Observing Meteorology Across Scales

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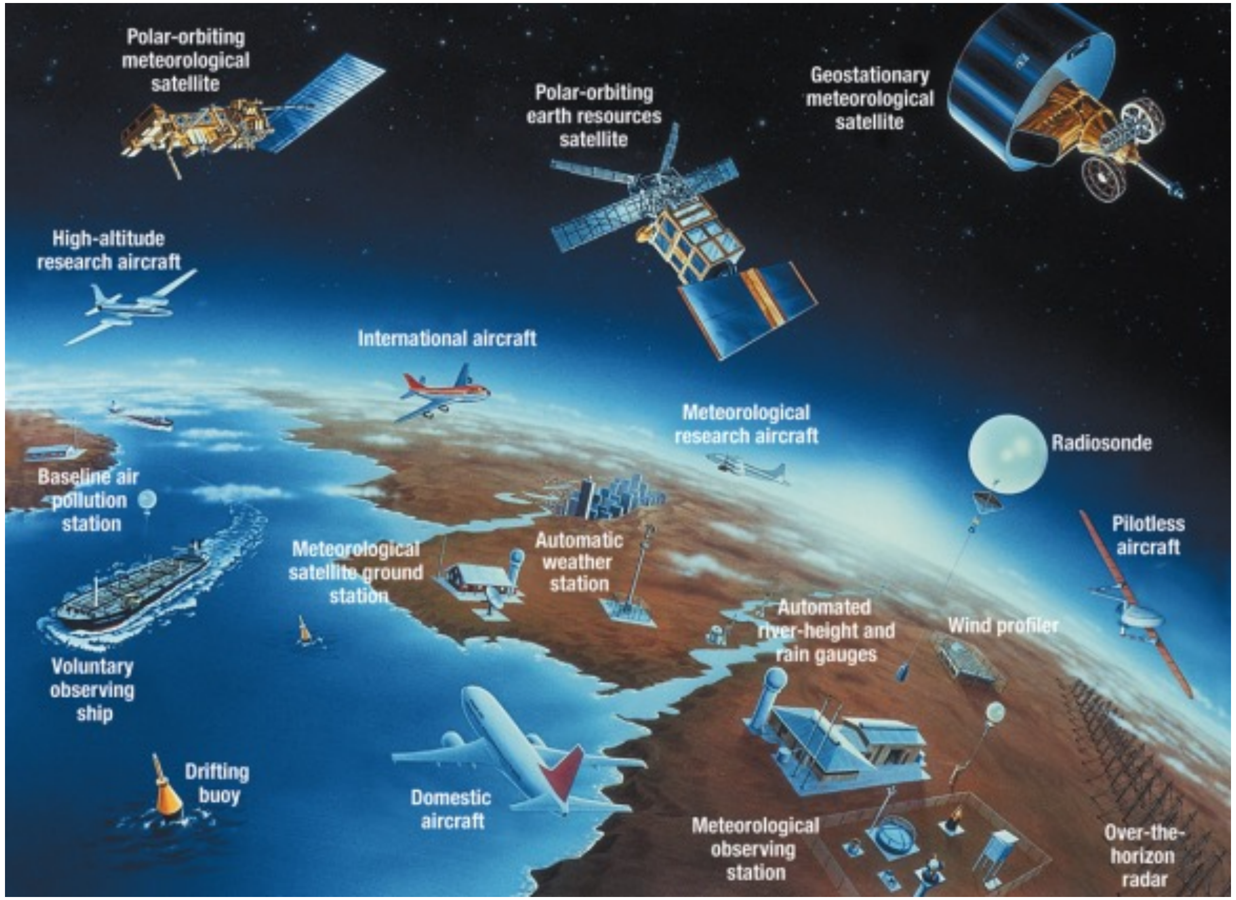
Meteorological Observations

- Measurements of atmospheric state (temperature, pressure), dynamics (3D wind vector components), and water vapor
- Made by a diverse set of instruments
  - on the surface (land and ocean)
  - in air (airplanes and balloons)
  - in space
- Each has strengths and weaknesses

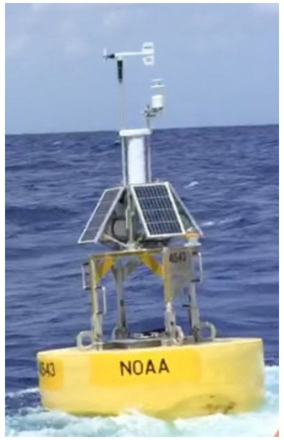
WMO Integrated Global Observing System - WIGOS

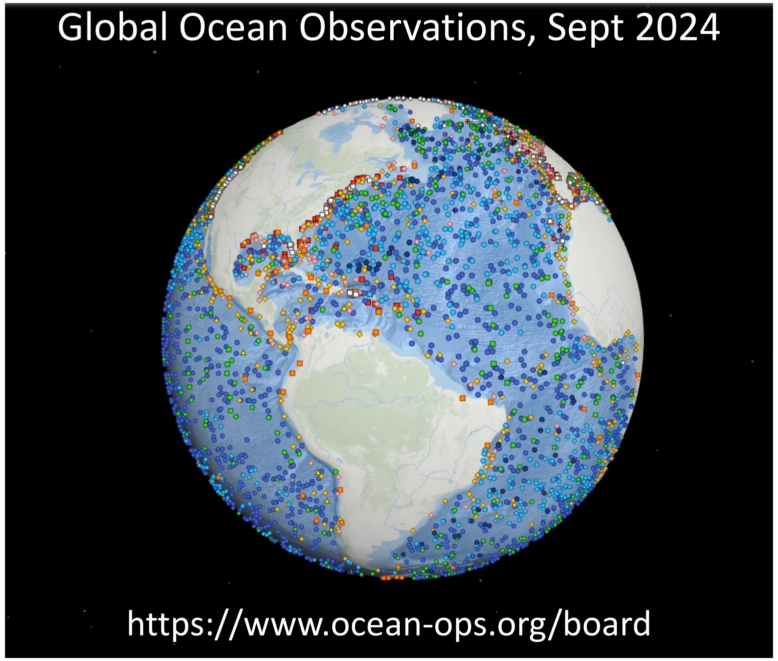


https://community.wmo.int/en/activity-areas/WIGOS

In-Situ Observations: Land and Ocean

- Land surface meteorological data collected routinely ~hourly (or less) at 11,000 sites
- Ocean observations also include sea state data



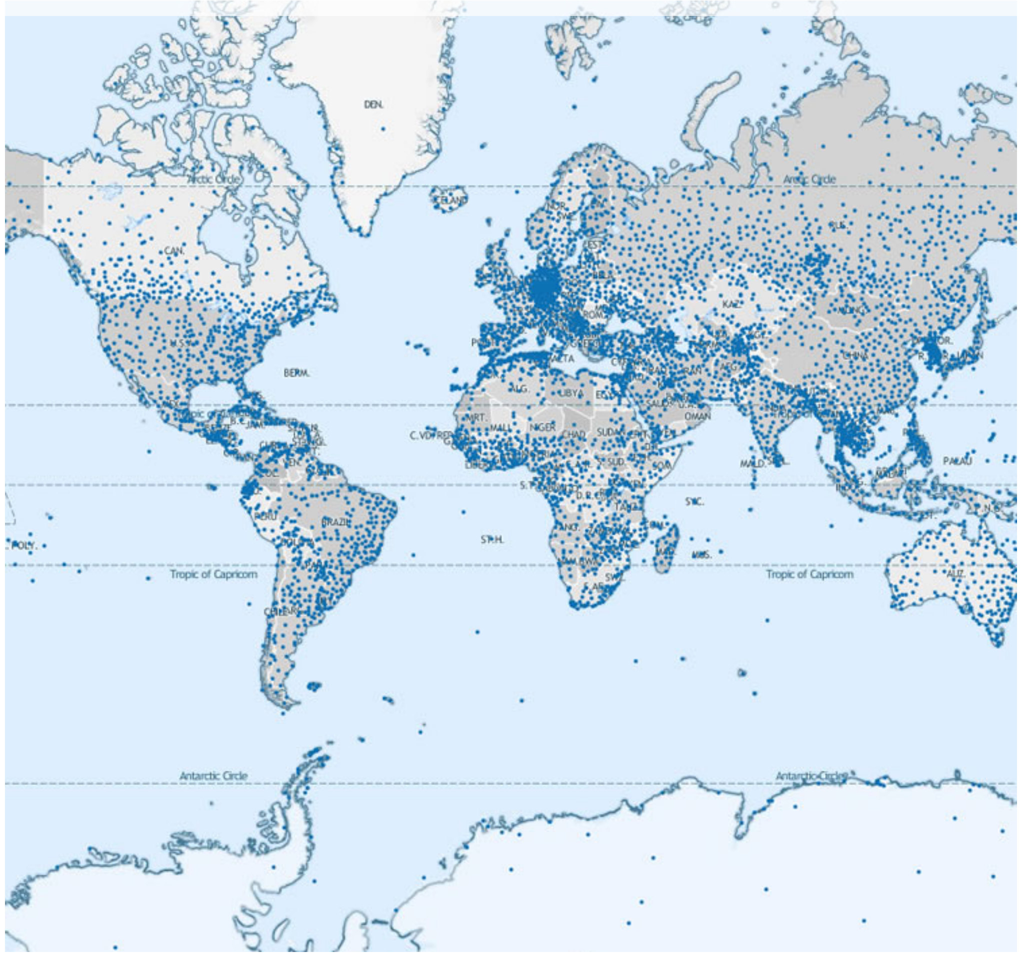


Mobile systems
- Core floats - Argo
- Deep floats - Argo
- Biogeochemistry floats - Argo
- Underwater gliders - OceanGliders
- Drifting buoys - DBCP
- Polar buoys - DBCP
- Animal borne sensors

Fixed systems
- Tsunameters - DBCP
- Offshore platforms - DBCP
- Moored buoys - DBCP
- Ocean reference stations - OceanSITES
- Sea level gauges - GLOSS
- High Frequency radars

Ship based measurements
- Manned weather stations - SOT/VOS
- Automated weather stations - SOT/VOS

Land Surface Observations in WIGOS, 2017



https://community.wmo.int/en/observation-components-global-observing-system

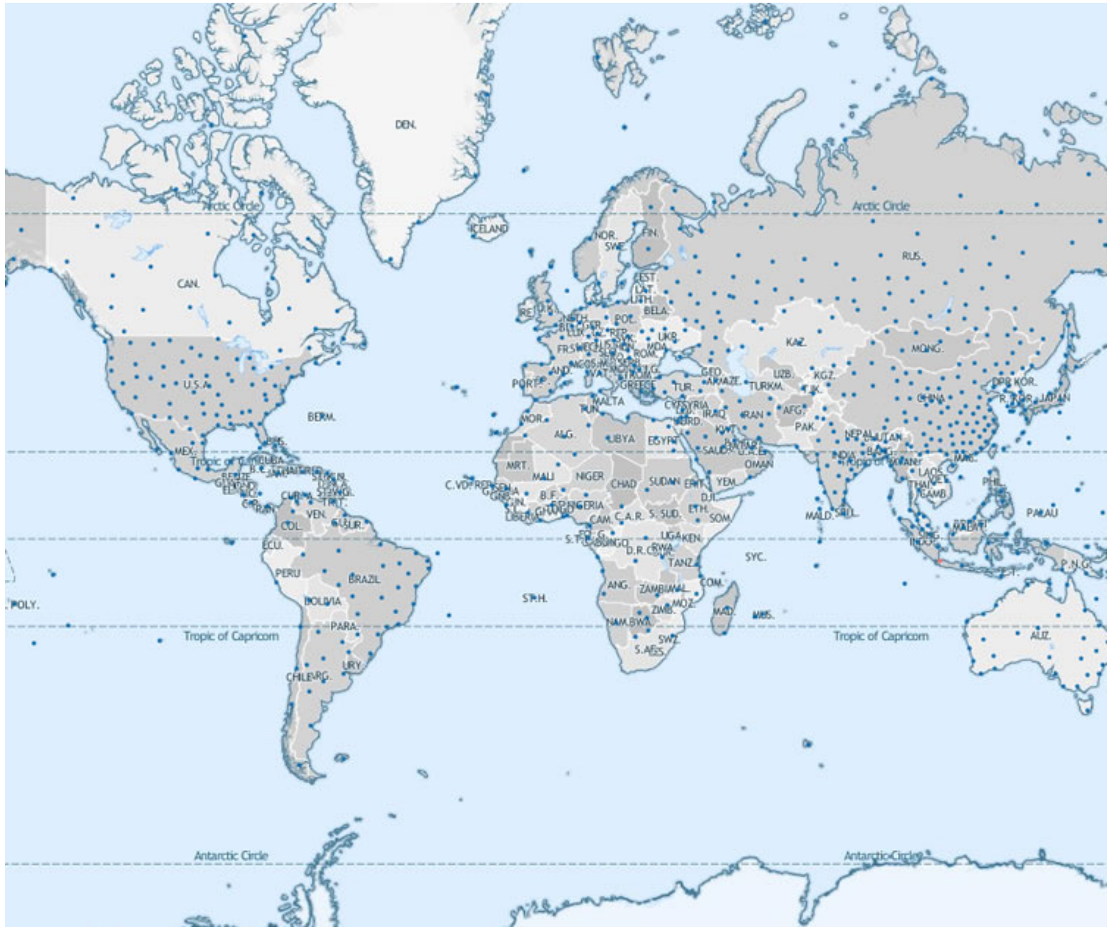
In-Situ Observations: Upper-Air

- Balloon-borne measurements of state and wind variables remain an important part of the global observing system
- ~1300 sites, 2x / day

1936
https://en.wikipedia.org/wiki/Radiosonde

2024
https://incus.colostate.edu

Upper Air (Radiosonde) Observations, 2017

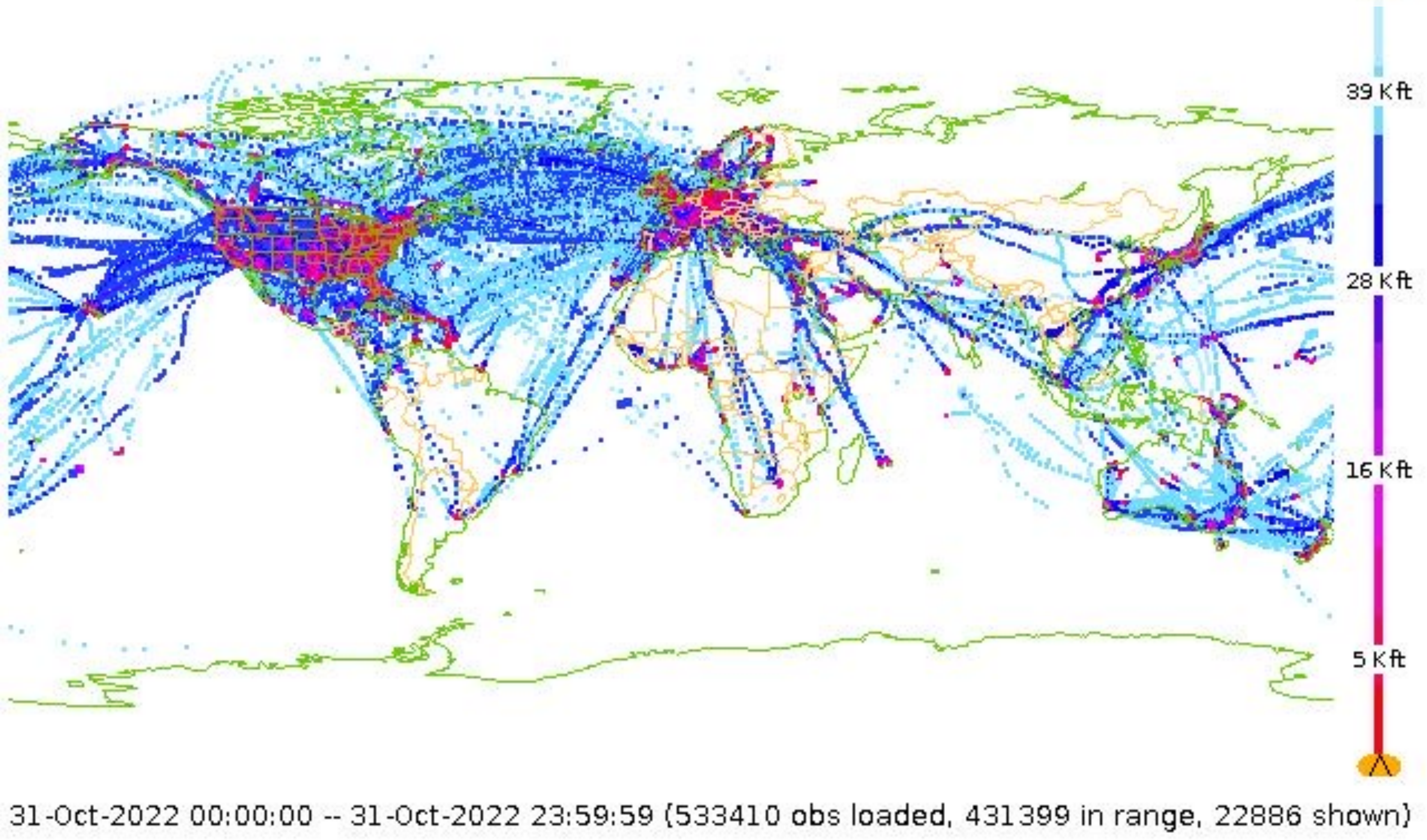


https://community.wmo.int/en/observation-components-global-observing-system

In-Situ (In-Place) Observations: Aircraft

- Commercial aircraft report temperature, pressure, wind
- A subset include water vapor measurements
- Profiles concentrated near airports
- Upper air observations along major airways

24 Hours of Aircraft Meteorological Observations, 31 Oct 2022



https://community.wmo.int/en/activity-areas/aircraft-based-observations/newsletter/volume-24

Space-Borne Observations

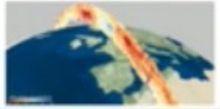
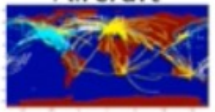
- International community maintains a fleet of satellites
- Provide operational (routine, timely) observations
- Strength:
  Global coverage
- Weakness:
  Indirect measurements

Space-Based Observations in WIGOS

https://wmo.int/activities/global-observing-system-gos/global-observing-system-gos

Focus on Winds

- Globally, there are millions of above-surface wind observations every 6h
- Vast majority of these are in the upper troposphere, derived from spaceborne measurements
- Very few measurements in lower troposphere, and fewer still in the planetary boundary layer

The main sources of wind measurements	Error [ms^{-1}]	Obs available for DA every 6 h	Pros & Cons
GEO VIS/IR AMV* 	~4	≈5,000,000	Quasi global coverage at high temporal resolution; only cloud tops with uncertainties related to height
Aeolus 	~4 or >	≈50,000	Vertical profiles in clear sky and in thin clouds; Moderate errors for Rayleigh winds, low revisit time
Aircraft 	~2 or >	≈270,000	Very accurate; vertical profiles near airports; only at flight time/height on aircrafts routes
Radiosondes 	~2	≈14,000	Very accurate; vertical profiles at given location and UTC time; in decaying numbers

*Atmospheric Motion Vectors: from the movement of clouds/moisture in successive satellite images

Image courtesy European Space Agency

Focus on Spaceborne Winds

- Distribution of surface, balloon, and aircraft observations not expected to change significantly – and have limited coverage
- Primary candidate for improved wind coverage: satellite
- Two methods:
    - Passive: track the motion of images/features
    - Active: use Doppler shift due to motion of clouds/precipitation (radar) or air/particulates (lidar)

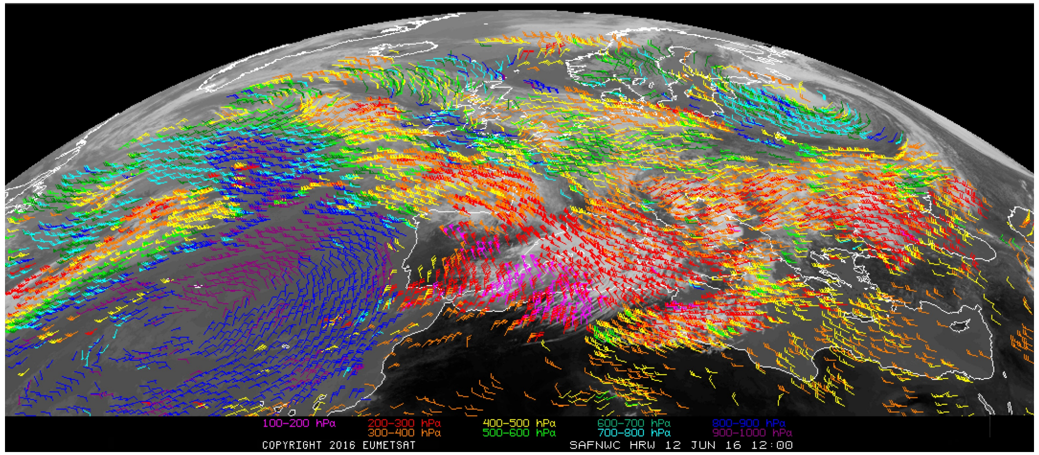


Image courtesy EUMETSAT

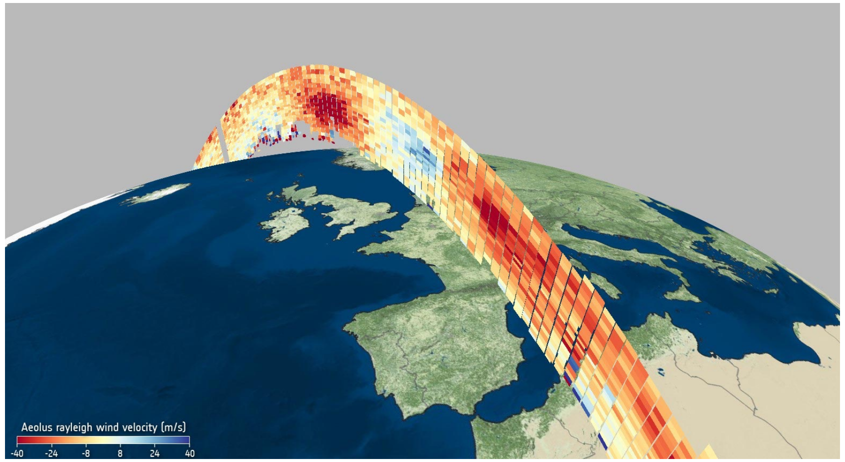
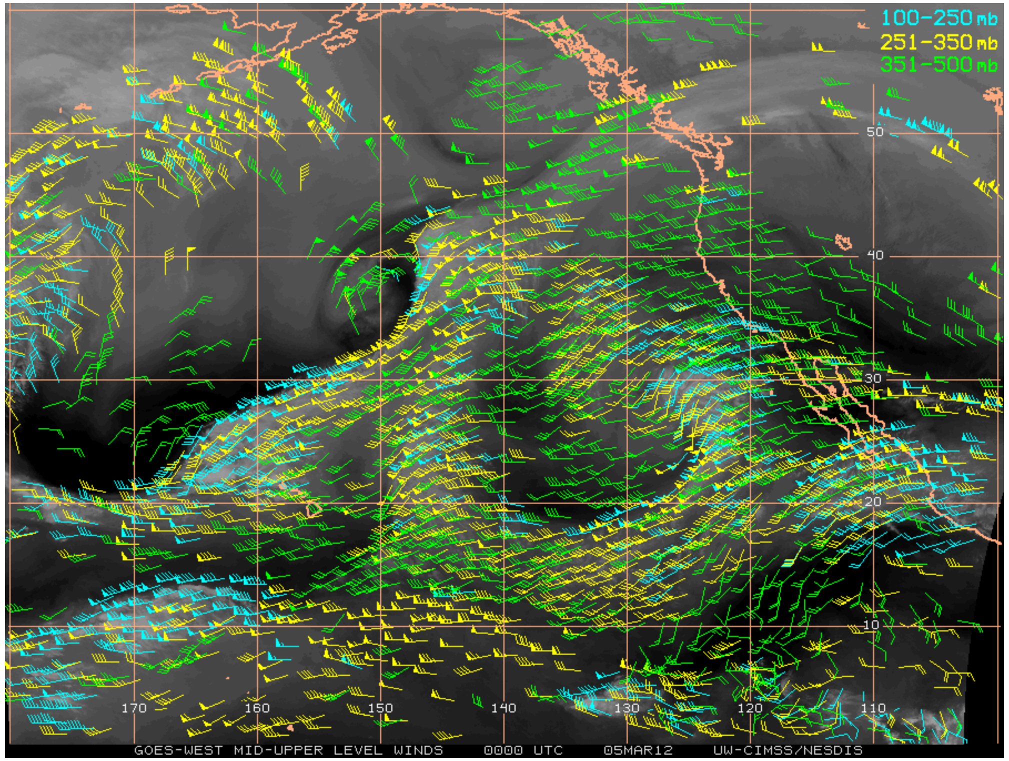


Image courtesy European Space Agency

Tracking Features in Imagery

- Atmospheric Motion Vectors
- Obtained from sequences of images
- Require:
  - Spatial overlap between images
  - Time delay of 1 hour or less
  - Resolved features
  - An image registration and feature tracking algorithm
- Strength: coverage
- Weakness: large uncertainty

Winds obtained from tracking 3 water vapor channels in GOES-West 5-6 March 2012



https://cimss.ssec.wisc.edu/satellite-blog/archives/9928

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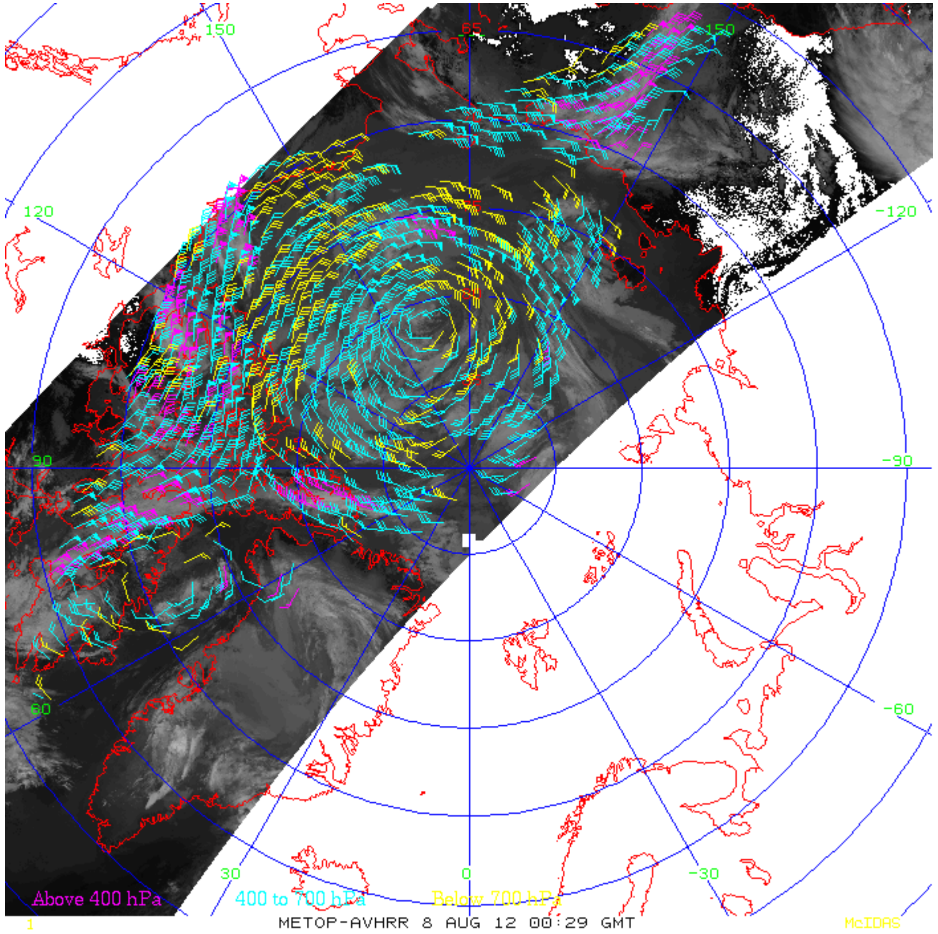
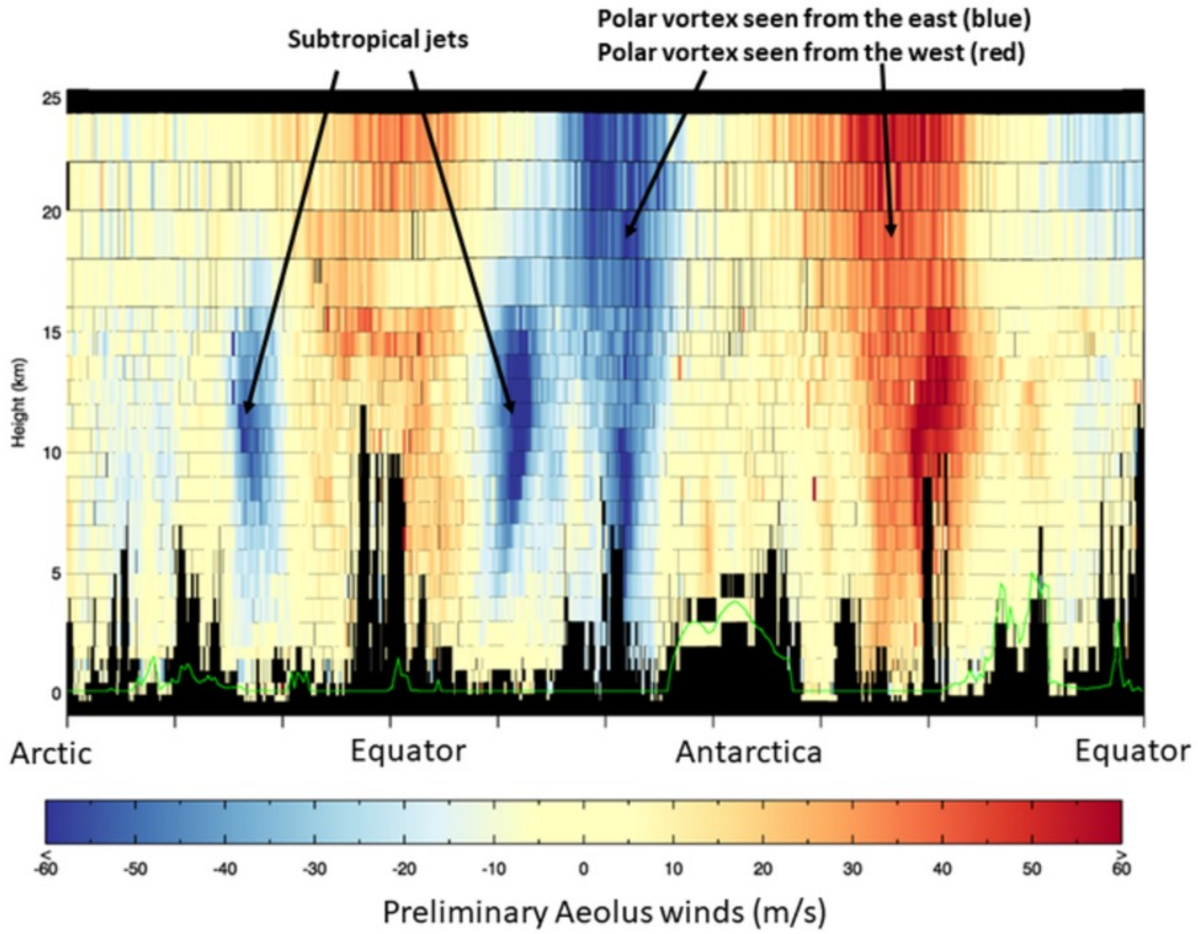
Winds obtained from tracking cloud features from multiple low-Earth orbit satellites 8 Aug 2012



https://cimss.ssec.wisc.edu/satellite-blog/archives/11038

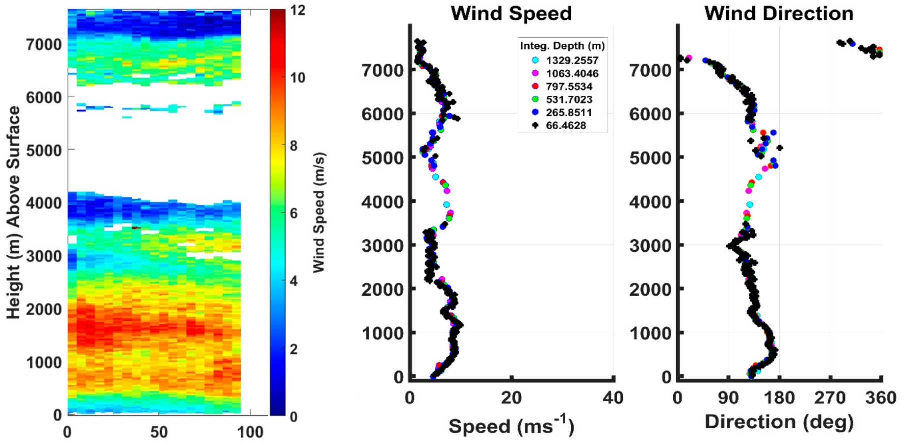
Winds from Spaceborne Lidar

- Doppler wind measurements depend on frequency shift – movement toward or away from the sensor
- Doppler radar: motion of rain, snow, and hail
- Doppler lidar: motion of air molecules or particulates
- ESA Aeolus was the first spaceborne doppler lidar
- Planning Aeolus-2 for 2030s
- Strength: accurate and unbiased
- Weakness: very limited coverage, cannot see through clouds

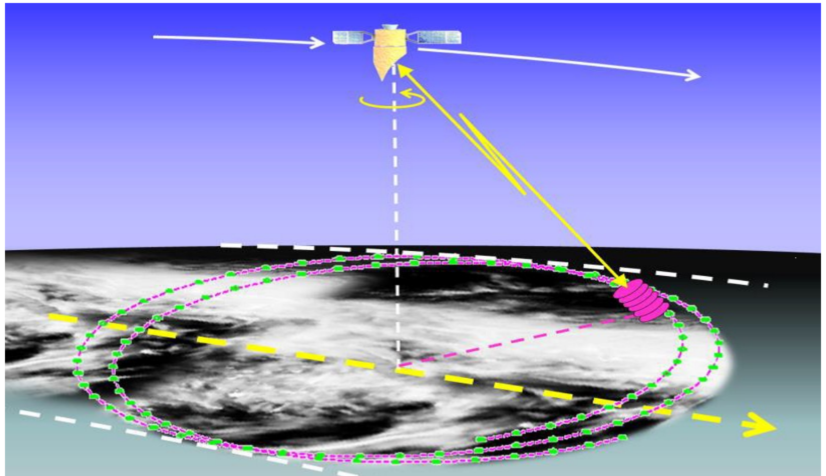


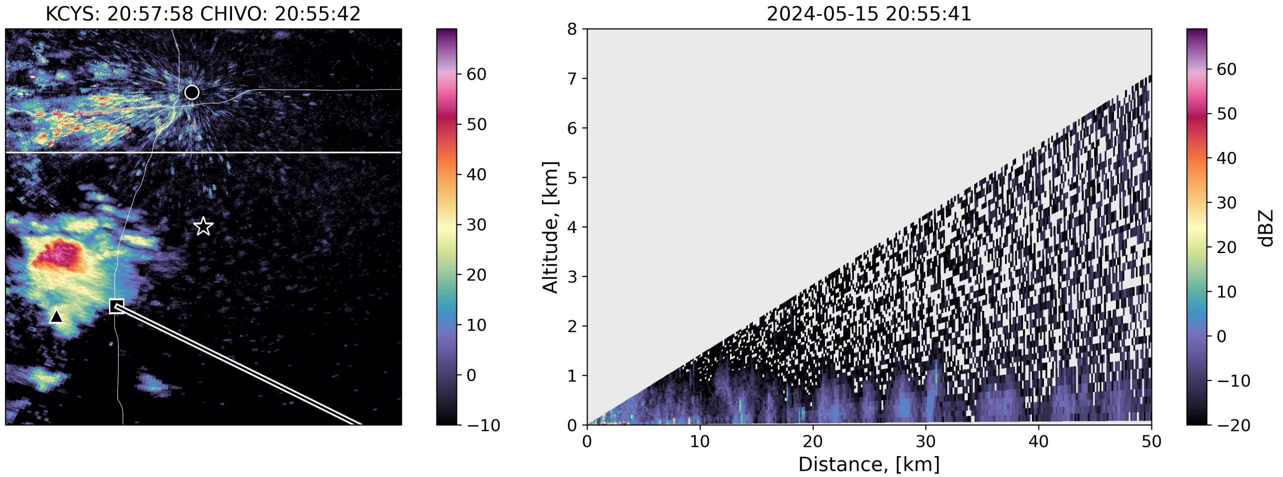
Non-Routine Observations

Research measurements
- Field campaigns
- New observing strategies
- Uncrewed aerial vehicles
- Specialized spaceborne observations

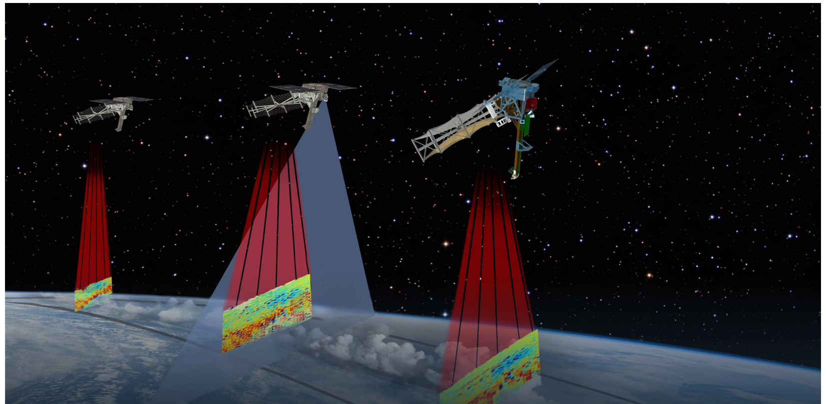


Airborne Doppler Wind Lidar


ESA WIVERN: Scanning Doppler Cloud Radar



Ground Radar: Multisensor Agile Adaptive Scanning


NASA INCUS: High Time Resolution Radar

Observing System: 2030s

- Major advance in routine observations
- Geostationary space-borne temperature and water vapor profiling
- ~10-20 vertical layers
- 1 hourly time resolution
- As with current passive measurements, winds are obtained through feature tracking

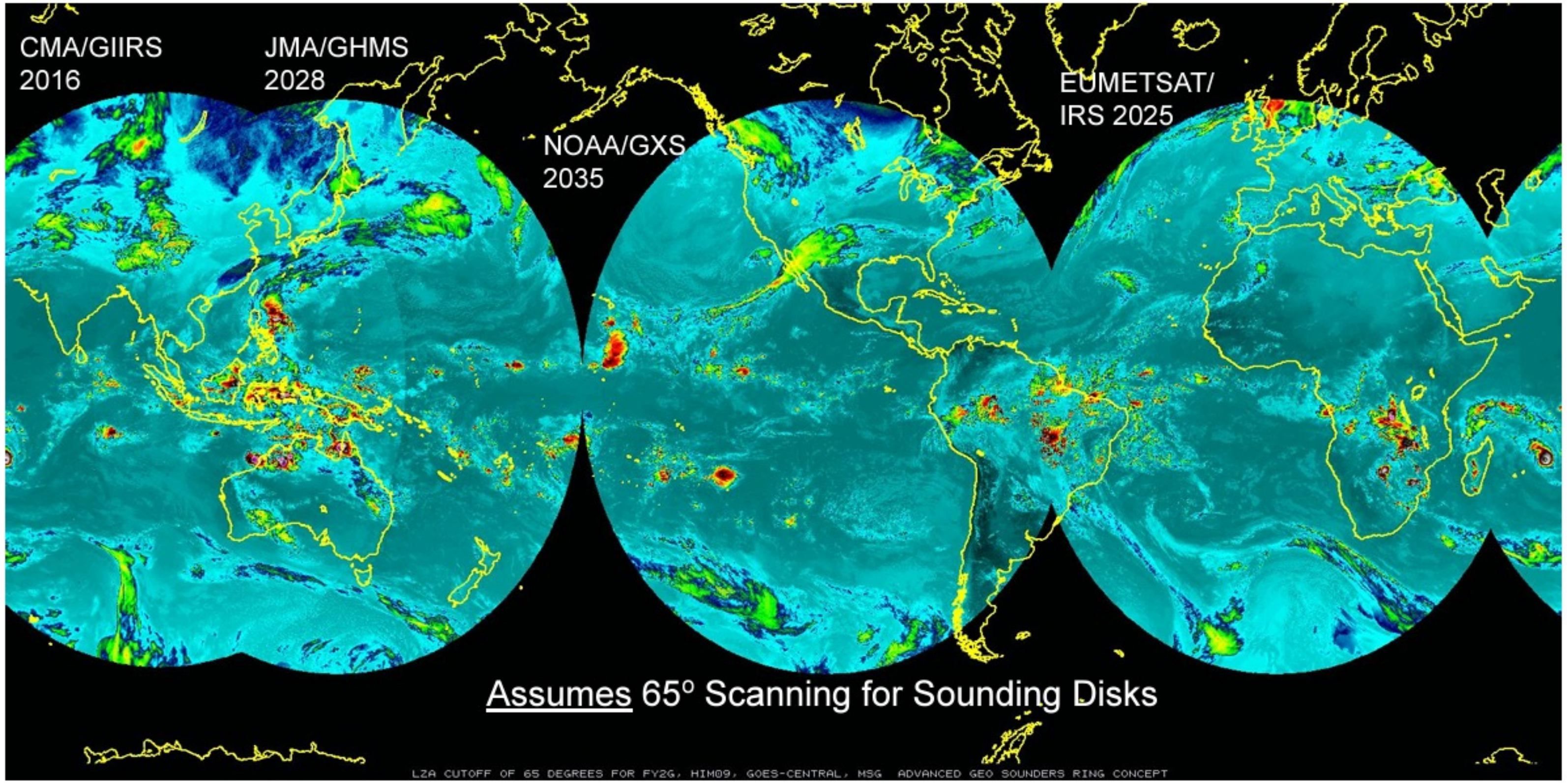
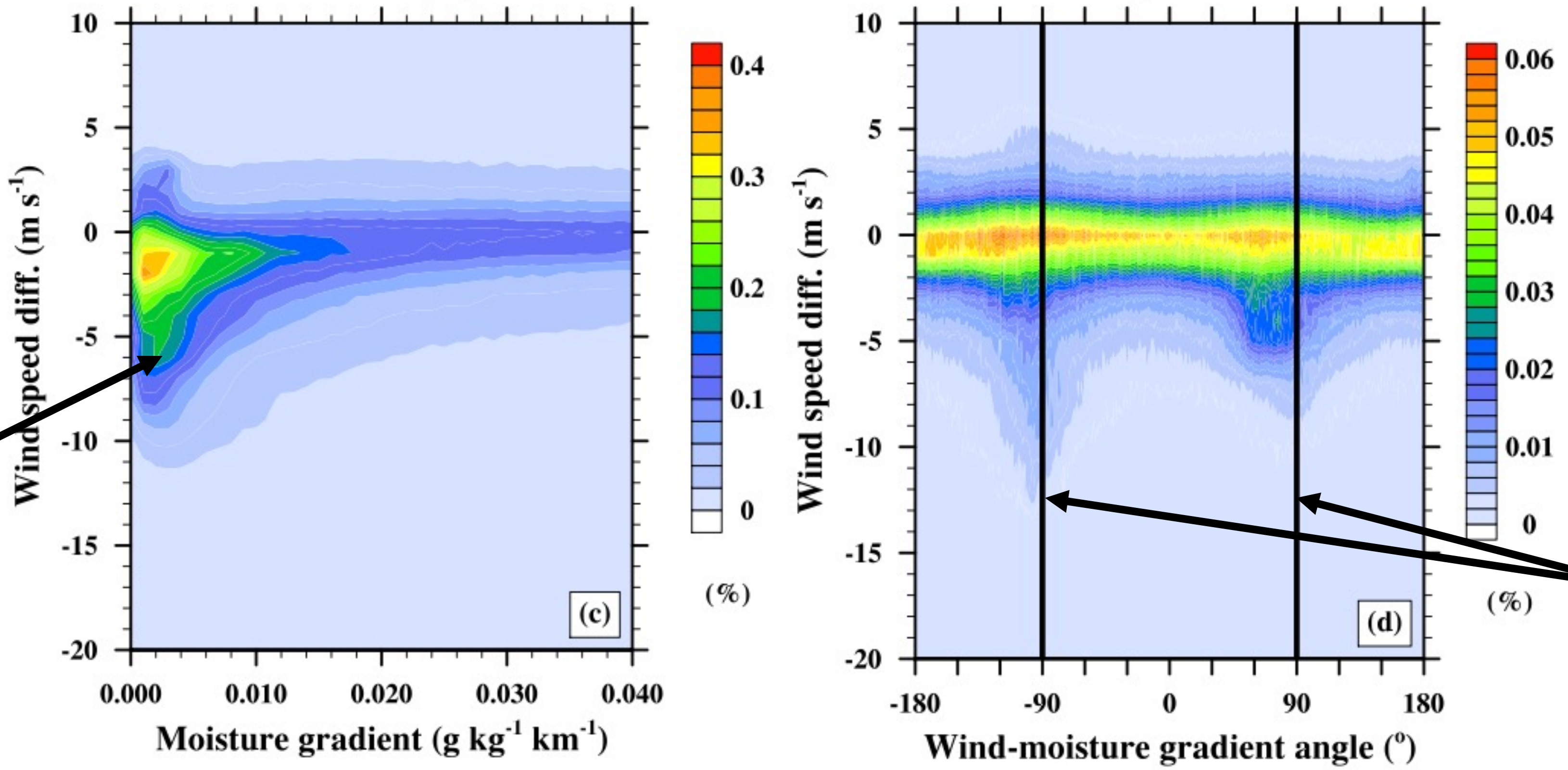


Image courtesy Tim Schmit, Univ. Wisconsin SSEC-CIMSS

Persistent Challenges

- Tracking winds from motion of features retains significant biases
- These biases persist, despite improvements in processing techniques

Large errors at low water vapor contents



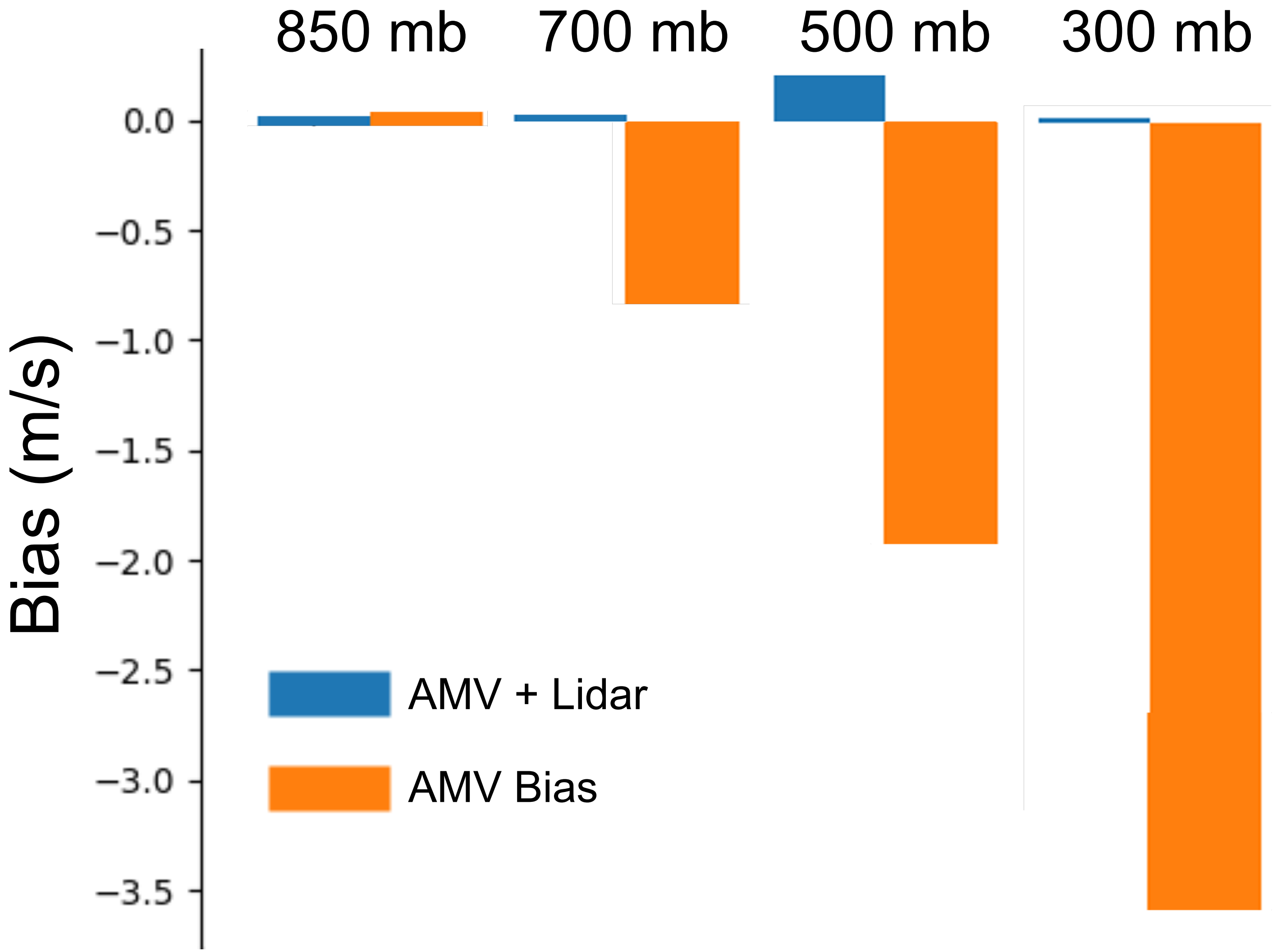
Results courtesy Igor Yanovsky and Longtao Wu

Adapted from Fig. 16 Yanovsky et al., 2024 (JAMC)

Errors largest where winds flow parallel to water vapor contours

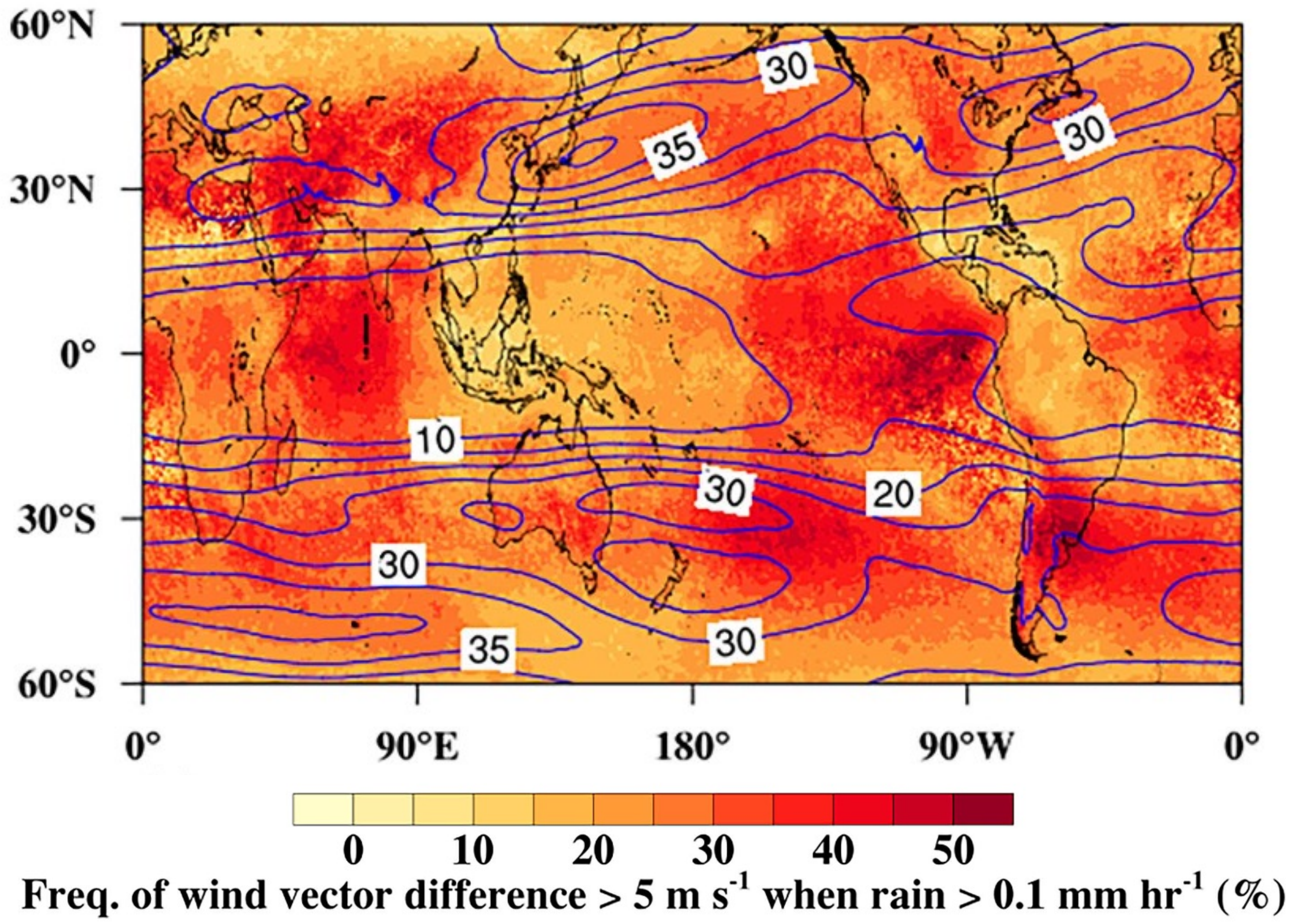
Solutions: Measurement Synergy

- AMVs: broad spatial and temporal coverage, significant biases
- Lidar: very limited spatial and temporal coverage, minimal bias
- Use collocated lidar + AMVs to correct AMV biases
- Use of lidar corrects biases in AMVs
- Demonstration of synergy



Current and Future Measurement Gaps

- Temporal refresh is often too long for process studies
- Vertical resolution is currently too poor to resolve wind shear
- It is not currently possible to observe winds inside and under clouds
- It is challenging to measure close to the Earth's surface



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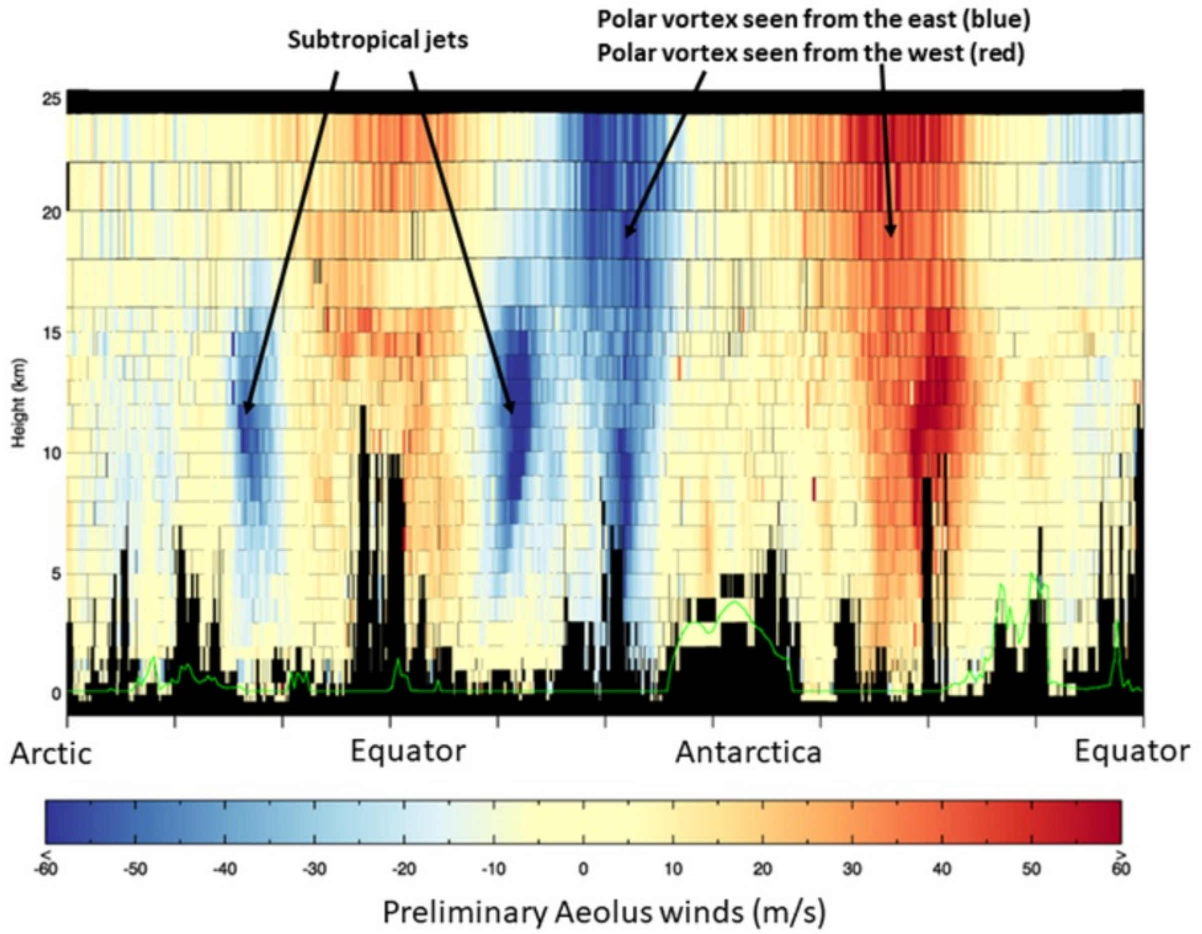

Measurement gaps in clouds and close to the surface

Making Connections: Winds + GHG

- Global observations of GHG, especially those made at high time resolution, contain significant wind information
- Conversely, tracking the source and dispersion of GHG's requires wind information
- There is a mutual interdependence that needs to be quantified
  - How much information on winds can be obtained from GHG measurements?
  - What is the wind information accuracy required to constrain GHG concentrations and evolution?
- Winds from GHG concentration measurements: <= 1 hour time difference, resolution of gradients in quantities

Summary

- There are multiple ways to measure meteorological variables and winds
- Major gaps persist, and will continue to persist
  - Planetary boundary layer (PBL)
  - Cloudy regions
- Innovative data fusion and bias correction strategies can help
- Ultimately, data assimilation may be the best tool for integration of information, but shortcomings in cloudy regions and in PBL will persist, especially for global models

Looking Forward

- Currently, Aeolus-2 is the only planned mission with a focus on atmospheric winds
- Winds seen as an *enabling* measurement – a crucial *component* in numerous science and applications questions
- Take a holistic perspective:
  - Where can existing winds measurements be used more effectively?
  - How might future measurements, not made for the purpose of observing winds, return wind information?

Resources

Observations

- WMO: https://community.wmo.int/en/activity-areas/WIGOS
- NASA: https://science.nasa.gov/earth-science/missions/
- NOAA: https://www.nesdis.noaa.gov/our-satellites/currently-flying

Winds

- International winds working group: https://cimss.ssec.wisc.edu/iwwg/iwwg.html
- NOAA System for Analysis of Wind Collocations (SAWC): https://www.star.nesdis.noaa.gov/sawc/