Atmospheric Motion Vectors: Past, Present and Future

ECMWF Annual Seminar, Sep 2007

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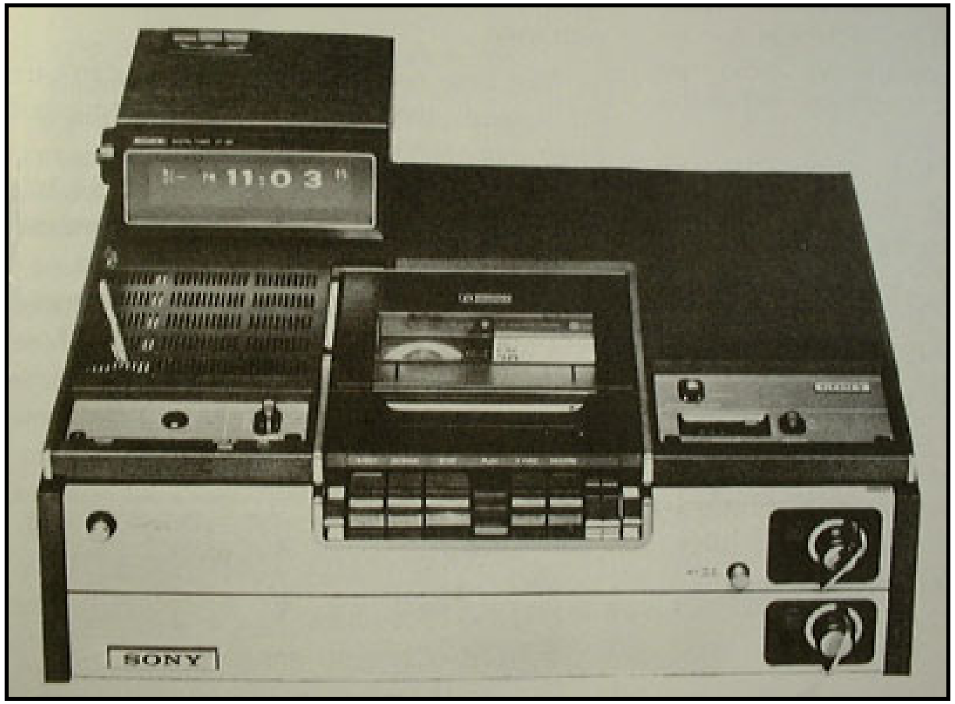
Thanks to Howard Berger, Chris Velden, Niels Bormann, Claire Delsol, Jo Schmetz, Dave Santek, Nancy Baker, Sakari Uppala, Jaime Daniels, Jörgen Gustafsson, Kris Bedka and Steve Wanzong for providing material for this talk

One of the original satellite observations



But …

They are not done and dusted

AND

They are not obsolete

During this talk I will demonstrate

Why they are still useful

AND

What those in the field are doing to improve the impact of atmospheric motion vectors (AMVs) in NWP

Go by many names……

Atmospheric motion vectors (AMVs)

Satellite winds

Satwinds

Cloud track winds

Cloud motion winds

Feature track winds

NOT to be confused with

Scatwinds

Windsat

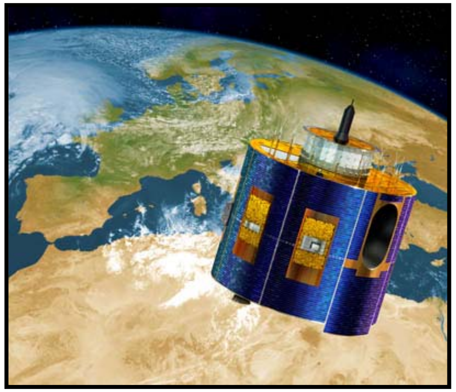
What are they?

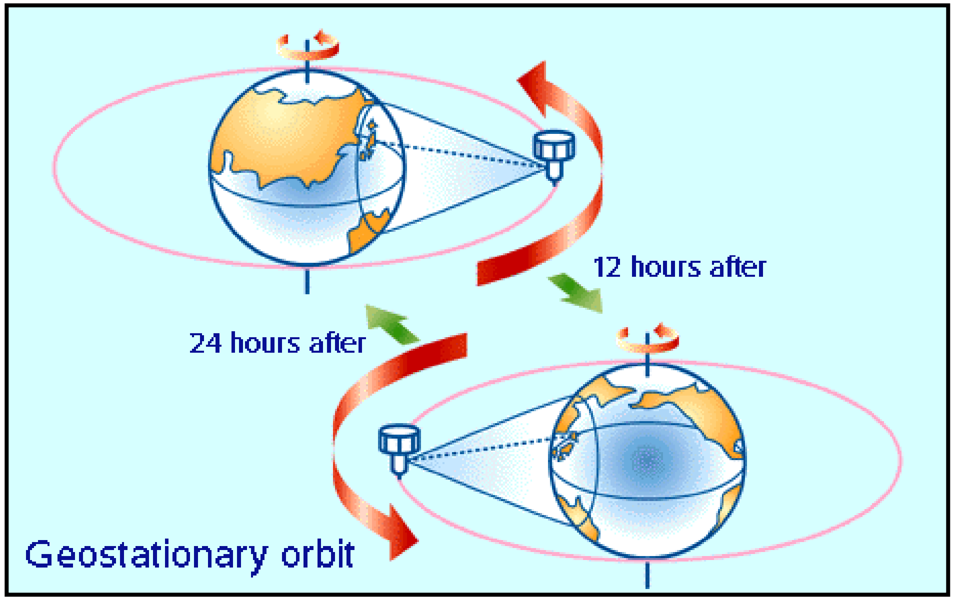
Produced by tracking clouds or gradients in water vapour through consecutive satellite images

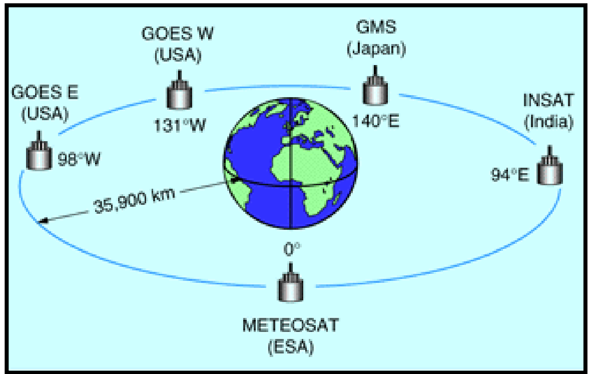
Courtesy of EUMETSAT

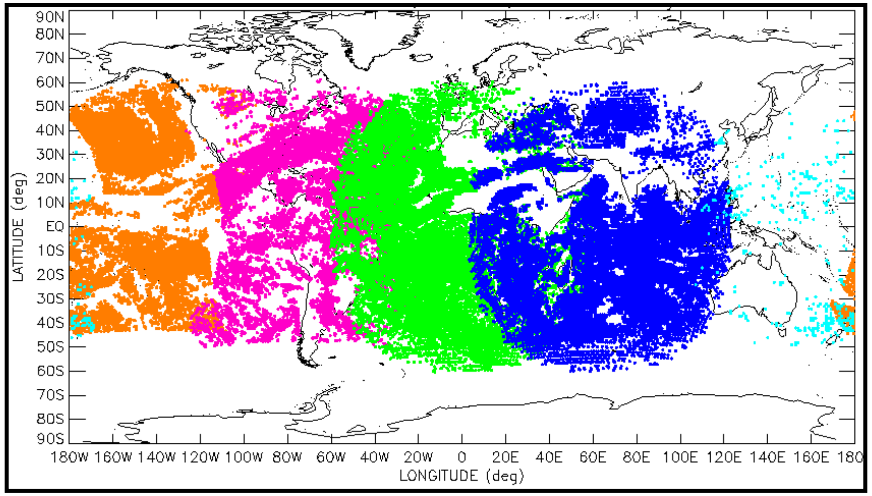
Satellites

AMVs are traditionally produced using geostationary satellite imagery

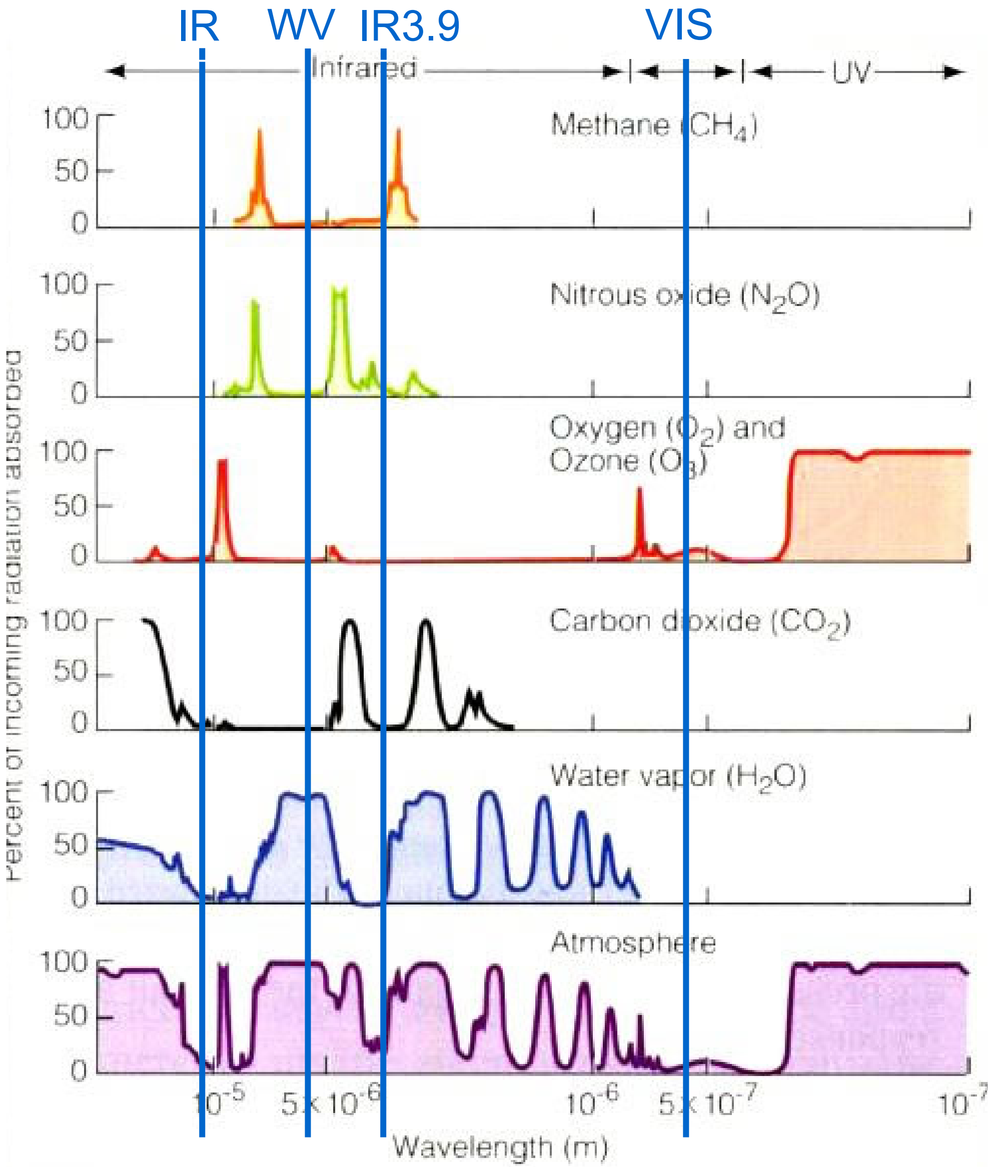






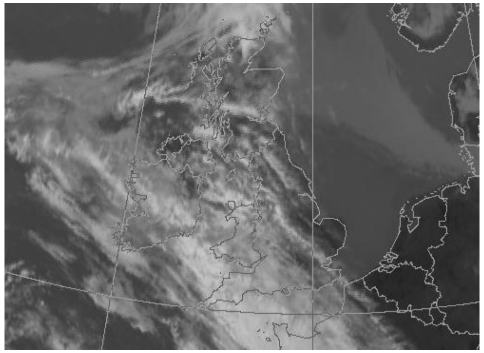


Channels



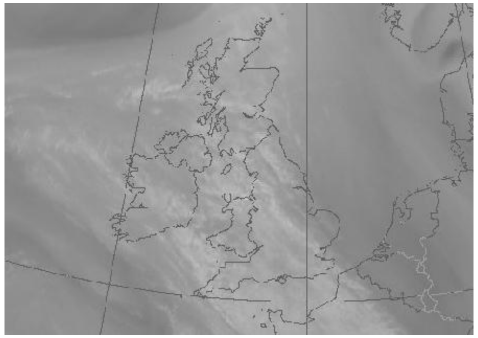
IR window ~ 10.8µm

clouds



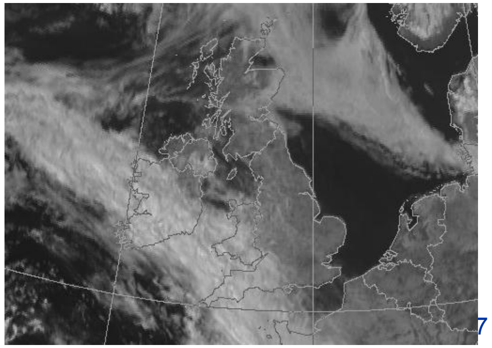
WV absorption ~6.7µm

clouds and clear sky



VIS ~0.6µm

clouds



How are they produced?

Initial corrections (image navigation etc.)

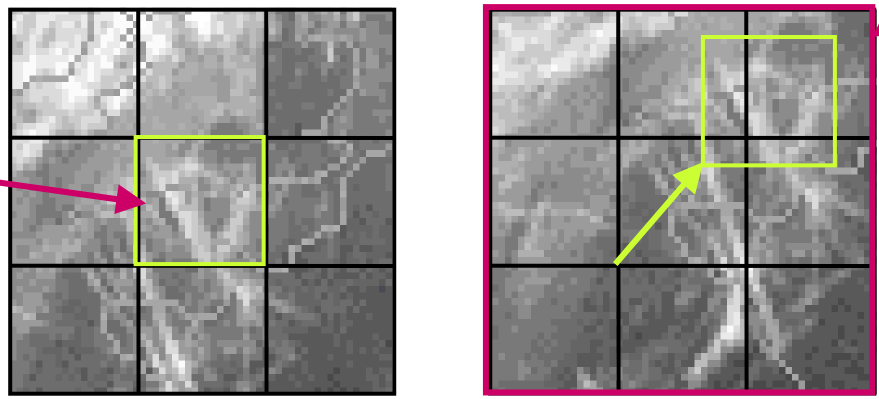
Search Area

80 x 80 pixels centred on target box

Target Box / Tracer

24x24 pixels

Pixel – 3 km



T T + 15 min

Infrared Imagery

New location determined by best match of individual pixel counts of target with all possible locations of target in search area (use cross-correlation in Fourier domain).

Need to assign a height to the derived vector

AMVs as a measure of the wind

Schmetz & Nuret (1989) stated

“The AMVs could only give an unbiased estimate of the winds if clouds were conservative tracers randomly distributed within and floating with the airflow. “

Who produces the AMVs?

Currently produced by:

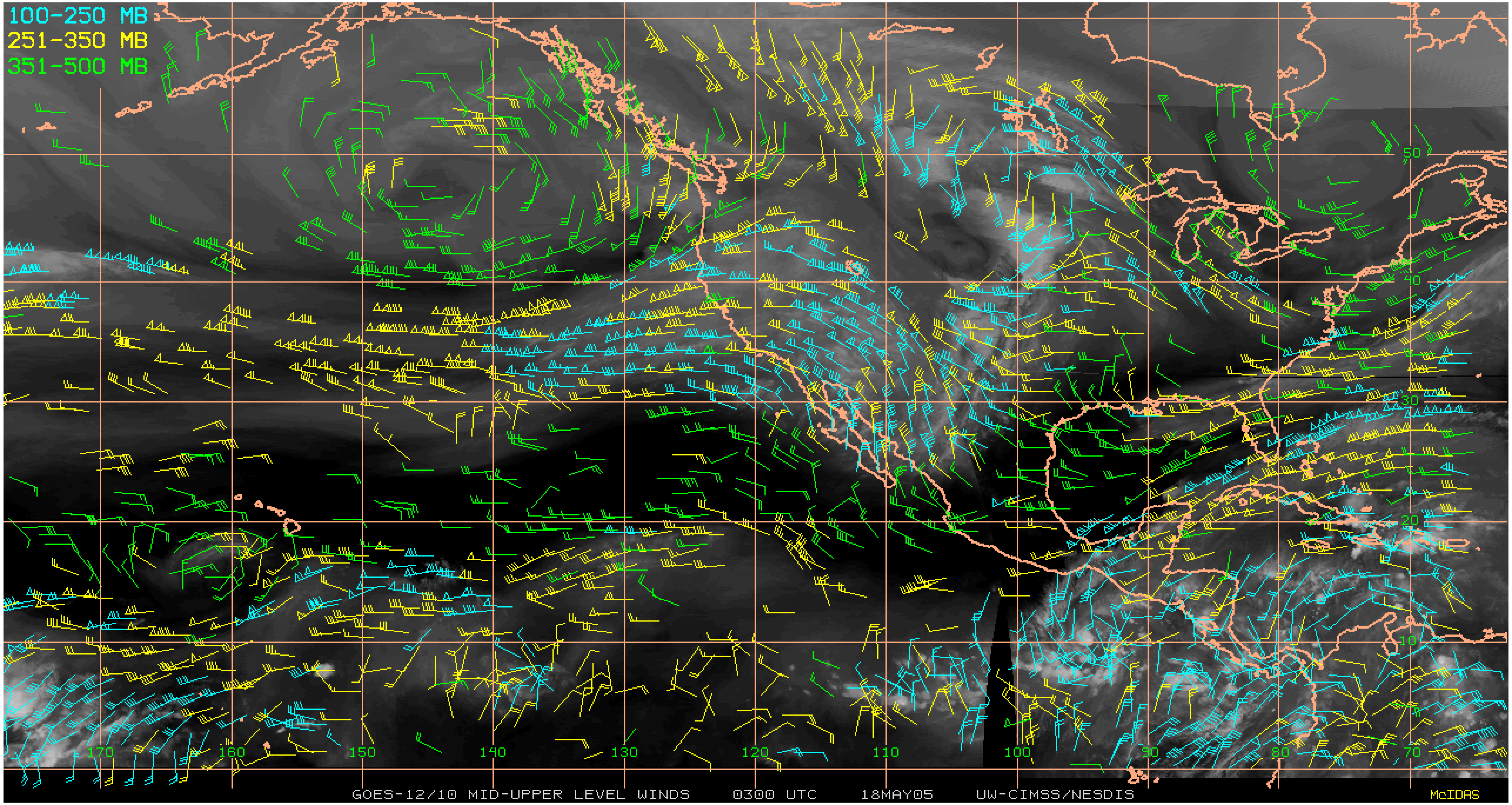
- EUMETSAT in Europe (Meteosat-9, Meteosat-7)
- NOAA/NESDIS in the USA (GOES-11, GOES-12, Aqua, Terra)
- CIMSS in the USA (NOAA 15-18)
- JMA in Japan (MTSAT-1R)
- IMD in India (Kalpana, INSAT-3a)
- CMA in China (FY-2C, FY-2D)
- CPTEC in Brazil (GOES-10)

——	Geostationary satellites
——	Polar satellites

Future

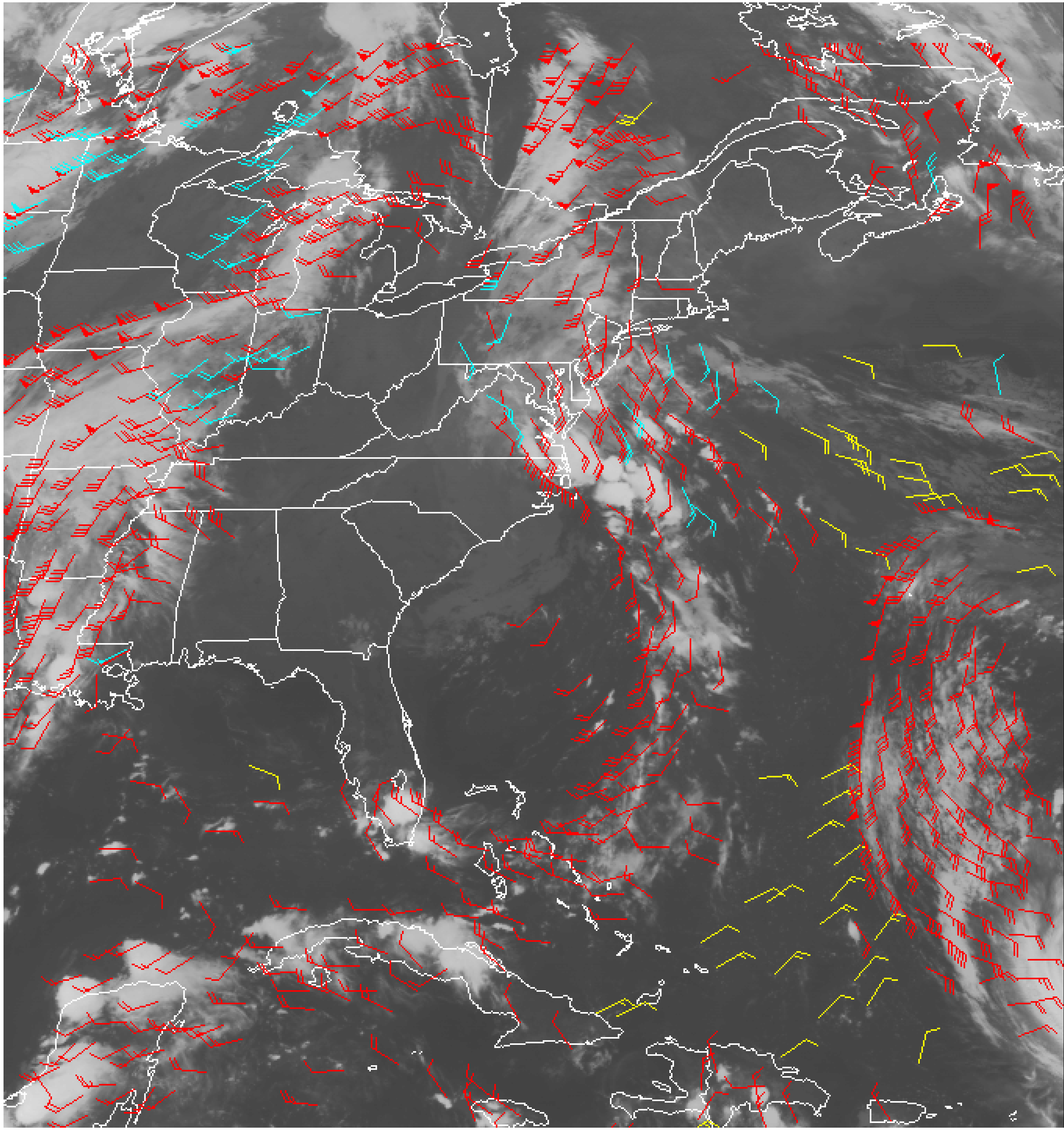
- KMI in South Korea (COMS)

What does the data look like?



Real-time visualisation available from http://cimss.ssec.wisc.edu/tropic2/

Hurricane Isabel



Hourly GOES-12 IR Cloud-Drift Winds

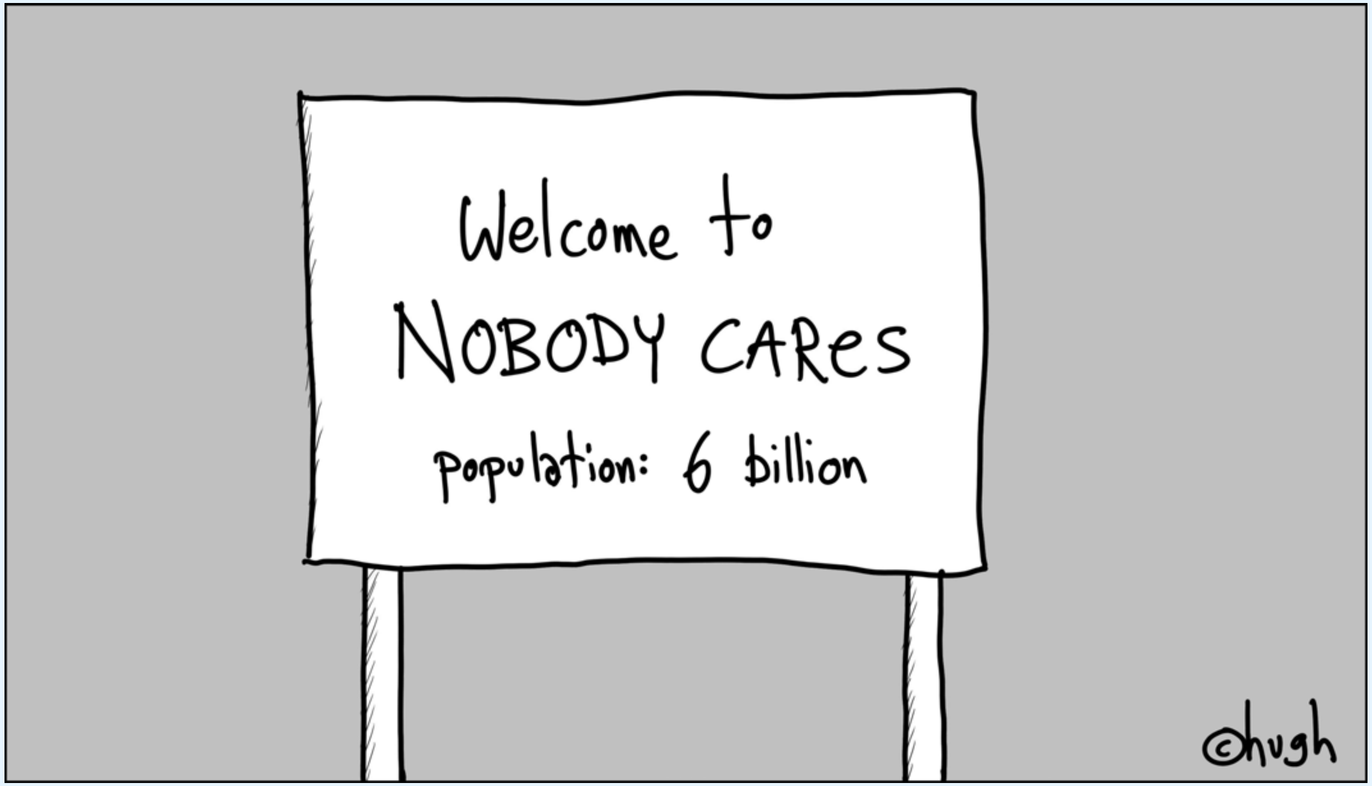
Sept 13-22, 2003

From Jaime Daniels' talk at IWW8

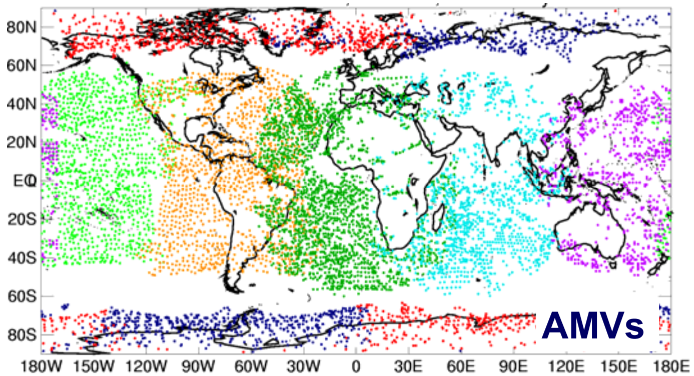
Talk Outline

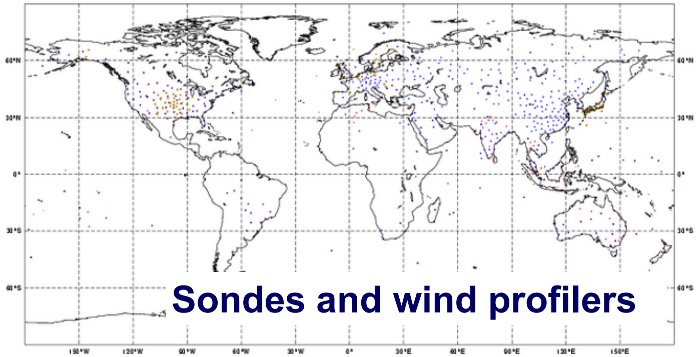
1. **Why do we care?**
2. **The Past – key events**
3. **The Present – current work**
4. **The Future – where do we go from here?**

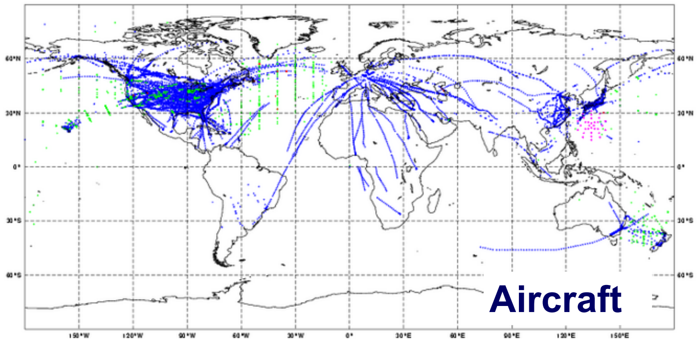
Why do we care?



Why do we care?





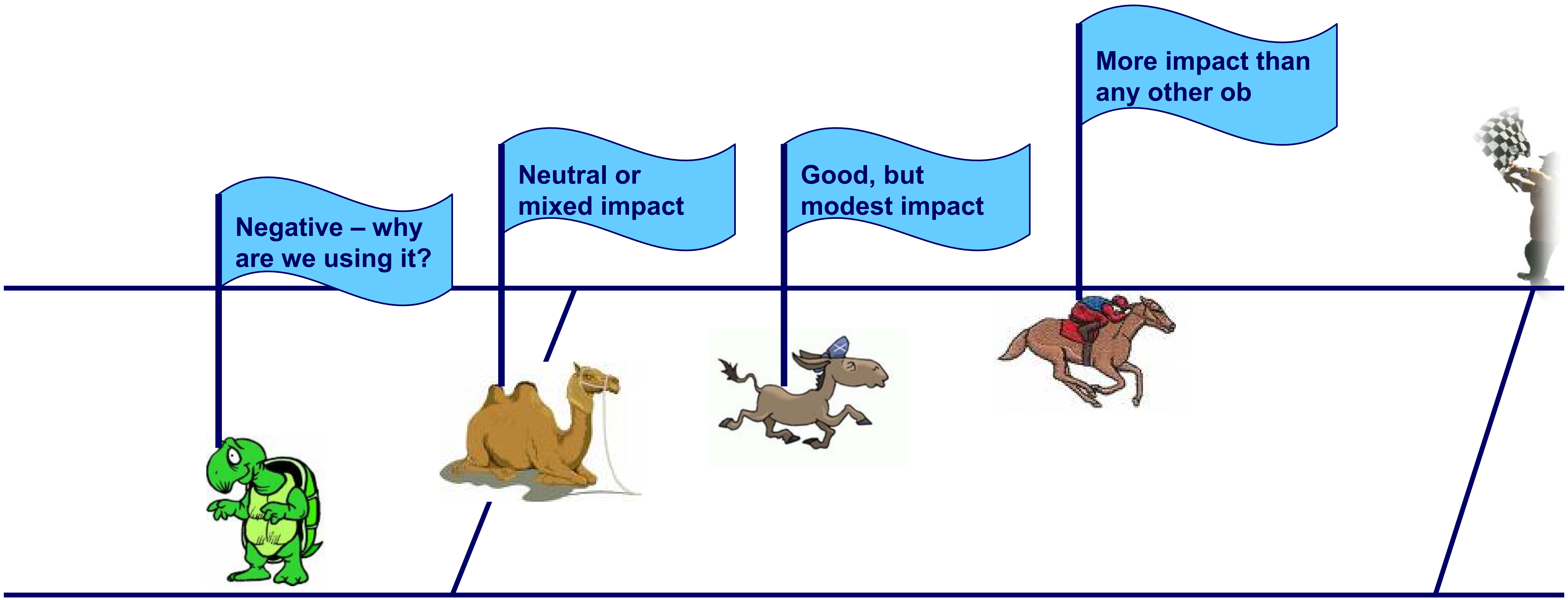


For best results, models require information on both the mass field and the wind field.

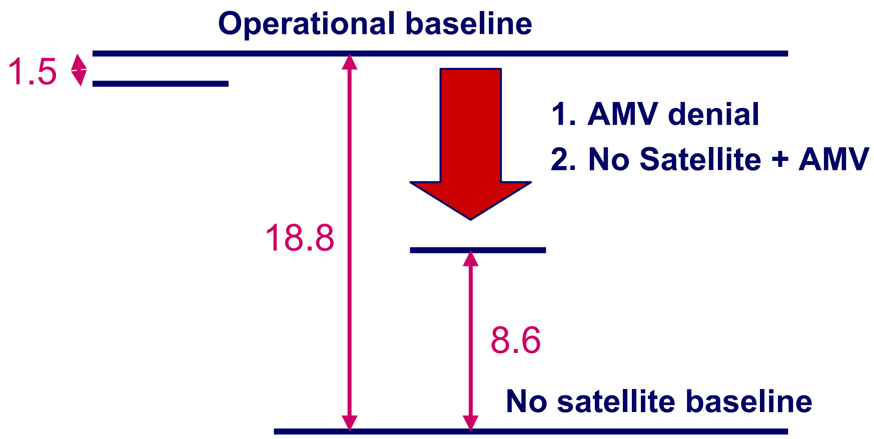
AMVs are the only observation type to provide good coverage of upper tropospheric wind data over oceans and at high latitudes.

For the AMVs each dot represents a single level wind not a wind profile

What is the impact on forecasts?

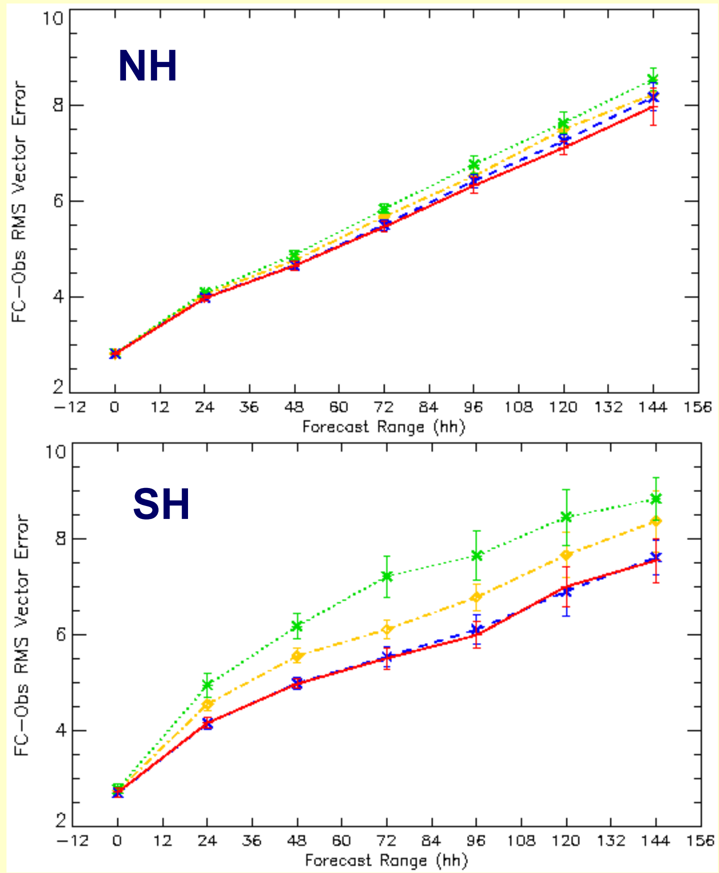


AMV impact

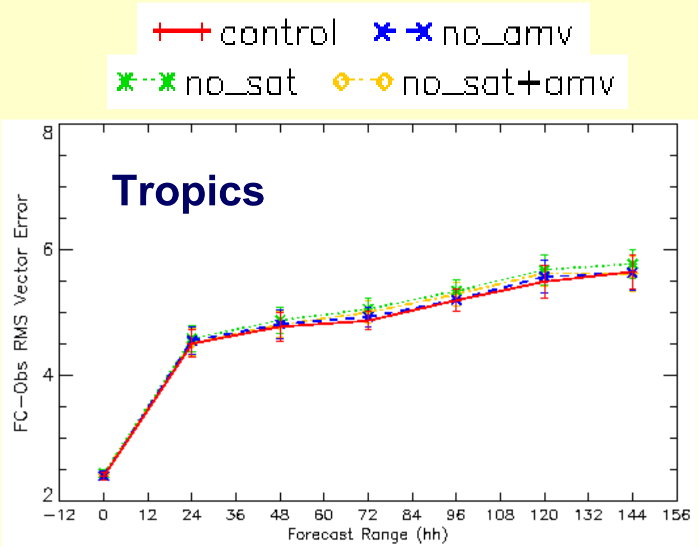


Answer

AMVs improve forecasts, although impact is modest compared to ATOVS radiance data.



wind at 850 hPa : Sonde obs



Tropical cyclone track impact

Several studies have shown the benefit of AMV data on tropical cyclone track forecasts (Goerss & Hogan, 2006; Soden et al., 2000).

Forecast track error from a 2007 CIMSS study by Howard Berger

Forecast Time (hrs)	12	24	36	48	60	72	84	96	108	120
CNTRL (km)	82.3	127.3	161.1	191.2	230.8	278.0	322.5	369.0	413.1	450.2
NO GOES AMV (km)	85.9	133.5	172.2	201.2	234.7	299.5	361.4	413.0	488.0	567.7
% Improvement	4.3	4.8	6.9	5.2	1.6	7.7	12.0	12.0	18.1	26.0
Number of Cases	81	79	69	62	55	54	49	45	40	34

- T126 28-Levels
- GFS and assimilation (SSI) run from July 28th - October 28th 2005
- Control: All operational observations assimilated
- Experiment: GOES IR/WV AMVs removed

Summary of why we care

1. Access to information on mass and wind field is important.
2. AMVs provide global wind coverage and can be the only source of tropospheric wind data over some areas of ocean and at high latitude
3. Positive impact on forecast accuracy, but less so than some other observations e.g. ATOVS radiances
4. Can be important for improving tropical cyclone track forecasts

The Past

The Past

Met Office

TIROS-1 launch

Ted Fujita

Vern Suomi (seated)

ATS-1 image

1960s	1970s	1980s	1990s	2000s

1960
First TIROS
polar imagery
shows potential

1966
ATS1
geostationary
spin-scan cloud
camera

1979
AMVs from 5
geostationary
satellites for FGGE

Increasing

-automation

-image resolution

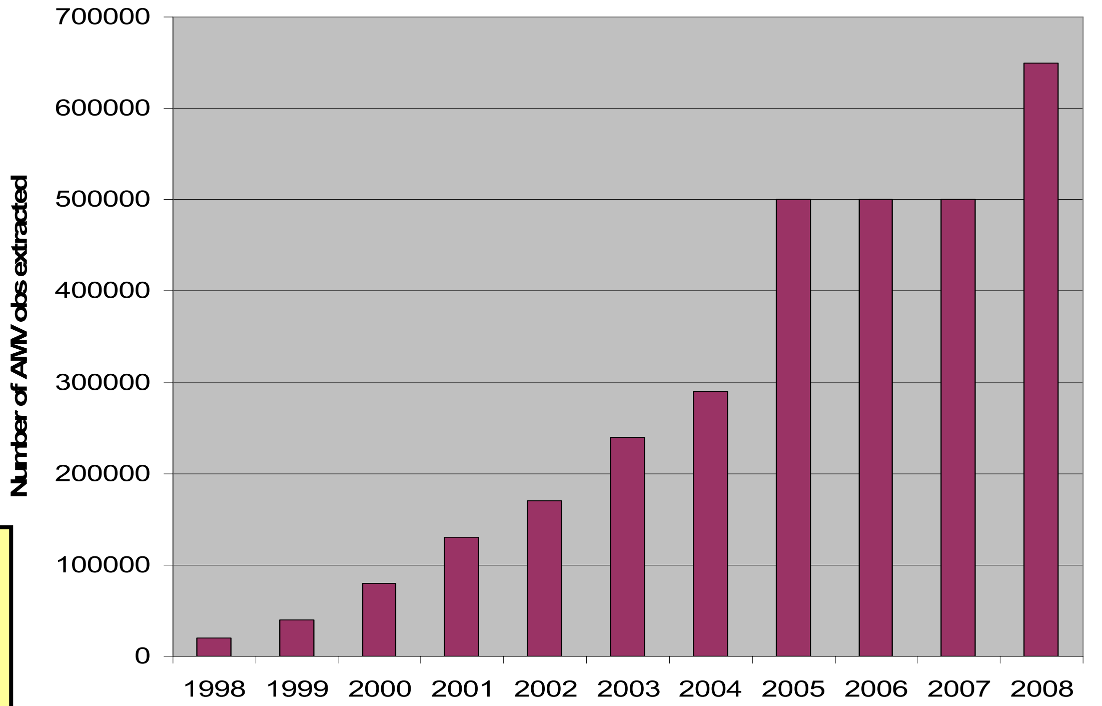
-channels (VIS, WV)

lead to increasing data volume and coverage

2002
Routine
production of
polar winds
from MODIS
imagery

Increasing data volumes

Number extracted in a typical 12z update run in June of each year



1998

Geostationary

Meteosat-7
Meteosat-5
GOES-8
GOES-9
GMS-5
INSAT

Polar

None

x30 in 10 years

2007

Geostationary

Meteosat-9
Meteosat-7
GOES-11
GOES-12
MTSAT-1R
INSAT-3a
Kalpana
FY-2C

Polar

Terra
Aqua
NOAA-15
NOAA-16
NOAA-17
NOAA-18

Key changes

Satellite imager improvements

- Shorter image intervals (15 min for Meteosat Second Generation, 5-10 min shown to be optimal for cloud tracking)
- Improved pixel resolution (1 km, although 3-4 km more typical)
- More channels e.g. WV, IR3.9, CO_2 – useful for tracking and height assignment (semi-transparency corrections).

Derivation improvements

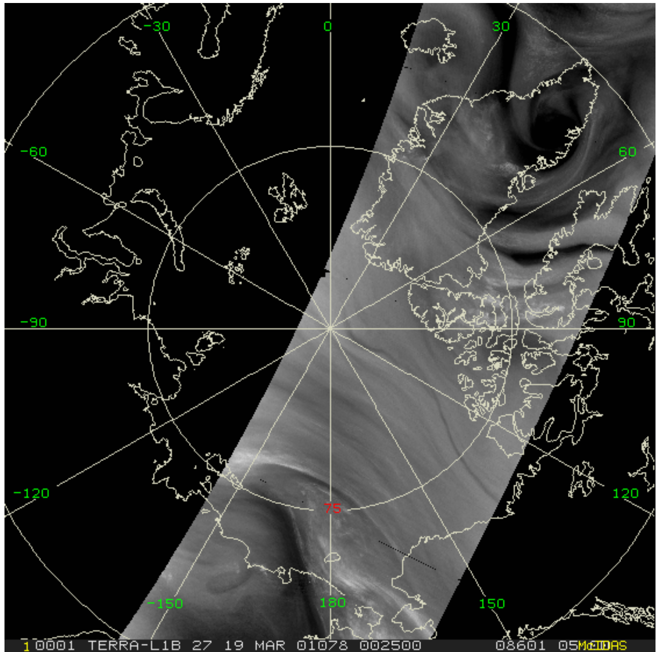
- Fully automated production enables higher density datasets (spatial and temporal).
- Move to BUFR format – more information sent with each wind including quality indicators (from 1997)
- Improved methods of target selection, tracking and height assignment.

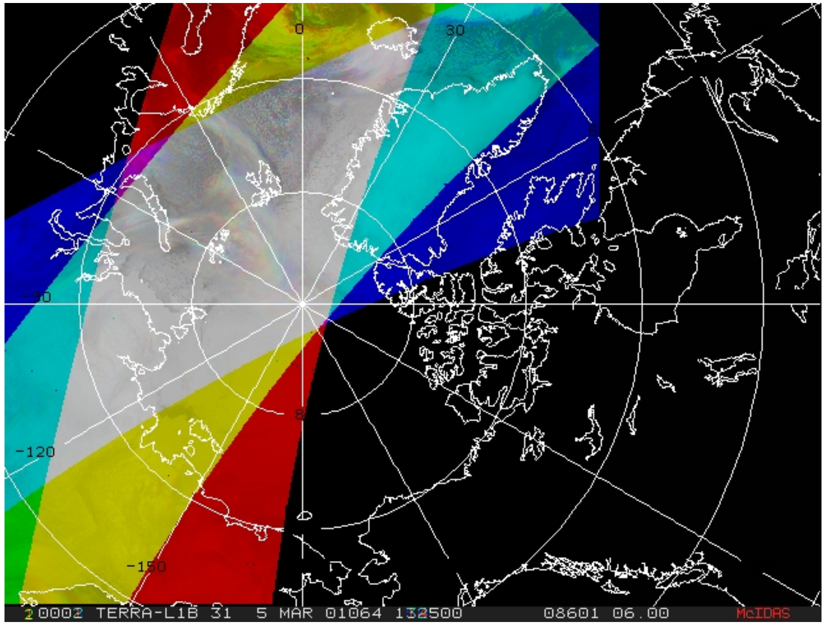
Other developments

- Polar winds (from 2002)

Polar AMV data

- AMVs can be derived from polar-orbitting satellite imagery where the successive overpasses overlap (shown in white) in the polar regions.
- Produced from:
  - MODIS IR and WV imagery on Terra and Aqua since 2002
  - AVHRR IR imagery on NOAA 15-18 since 2007
- Main difficulty is timeliness – 3.5-7 hour lag time.

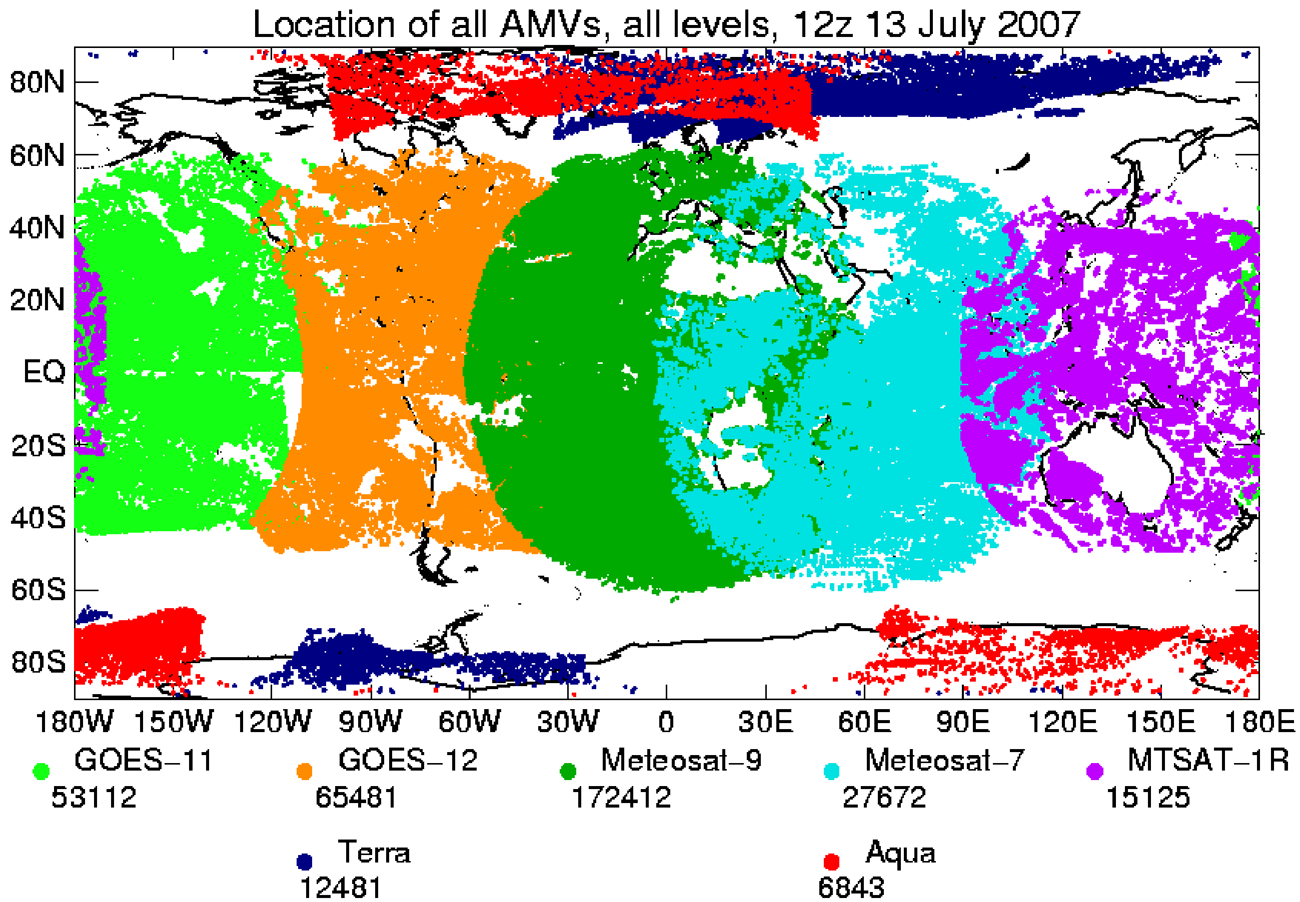




Pictures courtesy of Dave Santek, CIMSS

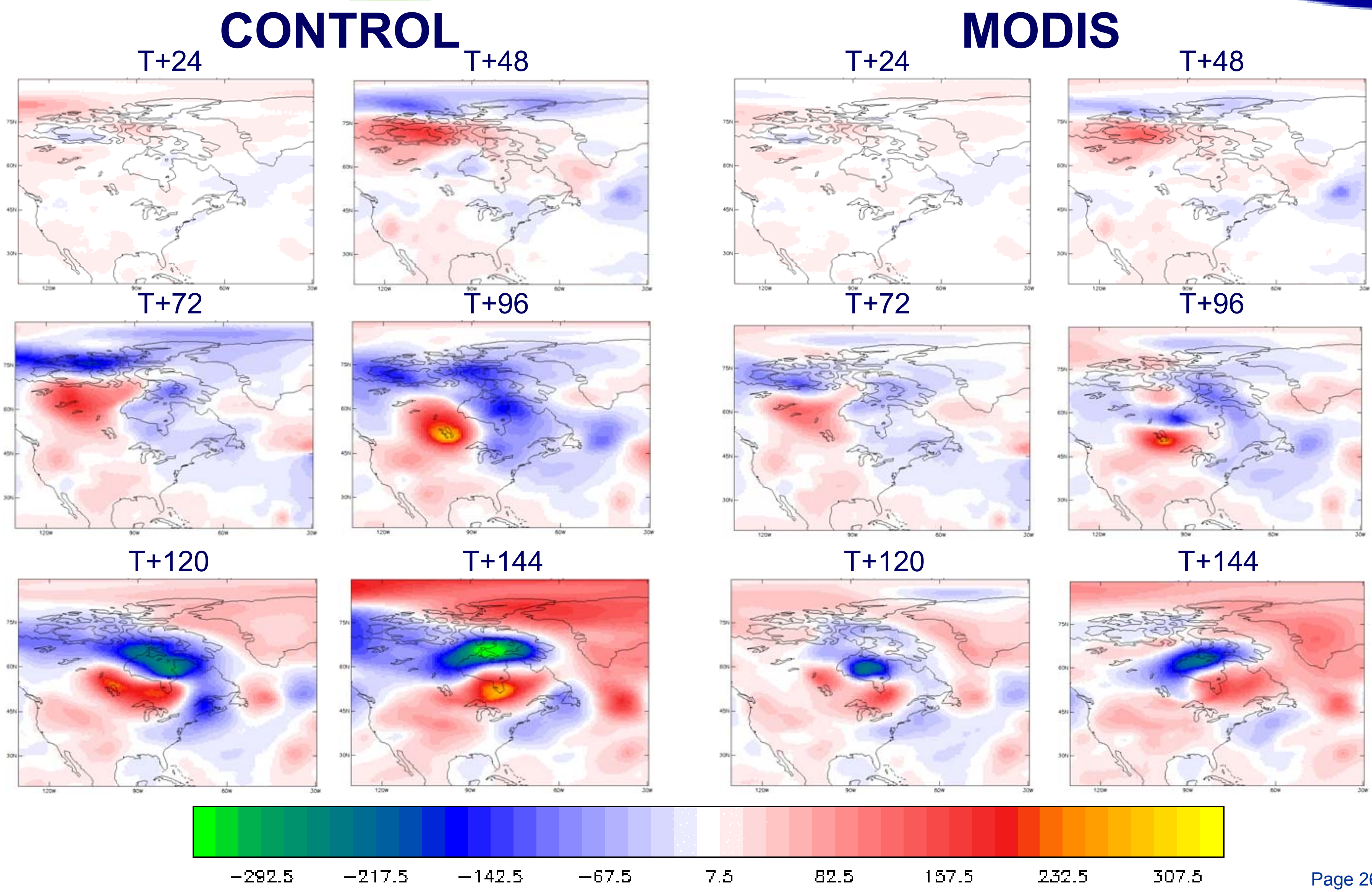
Polar AMV data

- Provide the main source of tropospheric wind information over the polar regions.
- Complementary coverage to the geostationary AMV data



Forecast error evolution Aug 14th, 2004

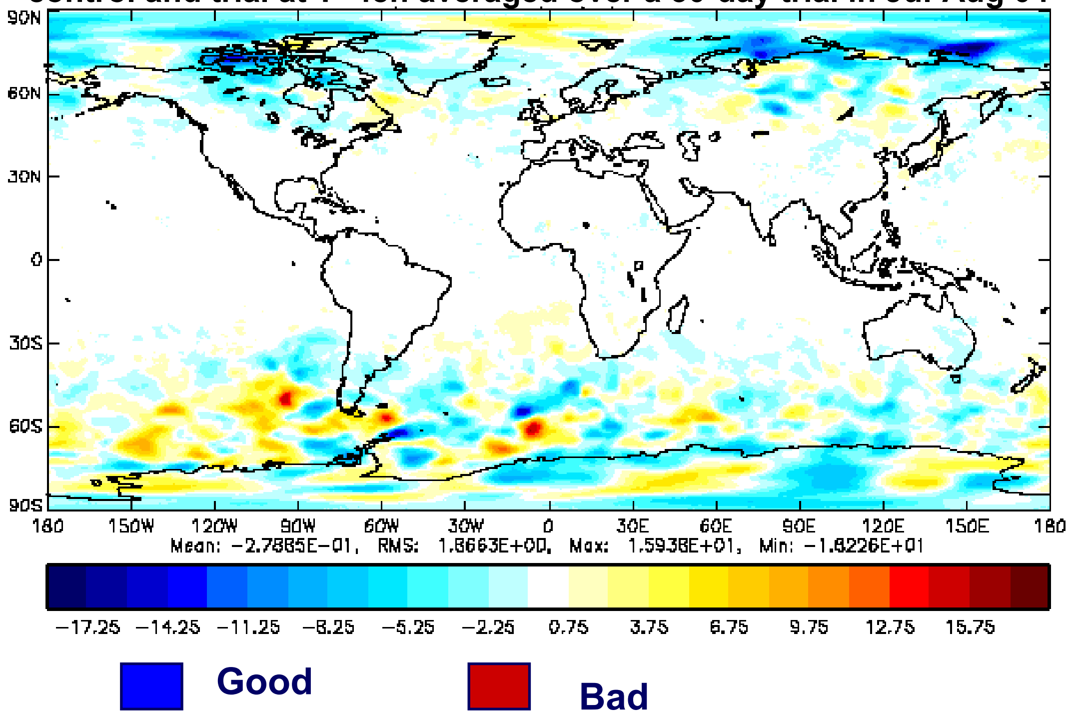
500 hPa geopotential height



Polar wind summary

- Impact trials show modest positive impact on forecast skill, most impact is in the polar regions.

Difference in 500 hPa geopotential height forecast error between control and trial at T+48h averaged over a 30-day trial in Jul-Aug 04



- MODIS winds are assimilated operationally at more than 8 NWP centres.

Recent development

Timeliness improvement through use of direct broadcast stations (since 2006).

The Past: summary

1. AMVs were first produced routinely in the 1970s.
2. Since then the data has continued to improve and expand through use of newer satellite imager instruments (higher resolution, more channels) and better AMV derivation.
3. Polar AMVs are the latest milestone in the AMV history and have proved a useful contribution to the observing system.

The Present

The Present

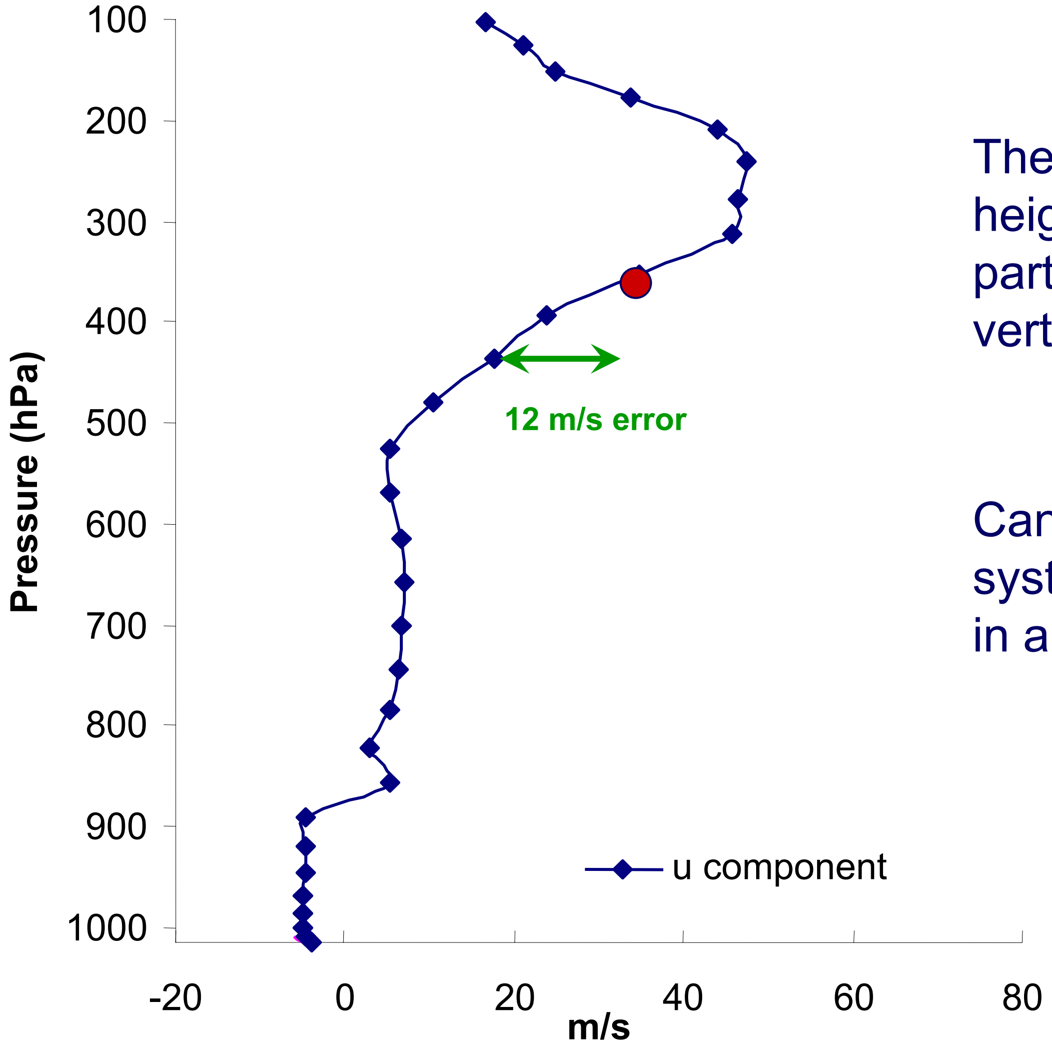
Can we improve the impact of AMVs in NWP?

Probably

One of main difficulties is that the errors are complicated and are spatially and temporally correlated.

Largest source is thought to be the height assignment.

Why do we care about height error?



The error in vector due to the height error can be significant, particularly in regions of high vertical wind shear.

Can also understand how a systematic height error can result in a systematic speed bias

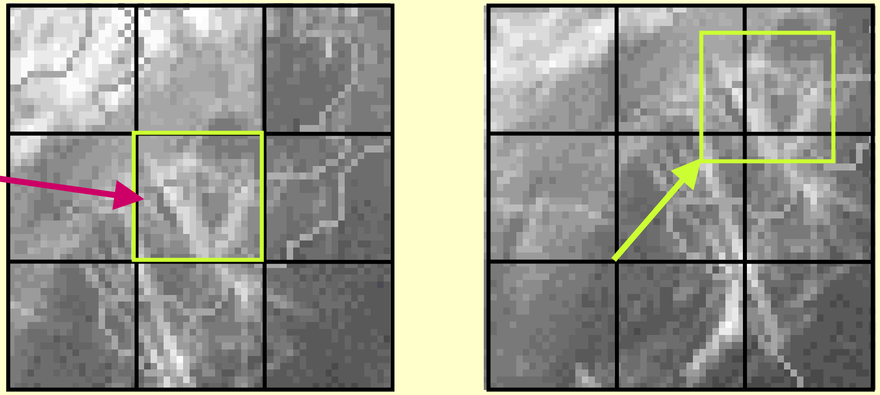
AMV height assignment: step 1

REMINDER

Target Box / Tracer

24x24 pixels

Pixel – 3 km



T   T + 15 min

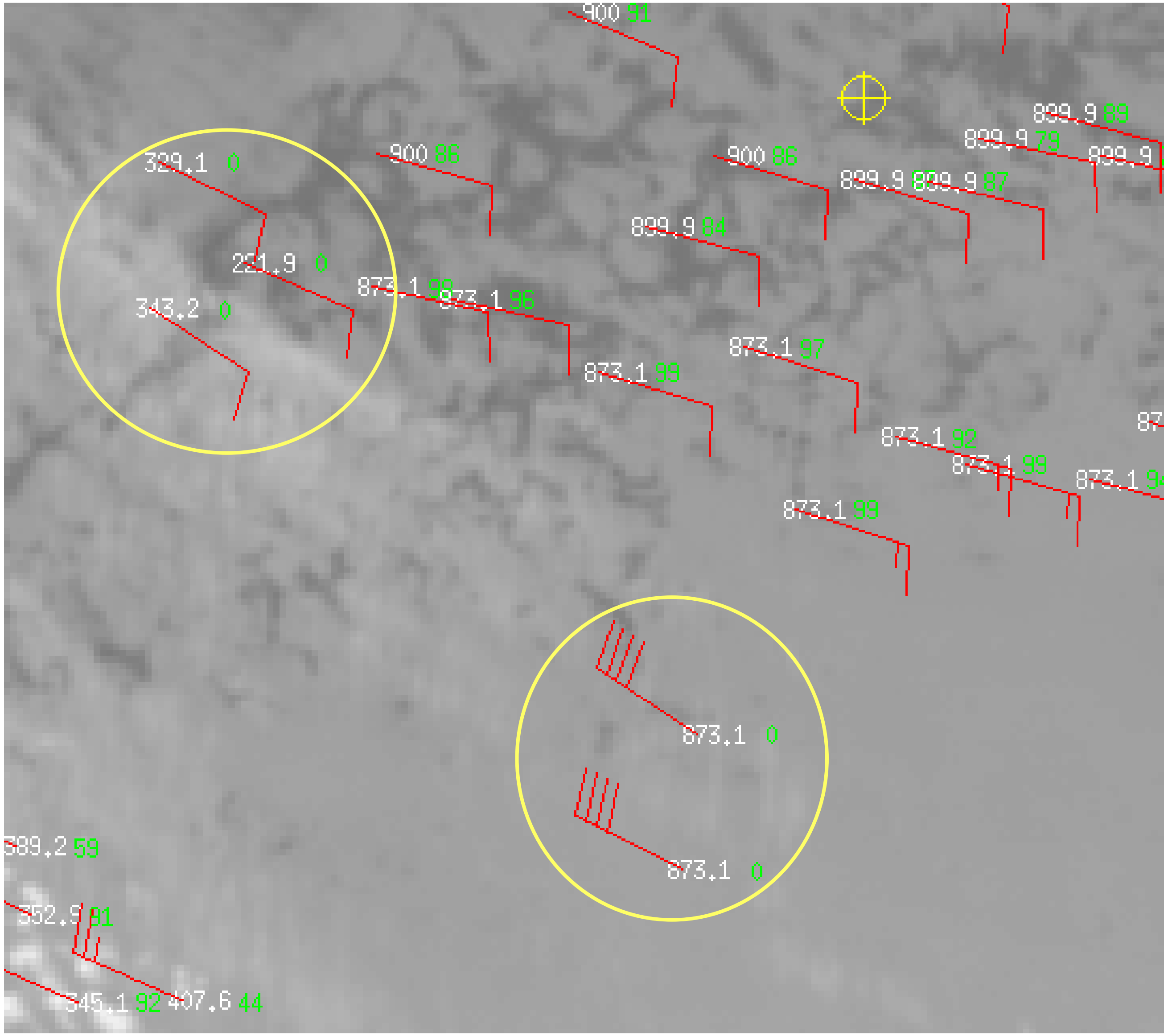
Infrared Imagery

New location determined by best match of individual pixel counts of target with all possible locations of target in search area (use cross-correlation in Fourier domain).

Vector is derived by tracking a target that contains many pixels

First challenge is to decide which pixels should be used for the height assignment

Choice of pixels – what can go wrong….



Example courtesy of Jörgen Gustafsson, EUMETSAT

AMV height assignment – step 2

Second challenge is to decide what level (or layer) is most representative of the cloud motion?

Mostly the AMVs are assigned the pressure of the cloud top

except …

some low level AMVs which are assigned an estimate of cloud base.

[Followed work by Fritz Hasler in the 1980s that showed that movement of marine trade wind cumulus was best correlated with the top of the marine boundary layer (cloud base)].

BUT

Should we really consider them as layer-average winds?

AMV height assignment – step 3

Third challenge is to calculate the cloud top pressure or estimate a cloud base pressure.

Two main approaches for cloud top pressure:

1. EBBT (equivalent black-body temperature)

Compares the measured brightness temperature to forecast temperature profiles from an NWP model to find the level of best-fit.

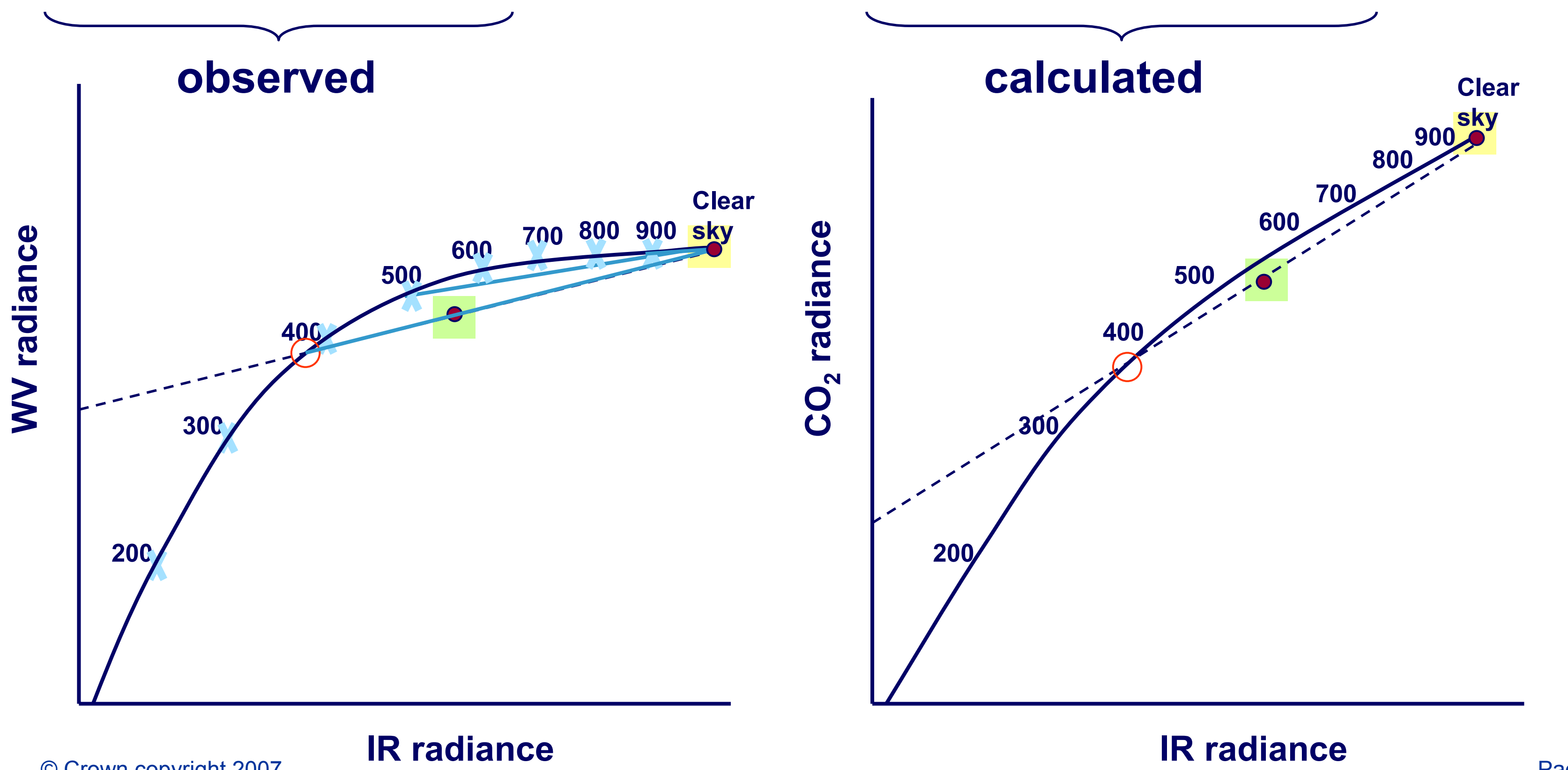
Advantage: available everywhere

Disadvantage: Will put semi-transparent or sub-pixel cloud too low due to radiance contributions from below the cloud.

AMV height assignment – step 3

2. Multi-channel – CO_2 slicing and WV intercept techniques

$$\frac{R_{CO2/wv} - R^{cs}_{CO2/wv}}{R_{IR} - R^{cs}_{IR}} = \frac{nE_{CO2/wv}[R^{bcd}_{CO2/wv}(P_c) - R^{cs}_{CO2/wv}]}{nE_{IR}[R^{bcd}_{IR}(P_c) - R^{cs}_{IR}]}$$



AMV height assignment – step 3

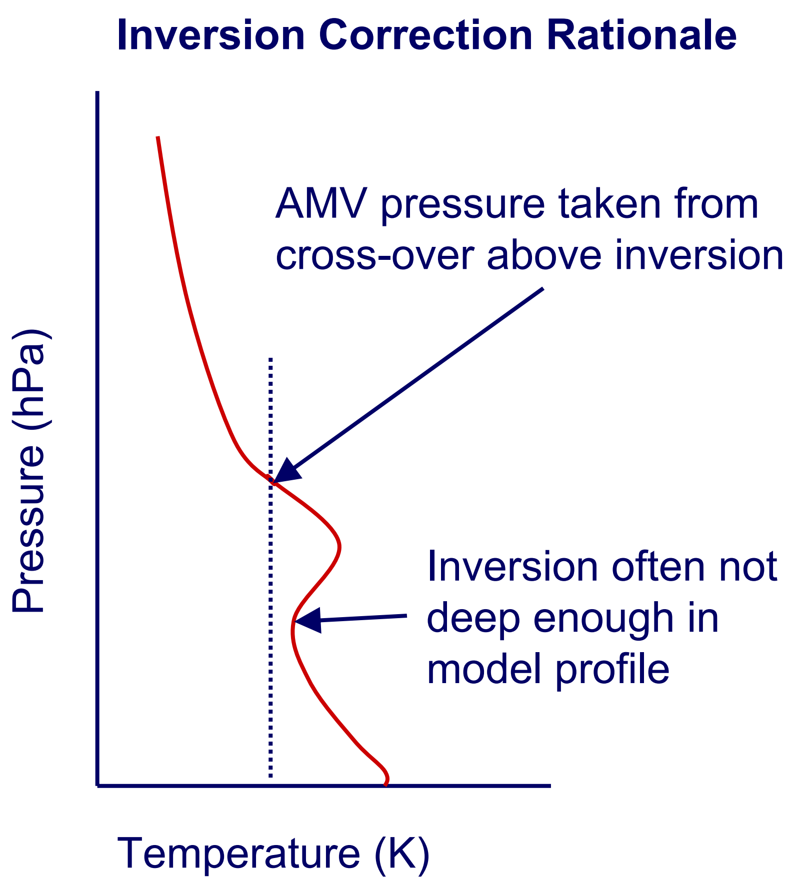
Cloud base pressure

• estimated using the mean and standard deviation of the cloud cluster temperatures.

One final check applied by some producers…

Inversion correction

• If an inversion is present in the forecast profile and the AMV is low level then relocate the AMV to the level of the minimum temperature of the inversion.



Height assignment error

In summary:

AMV height errors can be due to:

i) Choice of pixels to use for height assignment ii) Appropriateness of using cloud top or cloud base estimates	AMV specific problems
iii) Limitations of cloud top/base pressure methods	Can learn from cloud community

How do we improve the impact of AMVs in NWP?

AMV community meets biennially at the International Winds Workshops (IWW)

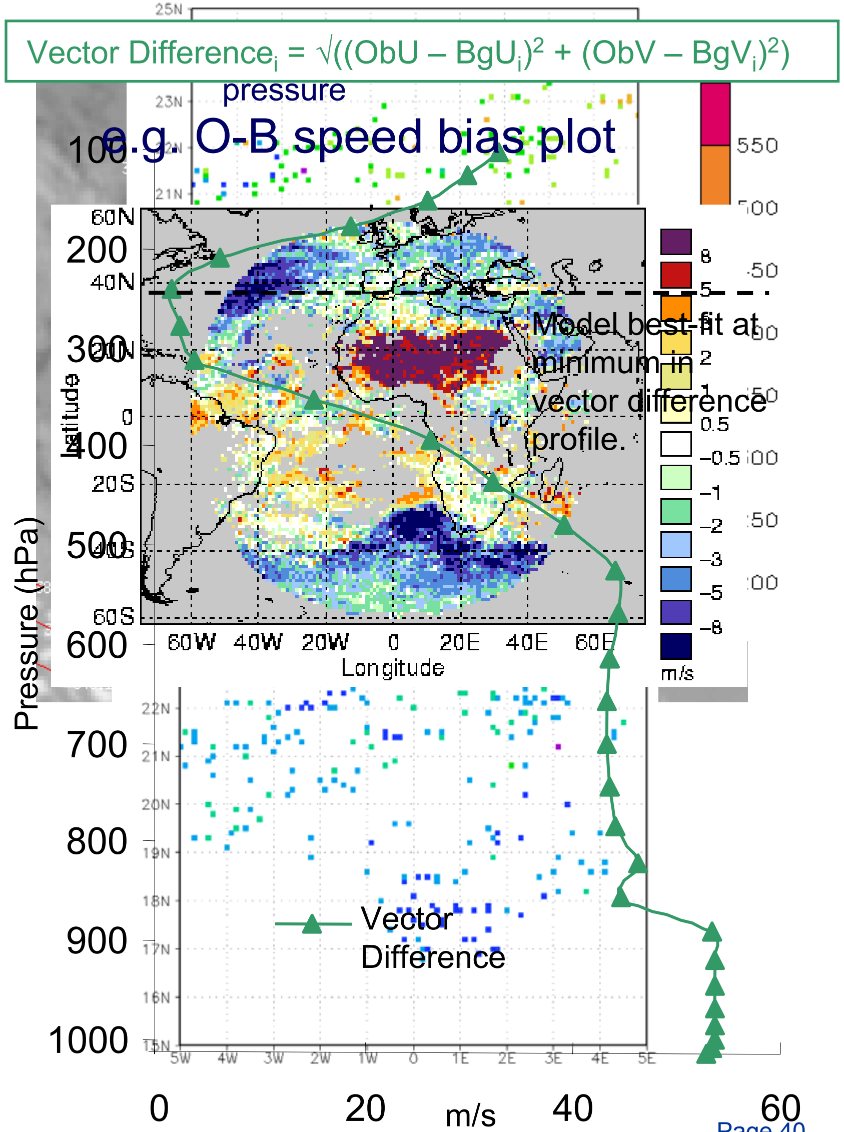
Most NWP centres have one person (if lucky) working on the AMVs – need to work together

1. Improve AMV data (reduce errors in u, v and p)
2. Harmonise AMV processing between data producers
3. Improve AMV quality information provided with data
4. Improve assimilation strategy

To do this we need to improve our understanding of the AMVs and their errors

How can we investigate AMV errors?

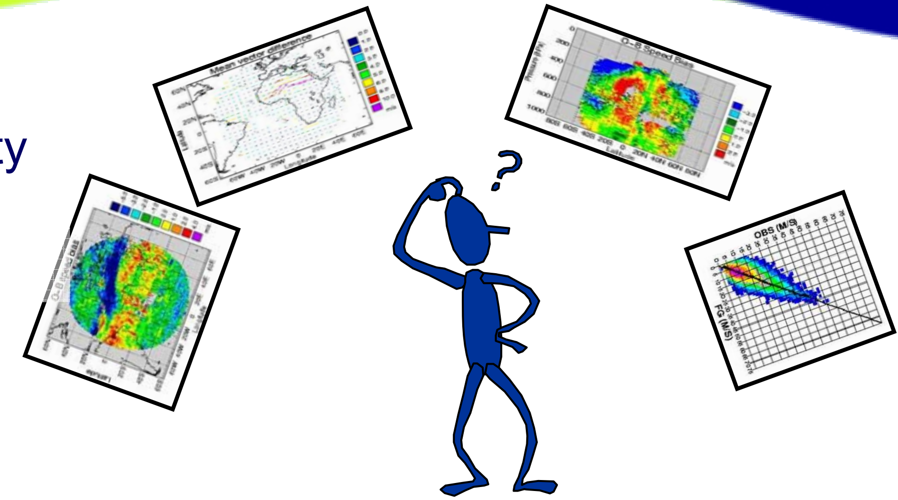
1. O-B statistics studies (e.g. NWP SAF) and comparisons to sondes and aircraft winds
2. Comparisons to rawinsonde/model best-fit
3. Comparisons with other cloud top pressure products (e.g. MODIS, Calipso …). Also consideration of other cloud properties (e.g. optical depth).
4. Analysis of AMVs overlain on imagery



NWP SAF AMV monitoring

NWP SAF – Numerical Weather Prediction Satellite Application Facility

A EUMETSAT-funded initiative

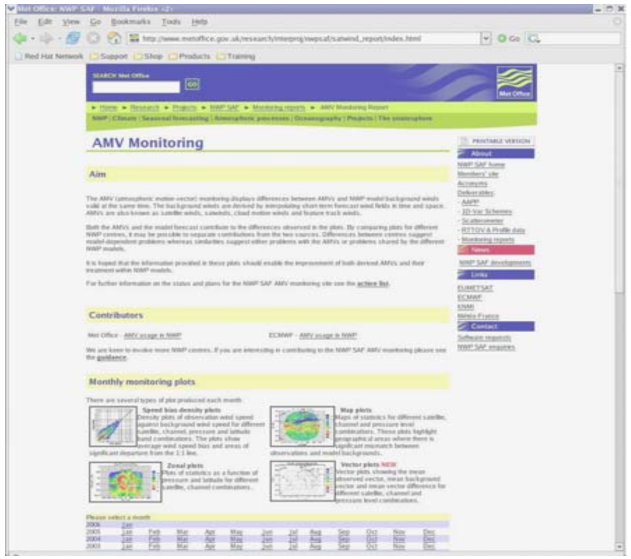


AMV Monitoring

Displays comparable AMV monitoring output from different NWP centres to help identify and partition error contributions from AMVs and NWP models.

Intended to stimulate discussion and to lead to improvements in AMV derivation and AMV use in NWP.

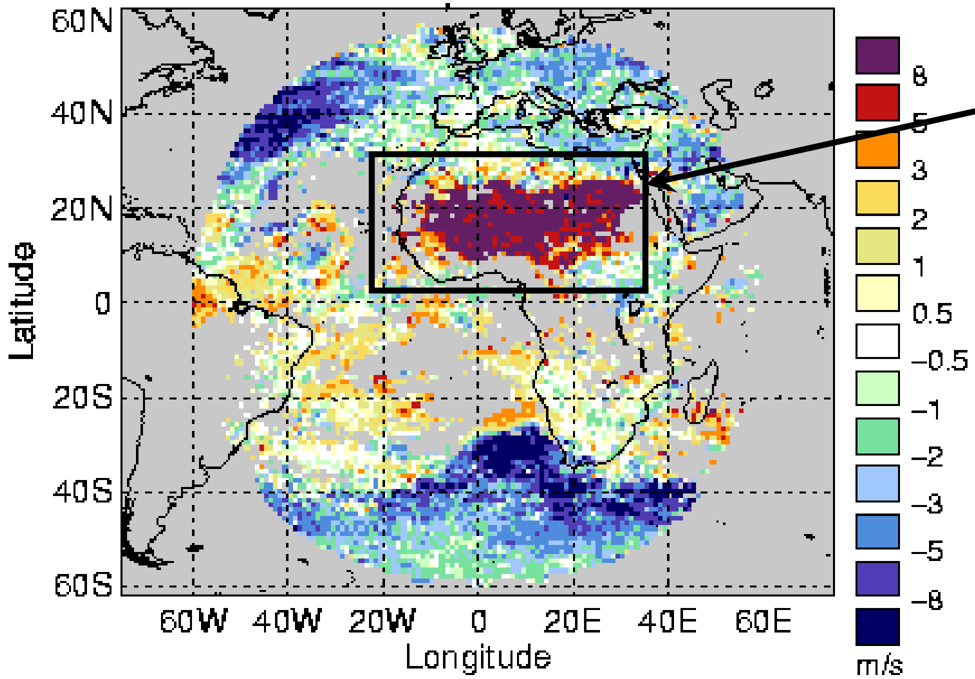
Analysis reports produced every 2 years.



http://www.metoffice.gov.uk/research/interproj/nwpsaf/satwind_report

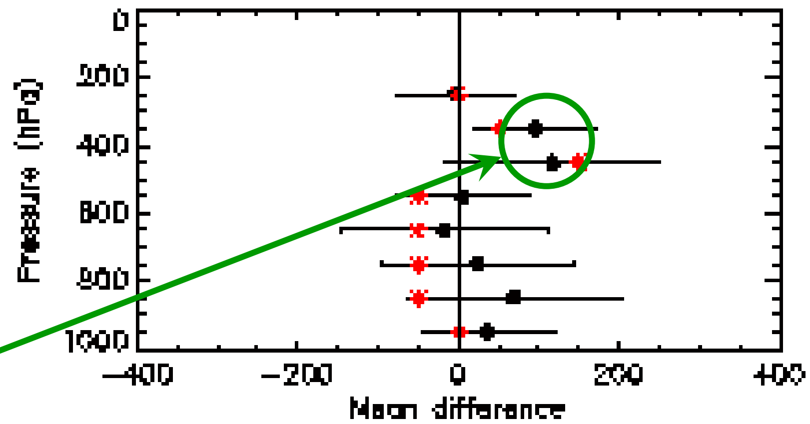
Example, Sahara region

Meteosat-9 IR 10.8
O-B speed bias, Feb 2007
400-700 hPa



Mid level fast speed bias in winter

Meteosat-8 IR 10.8 EBBT
Observed-Model best-fit pressure bias
Nov-Dec 06
Over land in tropics

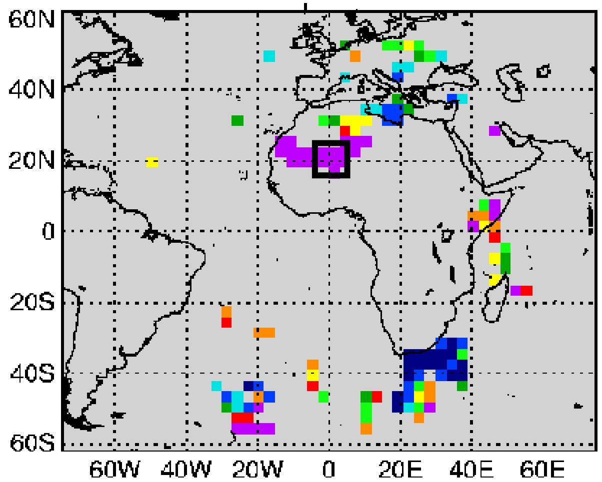


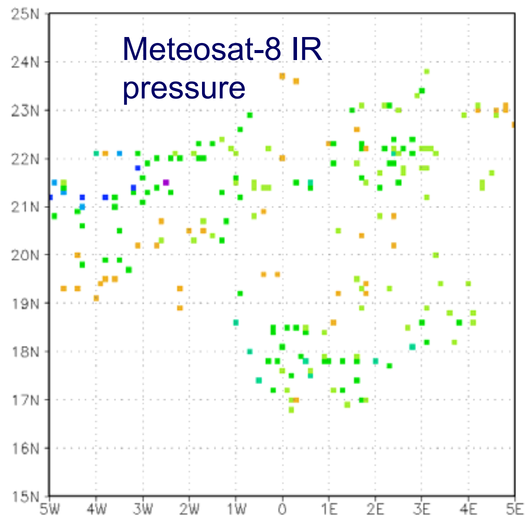
Associated with low height bias in best-fit statistics

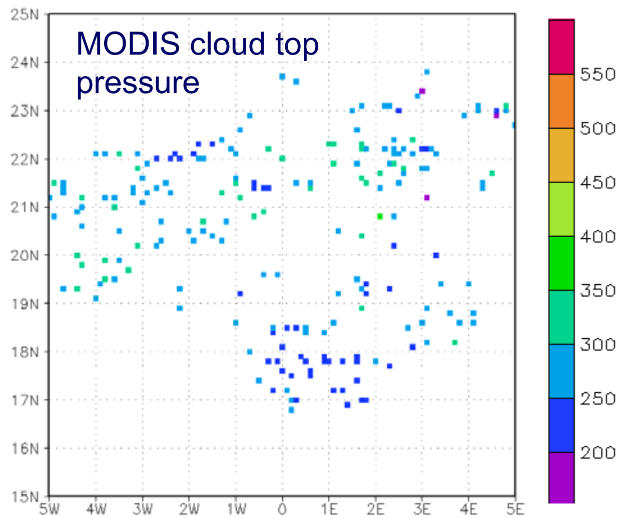
- Mean
- Mode
- standard deviation

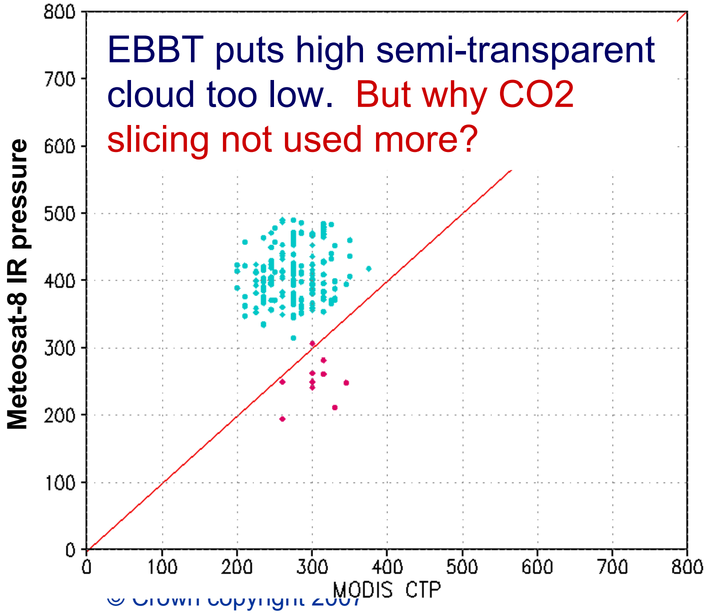
Example, Sahara region

8th Dec 2005 0z run









- Investigations at EUMETSAT highlighted problems in inversion regions, where can be more than one solution to CO_2 slicing.
- An amended decision strategy went operational on 22nd March 07 leading to reduction, but not elimination, of the fast speed bias over the Sahara.

CGMS-34 recommended activities

1. Inter-comparison of AMV operational algorithms using a common data set from MSG (all AMV producers).
2. Comparison of AMV height assignments with new measurements from instruments on the A-train (e.g. cloud lidar).
3. AMVs derived from simulated imagery – proposed plan involving ECMWF and EUMETSAT/CIMSS

AMV derivation from simulated imagery

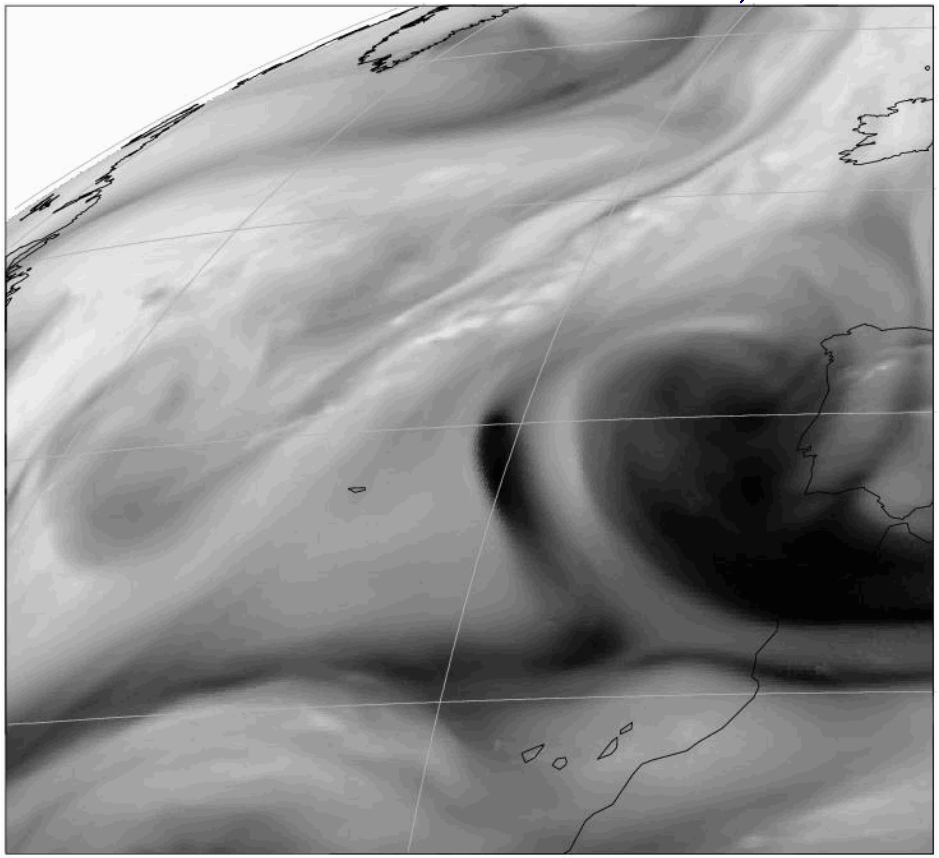
<u>Idea</u>: Derive AMVs from sequences of images simulated from high-resolution model fields (clear *and* cloudy).

<u>Advantage</u>: “Truth“ is completely known. Comparison of derived AMVs with model wind field should allow better characterisation of AMVs and their errors.

Aspects that could be investigated:

1. Height assignment.
2. Which height should be estimated (cloud top/base/...?)
3. Observation operators for cloudy and clear AMVs.
4. EUMETSAT‘s divergence product.
5. Influence of calibration/radiance biases.

Information from Bormann et al., IWW8

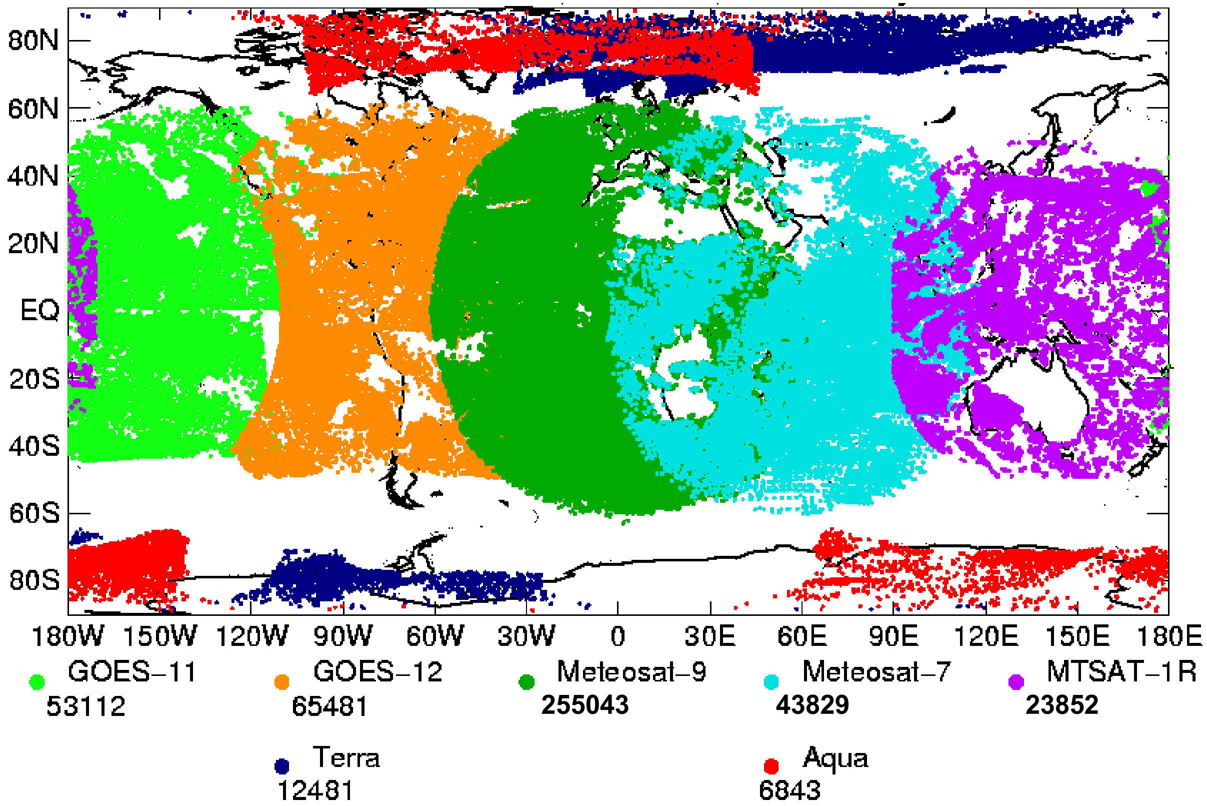


Met-8 6.2µm simulated from T2047 (~10 km) global model run using RTTOV-Cloud.

NWP quality control for AMVs

Extract all AMVs valid from 9z – 15z

Met Office, 13th Jul 07 QU12



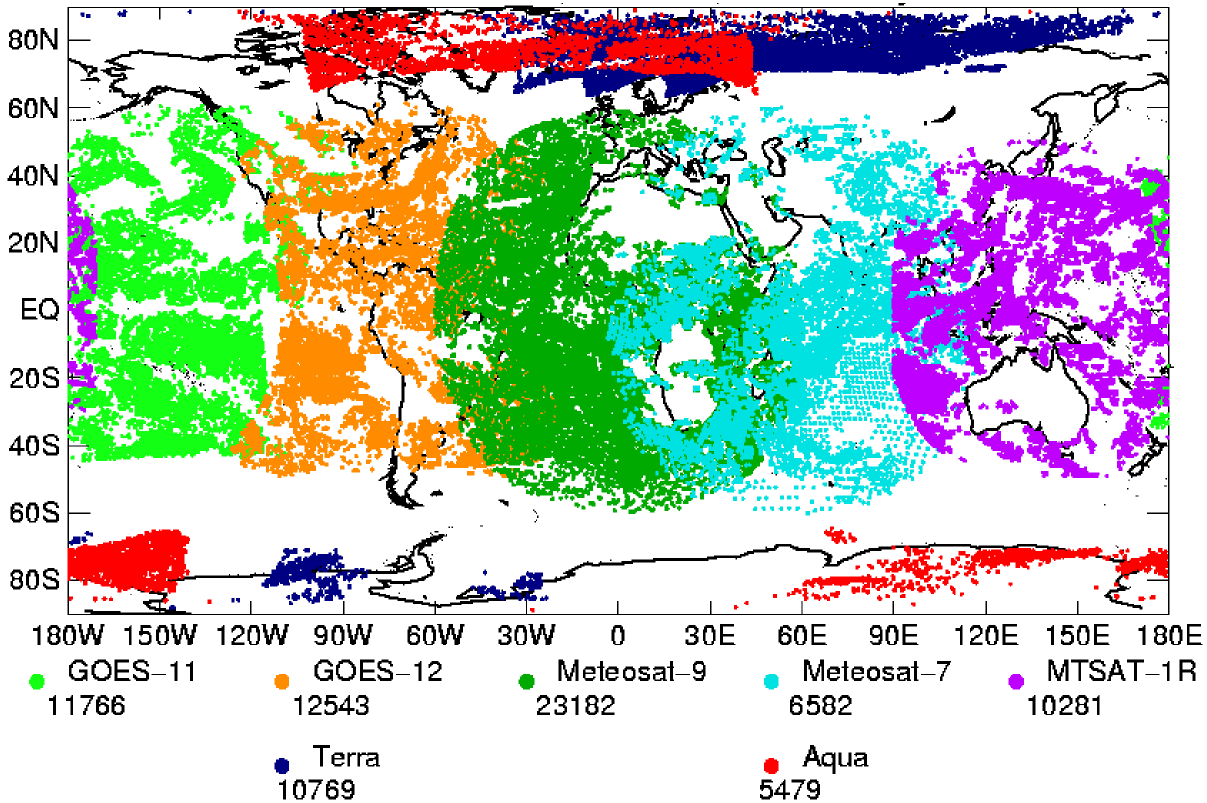
460641

NWP quality control for AMVs

Extract all AMVs valid from 9z – 15z

1. Blacklisting
- Apply QI thresholds
- Spatial and temporal checks
- Remove some satellite-channel combinations

Met Office, 13th Jul 07 QU12



80602
17%

NWP quality control for AMVs

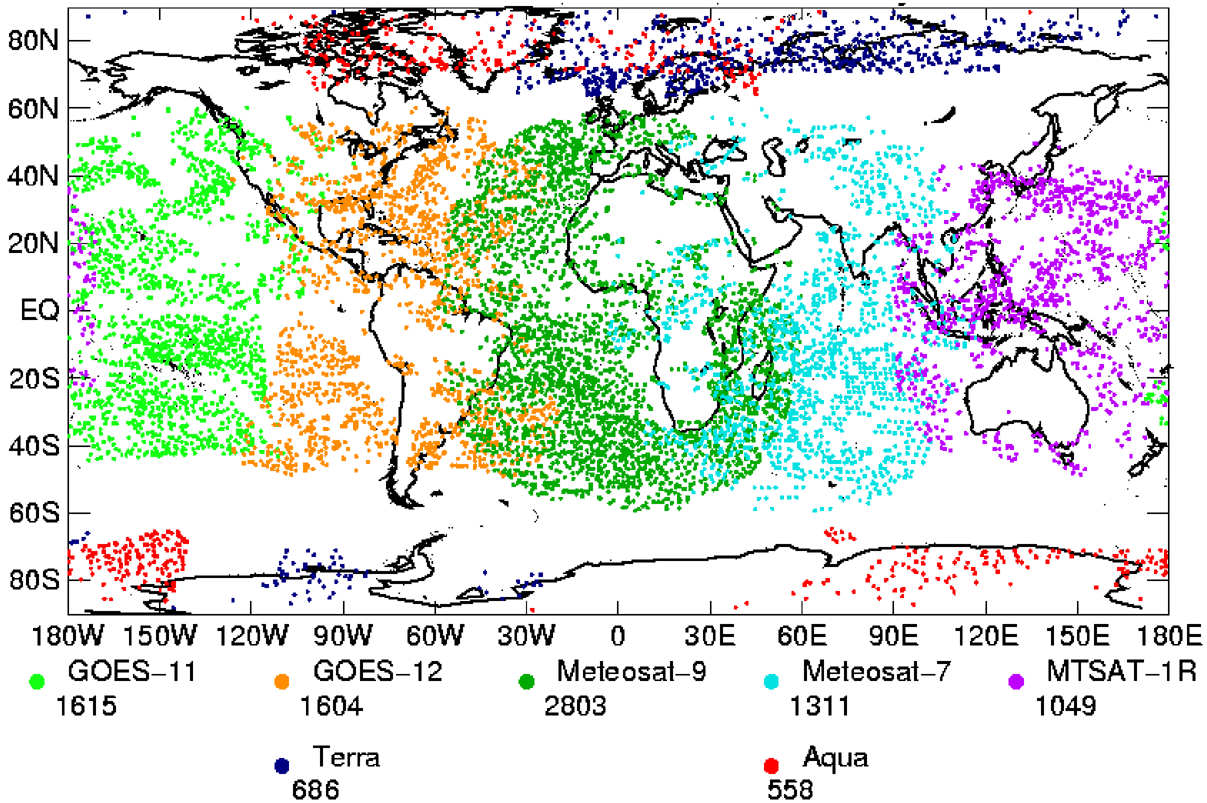
Extract all AMVs valid from 9z – 15z

1. Blacklisting
   - Apply QI thresholds
   - Spatial and temporal checks
   - Remove some satellite-channel combinations

2. Thinning
   - one wind per 200 km x 200 km x 100 hPa box.

3. Background check
   - Remove if deviates too far from background.

Met Office, 13th Jul 07 QU12



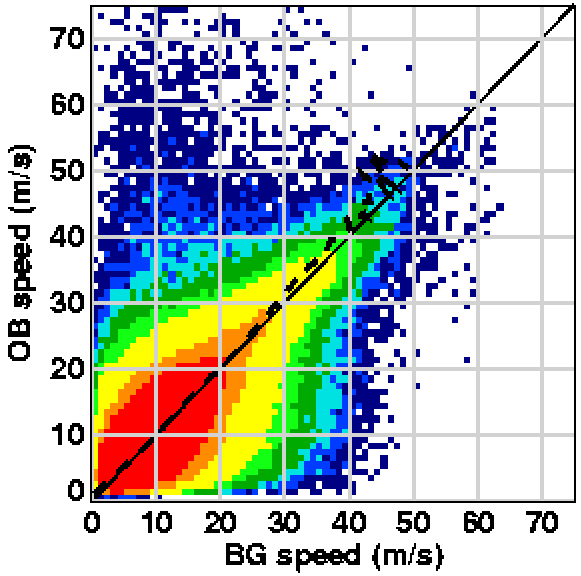
Assimilate only a small percentage of the data

9626 → 2%

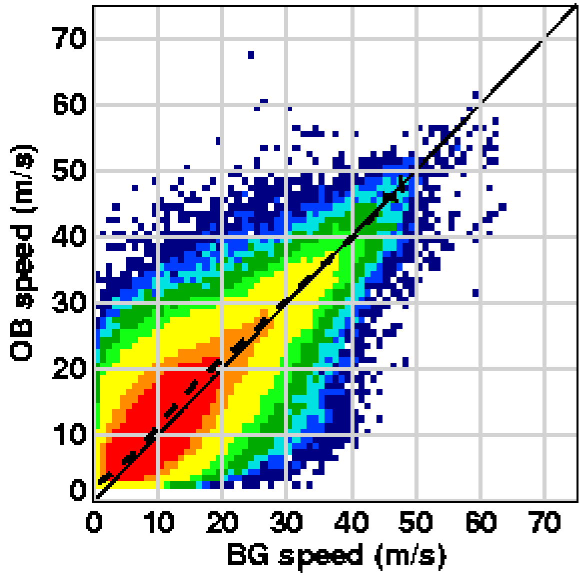
NWP quality control for AMVs

Met-9 TR IR winds, above 400 hPa, July 2007

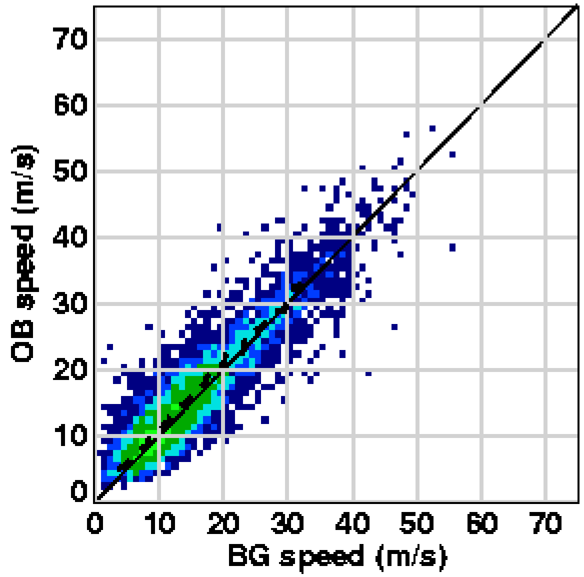
All received (985,236)
rms = 4.9 m/s



QI>80 (646,134)
rms = 4.1 m/s



Used (6,598)
rms = 2.6 m/s



Current thinning and quality control strategy is very wasteful.

Observation errors and observation operator

Observation errors

At most centres vary only with pressure (at Met Office: 2.8-6.6 m/s) – based on O-B statistics (but inflated).

Observation operator

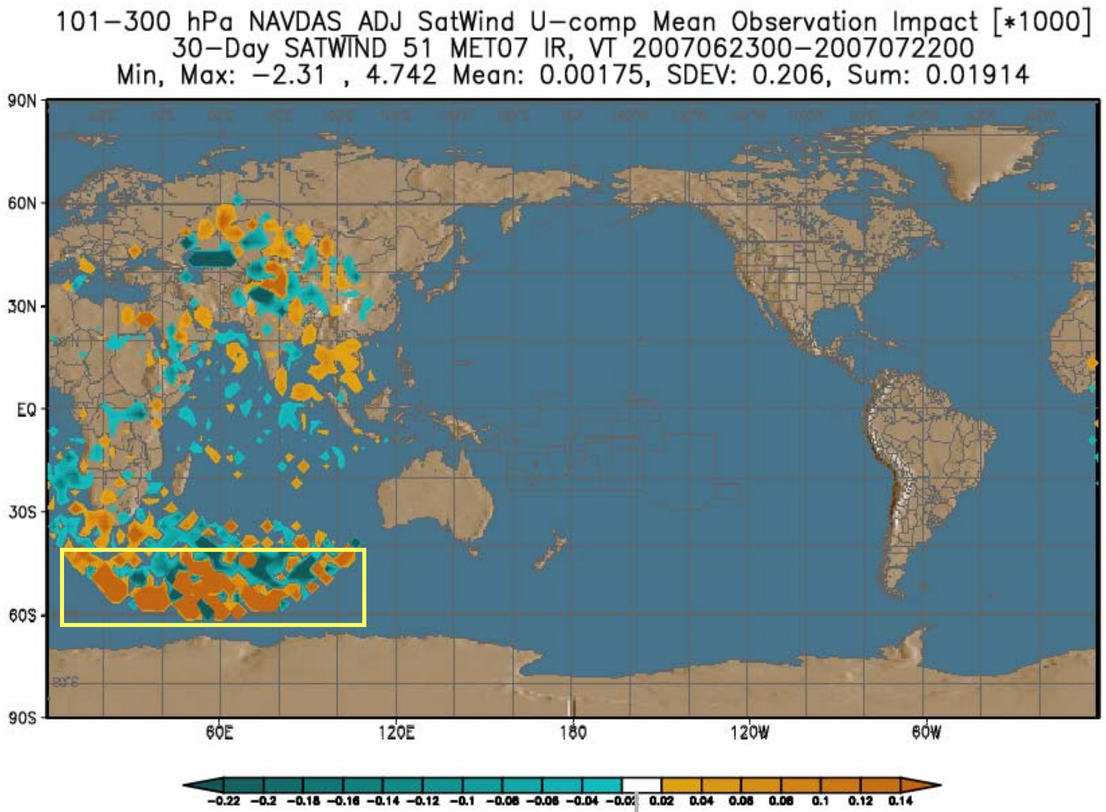
Treated as point observations in space and time (although neither are true).

Improving the AMV assimilation

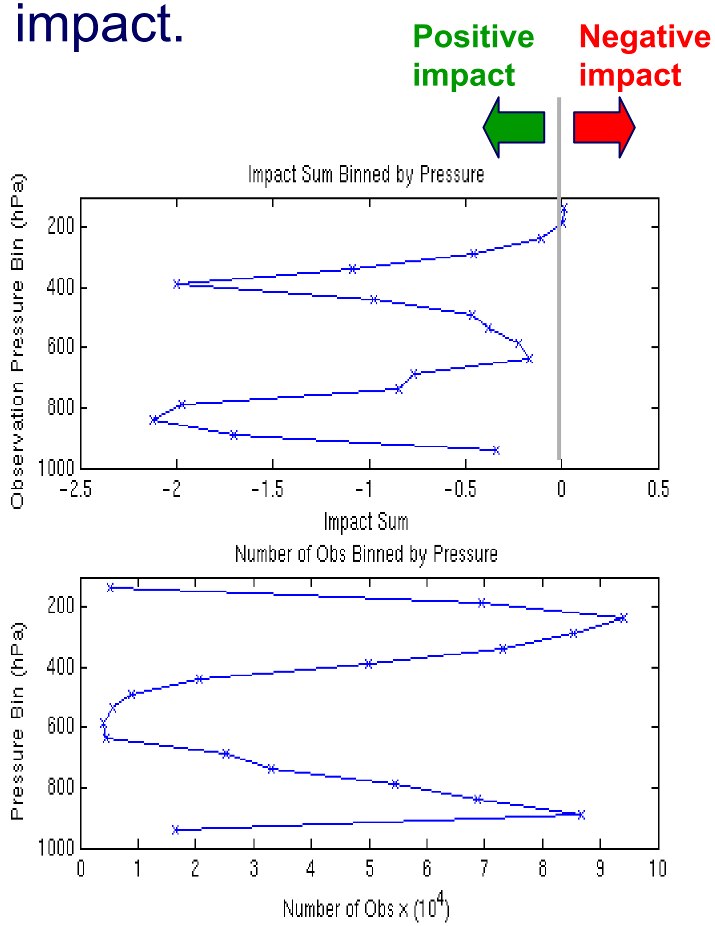
1. Can we learn more about the impact of AMVs in NWP?
2. Can we use what we learnt from the O-B monitoring, best-fit pressure statistics and other investigations to help improve our blacklisting and errors?
3. Should we develop a new observation operator to treat the winds as layer observations?
4. Is there a better way to handle spatial error correlations than thinning and inflated errors?

Adjoint investigations

NRL are using an adjoint approach (see Nancy Baker's talk) to identify where the data has most good/bad impact.



Positive impact **Negative impact**



Courtesy of Nancy Baker (NRL) and Howard Berger (CIMSS)

Improving the AMV assimilation

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Observation errors

A good specification of the observation error is essential to assimilate in a near-optimal way.

Current observation errors vary only with pressure.

New approach

Take into account…..

- Errors are variable and becoming better understood.
- Height assignment error often dominates, but is not a problem in regions of low wind shear.

AMV error = Error in vector + Error in vector due to error in height

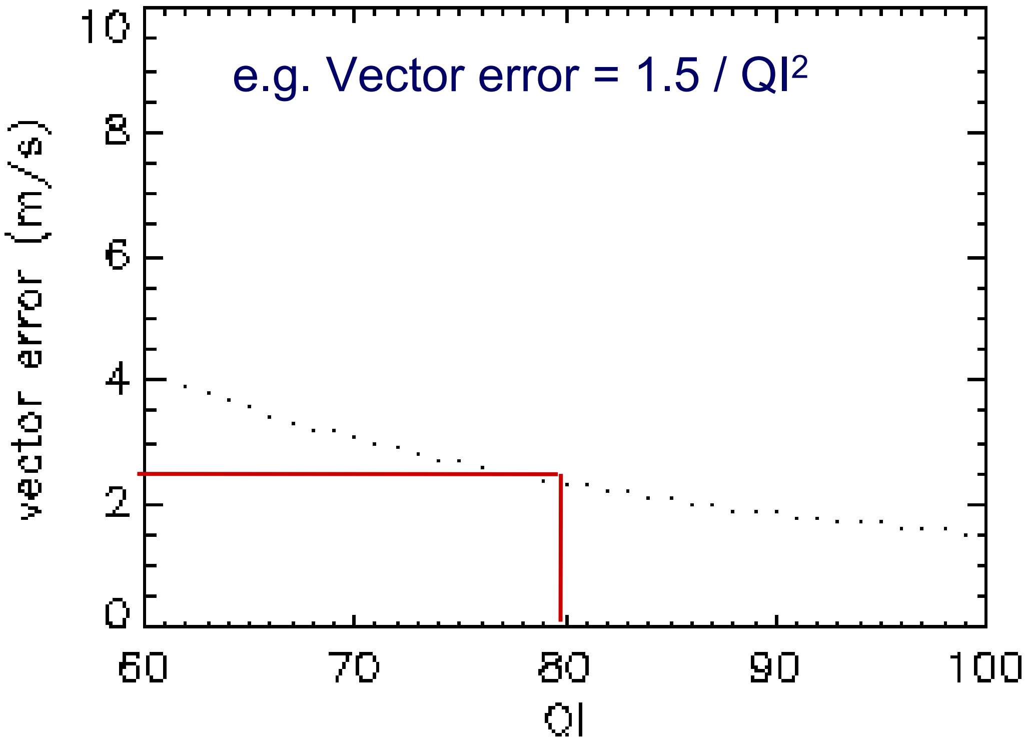
For this we need an estimate of:

1. Vector error
2. Height error

} Ideally from data producers

Vector error estimate (Ev)

Until vector error estimate provided by producers, we can estimate based on the model-independent quality indicator.

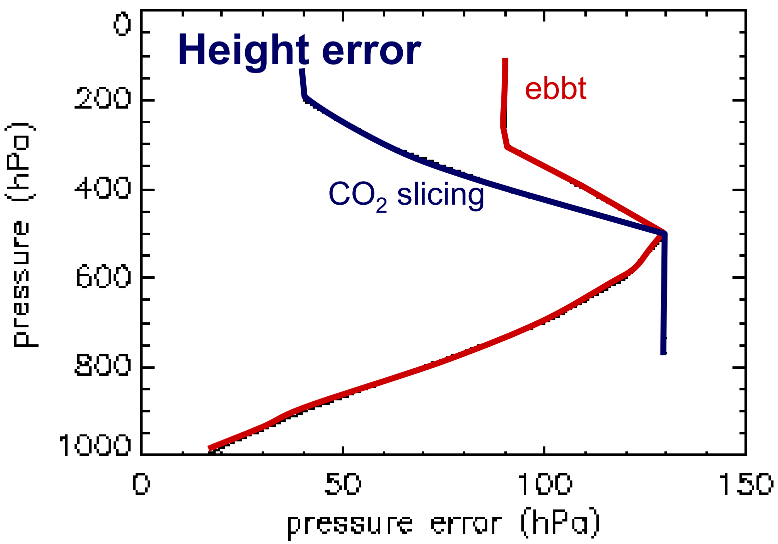


Example

At QI=80, Vector error=2.3 m/s

Height error estimate (Ep)

We may be able to use best-fit pressure statistics as a guide to generate height errors as a function of satellite / channel / height assignment method and pressure level



Can look at observed - model best-fit pressure distributions (black curves).

1. Fairly Gaussian
2. Mostly unbiased

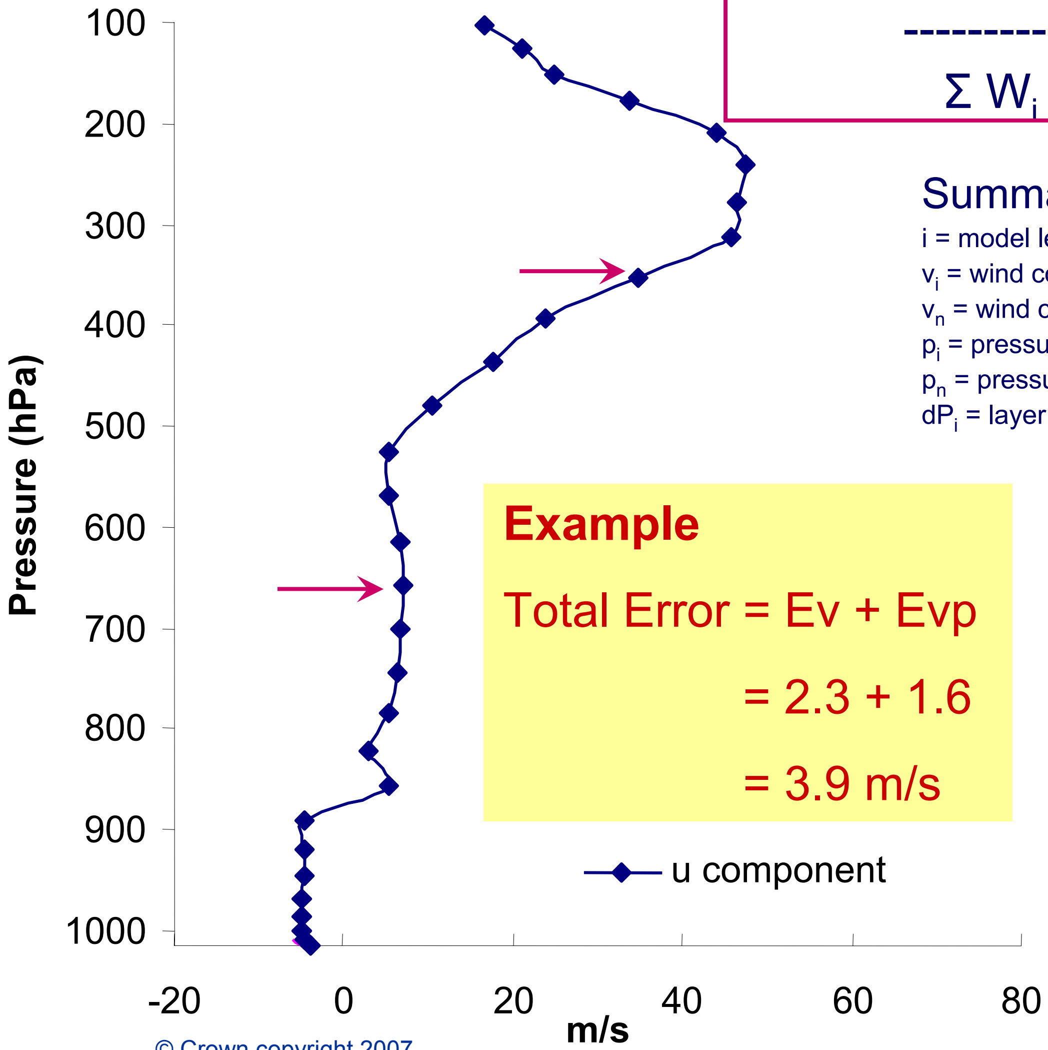
In cases with larger height bias can consider spatial blacklisting.

Elsewhere can use rms of distribution as proxy for the height error (this will contain a contribution from the error in best-fit).

Error in vector due to error in height (Evp)

$$Evp = \sqrt{\frac{\Sigma W_i (v_i - v_n)^2}{\Sigma W_i}}$$

where $W_i = e^{-((p_i - p_n)^2 / 2Ep^2)} * dP_i$



Summation over levels with a significant W_i

i = model level

v_i = wind component on model level

v_n = wind component at observation location

p_i = pressure on model level

p_n = pressure at observation location

dP_i = layer thickness

Example

Total Error = Ev + Evp

= 2.3 + 1.6

= 3.9 m/s

Pn = 350 hPa

Ep = 100 hPa Evp = 14.2 m/s

Ep = 80 hPa Evp = 12.8 m/s

Ep = 60 hPa Evp = 11.0 m/s

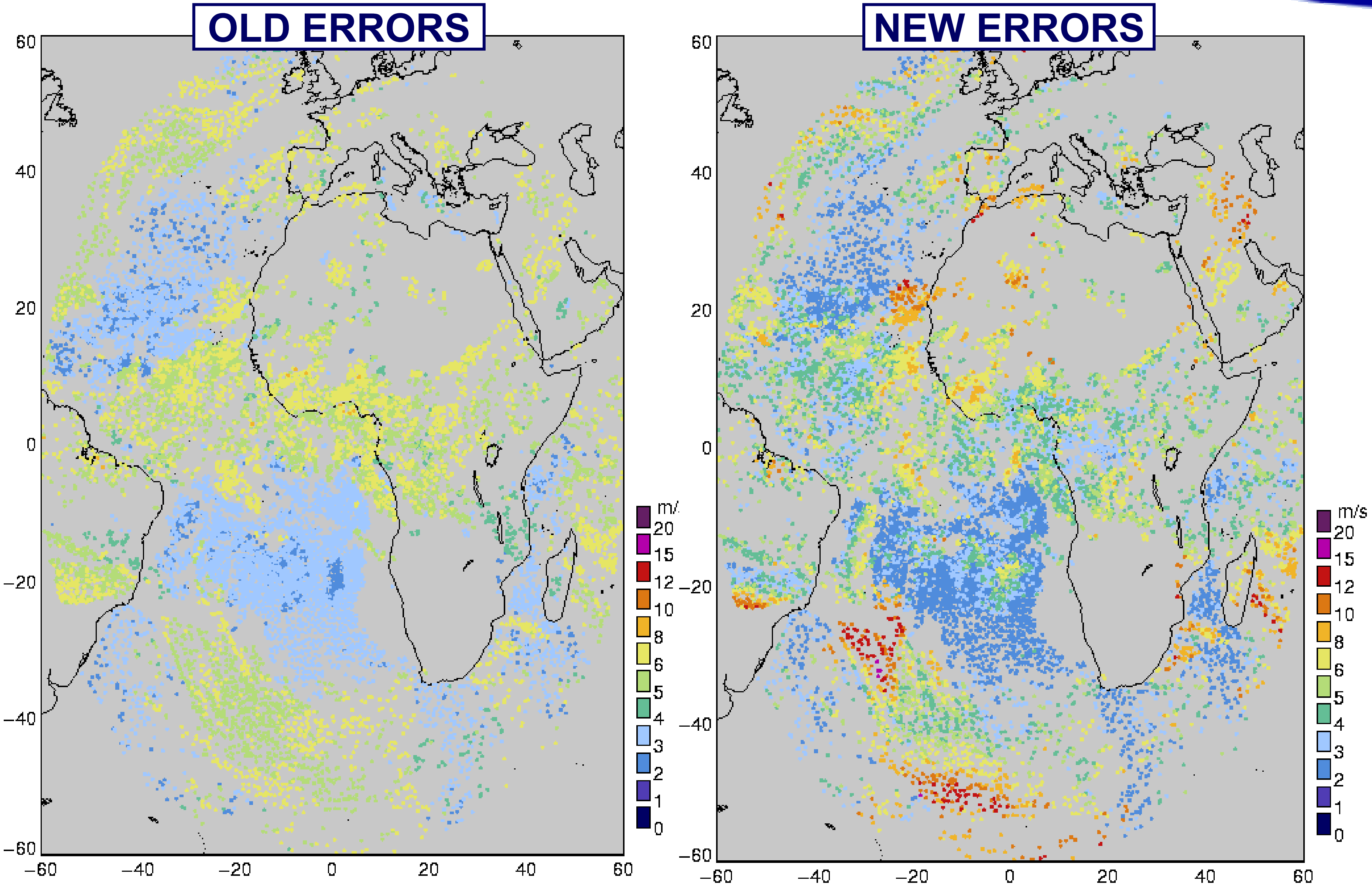
Pn = 660 hPa

Ep = 100 hPa Evp = 3.0 m/s

Ep = 80 hPa Evp = 1.6 m/s

Ep = 60 hPa Evp = 0.9 m/s

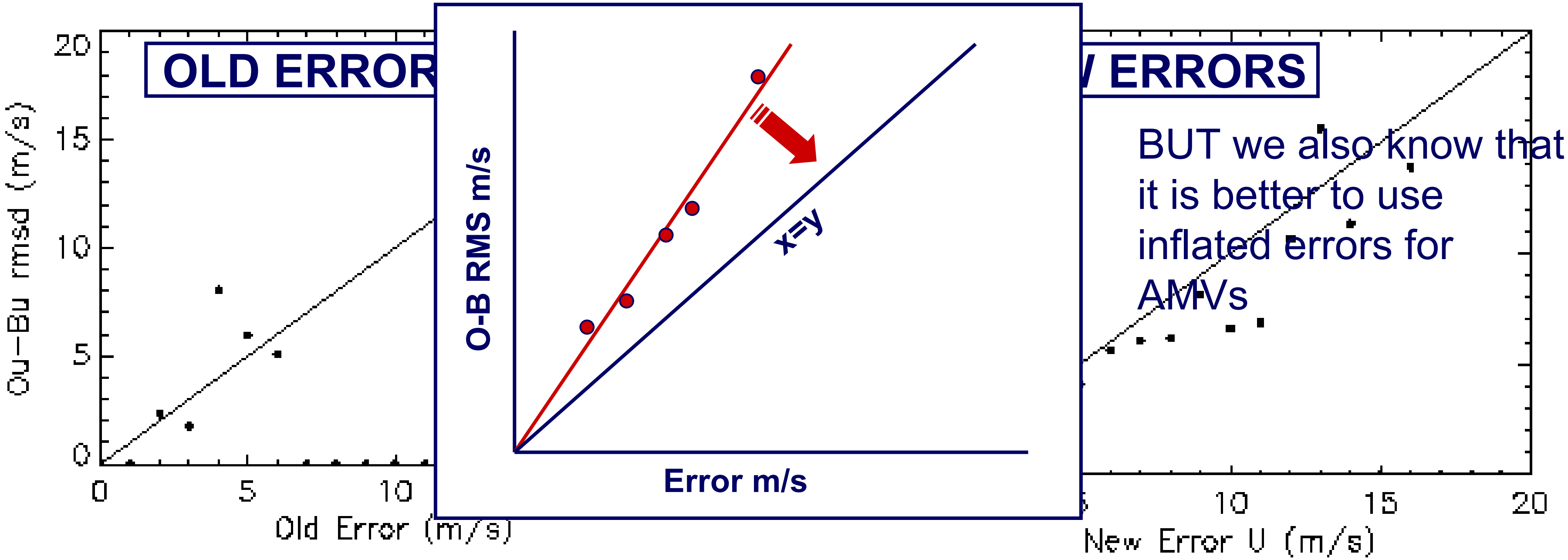
Observation errors – new approach examples



How good are the new errors?

Should see a positive correlation with O-B rms

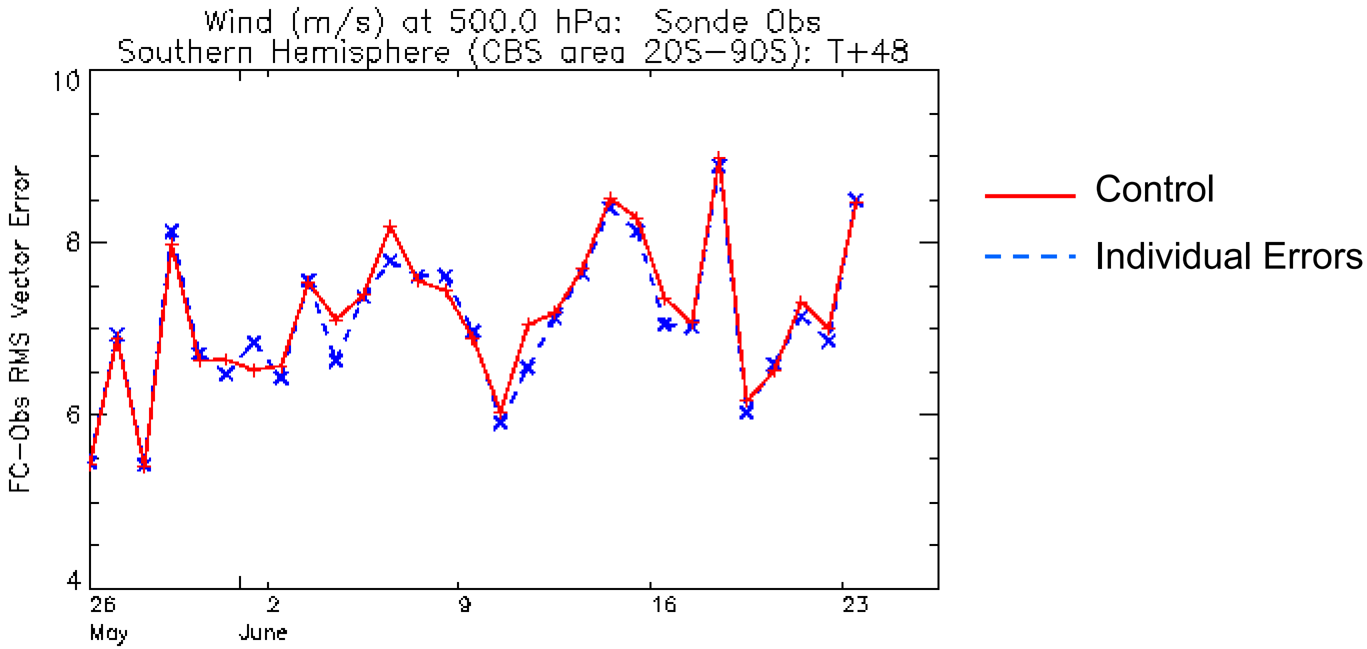
BUT O-B RMS will contain a contribution from background error.



BUT we also know that it is better to use inflated errors for AMVs

Fairly encouraging result

New observation errors – impact experiment



Small impact – Met Office NWP index of +0.2 (compare with 1.5 for all AMVs).

But running with own estimates of vector and height errors (may benefit from further tuning). Would expect more impact if error estimates provided by producers with each wind.

Improving the AMV assimilation

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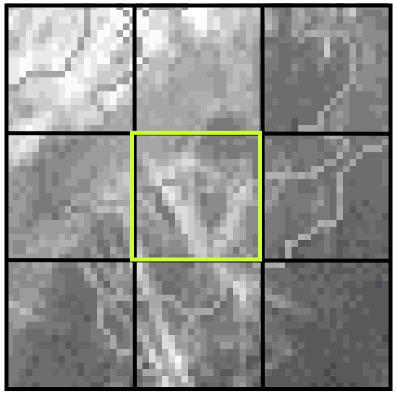
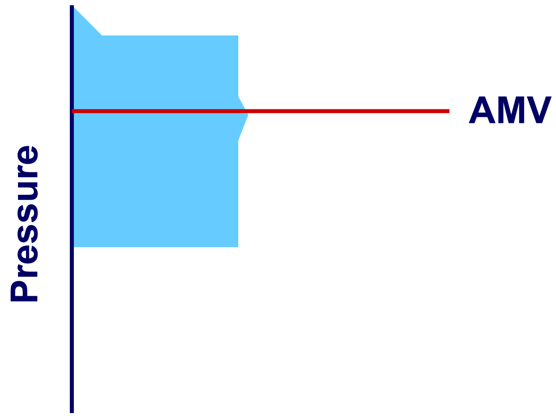
Observation Operator



AMVs are produced by tracking all the pixels in the target, although only some will dominate in the cross-correlation.

The cloud or WV feature also has a finite thickness, in case of CSWV can be 100's hPa thick.

Should we therefore represent them as layer observations?



BUT not trivial

- Placement of layer operator
- Width of layer operator
- Shape of layer operator

Investigations ongoing at CIMSS (Velden & Bedka)

Improved Representation of Satellite-Derived Atmospheric Motion Vectors by Attributing the Assigned Heights to Tropospheric Layers (draft)

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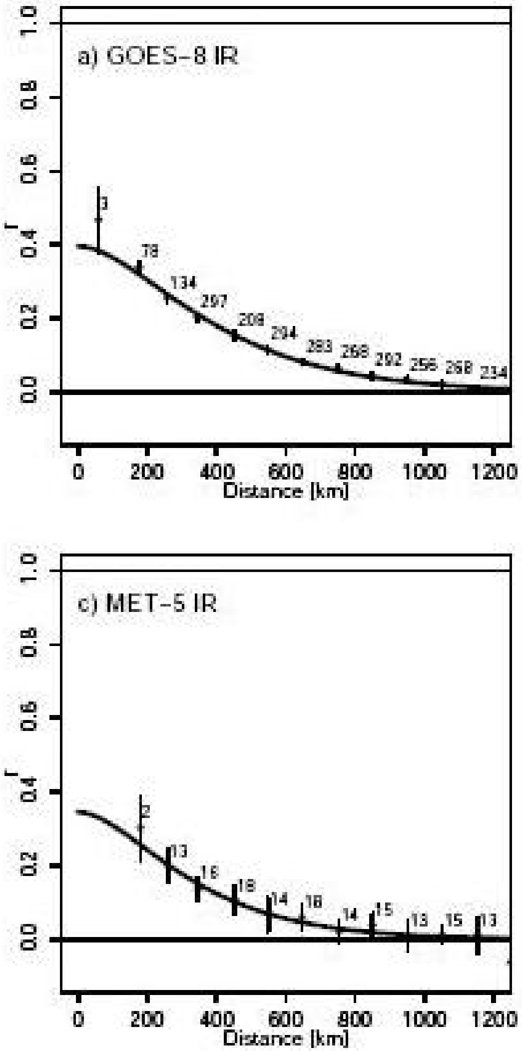
Spatial Error Correlations



Study by Bormann et al., 2003 (MWR, 131, 706-718) using a 1-yr dataset of AMV-radiosonde collocation pairs showed statistically significant spatial error correlations for distances up to ~800 km.

BUT

NWP systems assume uncorrelated error to reduce computation.

To alleviate problems, data is thinned and errors inflated.

New techniques to allow for correlated error are being considered at some centres (e.g. ECMWF), which would allow data to be used at higher resolution.

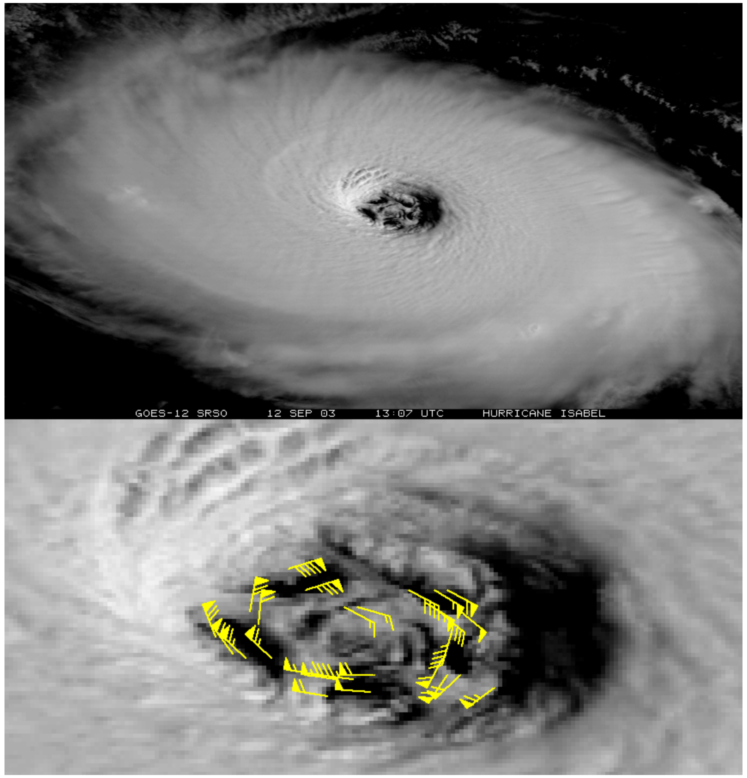
AMV-sonde departure correlations for NH winds, all levels, as a function of station separation. Error bars indicate 95% confidence intervals. Also shown is the fitted correlation function and the number of collocations used per data point (in hundreds).

AMVs for mesoscale applications

By tracking smaller targets and using small imager intervals it is possible to derive high resolution AMV datasets reflecting the motion of smaller scale features of the flow.

Applications:

1. Tropical Cyclone studies
2. Input to convective initiation nowcasting
3. Assimilation in mesoscale NWP models



From Velden et al, 2005

(Top) GOES-12 VIS imagery of Hurricane Isabel on 12 Sep 2003.

(Bottom) Low level AMVs in Isabel's eye derived from 3-min interval VIS imagery

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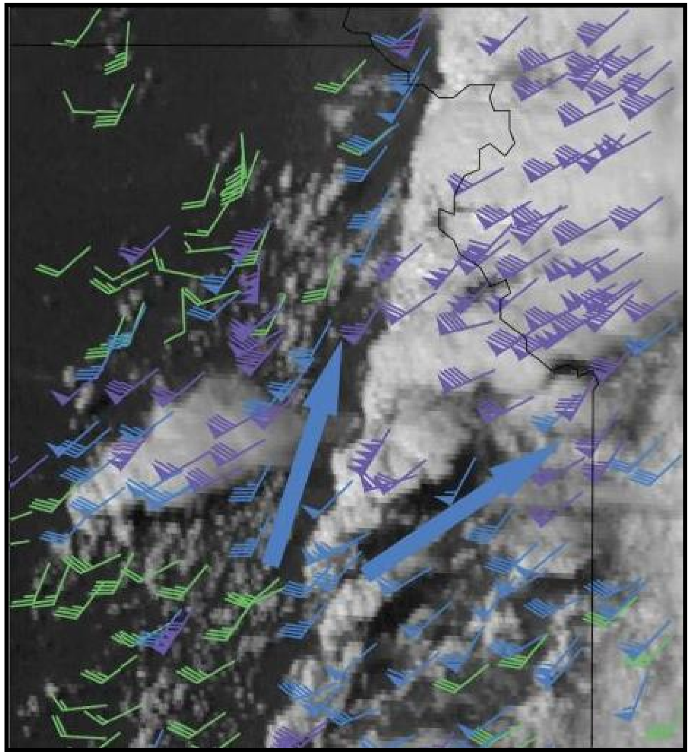

From Bedka and Mecikalski, 2005

Mesoscale AMVs overlaid on GOES-12 VIS imagery centred on developing convection over NE Kansas. Green - 1000–700 hPa, blue - 700–400 hPa and purple - 400–100 hPa. Blue arrows highlight mid tropospheric diffluence in the vicinity of the mature convection.

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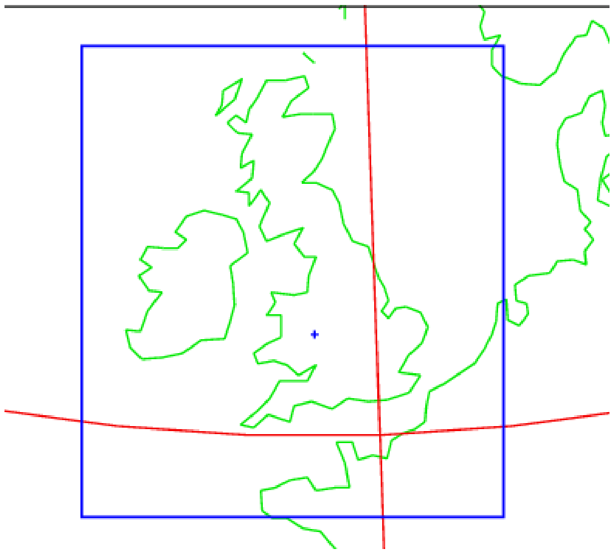


BUT spatially and temporally correlated error so hard to use data at full resolution.

Routine 5 minute interval rapid scan winds over Europe (Meteosat-8) from 2008

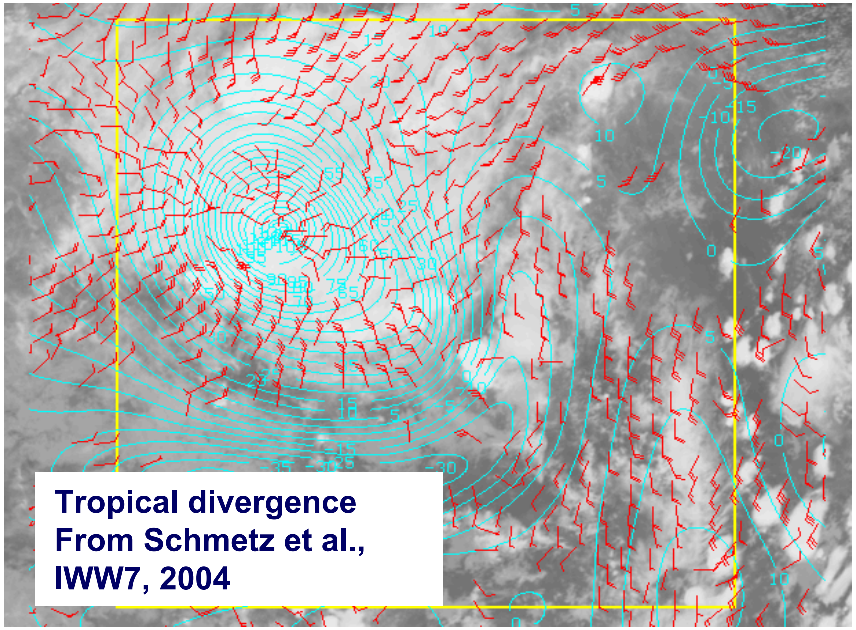
Derived products from AMVs

AMVs can be used to derive various fields including vorticity and divergence.

EUMETSAT are producing a tropical divergence product from the Meteosat-9 WV 6.2 AMVs.

Scale of features only 300-500 km. (AMVs thinned in 2° by 2° boxes).

Could be used for nowcasting and validation.

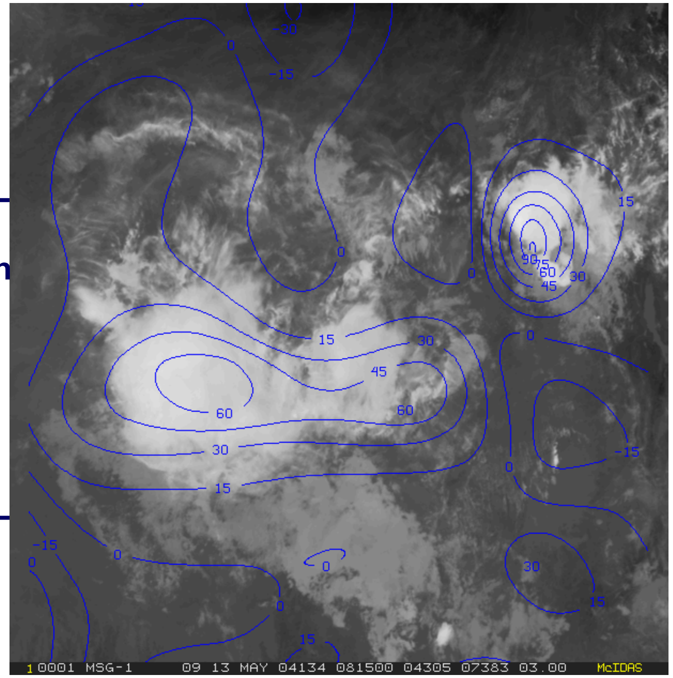


Tropical divergence From Schmetz et al., IWW7, 2004

Evolution of divergence pattern

13 May 2004 0815 – 2115

From Schmetz et al., IWW8, 2006

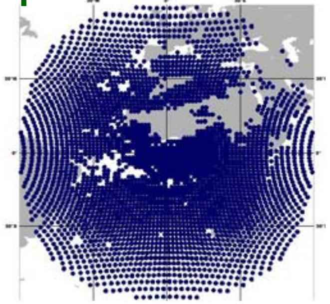


AMVs for reanalysis

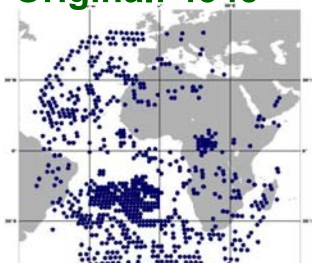
• EUMETSAT have reprocessed old satellite imagery to produce higher quality and higher resolution AMVs to support reanalysis projects e.g. ERA-40.

6th Feb 1989

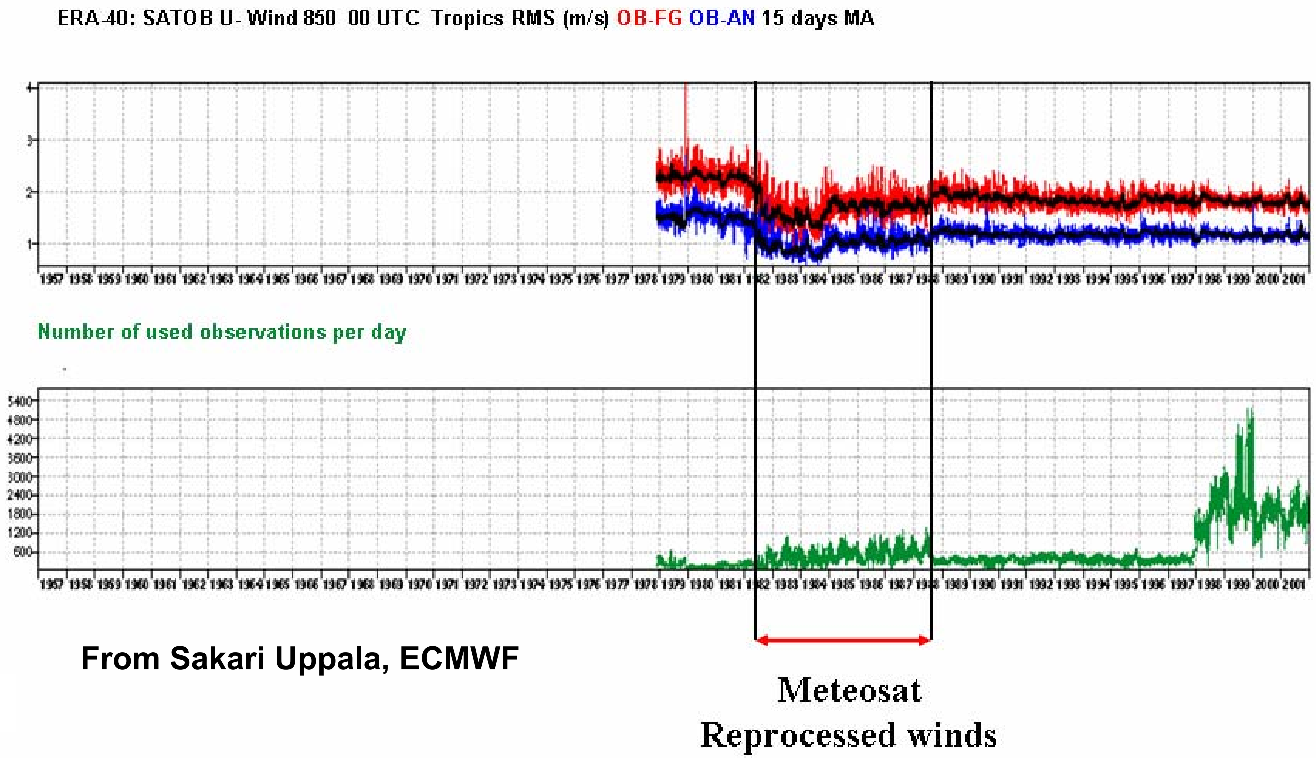
Reprocessed: 96615



Original: 4345



From Claire Delsol, ECMWF



From Sakari Uppala, ECMWF

• CIMSS are producing a 20-year AVHRR polar AMV dataset for assimilation in future reanalyses to help address the Arctic wind field errors in NCEP/NCAR and ECMWF reanalysis products (Dworak et al., 2006, IWW8).

The Present: summary

1. Current AMV assimilation is wasteful and quite crude.
2. Strategies to improve the assimilation include:
    - Individual errors
    - Observation operator changes to treat as layer
    - Allowance for spatially correlated error in VAR
3. We would benefit from:
    - Harmonisation of AMV derivation methodology
    - More information on AMV quality sent with each wind e.g. vector and height errors.
4. Various investigations (e.g. NWP SAF AMV monitoring, simulated data study) should continue to teach us more about the AMVs and their errors potentially leading to improvements in the AMV data.
5. AMVs can also be used for mesoscale studies, derived products and reanalysis.

The Future

Future requirements for wind data in NWP

NWP model will always need wind data to represent the divergent component of the flow properly.

Particularly important

1. in Tropics
2. for small-scale features of flow

Latter only likely to get more important as model resolution improves.

Therefore need to maintain/improve wind component of global observing system.

Preferably have good horizontal, temporal and vertical coverage

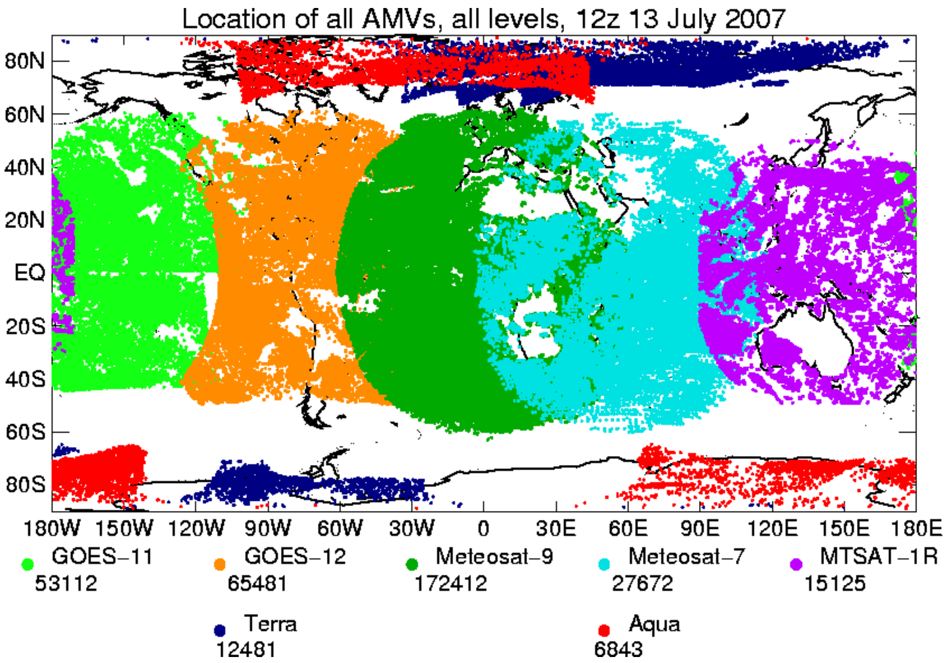
Maintaining the AMV observations

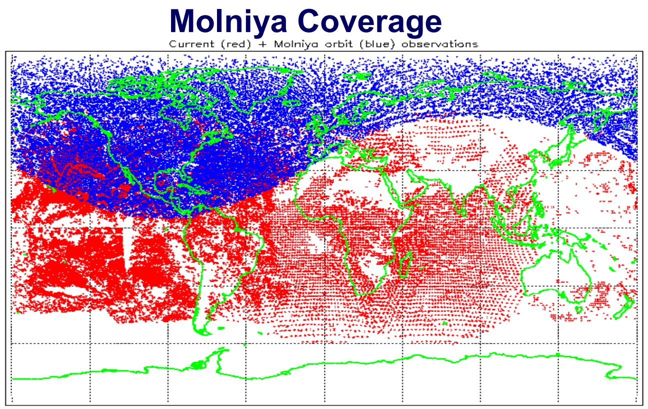
Ideally minimum of

- 5 geostationary
- 2 polar

Maintain good channel range on imagers (IR, VIS, WV, CO_2).

One concern is lack of a WV channel on polar imagers after MODIS until at least 2016.





From Riishojgaard, IWW8 talk

Other wind observations for the future

Doppler Wind Lidar Winds

Timescale: 2009

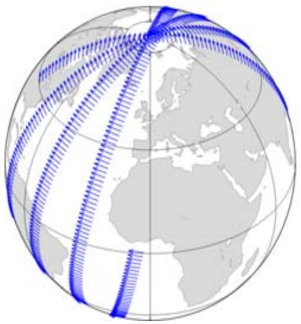
ADM-Aeolus 3 year mission (ESA)

Provide wind profiles

Expect positive impact on forecast quality (Tan and Andersson, 2005; Stoffelen et al., 2006)

BUT

1. Limited horizontal coverage
2. Only cross-track component of wind

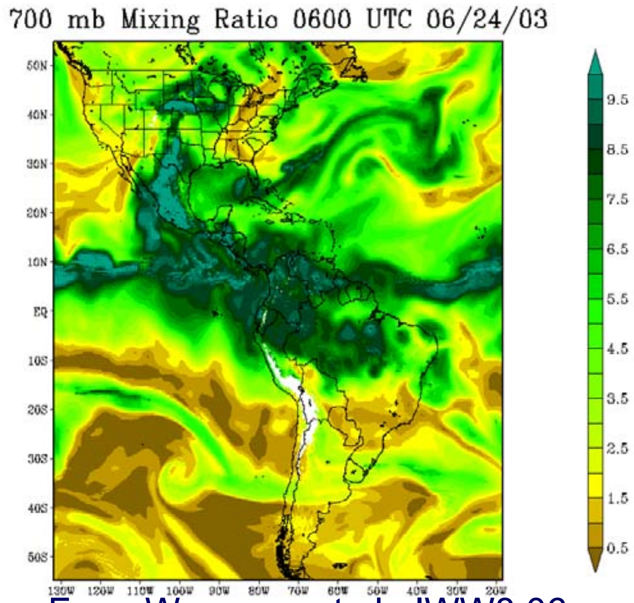


Other wind observations for the future

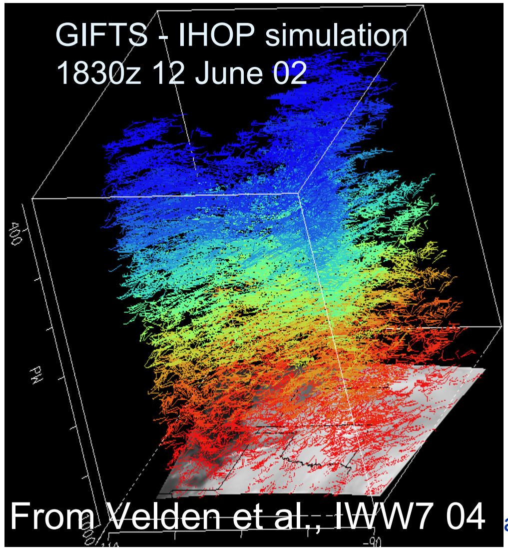
Hyperspectral sounder winds

Timescale: 2015-2020

- Advanced IR sounders on future geostationary platforms will have more and sharper weighting functions.
- Can use the sounder data to derive high vertical resolution moisture analyses in clear sky areas.
- Wind profiles can be derived by applying AMV tracking techniques to sequences of moisture analyses on different levels.
- Resulting winds should have more reliable heights than traditional AMVs.



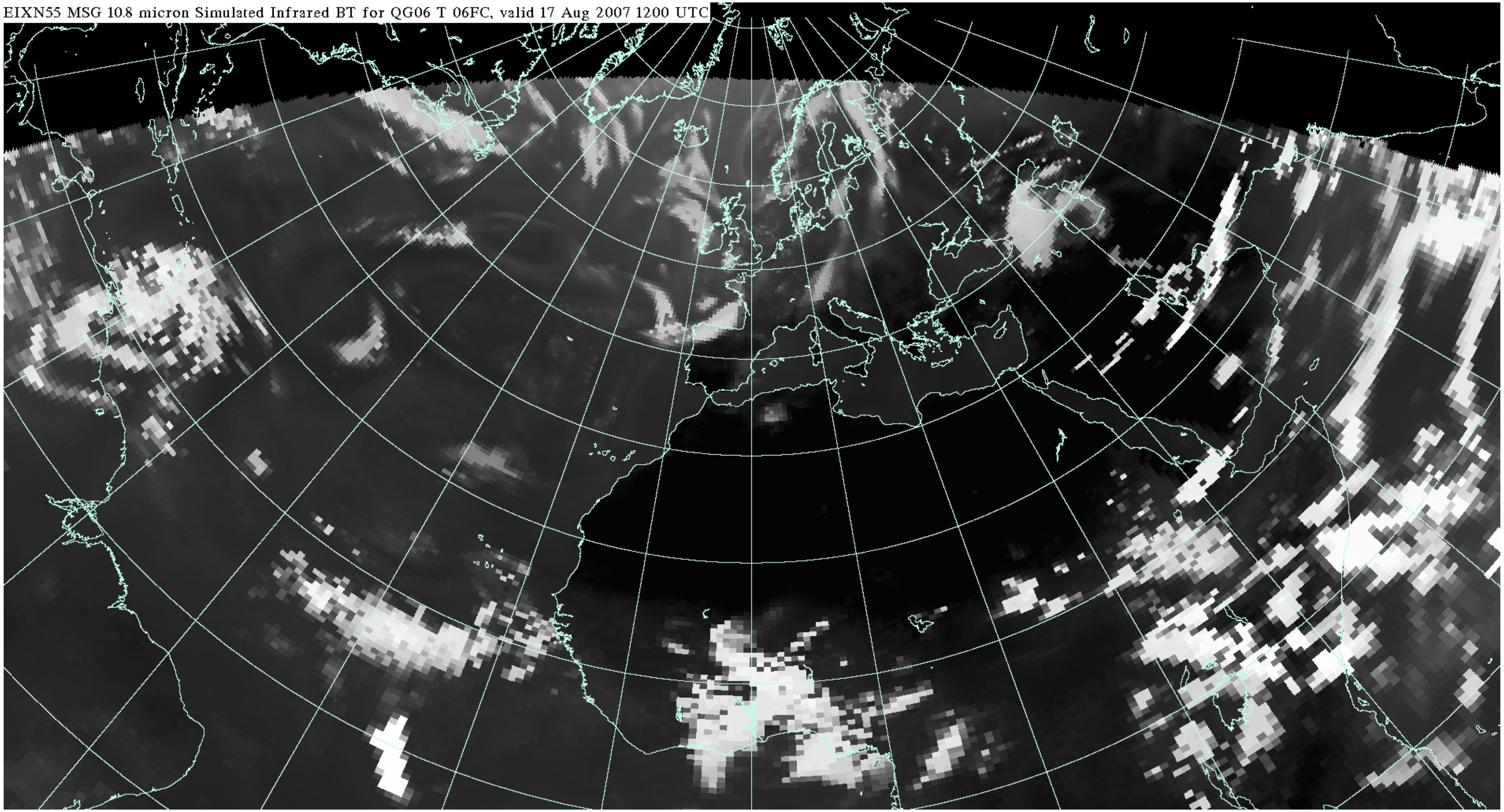
From Wanzong et al., IWW8 06



From Velden et al., IWW7 04

AMV assimilation versus radiance assimilation

Can also get wind information by assimilating cloud/moisture information in 4D-Var, but need to represent cloud well and horizontal and temporal resolution limited by analysis. Therefore AMVs likely to remain useful for many years.



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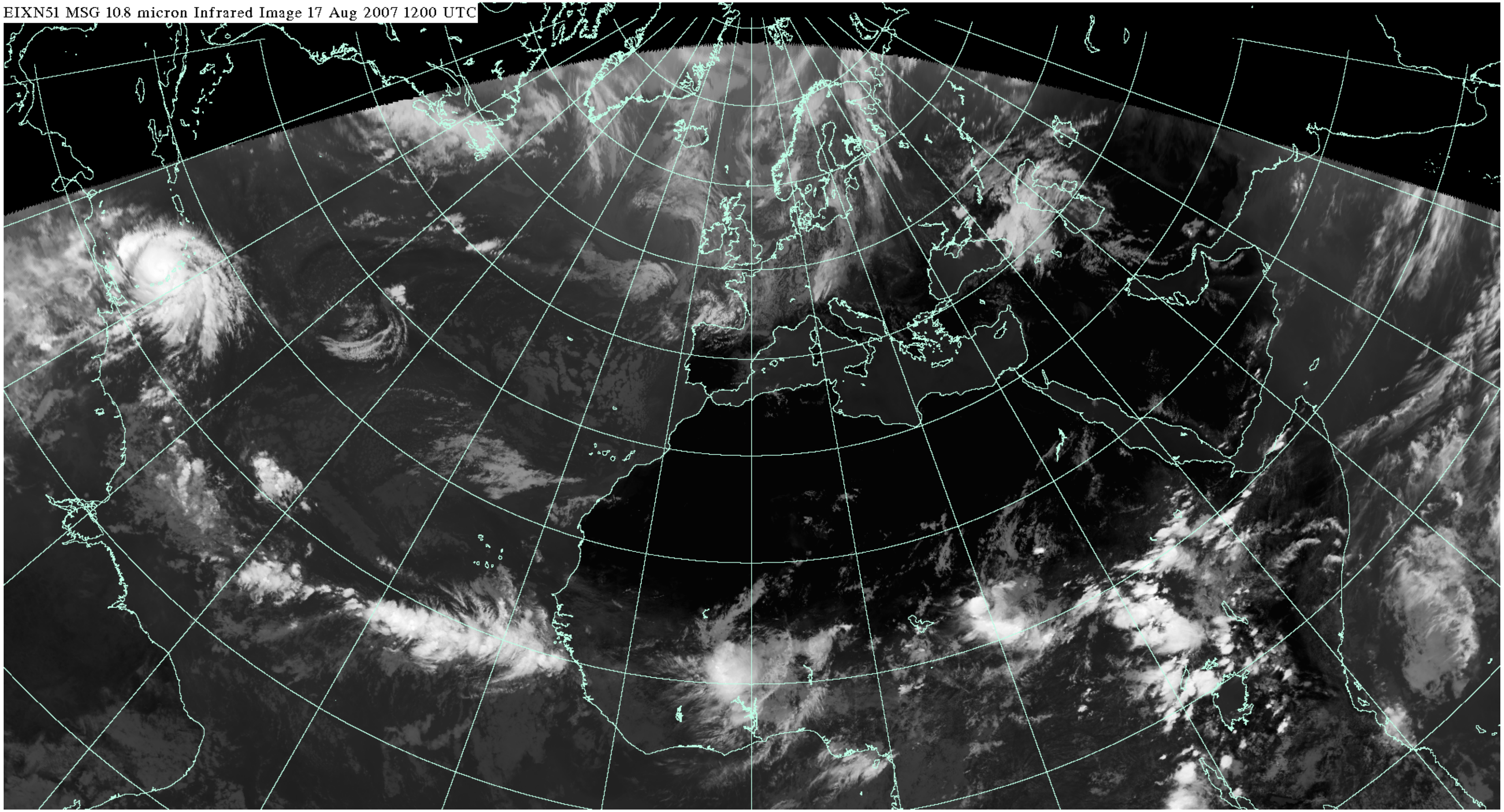

The Future: Summary

1. Wind observations will remain important for NWP.
2. Future tropospheric wind data likely to be provided by sondes, aircraft, wind profilers, AMVs, Doppler Wind Lidar and potentially hyperspectral sounder winds.
3. Direct assimilation of cloudy radiances may one day make AMVs redundant, but this is unlikely to happen for many years.

Talk Summary

1. AMVs were first produced in real-time in the 1970s, but since this time the data volume, coverage and quality has markedly increased.
2. Impact experiments show benefit to forecast accuracy and hurricane track forecasts.
3. A major limitation is the complicated and spatially correlated errors. It is important to consider what AMVs are representative of and to go back to fundamentals to understand error characteristics.
4. Greater benefit of AMVs in NWP should be possible through:
   - Improvements to data
   - More information on quality and representivity
   - Improvements to assimilation strategy

Any Questions?