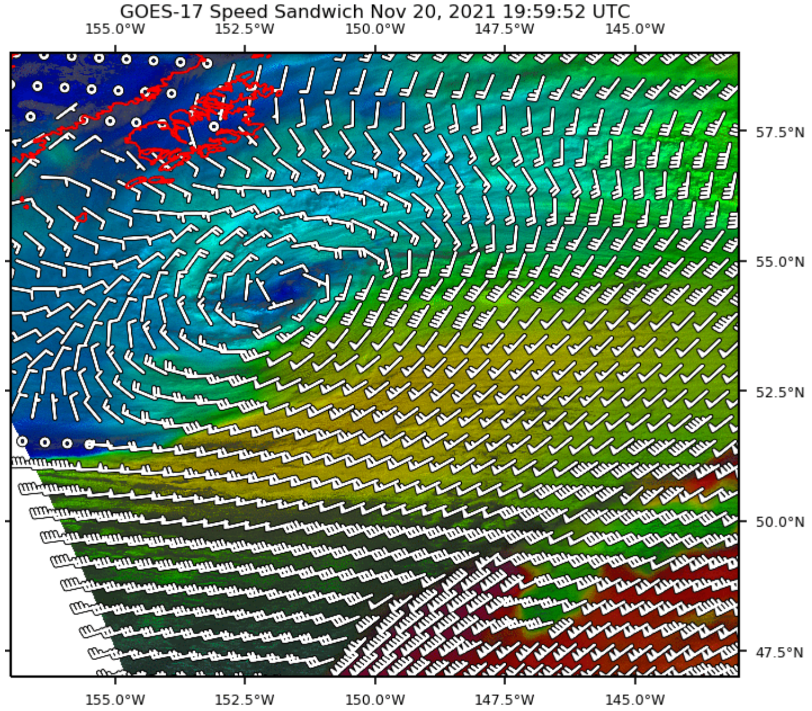
Barbs (Conventional)



Color Shaded Speed/Direction

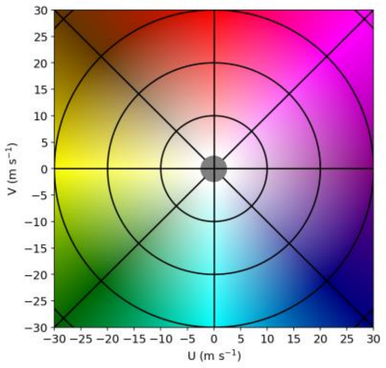


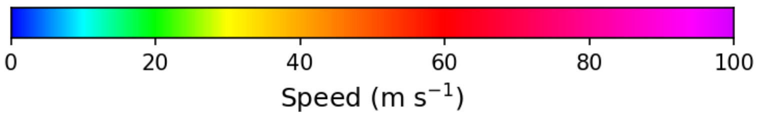
Speed/Imagery Blends (Exp.)



Advantage:
Interpretability
Disadvantages:
Cannot highlight dense motions
Noisy with slower motions

Advantages:
Highlights dense motions, edges, and directional changes
Disadvantages:
Ambiguous for wind speeds

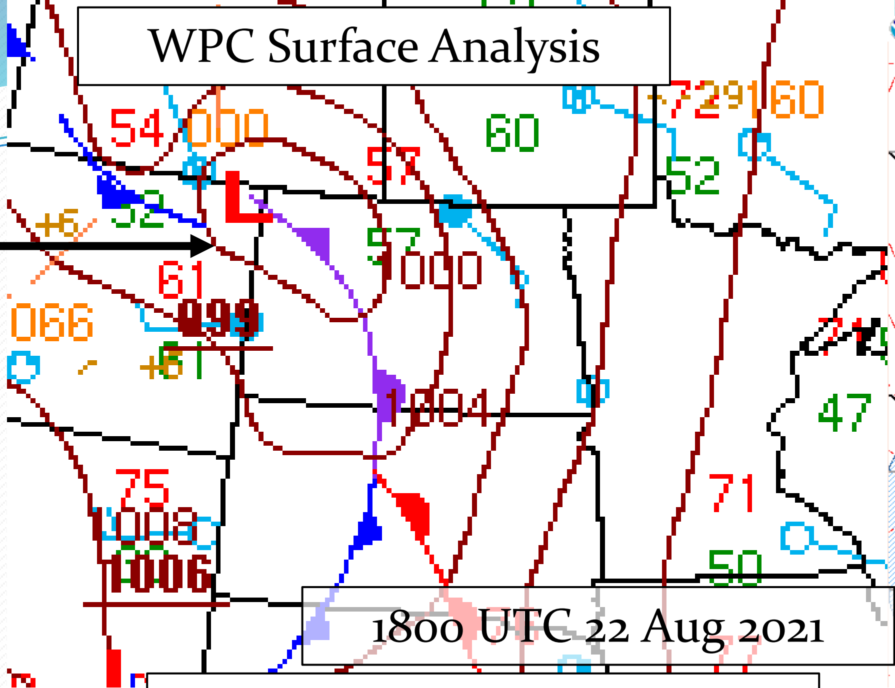


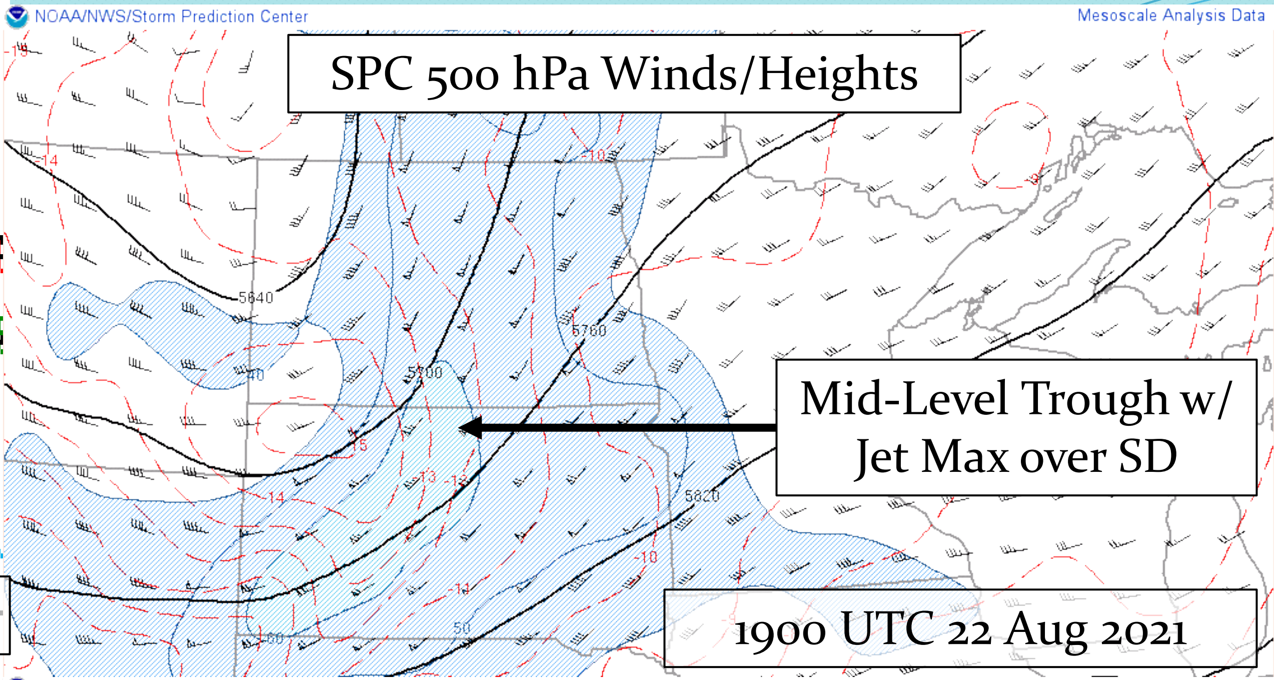


Advantages:
Highlights dense speeds and features producing motions, Interpretability
Disadvantages:
Ambiguous for direction

Case Study: Aug 22, 2021

Occluding Low w/ Moderate WAA in ND/SD

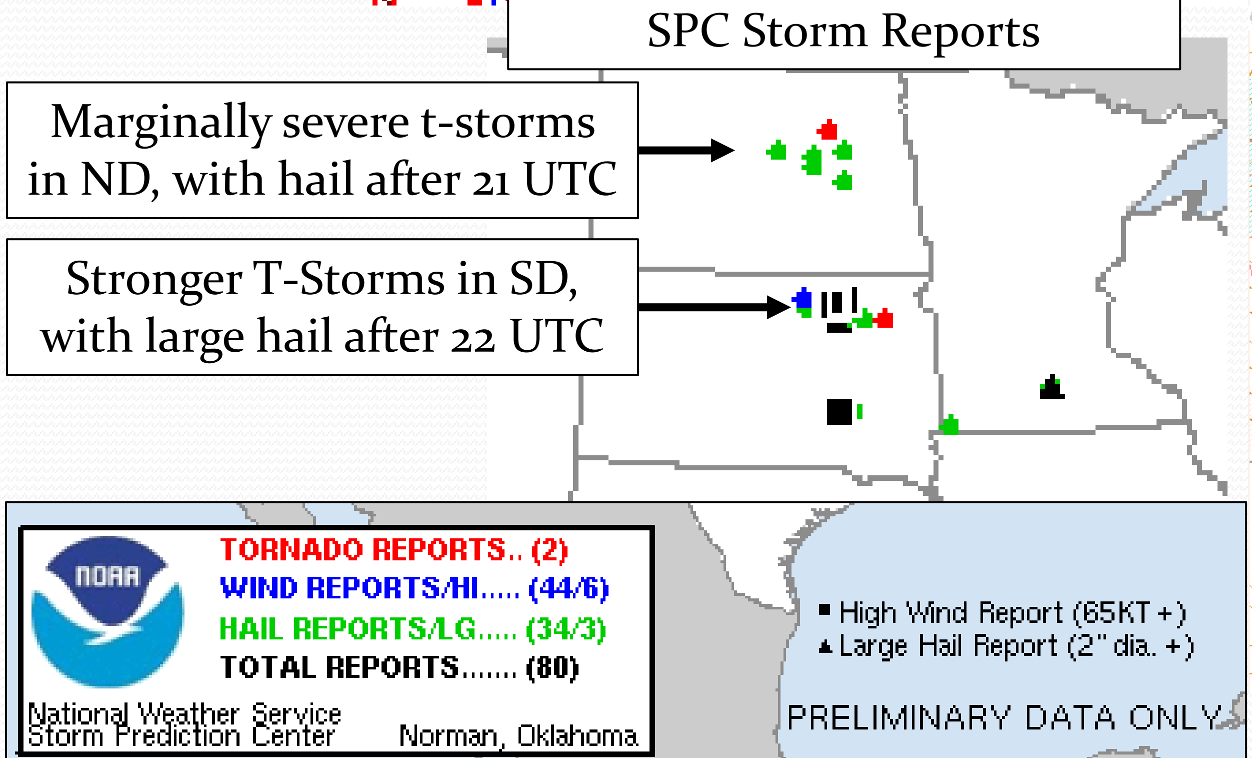


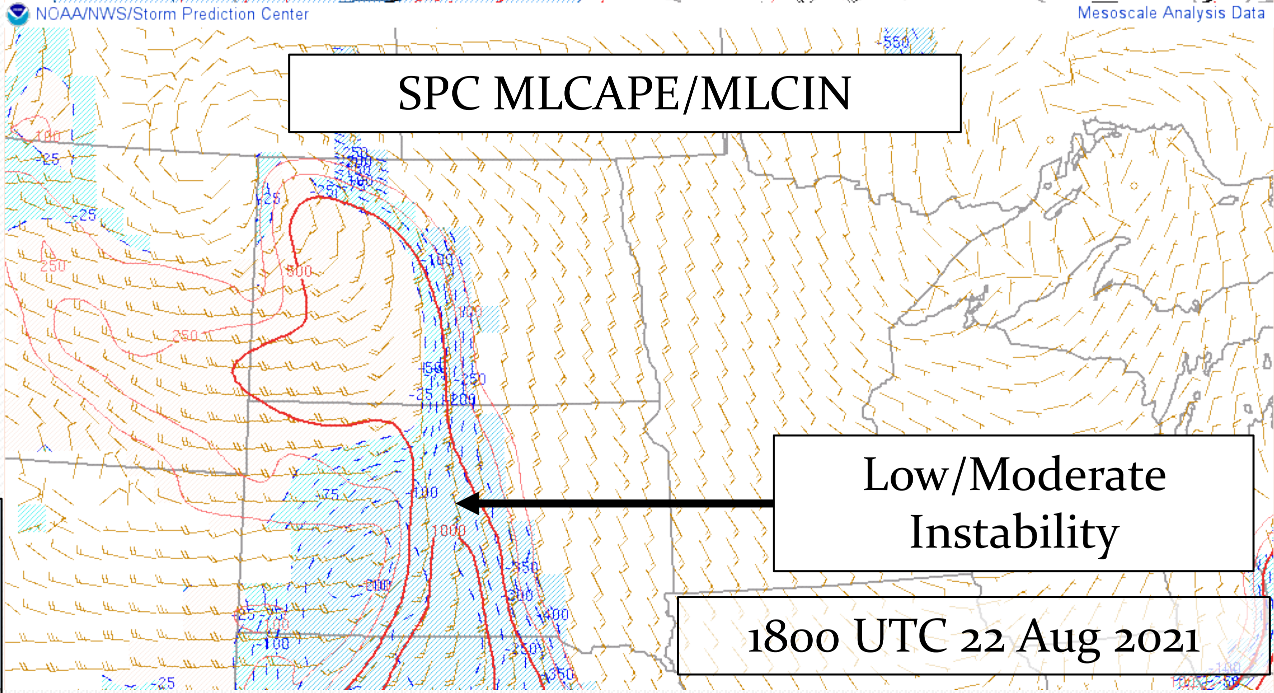


Mid-Level Trough w/ Jet Max over SD

Marginally severe t-storms in ND, with hail after 21 UTC

Stronger T-Storms in SD, with large hail after 22 UTC





Low/Moderate Instability

DOF Speed Sandwich

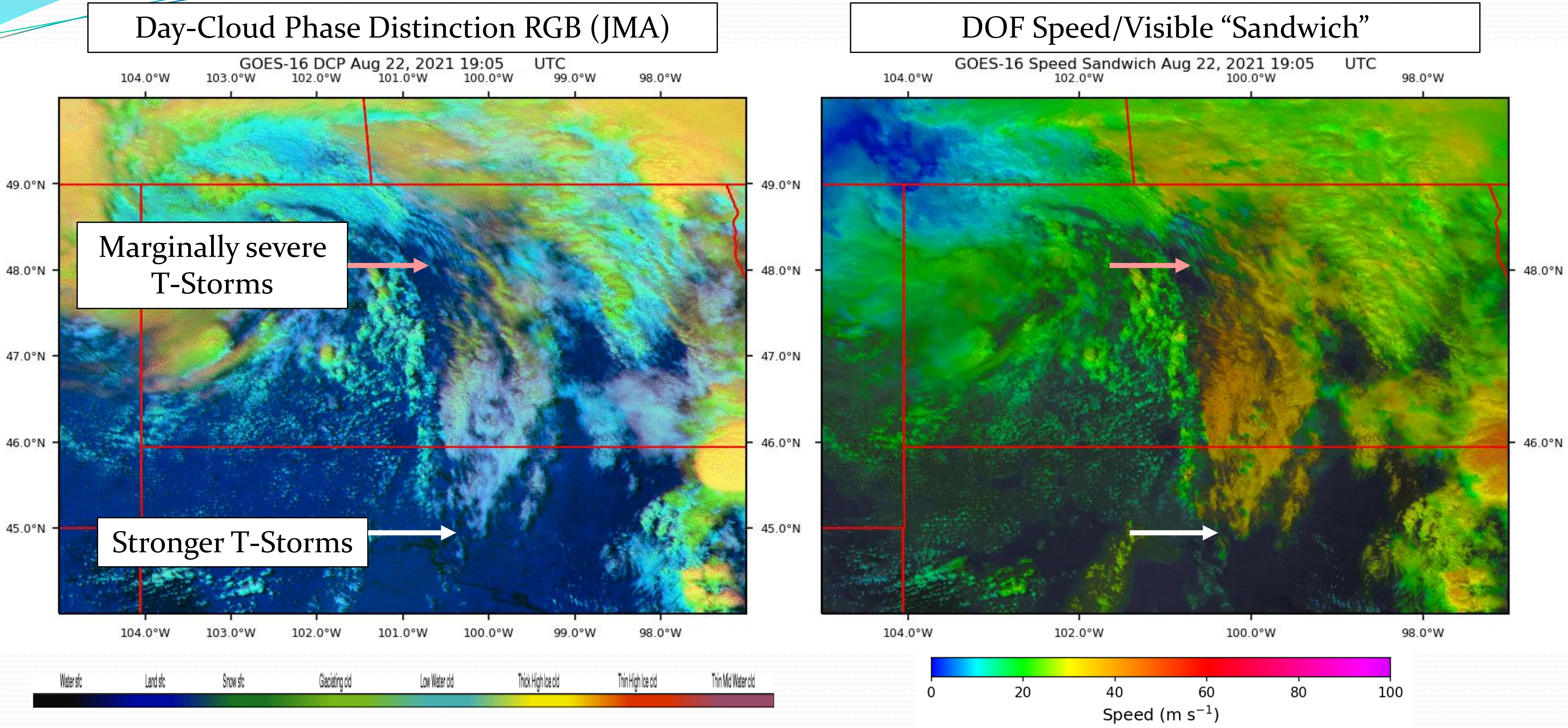


Figure 2. (*Left*) GOES-16 Day-Cloud Phase enhancement (from 0.64, 1.6, and 10.3 µm imagery) shown with (*Right*) Dense optical flow colored by wind speed with brightness indicating the 0.64 µm reflectance (The Speed Sandwich product).

DOF Warping/CTC Sandwich

CIRA
Connecting Models and Observations

Day-Cloud Phase Distinction RGB (JMA)	DOF-retrieved Cloud-Top Cooling (5-min)

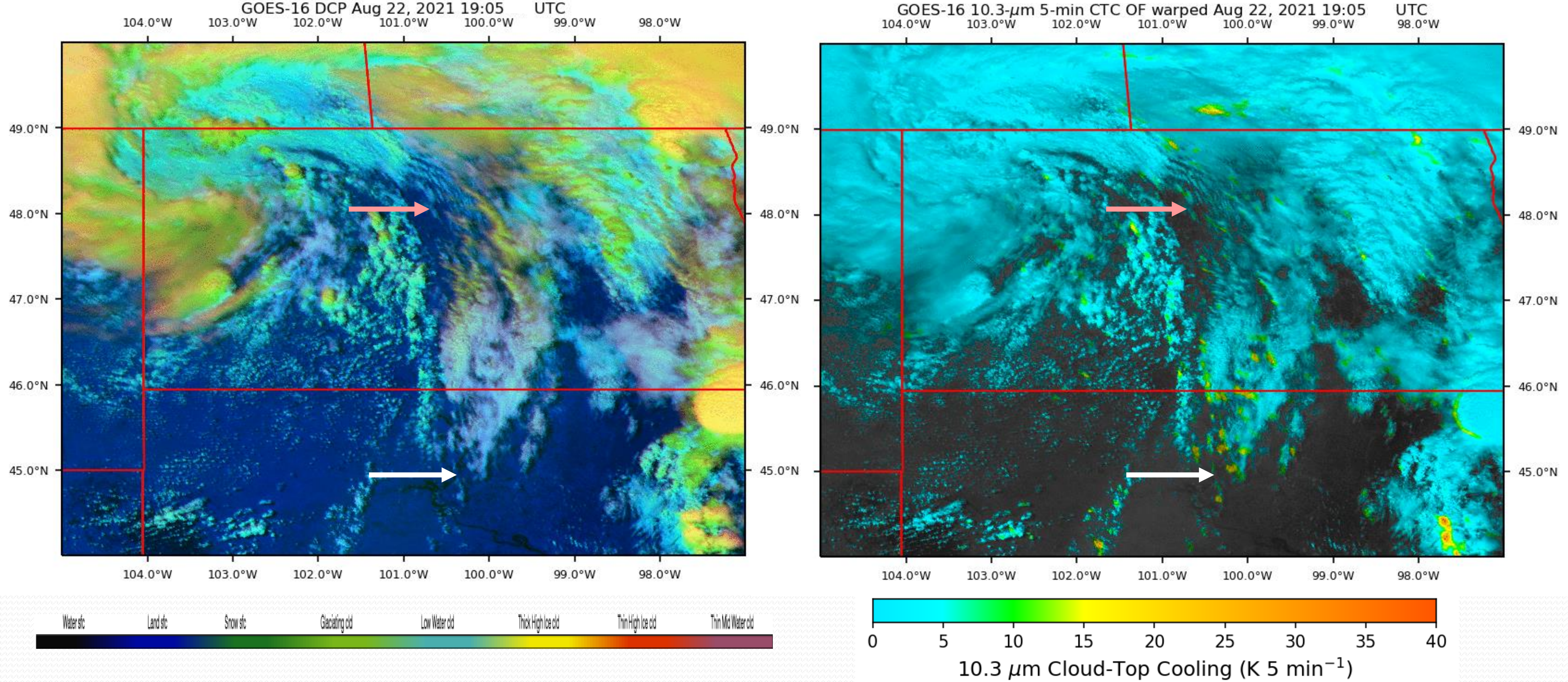
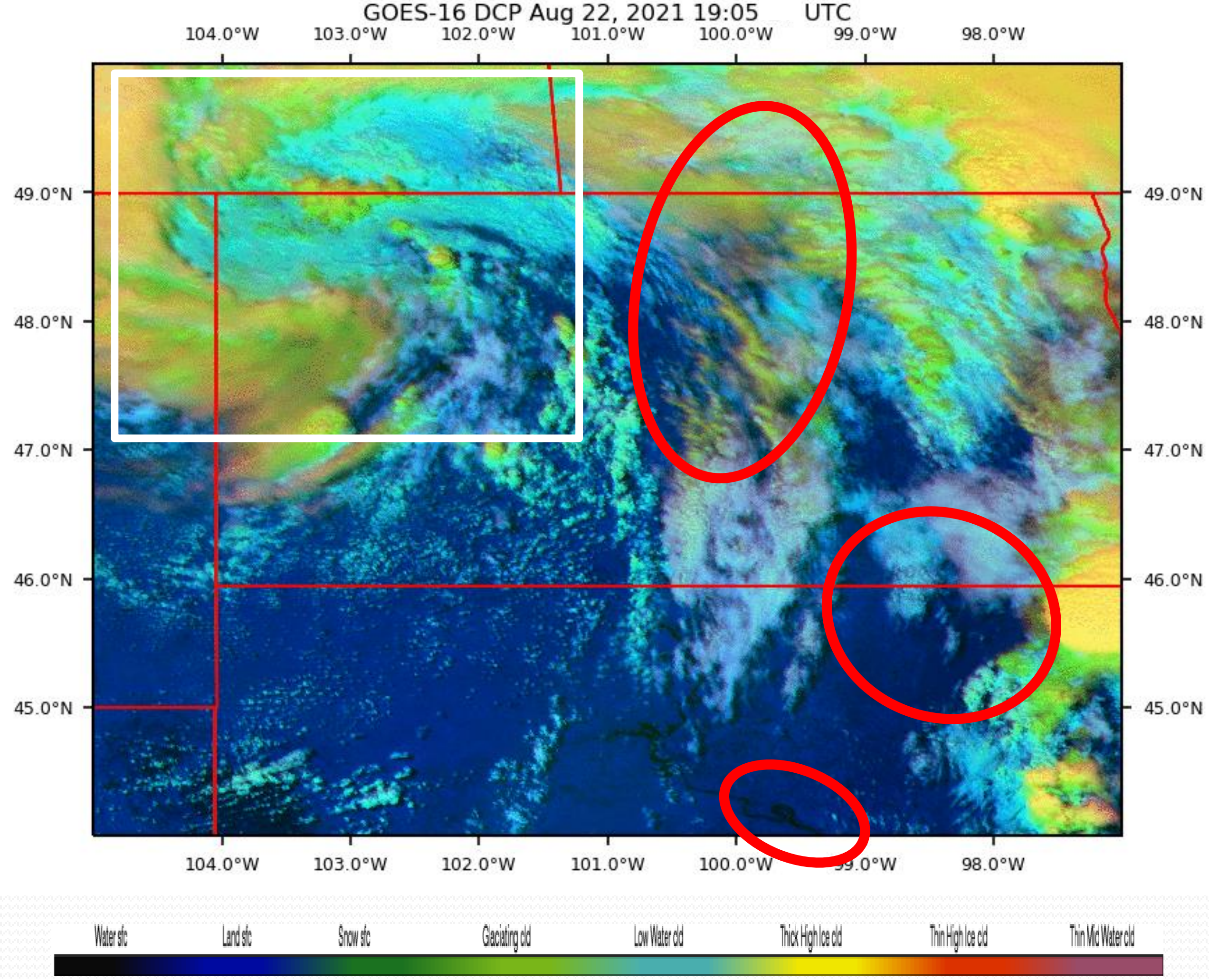


Figure 3. (*Left*) GOES-16 Day-Cloud Phase enhancement (from 0.64, 1.6, and 10.3 μm imagery) shown with (*Right*) Cloud-top cooling from the 10.3 μm dense optical flow-warped imagery colored by cooling rate with brightness indicating the 0.64 μm reflectance (The Cloud-Top Cooling Sandwich product).

DOF Warping/Temporal Interpolation

Connecting Models and Observations

Day-Cloud Phase Distinction RGB (JMA)



DOF 5-min Based Temporal Interpolation (1-min)

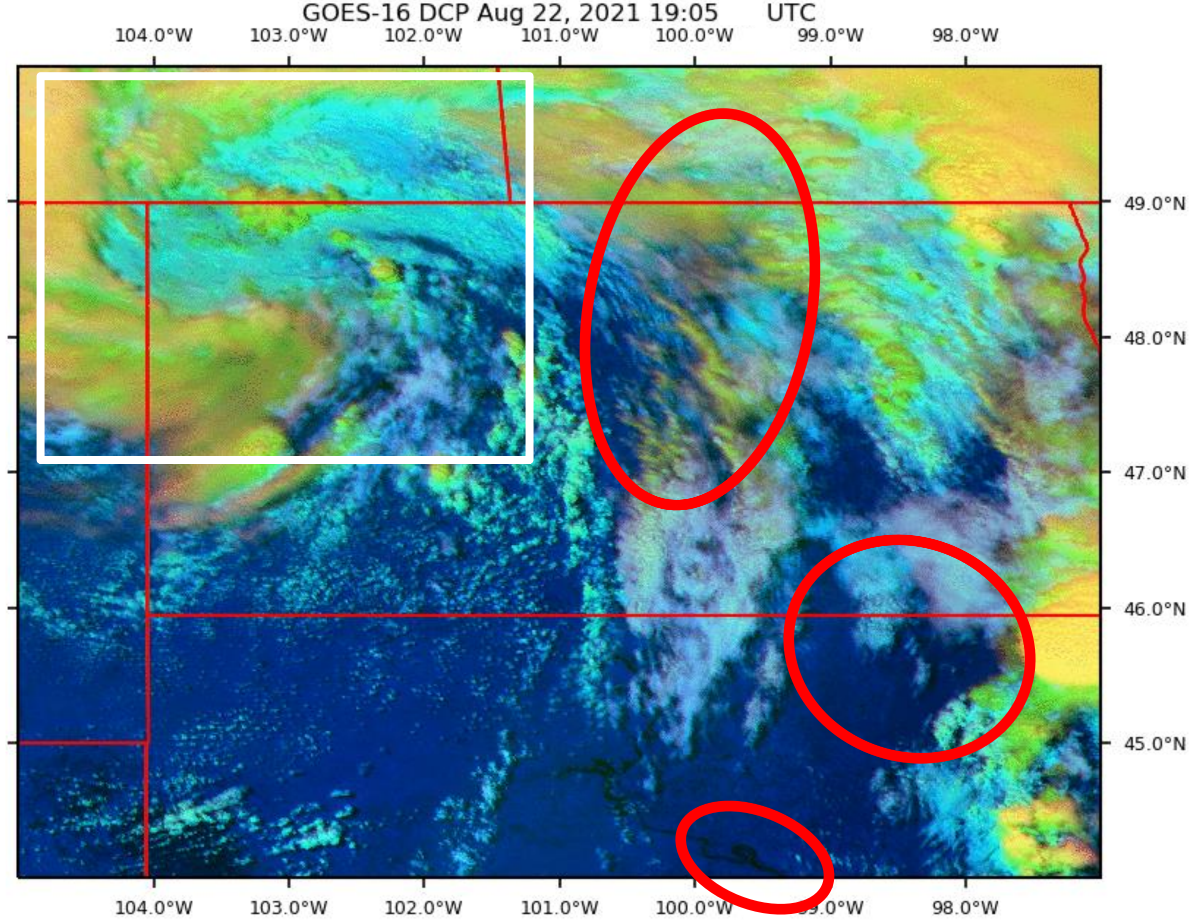


Figure 7. (*Left*) GOES-16 Day-Cloud Phase enhancement (from 0.64, 1.6, and 10.3 μm imagery) shown with (*Right*) 5-min Day-Cloud phase RGB imagery which has been interpolated to 1-min with dense optical flow motions. The white square (red circles) highlights where DOF performs well (poorly).

Interpolation works for any RGB!

Dense optical flow enables temporal interpolation of satellite imagery (e.g. 1-min GeoColor updates from GOES 5-min CONUS data)

Optical Flow Cloud Nowcasting

- **Advantages:** Uses observed cloud/feature motions, not sensitive to inaccurate models or cloud height assignments, pixel level nowcasts which are not sensitive to feature merging/splitting
- **Disadvantages:** May miss cloud evaporation/ condensation, will struggle in highly non-linear motions at longer forecast times, struggles to resolve occlusions/disocclusions (all topics of future research!)

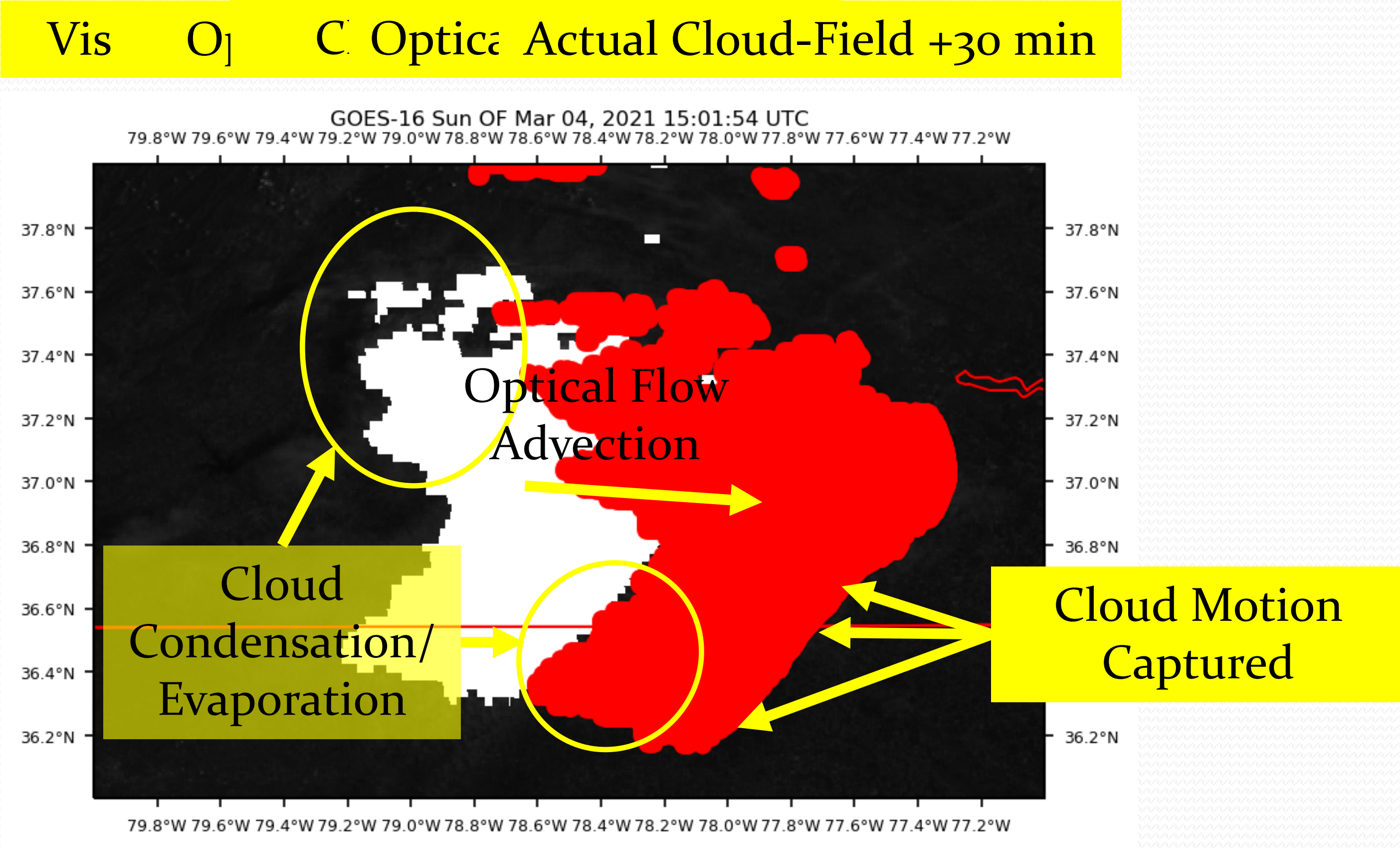


Figure 8. GOES-16 Ch-02 0.64 μm imagery over southern Virginia at 15 UTC showing an example of Optical Flow-based cloud nowcasting.

In Summary

- New generation satellite imagery enables retrieval of accurate DOF fields
- DOF fields enable many novel satellite remote sensing products which can enhance satellite mission value
- This presentation introduced several recently funded efforts at CIRA to explore and validate DOF products & create intuitive RGBs (e.g. Winds, Cloud-Top Cooling, Temporal Interpolation, Nowcasting)

Future Work:

- DOF is being run in real time at CIRA, RGB products will be available via SLIDER (https://rammb-slider2.cira.colostate.edu/) (on GOES mesosectors)
- Working to find best practices for retrieving and validating DOF products (Apke et al. 2022, in prep)
  - Includes exploring uncertainties related to imaging strategies
- Using DOF tools to enhance machine learning-based decision-making algorithms
- OCTANE will soon be made available on an Open-Source Repository

Acknowledgements

- Funding provided by NESDIS GOES-R Program Office award # NA14OAR4320125, NOAA Grant NA19OAR4320073, NASA Grant # 80NSSC21K0919, Multidisciplinary University Research Initiative (MURI) Grant N00014-16-1-2040, & ONR Award # N00014-21-1-2112

Citations

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Thank You For Listening!

For additional questions, contact:

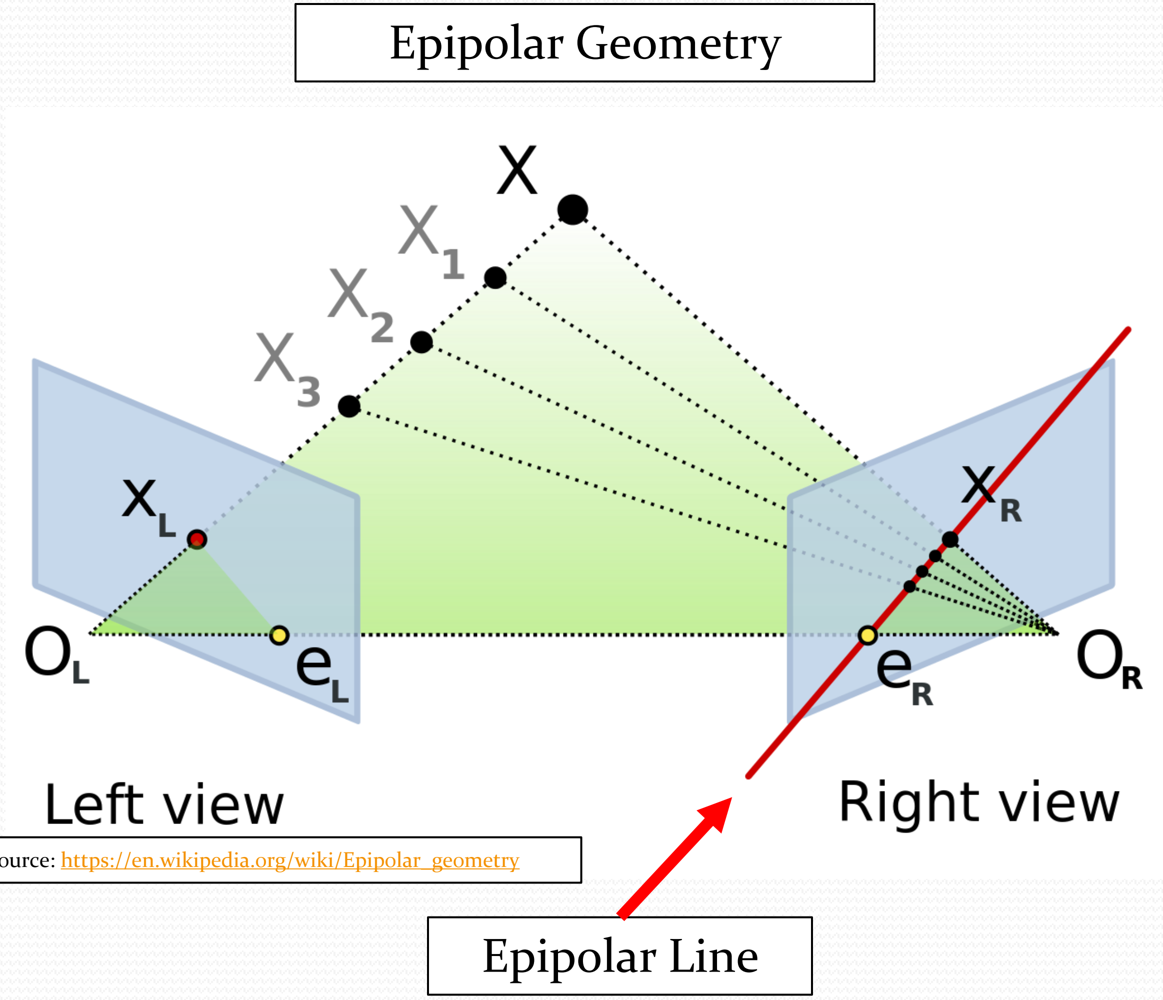
Jason Apke

jason.apke@colostate.edu

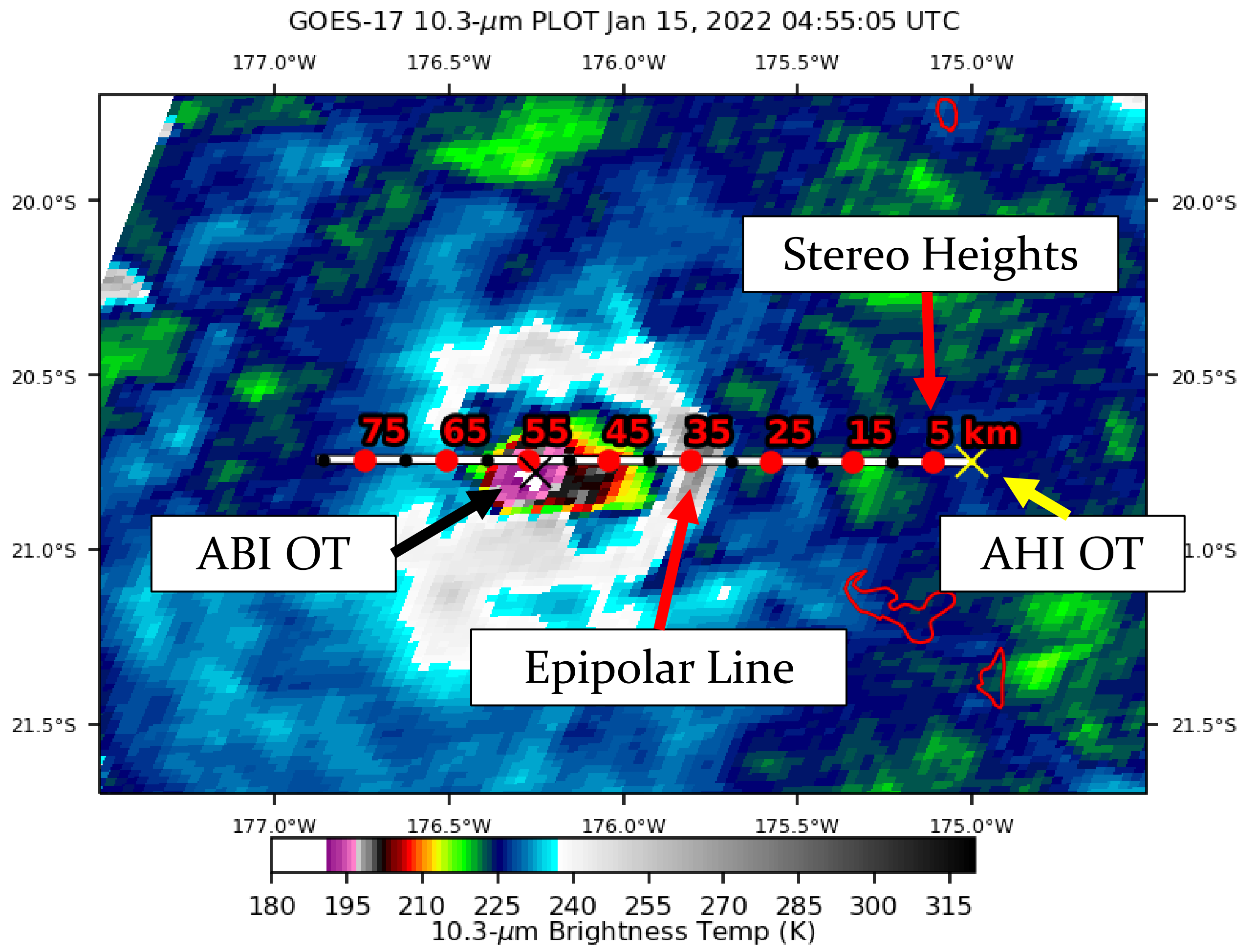
3925A West Laporte Ave. Fort Collins, CO 80523-1375

Tonga Eruption (In case someone asks)

Epipolar constraints are VERY important for image stereoscopy with Optical Flow



Source: https://en.wikipedia.org/wiki/Epipolar_geometry



***Note: Optical Flow is used to find where the yellow X is in AHI given the black X in ABI

DOF Speed Sandwich

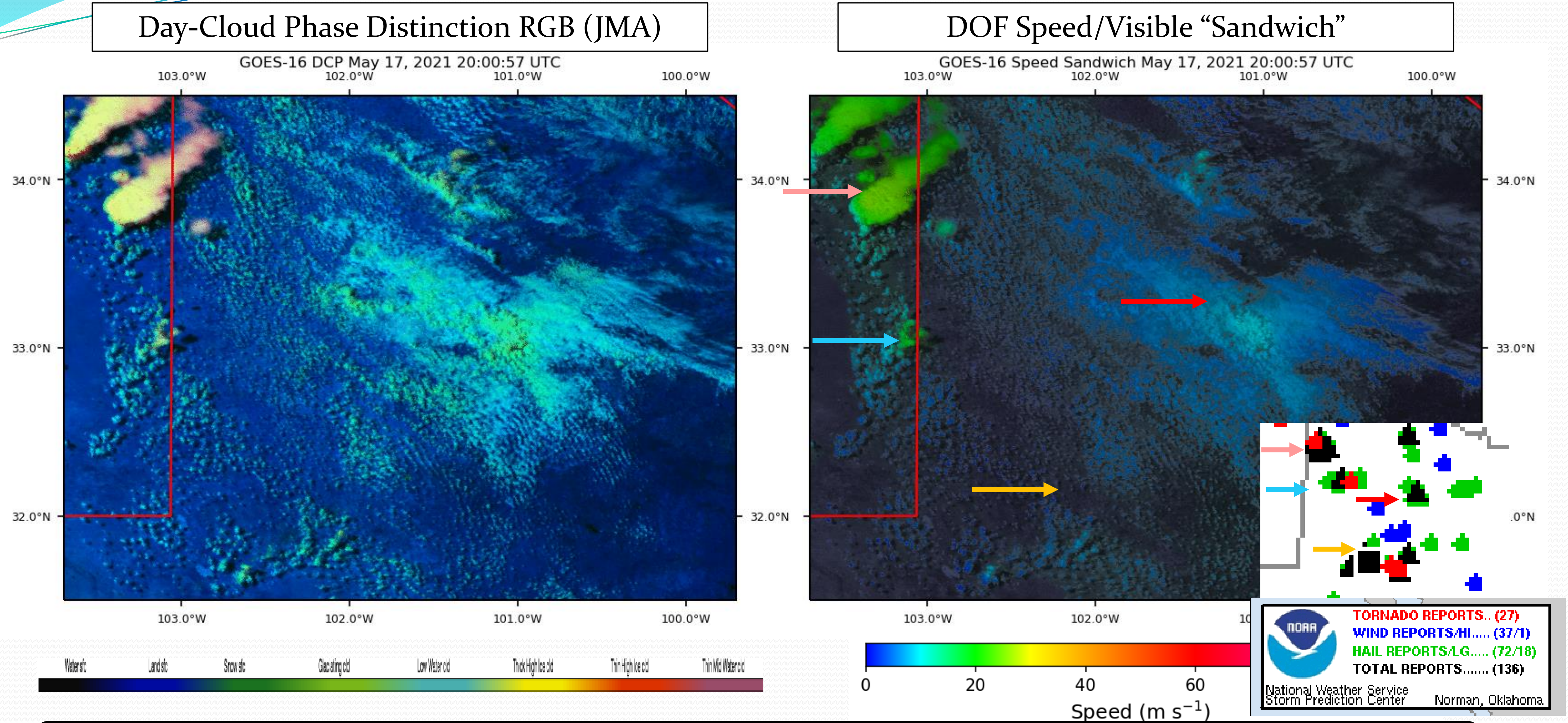


Figure 5. (*Left*) GOES-16 Day-Cloud Phase enhancement (from 0.64, 1.6, and 10.3 µm imagery) shown with (*Right*) Dense optical flow colored by wind speed with brightness indicating the 0.64 µm reflectance (The Speed Sandwich product).

Cloud-Top Cooling

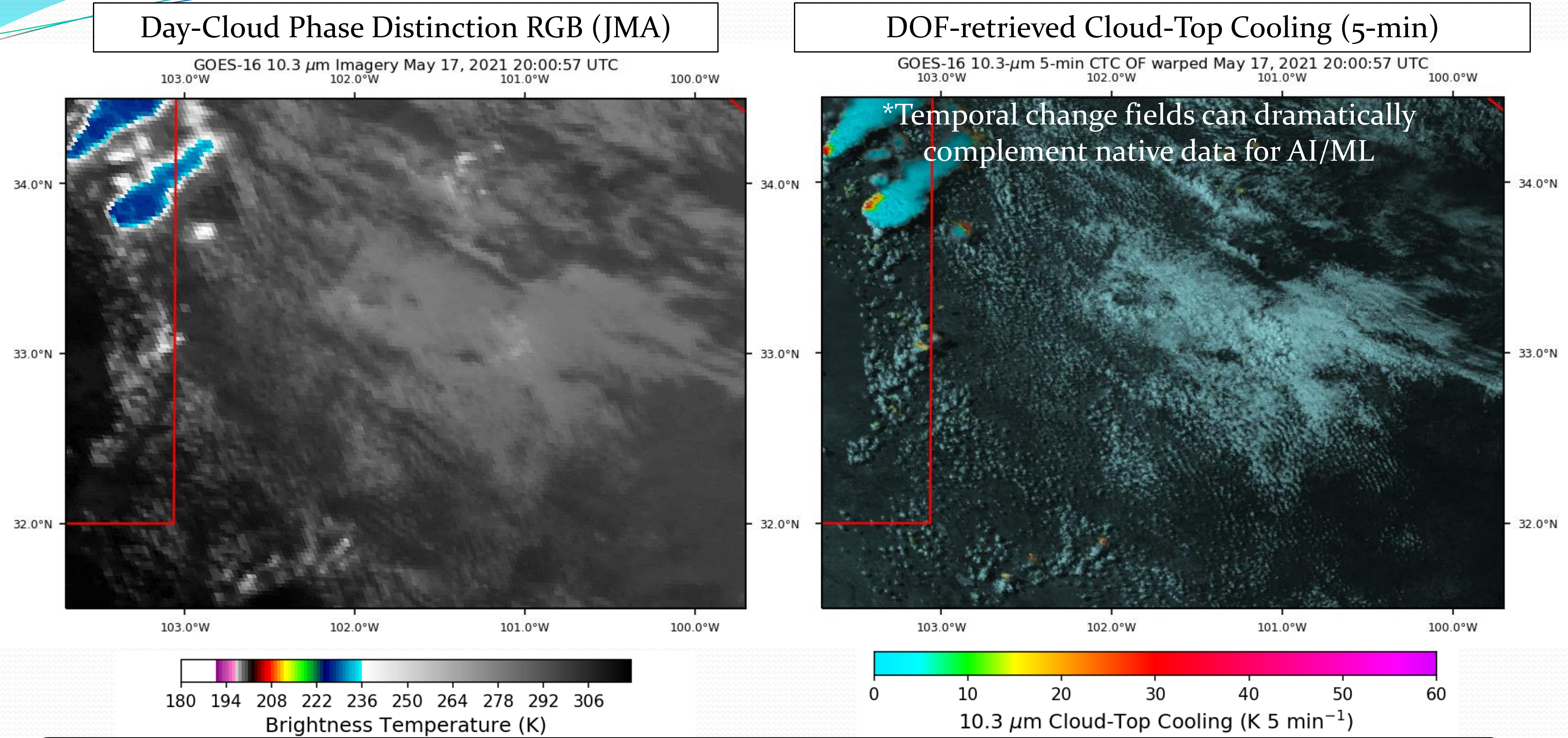


Figure 6. (*Left*) GOES-16 10.3 μm imagery shown with (*Right*) Cloud-top cooling from the 10.3 μm dense optical flow-warped imagery colored by cooling rate with brightness indicating the 0.64 μm reflectance (The Cloud-Top Cooling Sandwich product) without and with correction for motion across gradients.