Impact of Ground-based Wind Measurements on Mesospheric and Lower Thermospheric Weather Through Assimilation in a Whole Atmospheric Model

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This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Motivation

Space-based observation offers global coverage but is constrained by **mission lifetimes** and **discontinuous temporal sampling** in any given region.

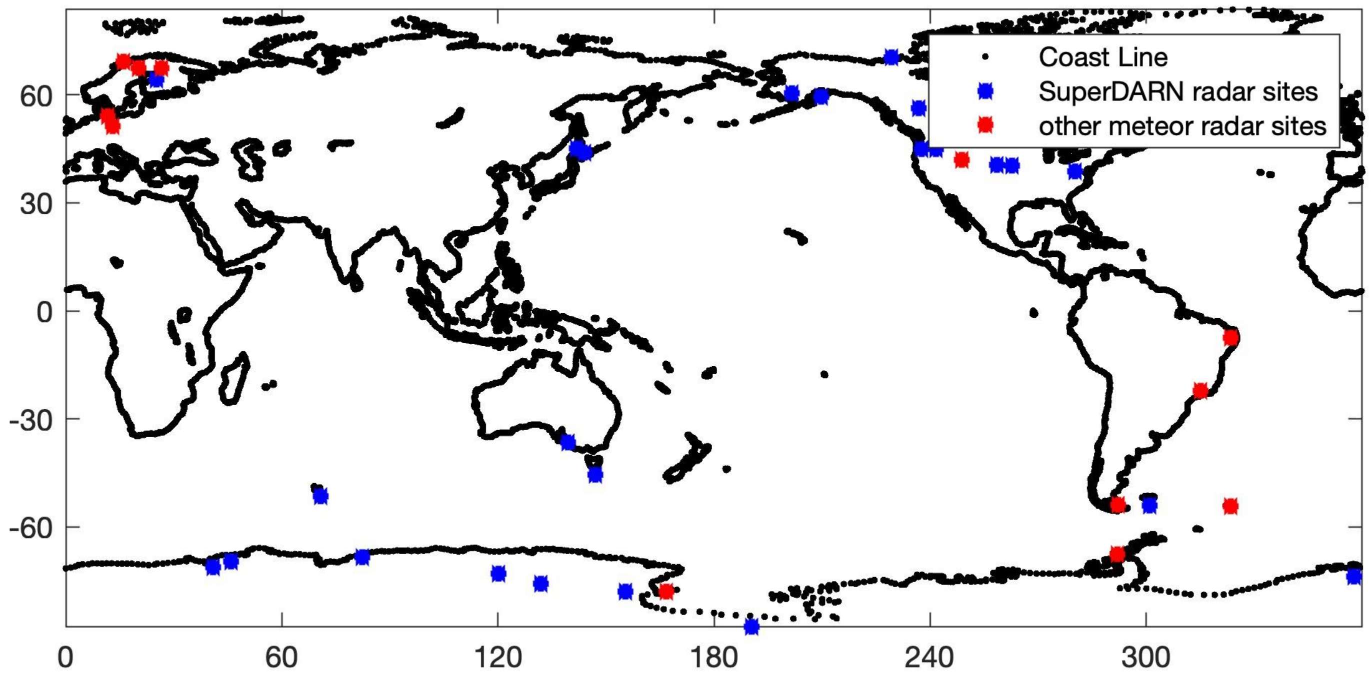
- *Ionosphere:* COSMIC-I/II, DMSP
- *Thermosphere:* CHAMP, GRACE, Swarm, GOLD, ICON

Ground-based observations provide more continuous regional coverage:

- *Ionosphere:* GNSS-TEC, ionosondes (foF2/NmF2), ISR, plasma drifts
- *Thermosphere:* assimilation of **neutral** measurements remains limited

GOAL: Assimilate **SuperDARN and meteor radar wind data** into a whole-atmosphere model to improve the specification of the **Mesosphere–Lower Thermosphere (MLT)**.

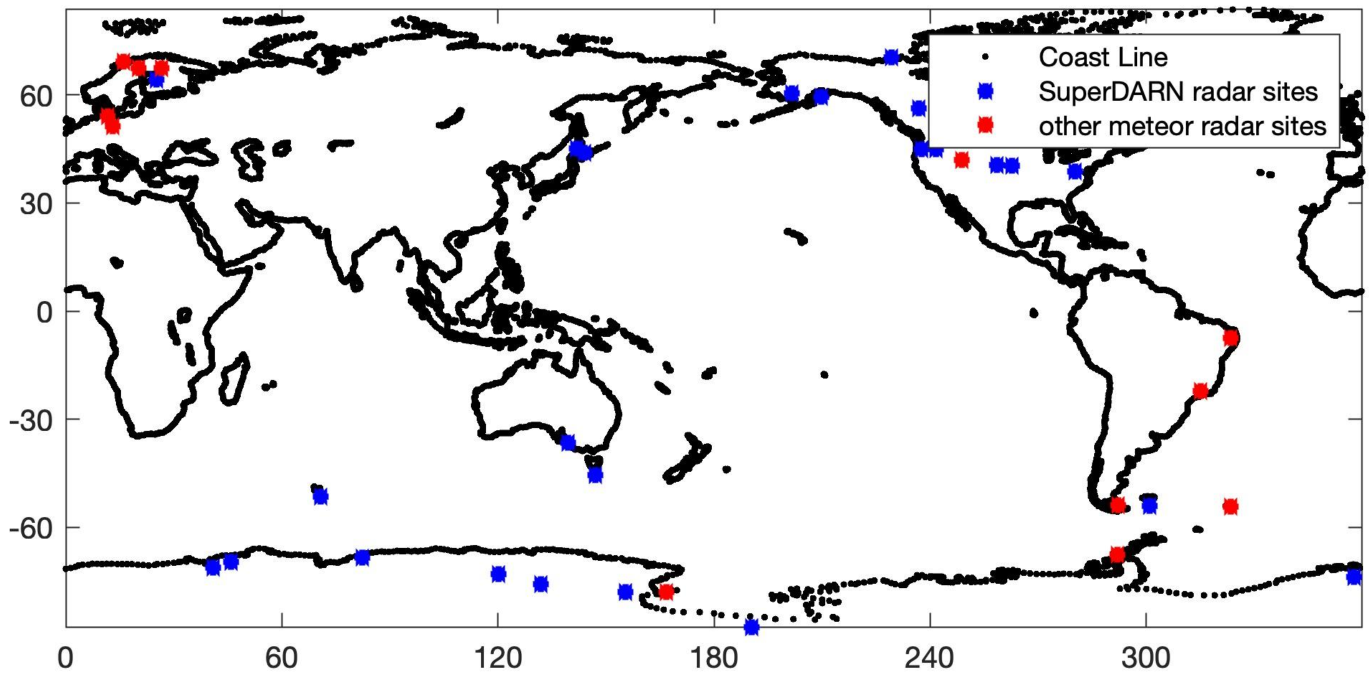
MLT Wind Measured by Meteor Radar



- Meteor radars provide neutral wind data from ~80 to 100 km, with a vertical resolution of ~2 km.
- Both zonal and meridional wind profiles of the following 12 stations are assimilated.
- **~ 250 data points per hour are assimilated.**

Station	Longitude	Latitude
Esrange	20.3	67.5
Bear Lake	-111.3	42
King-Edward-Point	-36.5	-54.3
Rothera	-68	-67.5
McMurdo	166.8	-77.9
Sodankyla	26.6	67.4
Cachoeira Paulista	-45.0	-22.2
Collm	13.0	51.3
SAAMER/Tierra del Fuego	-67.8	-53.8
MMARIA Norway	16.04	69.30
MMARIA German	11.70	53.98

MLT Wind Measured by SuperDARN



- The Super Dual Auroral Radar Network (SuperDARN) is an international collaboration of more than 35 radars worldwide.
- Each radar measures meteor echoes and derives **hourly mean** neutral winds **weighted average over the 70–120 km** altitude range.
- We focus on the most reliable component, the radar boresight direction.
- **~ 30 data points per hour are assimilated.**

DART/WACCM

DART

- NCAR's Data Assimilation Research Testbed
- Provides various ensemble-based data assimilation methods, including Ensemble Adjustment Kalman Filter (EAKF)
- Supports various models and datasets.

WACCM

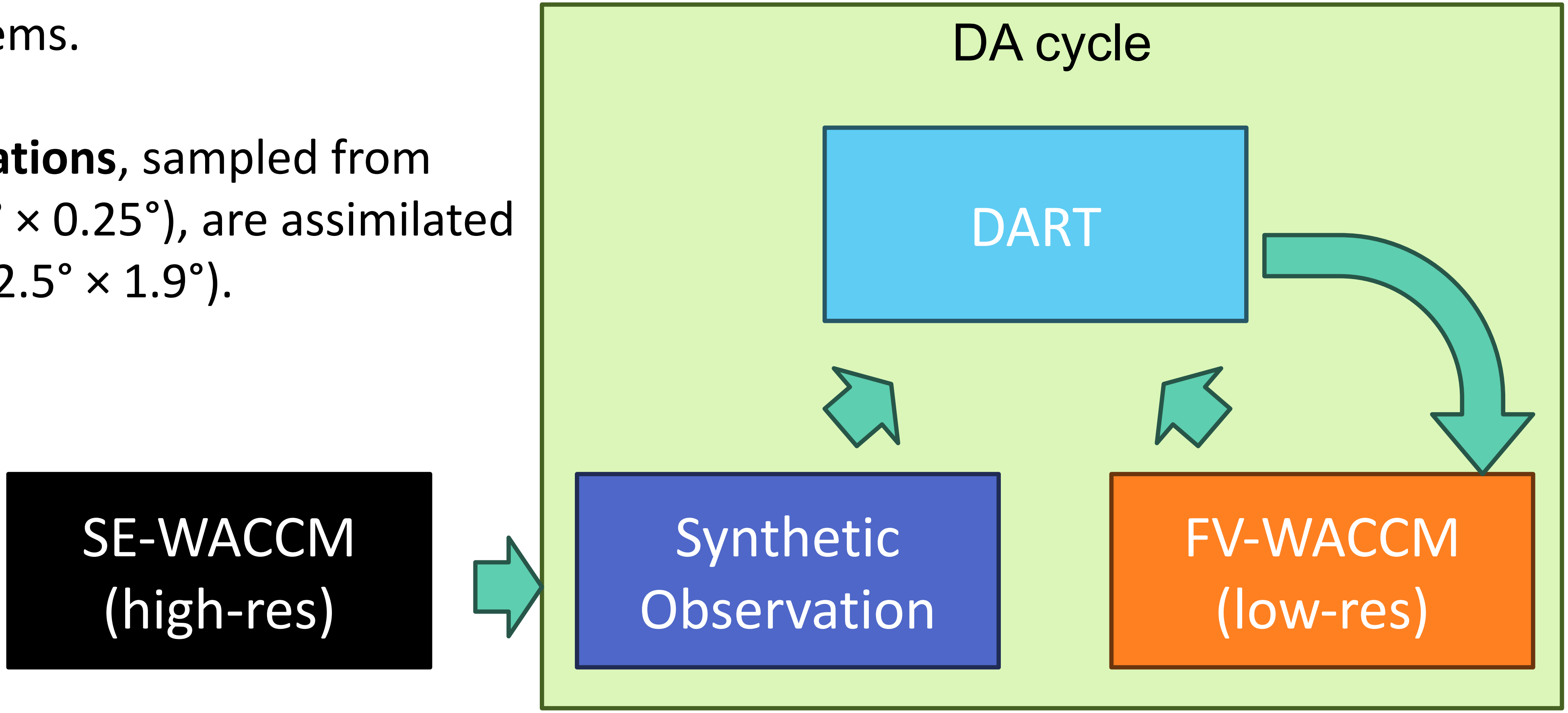
- NCAR's Whole Atmosphere Community Climate Model (WACCM)
- A general circulation model that simulates the atmosphere from the surface up to the lower thermosphere (~140 km).

From https://dart.ucar.edu/

Observing System Simulation Experiment (OSSE)

- **OSSEs** can be used to evaluate the impact of observing systems.

- **Synthetic observations**, sampled from SE-WACCM (0.25° × 0.25°), are assimilated into FV-WACCM (2.5° × 1.9°).



Experiment Design

In EAKF (or other deterministic ensemble-based Kalman filter), we have:

$$\bar{\mathbf{X}}^{\mathrm{a}} = \bar{\mathbf{X}}^{\mathrm{b}} + \mathbf{K}(\mathbf{y}^{\mathrm{o}} - \mathbf{H}(\bar{\mathbf{X}}^{\mathrm{b}}))$$

$$\mathbf{X}_{\mathrm{n}}^{\mathrm{a}} - \bar{\mathbf{X}}^{\mathrm{a}} = (\mathbf{X}_{\mathrm{n}}^{\mathrm{b}} - \bar{\mathbf{X}}^{\mathrm{b}}) + \widetilde{\mathbf{K}}(-\mathbf{H}(\mathbf{X}_{\mathrm{n}}^{\mathrm{b}} - \bar{\mathbf{X}}^{\mathrm{b}}))$$

x model state variable
y observation variable
K Kalman gain
H forward operator

	y_o	x
Exp 1	LA + SABER +MLS	T, U, V
Exp 2	LA + SABER +MLS + Meteor Radar wind+ SuperDARN wind	T, U, V

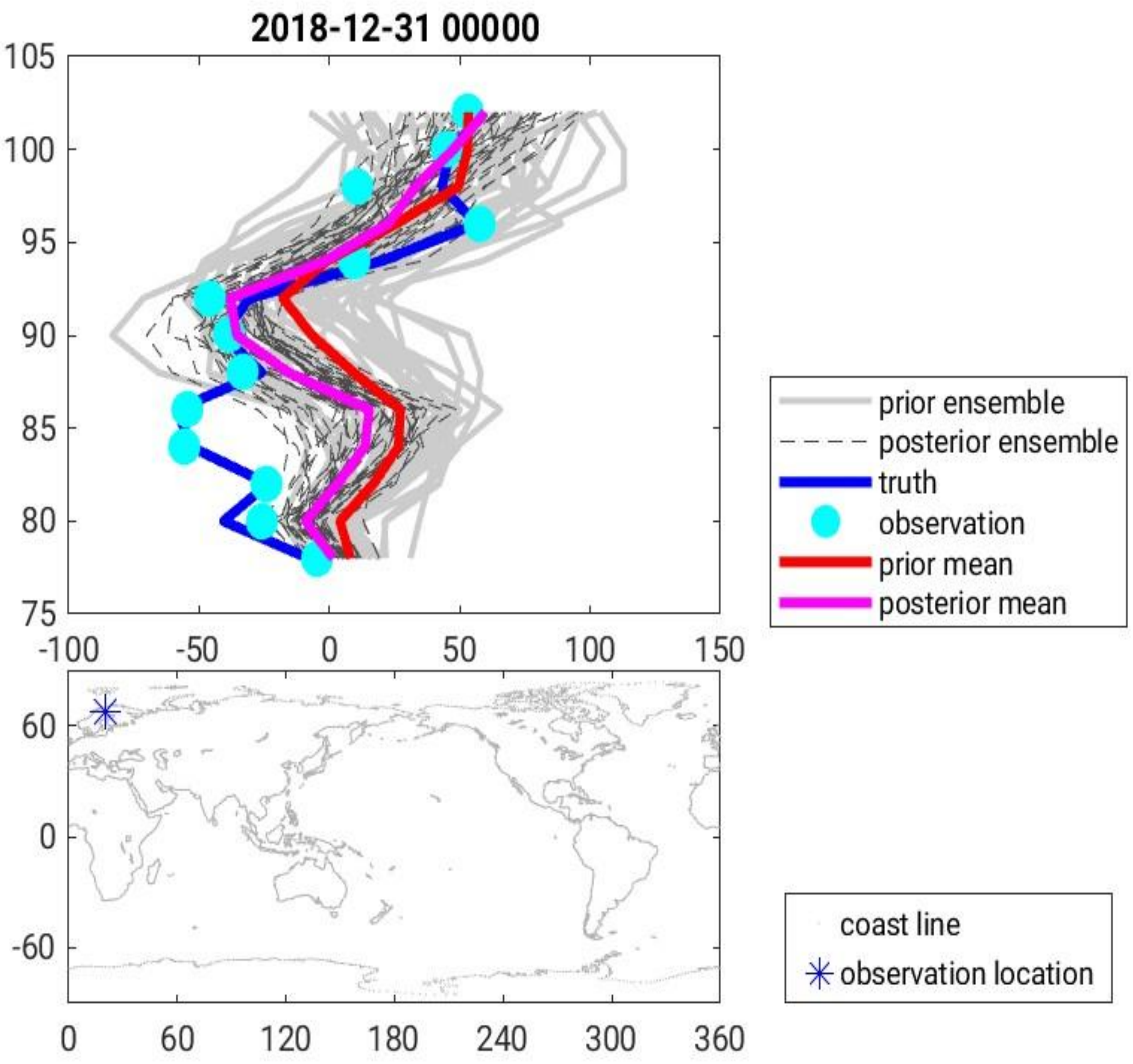
- 2018–2019 winter sudden stratospheric warming
- 40 ensemble members

Forward Operator:
Meteor radar wind
- linear interpolation

SuperDARN wind
- weighted average over the 70–120 km (Gaussian)

Example of Result

- Example of vertical zonal wind profiles from data assimilation at the Esrange meteor radar site.
- The ensemble of wind profiles converge after data assimilation
- Ensemble mean shifts toward the observation after data assimilation

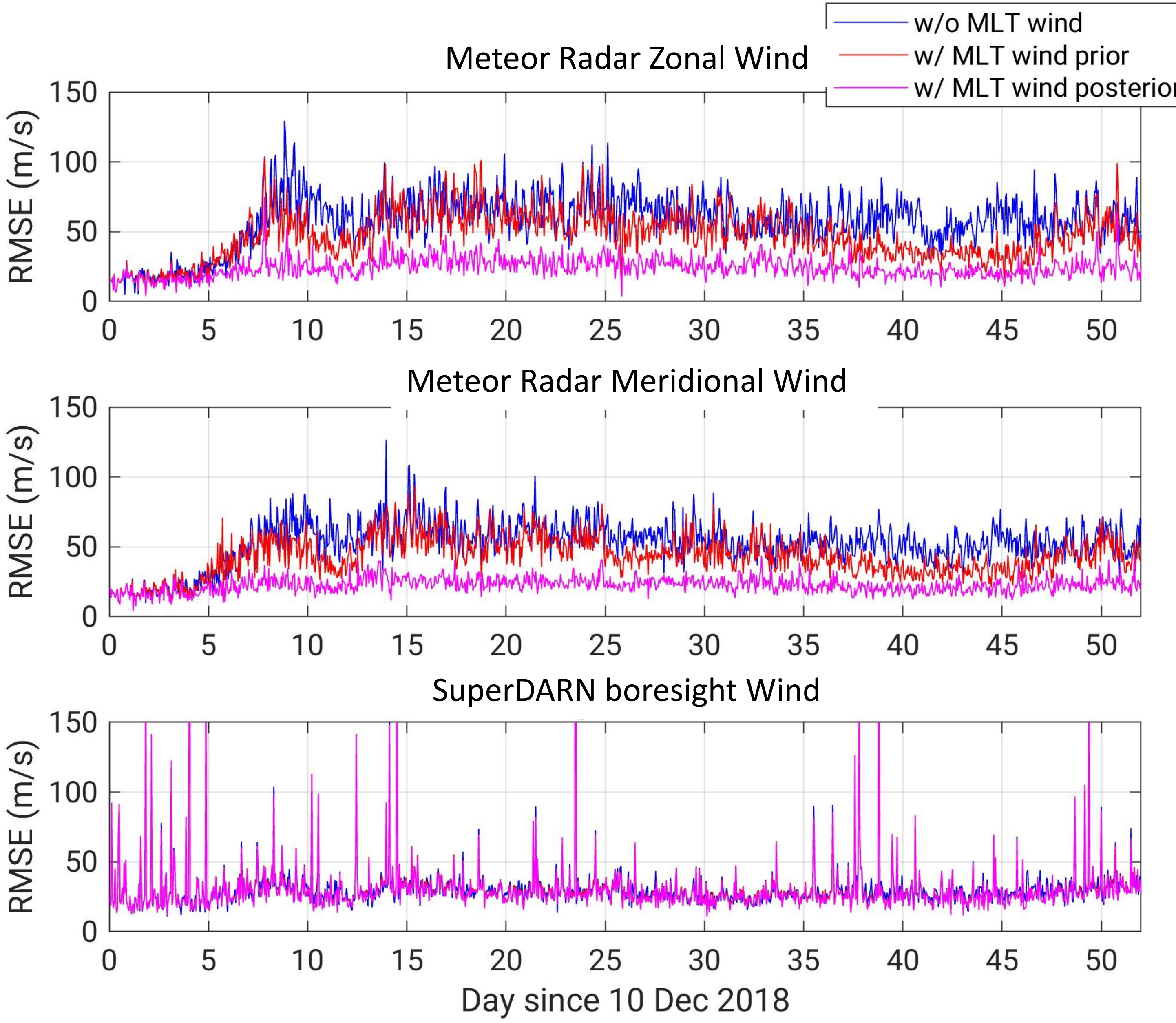


RMSE in Observation Space

$$RMSE(k) = \sqrt{\frac{\sum_{n}^{nobs}(y(n,k) - y^{truth}(n,k))^2}{nobs}}$$

n: *index of observation*
k: *index of time*

- Meteor radar winds show significant improvements in both the zonal and meridional directions.
- SuperDARN winds do not show a clear impact check the H operator.

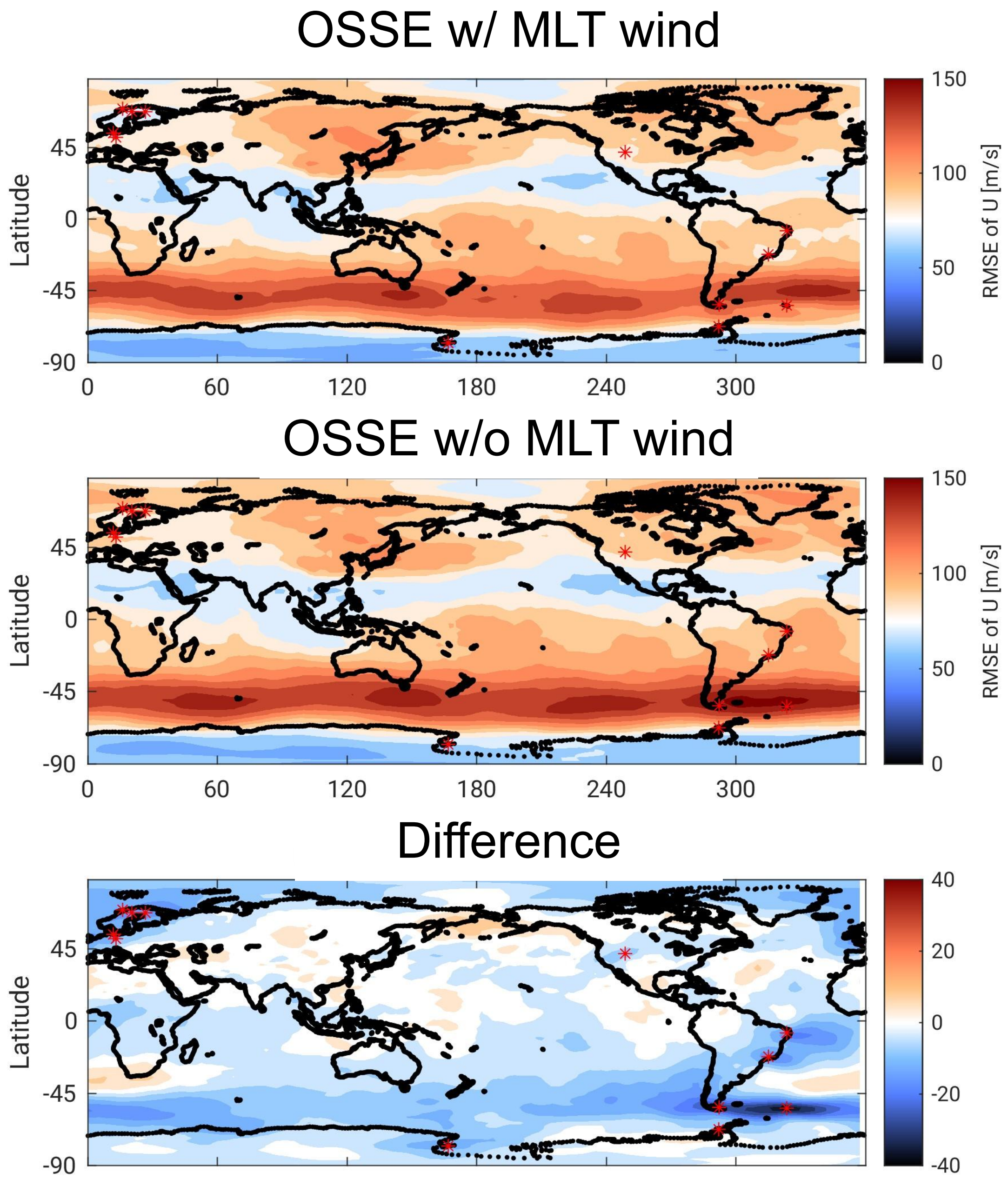


RMSE in Model Space
Zonal Wind at 92 km

$$RMSE(i,j,k) = \sqrt{\frac{\sum_k^{ntime}\left(x(i,j,k) - x^{truth}(i,j,k)\right)^2}{ntime}}$$

i: *index of longitude*
j: *index of latitude*
k: *index of time*

- Errors are reduced around meteor radar stations.



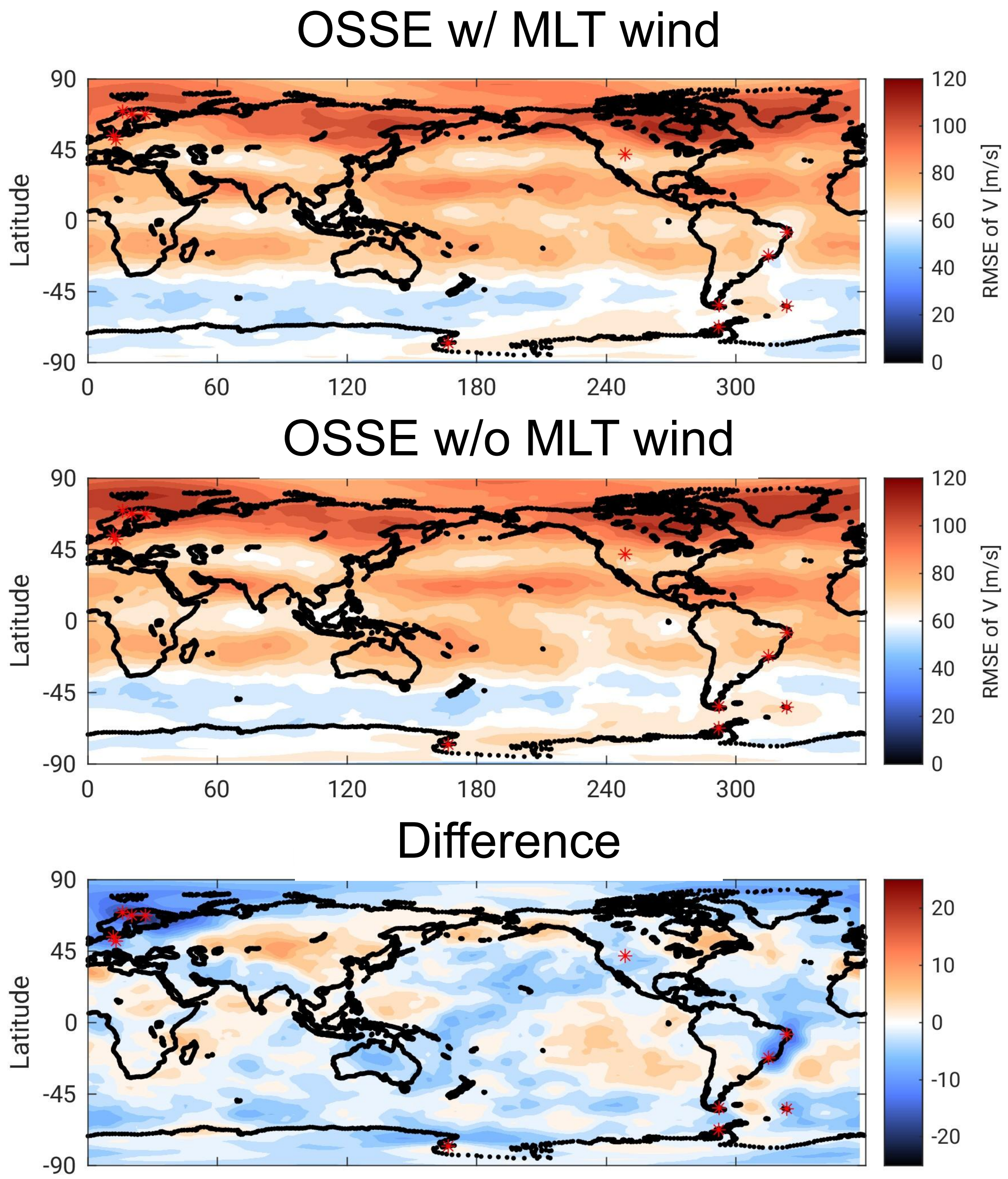
Red: error increases with MLT wind
Blue: error decreases with MLT wind

RMSE in Model Space
Meridional Wind at 92 km

$$RMSE(i,j,k) = \sqrt{\frac{\sum_k^{ntime}(x(i,j,k) - x^{truth}(i,j,k))^2}{ntime}}$$

i: index of longitude
j: index of latitude
k: index of time

- Significant error reductions are observed around meteor radar stations.



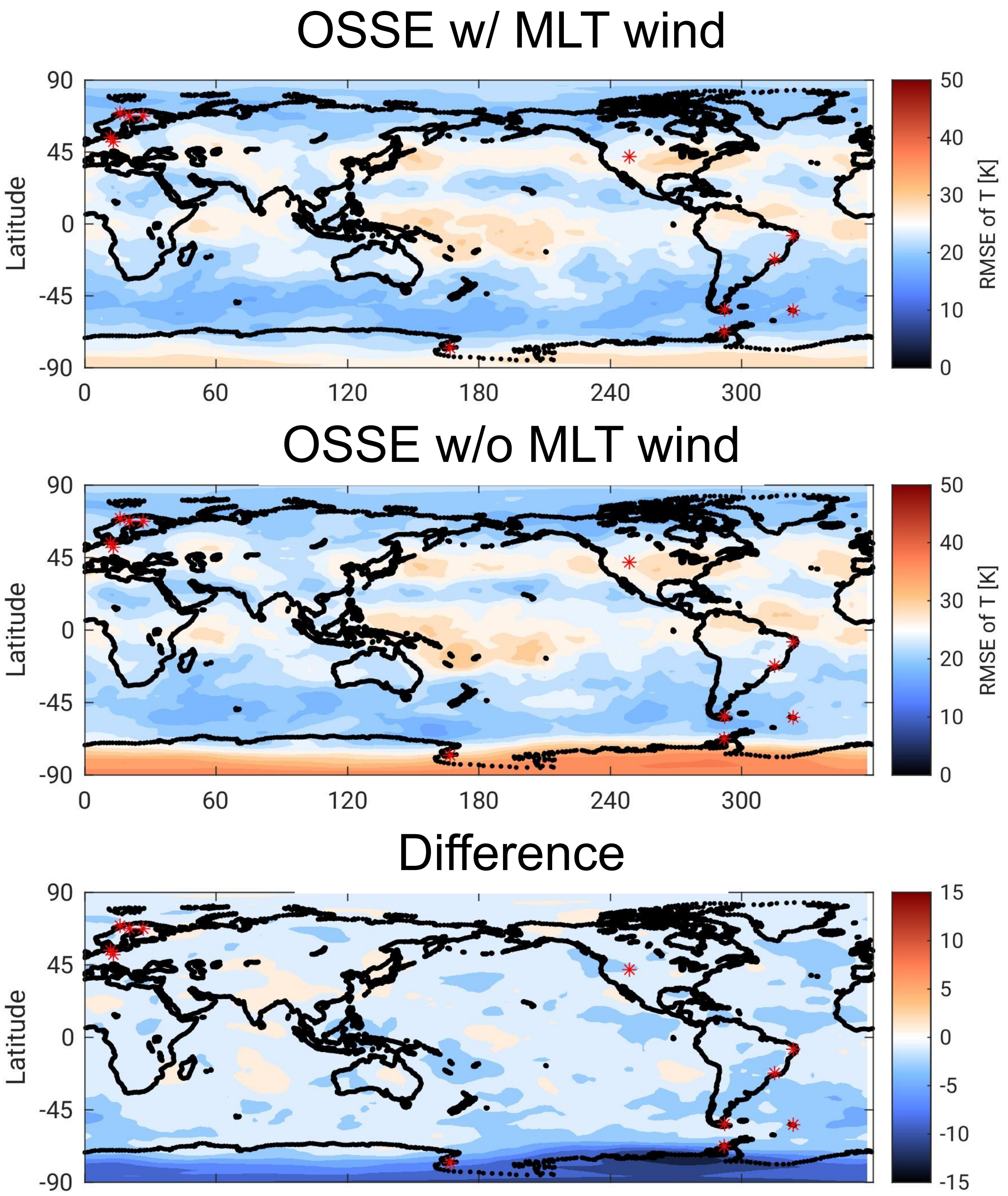
Red: error increases with MLT wind
Blue: error decreases with MLT wind

RMSE in Model Space
Temperature at 92 km

$$RMSE(i,j,k) = \sqrt{\frac{\sum_{k}^{ntime}\left(x(i,j,k) - x^{truth}(i,j,k)\right)^2}{ntime}}$$

i: index of longitude
j: index of latitude
k: index of time

- Clear error reductions are shown globally, even when assimilating neutral wind data.
- Aligned with previous studies (Chartier et al., 2013, 2016; Hsu et al., 2014)



Red: error increases with MLT wind
Blue: error decreases with MLT wind

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Conclusion

- This study assimilates **synthetic MLT wind** observations (SuperDARN + meteor radars) into a **WACCM** using **DART/EAKF**.
- **Key results:**
  - **SuperDARN impact:** Minimal on neutral wind specification due **to limited observation density and the H operator**.
  - **Meteor radar:** Clear local improvements in zonal/meridional winds near sites, but **spatially/temporally limited**; corrections don't propagate or persist well.
  - Assimilating MLT winds **significantly improves global neutral temperature**, indicating effective **multivariate updates**.
- **Future work:**
  - Optimize **localization/inflation** for MLT dynamics, especially for SuperDARN data.
  - Explore **joint updates** of temperature, wind, and composition.