Retrieval of 3D distribution of horizontal wind vector by combining lidar with passive water vapor sounders

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We need 3D wind measurements (i.e., 3D distribution of horizontal winds) for understanding and predicting weather and climate (WMO, NASA, NOAA, …).

Q1: What atmospheric horizontal wind measurements are available?

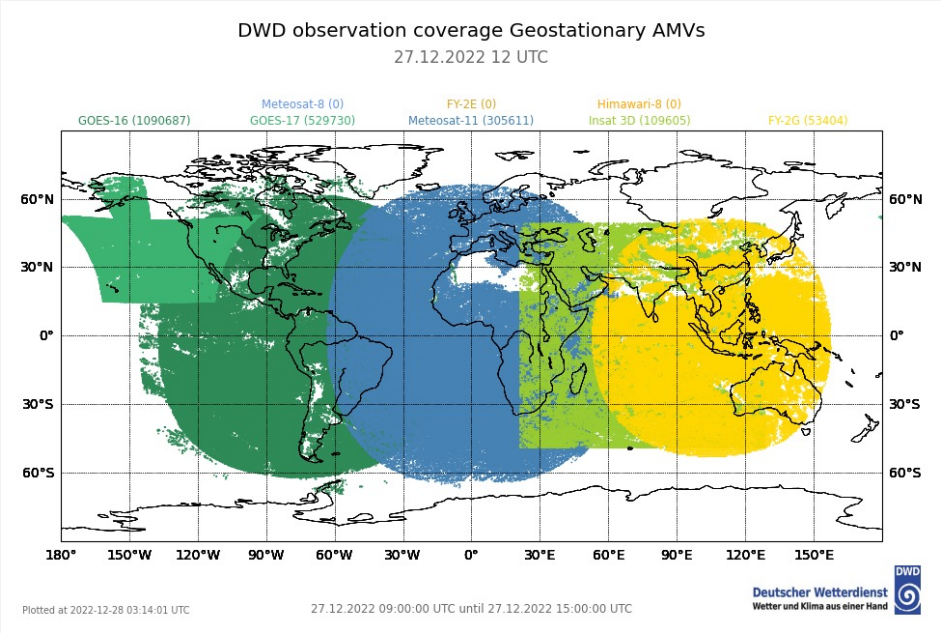
Atmospheric Motion Vector (AMV):

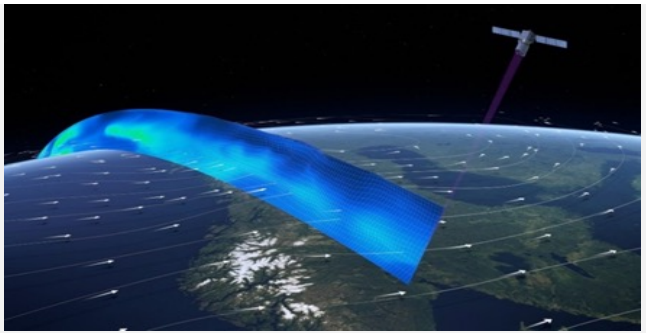
- ***traditionally***, by feature-tracking in:
  - satellite cloud top or
  - water vapor fields
- mostly at one pressure level at a given time and location

Doppler wind lidar (Aeolus):

- More accurate wind measurements
- provides a curtain of one wind component (in one direction) outside/above clouds only;

<u>3D winds are obtained from data assimilation</u>





Aeolus profiling the world's winds
- https://earth.esa.int

- Atmospheric winds are essential to transport heat, moisture, momentum, and chemical species and enable the interactions between components of Earth's climate system.
- However, direct observations of three-dimensional distributions of atmospheric winds are scarce as of now!
- **Reanalysis datasets provide the best estimate of the state of the atmosphere**.
- Existing studies rely heavily on the wind fields from reanalysis datasets.

Q2: Do reanalysis winds agree well with each other?

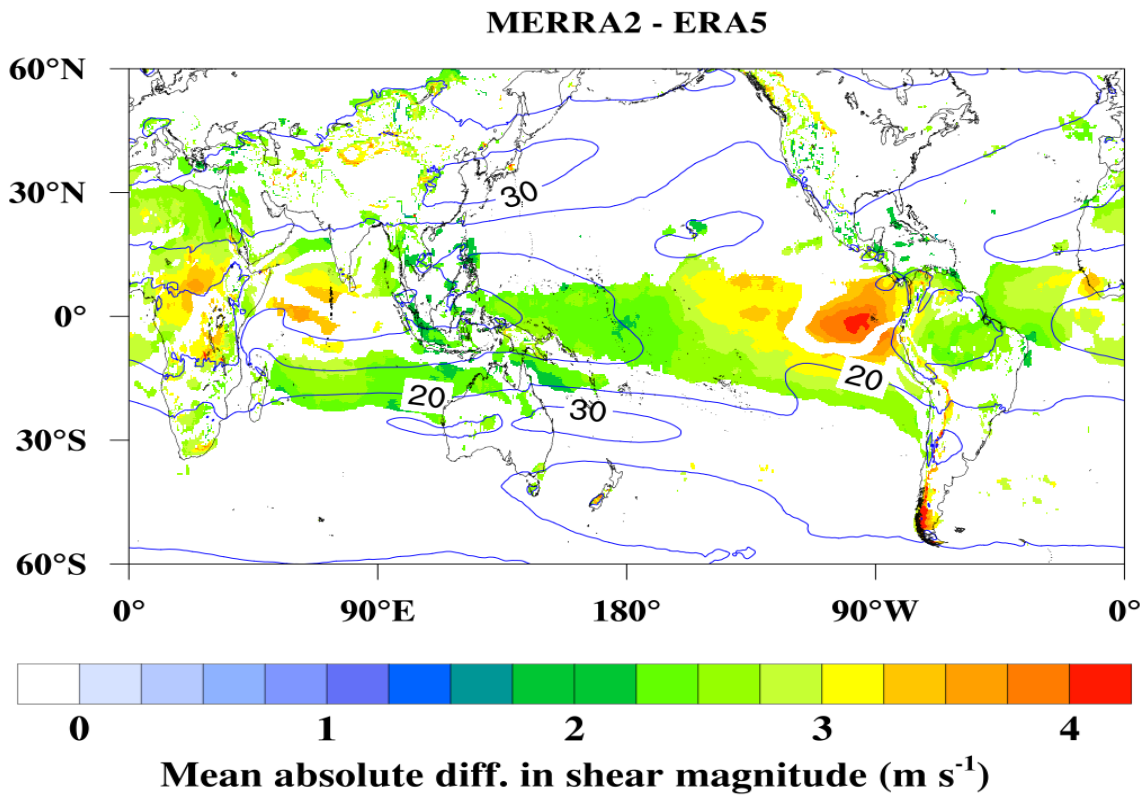
- Differences between reanalysis datasets can be used as a measure of wind uncertainty.
- **Large wind uncertainties exists among 3 reanalyses products (**ERA5, MERRA2 and CFSv2) **–** Wu et al., 2023 (submitted, conditionally accepted, pending revisions).

Q2: Do reanalysis winds agree well with each other?

Significant uncertainty in the tropics! Exactly where winds are needed the most!

- **Wind shear** (the horizontal wind vector difference between two pressure levels) is an important factor that affects turbulence, mixing, clouds and the development of convective systems.
  - rapid intensifying tropical cyclones tend to occur with weak shear
  - intense thunderstorms tend to have greater wind shear than weak thunderstorms in the mid-latitudes.

Wu et al. (2023, submitted)



Implication:
Needed are 3D wind observations

Q2: Do reanalysis winds agree well with each other?

$$WVD = \sqrt{(u_a - u_b)^2 + (v_a - v_b)^2}$$

- **In relation to Convection:**

When deep convection occurs (IMERG precipitation rate > 0.1 mm/hr), the ERA5 and MERRA2 reanalysis winds differ by 5 m/s or more for 30%-50% of the time over many regions.

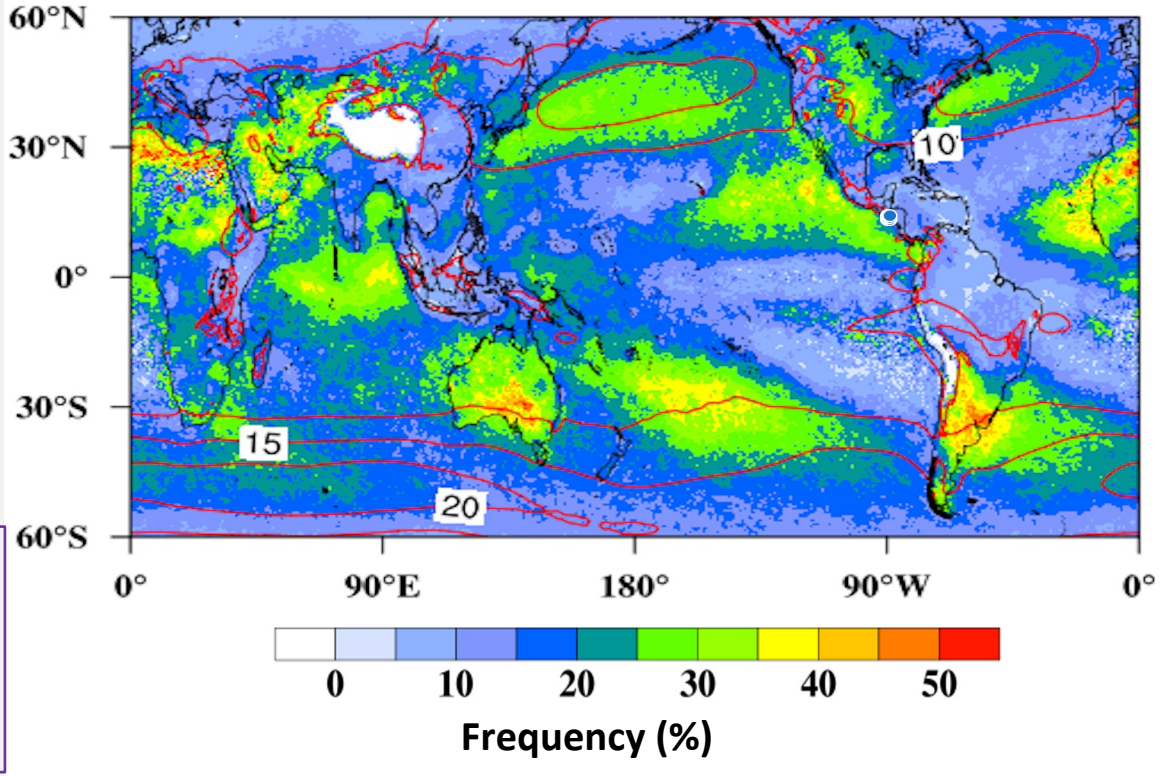
Wu et al. (2023, submitted)

Implication: Needed are 3D wind observations near convection!

(i.e. within the clouds; supported by passive microwave obs.)

700 hPa

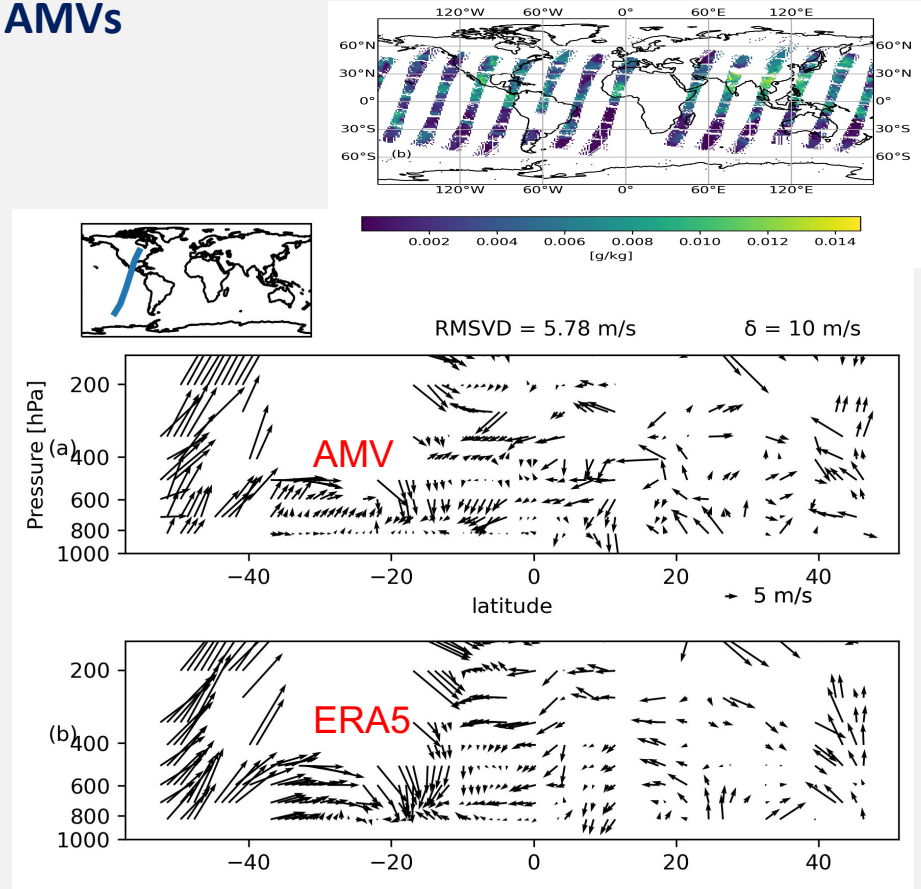
Freq. of wind vector difference > 5 m/s when rain > 0.1 mm/hr



Q3: Can we, actually, retrieve 3D distribution of AMVs using real observations of water vapor?

- Prior studies have derived such AMVs over polar regions only (using AIRS).
- Our team provided the **first** vertical distribution of AMVs from 60N to 60S ***from observations alone***
  - by tracking water vapor from
  - the hyper-spectral Cross-track Infrared Sounder **(CrIS)** aboard two polar satellites **(NOAA-20 and Suomi-NPP)** that have overlapped tracks **separated by 50 minutes**

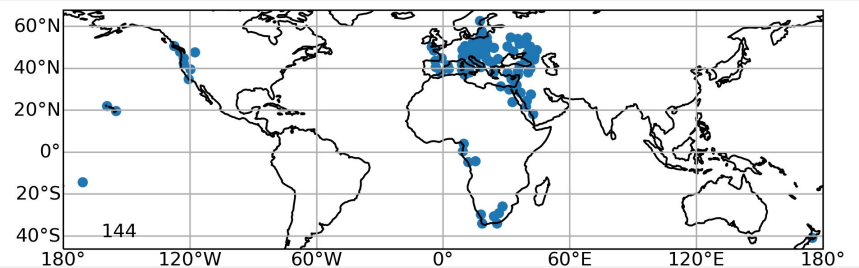
Ouyed et al. (2023, revised) – next talk !



Cross-section of winds for the descending orbit on 1 July 2020

Q4: How well do our team's 1-deg AMVs agree with *radiosonde measurements*?

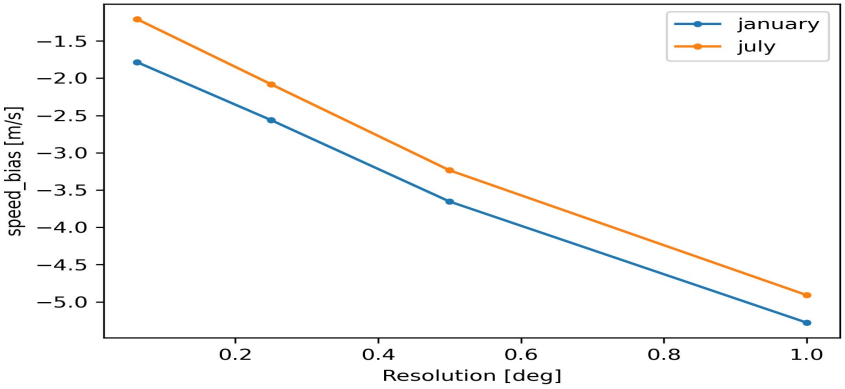
- RMSVD is comparable to those of GEO AMVs (with a smaller Δx)



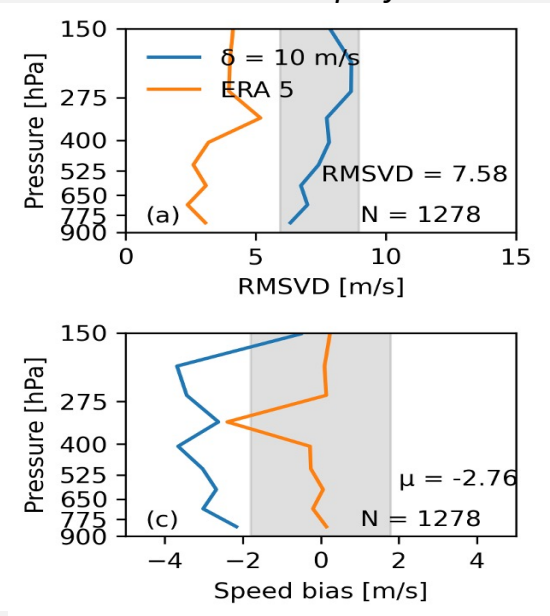
Locations of radiosonde stations for 1-7 January 2020, with 144 radiosonde profiles

Q5: Why is the speed bias more negative than GEO AMVs?

- Because of a much higher Δx (= 1 deg)



Based on NASA 7-km Nature Run



Shaded region corresponds to errors from operational GEO AMVs

Ouyed et al. (2023, revised) – next talk !

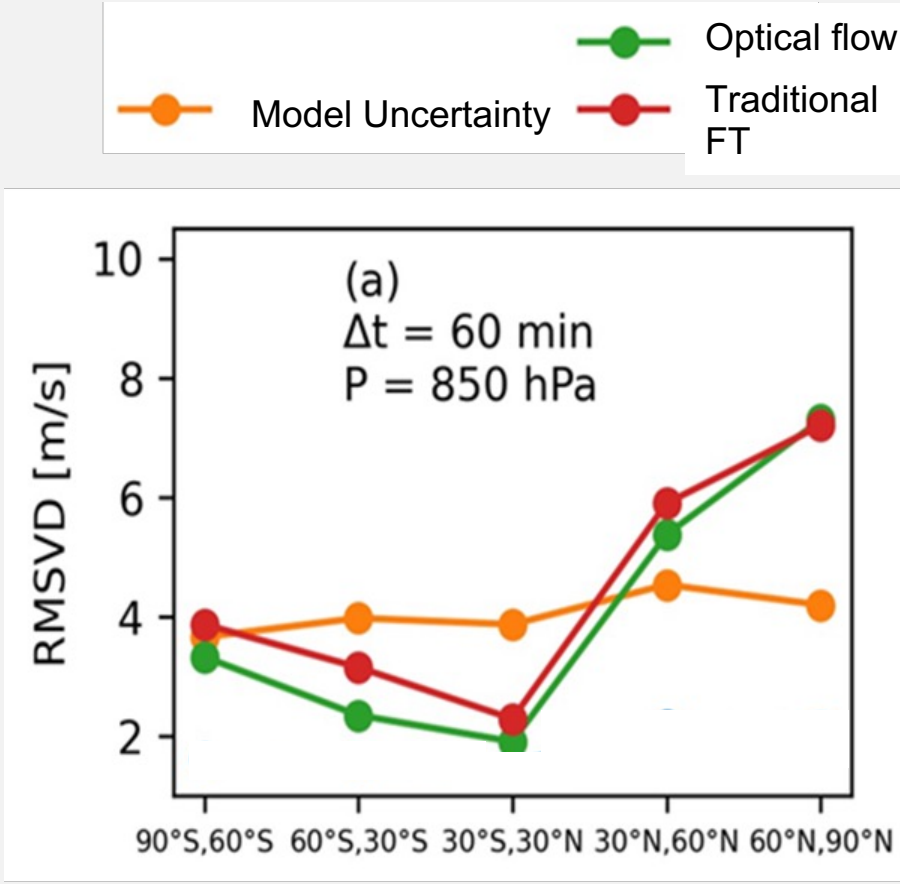
Q6: Can passive remote sensing measurements at 7 km resolution yield AMVs that outperform reanalysis?

From Nature Run (assuming water vapor can be accurately retrieved under all weather conditions):

No: Vertical distribution of AMVs are unlikely to outperform reanalysis (green line).
Ouyed et al. (2021, J. Appl. Meteor. Clim.)

However, note (Yanovsky et al., Monday)

- Compared to the conventional feature-tracking algorithm, the optical flow (OF) algorithm provides some improvement of the AMV accuracy.
- OF has higher yield (fraction of valid retrievals).
- OF performs well down to very low wind speeds.
- OF is not sensitive to the time interval between sequential images.



RMSVD: error of retrieved wind vector relative to the nature run truth

Q7: Can synergistic lidar + passive remote sensing measurements yield AMVs that outperform reanalysis?

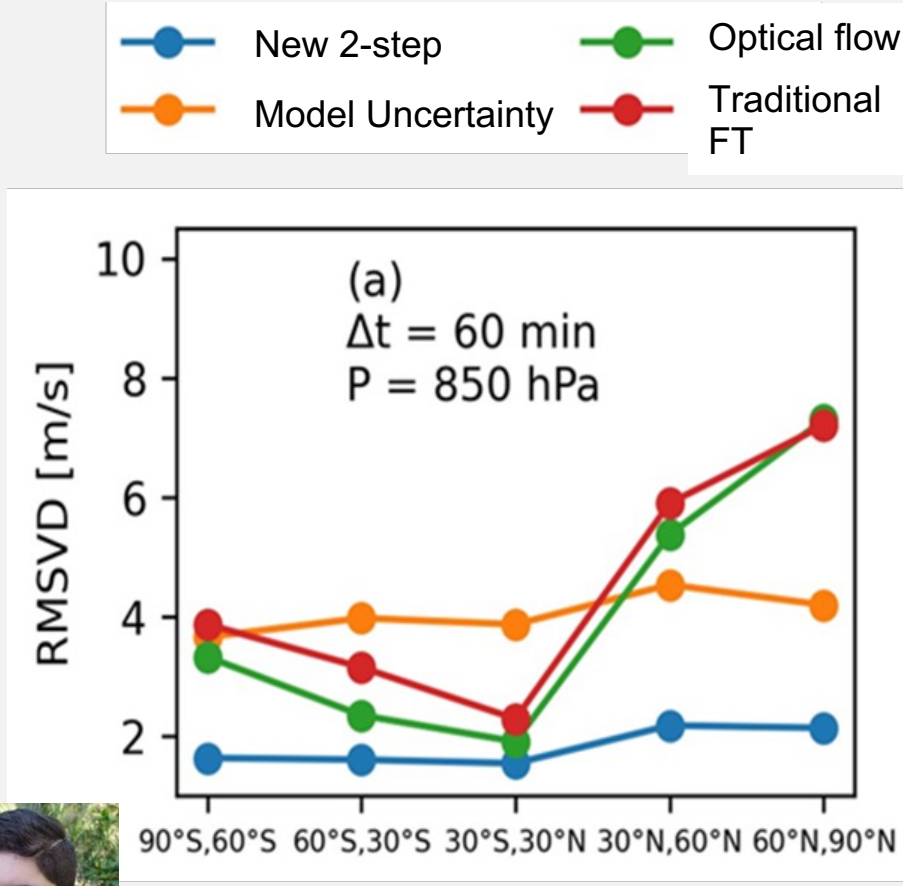
Using NASA's global 7 km Nature Run, we developed a **two-stage AMV retrieval:**

i) **Using multi-scale feature tracking of water vapor, to produce AMVs at pixel level** (rather than the smoothed AMVs in a traditional image feature-tracking algorithm), but with only slightly-smaller root-mean-square vector differences (RMSVDs).

ii) Assuming co-located higher-accuracy measurements are available for a small portion of the time/space, our **second stage retrieval based on machine learning (ML) is able to significantly reduce RMSVDs**, demonstrating the value of synergistic retrieval of 3D winds using water vapor sounders and (more accurate) wind lidar.

Yes: Our team has developed the 1st 2-stage retrieval algorithm for this purpose (blue line)

- Ouyed et al. (2021, J. Appl. Meteor. Clim.)

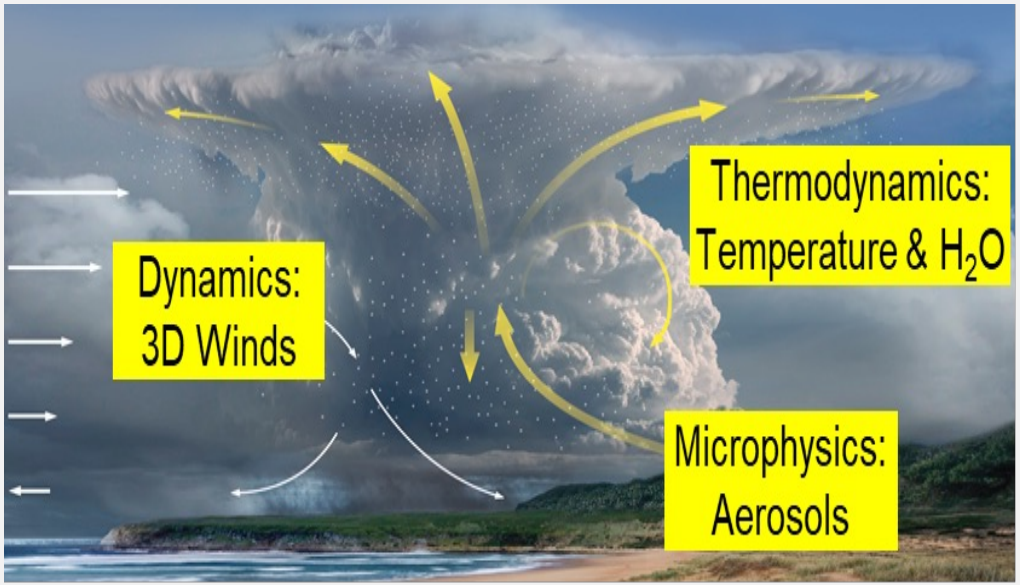


RMSVD: error of retrieved wind vector relative to the nature run truth

Q8: What can lidar + passive water vapor measurements provide ?
The VIENTOS (conVection Interacting with ENvironmenTs Observing System) mission concept

- **3D wind, Temperature, Humidity, and Aerosol profiles**
- **Bigger impacts on science and applications than lidar or AMVs alone**

  (following the highly successful example of NASA-JAXA GPM, as the active/passive combined GPM is much more impactful than the radar or MW imager alone for precipitation measurements):
  - NWP (e.g., ***prediction of severe weather***, ***hurricanes***)
  - ***address science questions*** (e.g., organized convection-environment interactions and extreme weather events)
  - other applications

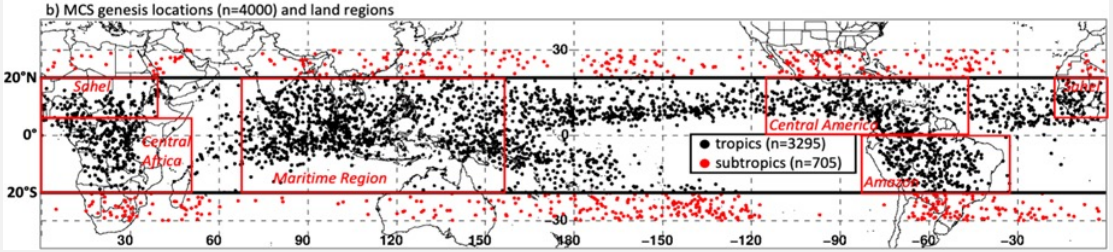


The Case for the MCSs

- Mesoscale convective systems (MCSs) in the tropics
  - play an integral role in the water cycle, transporting momentum, moisture and modifying the atmospheric composition
  - their evolution is associated with
    - the development of hurricanes,
    - Kelvin wave propagation
    - related to the onset of ENSO events
  - they are associated with local hazardous weather conditions,
  - and have significant remote impacts on the midlatitude jet stream.
- Although it is known that MCSs occur in relatively moist environments, it is unclear how far in advance favorable ingredients (lift, instability, and moisture) in the mesoscale environment precede MCS formation.
- **Galarneau et al. (2023, in press), used an automated MCS tracking algorithm and global reanalyses to examine the pre-MCS environment for 3295 MCSs that occurred in the tropics in a 3-month period.**

Q9: What are the distributions of MCSs?

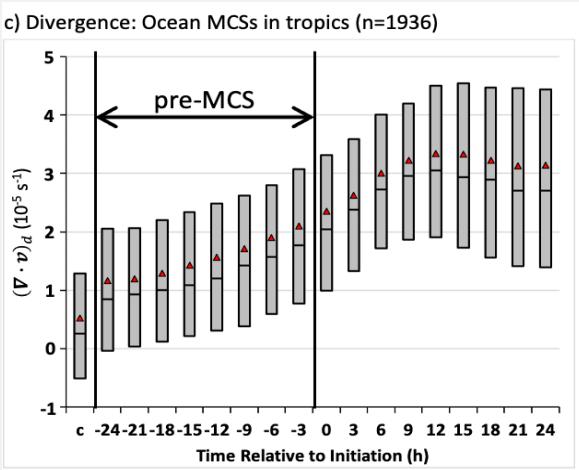
Mesoscale convective systems (MCS) genesis locations for 1 Sep–30 Nov 2018.

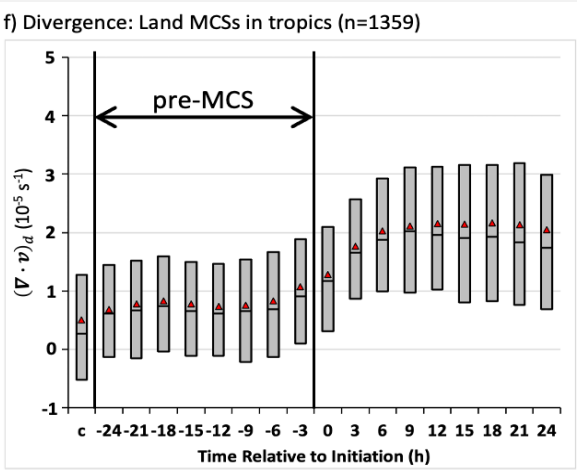


Q10: What wind information can be used as the precondition for the occurrence of MCSs?

- mesoscale ascent implied by low-level convergence and upper-level divergence preceded MCS formation by up to 24 h.
  - **(925 hPa – 250 hPa) divergence differences** provide a favorable precondition for the occurrence of MCSs over ocean, but not over land.

Galarneau et al. (2023, in press)





"c" means background climatology.
Median and mean values are denoted by the middle line and triangle in the grey box.

Summary

- Reanalysis winds disagree in the tropics and under precipitation conditions.
- We retrieved the first 3D AMVs from 60N to 60S from water vapor observations alone
- We developed a two-stage 3D AMV retrieval:
  - retrieve AMVs at pixel level from water vapor using variational method (i.e., optical flow method);
  - followed by an ML-based bias correction using a small number of co-located higher-accuracy measurements (from an active instrument)
- Differential divergence can be used as the precondition for the occurrence of MCS over tropical oceans
- **A new satellite 3D horizontal wind mission concept (VIENTOS) is proposed based on the combination of**
  - **(active) wind lidar measurements**
  - **with (passive) water vapor sounding data**
- The cost is above the cap ($310M) of the NASA Earth System Explorer;
- Multi-agency or international collaborations are needed