

Wind information from satellites:

Atmospheric Motion Vectors

Passive tracing with GEO radiances

Francis Warrick

Thanks to Katie Lean, Kirsti Salonen, Cristina Lupu and Niels Bormann

Contents

Atmospheric Motion Vectors

- What, when, where and why
- How are AMVs derived?
- How do we use them at ECMWF?

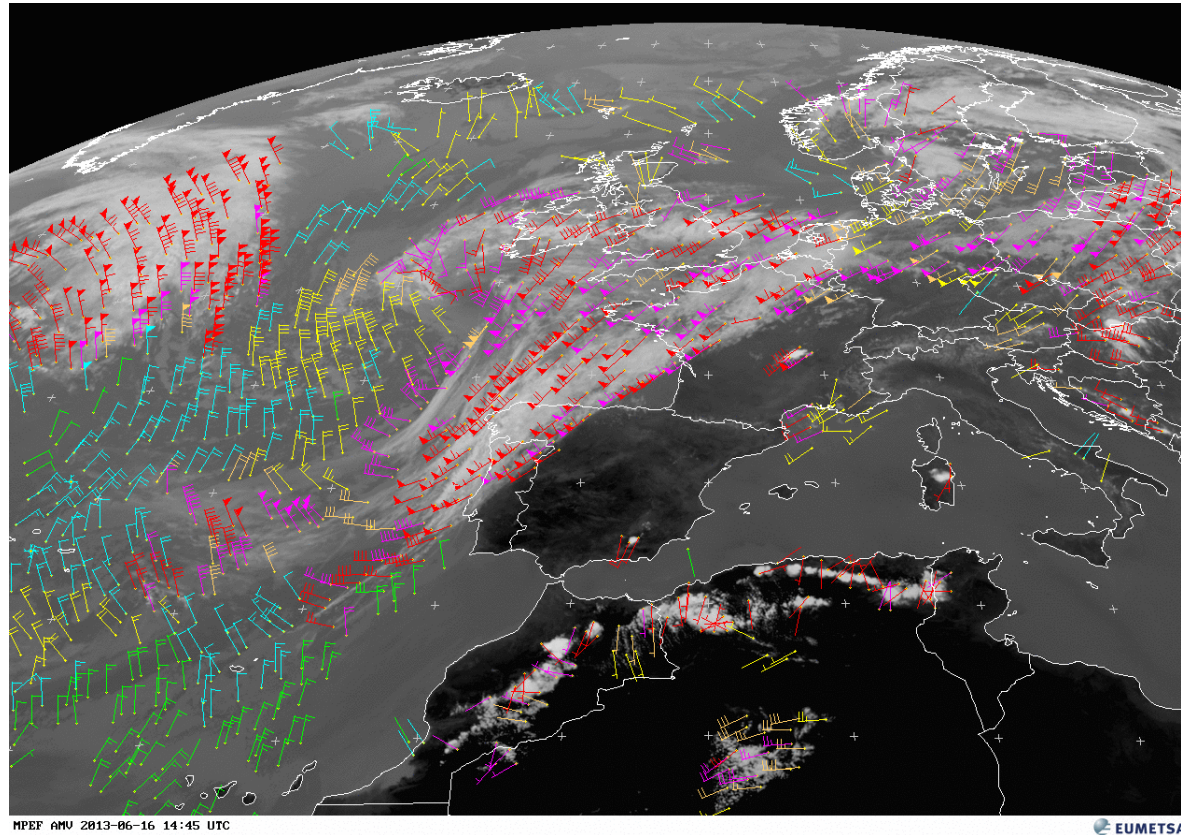
Wind indirectly from radiances

- Introduction to clear sky/all sky radiances
- Humidity tracing with radiances

Summary and future challenges

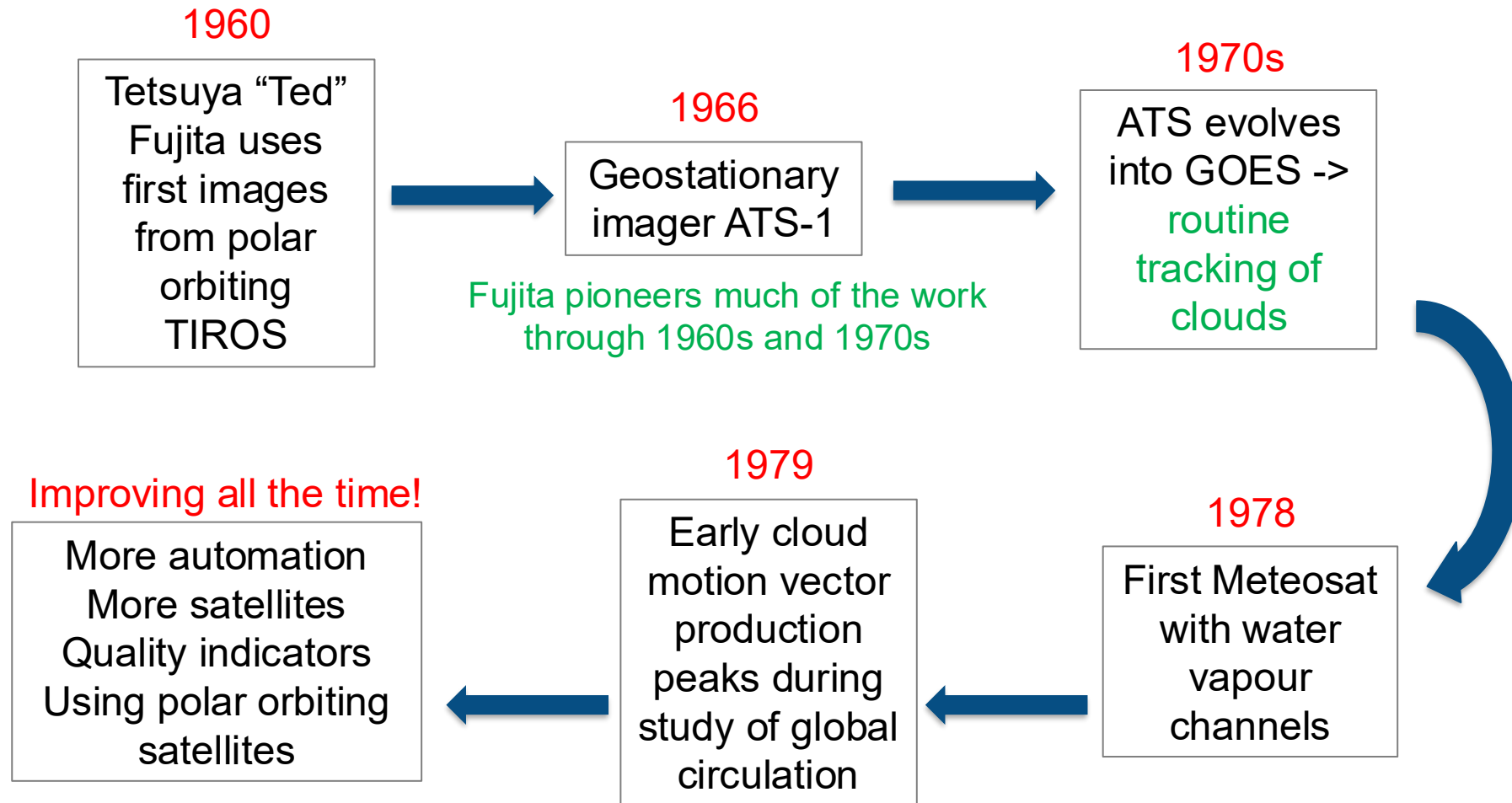
Atmospheric Motion Vectors – what are they?

Wind observations produced by tracking clouds or water vapour features
in consecutive satellite images.



Animation from: oiswww.eumetsat.org/IPPS/html/MSG/PRODUCTS/AMV/WESTERNEUROPE/index.htm

History of AMVs



AMV production today: geostationary

- Cover tropics and mid latitudes
- Successive images few minutes to ~30 mins apart
- Monitored/assimilated at ECMWF:

[EUMETSAT](#): Met-9, Met-10, Met-12

[JMA](#): Himawari-9

[NOAA/NESDIS](#): GOES-18, GOES-19

[CMA](#): FY-2G

[KMA](#): GEO-KOMPSAT-2A

AMV production today: polar orbiting

- Uses images from successive orbits from same satellite ~100 minutes apart
- Images from 2 satellites (using Metop-B and Metop-C, formerly Metop-A also), currently ~ 50 minutes apart

- Monitored/assimilated at ECMWF:

EUMETSAT: Metop-B, Metop-C, Dual-Metop AVHRR product,

Dual-Sentinel 3 SLSTR product

NOAA/NESDIS: NOAA-20, Suomi-NPP, NOAA-21

CIMSS: Composite LEO-GEO product, Terra+Aqua MODIS

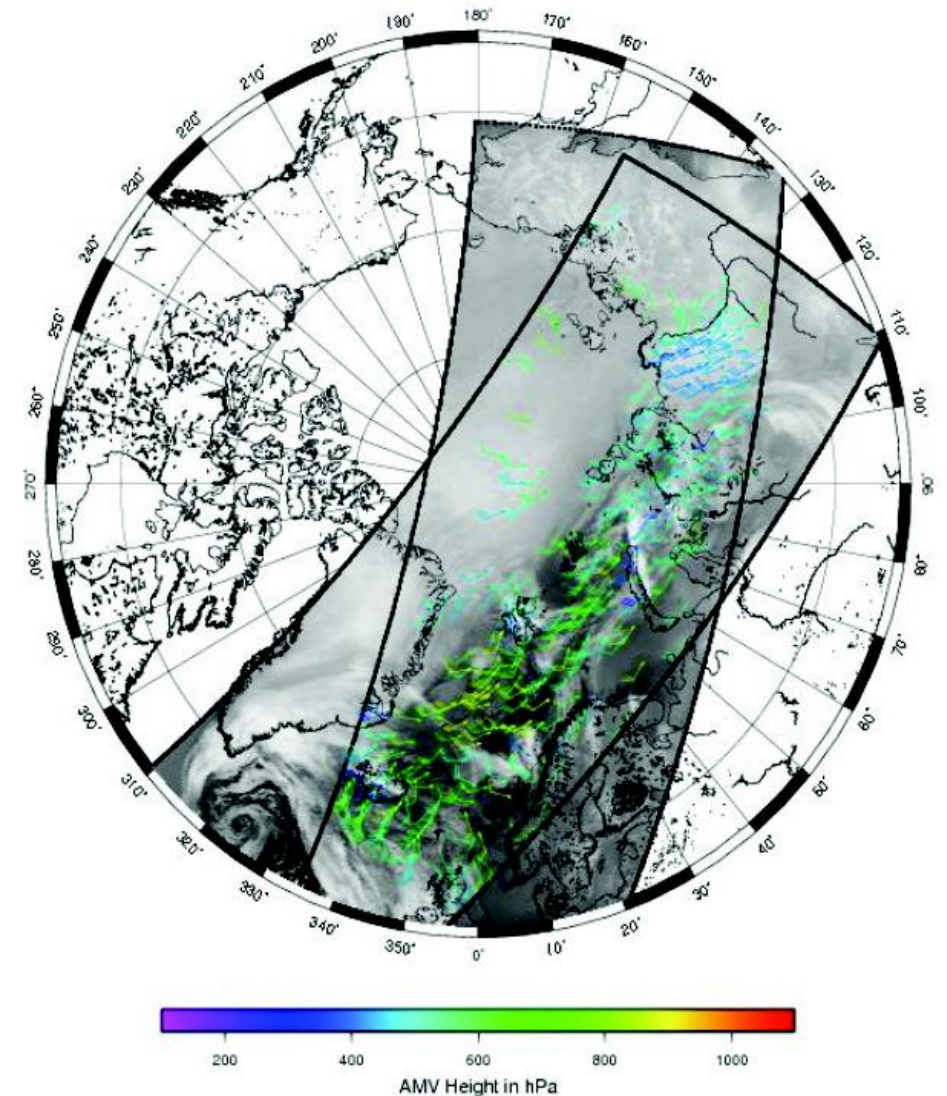
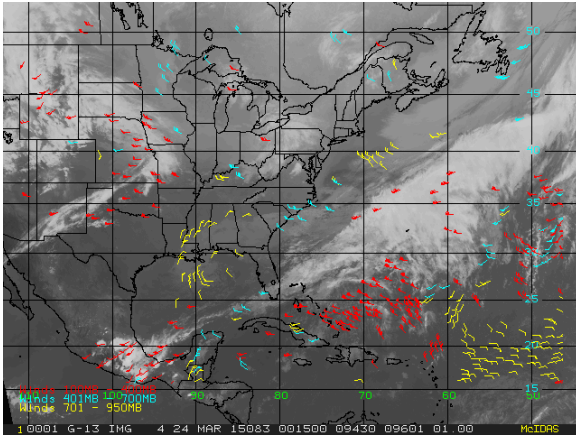
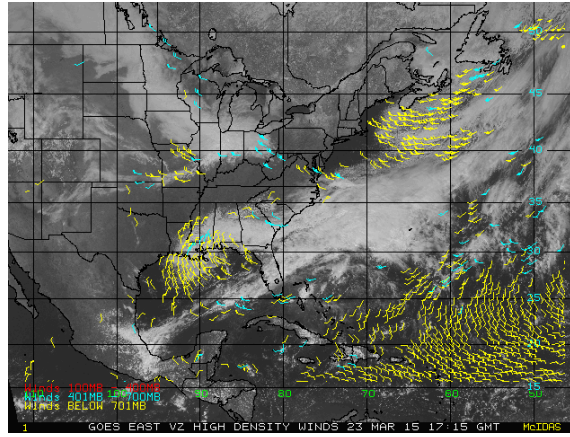


Figure from “AVHRR polar winds derivation at EUMETSAT: Current status and future developments”, Dew and Borde, IWW-11 presentation

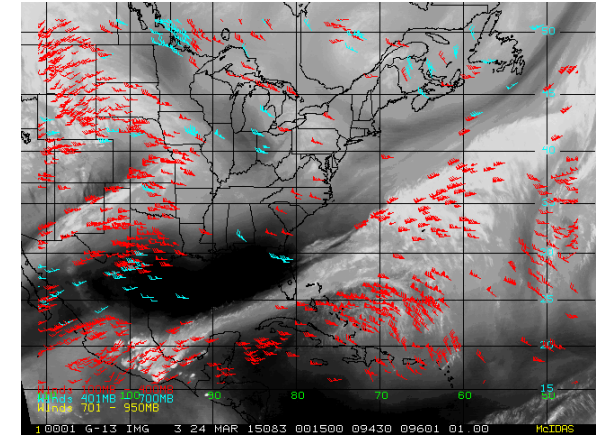
Wavelengths used in AMV production



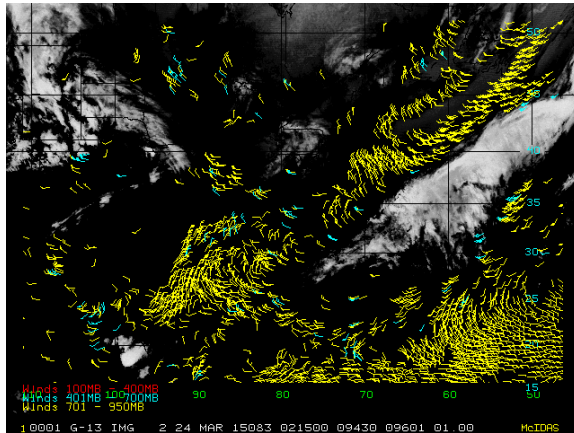
**IR window ($\sim 10.7 \mu\text{m}$):
Clouds**



**VIS ($\sim 0.65 \mu\text{m}$):
Clouds**



**Water Vapour absorption ($\sim 6.7 \mu\text{m}$):
Clouds
Clear sky WV features**



**Short Wavelength IR ($\sim 3.9 \mu\text{m}$):
Clouds**

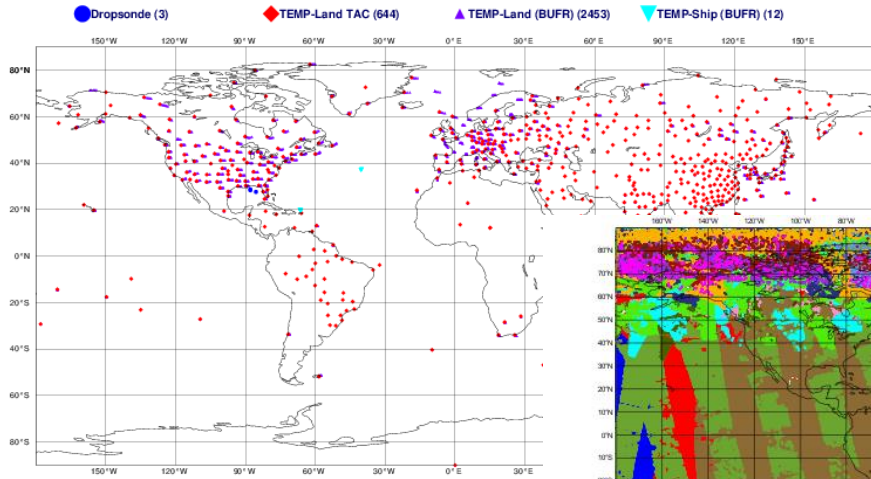
AMVs mostly cover:
Low troposphere $\sim 850\text{hPa}$
High troposphere $\sim 200\text{hPa}$

Figures from:

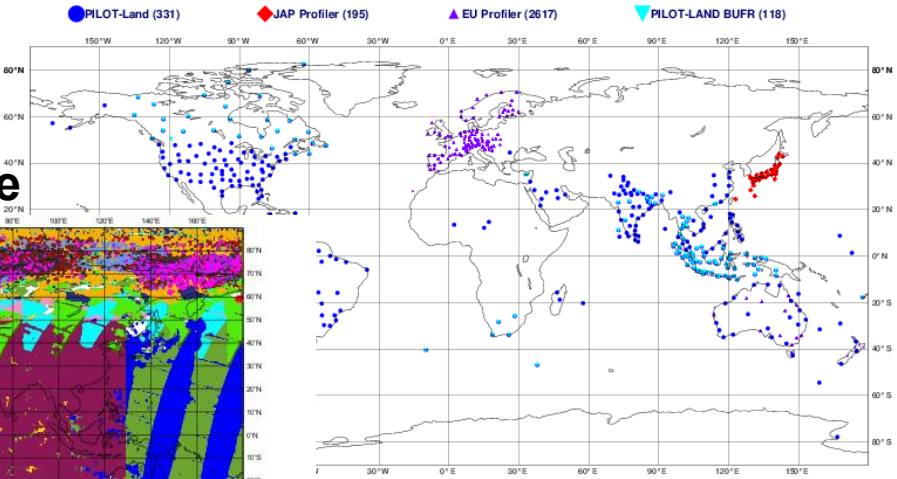
<http://www.ospo.noaa.gov/Products/atmosphere/hdwinds/goes.html>

AMVs – why do we need them?

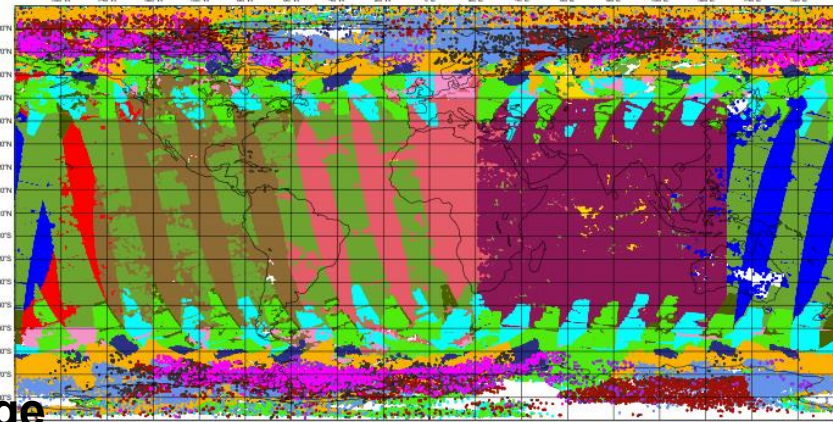
Radiosonde coverage



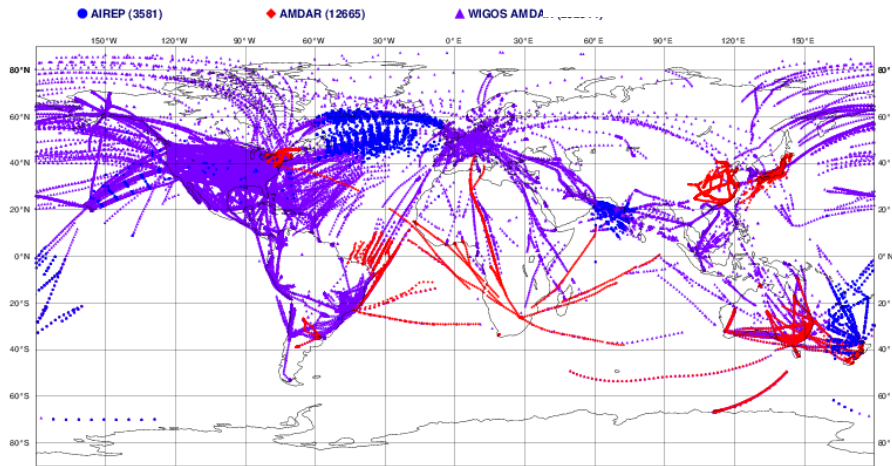
Pilot-Profiler coverage



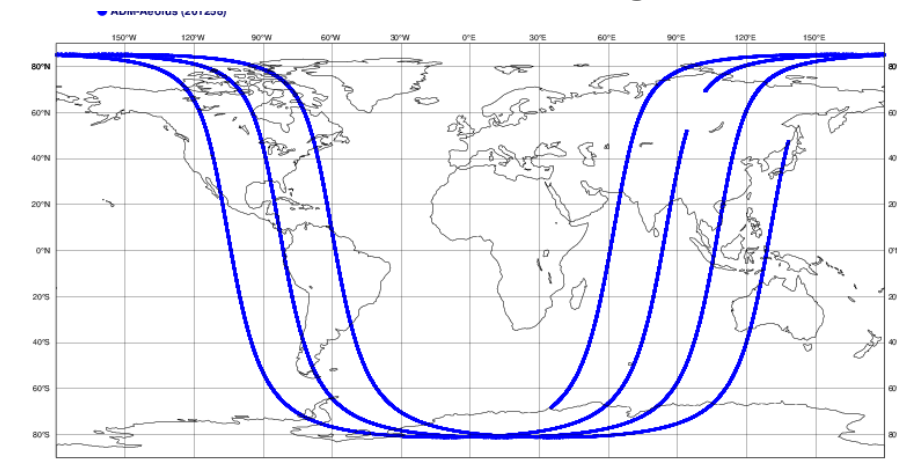
AMV coverage



Aircraft coverage



Aeolus coverage (up to April 2023)



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- **How are AMVs derived?**
- How do we use them at ECMWF?

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- Humidity tracing with radiances

Summary and future challenges

How are AMVs derived?

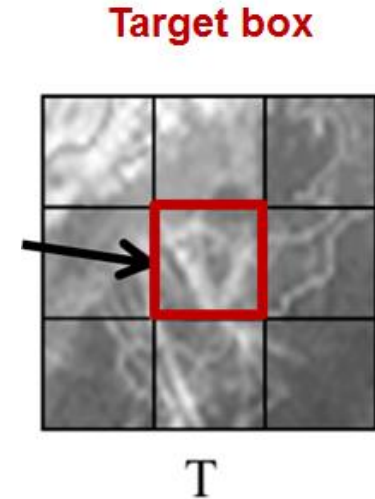
Part 1: Tracking

Part 2: Height assignment

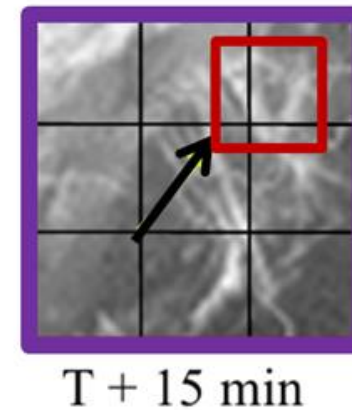
Part 1: Tracking

1. Correct raw data
2. Locate suitable tracer (target box), Typical area 24x24 pixels
3. Locate same feature in later/earlier image using pattern matching methods
4. Calculate displacement vector
(Some new algorithms use nested tracking – track multiple targets and take average)

Assumption: tracked feature travels with local wind

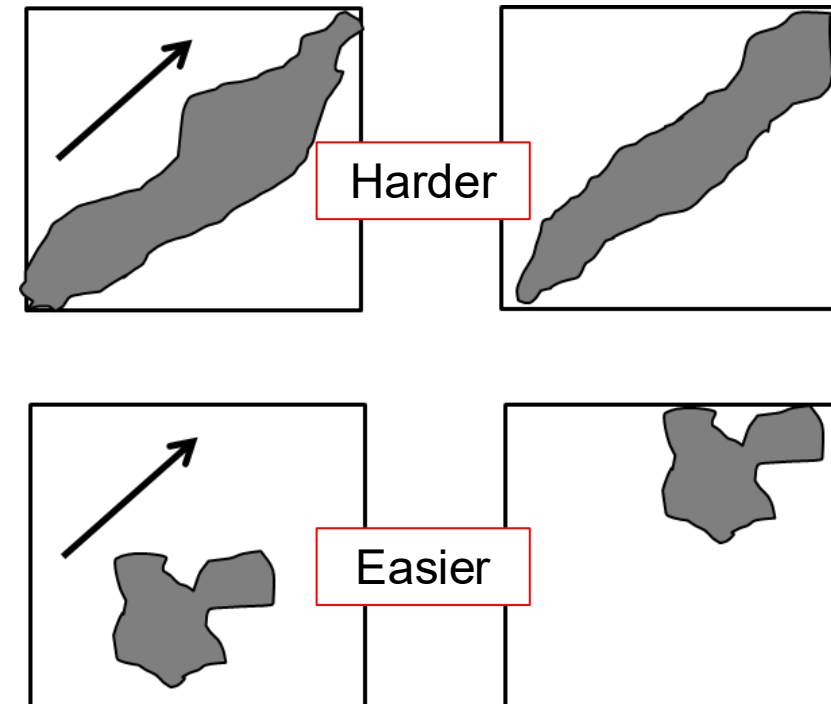


Search area centered
on the target box

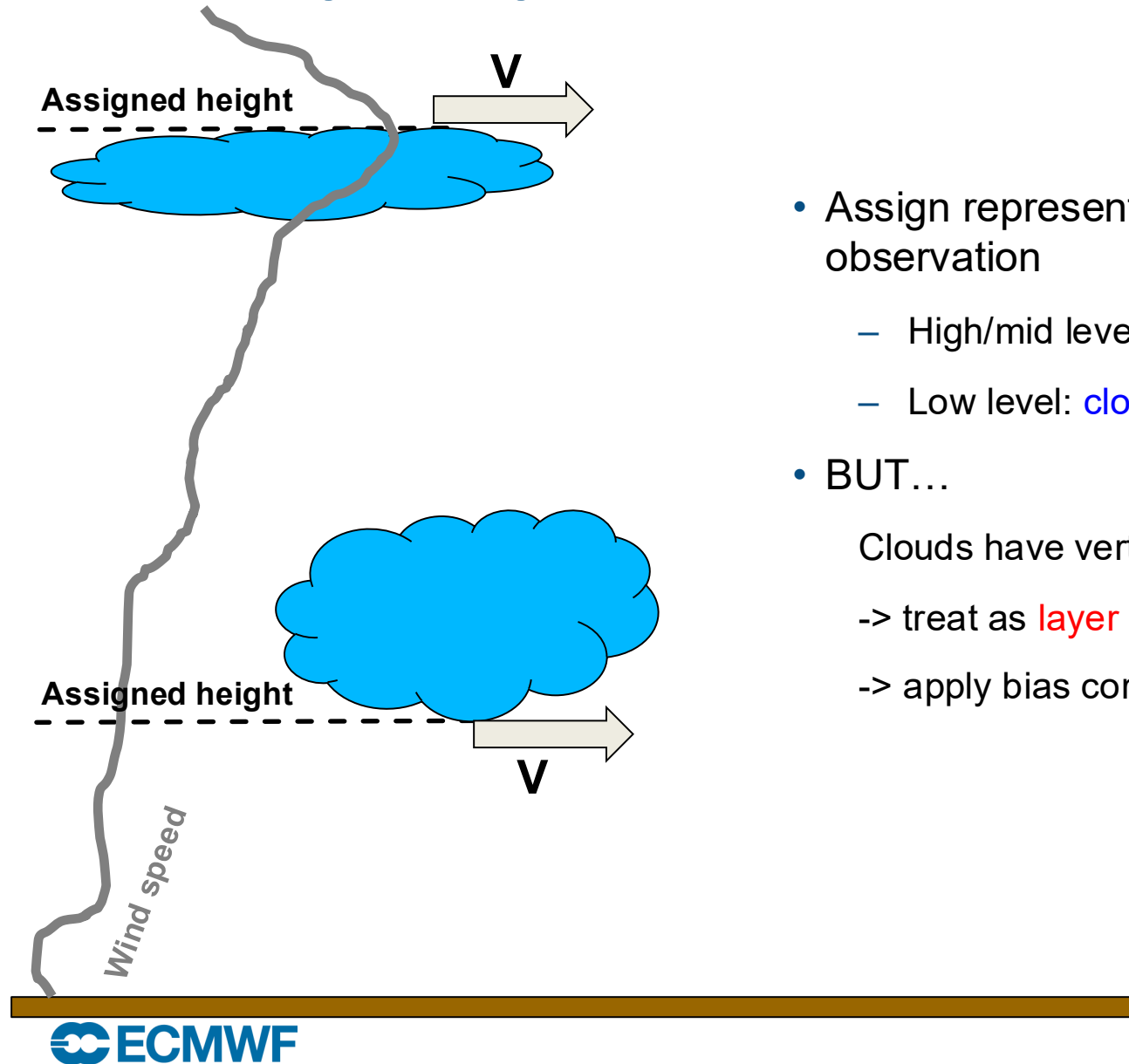


Tracking errors

- Target box doesn't have features with uniform speed/direction – cloud may change shape
- Cross correlation locates incorrect tracer
- Shape/orientation of tracked feature
- Short time interval causes difficulty for slow wind speeds...
- ...But for a long time interval, more evolution of feature possible.... could leave the search area entirely



Part 2: Height assignment



- Assign representative height to **single level** wind observation
 - High/mid level: **cloud top**
 - Low level: **cloud base or top**
- BUT...
 - Clouds have vertical extent
 - > treat as **layer average**?
 - > apply bias correction to height?

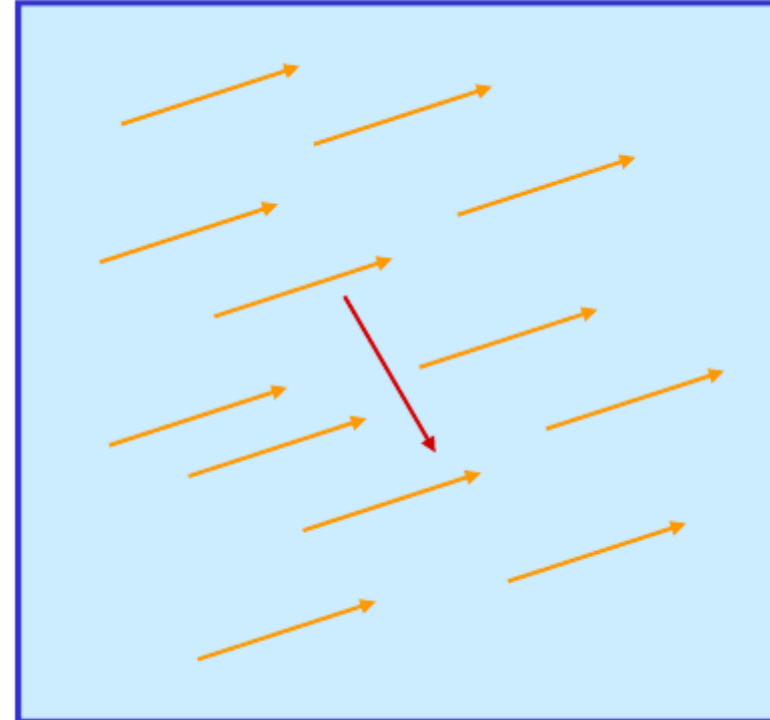
Height assignment methods

- Various methods:
 - Equivalent Black Body Temperature
 - Carbon dioxide slicing
 - Water vapour intercept
 - Cloud base techniques
 - Optimal cloud analysis – gaining popularity
 - Stereo method
- All have assumptions affecting accuracy
- NWP information used
- May include errors in short range NWP
- Errors in radiative transfer

Error in height assignment dominant source of error for AMVs

Indication of quality

- Variety of independent quality tests:
 - Spatial consistency
 - Temporal consistency (e.g. speed, direction)
 - Forecast consistency (optional)
- Final quality indicator weighted mean of tests
- Use for screening



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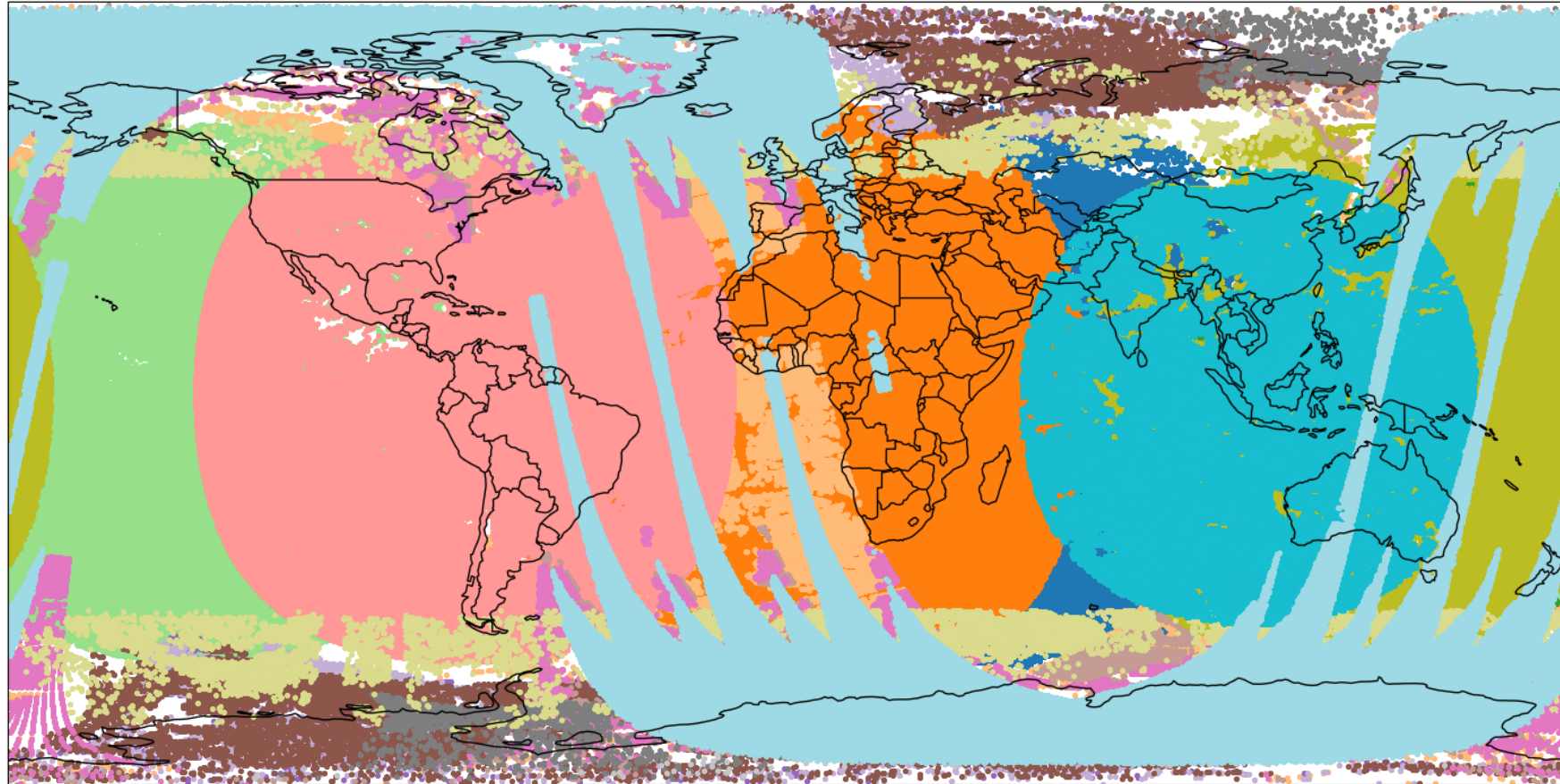
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AMV sample coverage: monitored data for one 12hr cycle (00Z 13th February 2026)

Monitoring approximately 33 million winds per cycle



- Meteosat-9
- Meteosat-10
- Meteosat-12
- Dual Metop
- Himawari-9
- GOES-18
- GOES-19
- Suomi NPP
- NOAA-20
- NOAA-21
- Metop-B
- Metop-C
- Aqua
- Terra
- GeoKompsat-2A
- LeoGeo
- FengYun-2G
- Dual Sentinel-3

Actively used

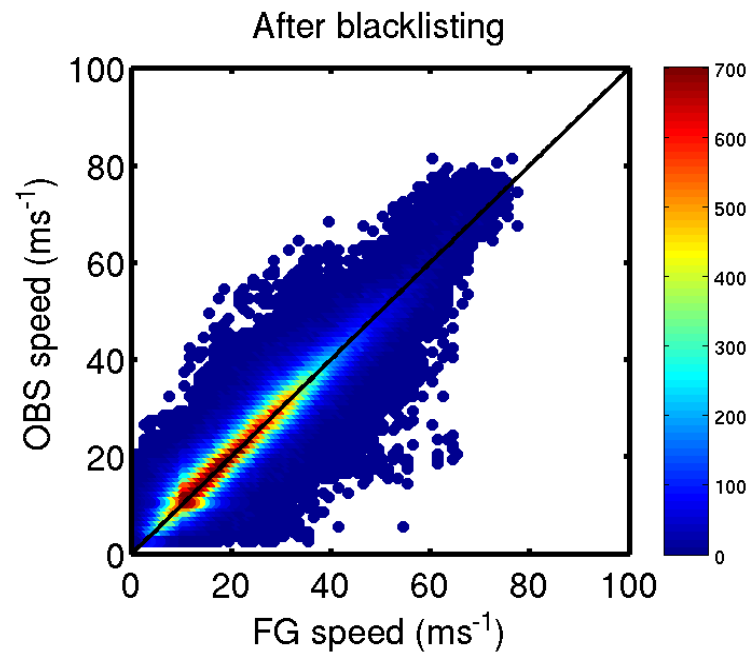
Now we will apply blocklisting, a first guess check and thinning

AMV selection: blocklisting

- Apply quality indicator thresholds
- Channel specific selection
- Regional screening
- Seasonal screening

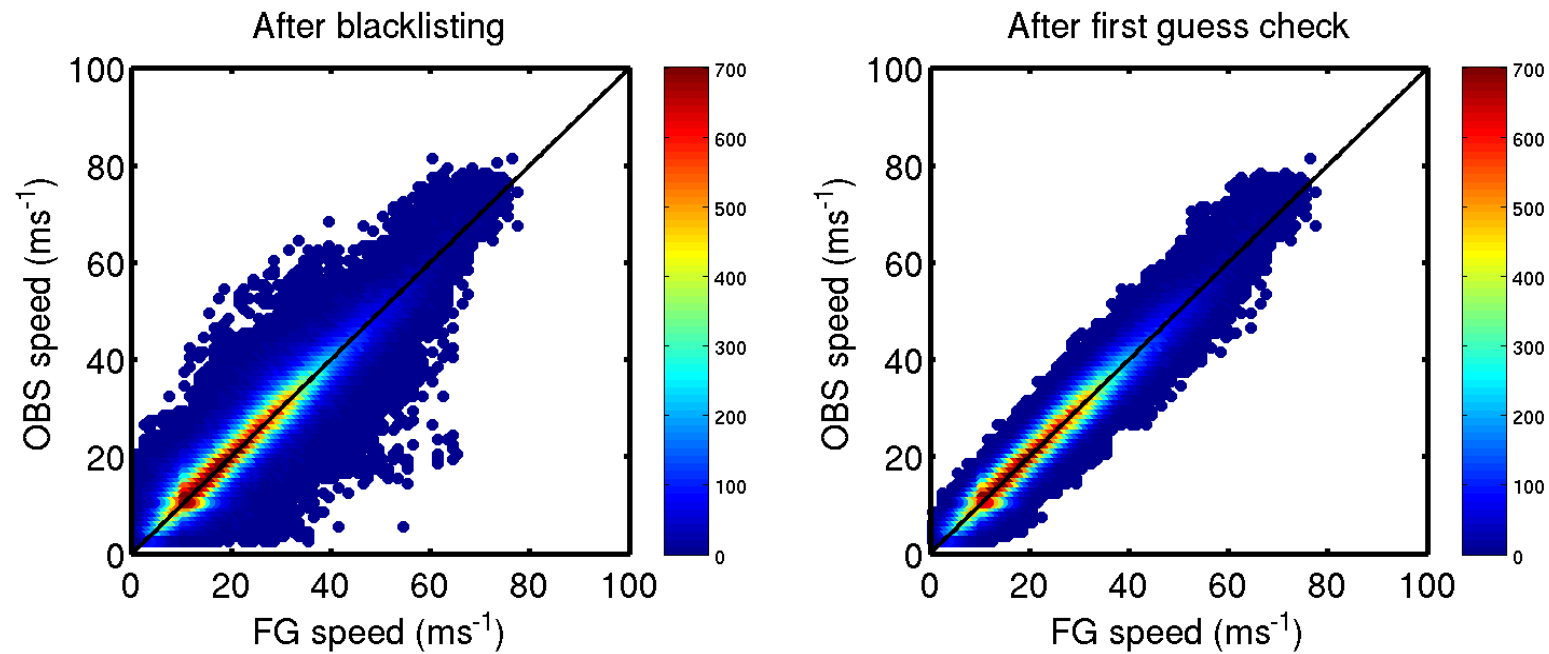
AMV selection: First Guess check

- Comparison with short-range forecast from previous model run
- Observations deviating too much are rejected



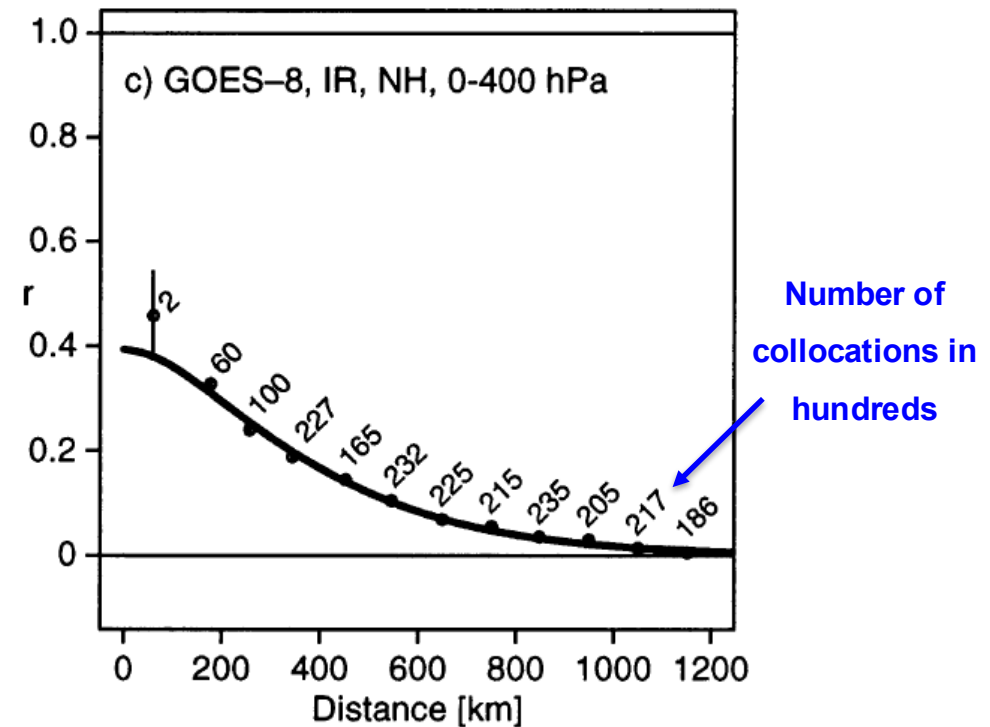
AMV selection: First Guess check

- Comparison with short-range forecast from previous model run
- Observations deviating too much are rejected



AMV selection: thinning

- Assuming **uncorrelated** observation errors -> thinning required
- Significant spatial error correlations up to **~ 800km**
- Compensate with increased AMV observation errors
- Thin by
 - 200x200km
 - 50-175hPa boxes (vertical extent varies with height)
 - 30 mins

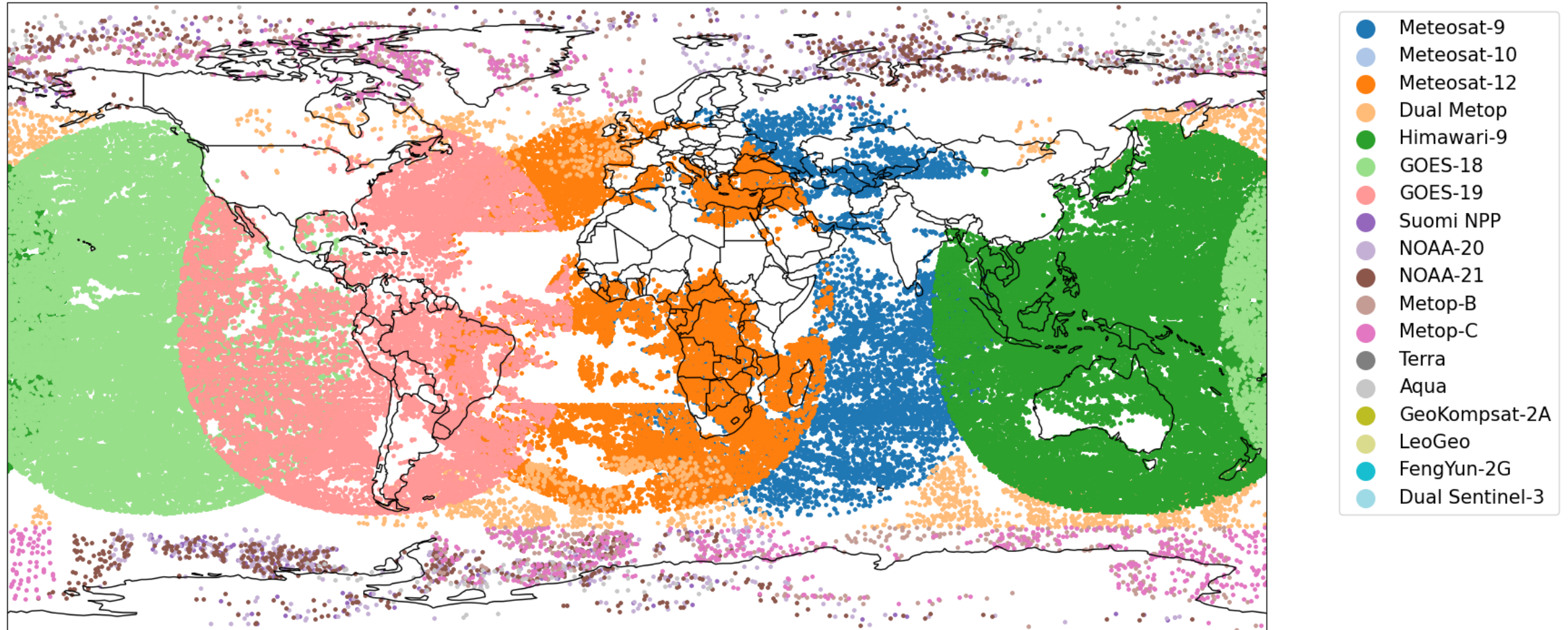


**AMV-radiosonde departure correlations
as a function of station separation.**

Bormann et al., 2003: The spatial structure of observation error in atmospheric motion vectors from geostationary satellite data. MWR, 31, 706 - 718.

All AMVs used – one cycle 00Z 13th February 2026

Assimilating in region of 230,000 winds per 12 hour cycle cycle



Operational use

- AMVs from 5 geo and 8 polar orbiting satellites/products
- Example of data reduction: typical 12 hr window, **Meteosat-9 AMVs**
 - ~500 000 AMVs available
 - 15-20% remain after blocklisting
 - 2-10% used in assimilation
- Single-layer observation operator (to convert between model and observed quantities)
- Low-level height reassignment
- Situation dependent observation errors

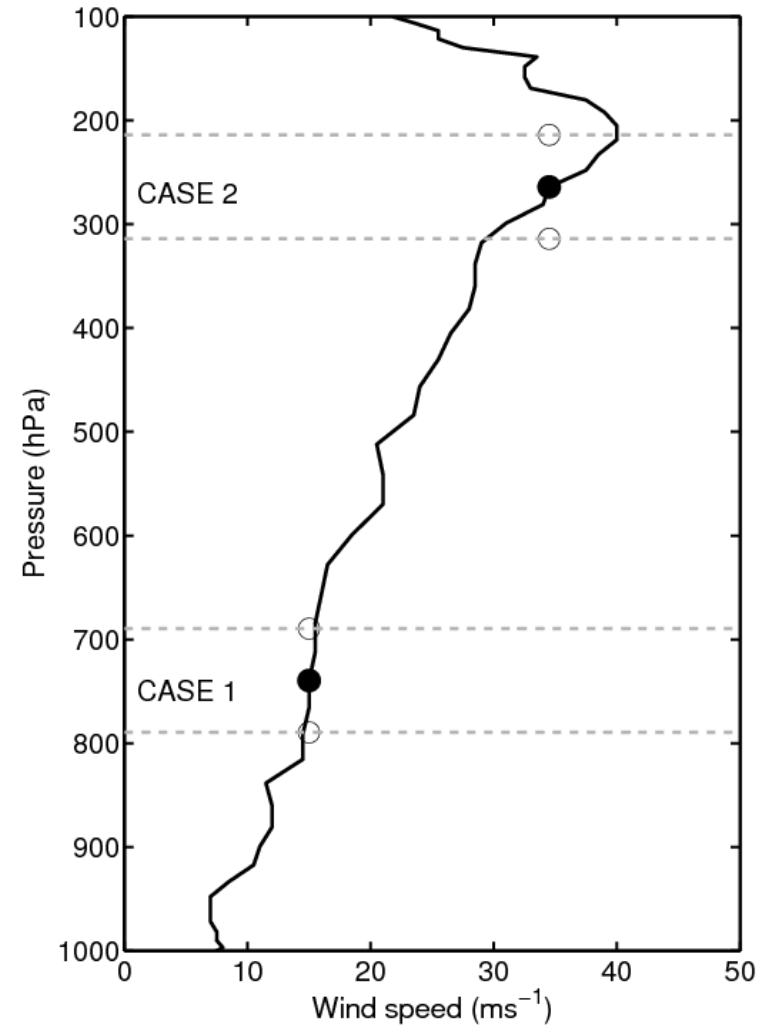
$$[\text{Total u/v error}]^2 = [\text{Tracking error}]^2 + [\text{Error in u/v due to error in height}]^2$$

Impact of height assignment errors

Example: ± 50 hPa error in height assignment

CASE 1: Wind speed varies little with height, ± 0.5 m/s error in wind speed.

CASE 2: Wind shear in vertical, error up to 7 m/s.

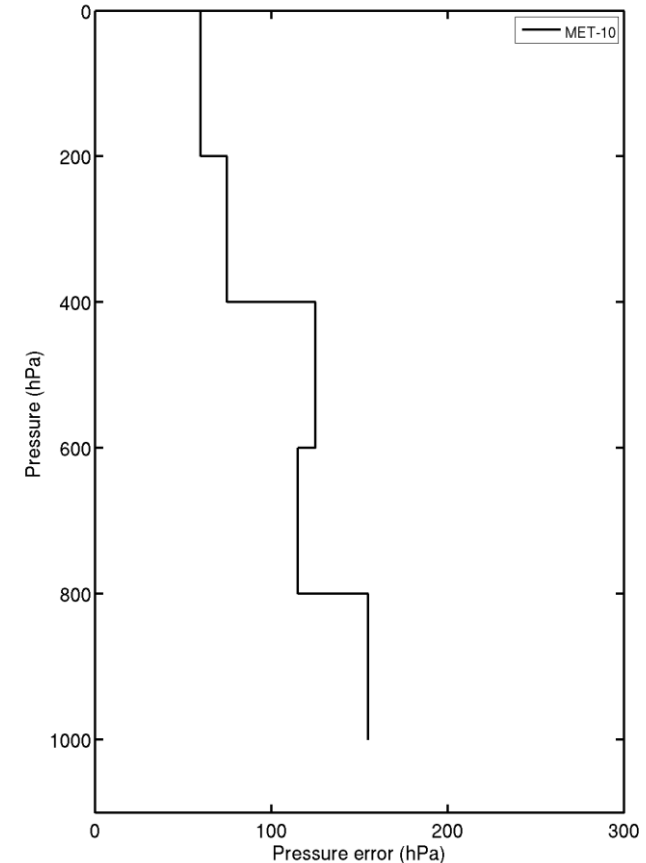


Situation dependent observation errors: error in height

- Assumes Gaussian distribution of height error
- Estimate error in height assignment using:

Standard deviation (AMV pressure - model pressure
minimising vector diff (observed – model) wind)

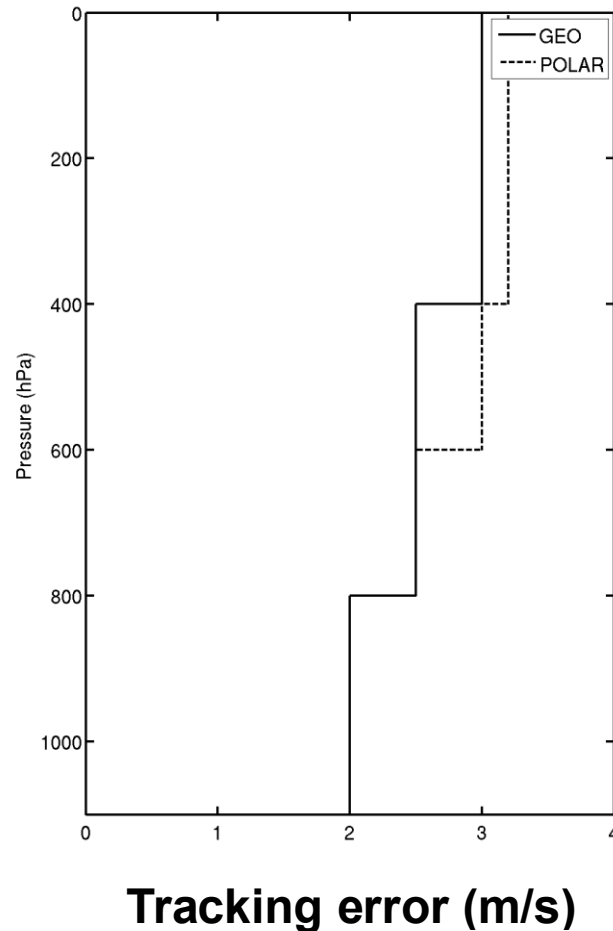
- Apply Gaussian weights to model wind shear about assigned height to estimate error in speed



**Height assignment error
(hPa) for Meteosat-10**

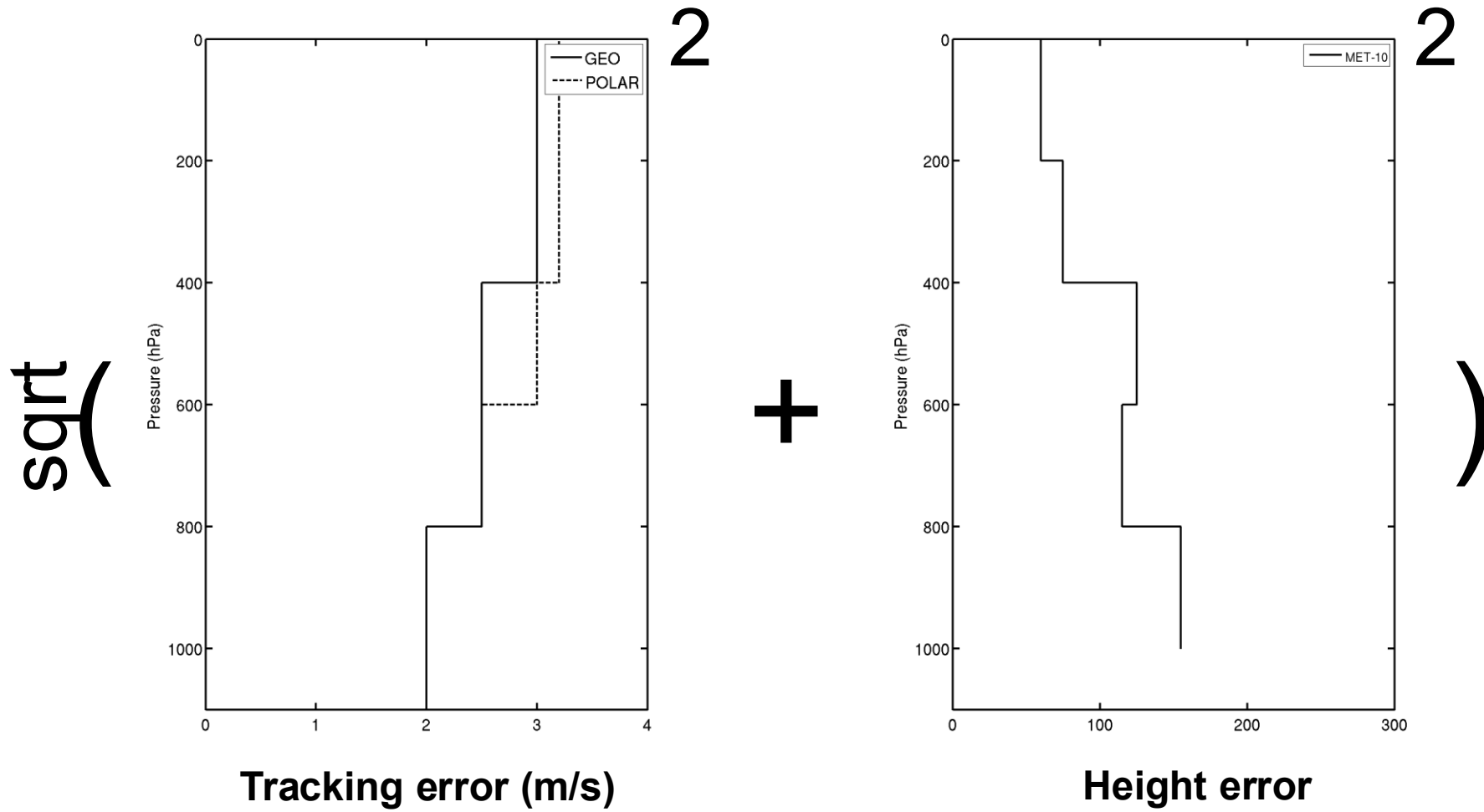
Situation dependent observation errors: tracking error

$$[\text{Total u/v error}]^2 = [\text{Tracking error}]^2 + [\text{Error in u/v due to error in height}]^2$$



- Estimated using **root mean square vector difference** between AMV and first guess **where height error is small**
- Likely to be an overestimate
- Same values used across geostationary ring
- Small variations across polar

Situation dependent observation errors

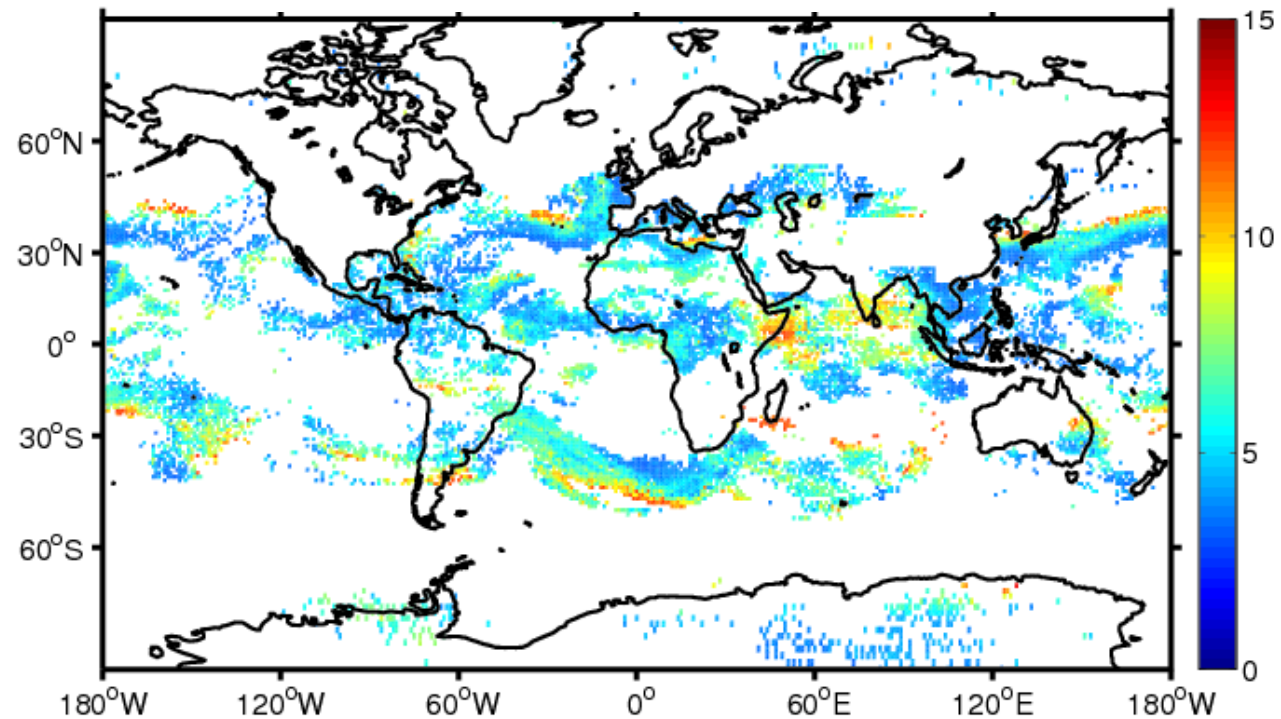


Situation dependent observation errors

Total observation error (m/s)

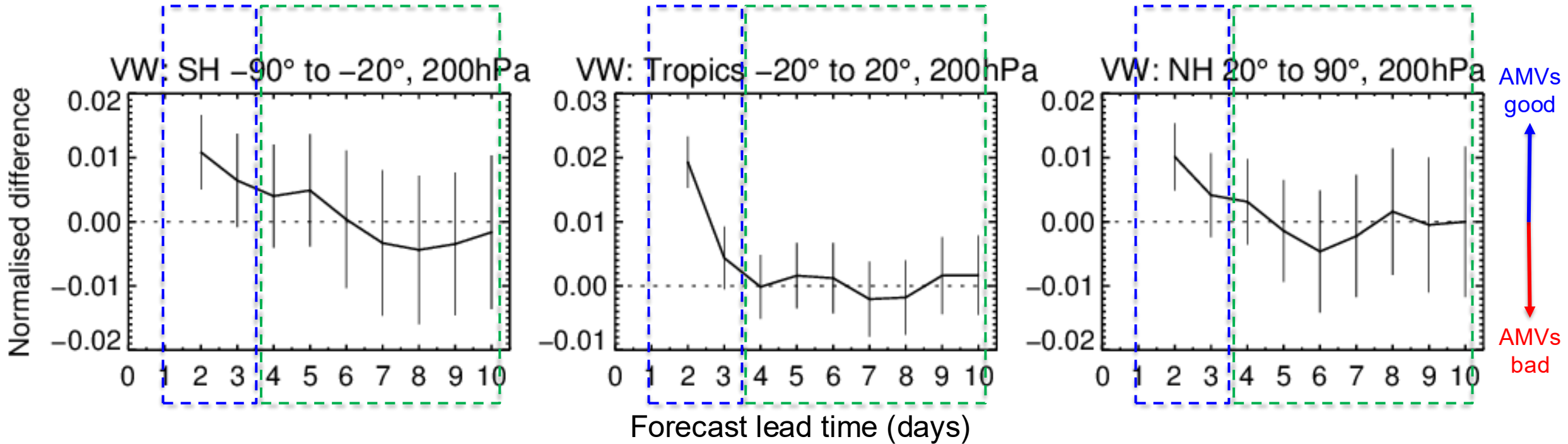
Example: cloudy WV, high levels

==



AMV forecast impacts

Change in Vector Wind Error
Ctrl (no AMVs) – Expt (with AMVs)

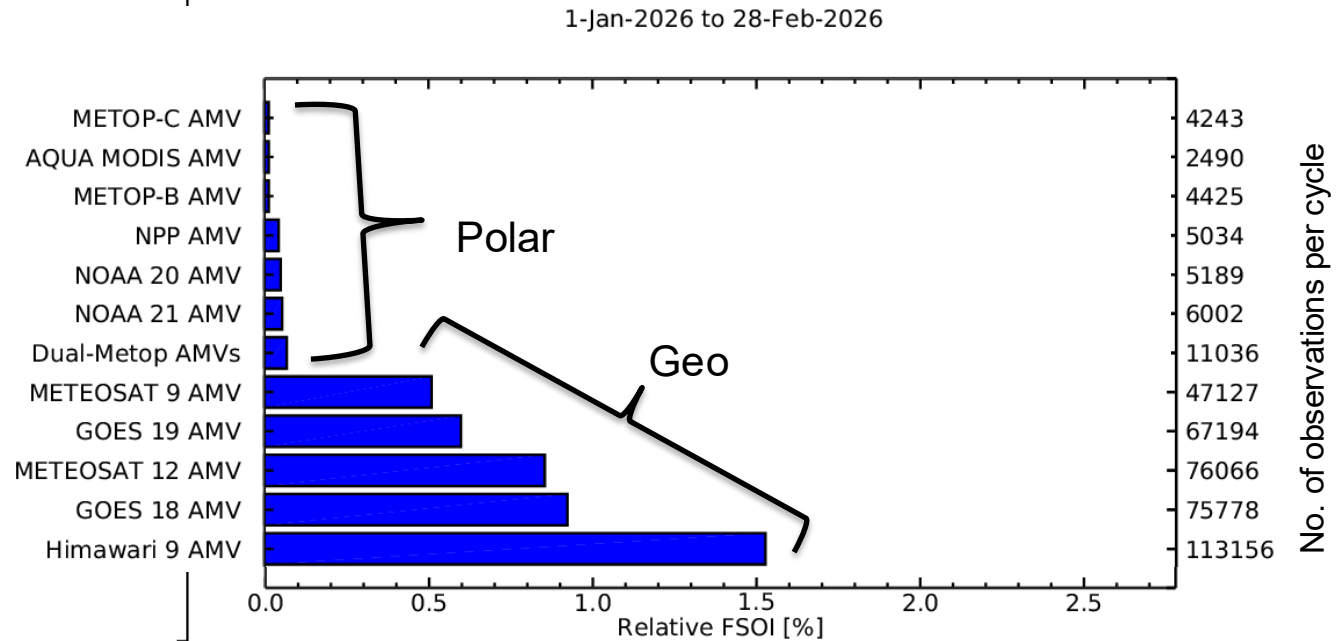
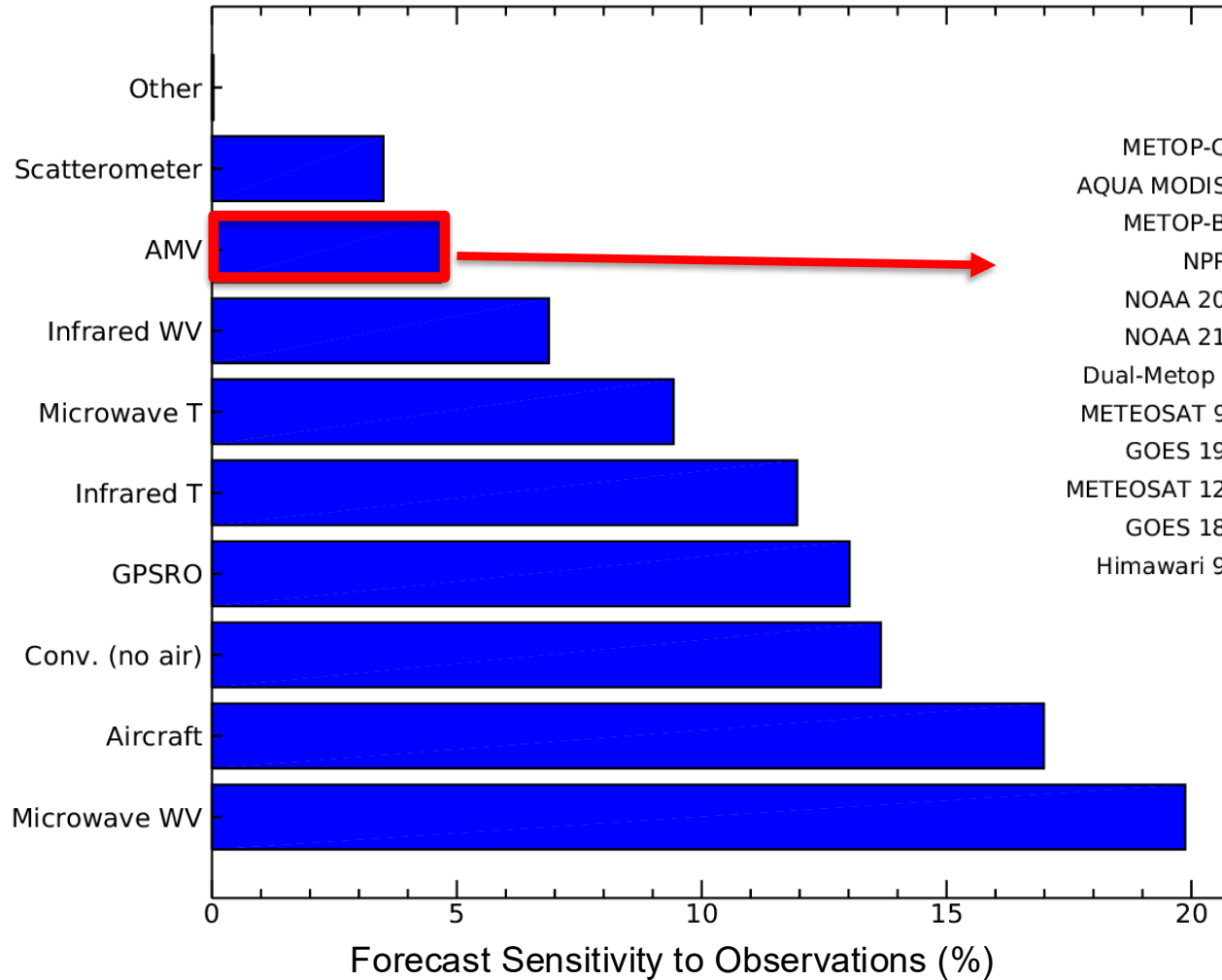


Generally +ve for
2-3 days

Neutral at longer
ranges

Forecast system performance

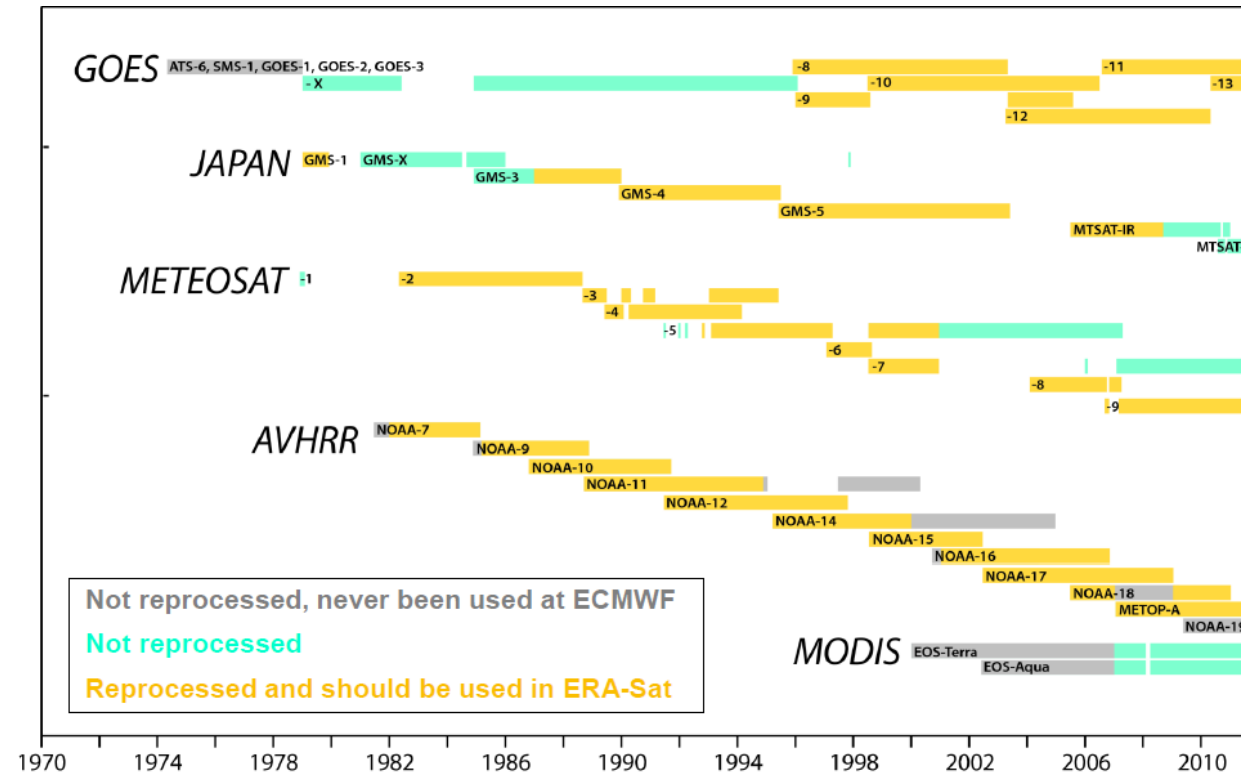
January+February 2026



Measures reduction in 24hr forecast error due to each source

AMVs for Reanalysis

- Reprocess and improve AMV data for reanalysis
- Coverage and quality much improved
- More impact in earlier period as observing system more sparse



Assumptions and challenges

- Tracked feature exactly follows speed and direction of local wind

But some clouds don't move with the local wind

- Representing wind field at specific time, height and location
- Detected motion represents cloud top or base

But clouds have depth, using images over finite time etc.

New scheme in operational use at ECMWF: reassigning height of subset of low level AMVs using average pressure of estimated cloud layer from model

- Errors are uncorrelated

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4D-Var tracing:

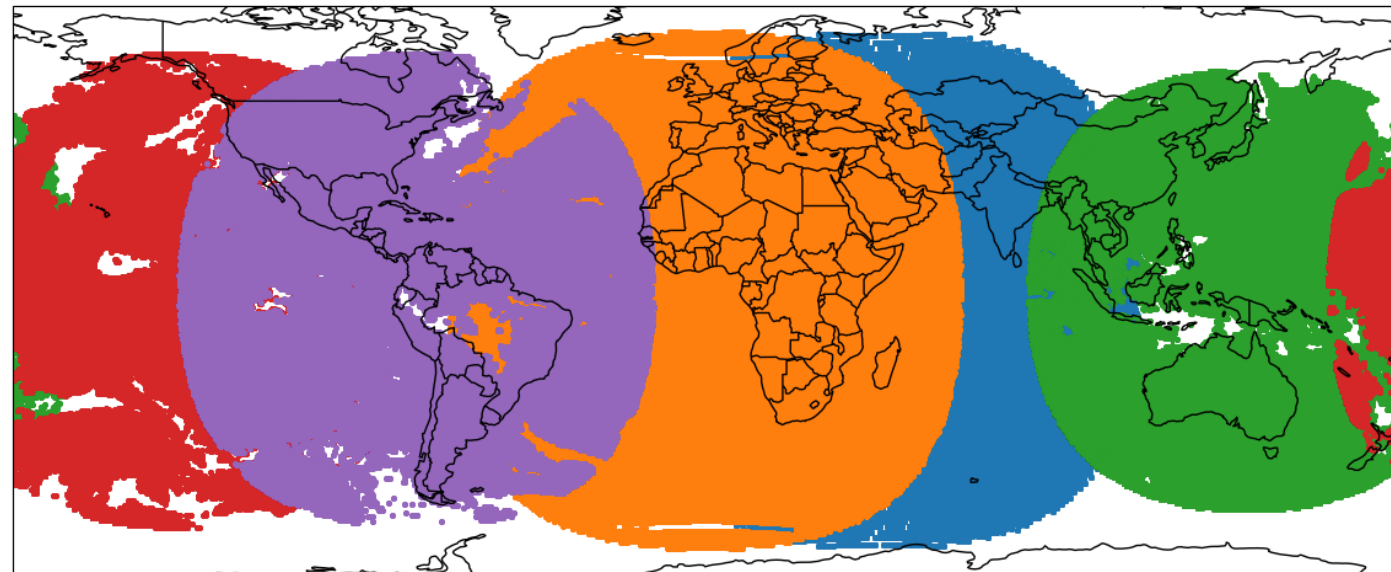
Changing wind fields by direct assimilation
of radiances

Introducing radiances from geostationary satellites

- 2 types:
 - Clear Sky Radiances (CSR) – Himawari-9, GOES-18, GOES-19
 - All Sky Radiances (ASR) – Met-9/12

Combines CSR and totally overcast scenes

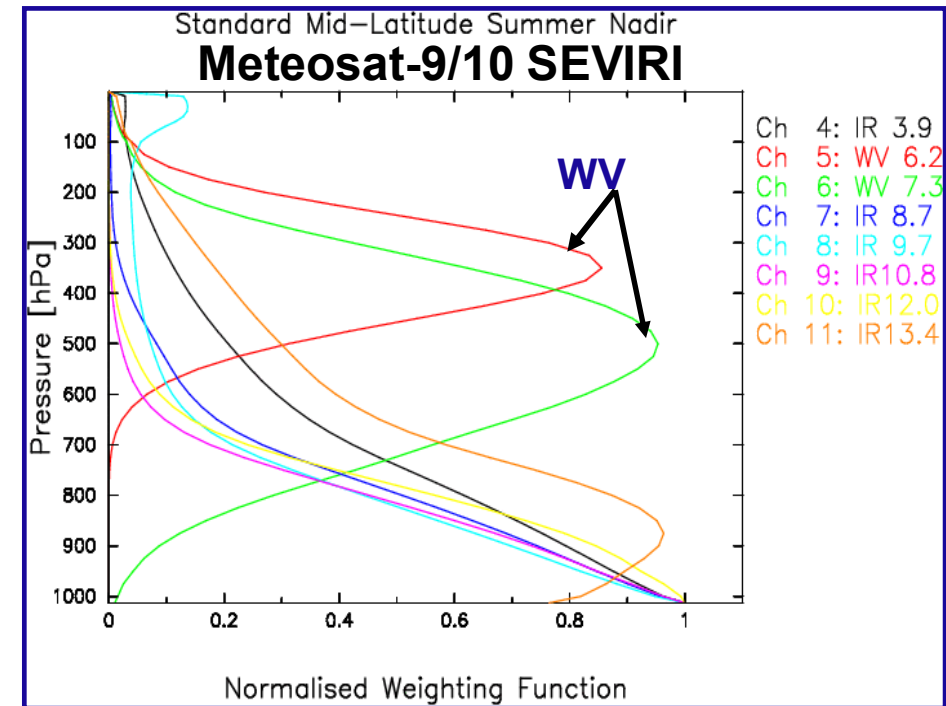
Monitored geostationary CSR/ASR 00Z 13th February 2026



- Product assimilated hourly, sometimes received more frequently
- Area averaged e.g. 32x32km at nadir for Met-9

Use of GEO radiances at ECMWF

- Select channels peaking in water vapour absorption band
- Peak in weighting function mid-upper troposphere
 - > complementary to height of AMVs
- Similar to AMVs apply
 - Blocklisting
 - Thinning
 - First guess check
- Apply bias correction

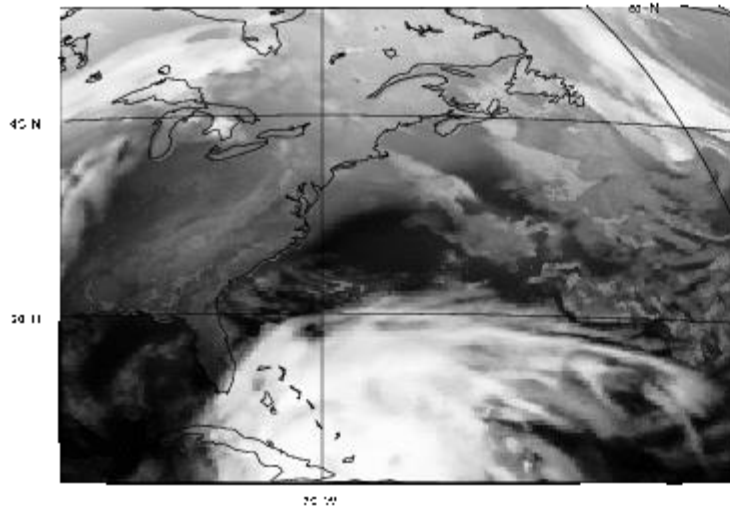


Data selection and thinning

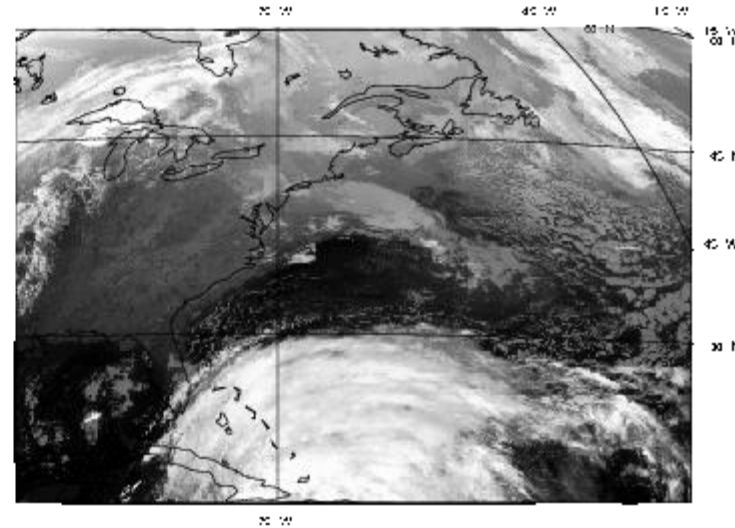
- Geographical rejection:
 - Satellite zenith angle $> 74^\circ$
 - Over high terrain (1500m)
- Satellite specific rejections
- Cloud contamination
 - Threshold for number of clear pixels in CSR
 - Window channel has large departures (3K) from model (sea)
- Thinning
 - 75km

First guess check

$H(\mathbf{x}_b)$; $H = \text{Obs. operator}$



CSR Observations (\mathbf{y})



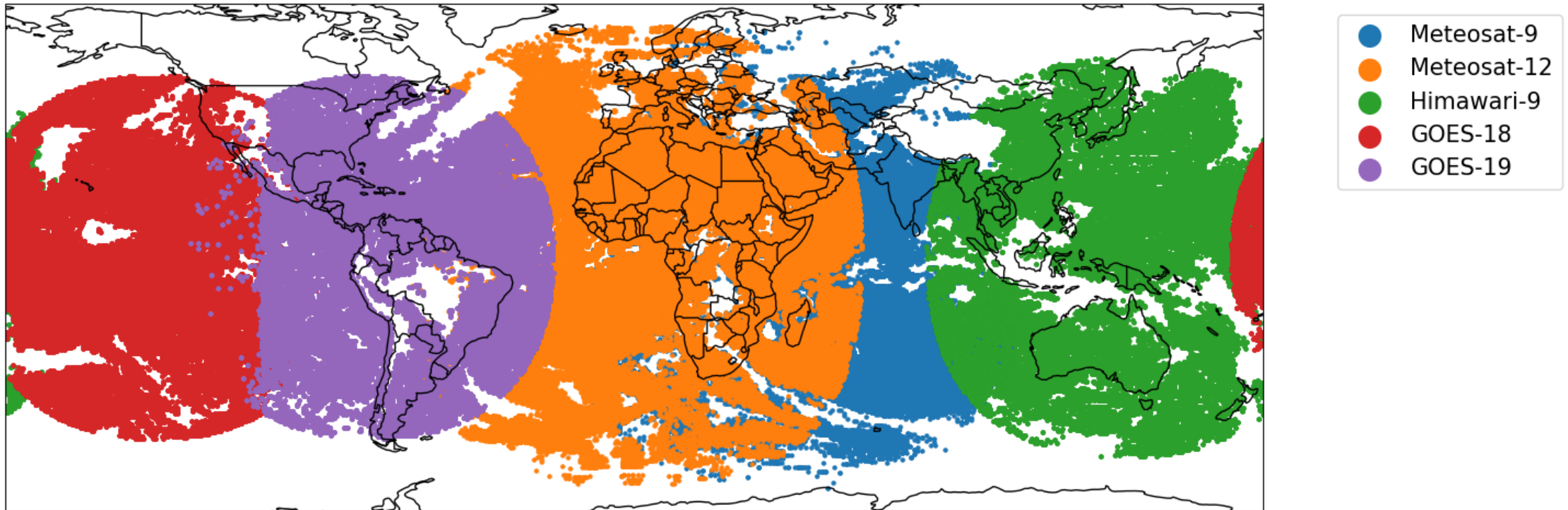
$$(\mathbf{y} - H\mathbf{x}_b)^2 > \lambda^2 (\sigma_o^2 + \sigma_b^2)$$

$$\lambda = 2.25; \sigma_o \sim 1.35 \text{ to } 1.66K$$

(Observation error)

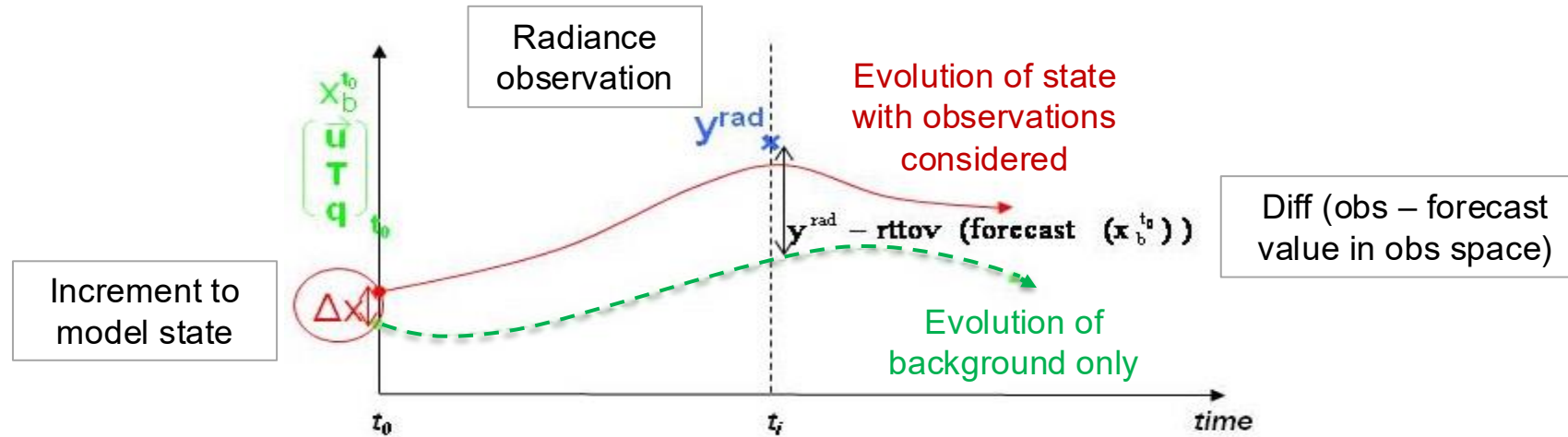
CSR/ASR sample coverage: active

- Example typical 12-hour data window (00Z 13th February 2026)
 - Depending on satellite, ~ 2 – 11 million CSR/ASRs available
 - ~2-4% used in the assimilation



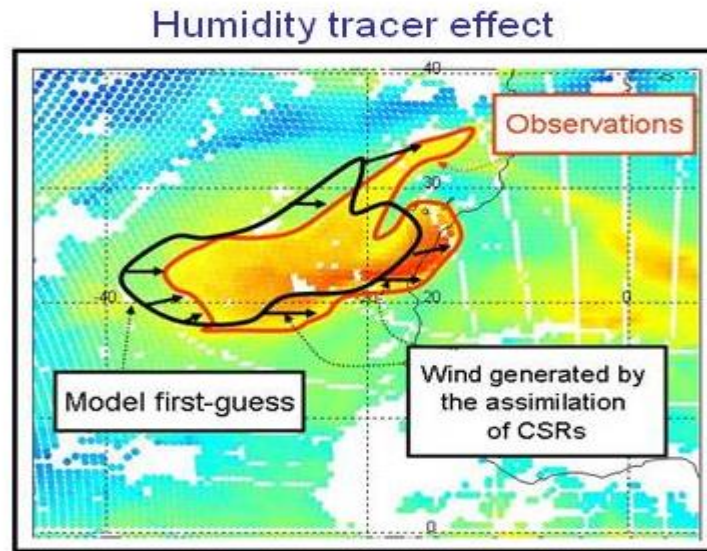
How do the radiances affect the wind field?

- In 4D-Var fitting time series of model states to observations

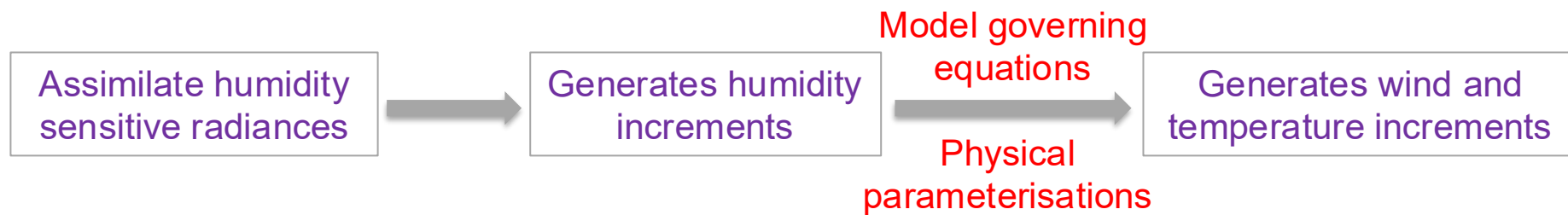


- To fit time/spatial evolution of **humidity** (also potential to use ozone) in radiance data:
 - Create constituents locally OR
 - **Advect constituents** to/from other areas i.e. **changing the wind field**

Humidity tracer effect

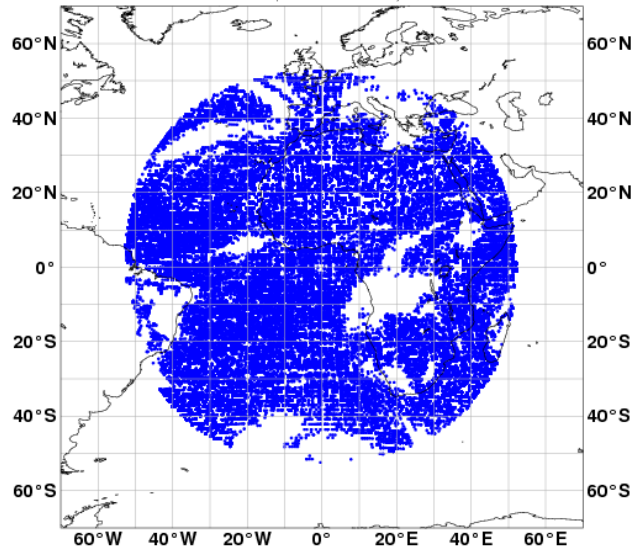


Adjust wind field in initial conditions

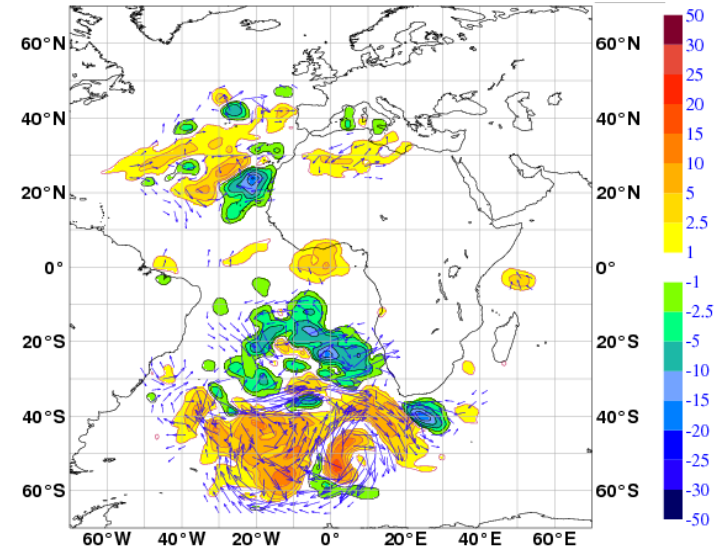


4D-Var tracing vs. AMVs

Radiance observations



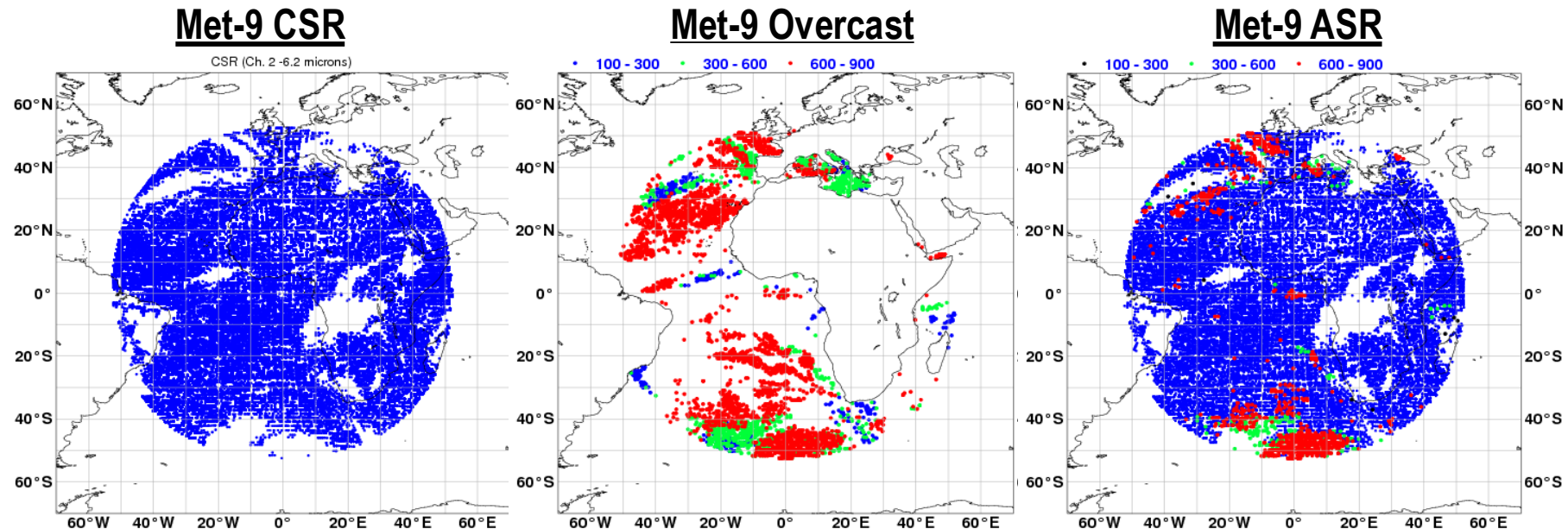
RH and VW increments 300hPa



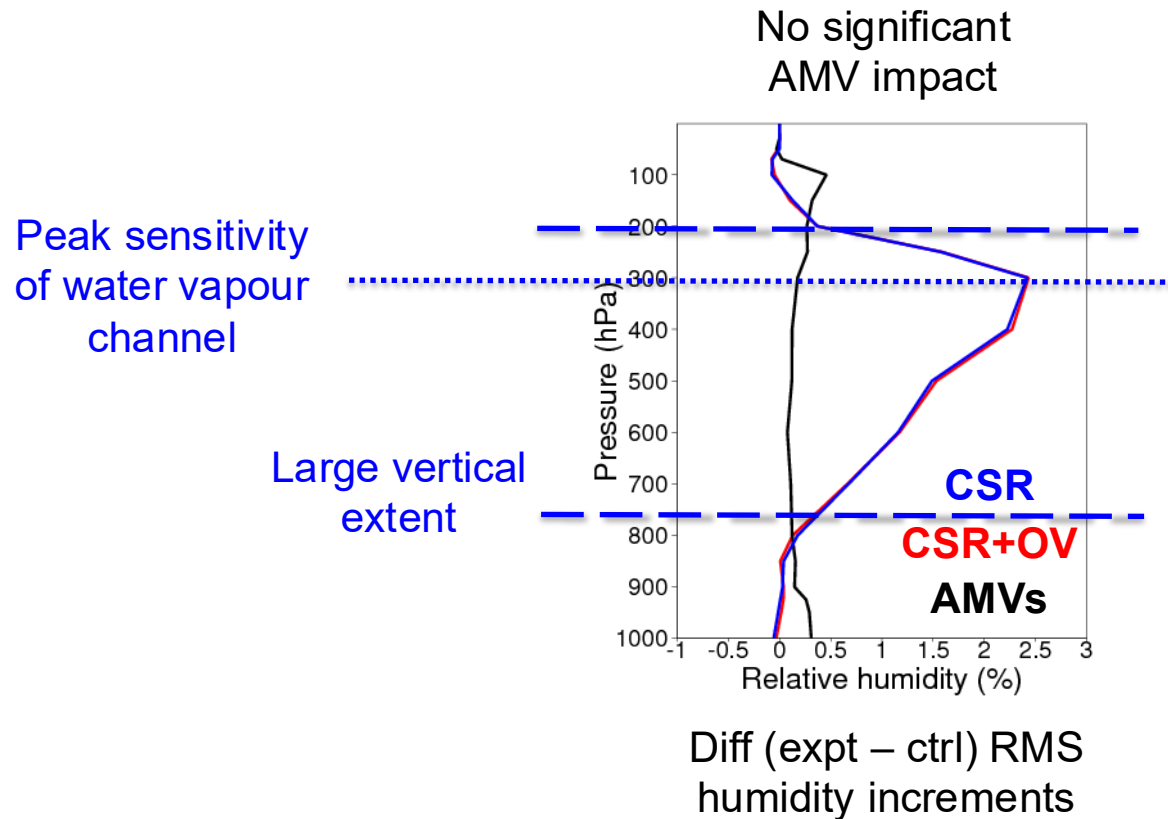
- Still 'tracking' feature but assimilation system has extra constraints
- Due to averaging/thinning tracing better for **broad scale motions**

A closer look at the impacts

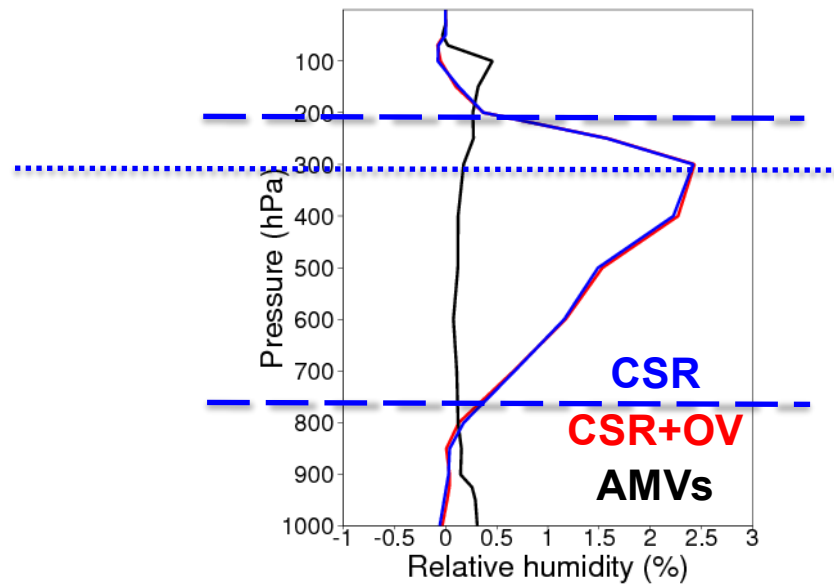
- Control: no satellite obs, conventional only, 12 hr 4D-Var
- Experiments using Meteosat-9 only:
 1. CSR
 2. ASR: CSR + Cloudy radiances only (“Overcast”) – sea only
 3. AMV



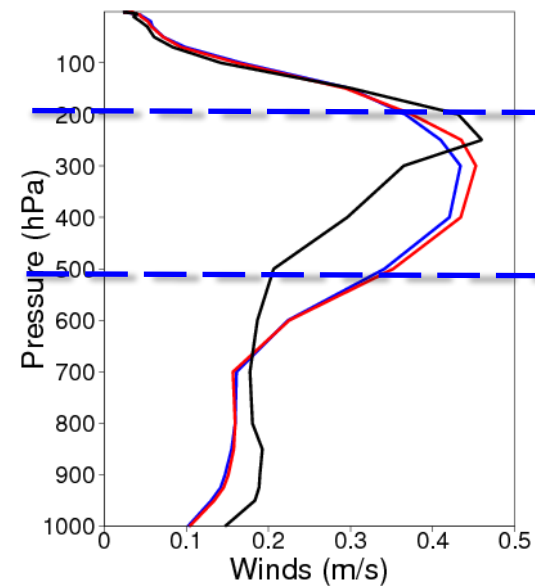
Impact on analysis: humidity increments from radiances



Impact on analysis: wind increments from AMVs and radiances



Diff (expt – ctrl) RMS
humidity increments

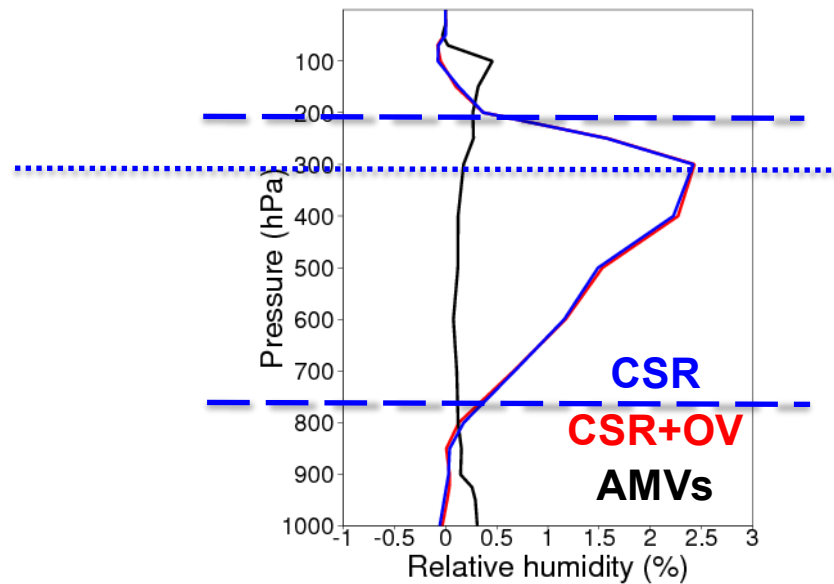


Diff (expt – ctrl) RMS
wind increments

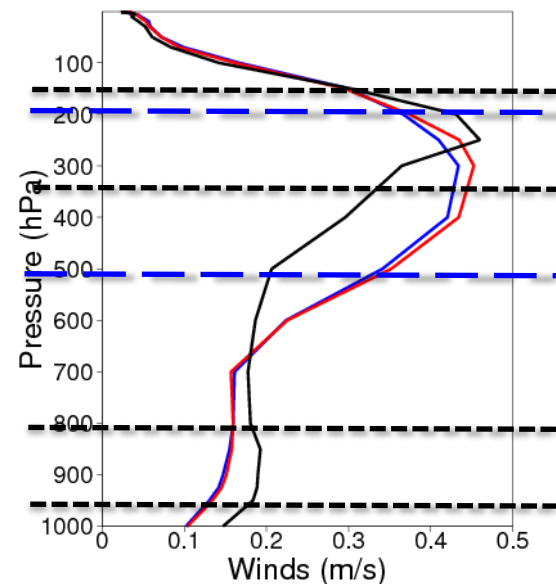
4D-Var tracing fits
CSR by advecting
deep layer of
humidity...
...leading to deep
layer changes to
wind field

Overcast
radiances add
wind information
at similar height
to AMV

Impact on analysis: wind increments from AMVs and radiances



Diff (expt - ctrl) RMS
humidity increments



Diff (expt - ctrl) RMS
wind increments

Largest AMV
impacts at high
and low levels

Wind analysis scores

- Use ECMWF operational analysis as 'truth'
- 0%: no improvement over baseline
- 100%: no error with respect to high resolution operational analysis that assimilated all satellite data

Root mean square analysis error for cycle j

$$RMSE_j = \sqrt{\frac{1}{n} \sum_{i=1}^n [(u_i - u_i^r)^2 + (v_i - v_i^r)^2]}$$

No. of grid points in Meteosat disc area

Analysis values at grid point from operations

Analysis values at grid point

Sum over all cycles

$$\Delta RMSE = \frac{\sum_{j=1}^m (RMSE_j^{Base} - RMSE_j)}{\sum_{j=1}^m RMSE_j^{Base}}$$

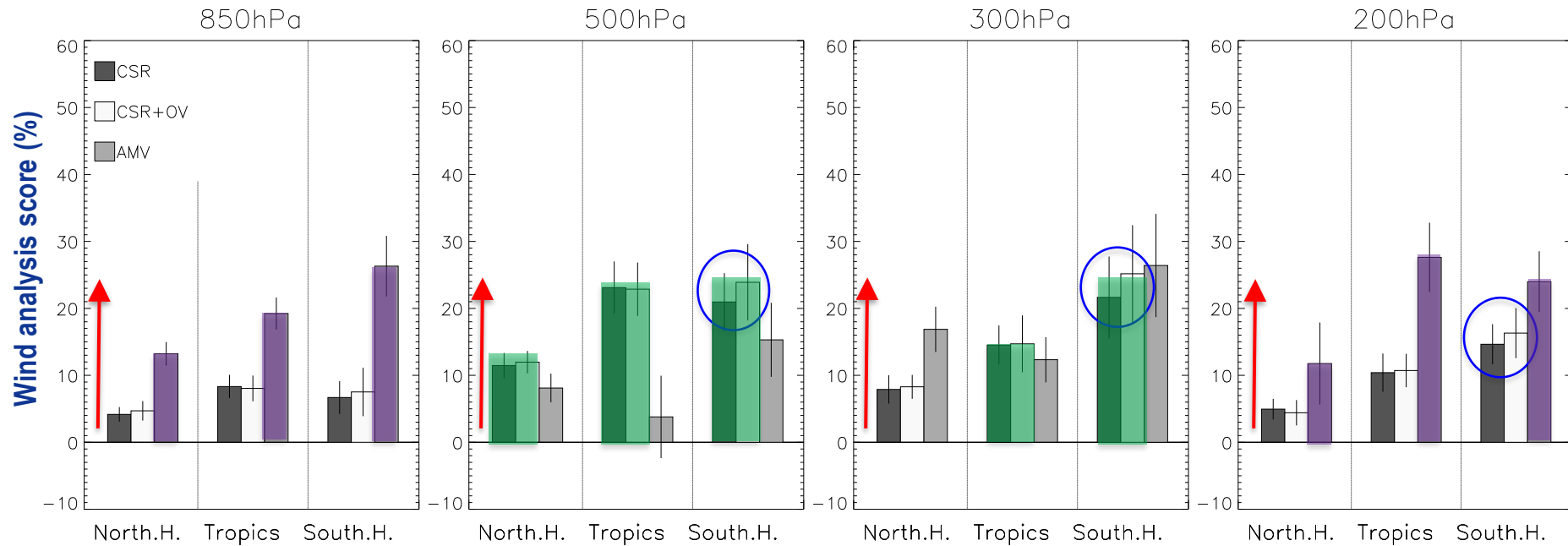
Using experiment analysis

Using control ('base') analysis

Wind analysis scores

CSR/ASR best results around peak in water vapour weight function

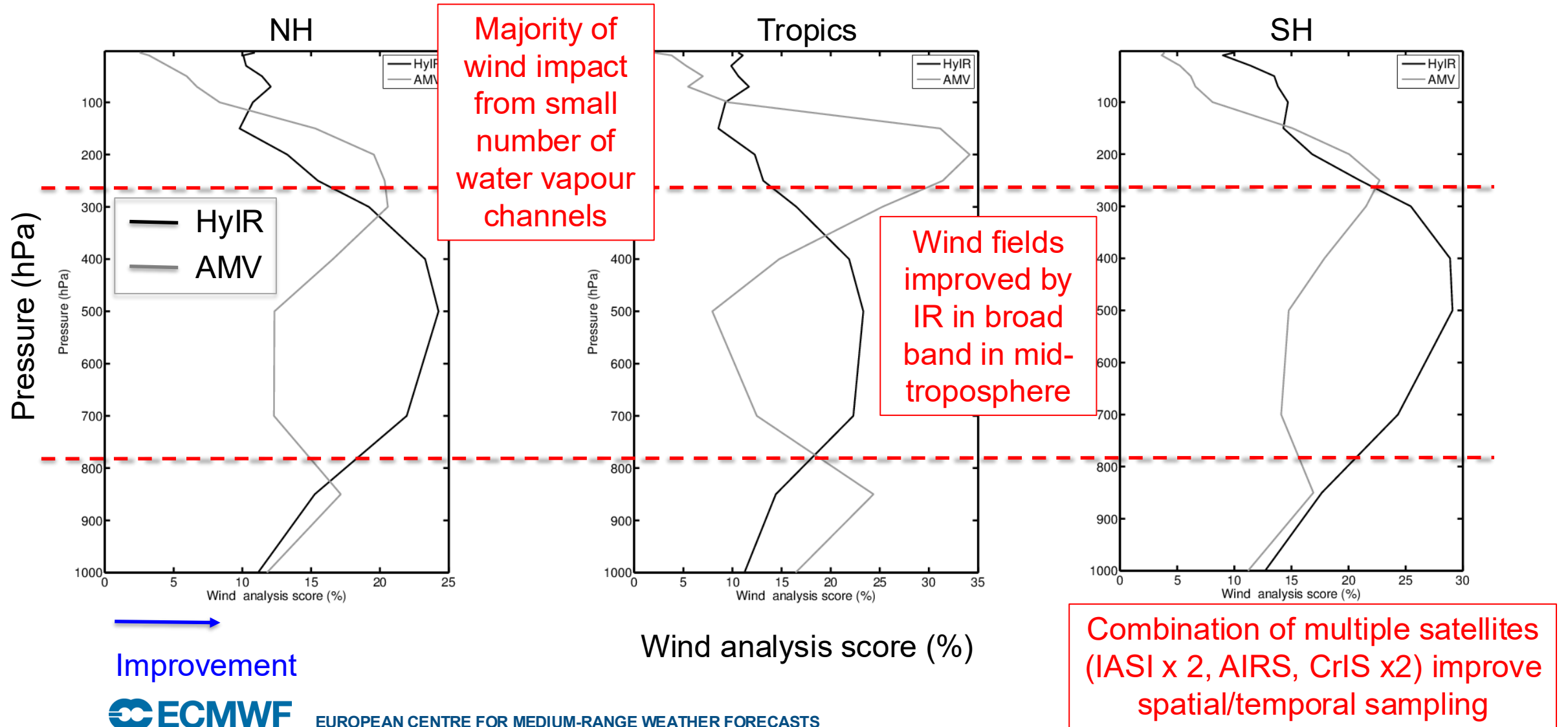
AMV impact larger at high/low pressure
 → Complementary to radiances



Positive impacts throughout troposphere

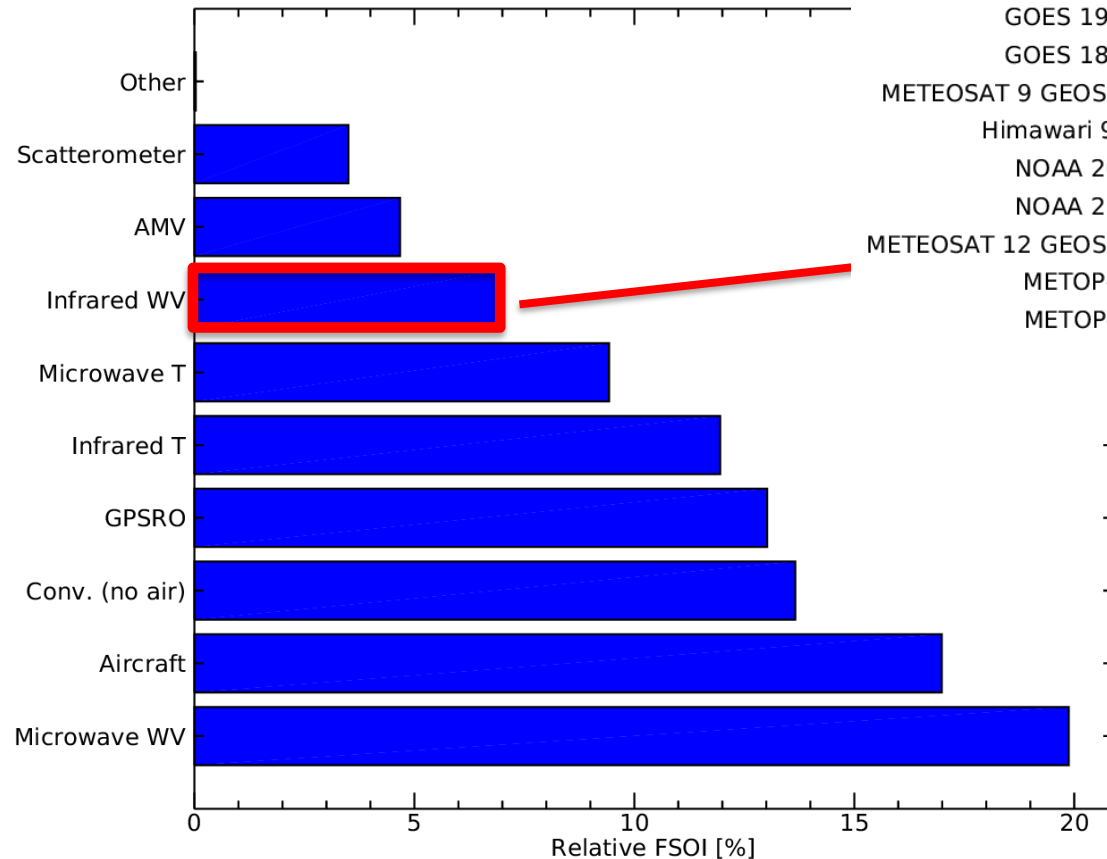
ASR similar to CSR, better in SH

4D-tracing from polar orbiting satellites: Wind analysis scores from hyperspectral IR



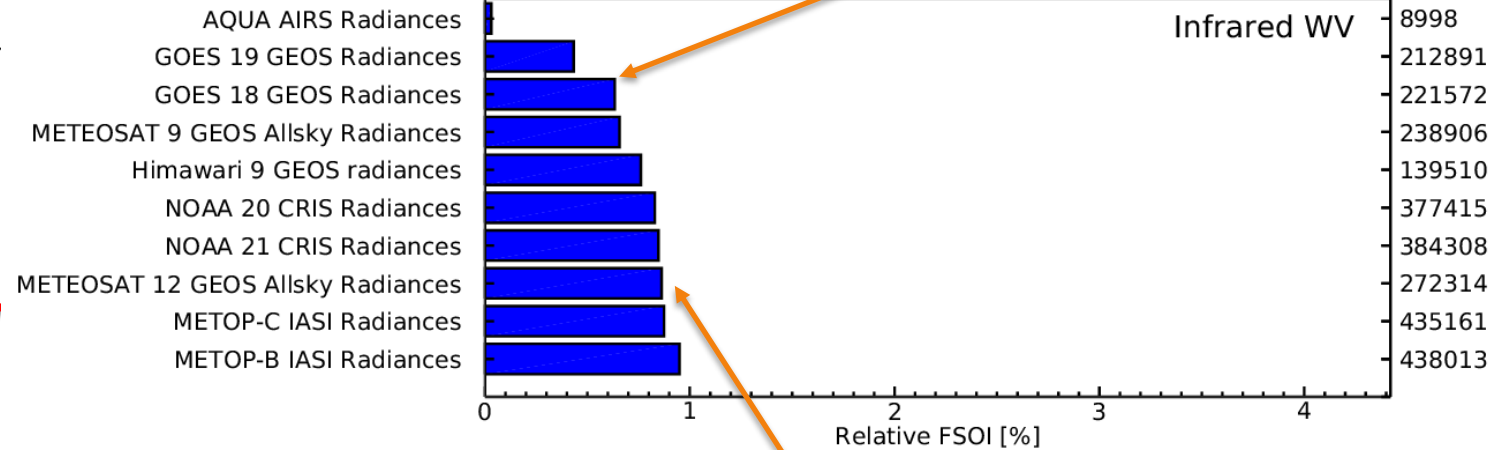
Forecast system performance

January+February 2026



Forecast Sensitivity to Observations (%)

GOES-16/18 should increase soon with expansion of used area



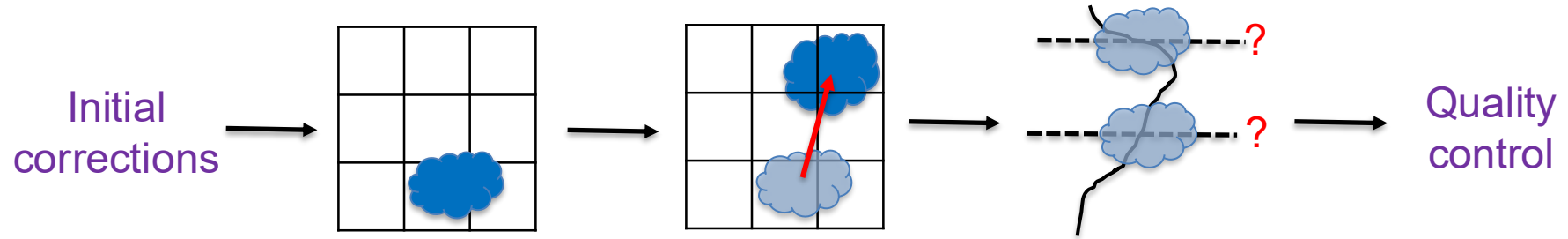
Forecast Sensitivity to Observations (%)

Instruments thinned separately – boosts Himawari and Meteosat-12

Measures reduction in 24hr forecast error due to each source

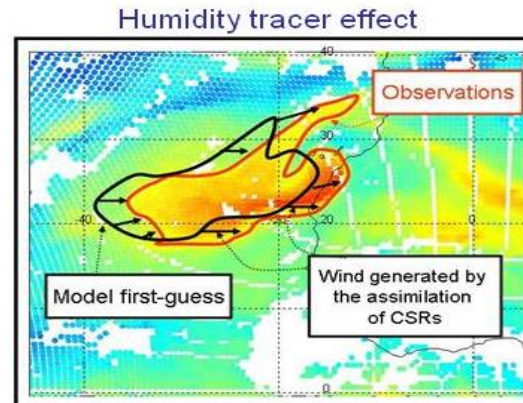
Summary and a look to the future

Summary: AMVs



- Early use of satellite observations but lots of improvements
- Most impact in low and high troposphere
- Complicated and correlated errors
- Positive impact on forecast

Summary: 4D-Var tracing



- Complementary to AMVs
- Good for broad scale motion

NWP models need information on the wind field – AMVs and CSR/ASR will continue to provide good quality observations with good coverage

Future challenges

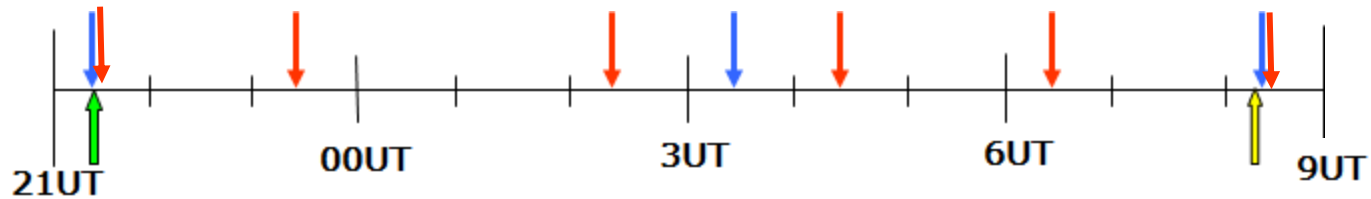
- Increases in spatial resolution
 - How to use more AMVs – better handling of correlations?
- Increases in temporal resolution
 - E.g. GOES-18/19 / FCI – use every 30 mins?
- Increases in spectral resolution
 - 3.8 micron AMVs – extra low level clouds tracked at night
- Hyperspectral instrument in geostationary orbit
 - “3D winds” tracking temp/humidity/ozone profiles
 - MTG-IRS

Thank you for listening!
Any questions?

Further information

Frequency of assimilated images

How does the timing and frequency of the CSR images matter?



12 images

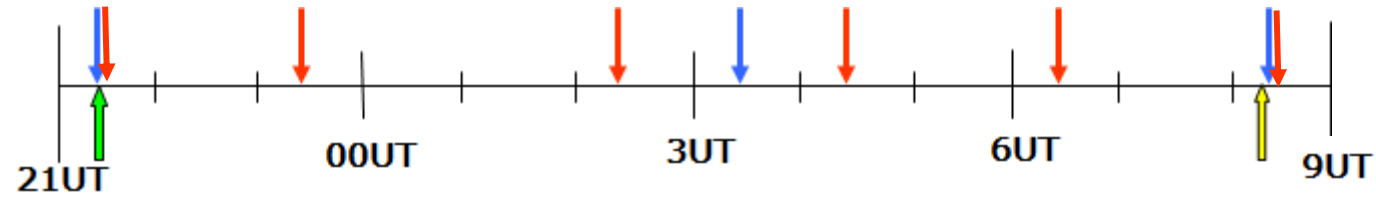
6 images

3 images

1 single image at the beginning of the window

1 single image at the end of the window

Frequency of assimilated images



Highest frequency provides most impact

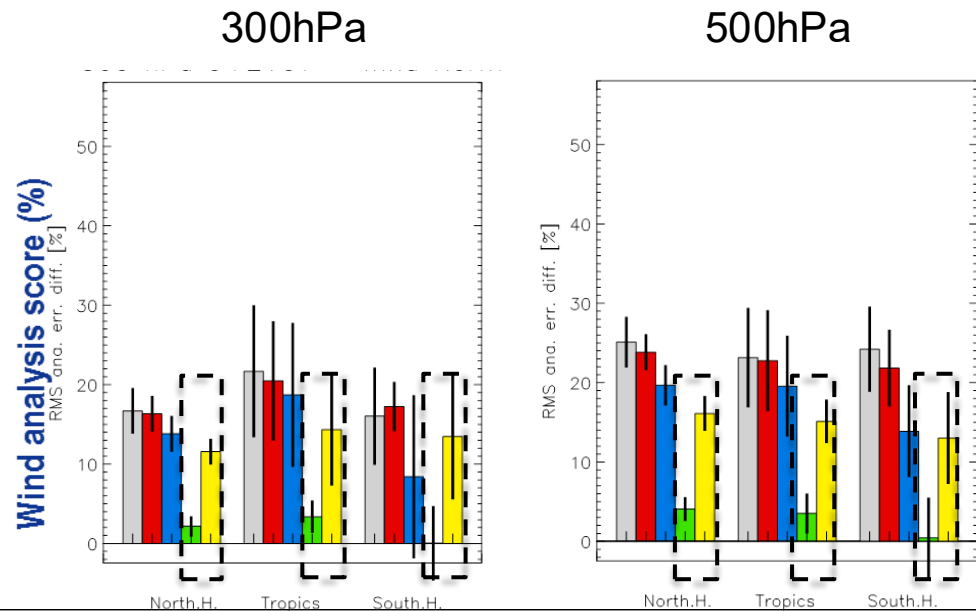
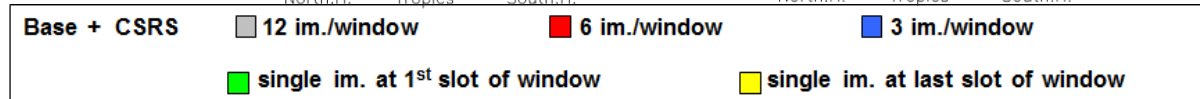
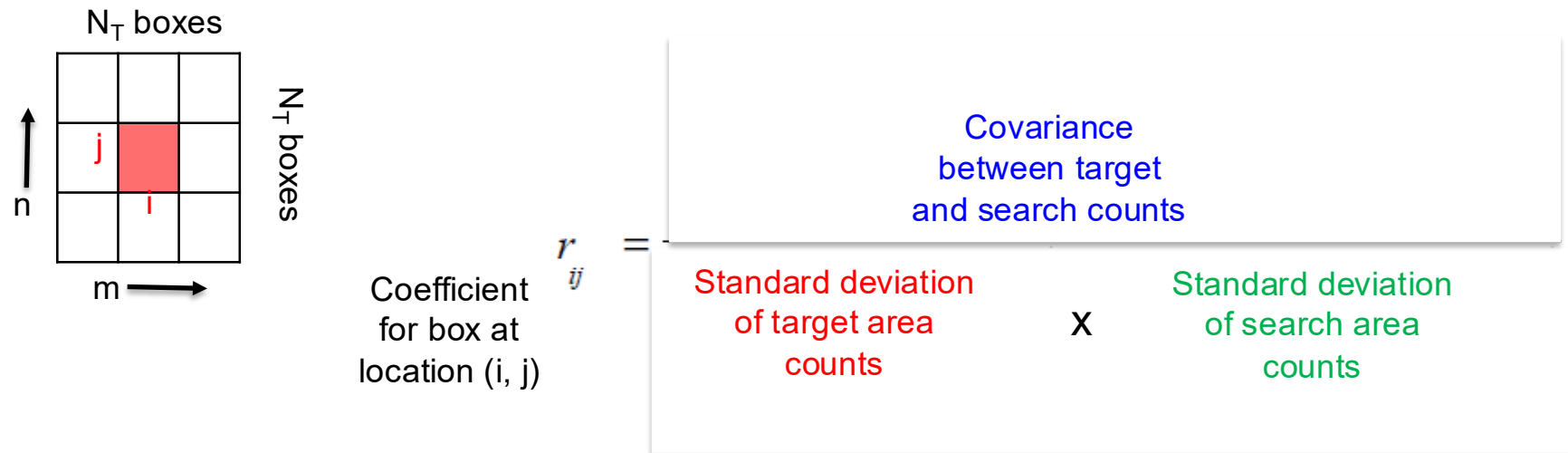


Image at end of window scores better than at beginning of window



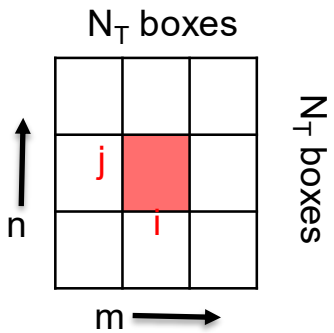
Pattern matching: how are the features tracked for AMVs?

- Commonly based on cross-correlation statistics



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Covariance between target and search counts

$$r_{ij} = \frac{\sum_{m=1}^{N_T} \sum_{n=1}^{N_T} (T_{mn} - \mu_T)(S_{i+m, j+n} - \mu_{Sij})}{\left[\sum_{m=1}^{N_T} \sum_{n=1}^{N_T} (T_{mn} - \mu_T)^2 \right]^{1/2} \left[\sum_{m=1}^{N_T} \sum_{n=1}^{N_T} (S_{i+m, j+n} - \mu_{Sij})^2 \right]^{1/2}}$$

Coefficient for box at location (i, j)

Pixel counts in target area at (m,n)

Mean target area counts

Pixel counts in search area at (i+m, j+n)

Mean search area counts

Standard deviation of target area counts

Standard deviation of search area counts

- Calculate r_{ij} linking pixel count values for **each pixel** in target and search area
- Maximum in the correlation surface = best match

AMV height assignment methods

1. Equivalent black-body temperature: comparing measured brightness temps (BTs) to forecast temp profiles. Best agreement = height
2. Carbon dioxide slicing:

$$\frac{\text{Diff (cloudy – clear) actual radiances CO}_2}{\text{Diff (cloudy – clear) actual radiances IR window}} = \frac{R(\text{CO}_2) - R_{c1}(\text{CO}_2)}{R(\text{IRW}) - R_{c1}(\text{IRW})}$$

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Cloud fraction x cloud emissivity

Diff (cloudy at varying cloud pressure – clear) estimated radiances CO₂

Diff (cloudy at varying cloud pressure – clear) estimated radiances IR window

1. Water vapour intercept: uses same method as CO₂ slicing with water vapour

Details e.g. in Nieman et. al, 1993: A Comparison of Several Techniques to assign heights to cloud tracers. J. Appl. Meteor. 1559-1568

Height assignment methods cont.

4. Cloud base techniques: histogram of BTs for target area. Cloud base temp estimated from histograms and compared with forecast temp to get best cloud base height
 5. Optimal Cloud Analysis: uses a 1-D optimal estimation approach to get cloud parameters and tests for multi-layer cloud situations
- All have assumptions affecting accuracy
 - Errors in short range NWP
 - Errors in radiative transfer

Error in height assignment dominant source of error for
AMVs

Situation dependent observation errors: equation for error in height

Diff wind component
(model level – at
observation location)

Height
error

$$E_{vp} = \frac{\sqrt{\sum W_i (v_i - v_n)^2}}{\sum W_i}$$

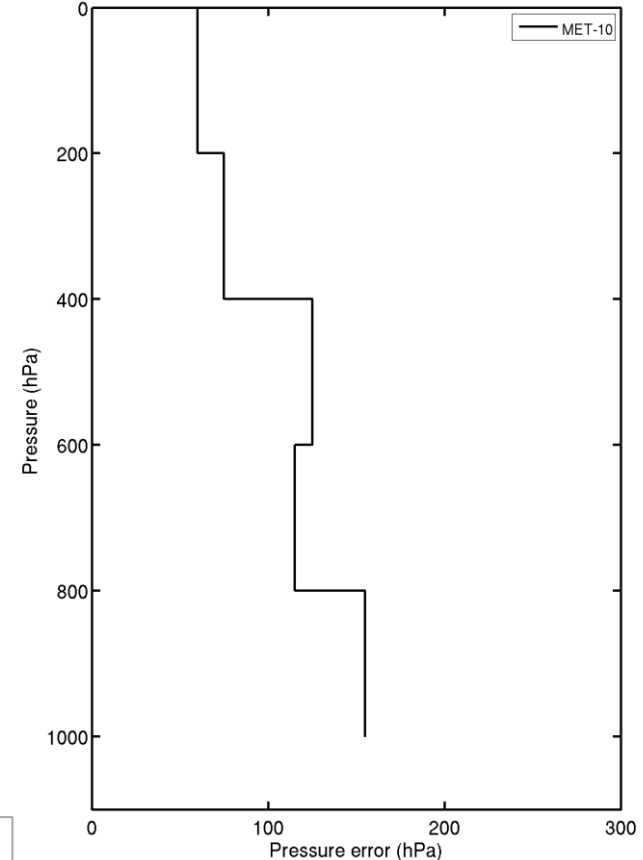
Weight per
model level, i

Diff pressure (model level at obs
location – assigned pressure)

$$W_i = \exp\left(-\frac{(p_i - p_n)^2}{2E_p^2}\right) * dP_i$$

Layer
thickness

Error in height assignment estimated by standard deviation (AMV pressure - model pressure minimising vector diff (observed – model) wind)



**Height assignment error
(hPa) for Meteosat-10**

Calculate separately for u and v components