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

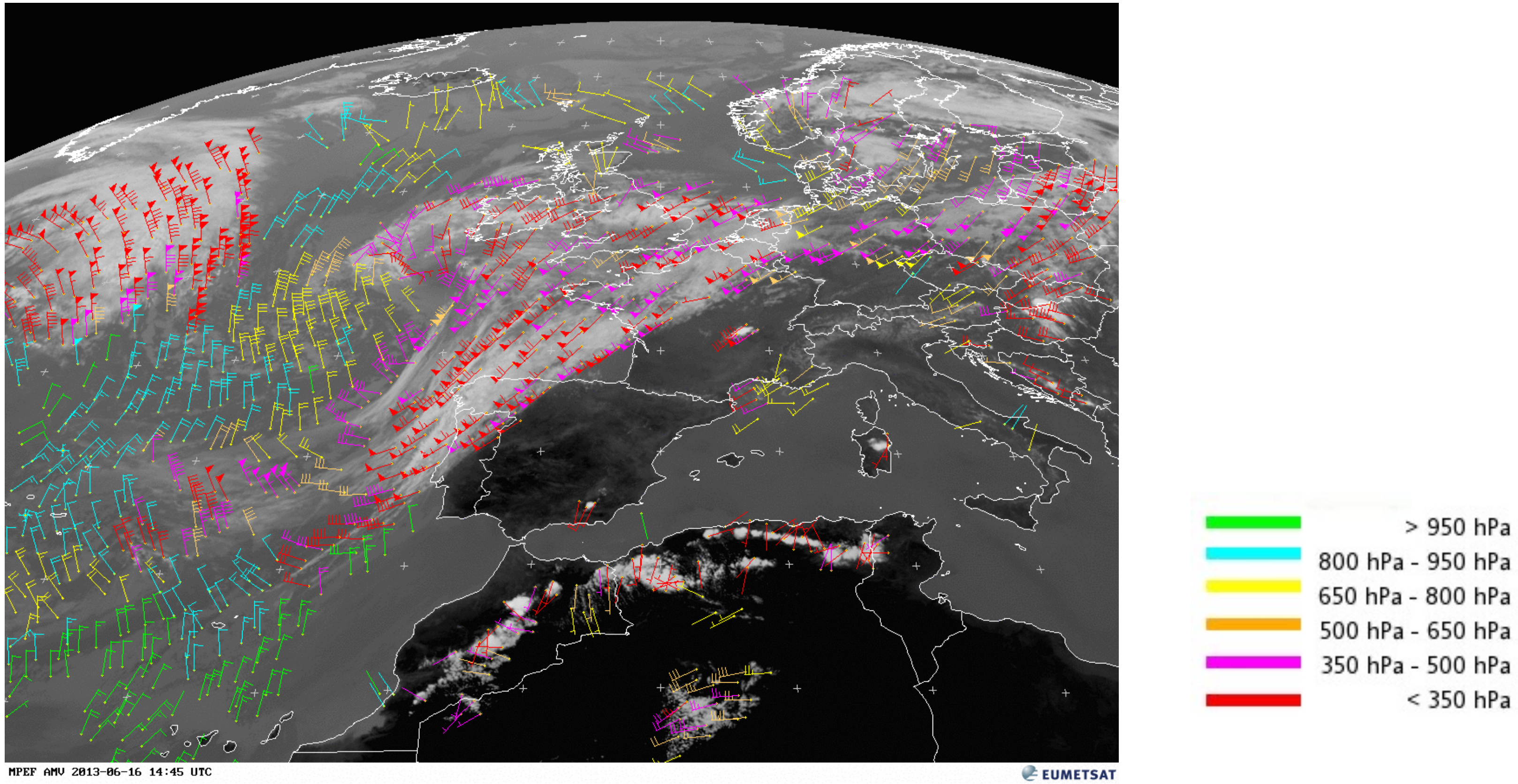
ECMWF

Contents

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

1960

Tetsuya "Ted" Fujita uses first images from polar orbiting TIROS

→

1966

Geostationary imager ATS-1

Fujita pioneers much of the work through 1960s and 1970s

→

1970s

ATS evolves into GOES -> routine tracking of clouds

→

1978

First Meteosat with water vapour channels

←

1979

Early cloud motion vector production peaks during study of global circulation

←

Improving all the time!

More automation
More satellites
Quality indicators
Using polar orbiting satellites

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

  JMA: Himawari-9

  NOAA/NESDIS: GOES-16, GOES-18

  IMD: INSAT-3D

  CMA: FY-2G

AMV production today: polar orbiting

- Uses images from successive orbits from same satellite ~100 mins apart
- Images from 2 satellites (using Metop-B and Metop-C, formerly Metop-A also), currently ~ 20-50 mins apart

- Monitored/assimilated at ECMWF:

EUMETSAT: Metop-B, Metop-C, composite Metop product

NOAA/NESDIS: NOAA-20, Suomi-NPP

CIMSS: Composite LEO-GEO product, NOAA-15, -18, -19,

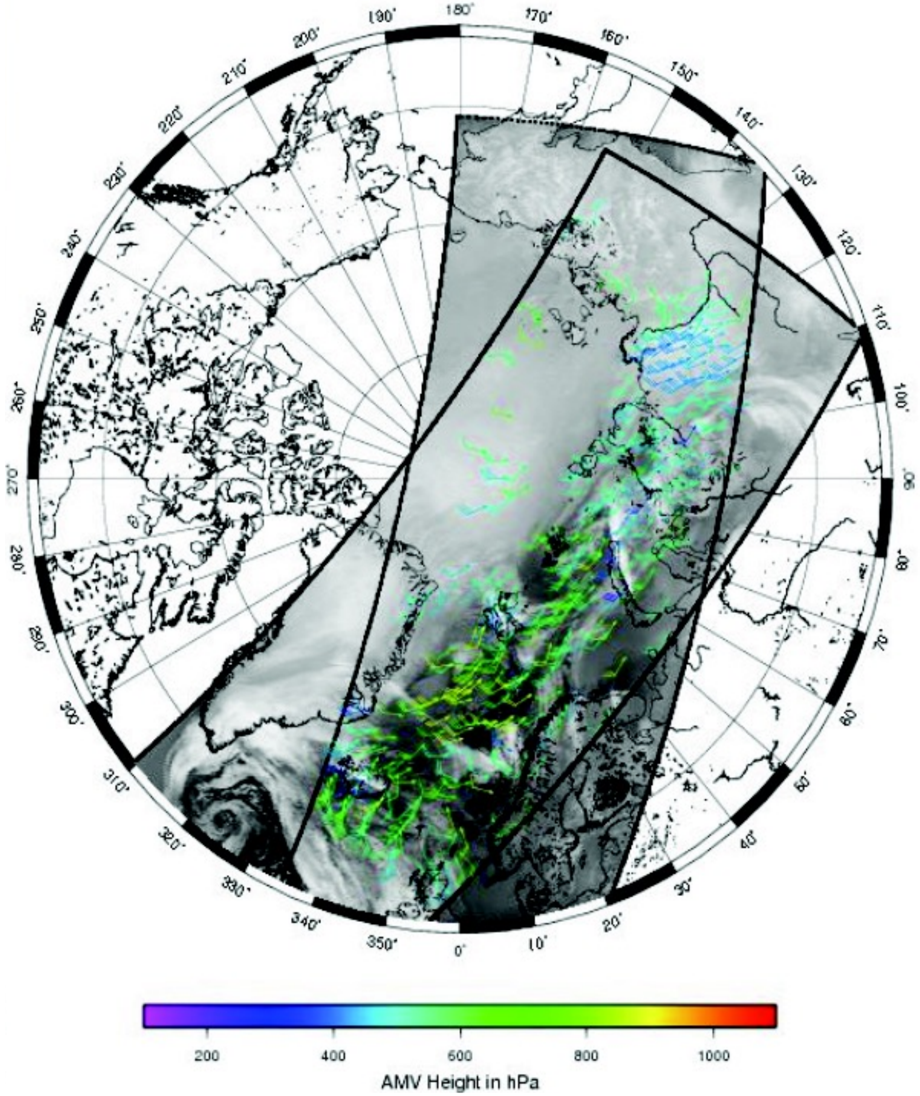
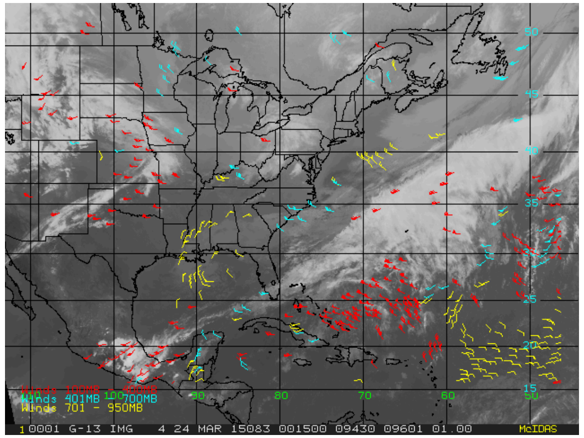
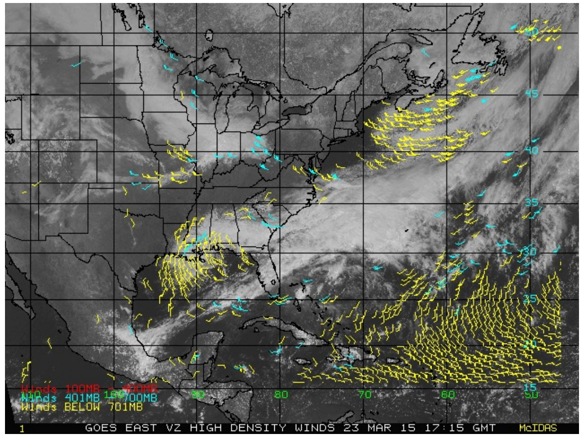


Figure from "AVHRR polar winds derivation at EUMETSAT: Current status and future developments", Dew and Borde, IWW-11 presentation

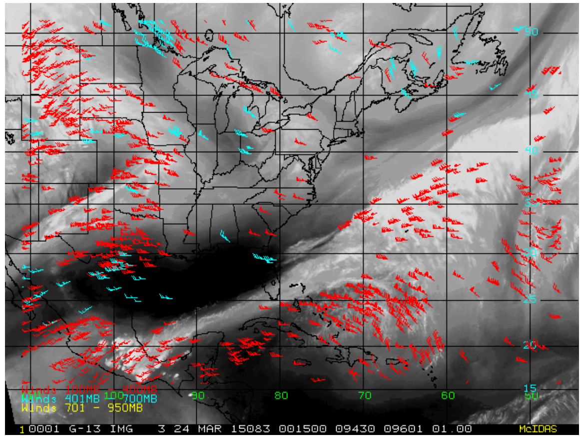
Wavelengths used in AMV production



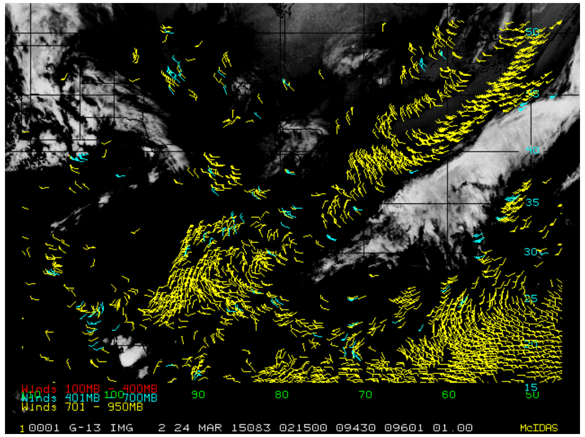
IR window (~10.7 µm): Clouds



VIS (~0.65 µm): Clouds



Water Vapour absorption (~6.7 µm): Clouds
Clear sky WV features



Short Wavelength IR (~3.9 µm): Clouds

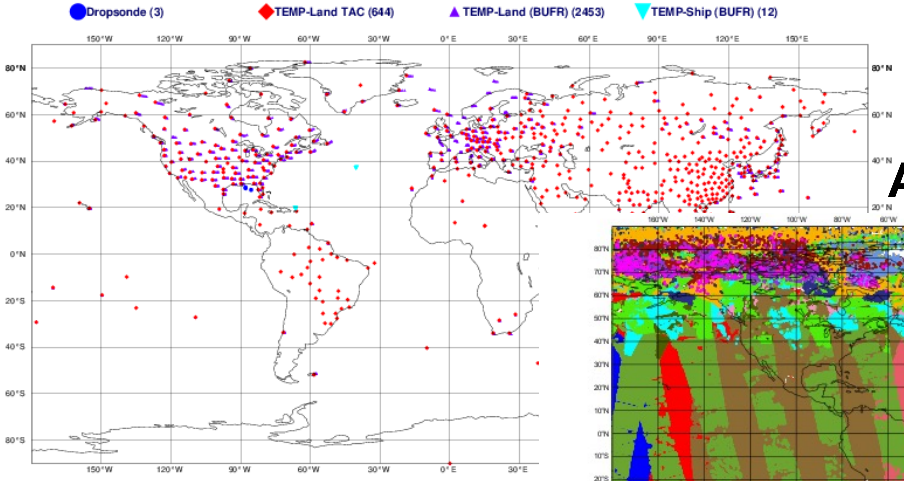
AMVs mostly cover:
Low troposphere ~850hPa
High troposphere ~200hPa

Figures from:

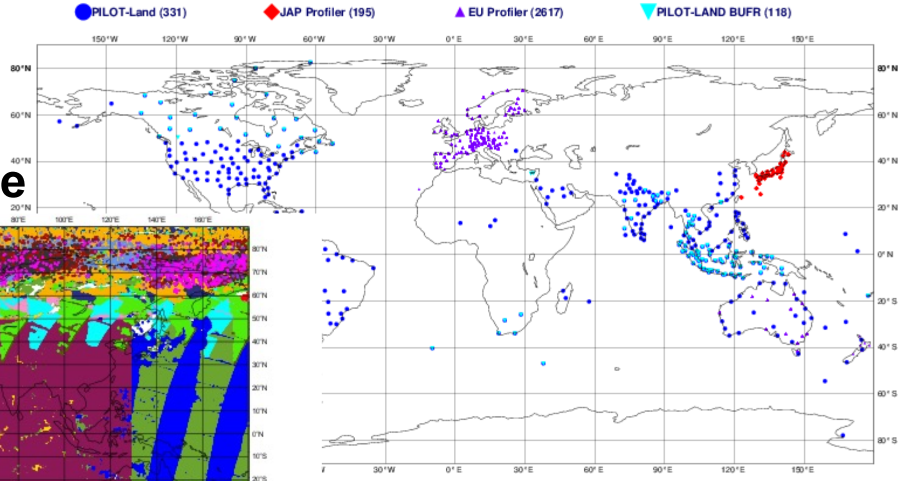
http://www.ospo.noaa.gov/Products/atmosphere/hdwinds/goes.html

AMVs – why do we need them?

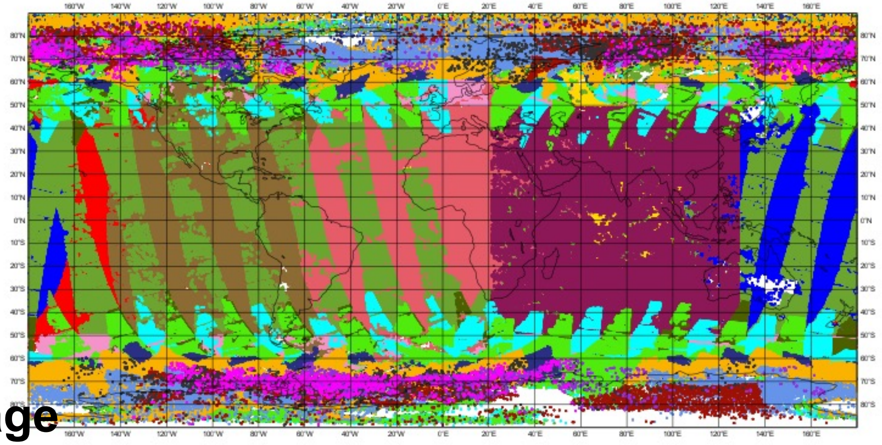
Radiosonde coverage



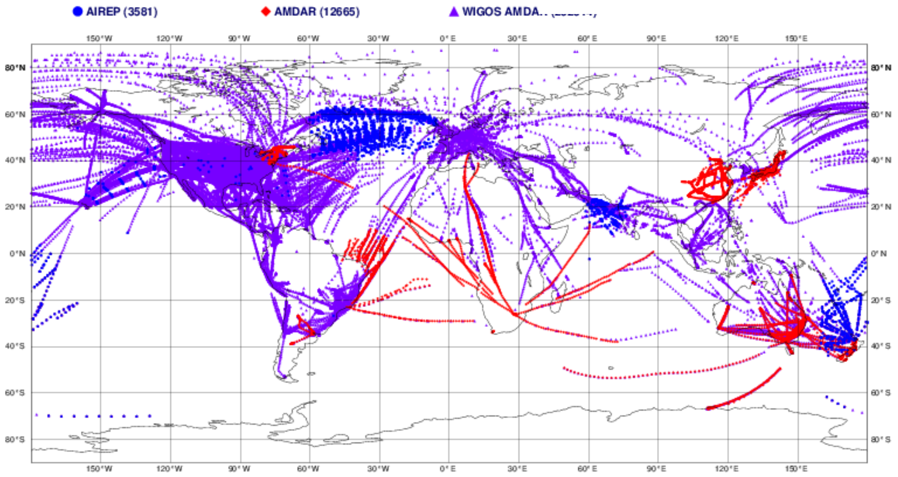
Pilot-Profiler coverage



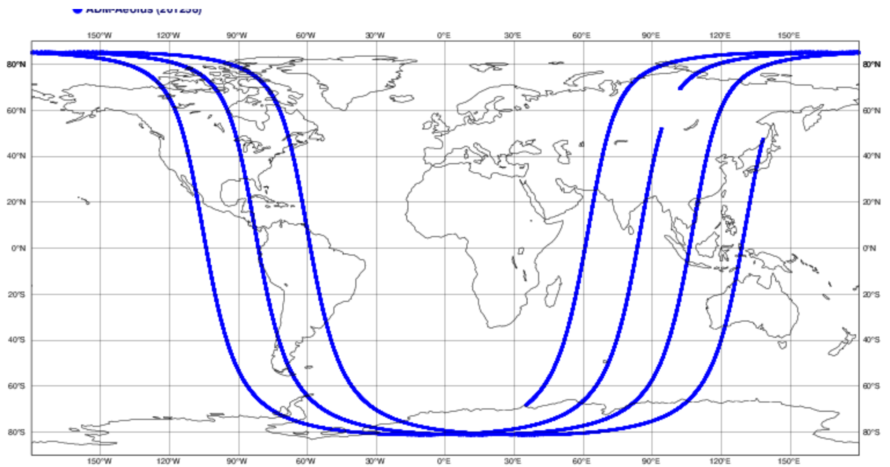
AMV coverage



Aircraft coverage



Aeolus coverage (up to April 2023)



Contents

How are AMVs derived?

Part 1: Tracking

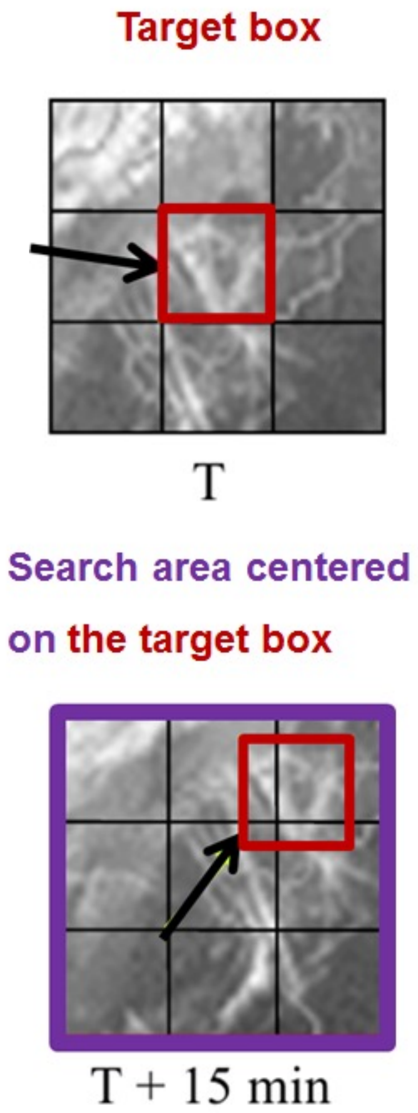
Part 2: Height assignment

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 advanced pattern matching methods
4. Calculate displacement vector

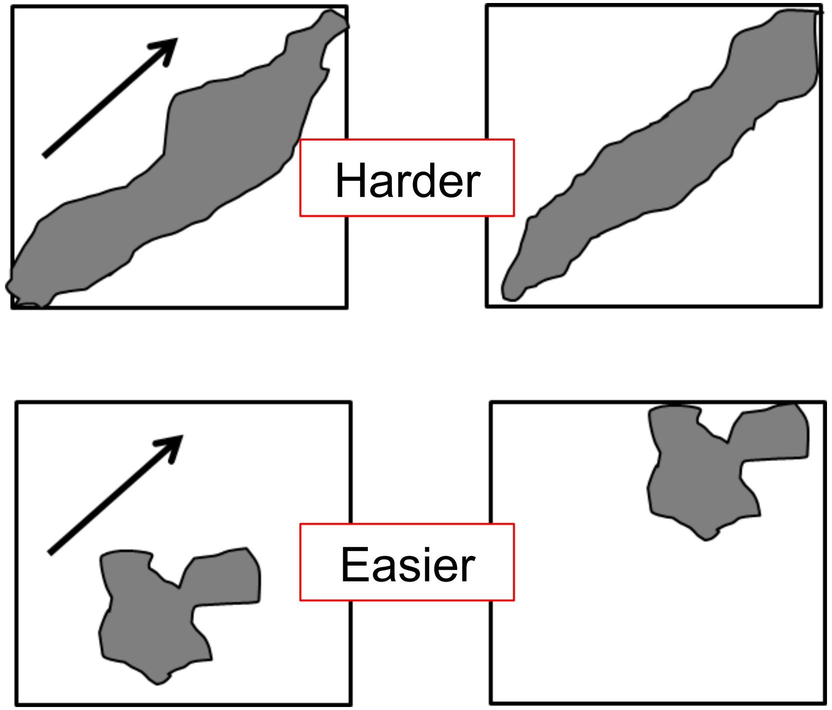
   (Some new algorithms use nested tracking – track multiple targets and take average)

Assumption: tracked feature travels with local wind

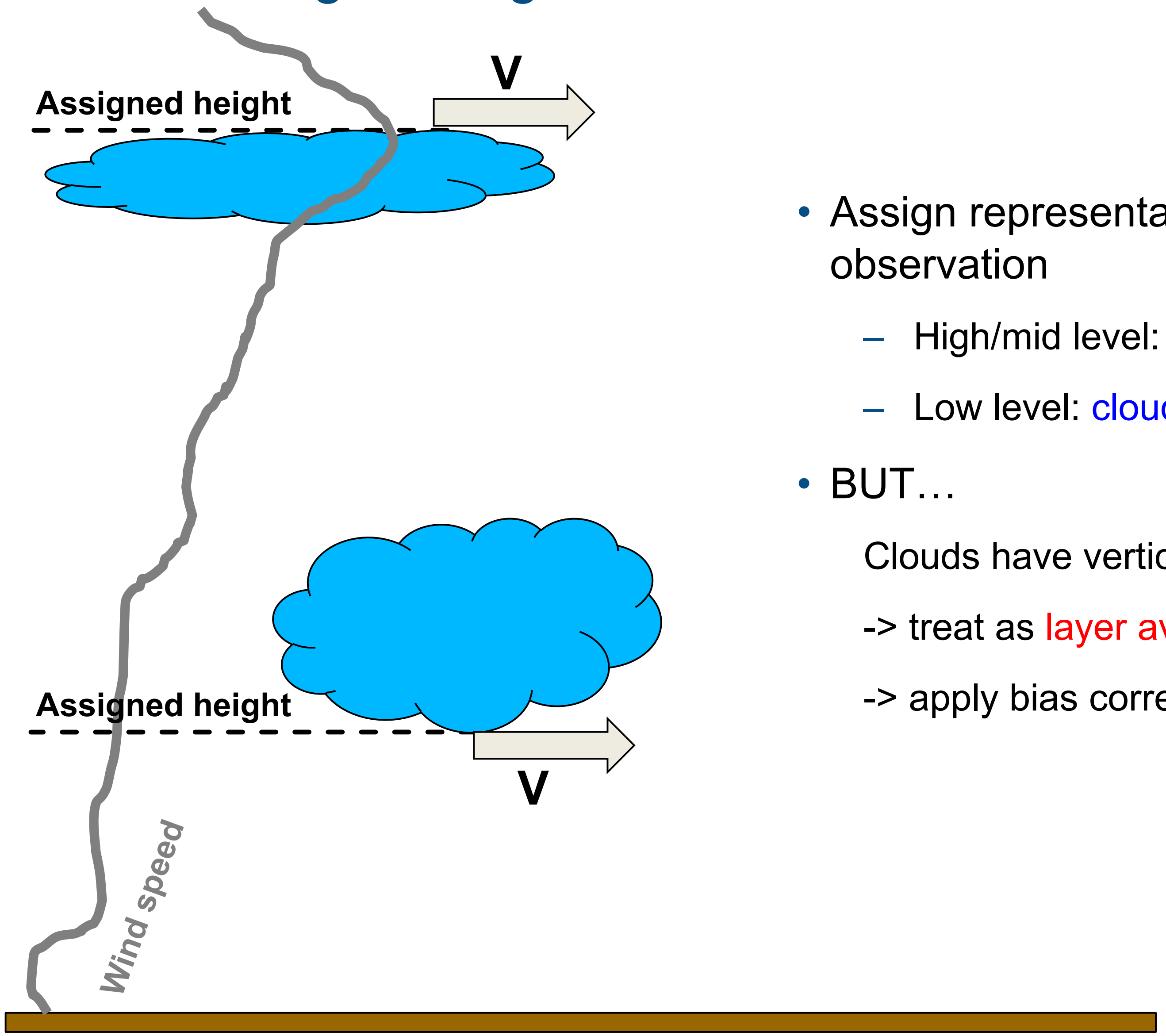


Tracking errors

- 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?

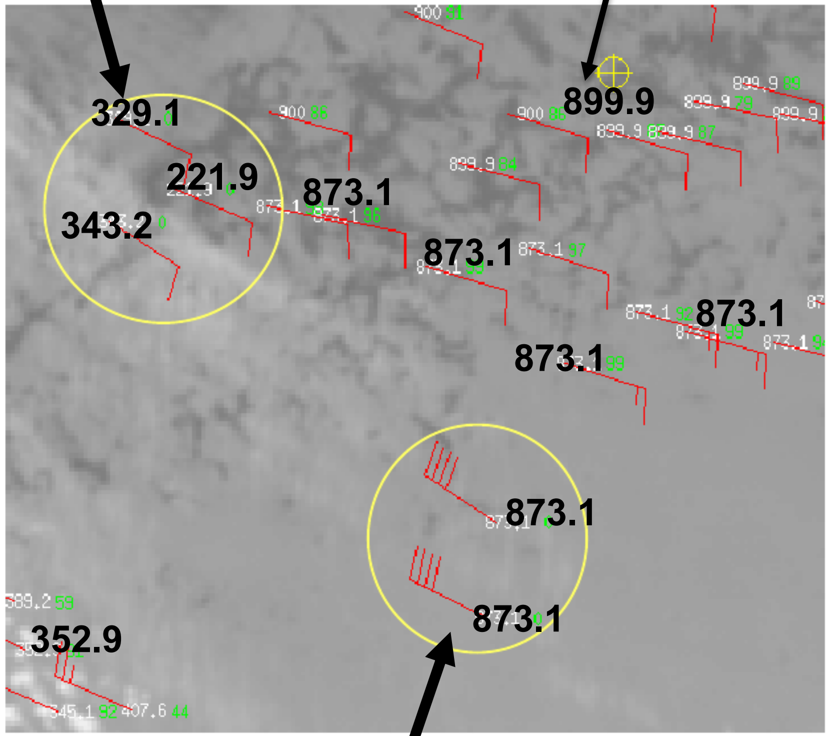
  -> apply bias correction to height?

Which pixels are used for the height?

Highest contrast dominates tracking -> usually edge of coldest cloud...

…but not always:

Example – thin high cloud overlying low cloud



Just using coldest pixels less good…

…new method uses pixels that contribute most to cross correlation during tracking

Example from Forsythe M. and M. Doutriaux-Boucher, 2005: Second Analysis of the data displayed on the NWP SAF AMV monitoring website.

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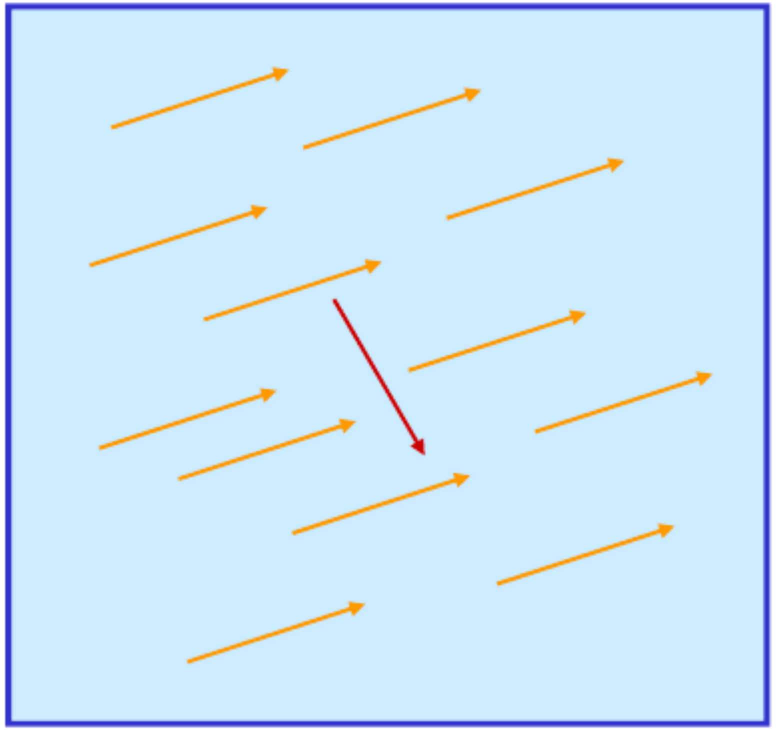
Height assignment methods

- 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



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

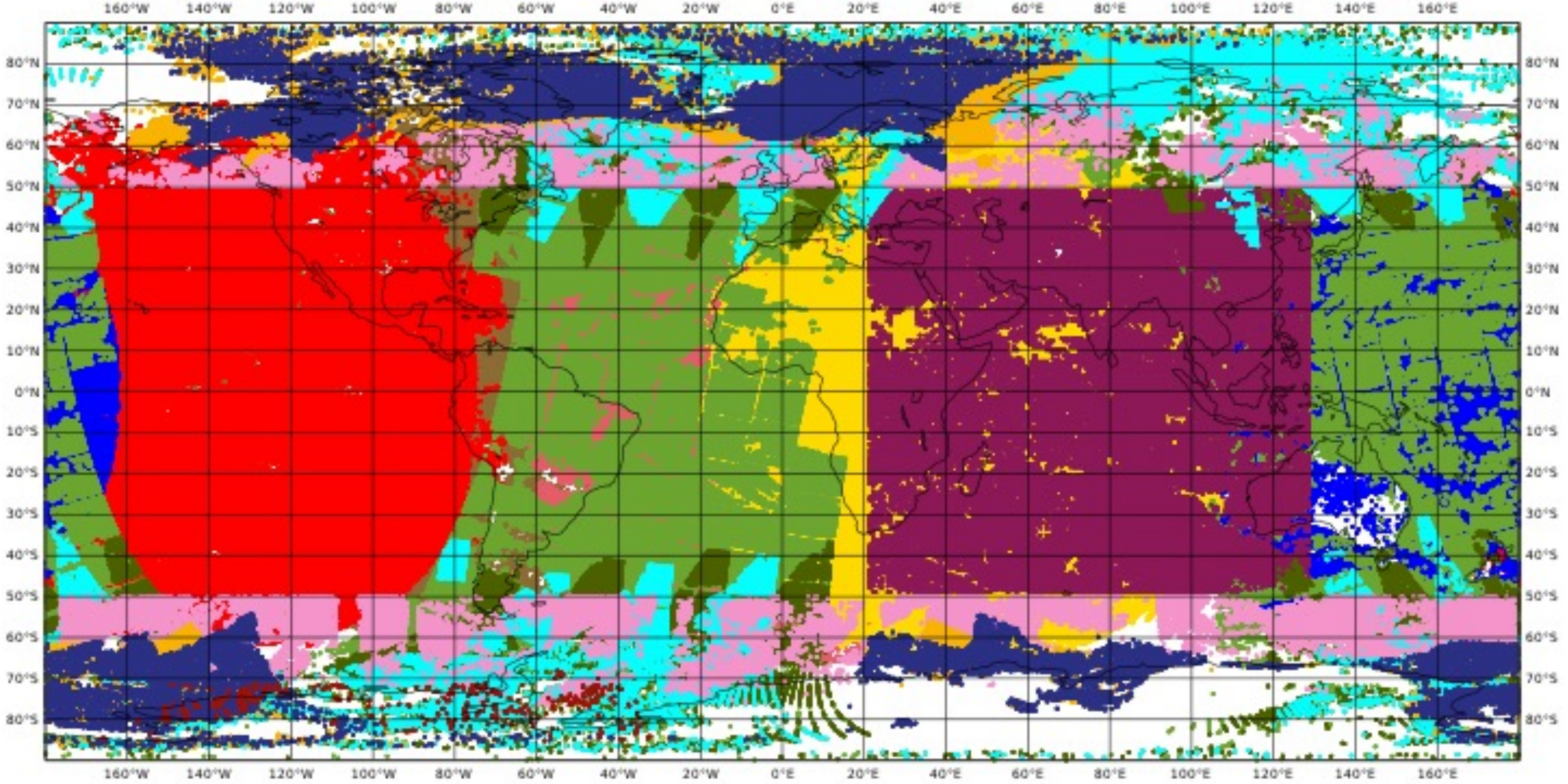
AMV sample coverage: monitored data for one 12hr cycle (12Z 22th April 2023)

Monitoring in region of 17 million winds per cycle

Metop-B Metop-C Meteosat-9 Meteosat-10 Himawari-9 NOAA-15 NOAA-18 NOAA-19 NPP NOAA-20 GOES-16 GOES-18 Dual-Metop

LeoGeo Insat-3D

Actively used



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

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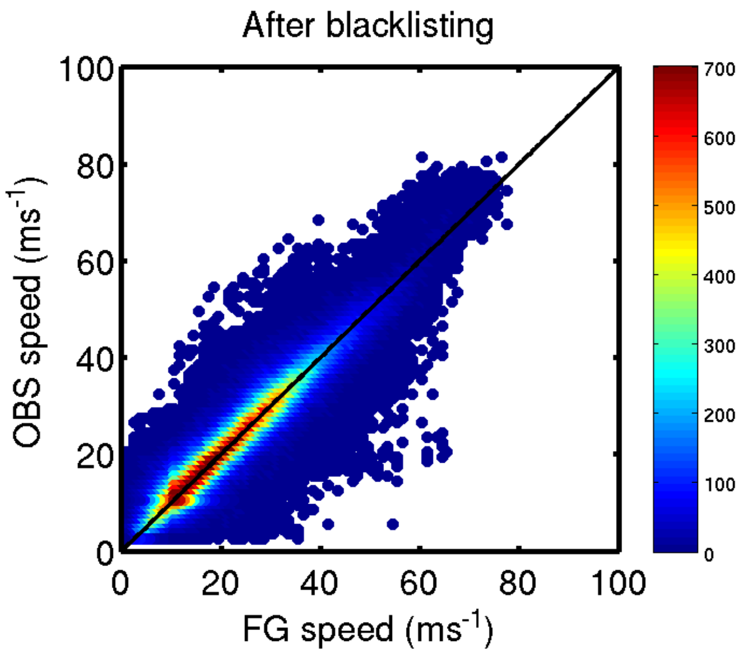
AMV selection: blocklisting

- 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



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AMV selection: First Guess check

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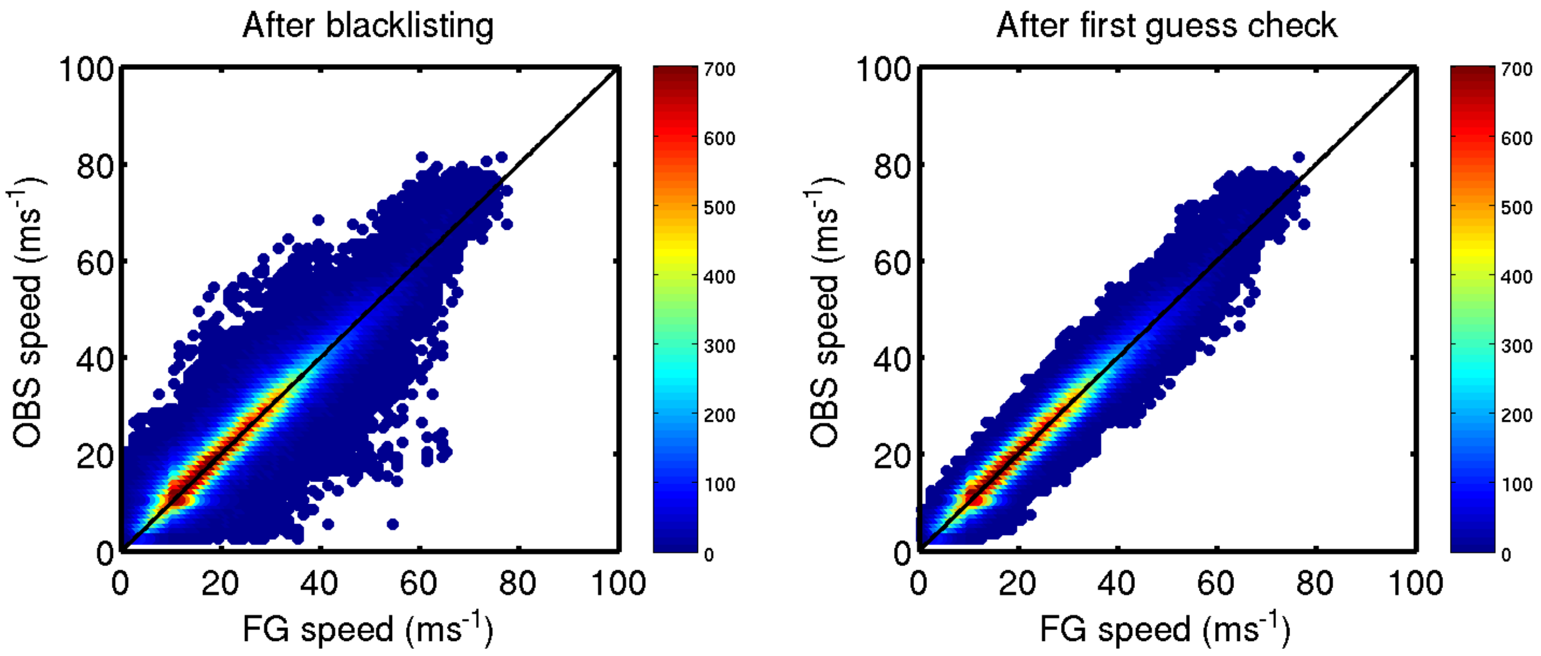

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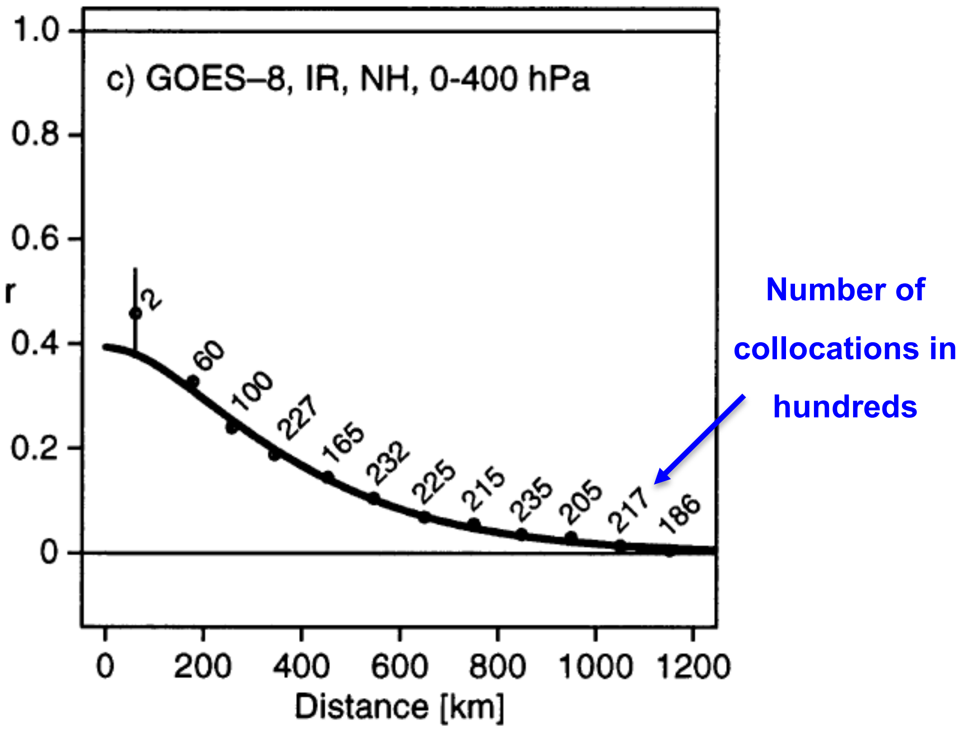
AMV selection: thinning

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



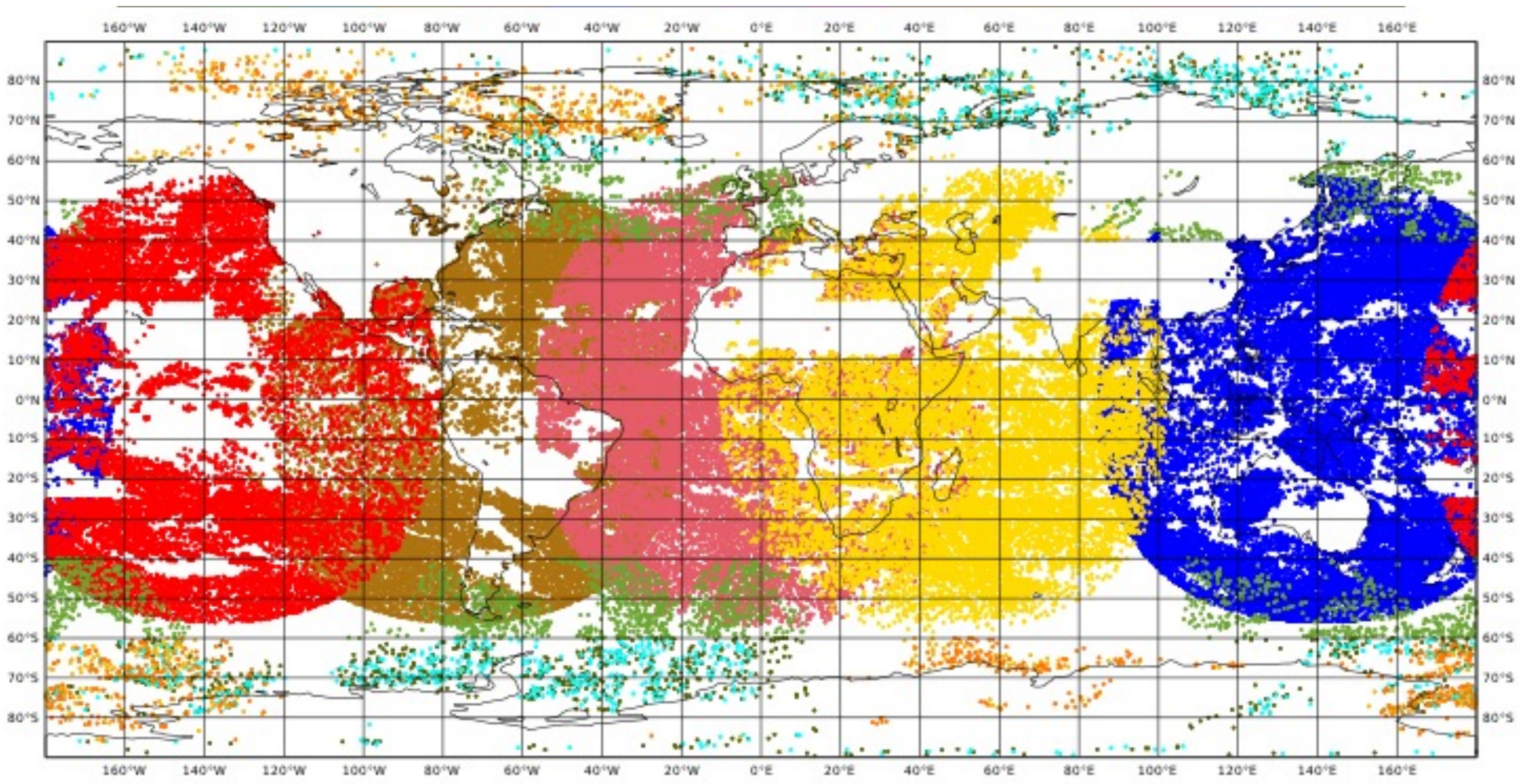
AMV-radiosonde departure correlations as a function of station separation.

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 12Z 22nd April 2023

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

Metop-B Metop-C Meteosat-9 Meteosat-10 Himawari-9 NOAA-15 NOAA-18 NOAA-19 NPP NOAA-20 GOES-16 GOES-18 Terra Dual-Metop



Operational use

- AMVs from 5 geo and 8 polar orbiting satellites/products
- Example of data reduction: typical 12 hr window, Meteosat-10 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

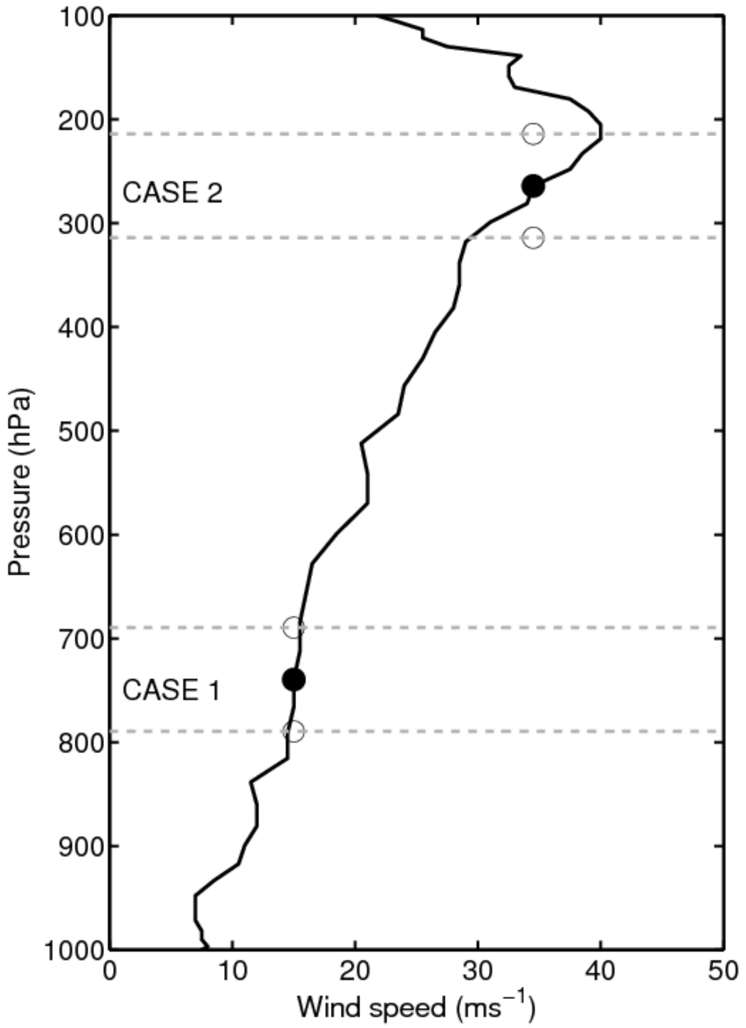
[Total u/v error]^2 = [Tracking error]^2 + [Error in u/v due to error in height]^2

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.

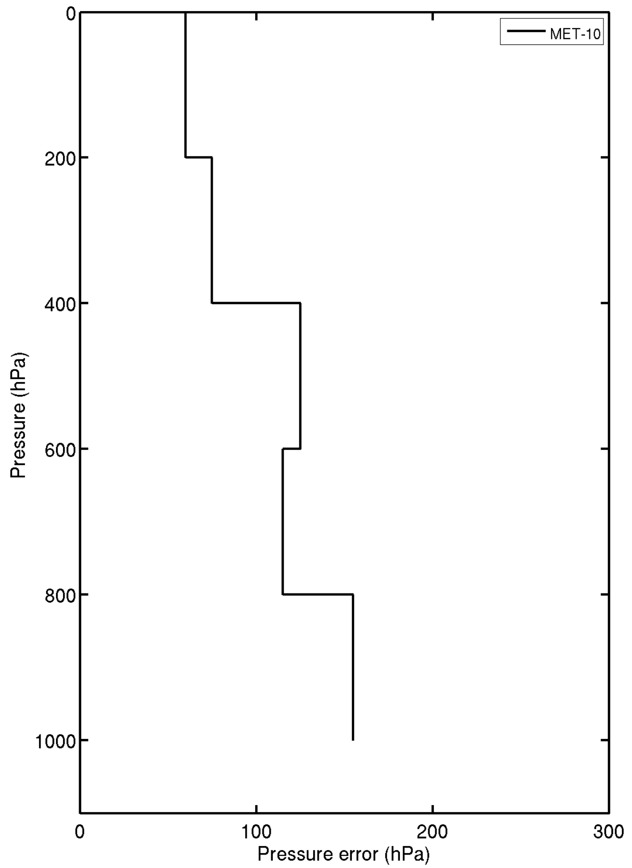


Situation dependent observation errors: error in height

- 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

Calculate separately for u and v components

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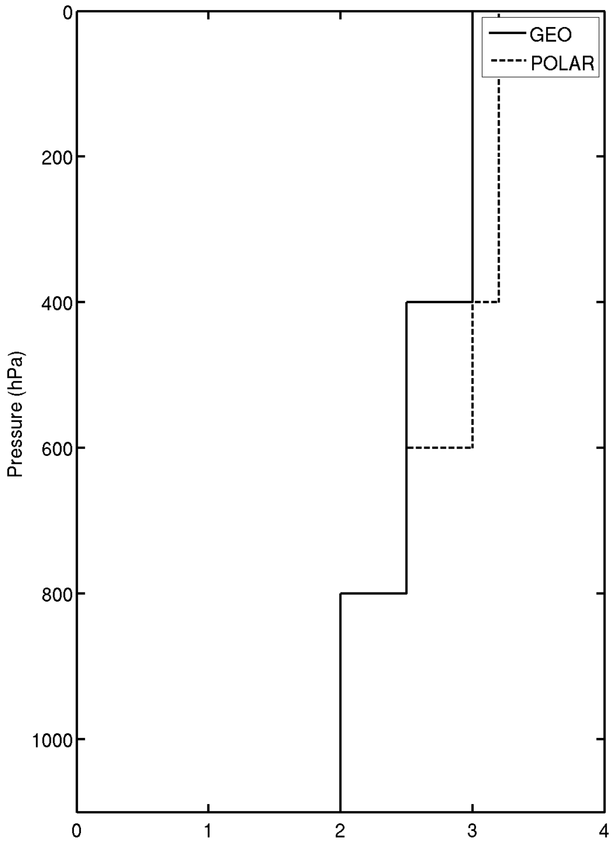
Situation dependent observation errors: tracking error

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



Tracking error (m/s)

- 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

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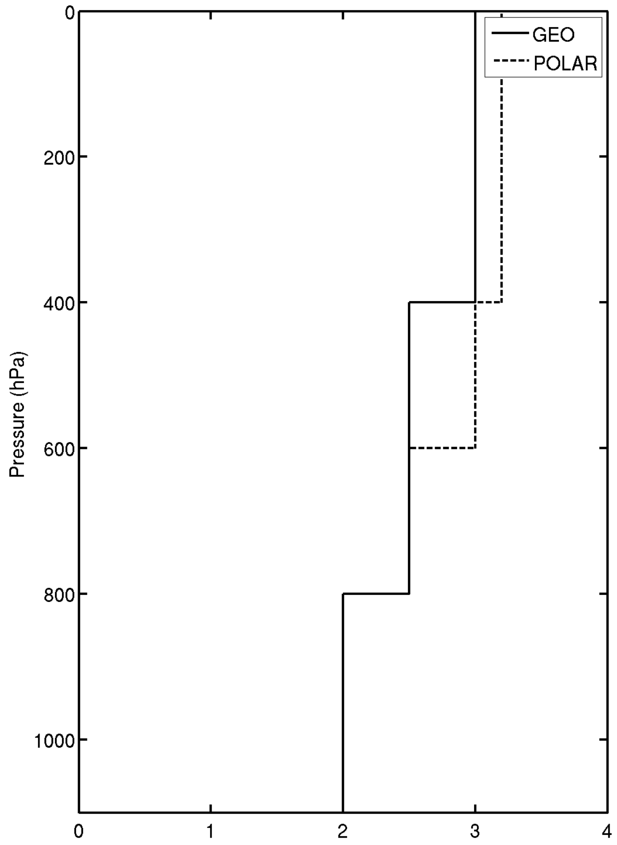
Forsythe M, Saunders R, 2008: AMV errors: A new approach in NWP. Proceedings of the 9th international winds workshop.

Situation dependent observation errors

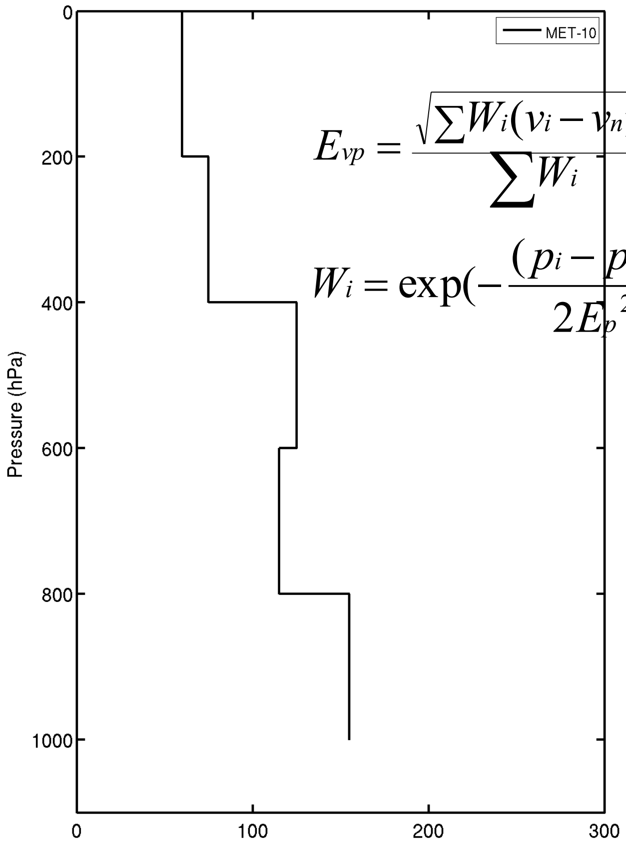
sqrt(



Tracking error (m/s)

2

+



Height error

2

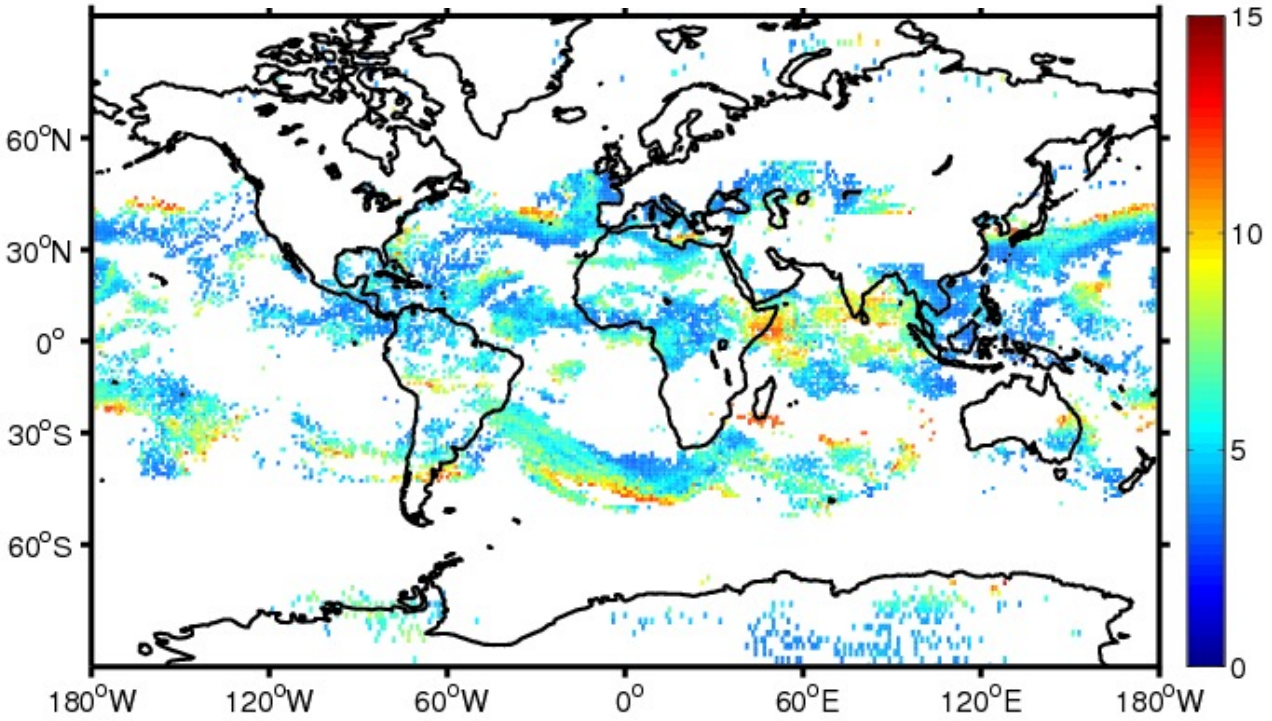
$$E_{vp} = \frac{\sqrt{\sum W_i (v_i - v_n)^2}}{\sum W_i},$$

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

)

Situation dependent observation errors

=



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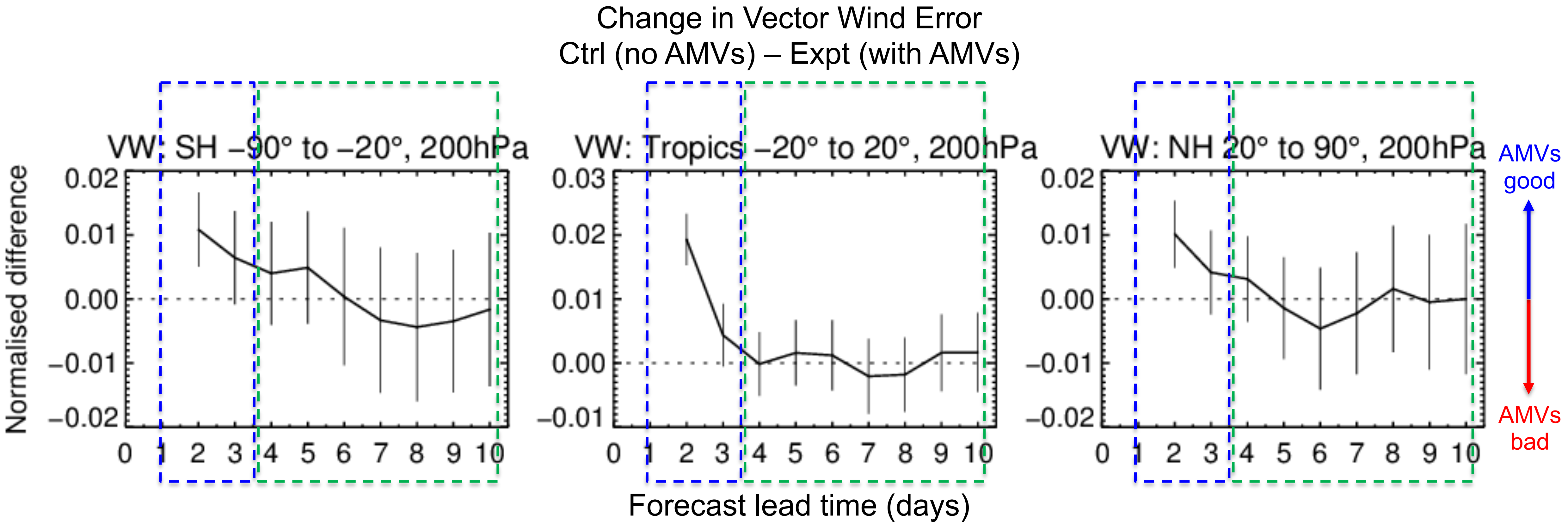
AMV forecast impacts



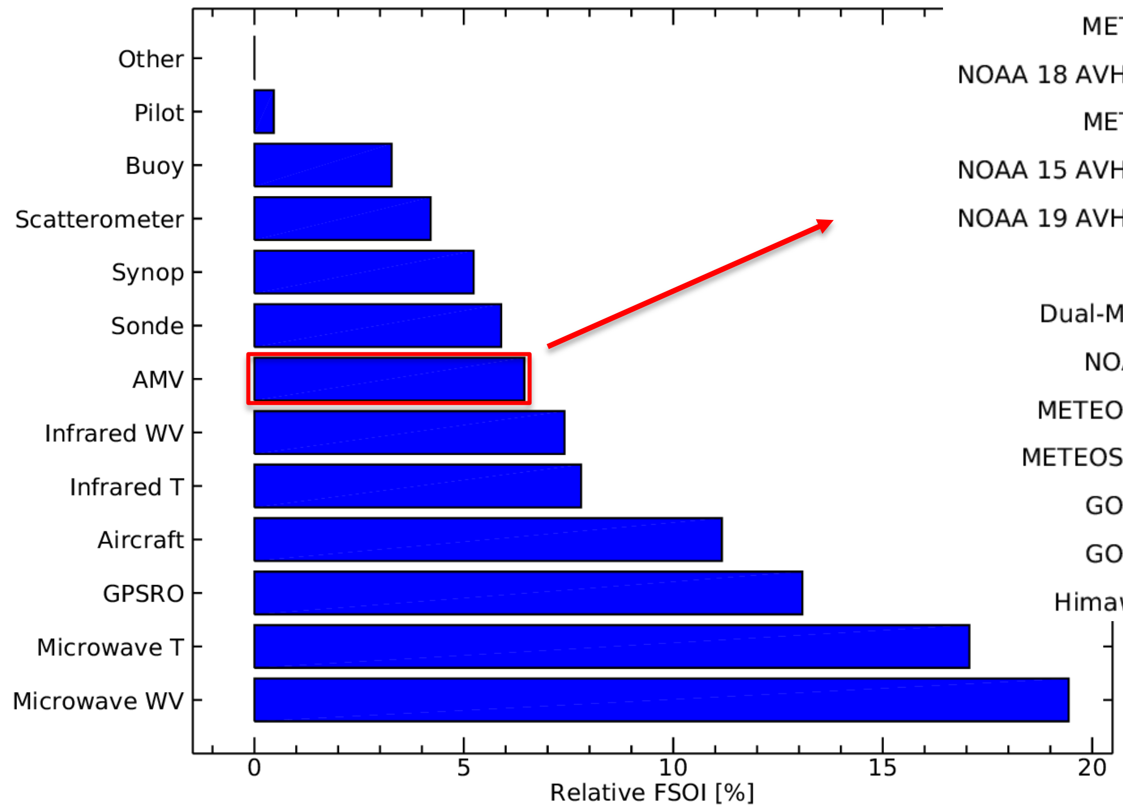
Generally +ve for 2-3 days

Neutral at longer ranges

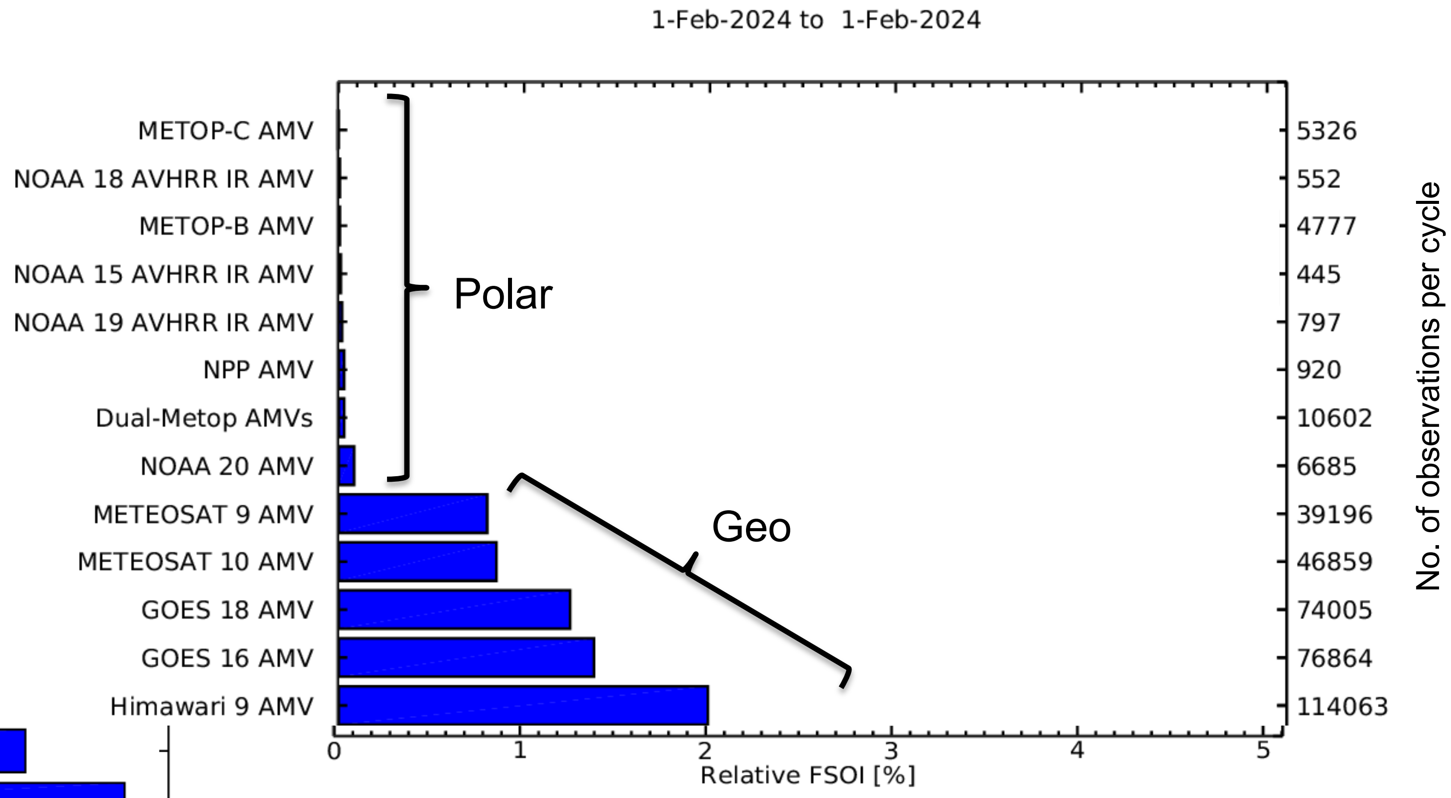
AMV denial experiments (8 months, summer 2016, winter 2017/2018)

Forecast system performance

February 2024



Forecast Sensitivity to Observations (%)



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 sparser

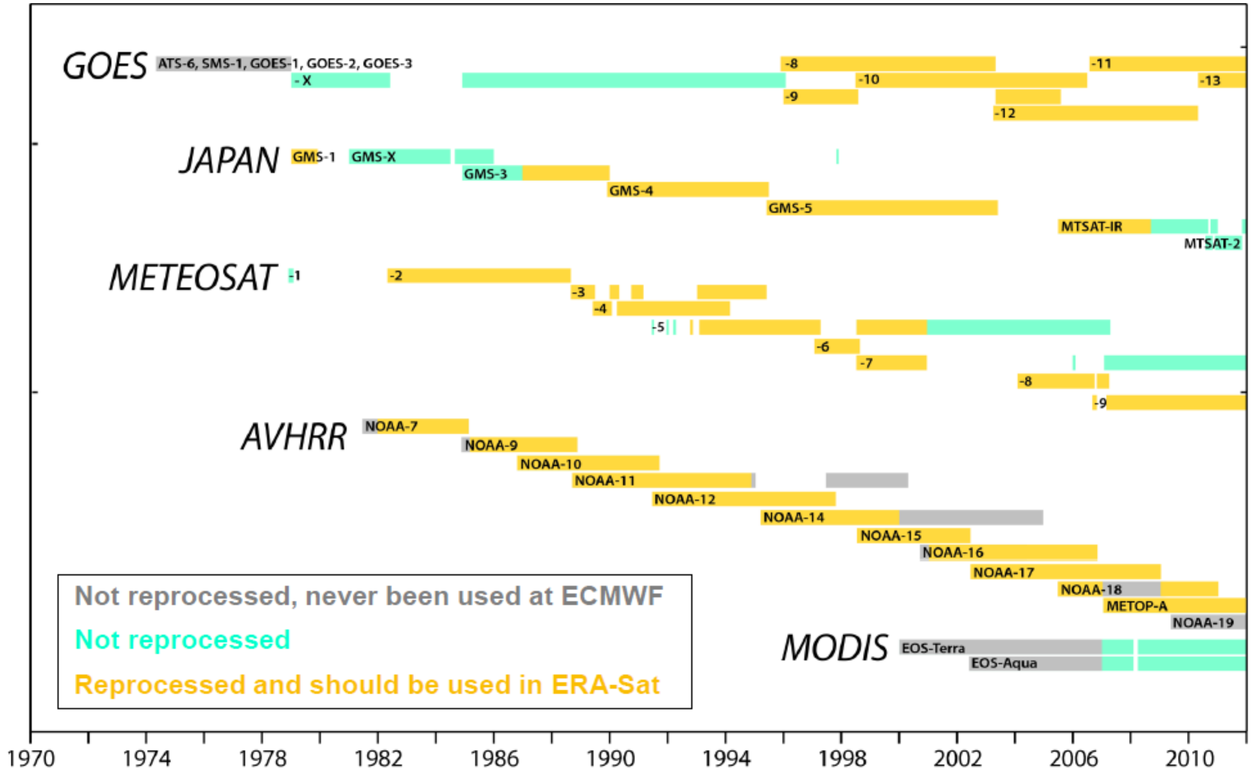


Figure from Carole Peubey

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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

Contents

4D-Var tracing:

Changing wind fields by direct assimilation of radiances

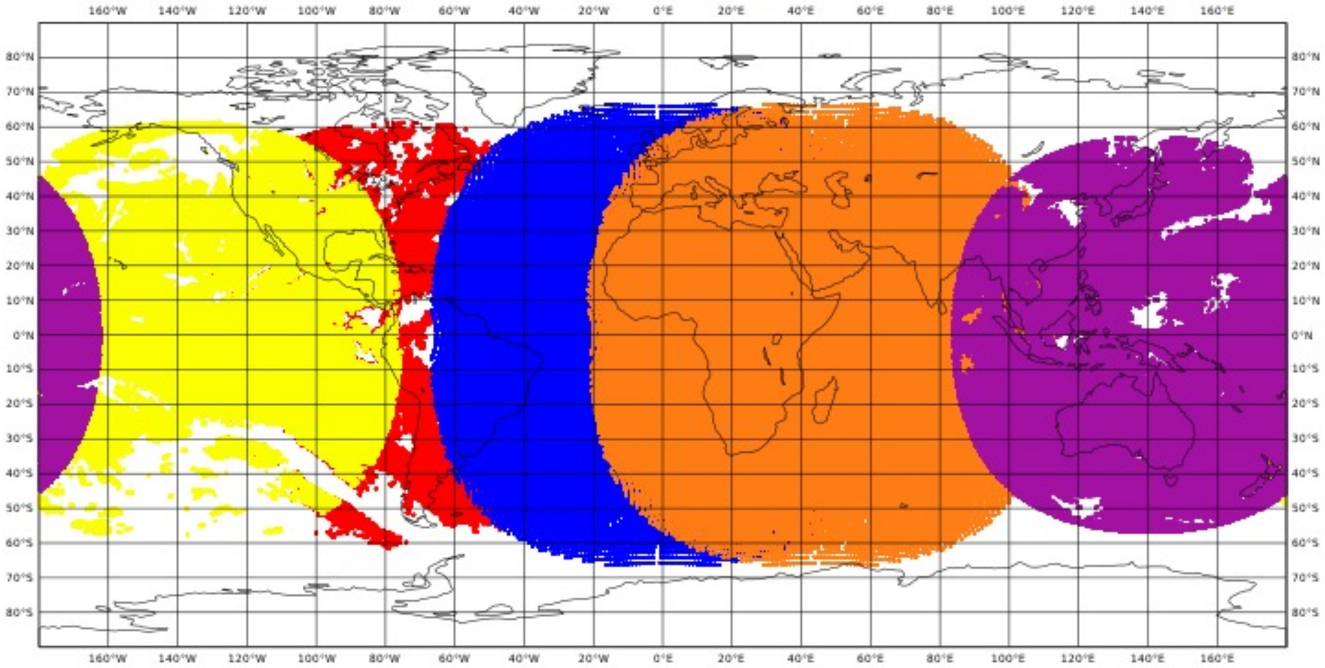
Introducing radiances from geostationary satellites

- 2 types:
  - Clear Sky Radiances (CSR) – Himawari-9, GOES-16, GOES-18
  - All Sky Radiances (ASR) – Met-9/10

    Combines CSR and totally overcast scenes

Monitored geostationary CSR/ASR 12Z 22nd April 2023

GOES-18 GOES-16 Met-10 Met-9 Himawari-9



- GOES-16/18 assimilated every 30 mins, others hourly
- Area averaged e.g. 48x48km for Met-10/9

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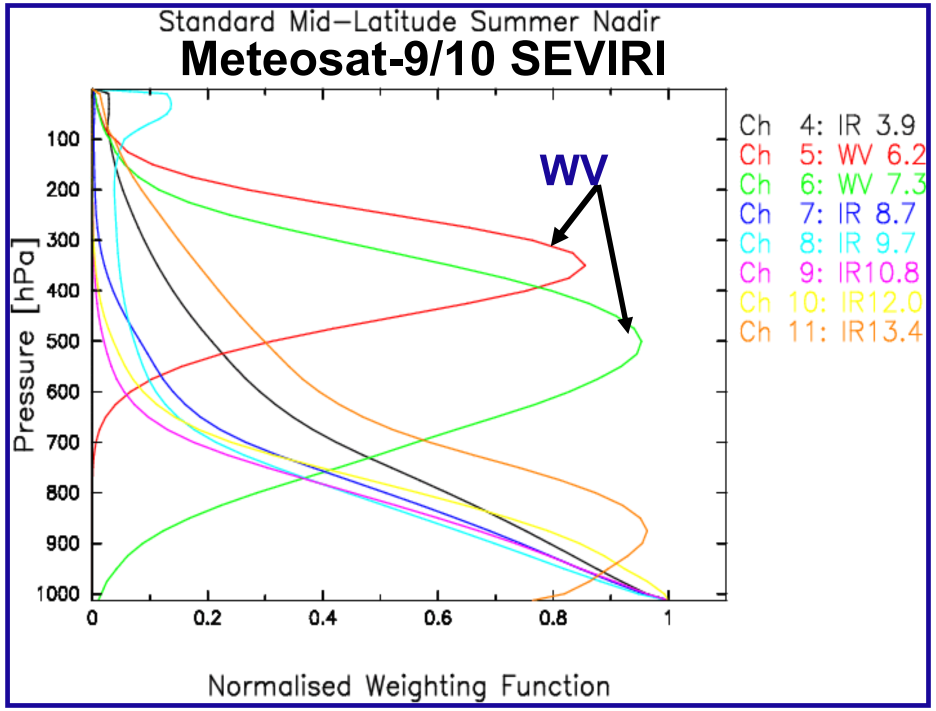
Use of GEO radiances at ECMWF

- 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



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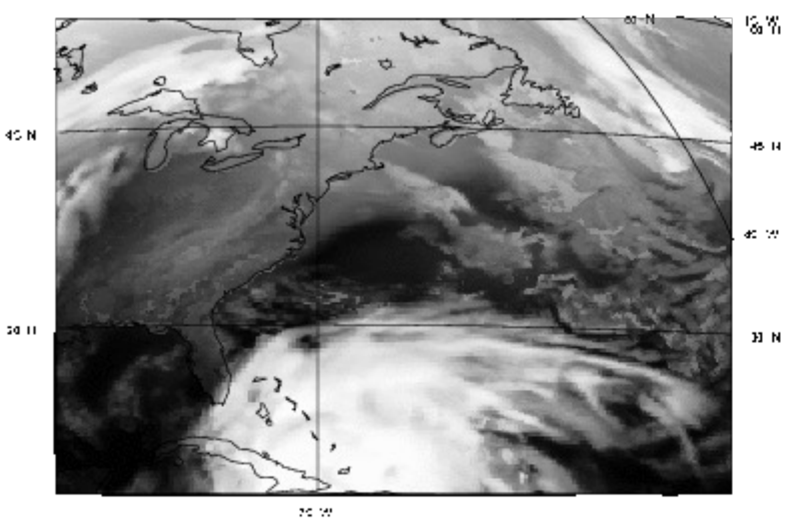
Data selection and thinning

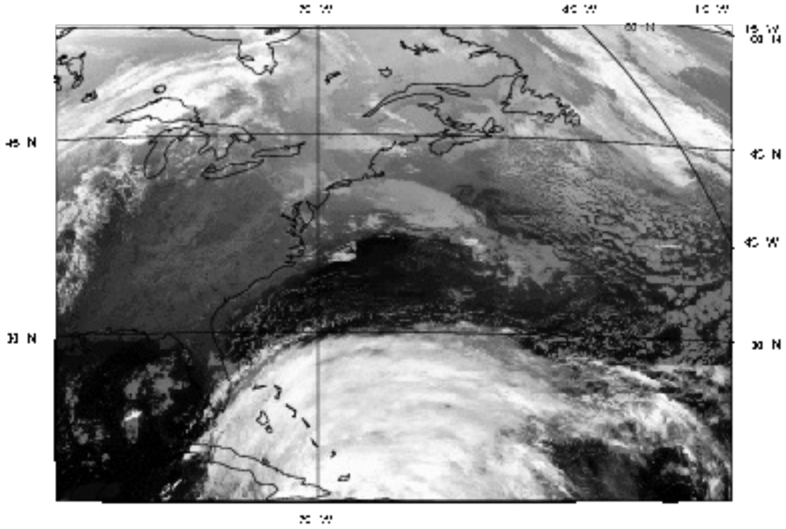
- Geographical rejection:
  - Satellite zenith angle > 74°
  - Over high terrain (1500m)
- Satellite specific rejections
- Cloud contamination
  - Threshold for number of clear pixels in CSR (land)
  - Window channel has large departures (3K) from model (sea)
- Thinning
  - 125km. (now SEVIRI 75km)

First guess check

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



CSR Observations (y)



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

$\lambda = 2.25; \sigma_o = 2\mathrm{K}$ (Observation error)

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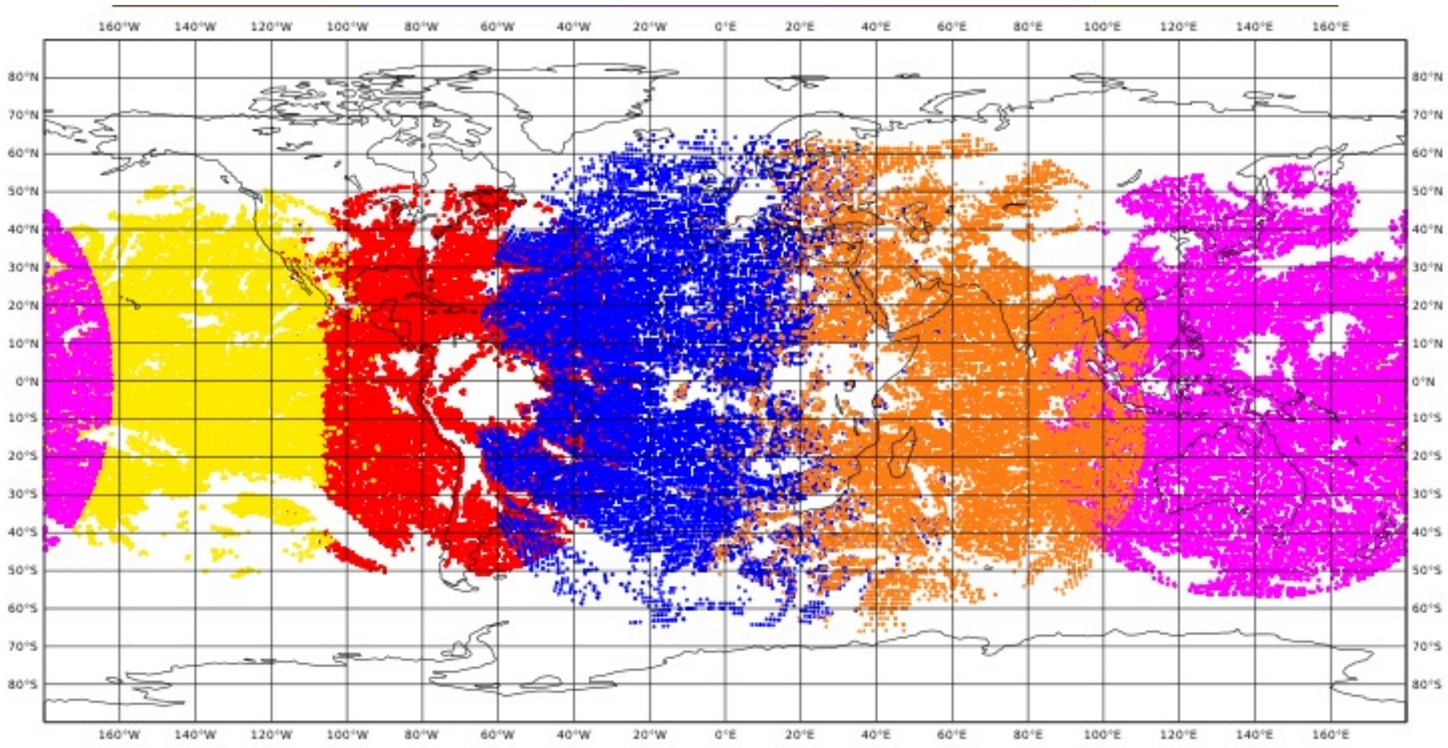
CSR/ASR sample coverage: active

- Example typical 12-hour data window (12Z 22nd April 2023)
  - Depending on satellite, ~ 2 – 11 million CSR/ASRs available
  - ~2-4% used in the assimilation

GOES-18 GOES-16 Met-10 Met-9 Himawari-9



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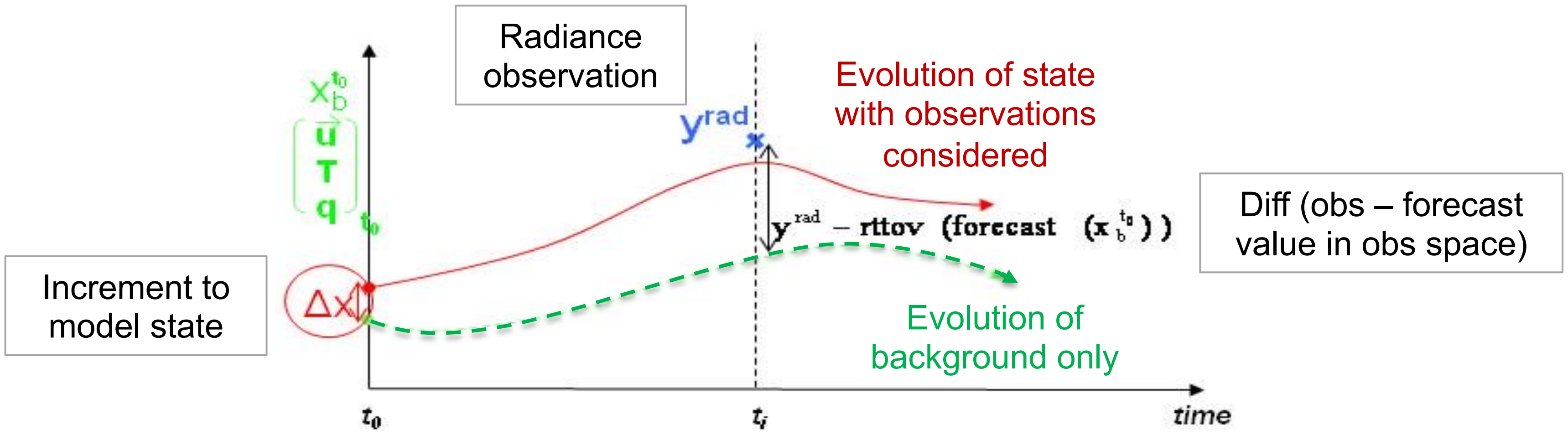
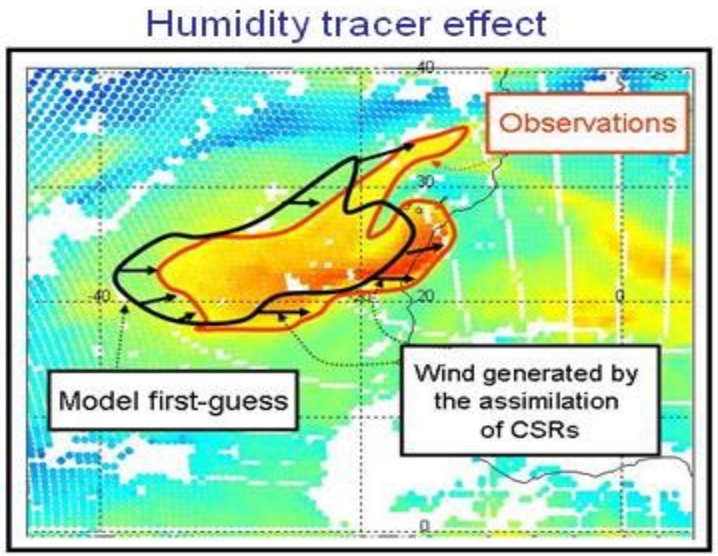
How do the radiances affect the wind field?

- 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

Assimilate humidity sensitive radiances → Generates humidity increments → (Model governing equations / Physical parameterisations) → Generates wind and temperature increments

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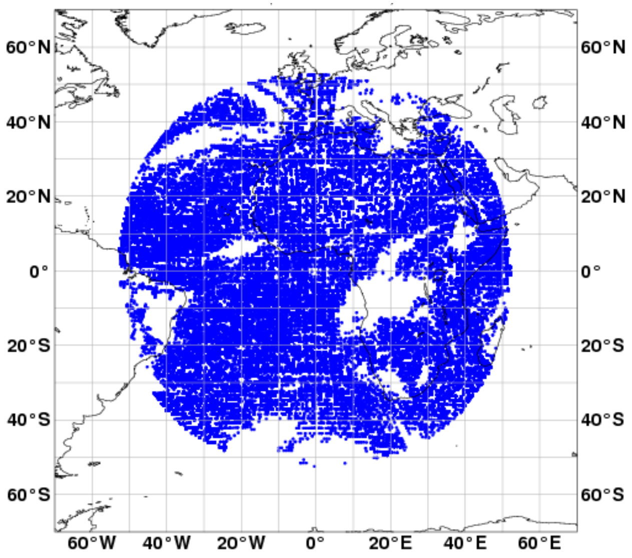
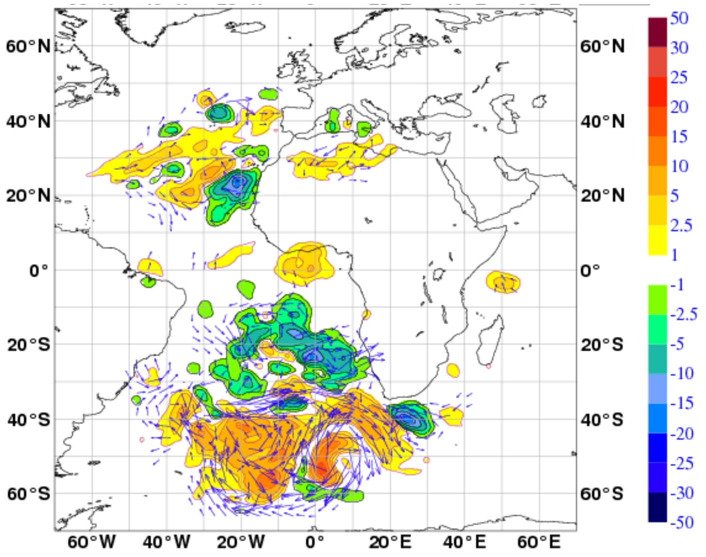
4D-Var tracing vs. AMVs

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

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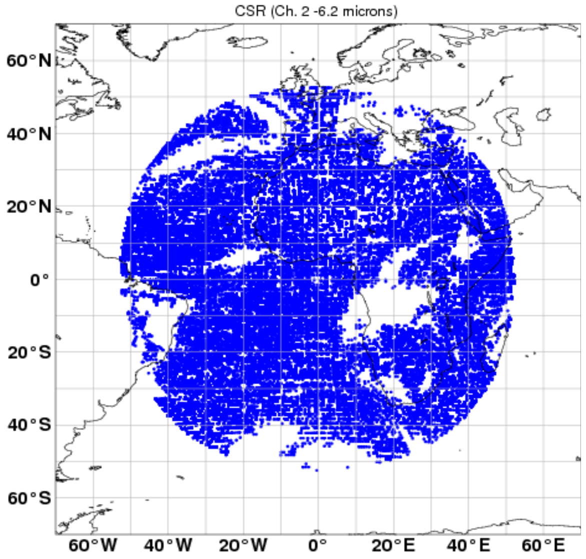
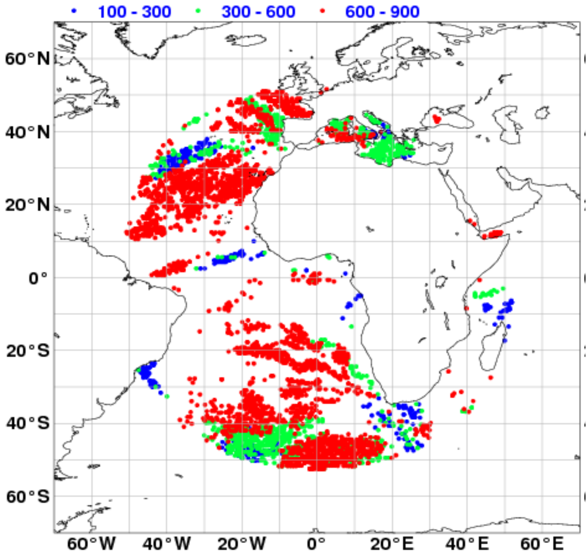
A closer look at the impacts

- 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

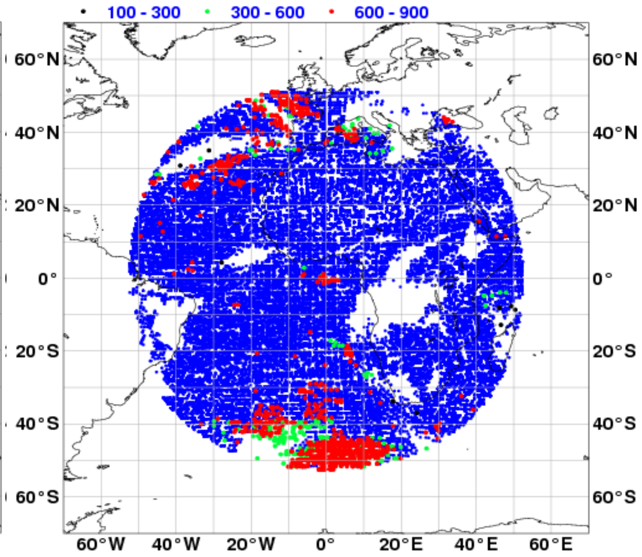
Met-9 CSR



Met-9 Overcast



Met-9 ASR

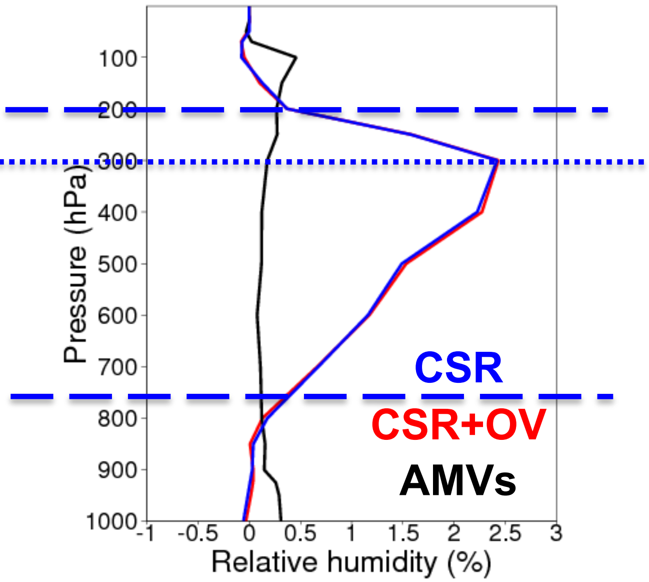


Impact on analysis: humidity increments from radiances

No significant
AMV impact

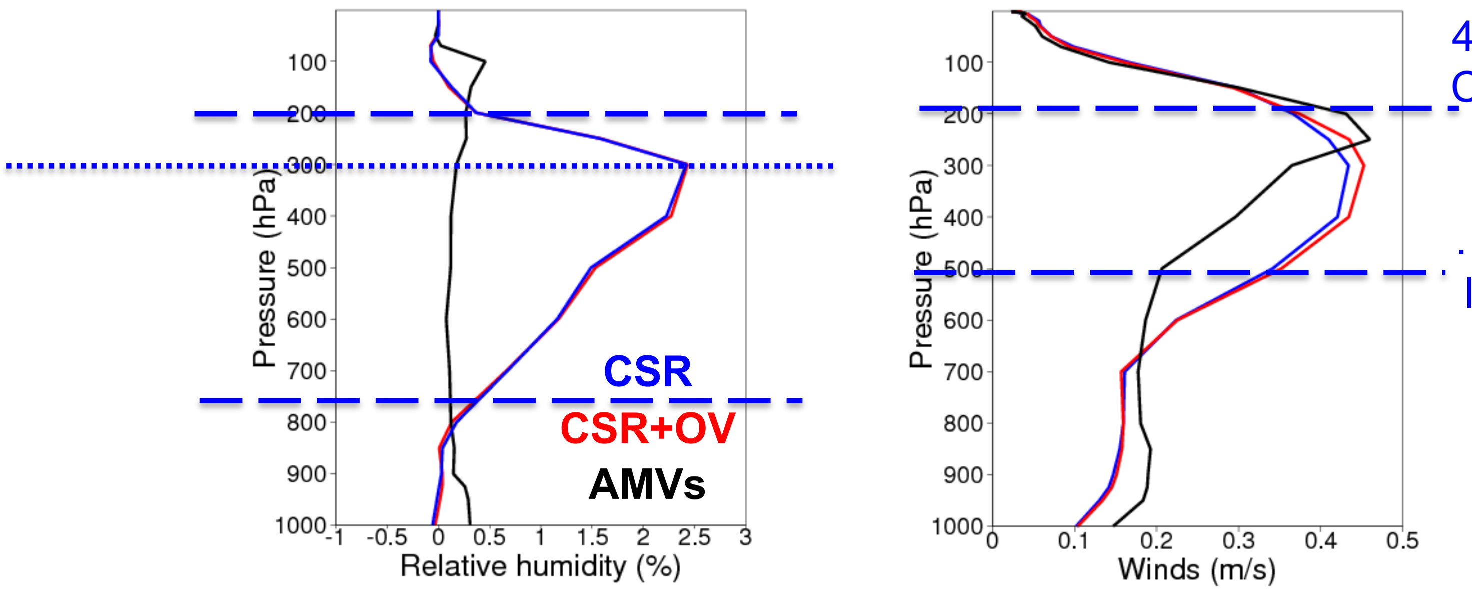
Peak sensitivity
of water vapour
channel

Large vertical
extent



Diff (expt – ctrl) RMS
humidity increments

Impact on analysis: wind increments from AMVs and radiances



Diff (expt – ctrl) RMS humidity increments

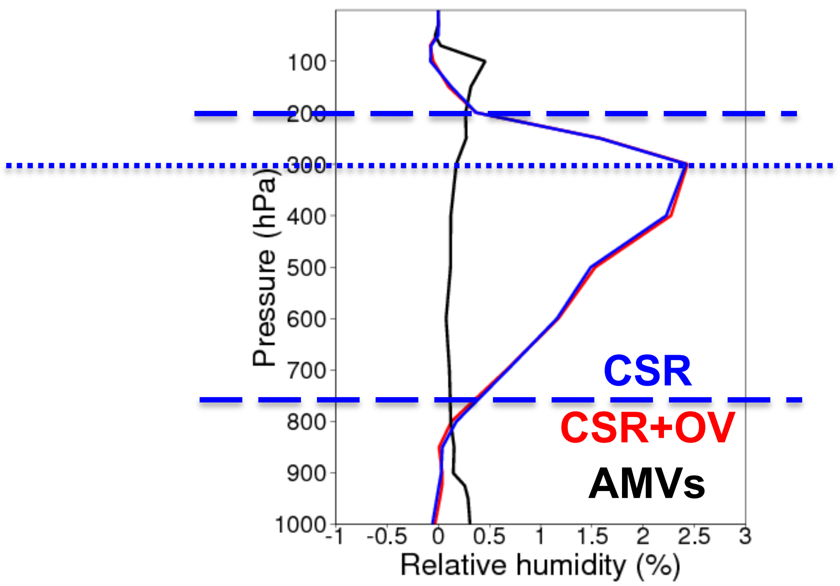
Diff (expt – ctrl) RMS wind increments

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

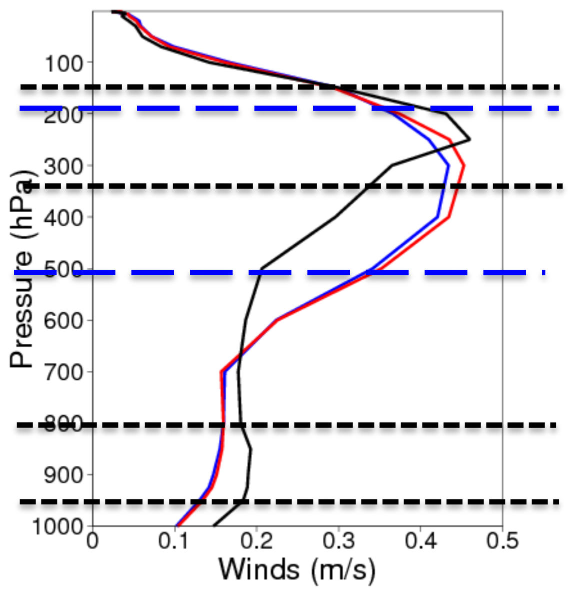
Overcast radiances add wind information at similar height to AMV

ECMWF

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

Root mean square analysis error for cycle j

Analysis values at grid point from operations

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

No. of grid points in Meteosat disc area

Analysis values at grid point

Sum over all cycles

Using experiment analysis

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

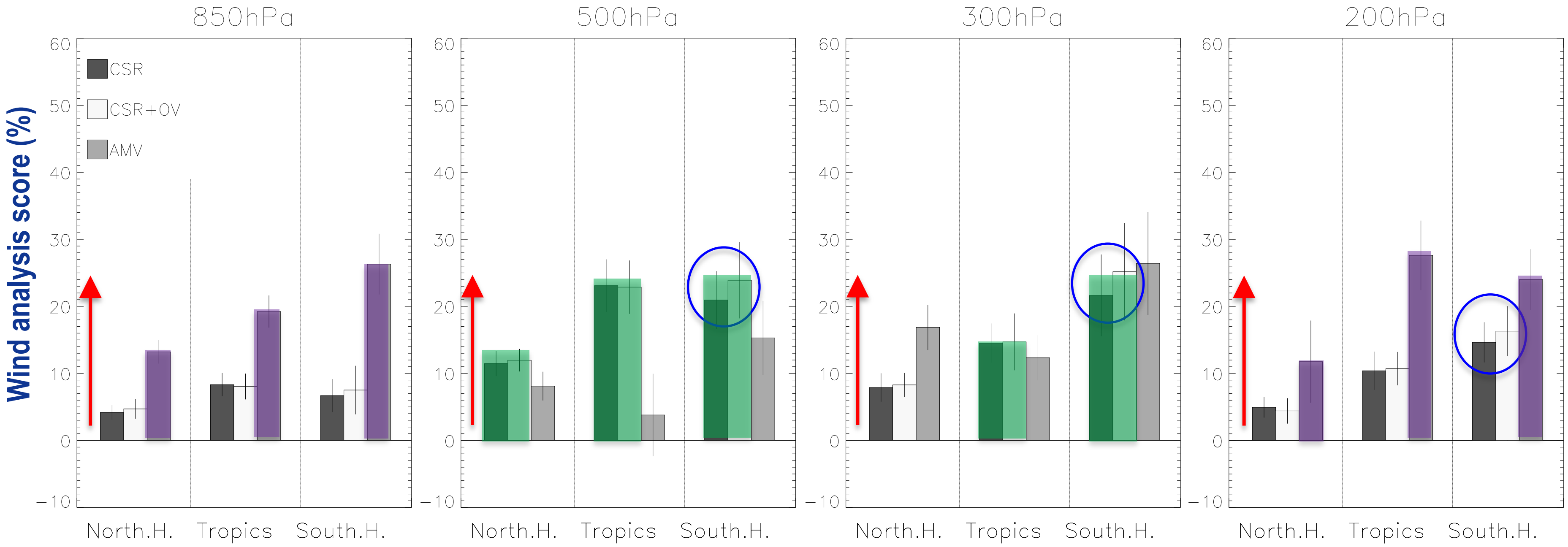
Using control (‘base’) analysis

ECMWF

Wind analysis scores

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

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



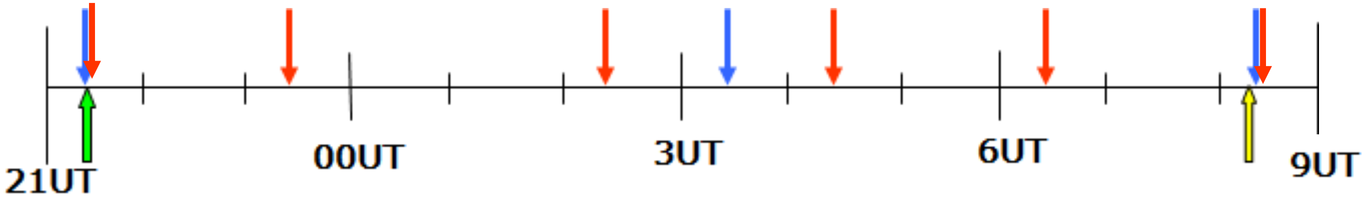
Positive impacts throughout troposphere

ASR similar to CSR, better in SH

ECMWF

Frequency of assimilated images

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



12 images

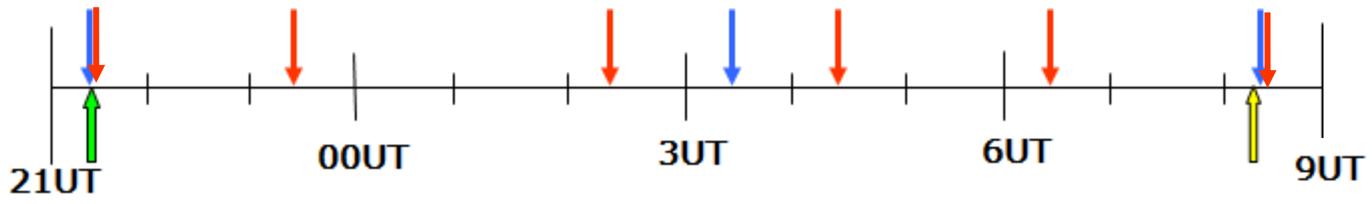
6 images

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

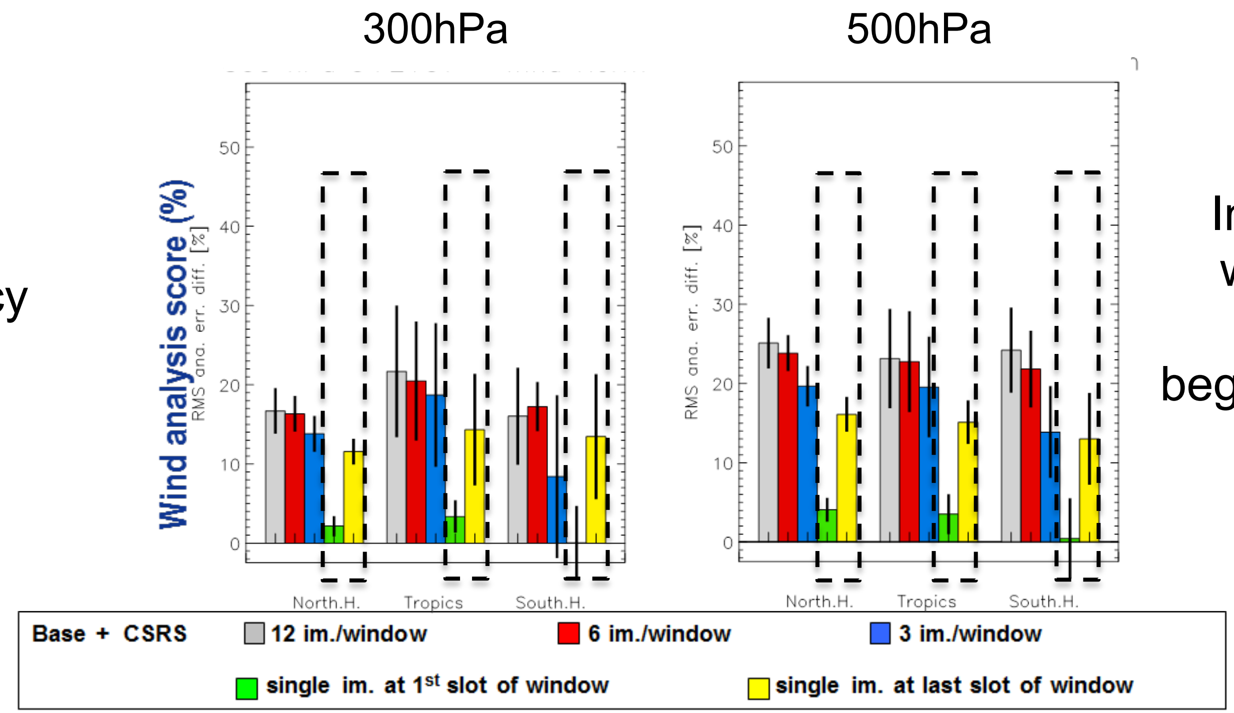
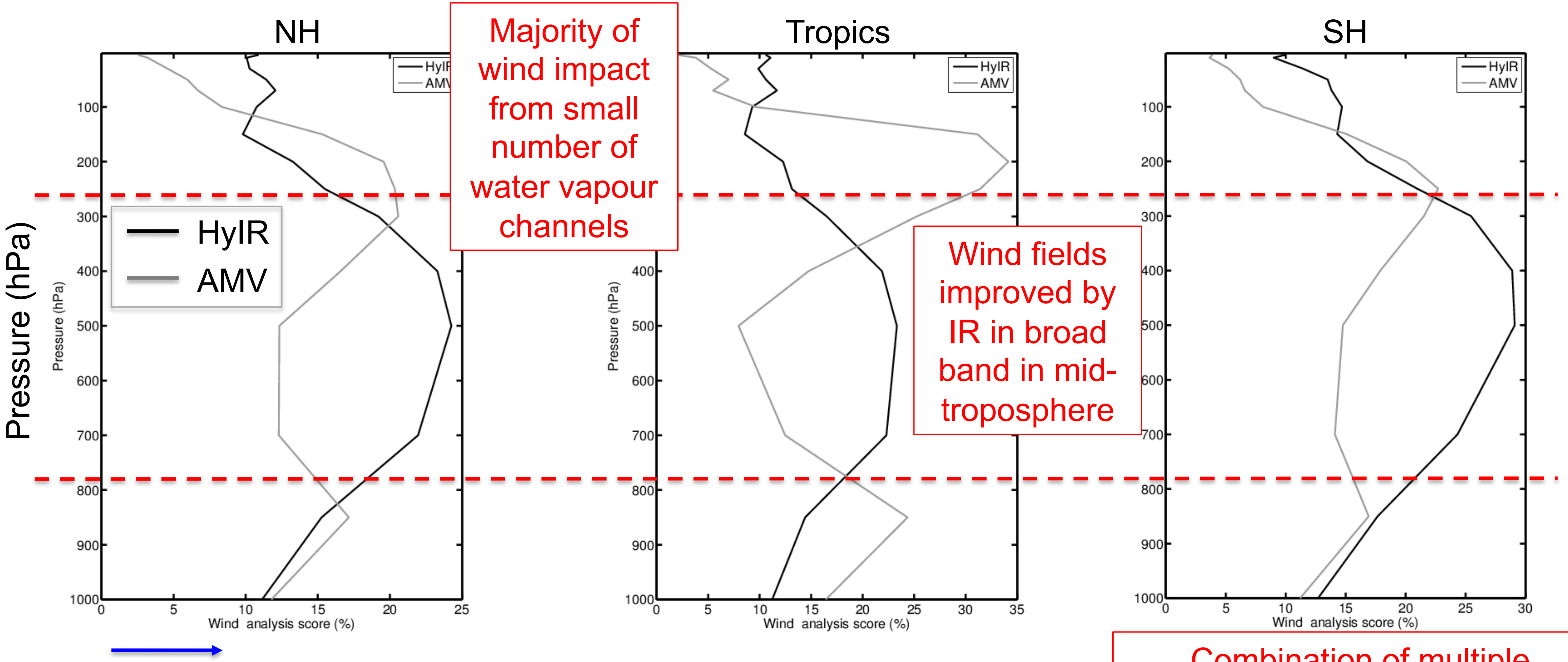


Image at end of window scores better than at beginning of window

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



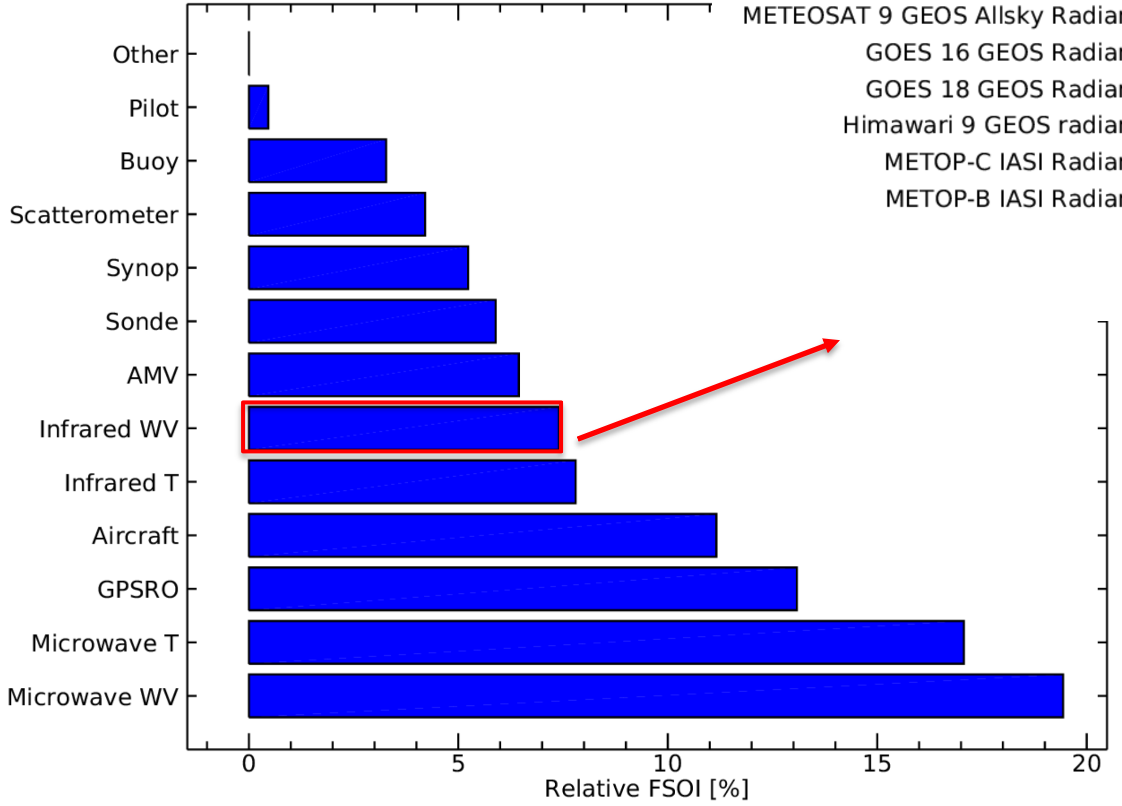
Improvement

Wind analysis score (%)

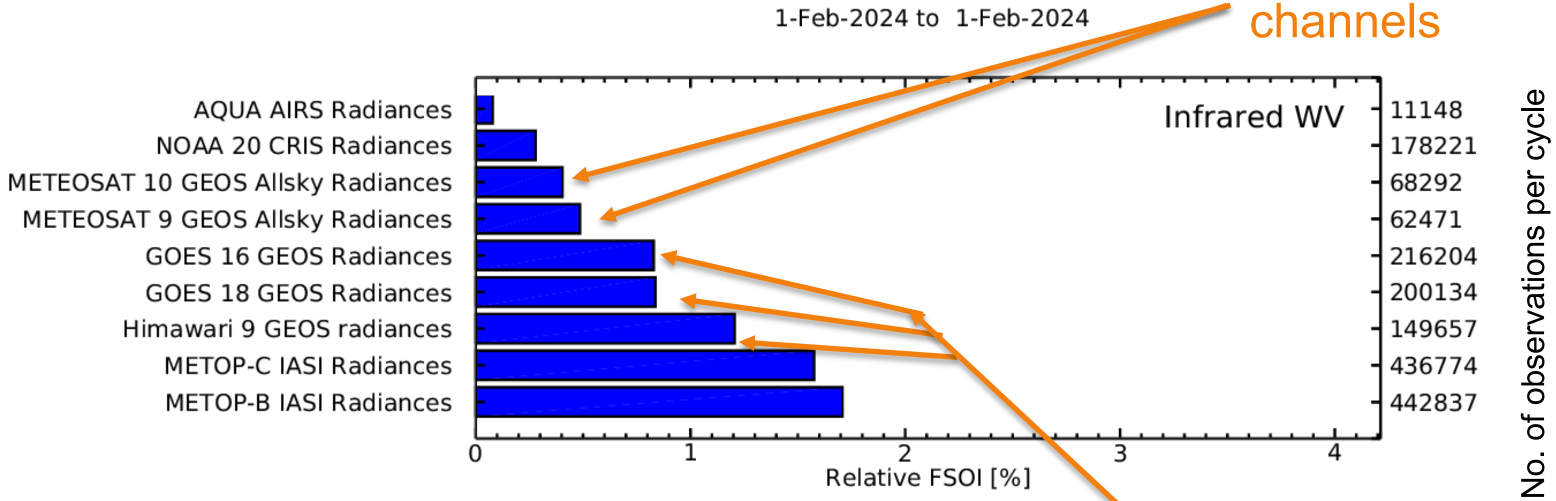
Combination of multiple satellites (IASI x 2, AIRS, CrIS) improve spatial/temporal sampling

Forecast system performance

February 2024



Forecast Sensitivity to Observations (%)



Met-9/10 have 2 WV channels

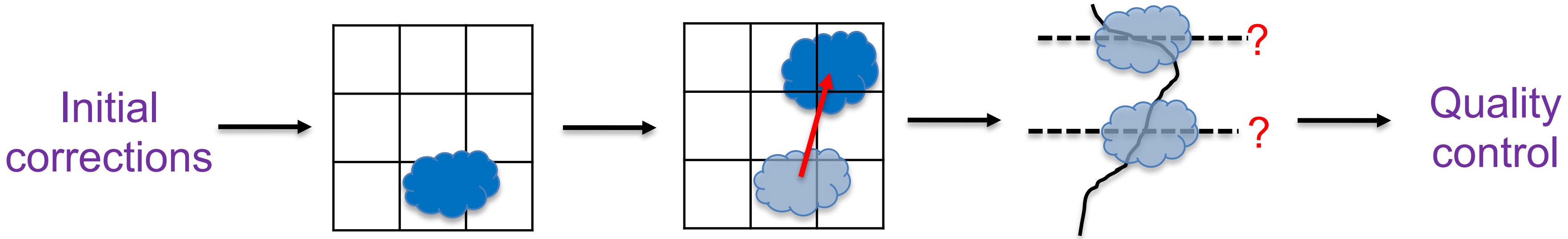
Forecast Sensitivity to Observations (%)

GOES-16/18/Himawari-9 have 3 WV channels

Measures reduction in 24hr forecast error due to each source

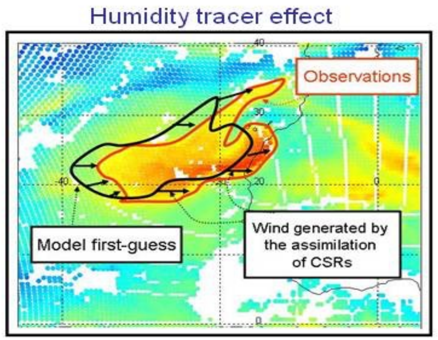
Summary and a look to the future

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 – new generation of imagers

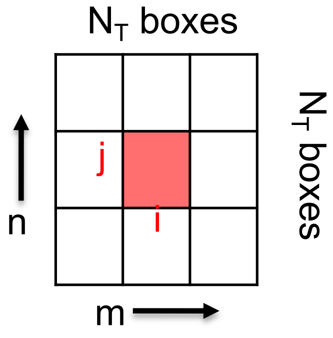
- Increases in spatial resolution
  - FCI – finer resolution than SEVIRI
  - Better cloud detection?
  - How to use more AMVs – superobbing? Dynamic thinning? Better handling of correlations?
- Increases in temporal resolution
  - E.g. GOES-16/18 / FCI – use every 10 mins?
  - Constrain error growth in 4D-Var?
- Hyperspectral instrument in geostationary orbit
  - “3D winds” tracking temp/humidity/ozone profiles
  - MTG-IRS

Thank you for listening!
Any questions?

Further information

Pattern matching: how are the features tracked for AMVs?

- Commonly based on cross-correlation statistics

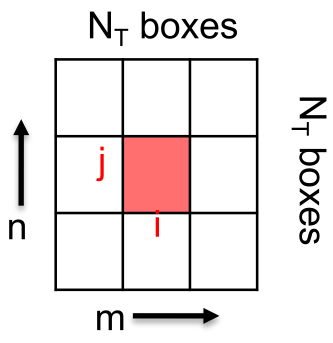


Coefficient for box at location (i, j)

$$r_{ij} = \frac{\text{Covariance between target and search counts}}{\text{Standard deviation of target area counts} \times \text{Standard deviation of search area counts}}$$

Pattern matching: how are the features tracked for AMVs?

- Commonly based on cross-correlation statistics



Pixel counts in target area at (m,n)

Mean target area counts

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

Covariance between target and search counts

Mean search area counts

Coefficient for box at location (i, j)

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

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:

Diff (cloudy – clear) actual radiances CO_2 / Diff (cloudy – clear) actual radiances IR window

$$\frac{R(CO_2) - R_{c1}(CO_2)}{R(IRW) - R_{c1}(IRW)} =$$

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

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

Diff (cloudy – clear) actual radiances CO_2
/ Diff (cloudy – clear) actual radiances IR window

$$\frac{R(CO_2) - R_{cl}(CO_2)}{R(IRW) - R_{cl}(IRW)} = \frac{nE(CO_2)[R_{bcd}(CO_2, P_c) - R_{cl}(CO_2)]}{nE(IRW)[R_{bcd}(IRW, P_c) - R_{cl}(IRW)]}$$

Cloud fraction x cloud emissivity

Diff (cloudy at varying cloud pressure – clear) estimated radiances CO_2
/ Diff (cloudy at varying cloud pressure – clear) estimated radiances IR window

1. Water vapour intercept: uses same method as CO_2 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

ECMWF

Situation dependent observation errors: equation for error in height

Diff wind component (model level – at observation location)

Height error

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

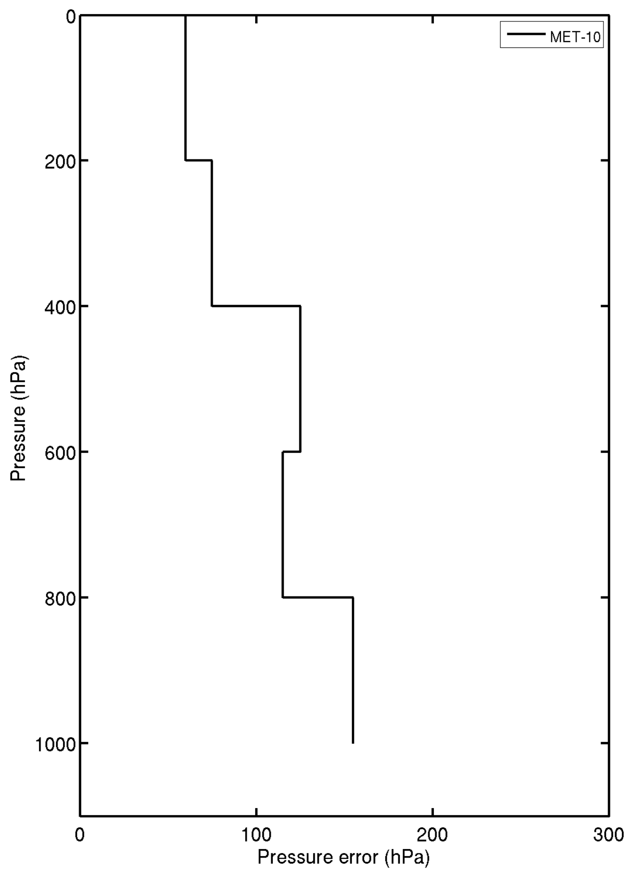
Weight per model level, i

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