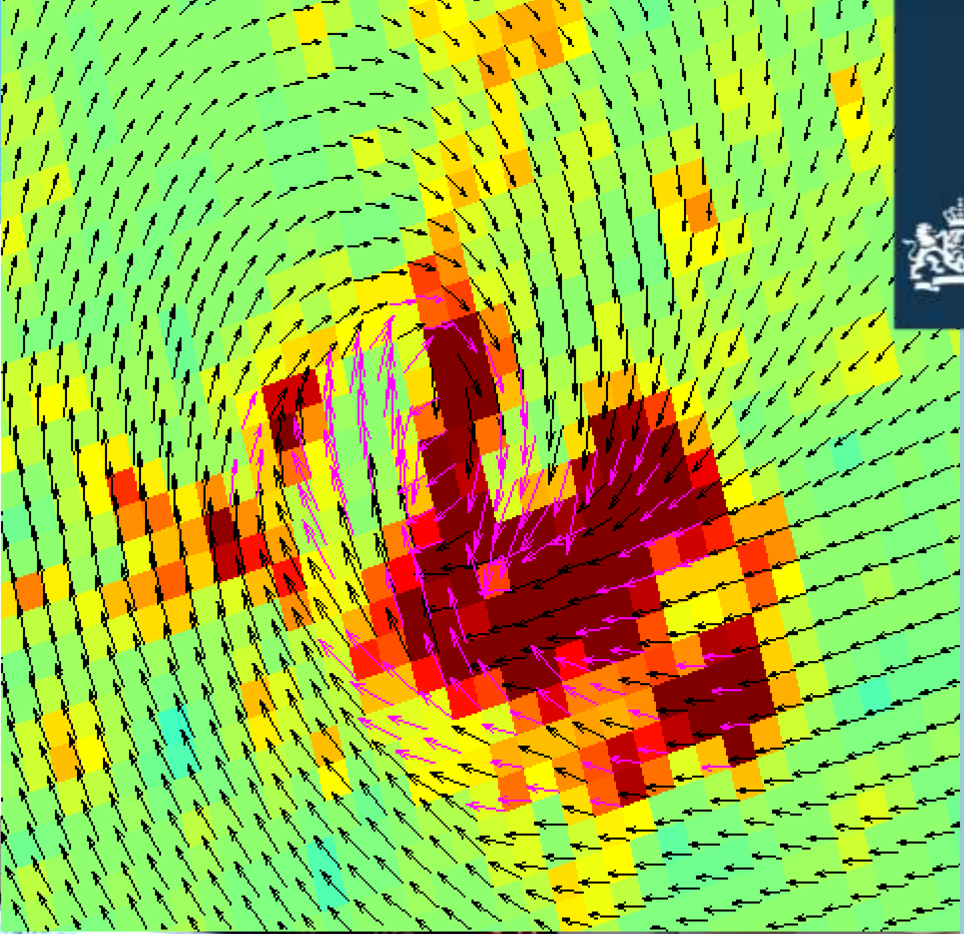
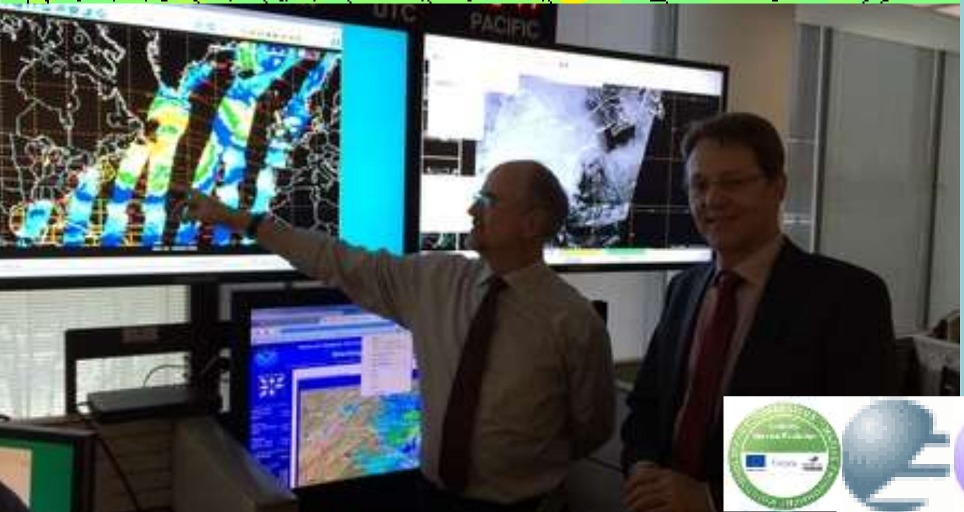




Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

Mesoscale Wind Data Assimilation

Ad.Stoffelen@knmi.nl

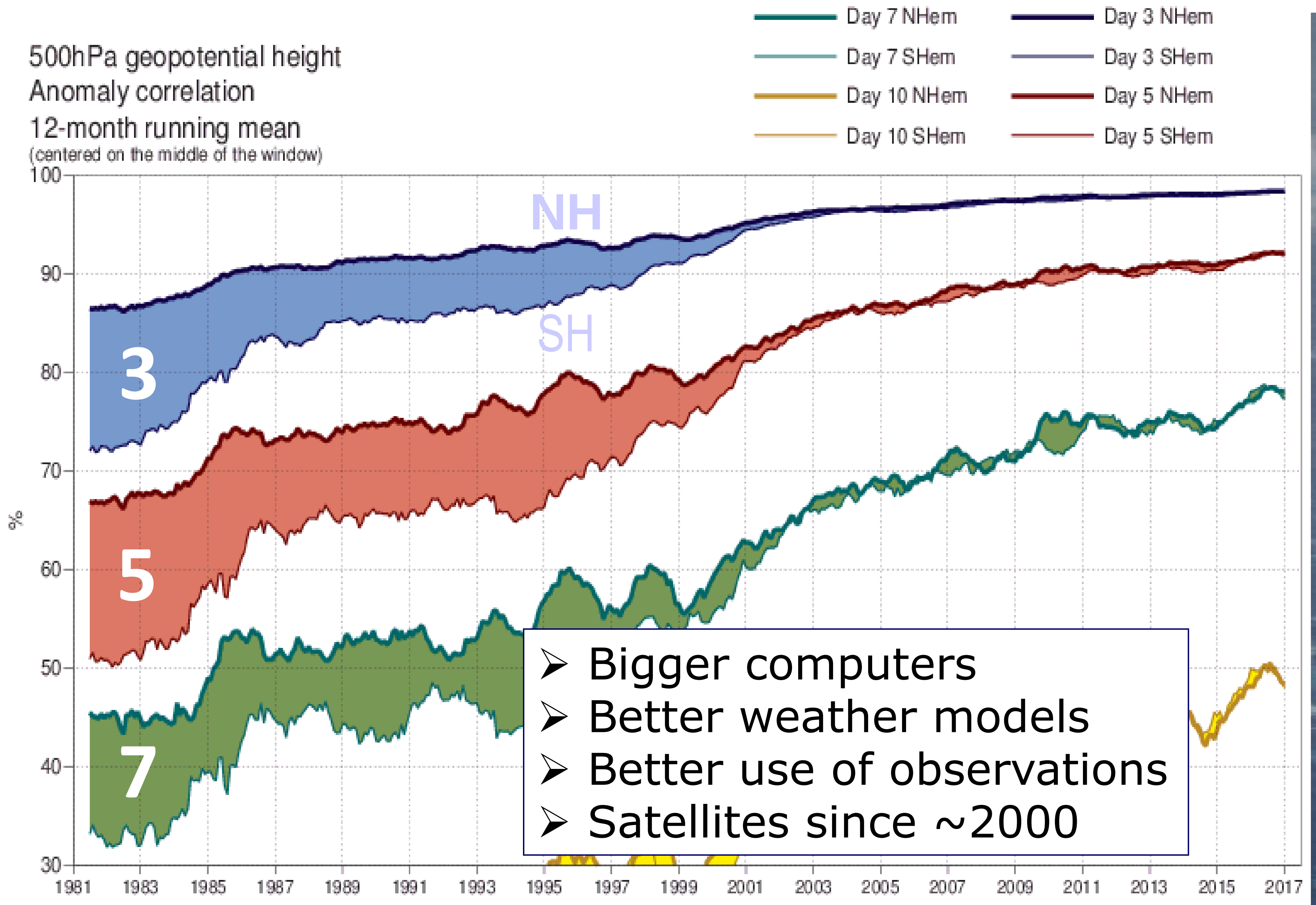
Leader Active Remote Sensing Group
Satellite Observations, KNMI

EUMETSAT OSI SAF
EU Copernicus Marine Core Services
ESA Aeolus L2 product development
EUMETSAT NWP SAF

Mesoscale Wind Data Assimilation

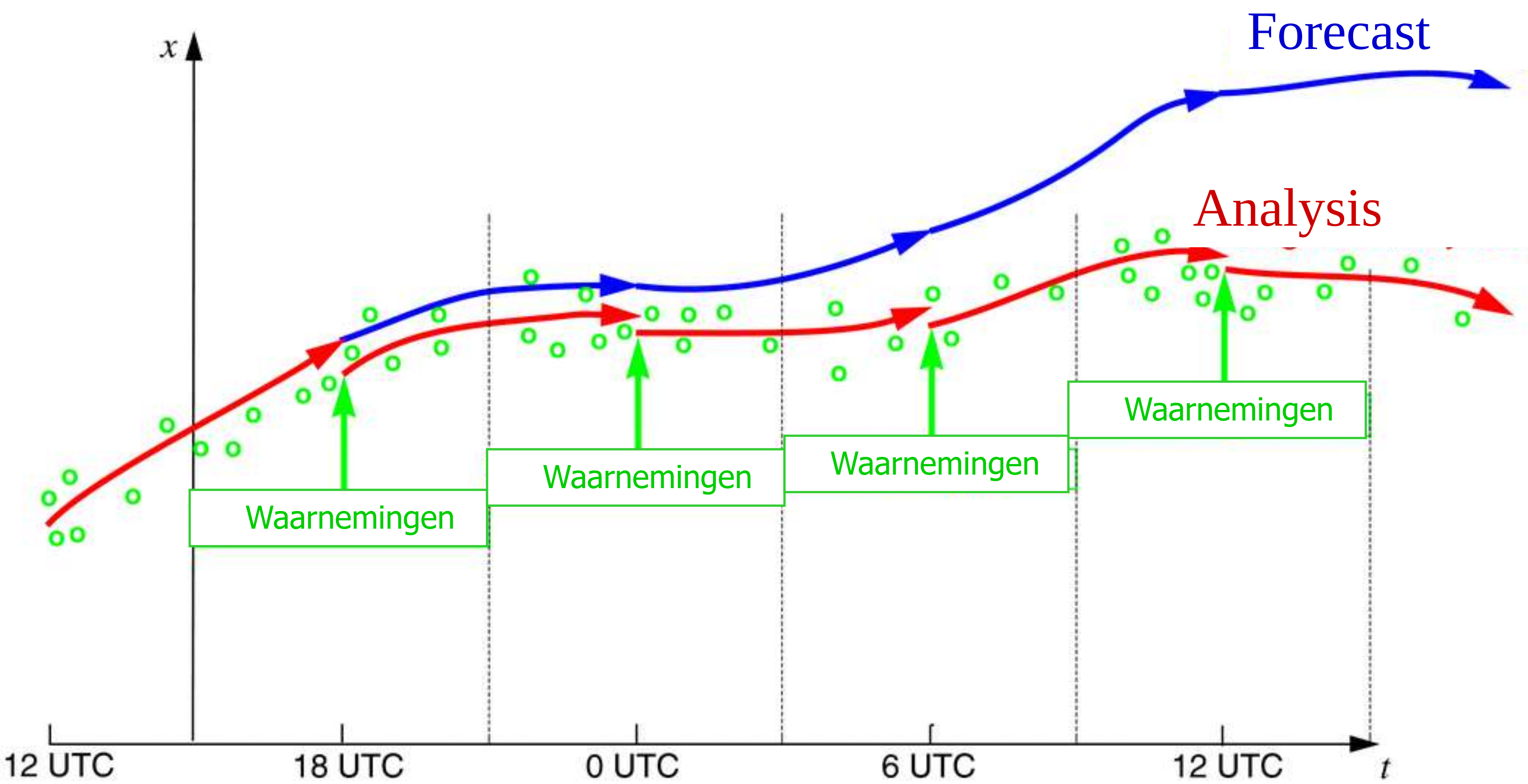
- What do we need ?
- Wind observations
- How well do we model ?
- How to assimilate observations ?

Weather Forecasts keep improving



- Bigger computers
- Better weather models
- Better use of observations
- Satellites since ~2000

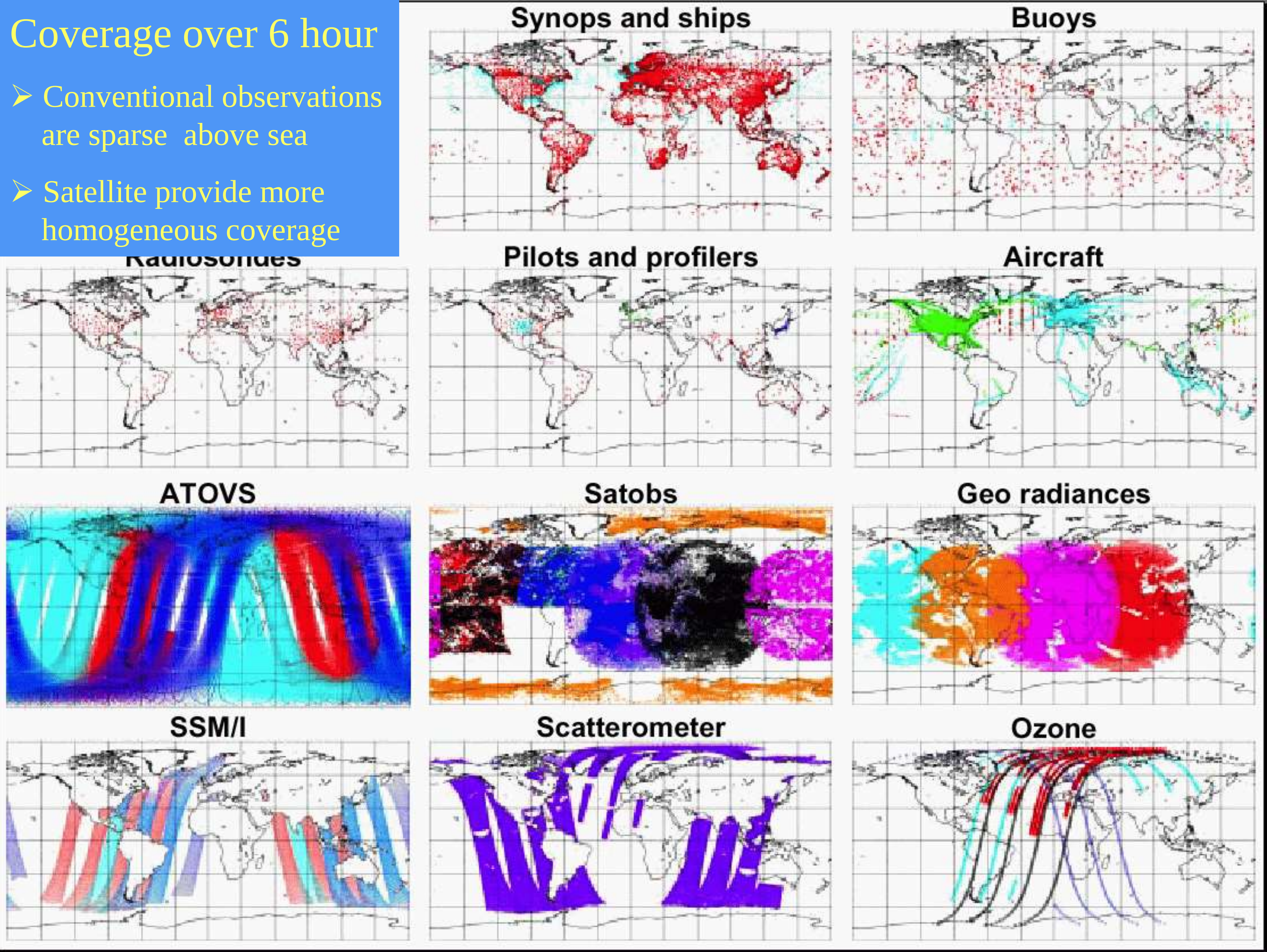
Observations lead weather models

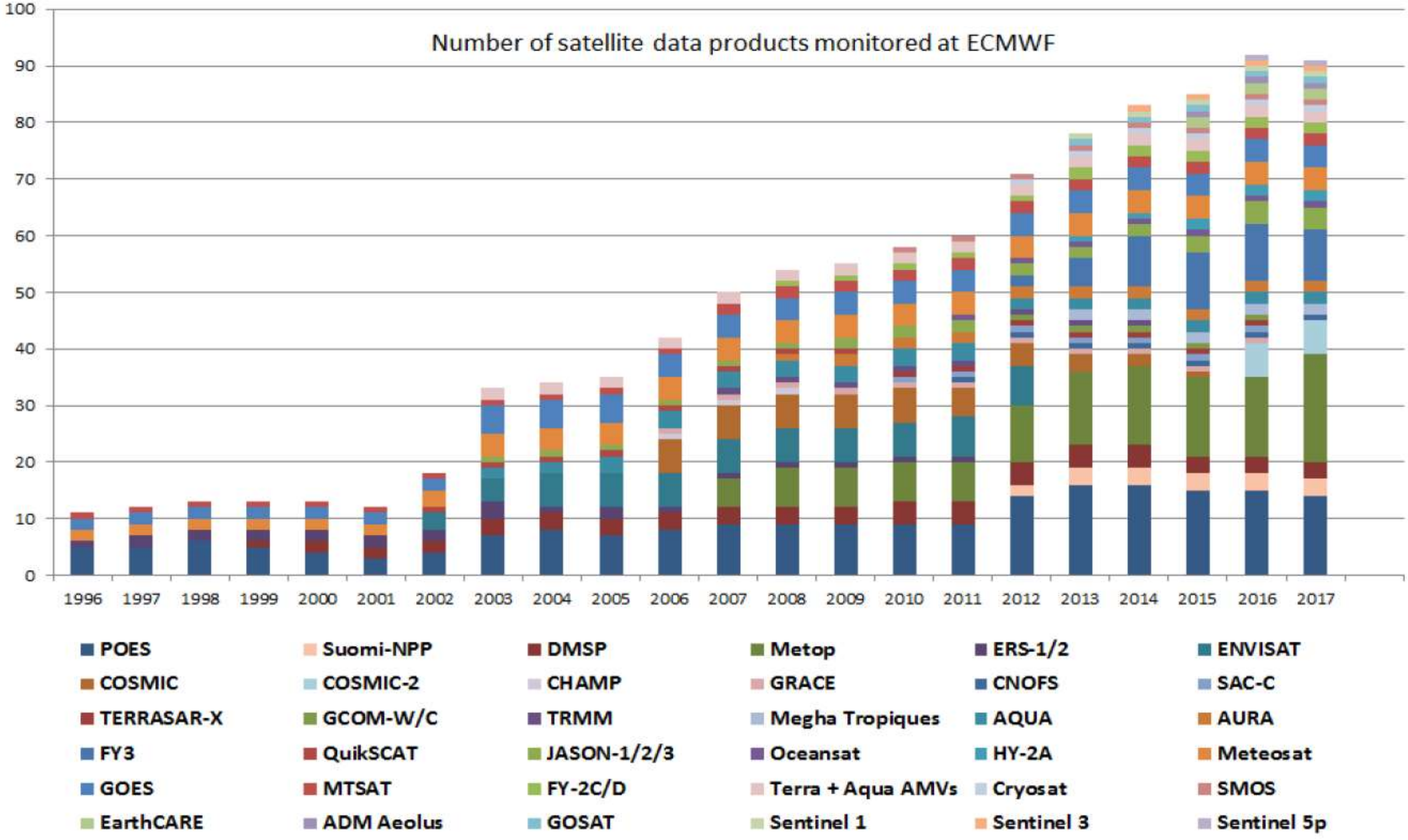


- Series of weather analyses determine climate

Coverage over 6 hour

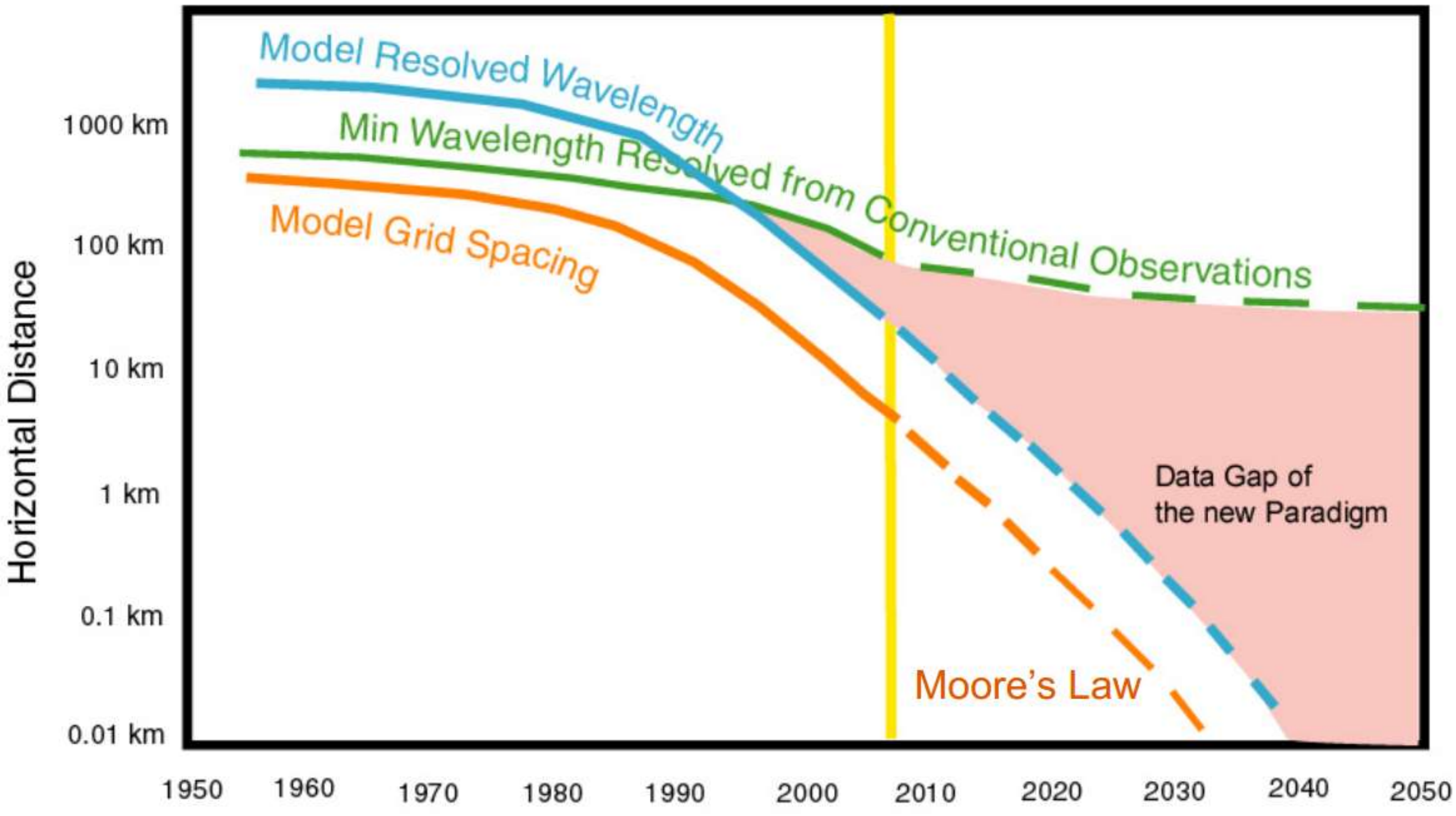
- Conventional observations are sparse above sea
- Satellite provide more homogeneous coverage





- Still new satellites with new instruments
- Are forecasts increasingly better?
- What observations are needed ?

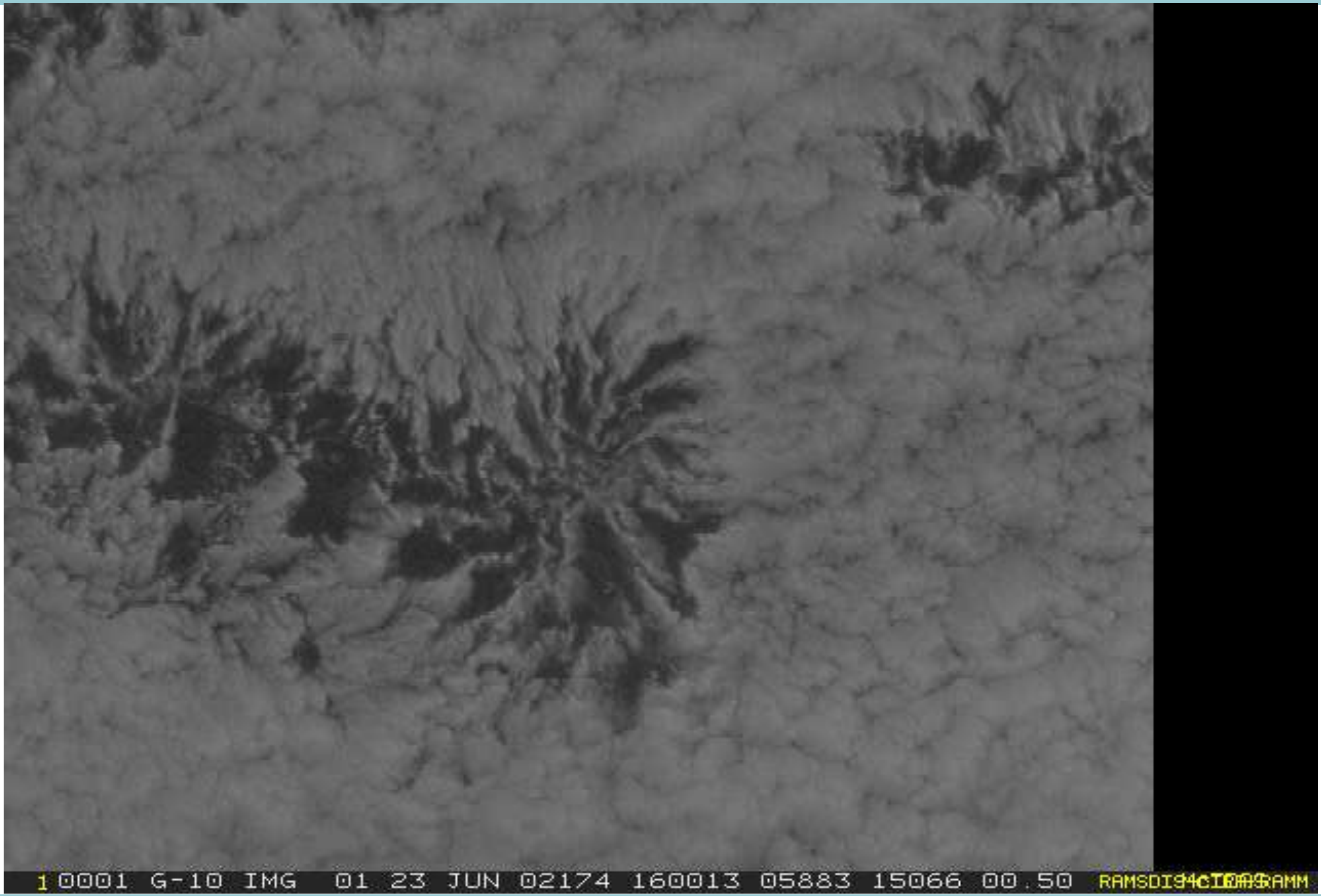
Can we still improve meteorology?



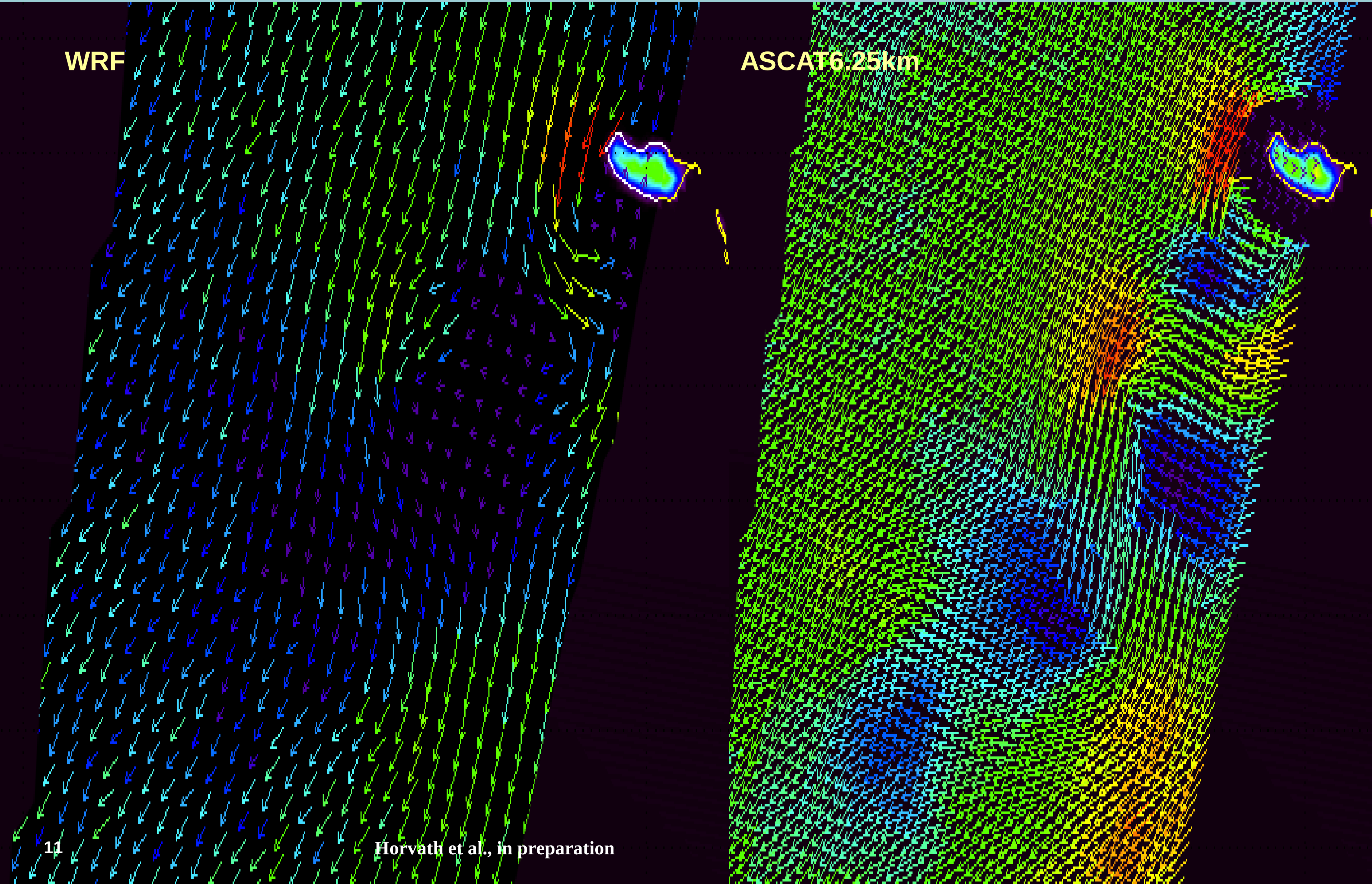
Greg.J. Tripoli, Un. Wisconsin

What steers convection?

And what stratiform processes?

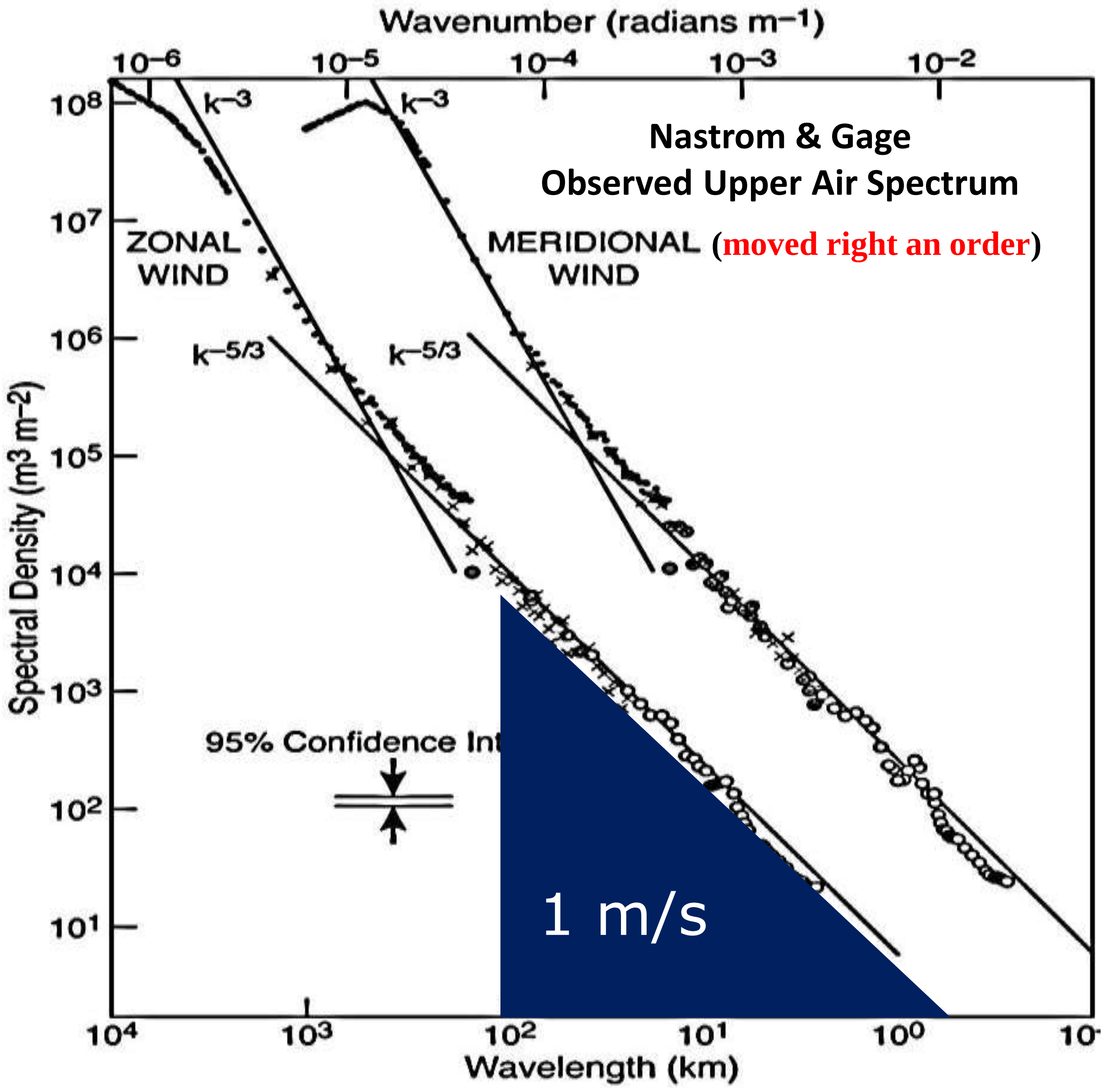


Observations and Models



Horvath et al., in preparation

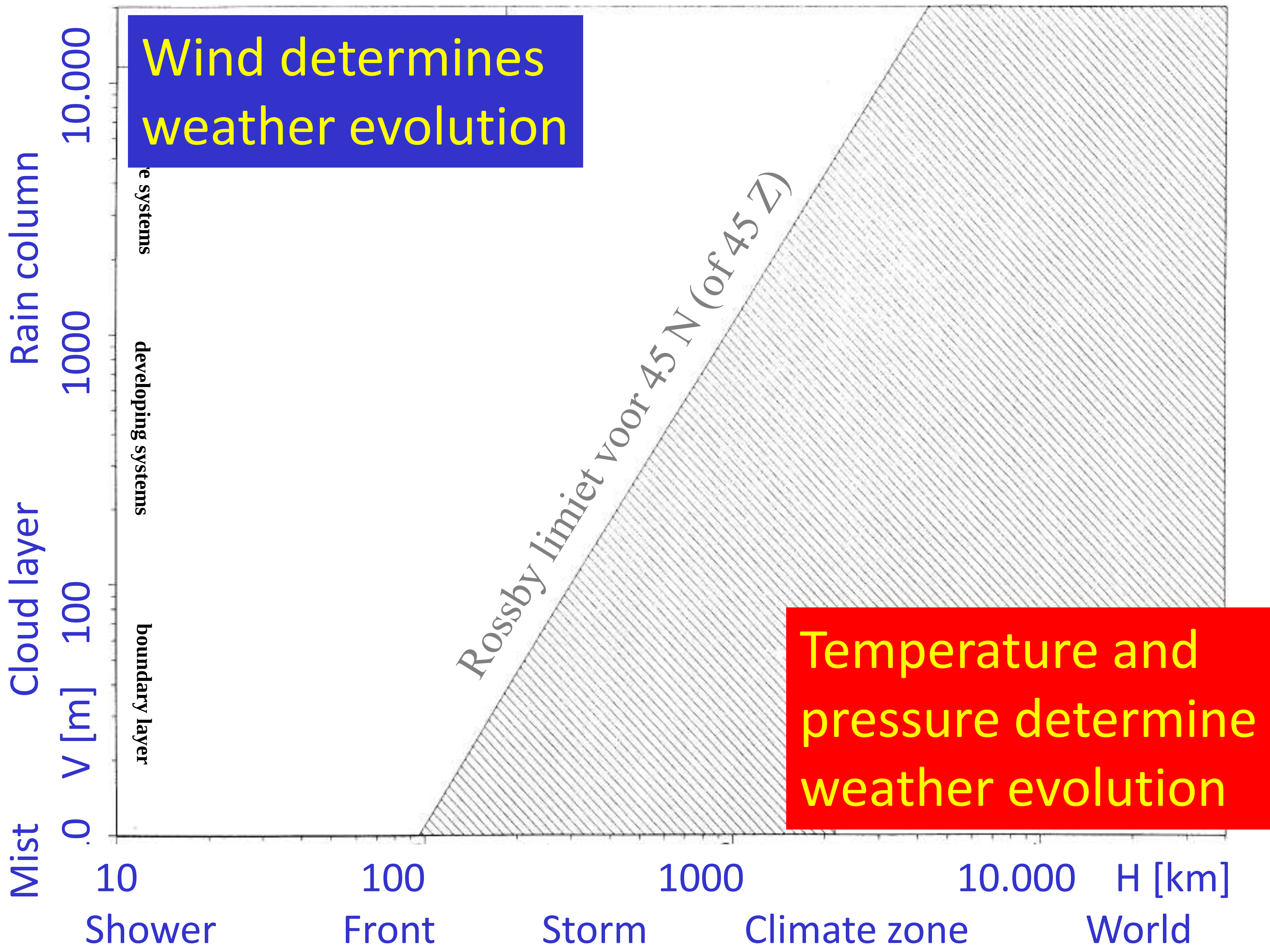
Mesoscale 3D turbulence



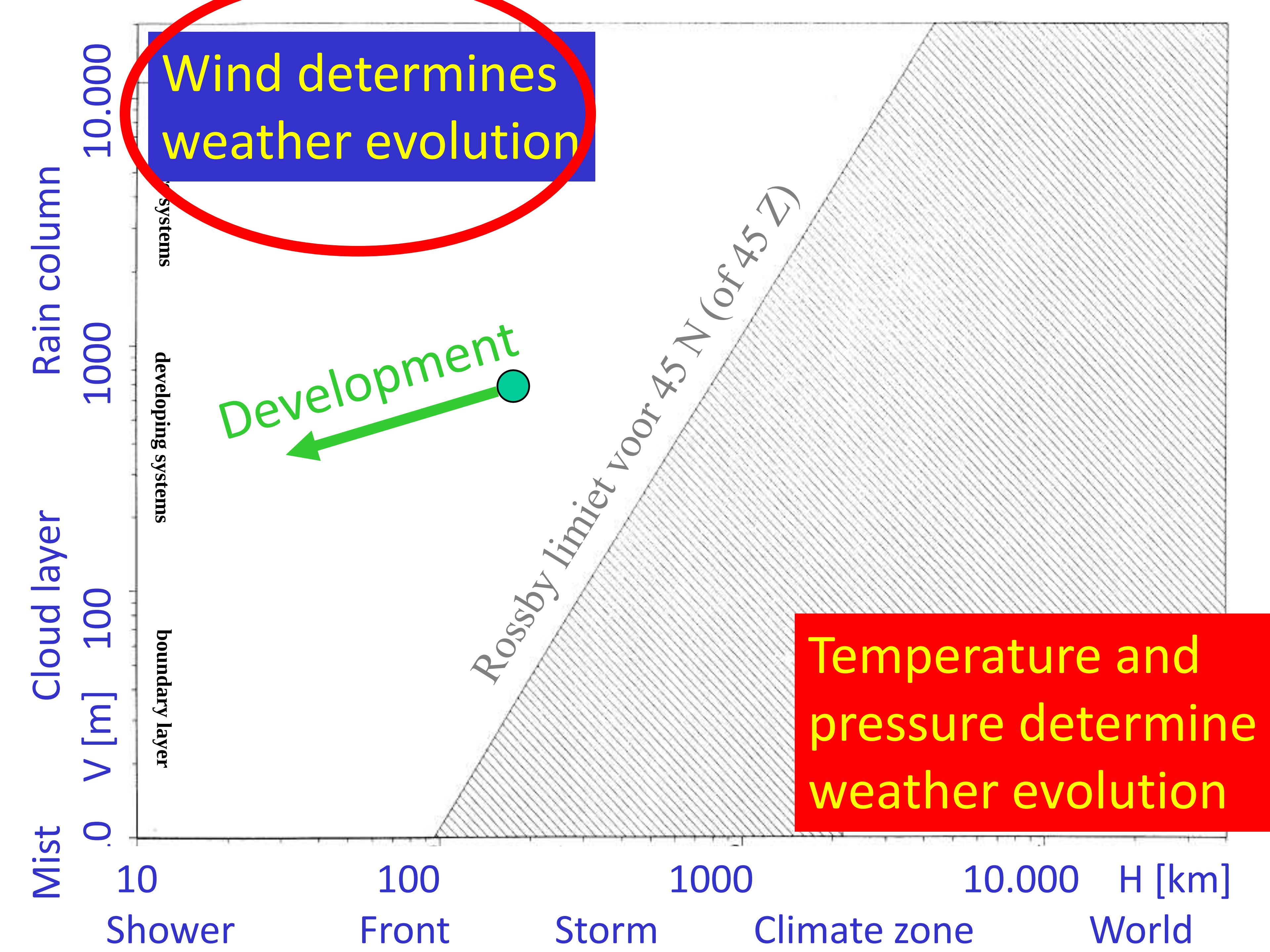
- Tropospheric spectra are close to $k^{-5/3}$
- 3D turbulence for scales below 500 km
- L/H ~ 100
- SD = 0.4 (log spectral density)

➢ Least variance/ detectability in small scales

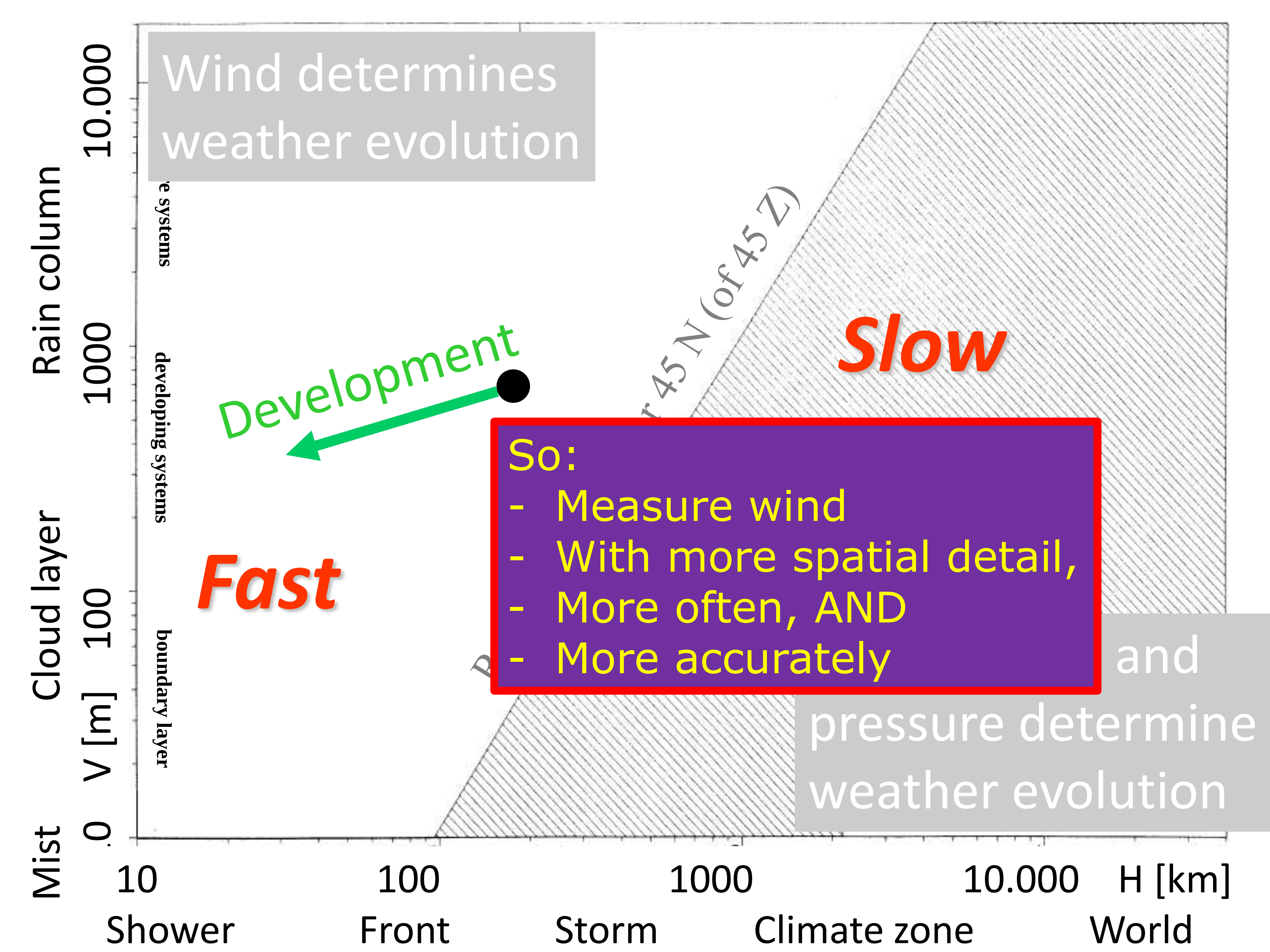
➢ Measure wind to forecast the weather



Wind determines weather evolution
Temperature and pressure determine weather evolution
Rossby limiet voor 45 N (of 45 Z)
e systems
developing systems
boundary layer
Mist
Cloud layer
Rain column
V [m]
0
100
1000
10.000
10
100
1000
10.000
H [km]
Shower
Front
Storm
Climate zone
World



Wind determines weather evolution
systems
developing systems
boundary layer
Development
Rossby limiet voor 45 N (of 45 Z)
Temperature and pressure determine weather evolution
Rain column
Cloud layer
Mist
10.000
1000
100
0
V [m]
10
100
1000
10.000
H [km]
Shower
Front
Storm
Climate zone
World



Wind determines weather evolution
Rain column
10.000
1000
Cloud layer
100
V [m]
0
Mist
developing systems
boundary layer
Development
Slow
Fast
So:
- Measure wind
- With more spatial detail,
- More often, AND
- More accurately
and
pressure determine
weather evolution
10
100
1000
10.000
H [km]
Shower
Front
Storm
Climate zone
World

Definition

Full name	Wind speed over the surface (horizontal)		
Definition	Module of the horizontal component of the 3D wind vector.		
Measuring Units	m/s	**Uncertainty Units**	m/s
Horizontal Res Units	km	**Vertical Res Units**	
Stability Units	m/s (Stability /decade)		
Comment:			
Last modified:			

Classification

- **Domain:** Atmosphere
  - **Sub-domain:** Basic atmospheric
    - **Variable:** Wind speed over the surface (horizontal)
      - **Measured in Layers:**
        - Near Surface
- **Cross-cutting themes:**

- **Used in Application Areas:**
  - Agricultural Meteorology
  - Global NWP
  - High Res NWP
  - Nowcasting / VSRF
  - Climate-OOPC

WMO OSCAR data base
https://www.wmo-sat.info/oscar/variables/view/181

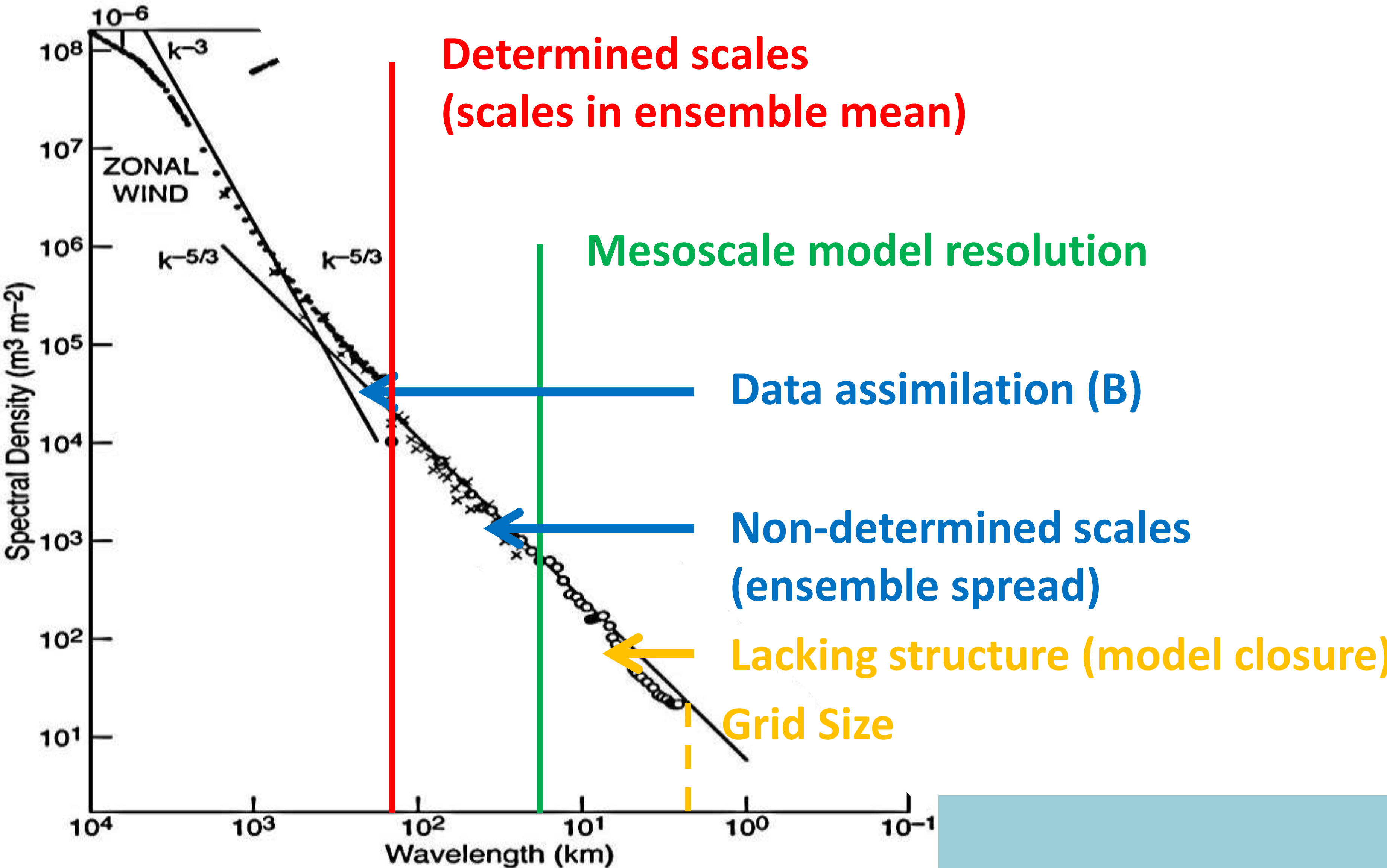
Requirements defined for *Wind speed over the surface (horizontal)* (8)

This tables shows all related requirements. For more operations/filtering, please consult the full list of Requirements

Note: In reading the values, goal is marked blue, breakthrough green and threshold orange

Id	Variable	Layer	App Area	Uncertainty	Stability / decade	Hor Res	Ver Res	Obs Cyc	Timeliness	Coverage	Conf Level	Val Date	Source
318	Wind speed over the surface (horizontal)	Near Surface	Global NWP	0.5 m/s 1.5 m/s 2 m/s		15 km 100 km 250 km		60 min 6 h 12 h	6 min 30 min 6 h	Global land	firm	2009-02-10	John Eyre
319	Wind speed over the surface (horizontal)	Near Surface	Global NWP	0.5 m/s 1.5 m/s 2 m/s		15 km 100 km 250 km		60 min 6 h 12 h	6 min 30 min 6 h	Global ocean	firm	2009-02-10	John Eyre
389	Wind speed over the surface (horizontal)	Near Surface	High Res NWP	0.5 m/s 1 m/s 3 m/s		0.5 km 5 km 20 km		30 min 60 min 3 h	15 min 30 min 2 h	Global land	firm	2011-08-04	T Montmerle
390	Wind speed over the surface (horizontal)	Near Surface	High Res NWP	0.5 m/s 1 m/s 3 m/s		0.5 km 5 km 20 km		30 min 3 h 12 h	15 min 30 min 2 h	Global ocean	firm	2011-08-04	T Montmerle
455	Wind speed over the surface (horizontal)	Near Surface	Nowcasting / VSRF	1 m/s 1.4 m/s 3 m/s		1 km 5 km 20 km		5 min 15 min 60 min	5 min 15 min 60 min	Global land	reasonable	2013-04-08	P. Ambrosetti
456	Wind speed over the surface (horizontal)	Near Surface	Nowcasting / VSRF	1 m/s 1.4 m/s 3 m/s		5 km 10 km 50 km		15 min 30 min 3 h	15 min 30 min 60 min	Global ocean	firm	2013-04-08	P. Ambrosetti

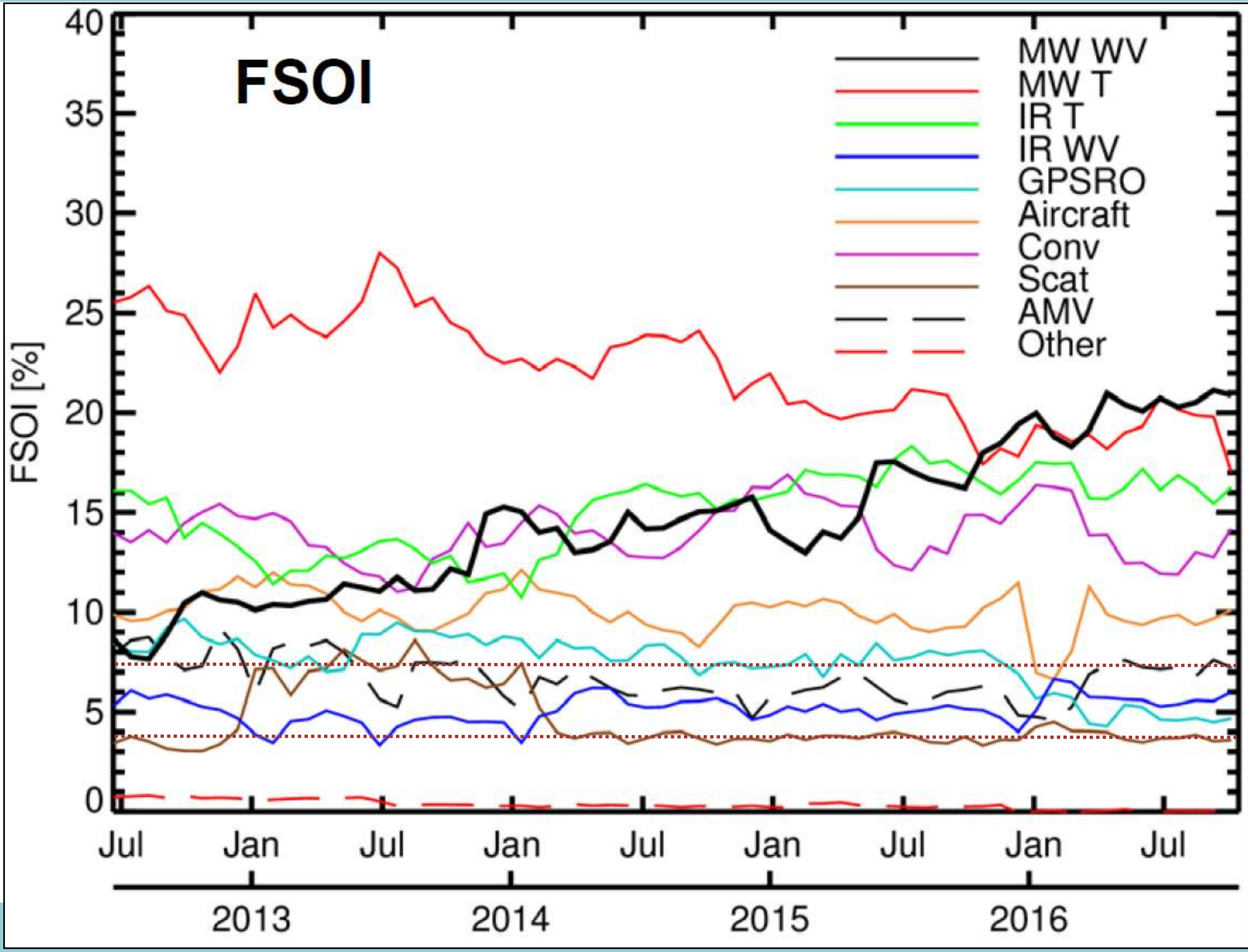
Nastrom & Gage Observed Spectrum



Needed time coverage of wind data

- ❖ Wind information at 12:00 from OSCAT in 2013 appears fully complement-ary to wind information at 9:30 from ASCATs in global NWP

- ➢ Fly a wind sensor every 3 hours



What do we need ?

- Winds for mesoscale dynamics, shear, convergence, . . .
- At high accuracy
- High spatial and temporal density
- Everywhere, not only in dynamic weather
- Fill gaps over the oceans, tropics and southern hemisphere, particularly UTLS
- Fast timeliness
- Well calibrated winds (no bias; BLUE)

Mesoscale Wind Data Assimilation

- What do we need ?
- Wind observations
- How well do we model ?
- How to assimilate observations ?

+ Above sea

– Only at the surface

Obs Type

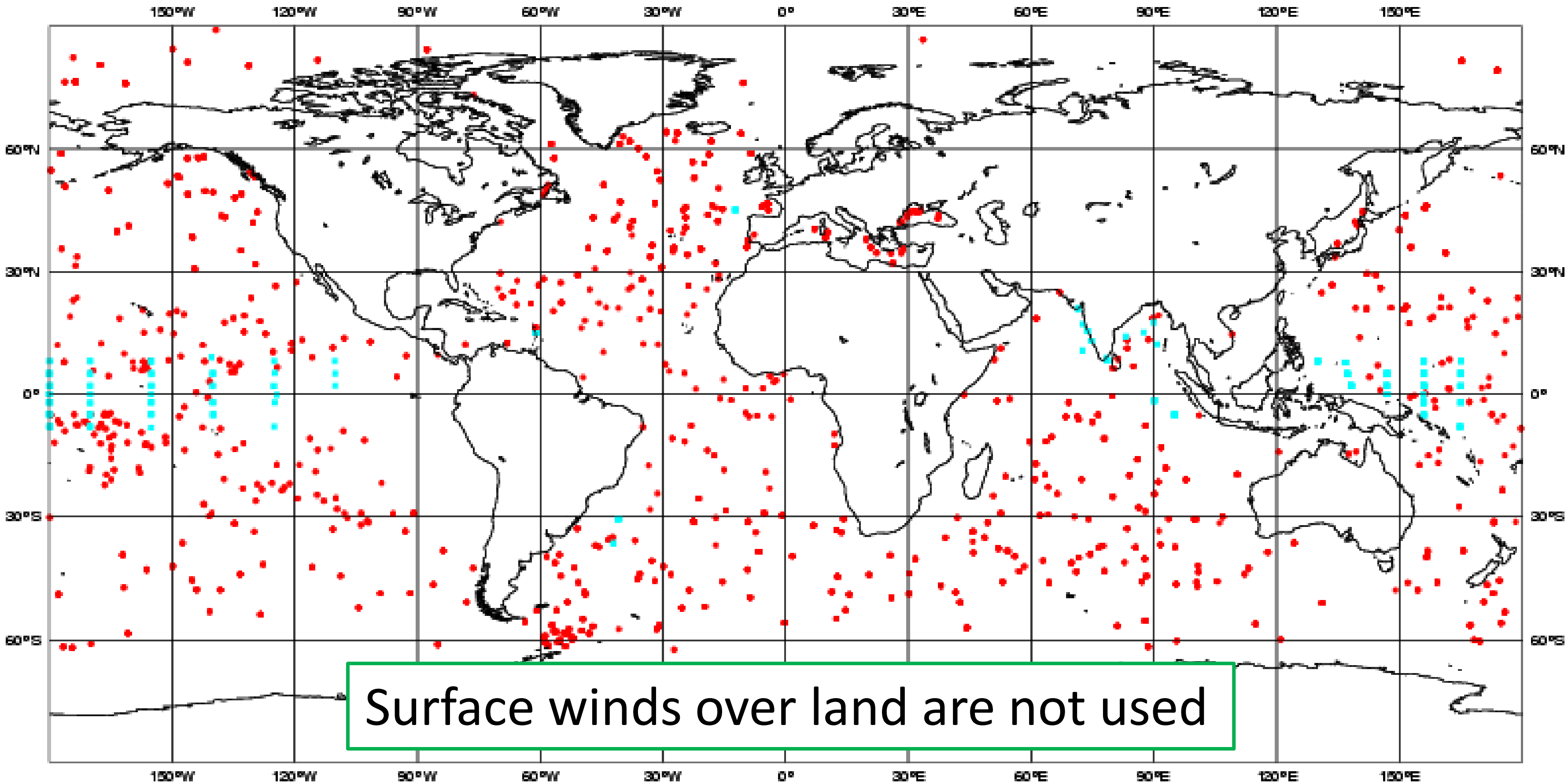
2567 DRIFTER

223 MOORED

ECMWF Data Coverage (All obs) - BUOY

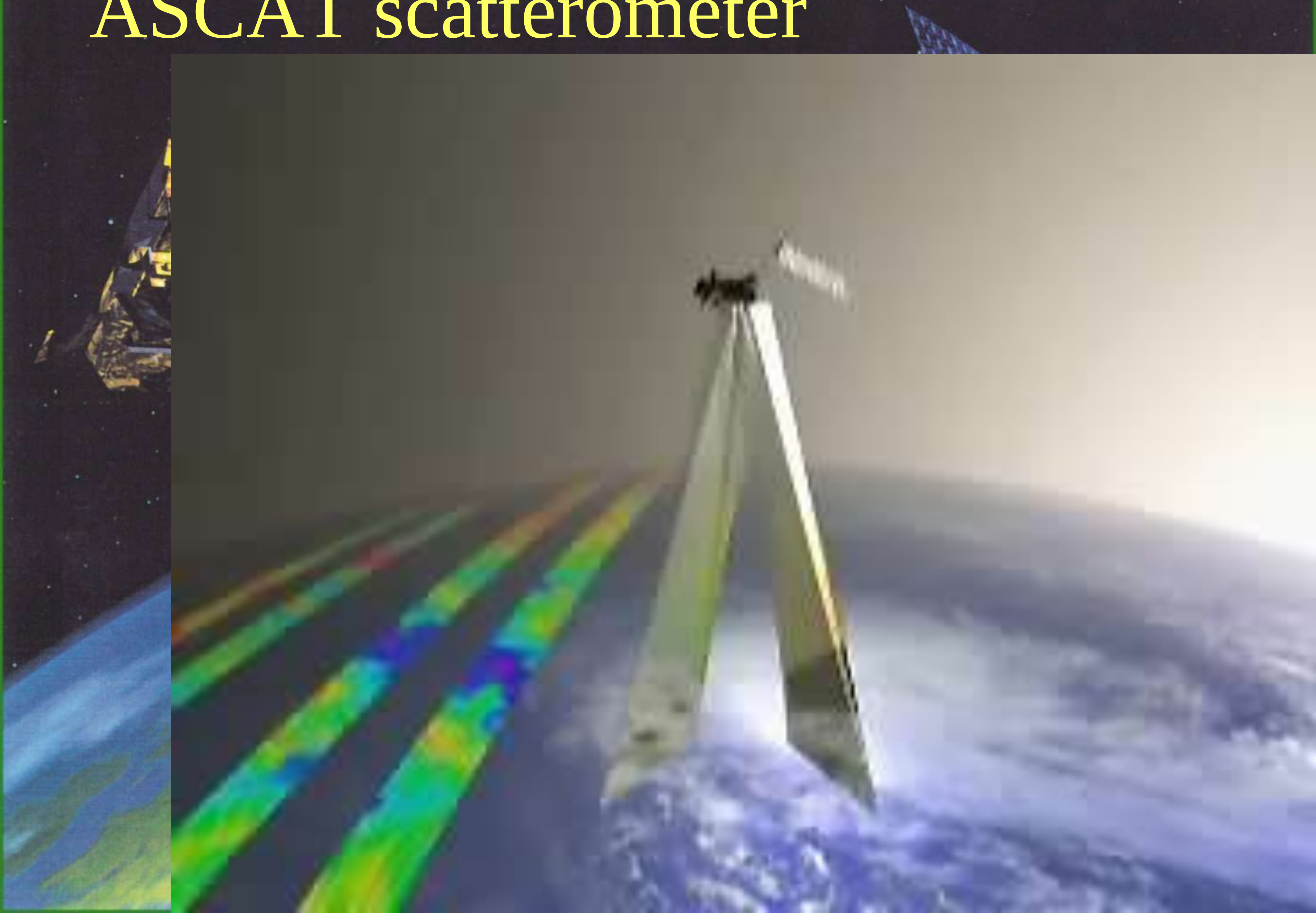
04/APR/2003; 00 UTC

Total number of obs = 2790

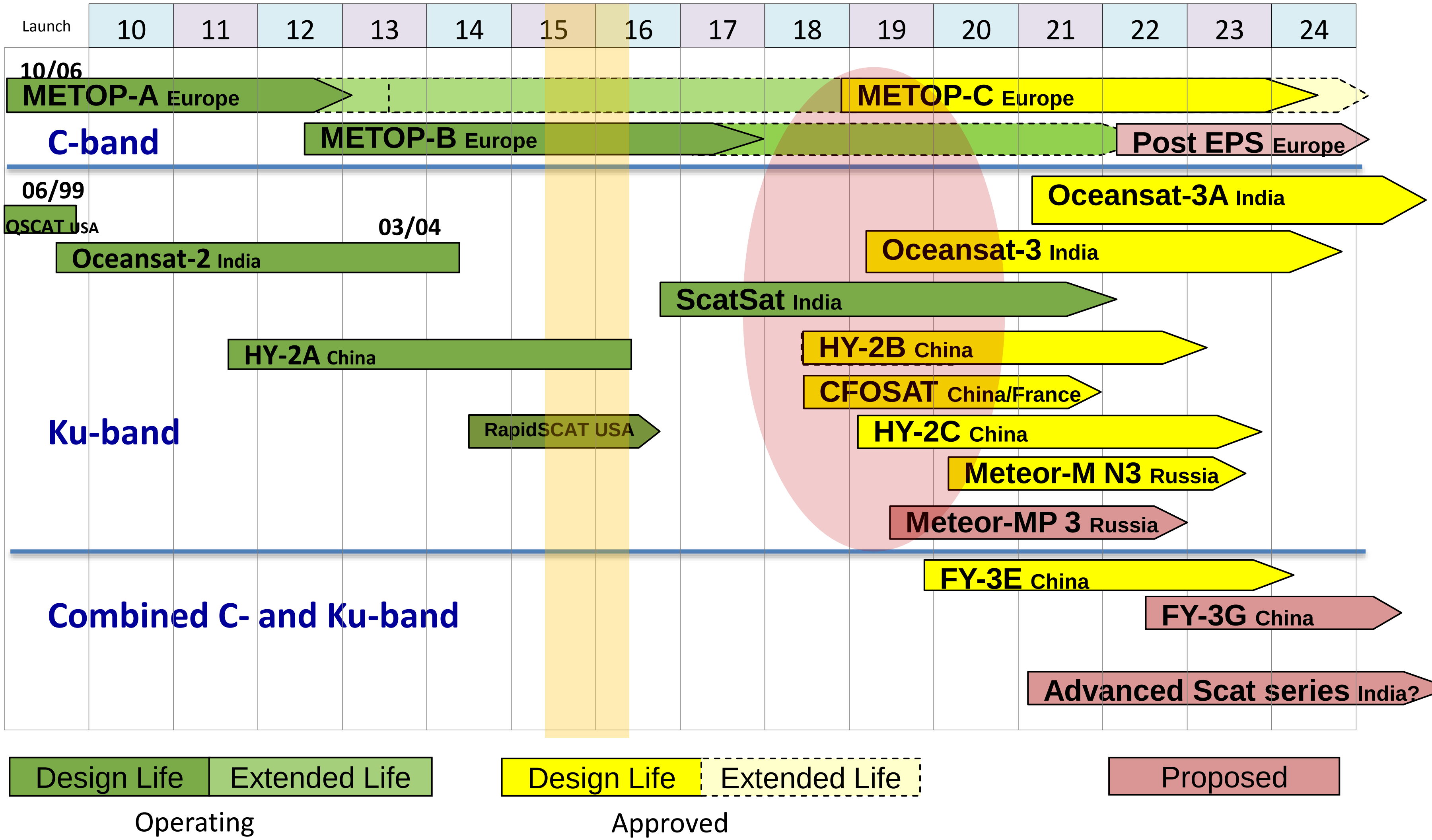


Surface winds over land are not used

ASCAT scatterometer

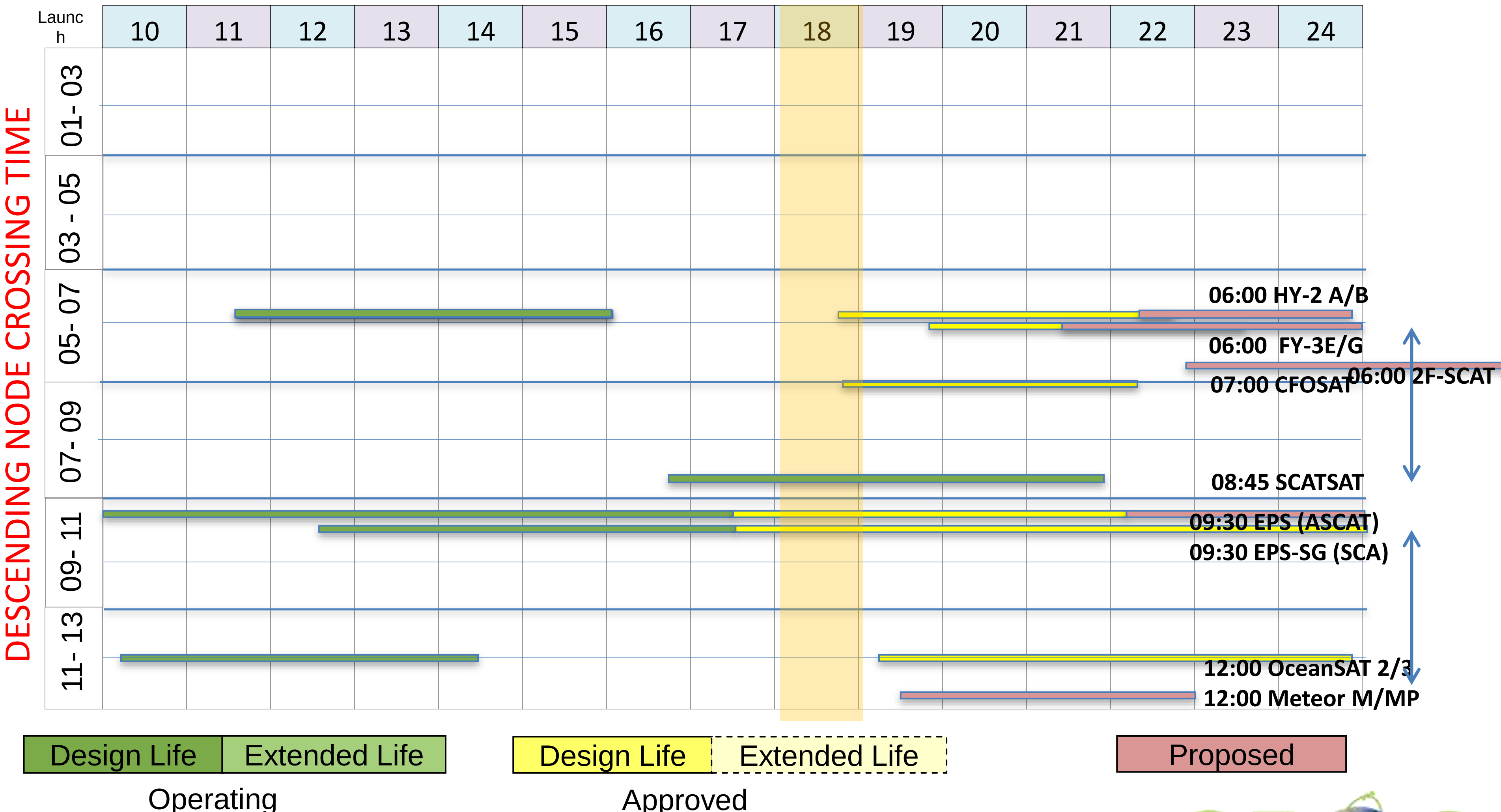


CEOS Ocean Vector Surface Winds Virtual Constellation (OSVW-VC) Current status and outlook – NRT data access



Source: WMO OSCAR database and direct interactions with agencies

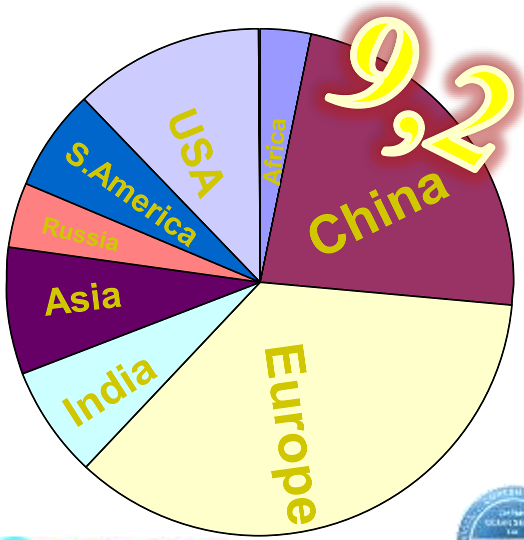
Ocean Vector Surface Winds Constellation
Local time coverage assessment (ground track) - NRT data access

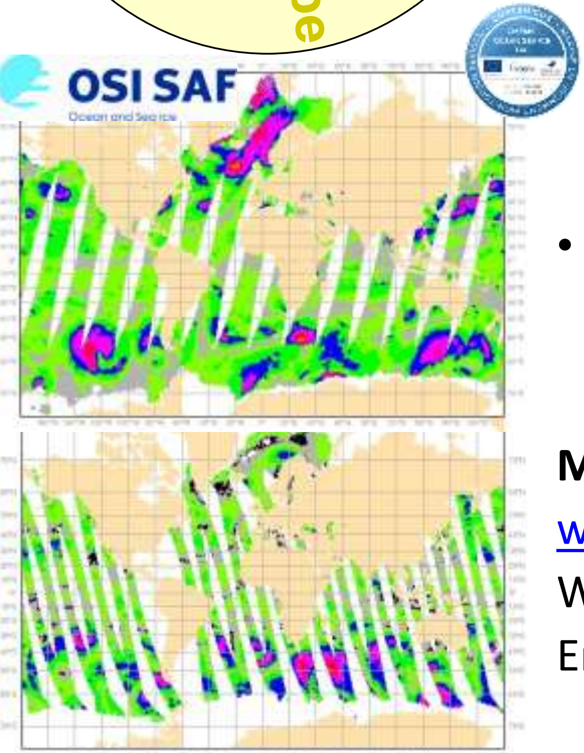


Source: WMO OSCAR database and direct interactions with agencies

CEOS
Committee on Earth Observation Satellites

Satellite Wind Services





- 24/7 Wind services (OSI SAF)
  - Constellation of satellites
  - High quality winds, QC
  - Timeliness 30 min. – 2 hours
  - Service messages
  - QA, monitoring
- Software services (NWP SAF)
  - Portable Wind Processors
  - Weather model comparison

  Organisations involved:
  KNMI, EUMETSAT, EU, ESA, NASA, NOAA, ISRO, SOA, WMO, CEOS, ..
- Users: NHC, JTWC, ECMWF, NOAA, NASA, NRL, BoM, UK MetO, M.France, DWD, CMA, JMA, CPTEC, NCAR, NL, . . .

More information:

www.knmi.nl/scatterometer

Wind Scatterometer Help Desk

Email: scat@knmi.nl

OSI SAF
Ocean and Sea Ice

Ocean and Sea Ice SAF

Wind Processing Centre

GO TO
OSI SAF CENTRAL
WEB SITE

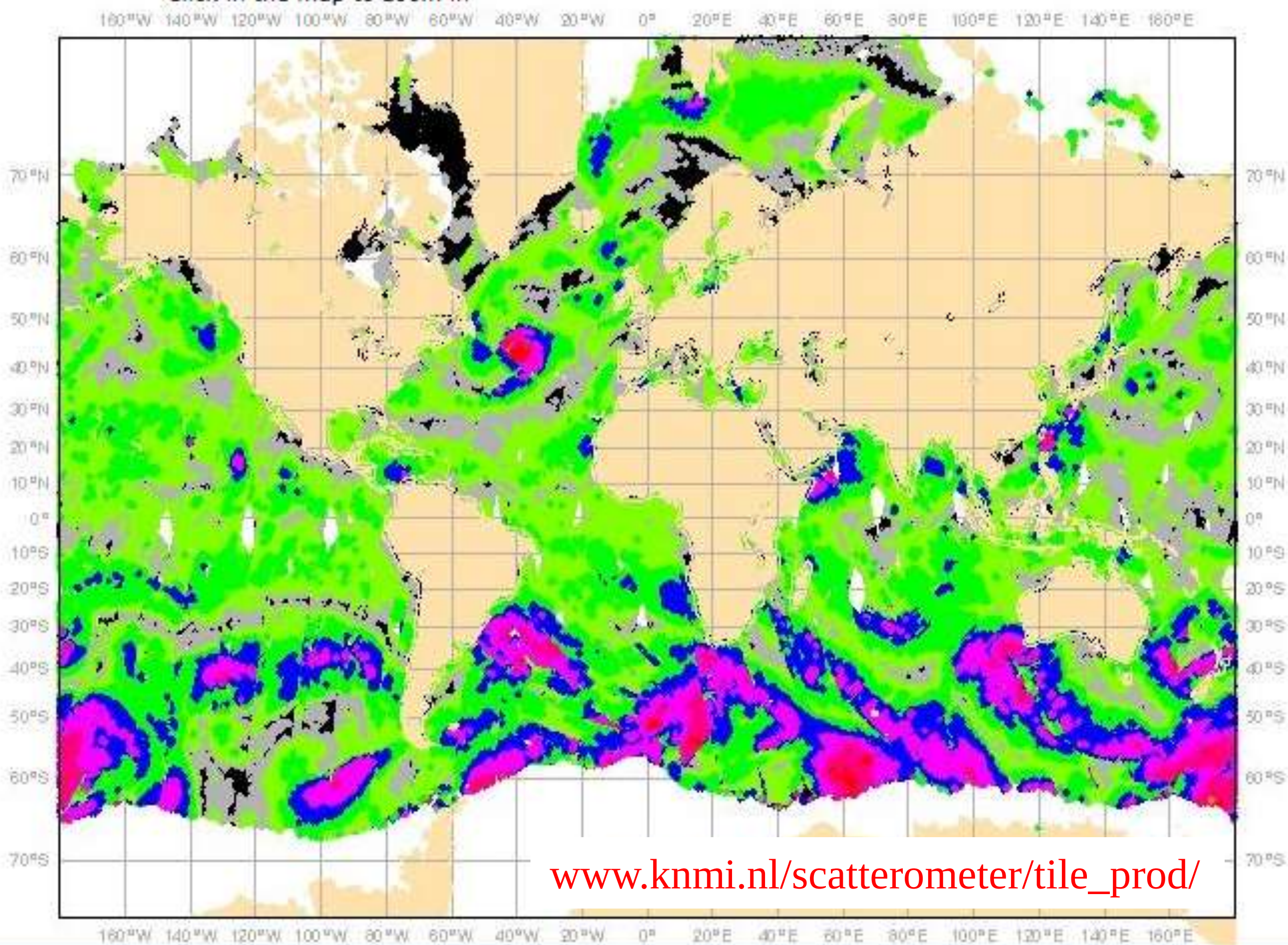
New!

Updated @ 2016-07-07 22:06 utc

OSI SAF multi-platform product viewer

OSI SAF
Ocean and Sea Ice

Click in the map to zoom in



Background information

- Home OSI SAF Wind Centre

OSI SAF Wind Products

- ASCAT-A 25-km winds
  Operational status
- ASCAT-A 12.5-km winds
  Discontinued status
- ASCAT-A Coastal winds
  Operational status
- ASCAT-B 25-km winds
  Operational status
- ASCAT-B Coastal winds
  Operational status
- RapidScat 25-km 2hrs
  Operational status
- RapidScat 25-km 3hrs
  Operational status
- RapidScat 50-km 2hrs
  Operational status
- RapidScat 50-km 3hrs
  Operational status
- Oceansat-2 50-km winds
  Discontinued status
- Reprocessed SeaWinds L2 winds
  CDR released
- Wind Products Processing Status
- Archived wind and stress products

Other Wind Services at KNMI

- ASCAT-A 25-km winds (EARS)
  Operational status
- ASCAT-A Coastal winds (EARS)
  Operational status

RE: SCATTEROMETER VISUALIZATION AT KNMI

by kleoniki tsioutra - Thursday, 7 July 2016, 7:40 AM

Dear Ad,

I found the website you recommended to us very interesting. It would be very useful to Greek forecasters.

Thank you for all the information you gave us during the training course.

RE: SCATTEROMETER VISUALIZATION AT KNMI

by Dionysia kotta - Tuesday, 5 July 2016, 4:36 PM

Dear Ad,

this is very useful, I like it!!!!

Thanks a lot for this information

Dionysia

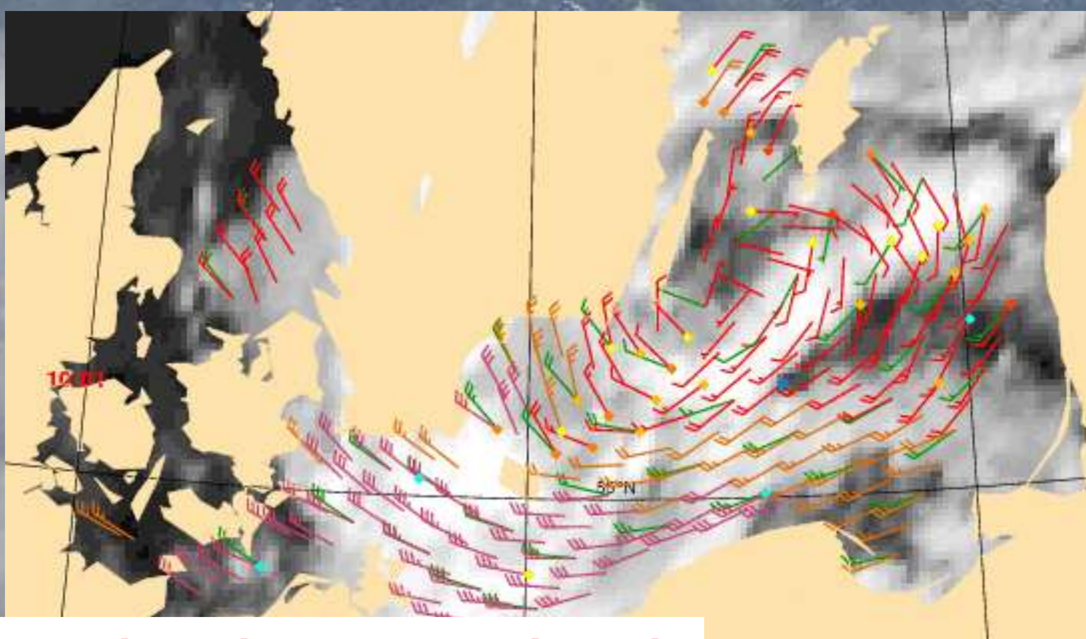
RE: SCATTEROMETER VISUALIZATION AT KNMI

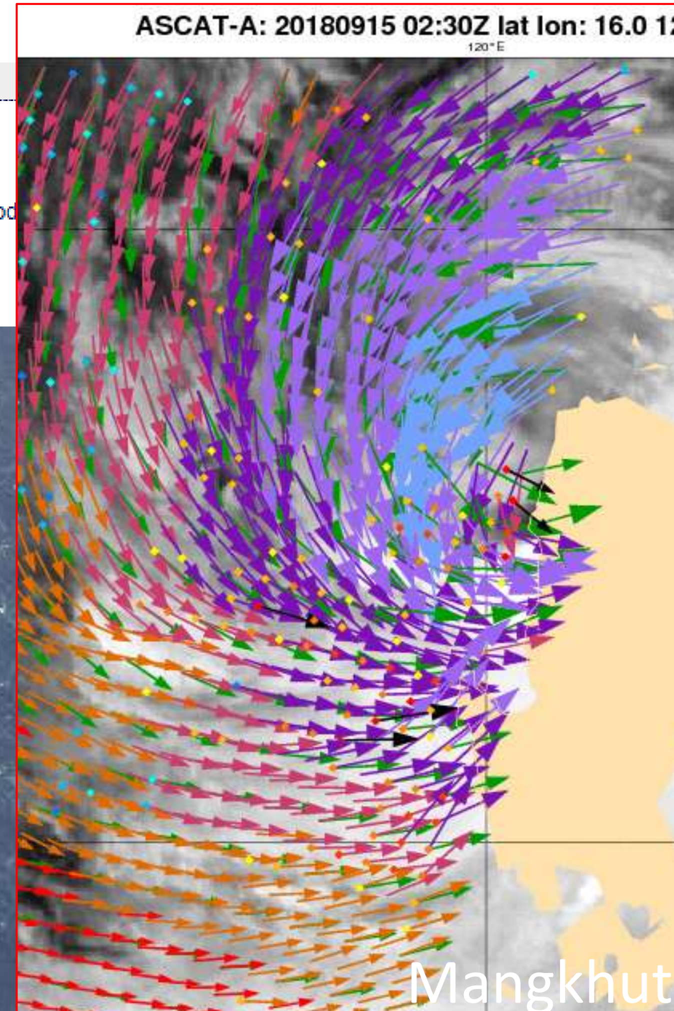
by Maja Jeromel - Thursday, 7 July 2016, 6:00 PM

Hi Ad,

great operational product! I really like the "Go North", "Go South" etc. options - used it right away :-) I also like "Prod
views!

And last, but not least - I found 7.7.2016 is a good day for the Adriatic Sea, even for the norhernmost part :-D

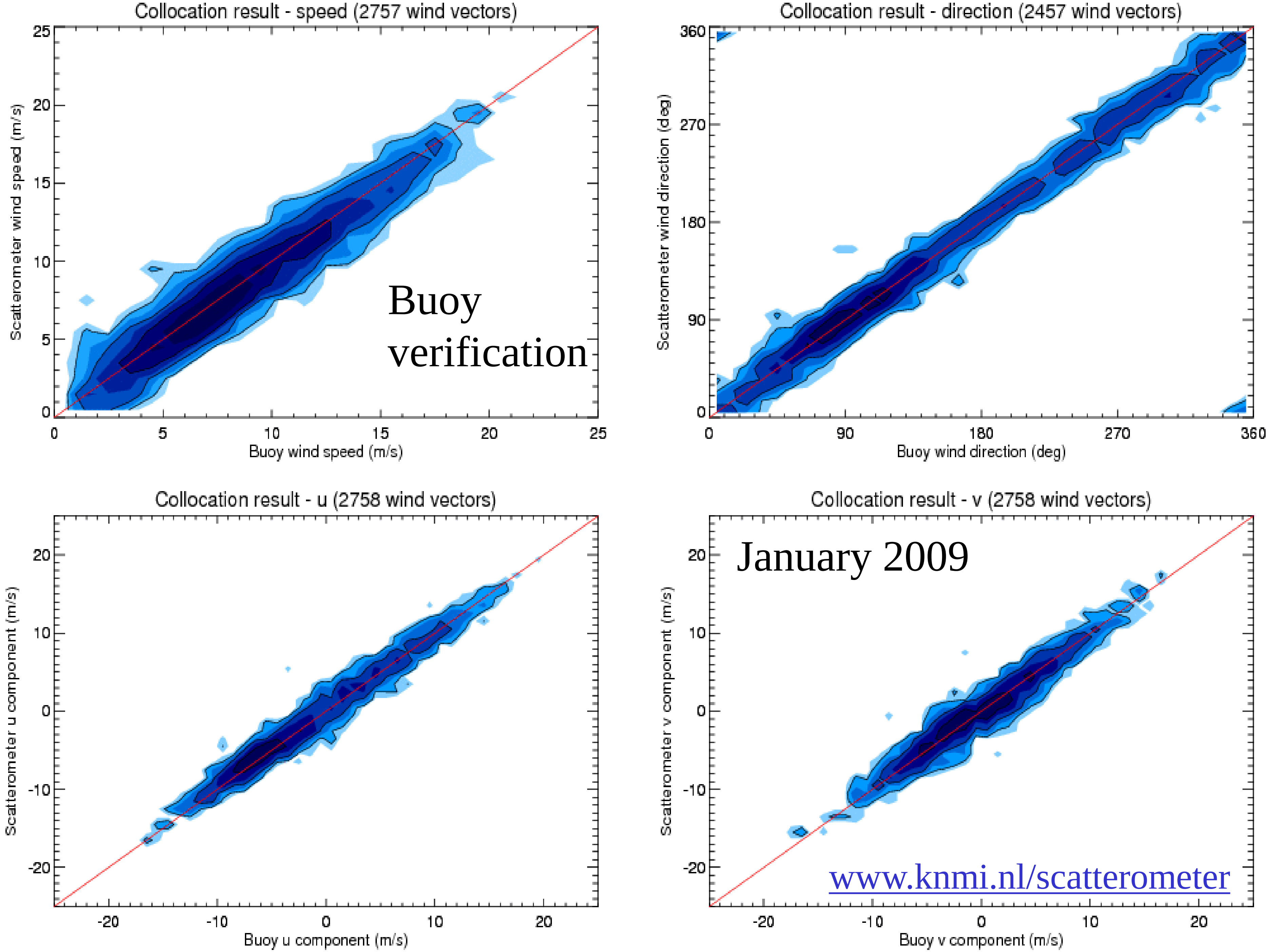




projects.knmi.nl/scatterometer/tile_prod/

Stress-equivalent wind, U10S

- Radiometers/scatterometers measure ocean roughness
- Ocean roughness consists in small (cm) waves generated by air impact and subsequent wave breaking processes; depends on gravity, air/water mass density, water viscosity, surface tension s, and e.m. sea properties (assumed constant)
- Air-sea momentum exchange is described by $\boldsymbol{\tau} = \rho_{air}\, u_* \boldsymbol{u}_*$, the stress vector; depends on air mass density ρ_{air}, friction velocity vector $\boldsymbol{u}_*$
- Stress-equivalent winds, $\boldsymbol{u}_{10\mathrm{S}}$, depend only on $\boldsymbol{\tau}$, and are currently used for backscatter geophysical model functions (GMFs)
- Surface layer winds (e.g., $\boldsymbol{u}_{10}$) depend on $\boldsymbol{u}_*$, atmospheric stability, surface roughness and the presence of ocean currents (drag)
- Buoy and NWP winds must be corrected for ocean currents, air stability, and air mass density before comparison to scatterometer wind, $\boldsymbol{u}_{10\mathrm{S}}$
- Correct for SST at Ku band

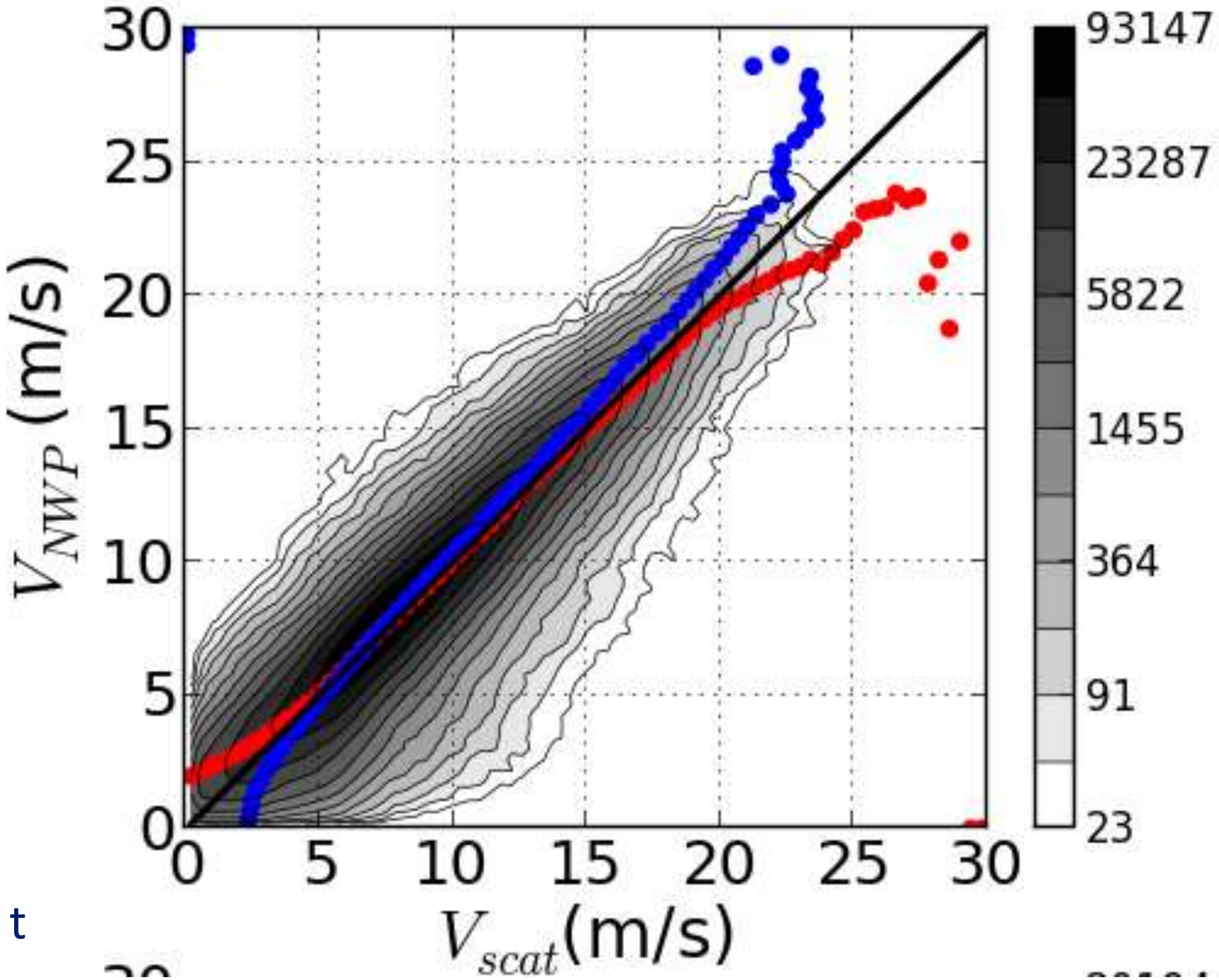


Collocation result - speed (2757 wind vectors)
Scatterometer wind speed (m/s)
Buoy wind speed (m/s)
0
5
10
15
20
25
Buoy verification
Collocation result - direction (2457 wind vectors)
Scatterometer wind direction (deg)
Buoy wind direction (deg)
0
90
180
270
360
Collocation result - u (2758 wind vectors)
Scatterometer u component (m/s)
Buoy u component (m/s)
-20
-10
0
10
20
Collocation result - v (2758 wind vectors)
Scatterometer v component (m/s)
Buoy v component (m/s)
January 2009
www.knmi.nl/scatterometer

Truthful?

- A binned result, e.g., <y|x> or <x|y>, is not meaningful if it is not known how faithful x represents y in terms of physical phenomena and time and space aggregation
- Particularly at the extremes of the PDF
- scatter plots are essential and conditional sampling may be misleading

$$\left.\begin{aligned} x &= t + e_x \\ y &= t + e_y \end{aligned}\right\} \text{Common } t$$



Triple Collocation

Triple collocation result

Scatterometer Scale Error SD	U m/s	V m/s
Buoy	1.21±0.02	1.23±0.02
ASCAT	0.69±0.02	0.82±0.02
ECMWF	1.54±0.02	1.55±0.02
Representativeness (r^2)	0.78±0.02	1.00±0.02

ECMWF Scale Error SD	U m/s	V m/s
Buoy	1.44±0.02	1.59±0.02
ASCAT	1.05±0.02	1.29±0.02
ECMWF	1.32±0.02	1.18±0.02

Trend	U m/s	V m/s
ASCAT	0.99	0.99
ECMWF	0.97	0.96

- ASCAT winds are very accurate
- ASCAT error SD is smaller than representativeness vector error SD
- Buoy errors appear large (current, wind variability)
- ECMWF winds appear smooth and biased low on average
- In extreme weather much larger deviations will occur

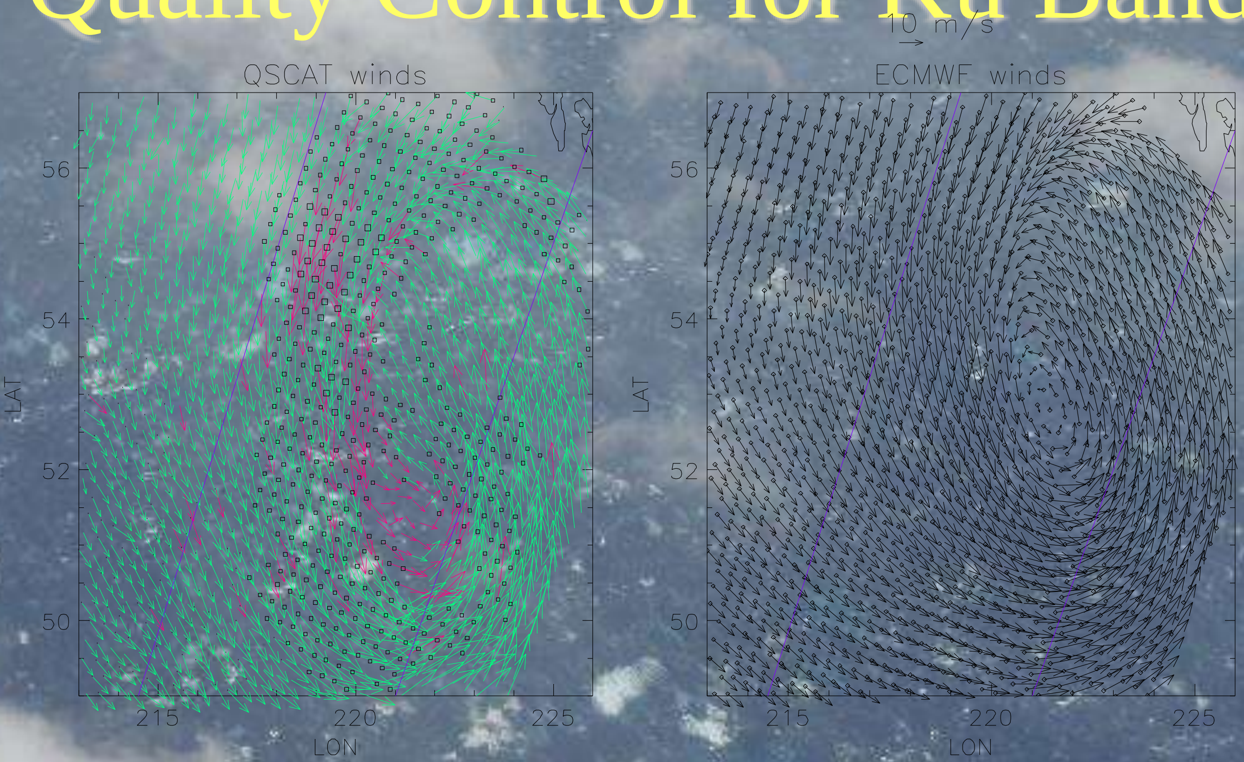
Vogelzang et al., JGR, 2011

SeaWinds ScatSat-1 OceanSat-2

Triple collocation in ms^{-1}	Scatterometer		Buoys		ECMWF	
	ε_u	ε_v	ε_u	ε_v	ε_u	ε_v
25 km ScatSat-1	0.77	0.60	1.37	1.40	1.10	1.13
25 km Oceansat-2	0.80	0.71	1.44	1.45	1.33	1.40
25 km SeaWinds	0.64	0.54	1.39	1.41	1.28	1.35
50 km ScatSat-1	0.60	0.44	1.45	1.50	0.99	1.00
50 km Oceansat-2	0.61	0.48	1.53	1.54	1.20	1.29
50 km SeaWinds	0.46	0.40	1.50	1.49	1.20	1.28

- ERAint: SeaWinds (1999 – 2009) en Oceansat-2 (2009 - 2014)
- OPS (clearly better quality): All ScatSat-1 v113
- ScatSat-1 quality well within requirements (~1.4 m/s)
- Better than OceanSat-1 quality
- Buoy quality best at smallest scale (25 km), NWP at largest scale (50 km)

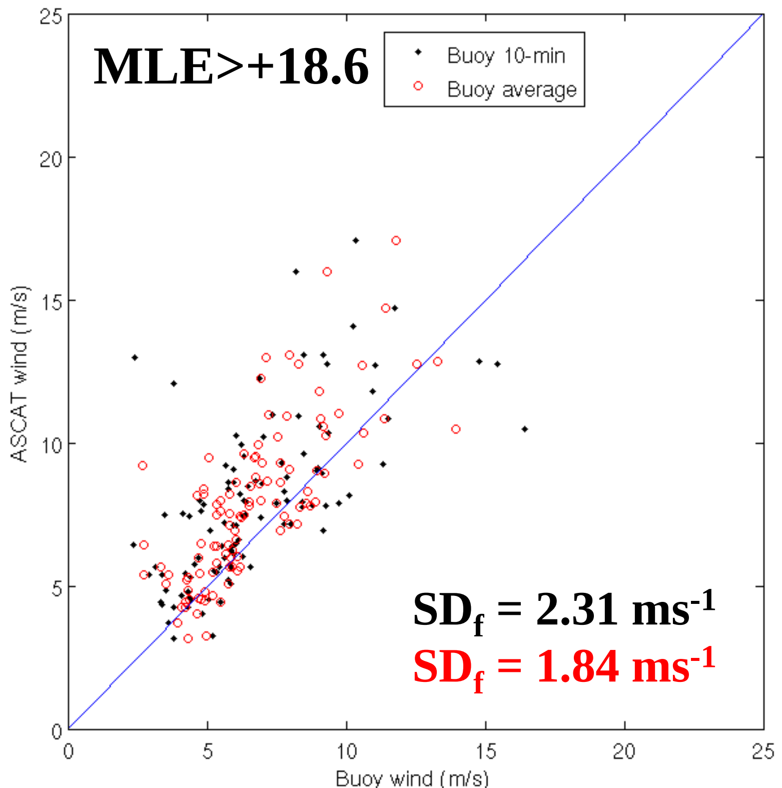
Quality Control for Ku Band

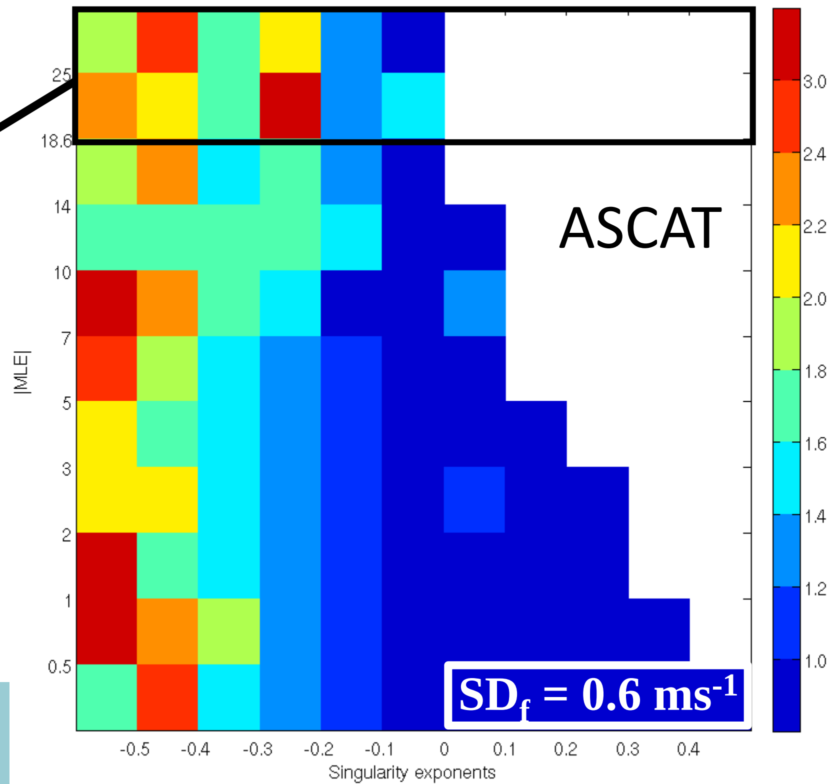


- Areas with significant Rain (large squares) effectively detected
- Frontal and low-pressure centre areas effectively removed
- Vast majority of spatially consitent winds are accepted (green arrows)

QC: Which error is acceptable?

- We can produce winds with SD of buoy-scatterometer difference of 0.6 m/s, but would exclude all high-wind and dynamic air-sea interaction areas
- The winds that we reject right now in convective tropical areas are noisy (SD=1.84 m/s), but generally not outliers!
- What metric makes sense for QC trade-off?

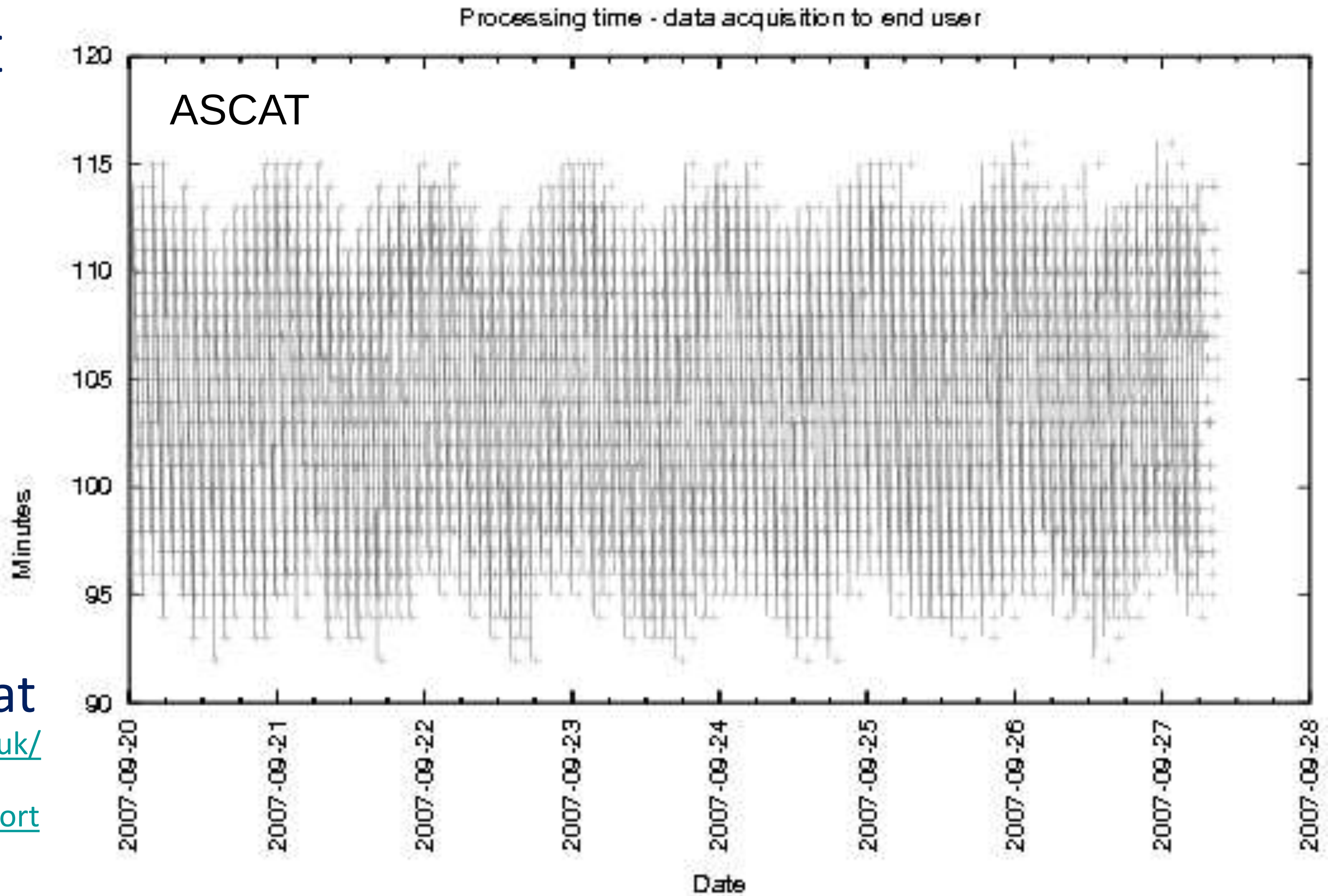


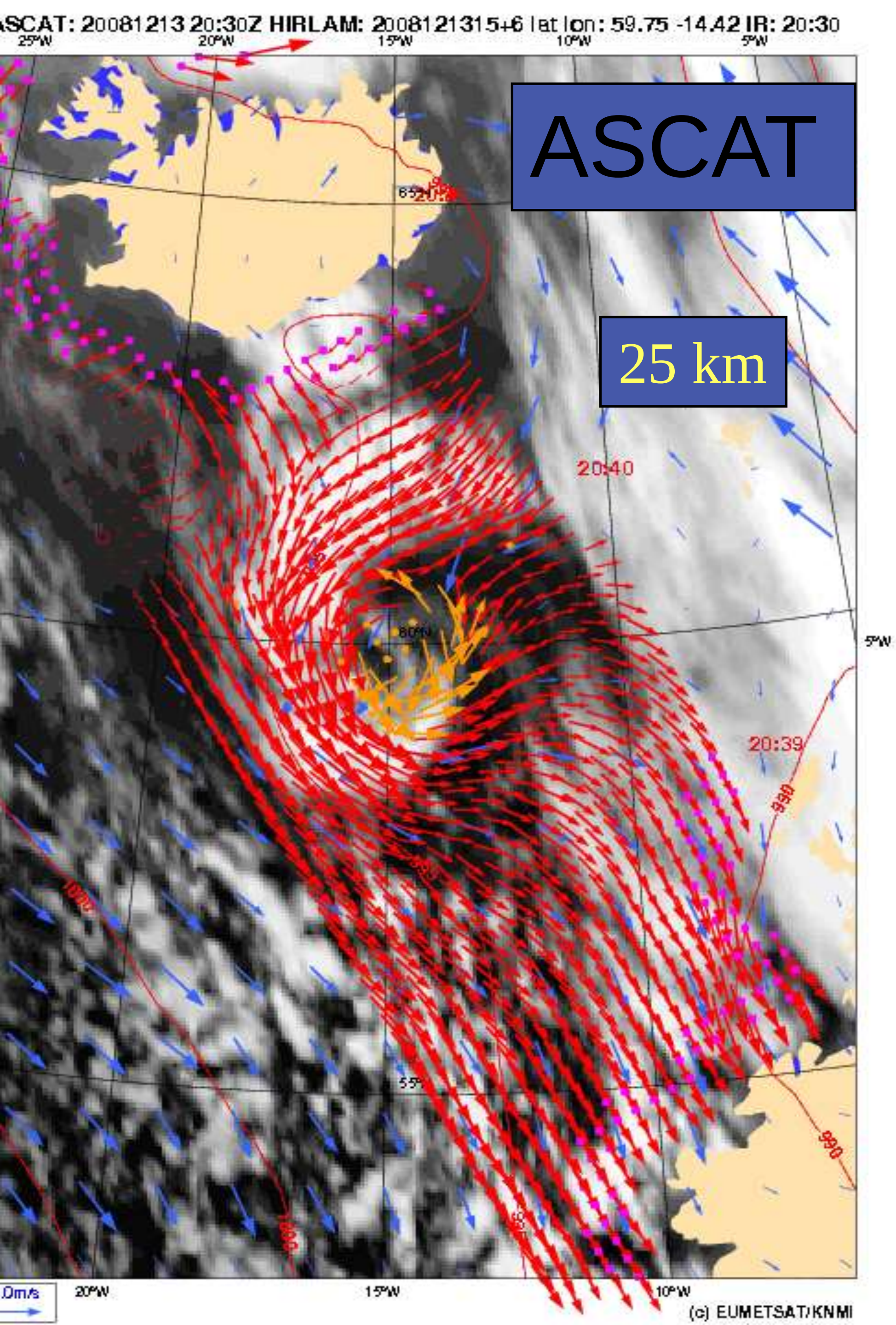


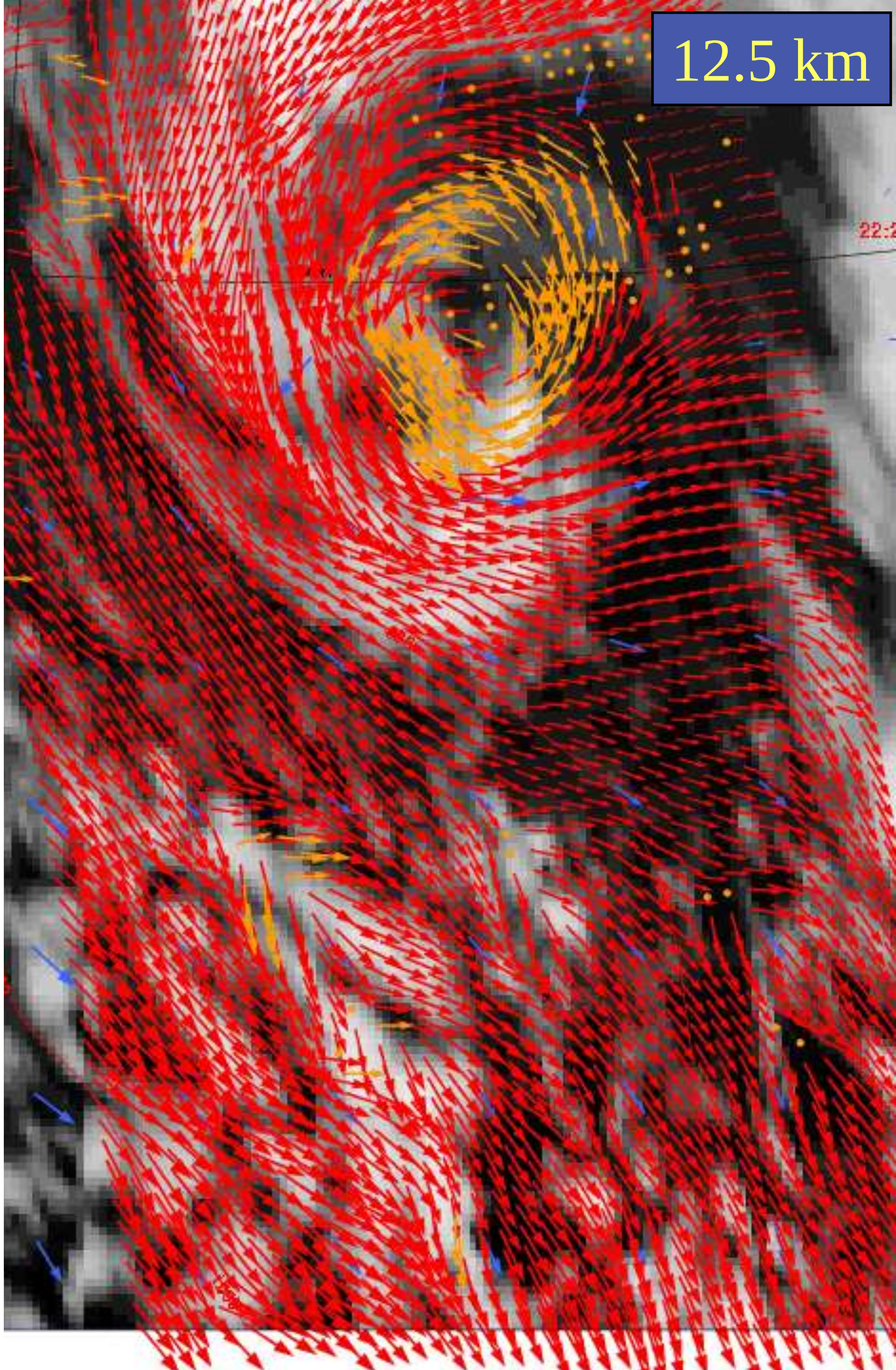
Monitoring of each product

- 1st rank MLE
- Speed bias
- RMS u&v scat - EC
- Timeliness
- Product flag

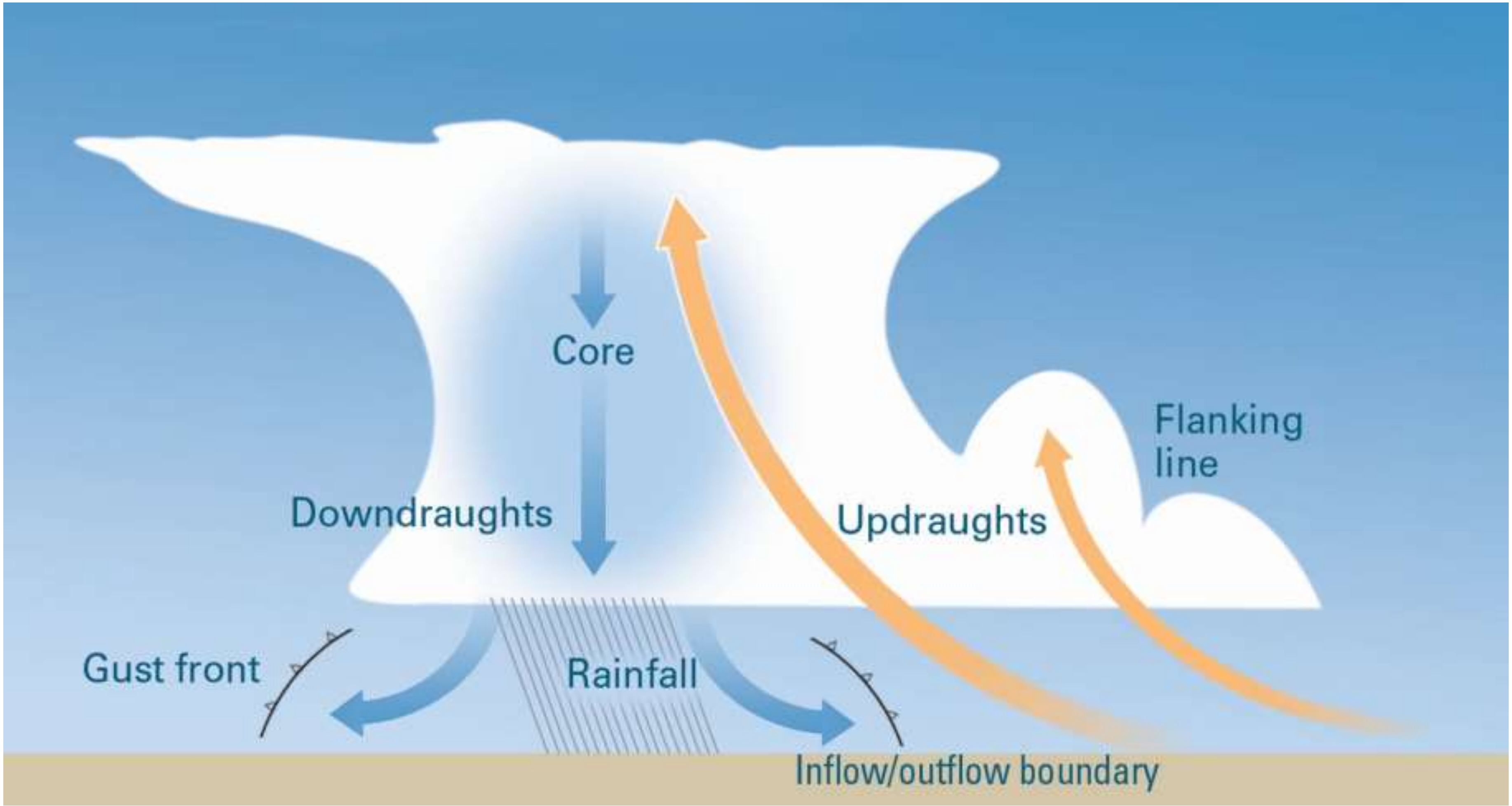
- NWP SAF integrated monitoring at www.metoffice.gov.uk/research/interproj/nwpsaf/scatter_report



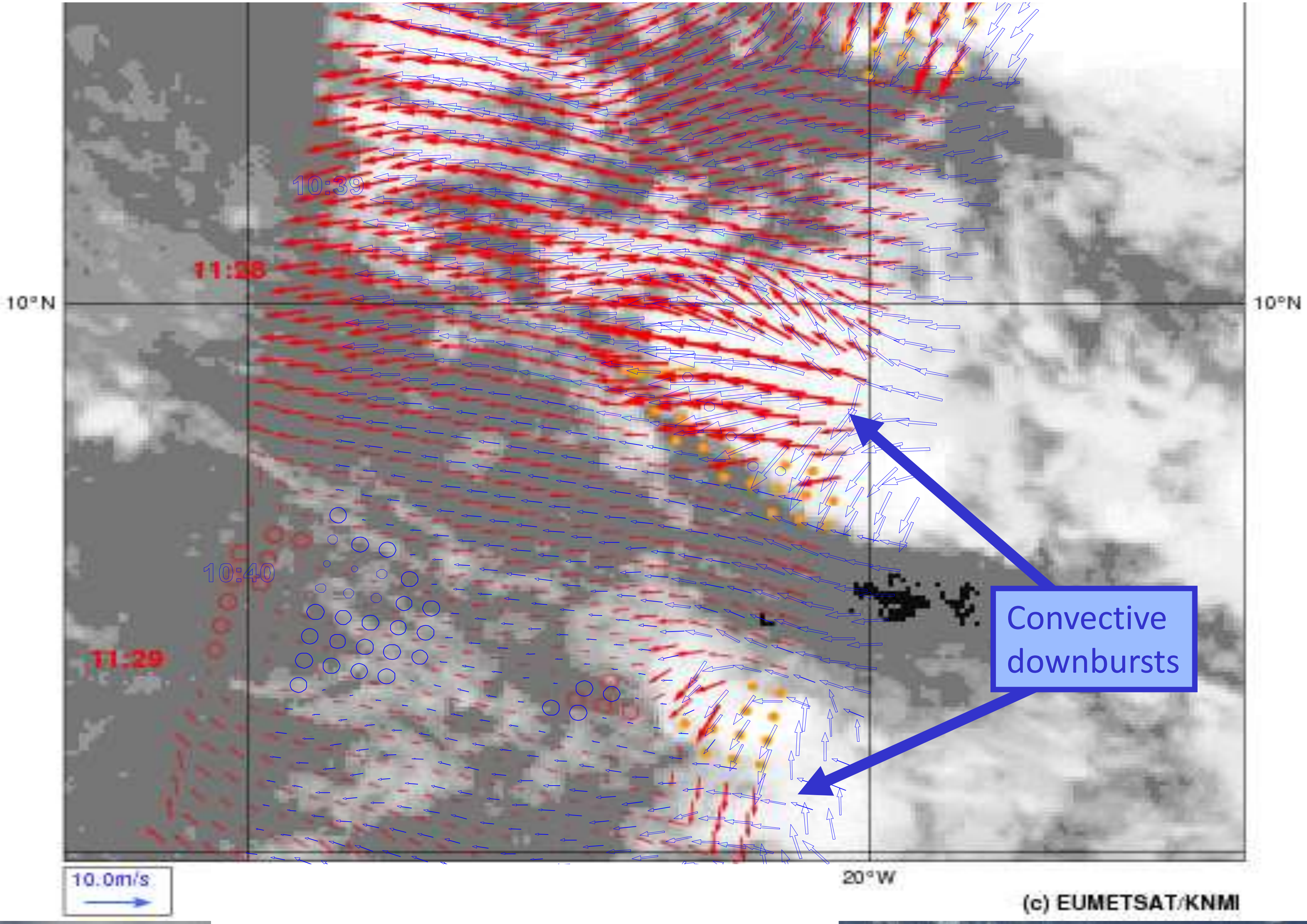

ASCAT: 20081213 20:30Z HIRLAM: 2008121315+6 lat lon: 59.75 -14.42 IR: 20:30
ASCAT
25 km
20:40
20:39
990
(c) EUMETSAT/KNMI

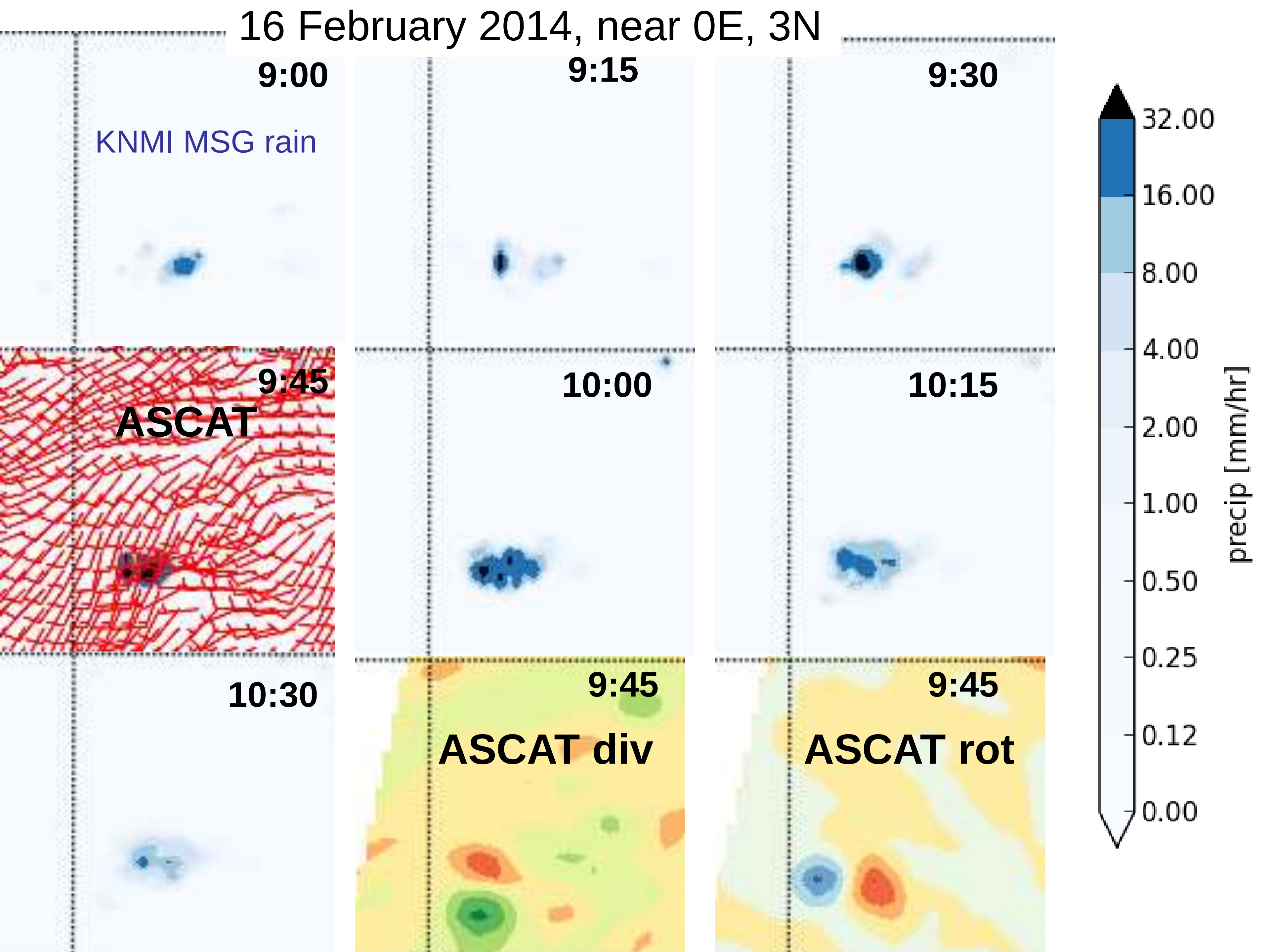

12.5 km

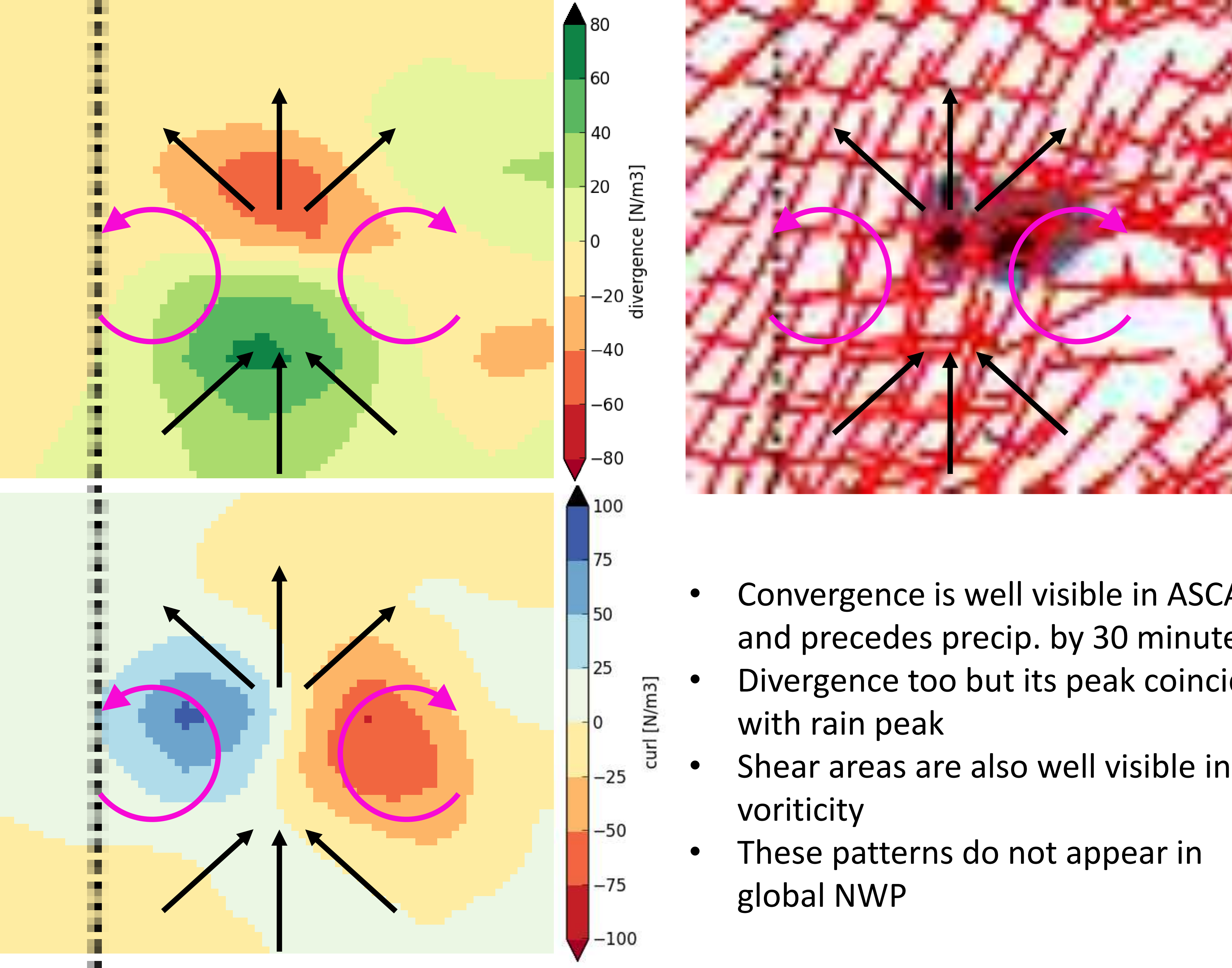
Convection


Core
Flanking
line
Downdraughts
Updraughts
Gust front
Rainfall
Inflow/outflow boundary

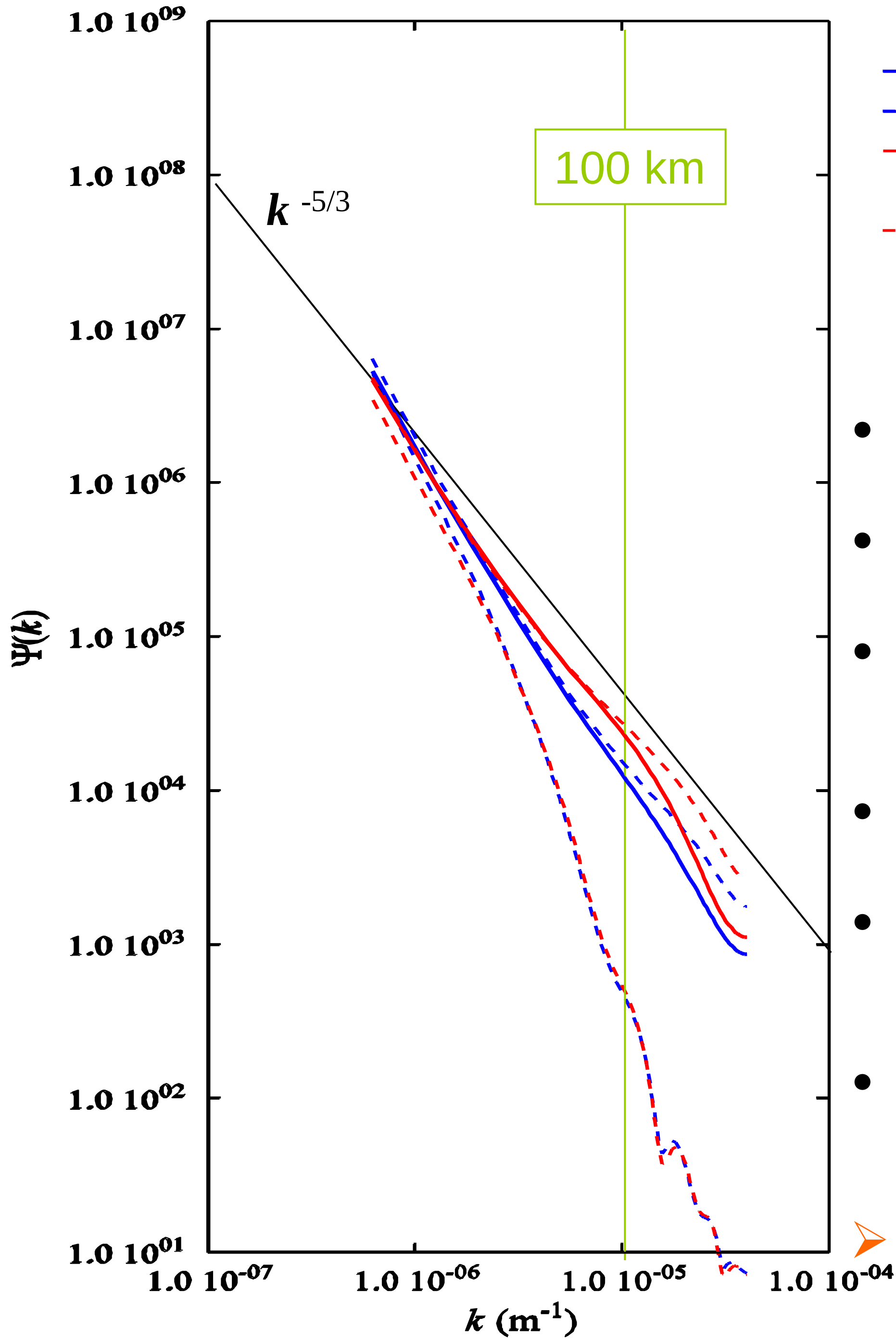
ASCAT-A and ASCAT-B come together




16 February 2014, near 0E, 3N
9:00
KNMI MSG rain
9:15
9:30
9:45
ASCAT
10:00
10:15
10:30
9:45
ASCAT div
9:45
ASCAT rot
32.00
16.00
8.00
4.00
2.00
1.00
0.50
0.25
0.12
0.00
precip [mm/hr]



- Convergence is well visible in ASCAT and precedes precip. by 30 minutes
- Divergence too but its peak coincides with rain peak
- Shear areas are also well visible in voriticity
- These patterns do not appear in global NWP



Upscale ?

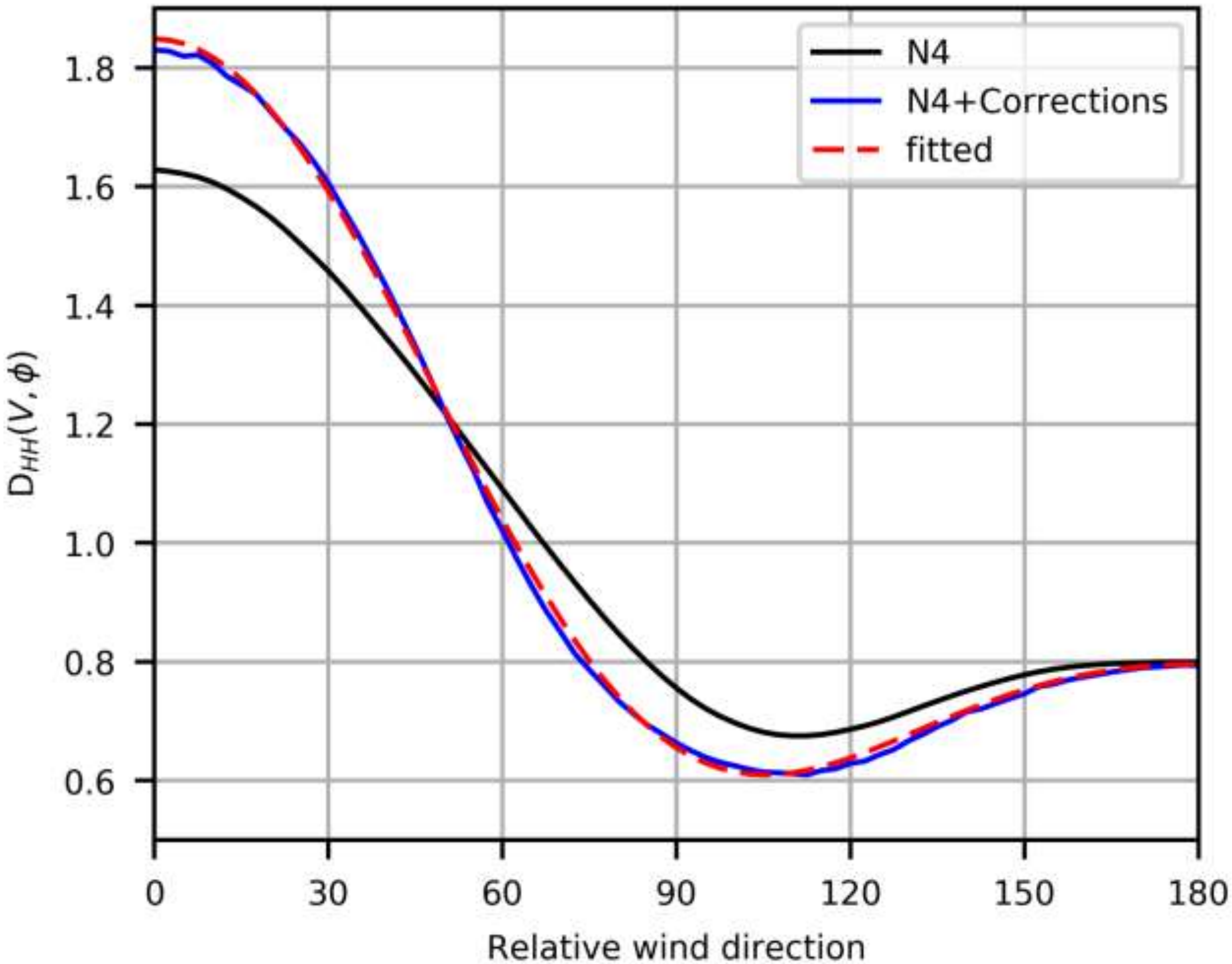
- Literature provides $k^{-5/3}$ 3D turbulence spectra on scales < 500 km
- ASCAT winds follow such behavior down to 25 km scales
- Global NWP models contain an order of magnitude less variance on scales of 100 km
- Regional NWP models contain noise above sea (weak forcing)
- Developments in 3D turbulence regime from small to large scales are not well described
- Small scale wind information is particularly relevant in cases of dynamical developments (upscale)

➢ Watch scatterometer winds above sea

GMF development

An Example for improving the New Wind Direction Modulation

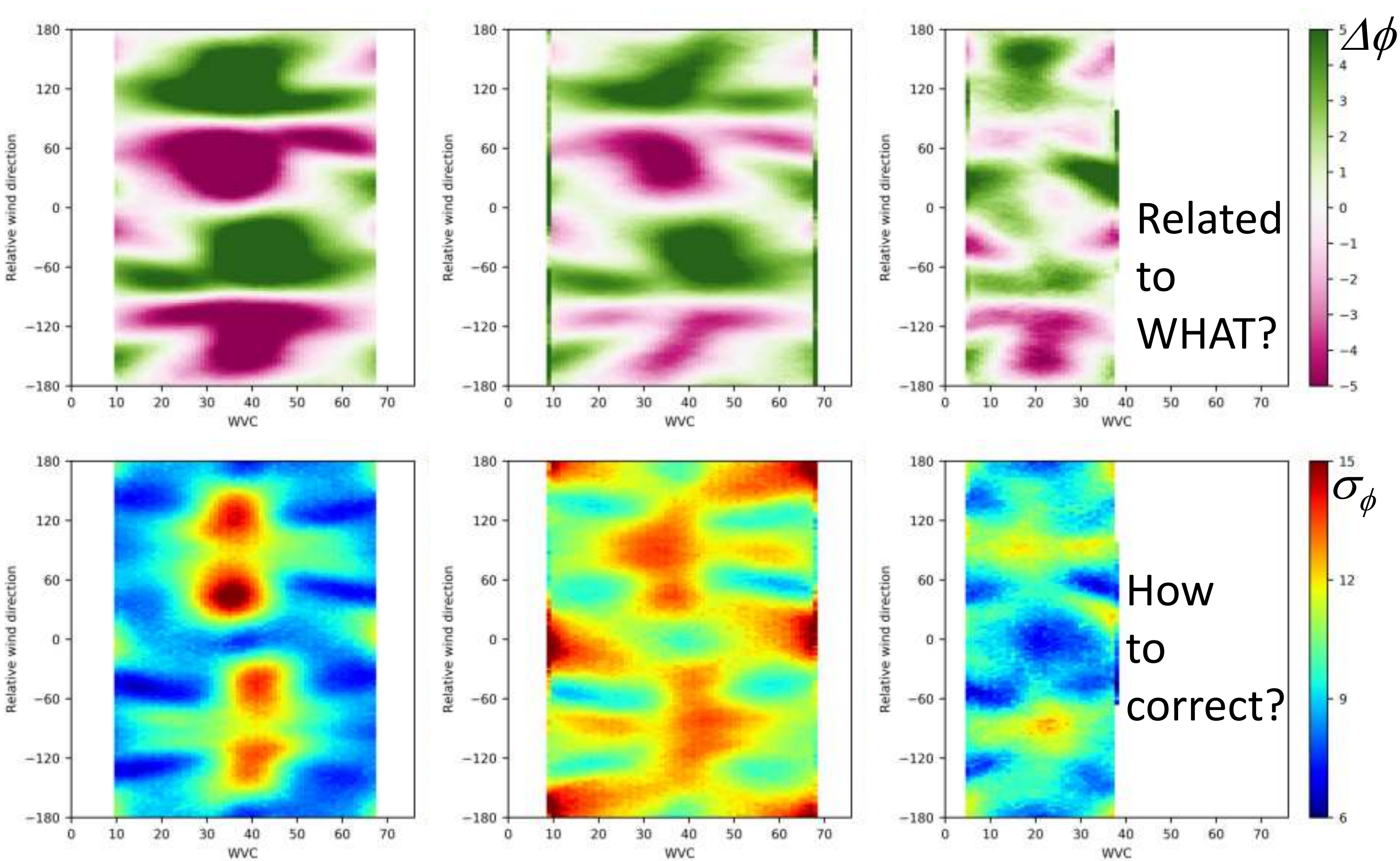
HH, for wind speed centered at 4.5 m/s



Wind directions

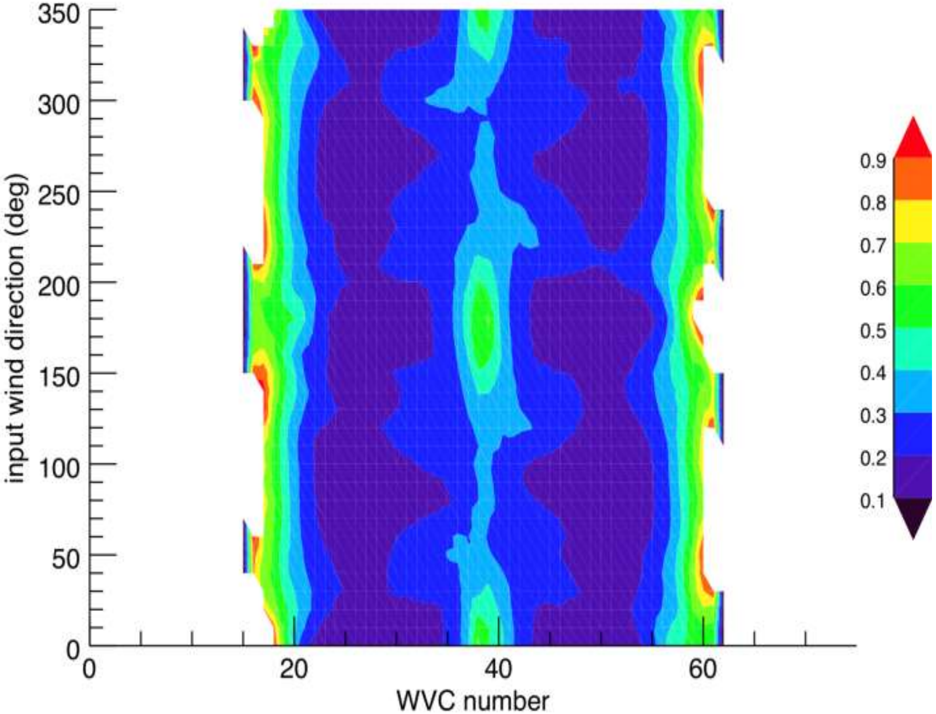
The **preferences** are produced by wind inversion algorithm (Bayesian approach), ambiguities removal method (2DVAR), or by GMF errors? → Zhen Li, Xingou Xu

SCATSCAT, ECMWF_Operational **QuikSCAT, ECMWF_ERA** **RapidSCAT, ECMWF_ERA**

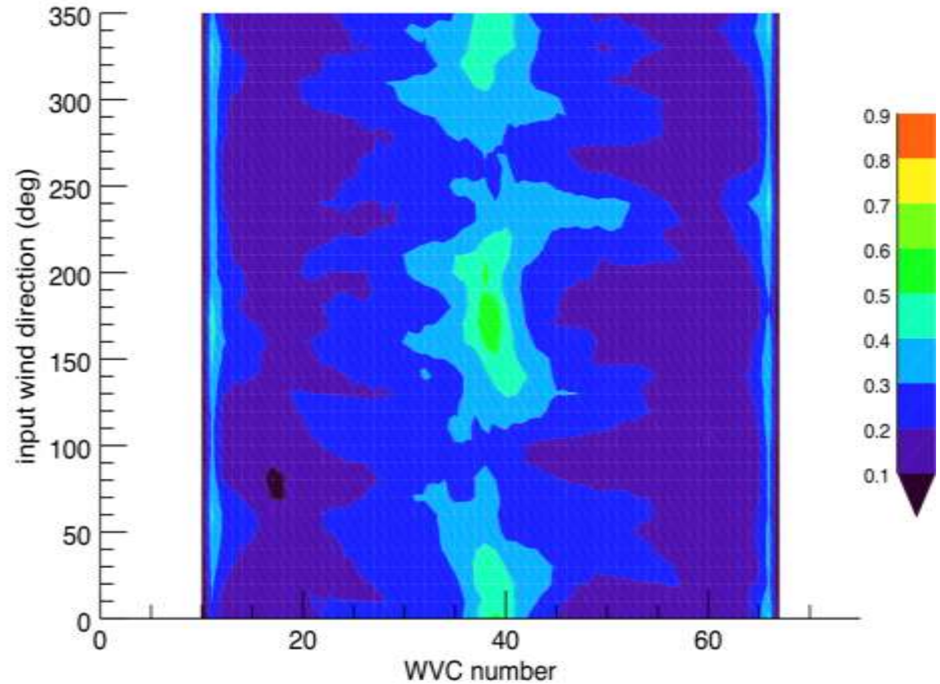


Wind Retrieval Performance CFOSAT and WindRad

Scaled VRMS over all wind directions at 9 m/s



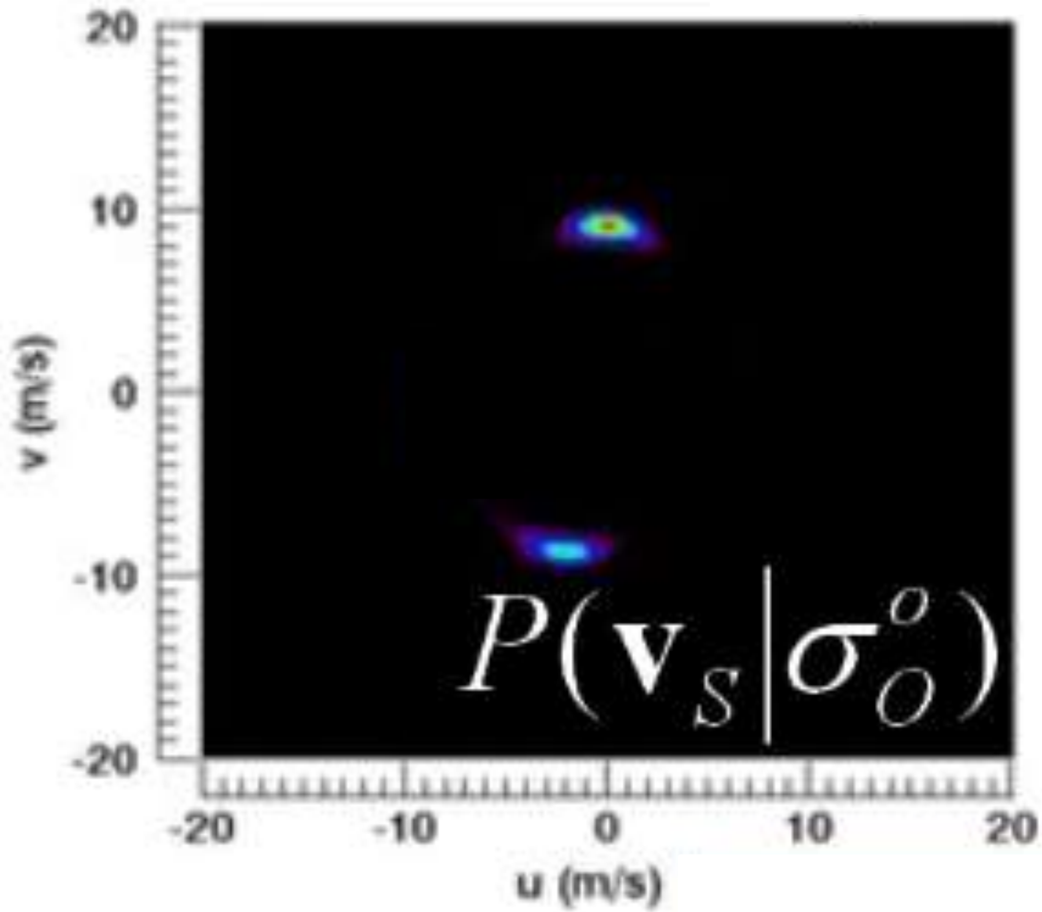
CFOSAT



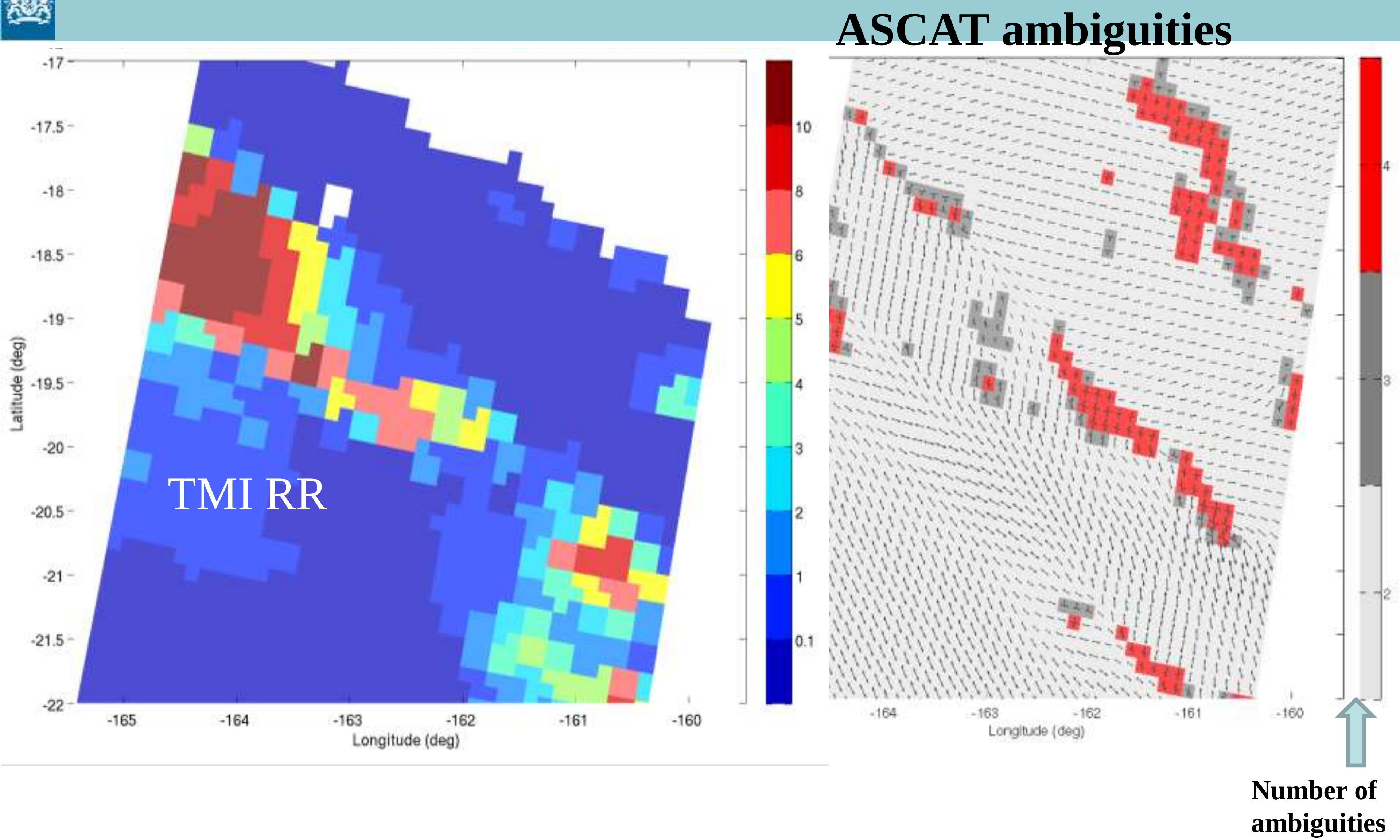
WindRad

ASCAT Wind Information Content

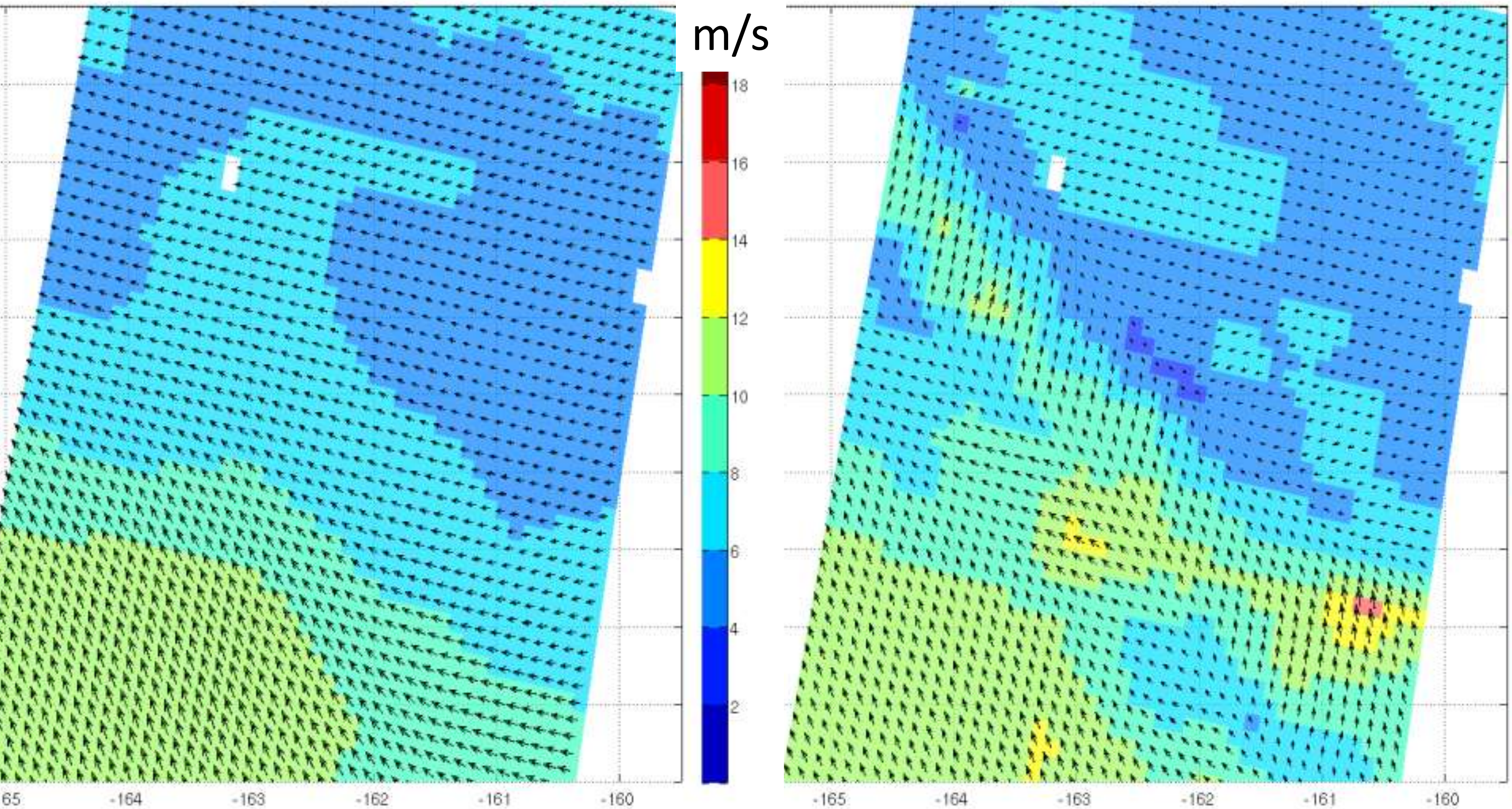
- Scatterometer winds are ambiguous
- Every WVC provides the true wind vector and its opposite
- 2D-VAR can use multiple solutions and a NWP background wind field to produce a wind analysis
- The closest ambiguity to the wind analysis is selected to remain independent from the background field



Wind front


ASCAT ambiguities
TMI RR
Latitude (deg)
Longitude (deg)
-17
-17.5
-18
-18.5
-19
-19.5
-20
-20.5
-21
-21.5
-22
-165
-164
-163
-162
-161
-160
10
8
6
5
4
3
2
1
0.1
Number of ambiguities

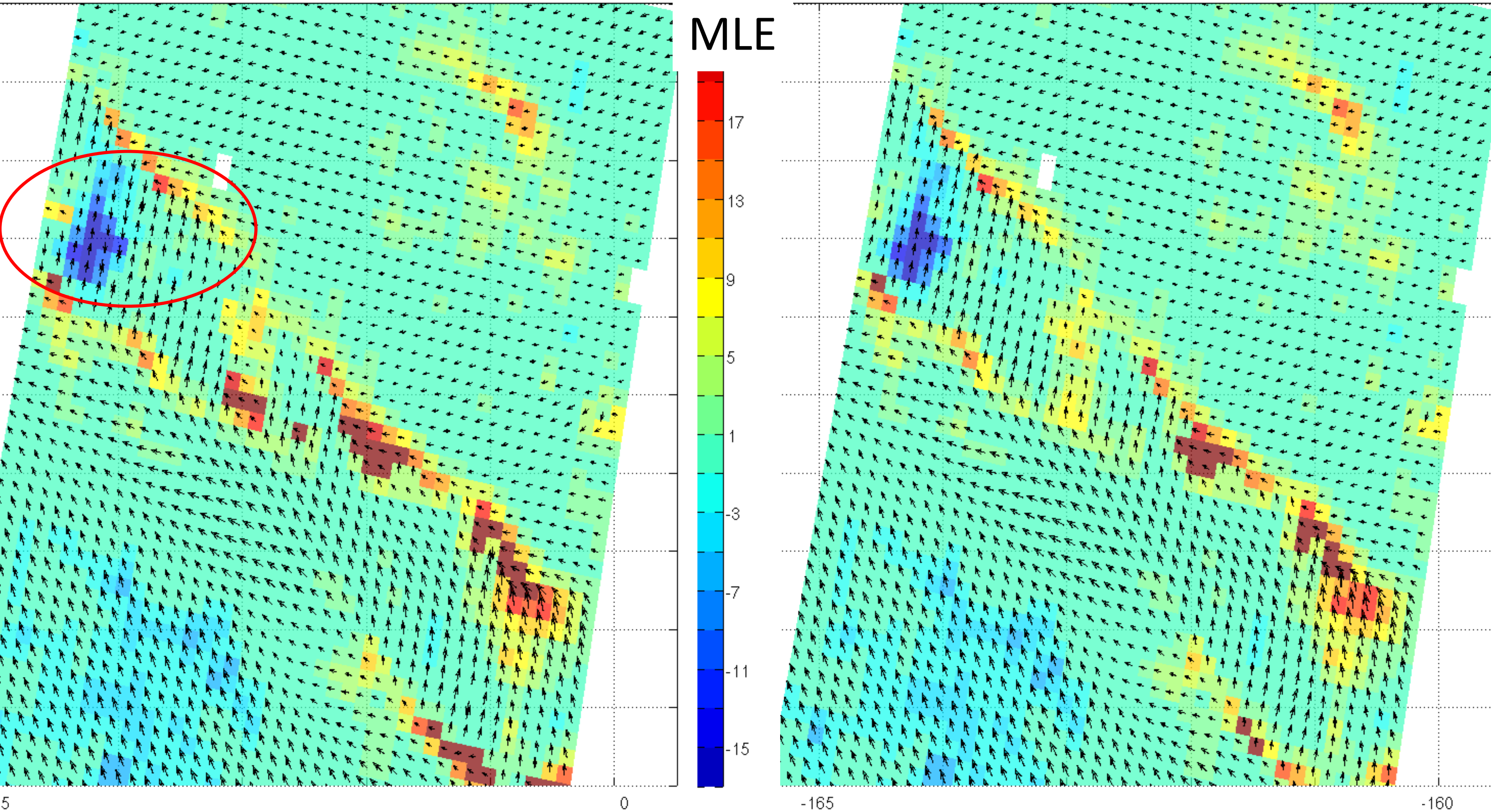
Wind front 2DVAR analysis



Default setting:
- ➢ Gaussian structure function
- ➢ Fixed O/B errors

New setting:
- ➢ Empirical structure function
- ➢ Flexible O/B errors

Wind front selections



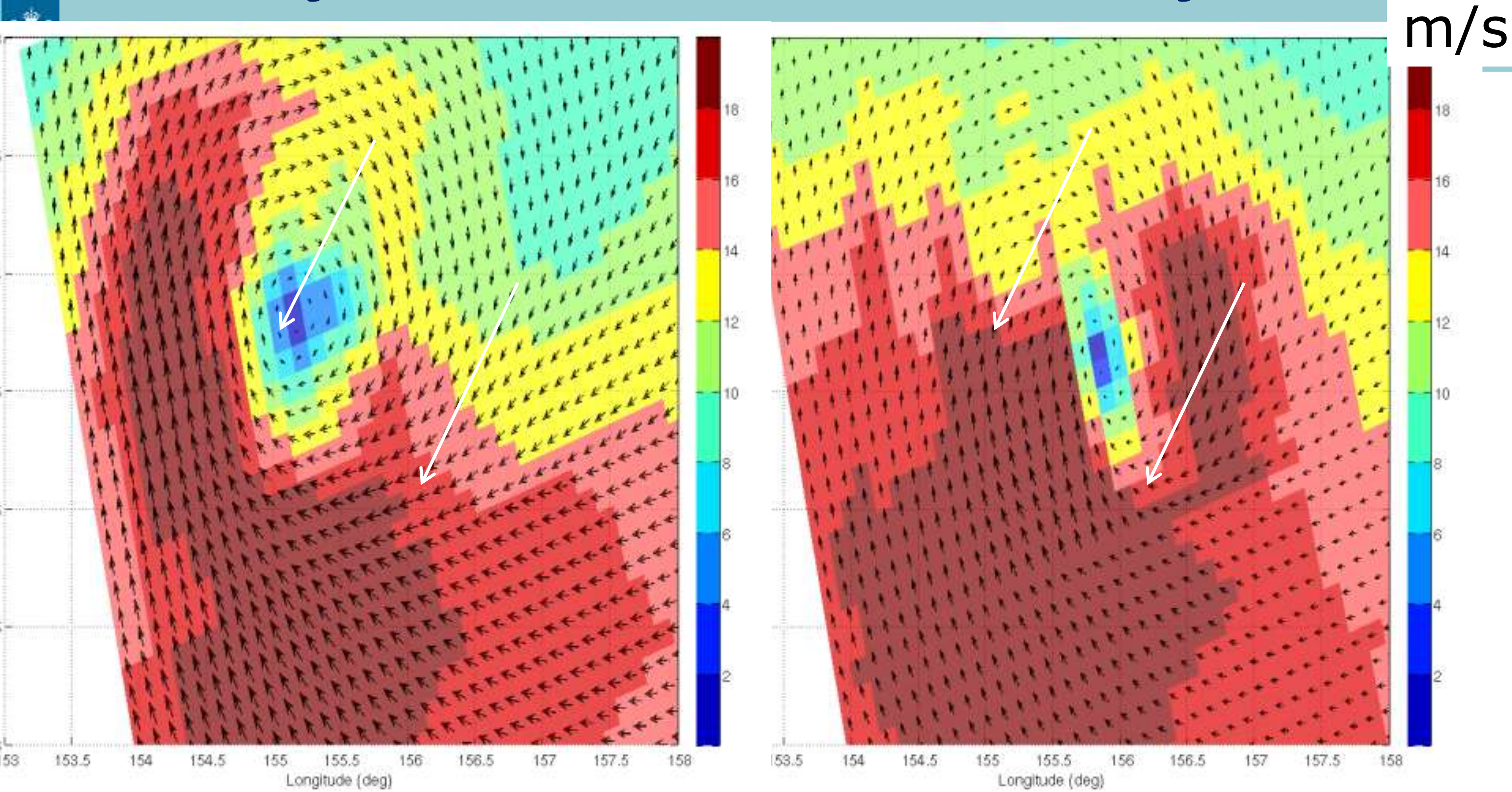
Default setting:

- ➢ Gaussian structure function
- ➢ Fixed O/B errors

New setting:

- ➢ Empirical structure function
- ➢ Flexible O/B errors

Cyclone SH, 2DVAR analyses



Default setting:

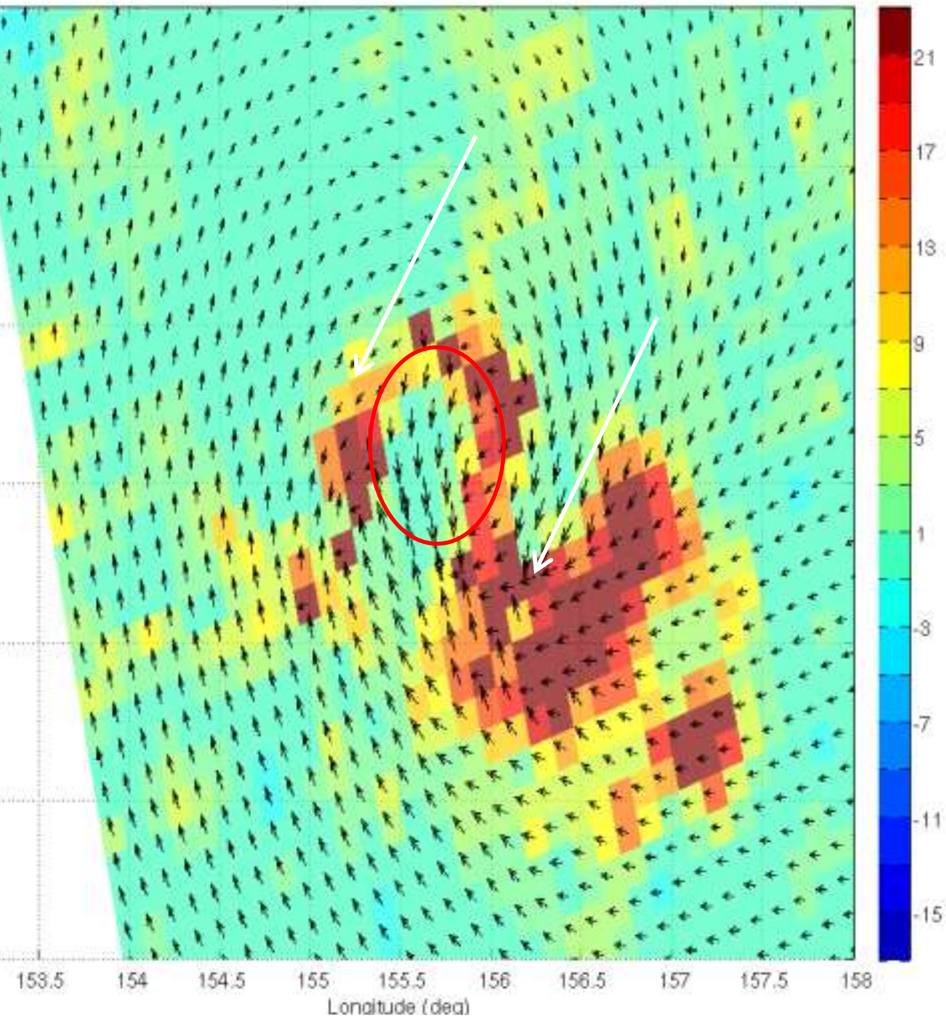
- Gaussian structure function
- Fixed O/B errors

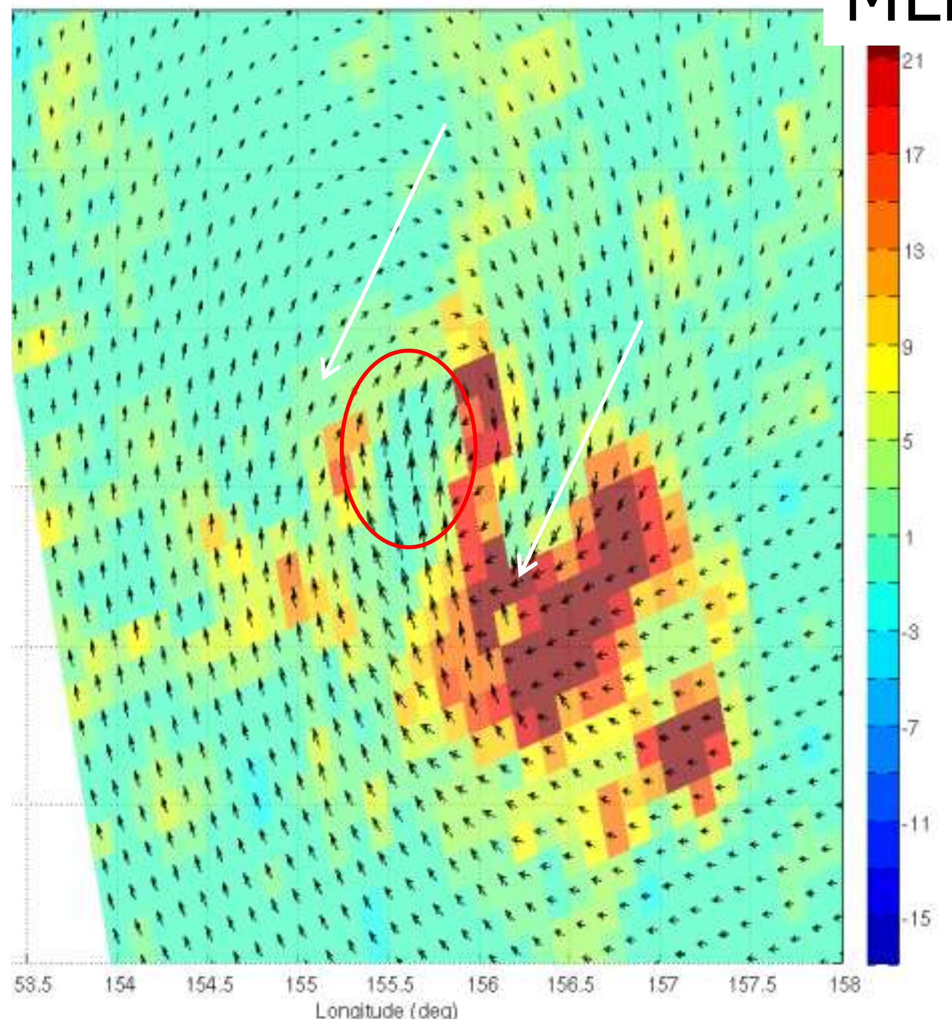
New setting:

- Empirical structure function
- Flexible O/B errors

Cyclone SH, selected solutions

ML





Default setting:

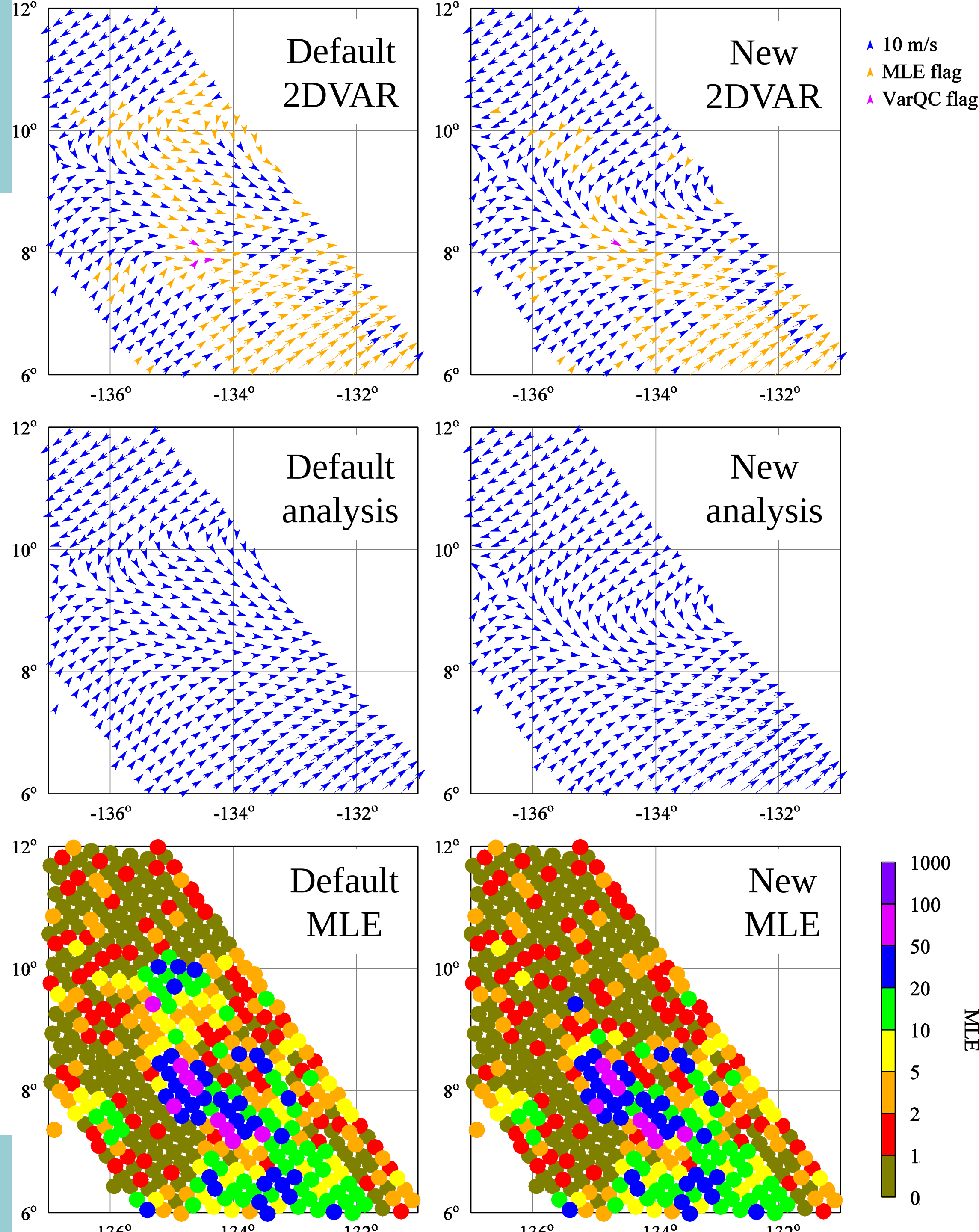
- Gaussian structure function
- Fixed O/B errors

New setting:

- Empirical structure function
- Flexible O/B errors

RapidScat

- Static background error correlations based on ASCAT
- Larger increments w.r.t background
- More mesoscale structure
- Lower MLE
- Better wind direction verification against buoys
- Works also for OSCAT

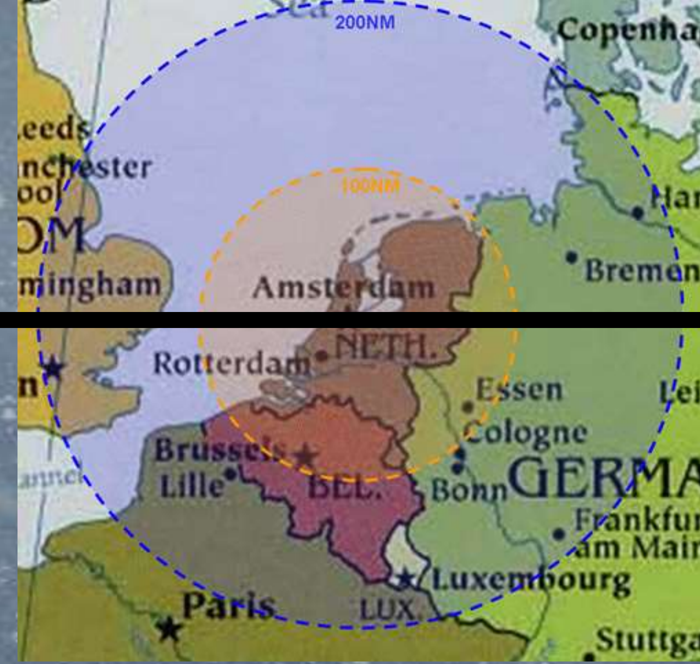


Scatterometer winds

- Represent the mean WVC wind
- Are provided as stress-equivalent (neutral) winds
- Verify very well with NWP model
- Verify very well with buoys
- Show spectra close to that expected for 3D turbulence for scales < 500 km
- Spatial plots show small-scale features in line with these three features: PBL rolls, moist and dry convection, subsidence, air-sea interaction

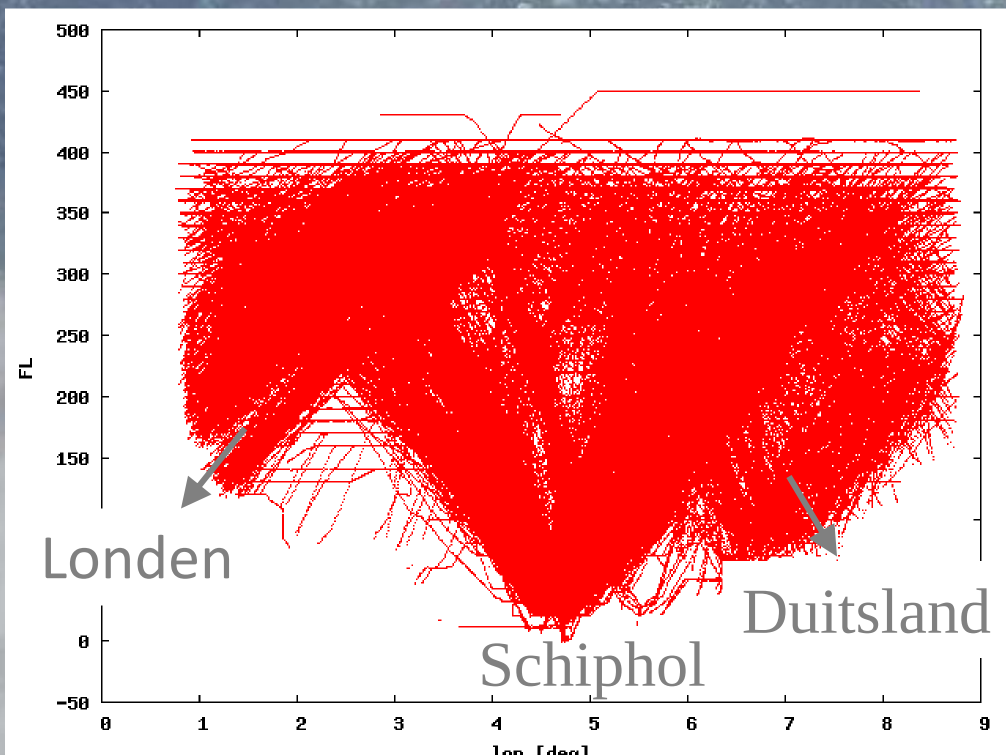
- Can be contaminated by land, sea ice and rain
- Winds > 30 m/s are difficult to measure/calibrate
- Are ambiguous

Aircraft Mode-S Winds



Example 15-03-2008

1 424 147 observations



+ Great density

– Only locally over land

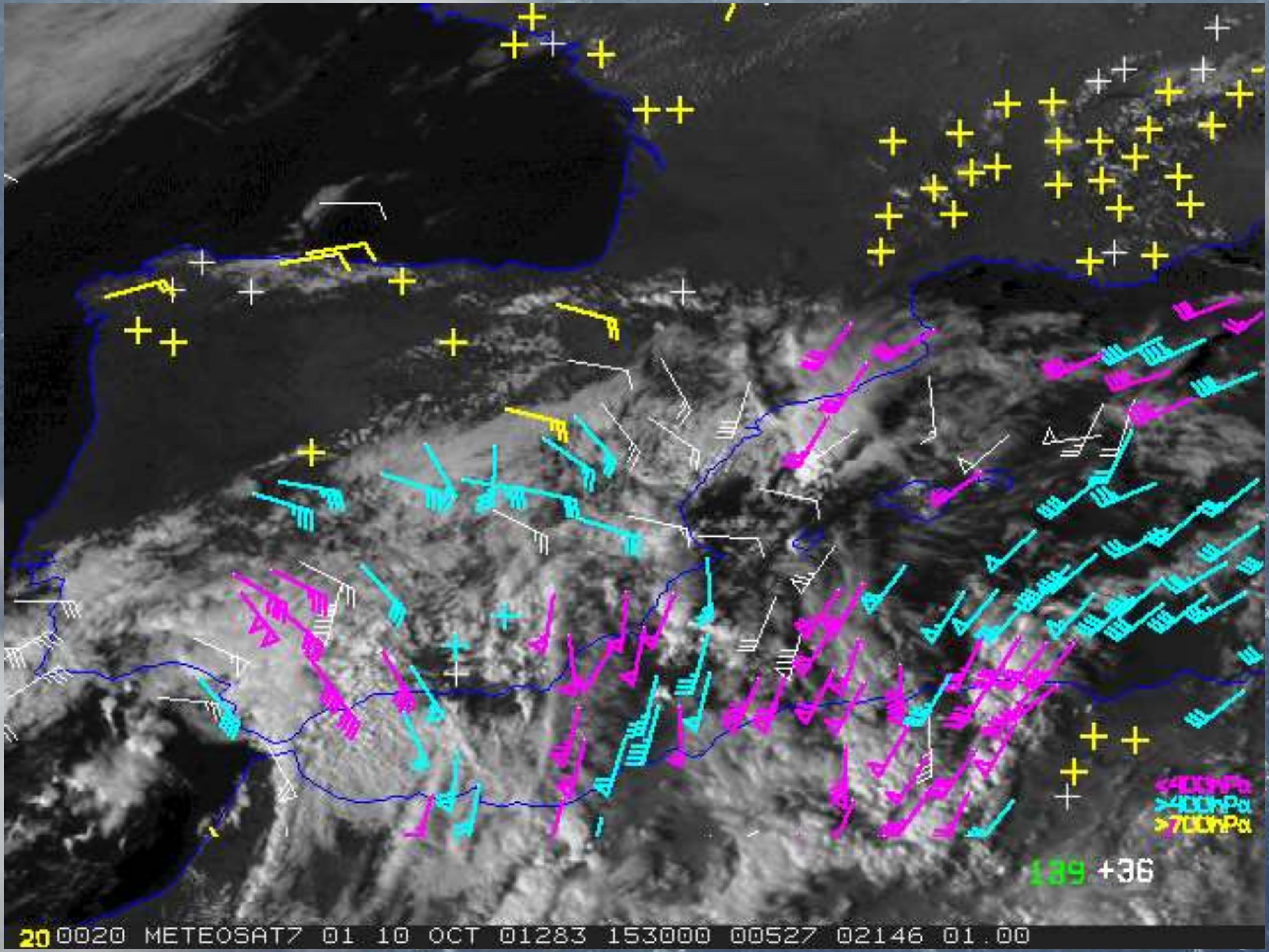
Use of NWC-SAF AMVs software and mesoscale AMVs

The group noted that a number of NWP centres are using the NWC-SAF AMVs software to derive higher density AMVs for their mesoscale assimilation systems. Further developments of this software are supported (e.g., production of o-b statistics).

At the same time, the group noted that the use of the NWC-SAF software is a response to an unmet requirement for mesoscale AMV datasets, and causes multiplication of undesirable overheads.

Recommendation to AMV producers: to provide higher-density AMV products that capture small-scale detail for mesoscale applications. Rapid-scan configurations are particularly suitable for this.

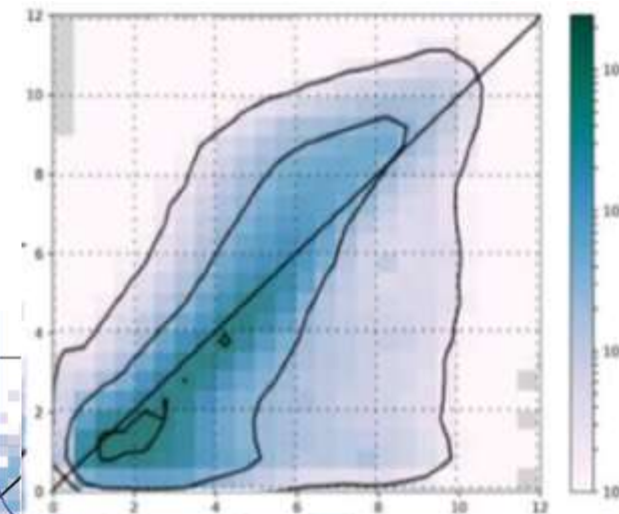
Wind from cloud motion

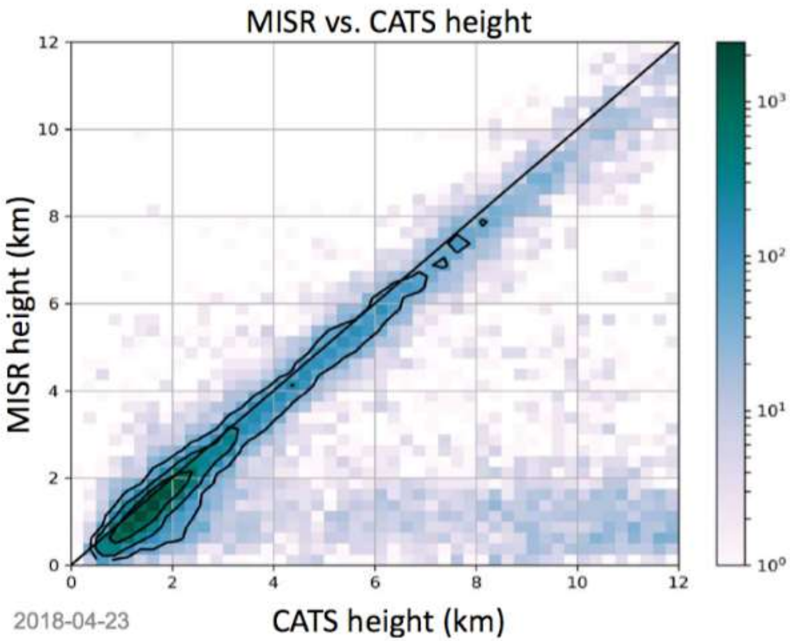


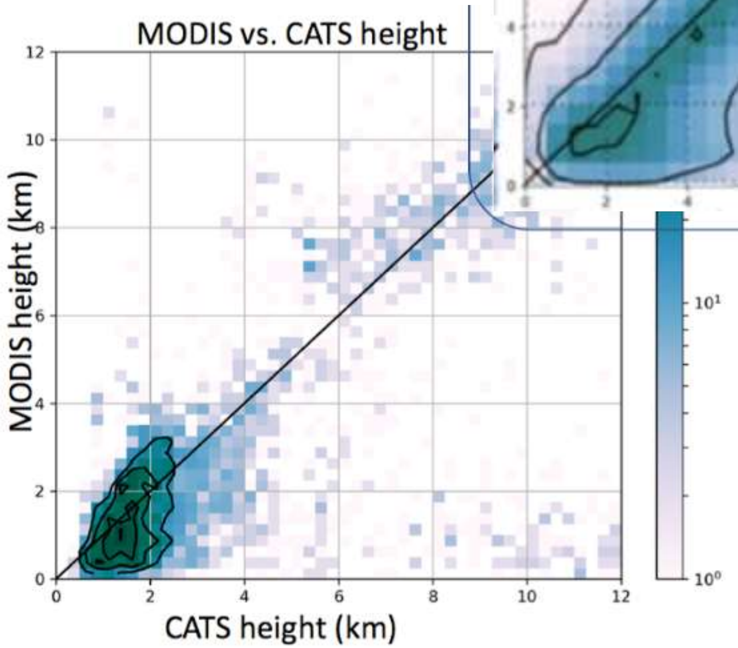
Accuracy versus height assignment

- Passive techniques lack accurate heights
- Average shear of 4 m/s per km
- Height uncertainty detriments wind accuracy
- 2 m/s accuracy implies σ_z = 500 m
- Only met by MISR and CATS . . .

MISR versus GOES

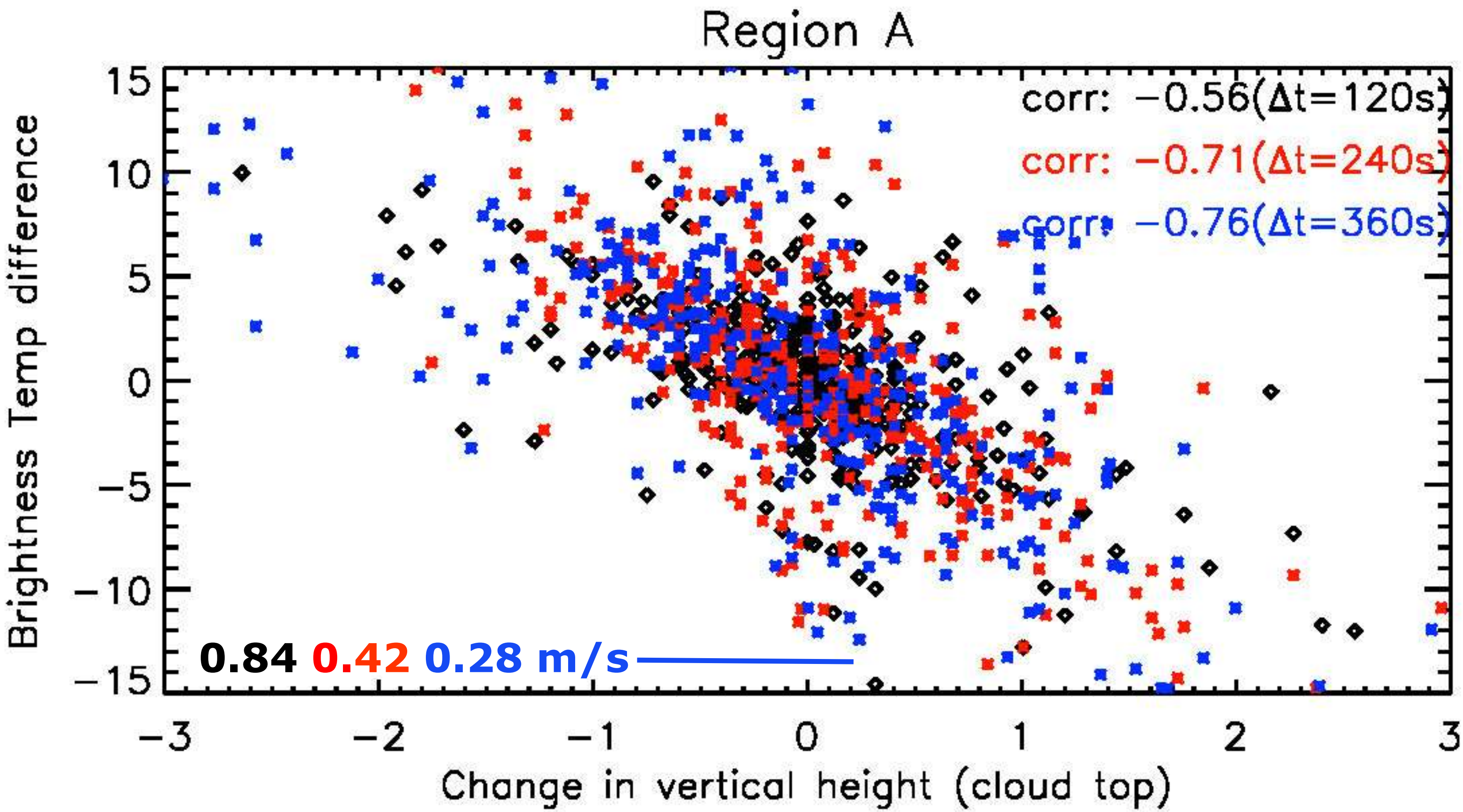






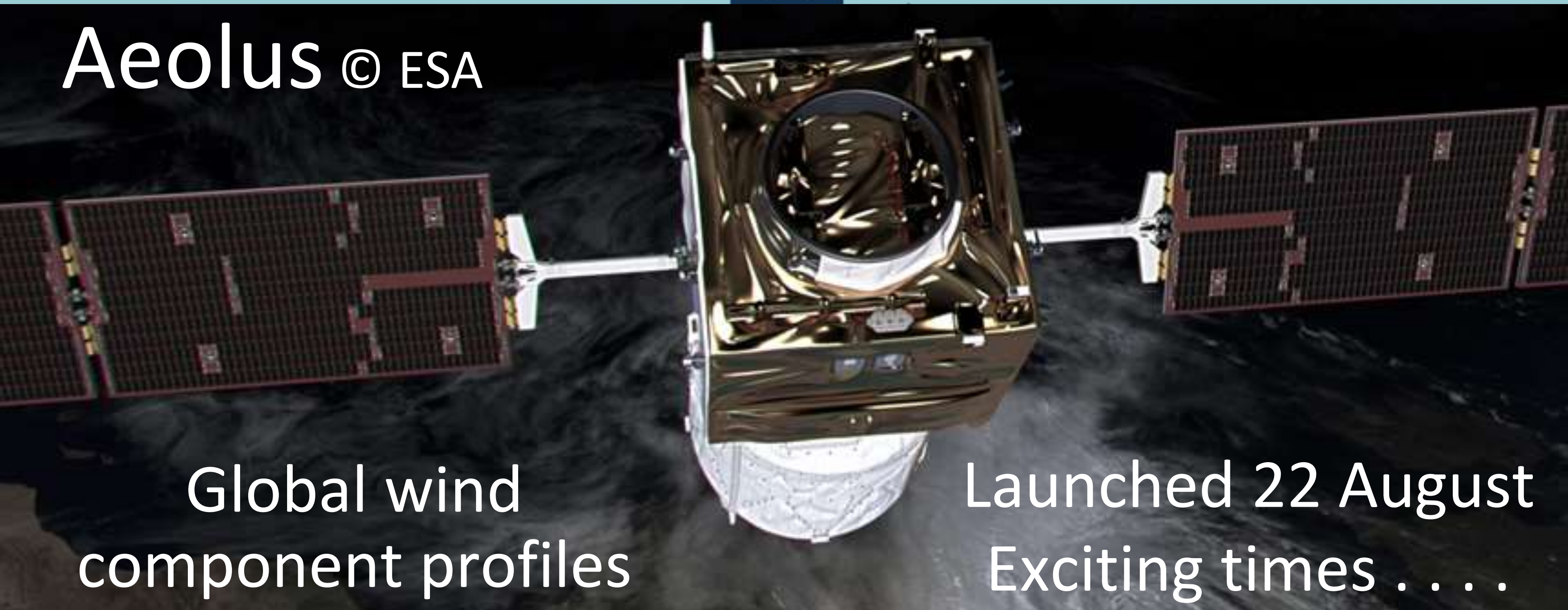
Kevin Mueller, JPL, 2018

Tb is not a good proxy for height

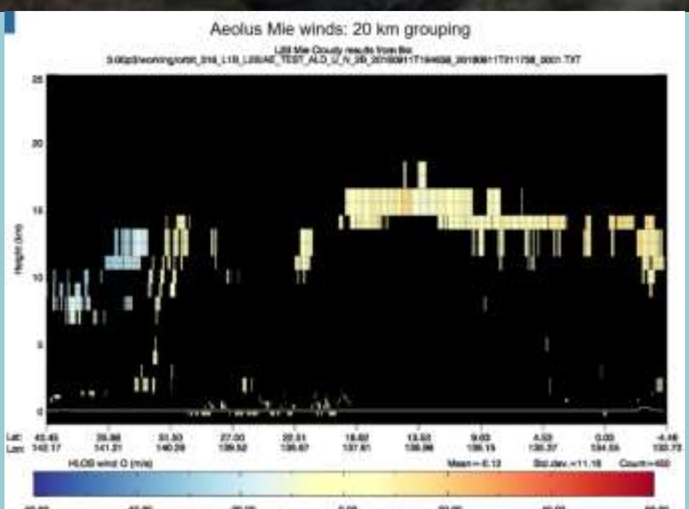


- Vertical speed is not a perfect proxy for vertical wind
- Tb and height relationship depends on cloud dynamics
- Tbs change due to divergence, shear, cloud dynamics, . . .

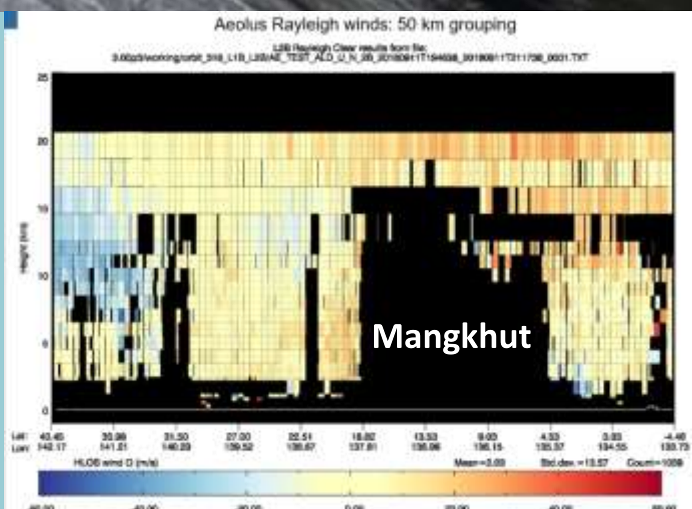
Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the



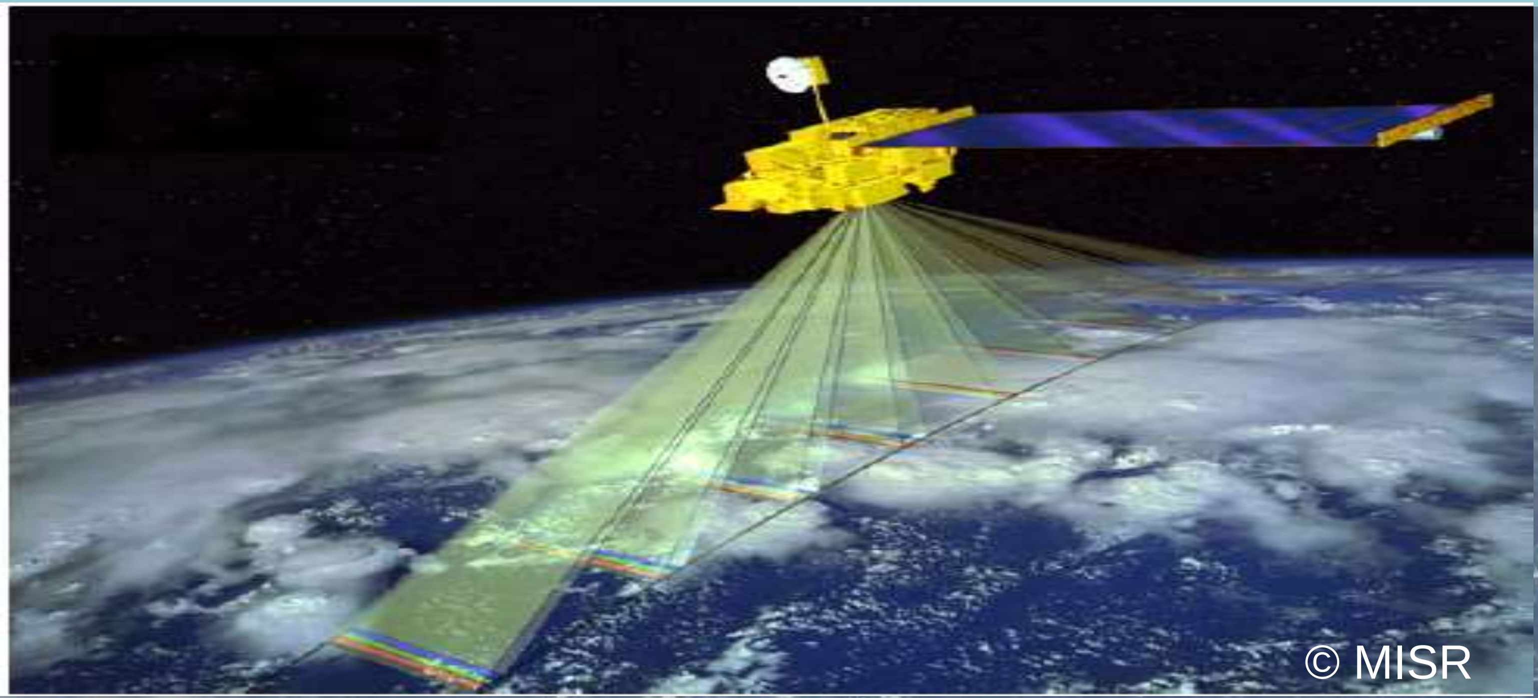
Mie:



Rayleigh:

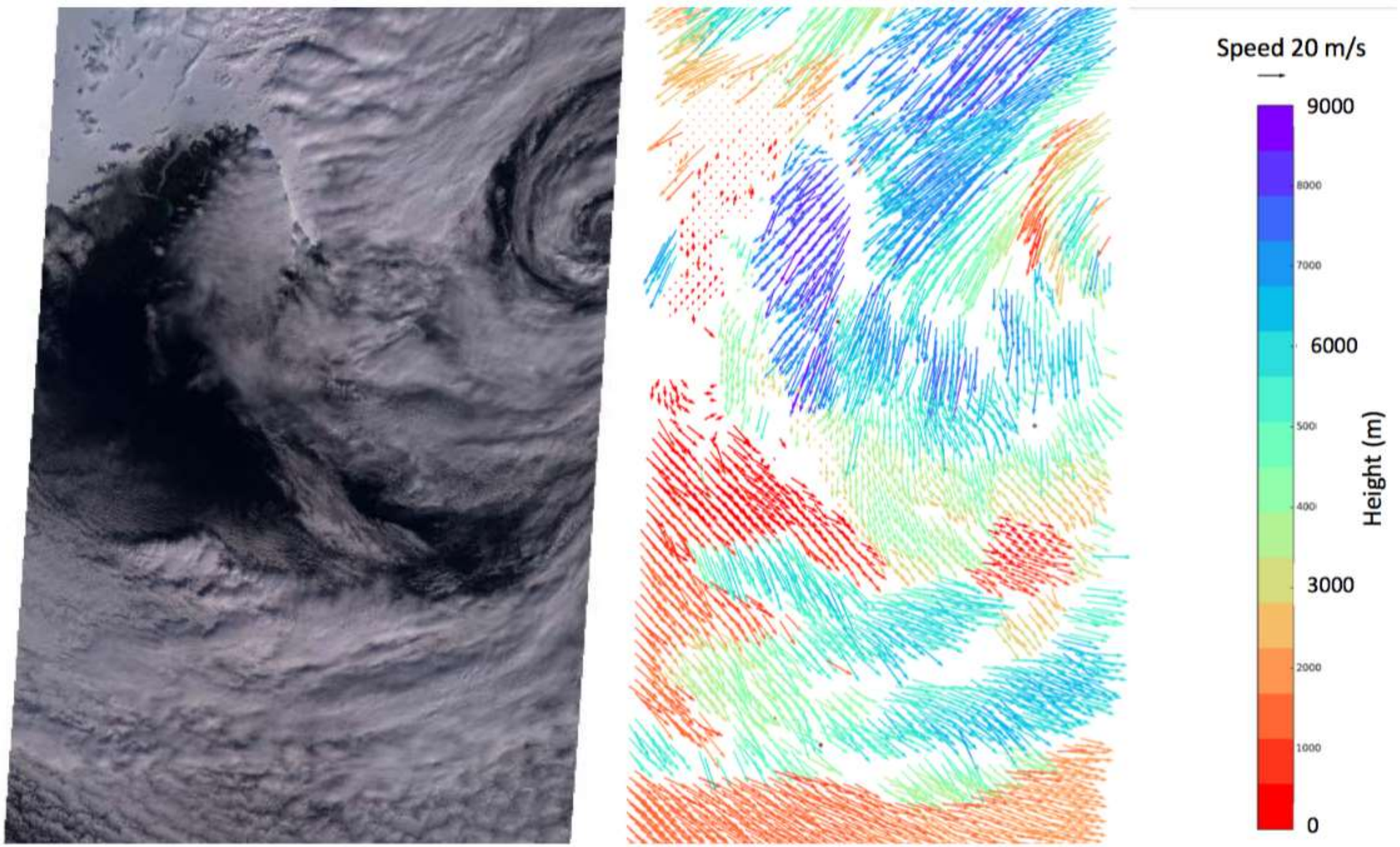


gCMW: Principle



- Geometric computation to obtain cloud height and cloud motion: gCMW
- Now computationally feasible at mesoscale grids
- Aim of gCMW: Height-resolved wind and optical information on mesoscale structures (processes of moist convection), complementing meteorological information by imagers and sounders, e.g., on MetOp-SG
- Tandem satellites provide better accuracy and vertical motion too

4.4-km Sampled Winds

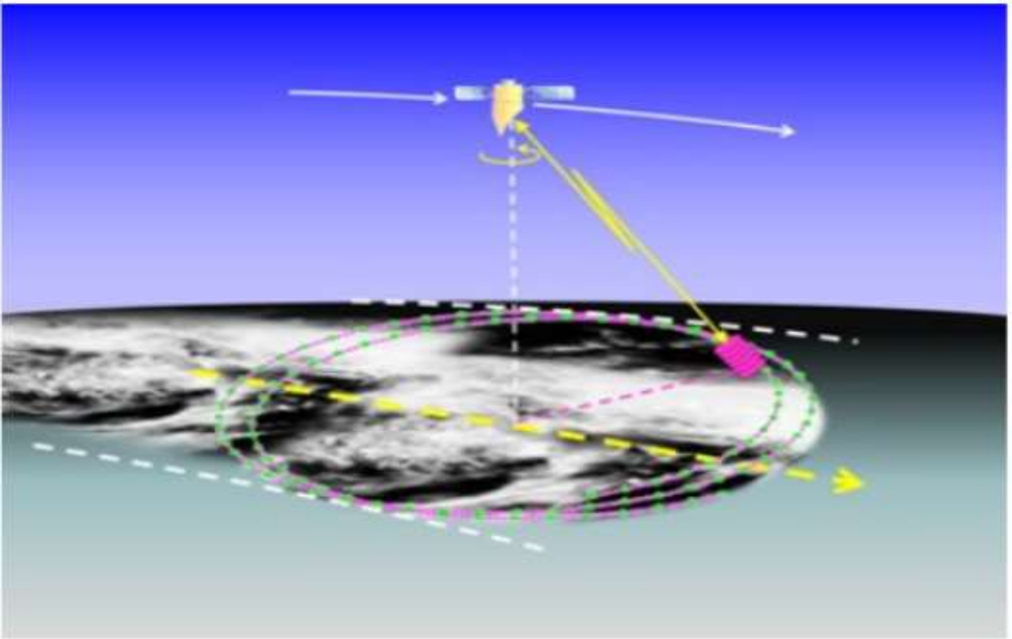


Kevin Mueller, JPL, 2018

Cloud Doppler Radar

1. WIVERN – RADAR CONCEPT

Illingsworth et al.



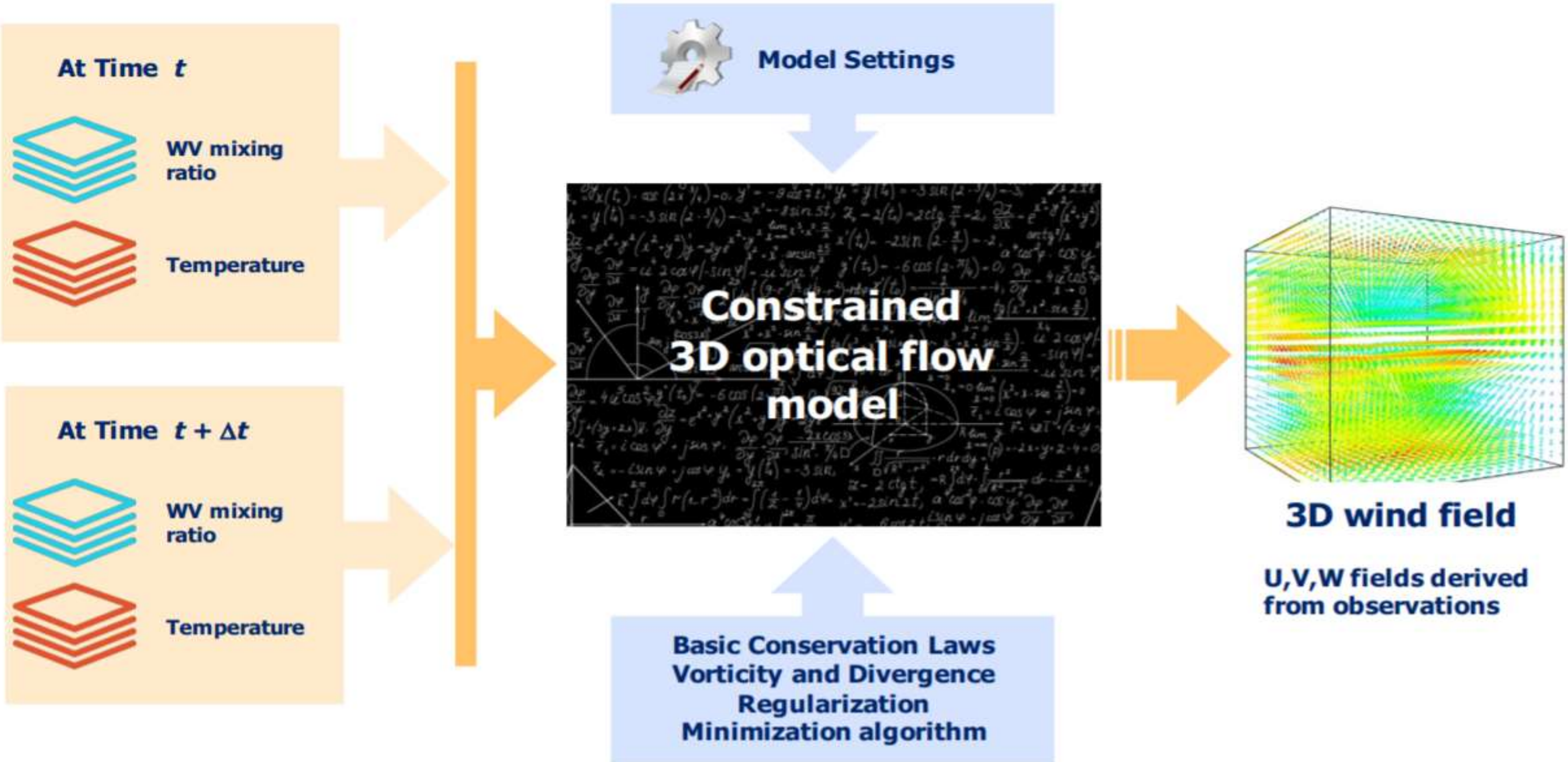
BASELINE: 800km swath:
Slant range 651km
Conical scan 37.9° off-nadir
(41.4° off zenith at surface)

Scan every 7 seconds
- move 50km along track
- sample every 50km along arc

NARROW BEAM - must use 94GHz – 2.9m elliptical antenna
- 3dB two-way beamwidth 0.001rad - pulse length 500m,
Detect line of sight winds - Doppler shift of cloud return
also precipitation rate and cloud ice water content.
Two configurations 1: 500km orbit /800km full swath, and
2: For shorter revisit time, 700km orbit/1800km swath

IASI winds/radiances

The concept



Hautecoeur et al., 2016

Wind Observations

- Will much increase over the sea surface
- Many upper air aircraft winds over land
  (if made available)
- Aeolus to provide wind profiles in the coming three years
- Many upper clair cloud winds, but less accurate at mesoscale
- Geometric cloud winds appear better (MISR)

Research:

- Proposed cloud radar mission
- IASI winds/radiances

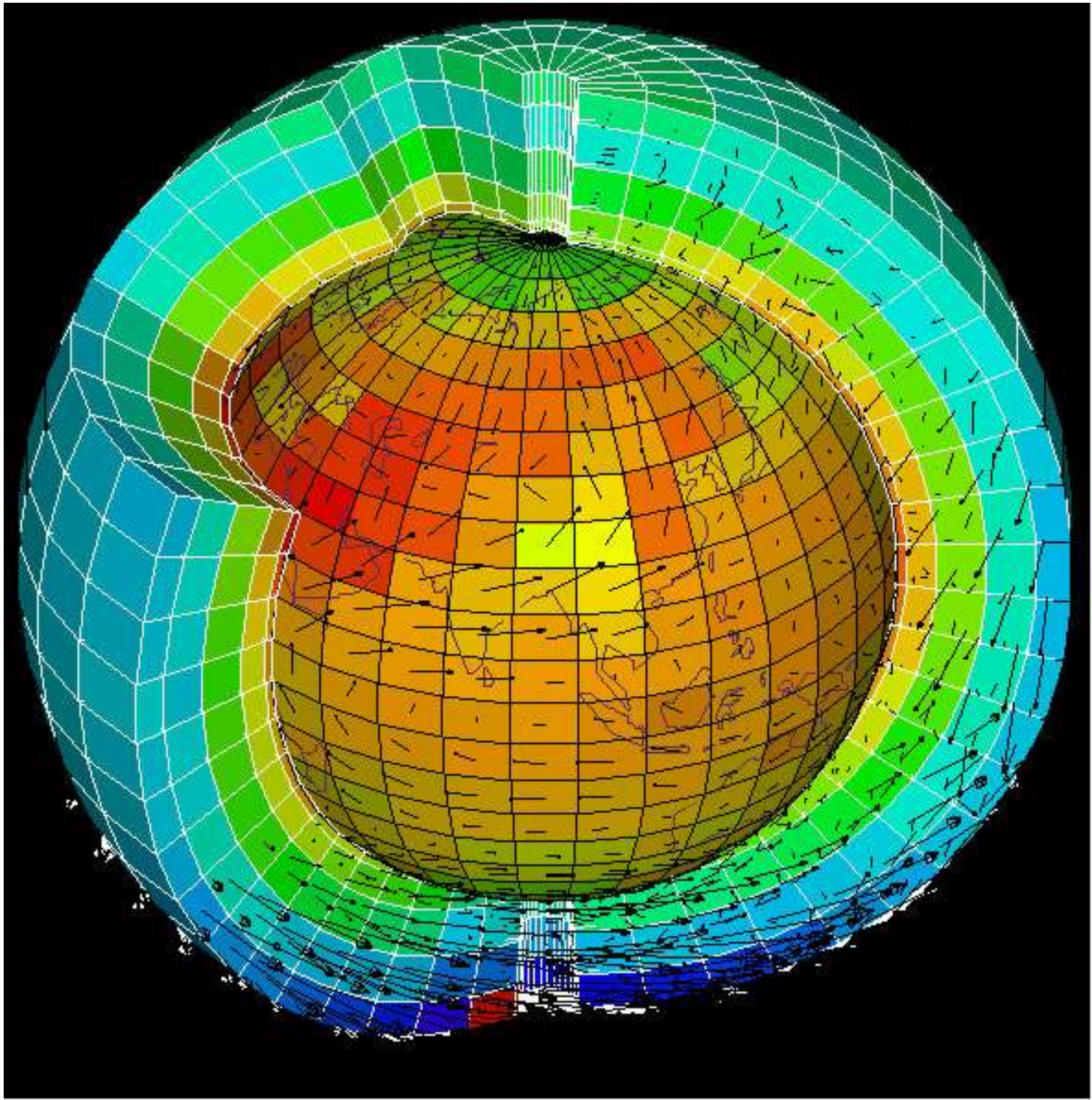
➢ Brightness temperatures not good for height knowledge

Mesoscale Wind Data Assimilation

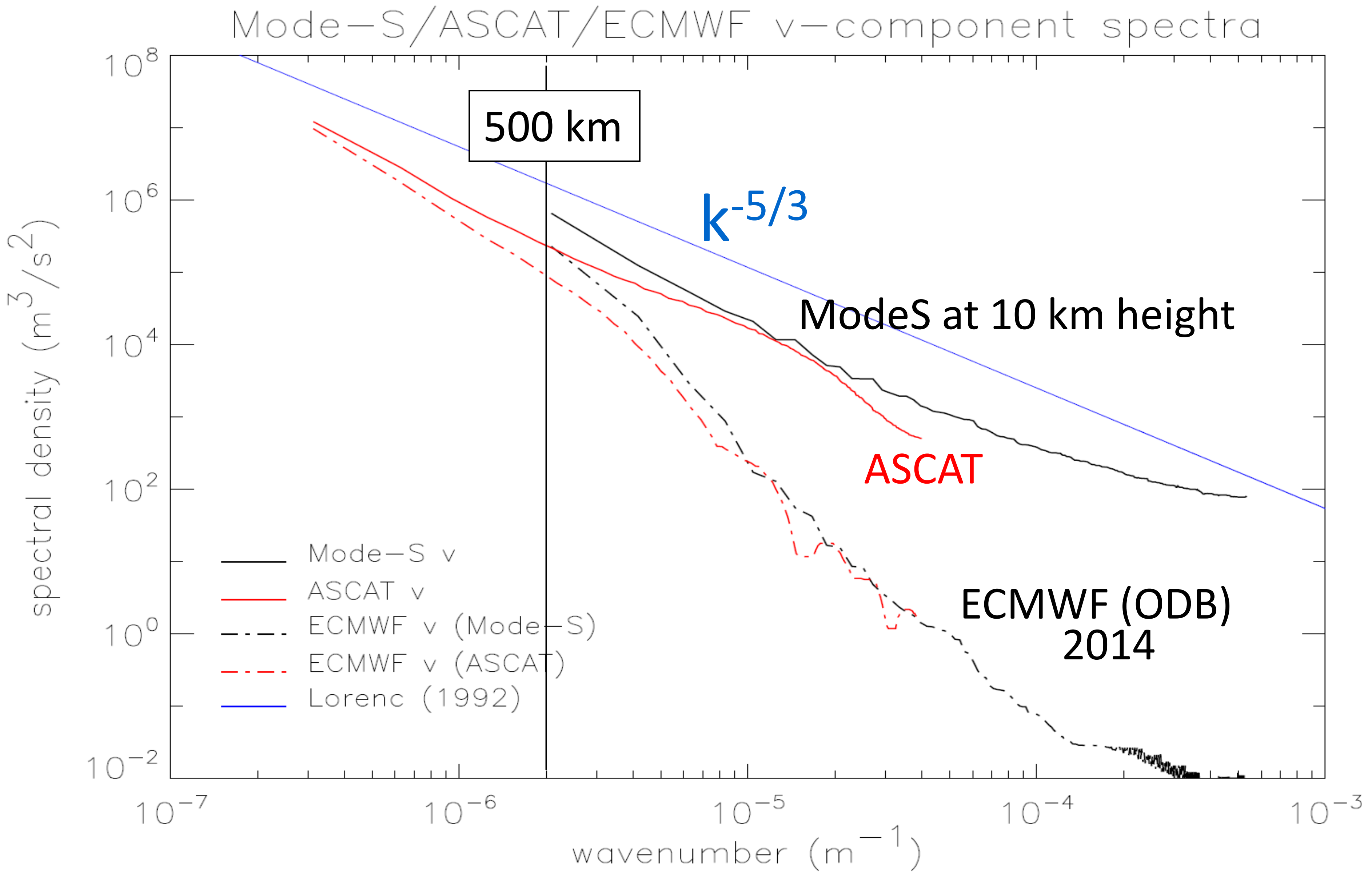
- What do we need ?
- Wind observations
- How well do we model ?
- How to assimilate observations ?

Global Circulation Models

- Used for transient weather prediction and climate scenarios
- ~ 100 x 1000^2 boxes with ~10 variables (p, T, u, v, w, CC, H2O+fase, O3, ..)
- Interaction between boxes and variables, new state every ~15 minutes; 100x a day
- Interaction with ocean and land surfaces
- Largest available supercomputers are used

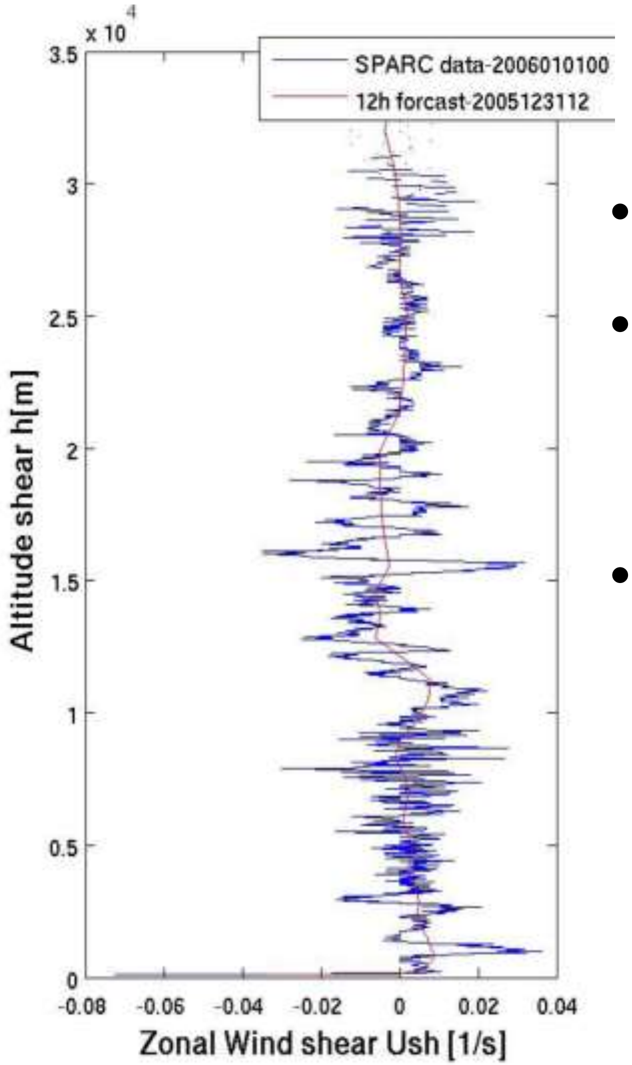


NWP gap for small scales upper air

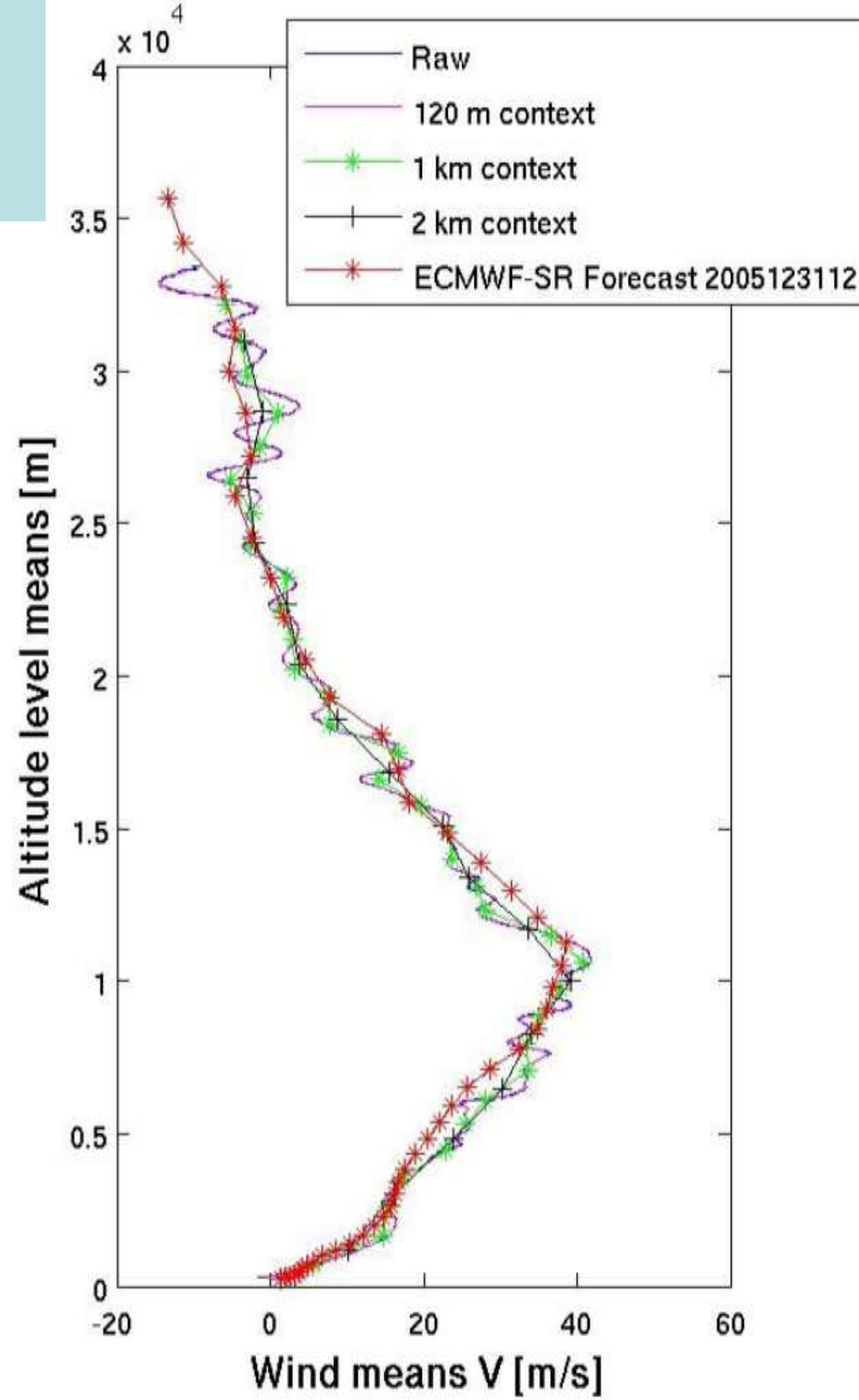


NWP model versus hi-res SPARC radiosondes

Houchi et al., 2010

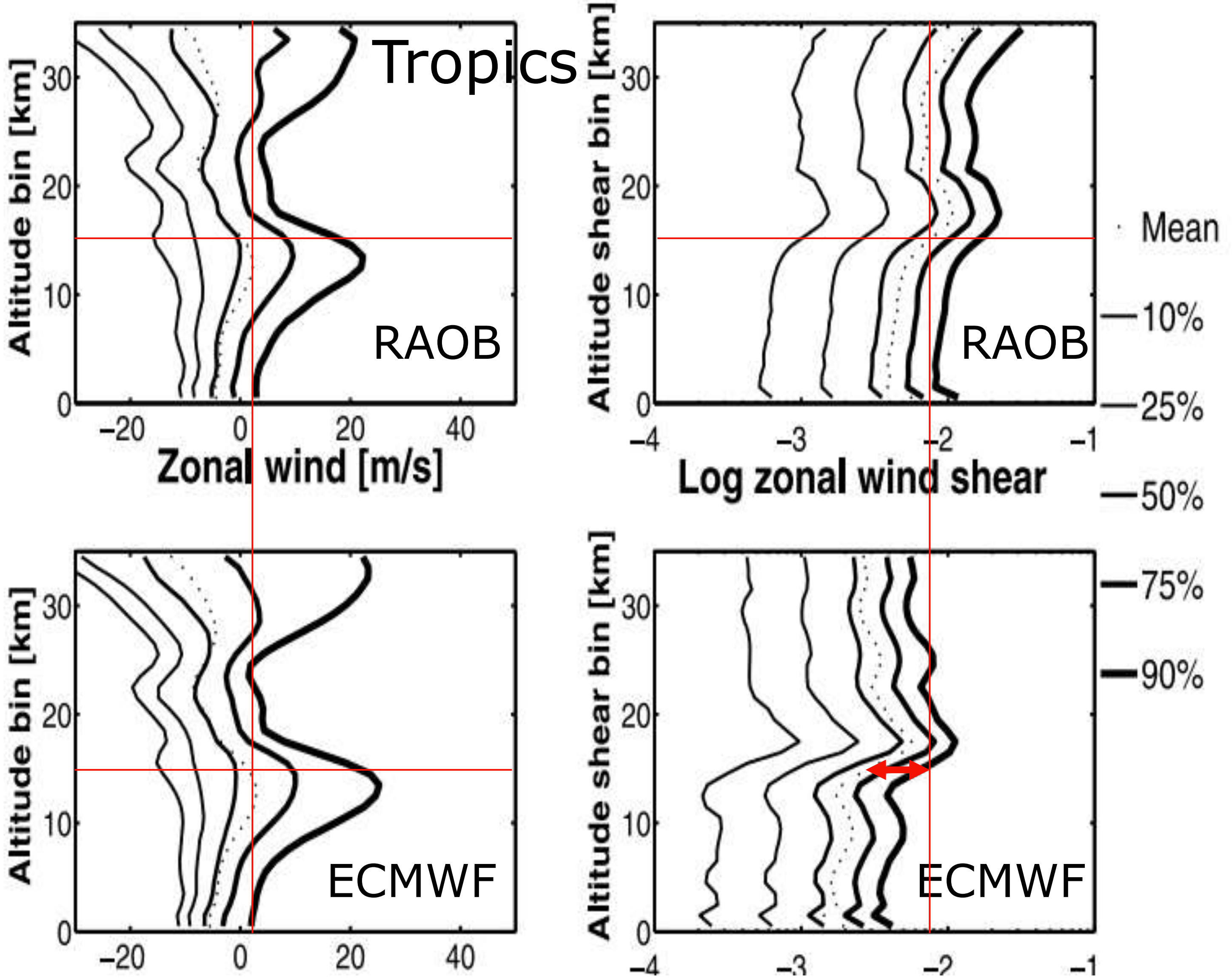


- ECMWF 1.5-2 km resolution
- SD : 2 m/s
- Shear 3 times too low even
- Physics tuned to poor vertical shear structure



Hi-res radiosonde shear

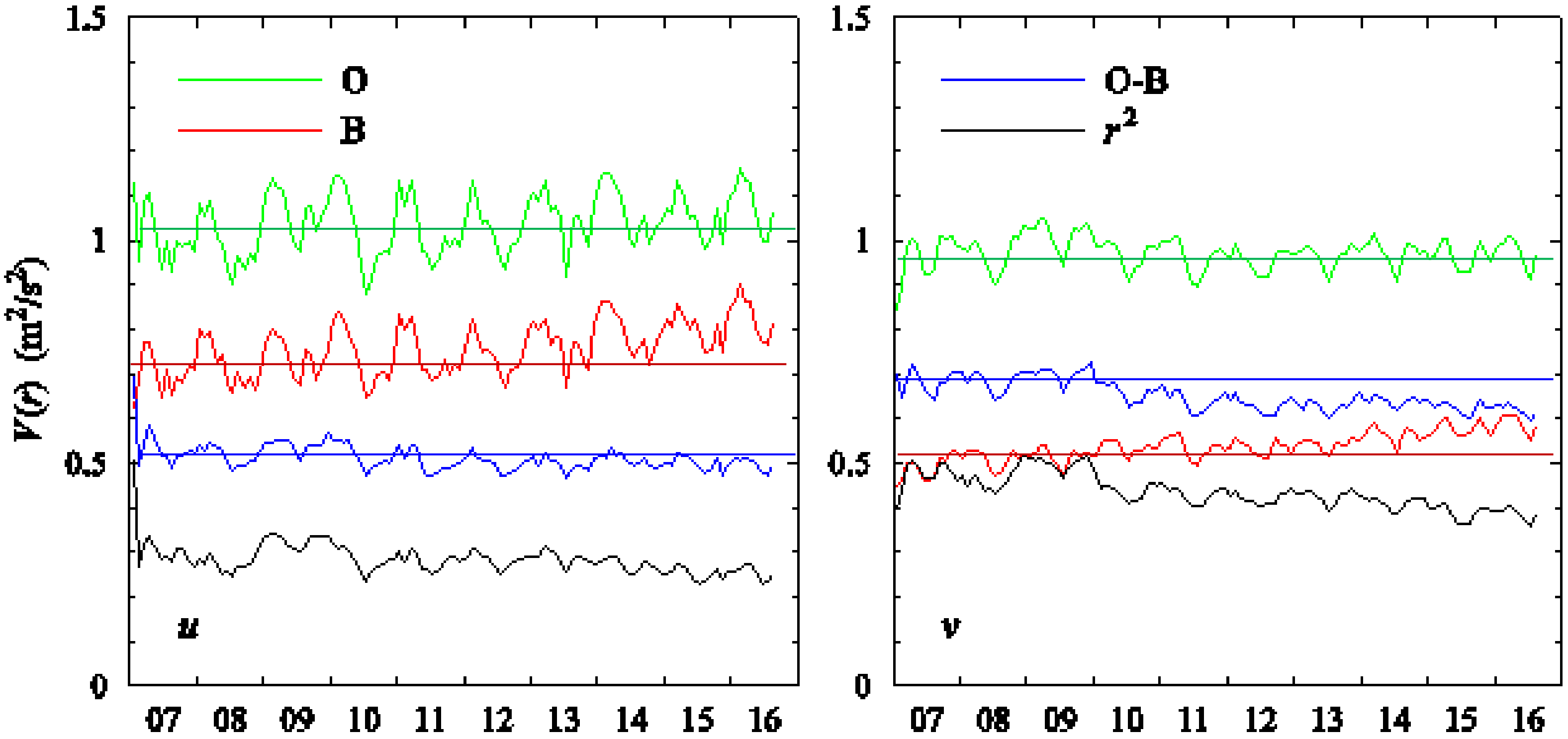
- ✓Collocation data base
- ✓ECMWF winds agree very well
- ✓Shear in ECMWF model 2-3 times lower, however
- ✓Tropical tropopause strongly variable
- ➢Shear determines mixing of air, cloud forming, ..



- Houchi et al. 2010

ECMWF OPS improves over time

- Variances on scales < 200 km only
- Scatterometer O variance under 200 km constant
- < 200-km variance B increases to
  80% (u), resp. 60% (v) of O
- O-B decreases, particularly for v, thus reducing B error



Does Dynamical Downscaling With Regional Climate Models add Value to Surface Marine Wind Speed From Reanalyses?

Jörg Winterfeldt[1*], Ralf Weisse[1], Matthias Zahn[1]

[1]Institute of Coastal Research, GKSS Research Centre, Geesthacht, Germany

*joerg.winterfeldt@gkss.de

Simulations with RCMs REMO and CLM: *(available from coastDat Database)*

- Three hindcasts with RCMs REMO (Jakob and Podzun, 1997) and CLM (Böhm et al. 2006)
- Initialization and forcing at lateral boundaries: NCEP/NCAR-Reanalysis (NRA), ~1.875° resolution,
- SN-REMO & CLM hindcasts are additionally forced by spectral nudging (von Storch et al., 2000)

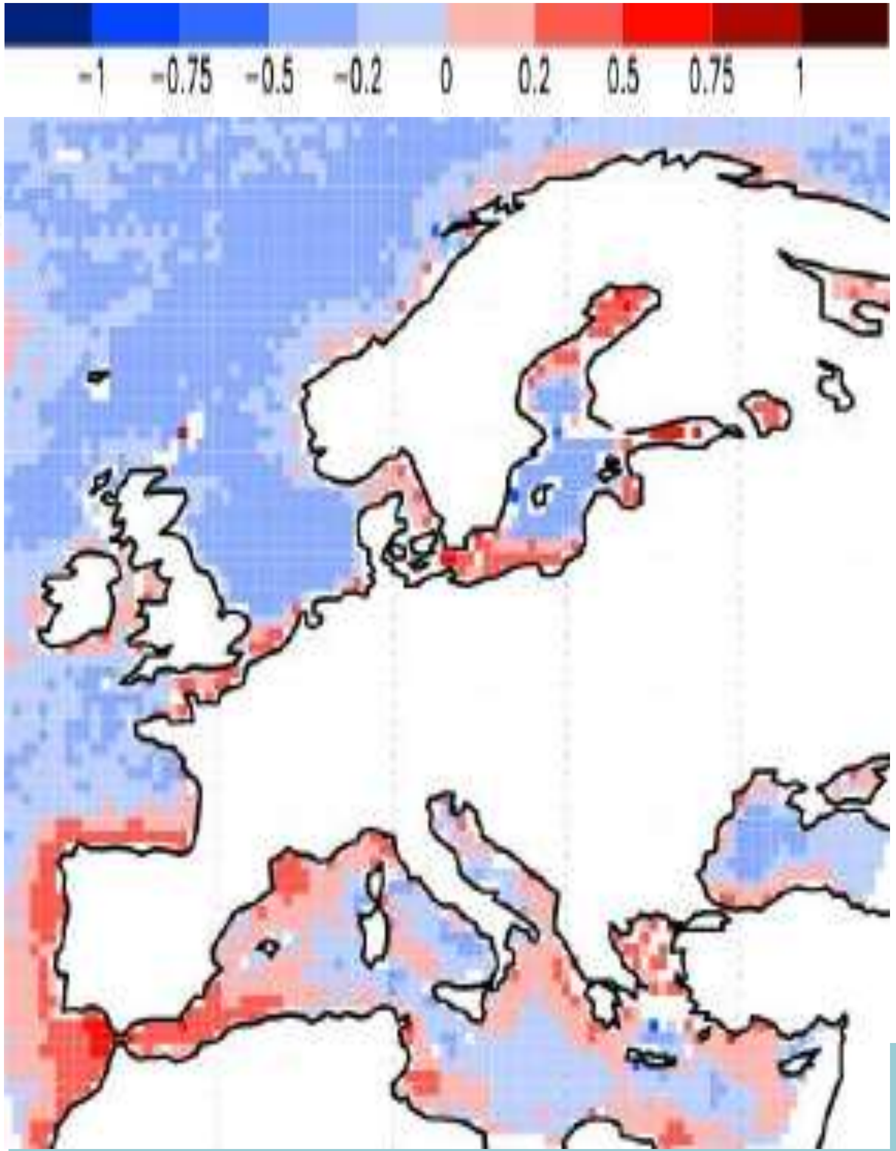
Hindcast	*STD-REMO (Standard)*	*SN-REMO*	*CLM*
Based on:	EM Hydrostatic	EM Hydrostatic	LM Non-hydrostatic
Forcing:	NRA	NRA	NRA
Spectral Nudging:	No	Yes	Yes
Resolution:	0.5°	0.5°	0.44°

- For that purpose a gridded QuikSCAT Level 2B 12.5 km swath (L2B12) data set is produced on SN-REMO grid (rain flagged L2B12 data discarded) co-location with SN-REMO: QuikSCAT wind speed retrieval max. 12.5 km and +/- 10 min from SN-REMO grid point / time step

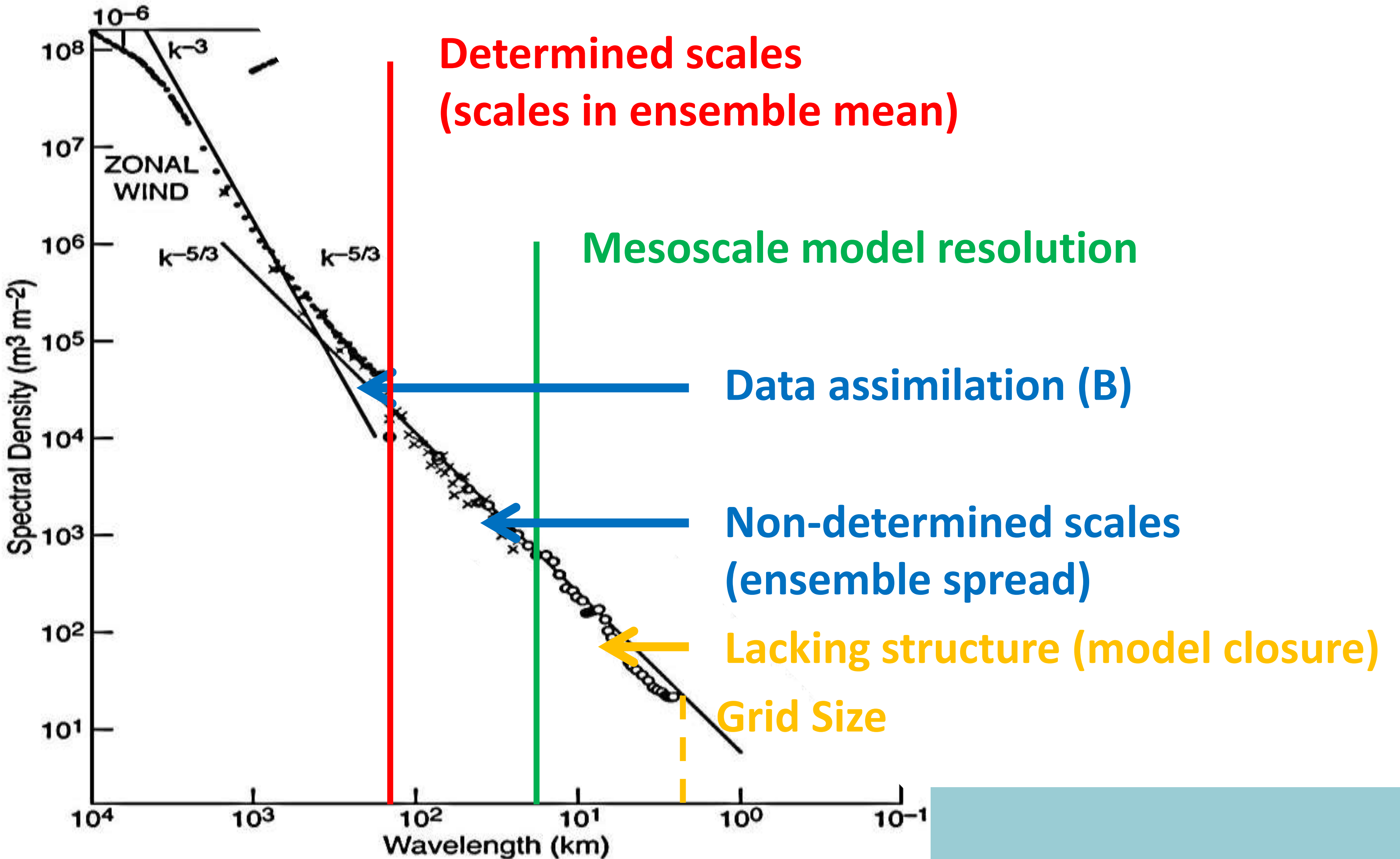
- Modified BSS =

$$\begin{cases} 1 - \sigma_F^2 \sigma_R^{-2} & \text{if } \sigma_F^2 \leq \sigma_R^2 \\ \sigma_R^2 \sigma_F^{-2} - 1 & \text{if } \sigma_F^2 > \sigma_R^2 \end{cases}$$

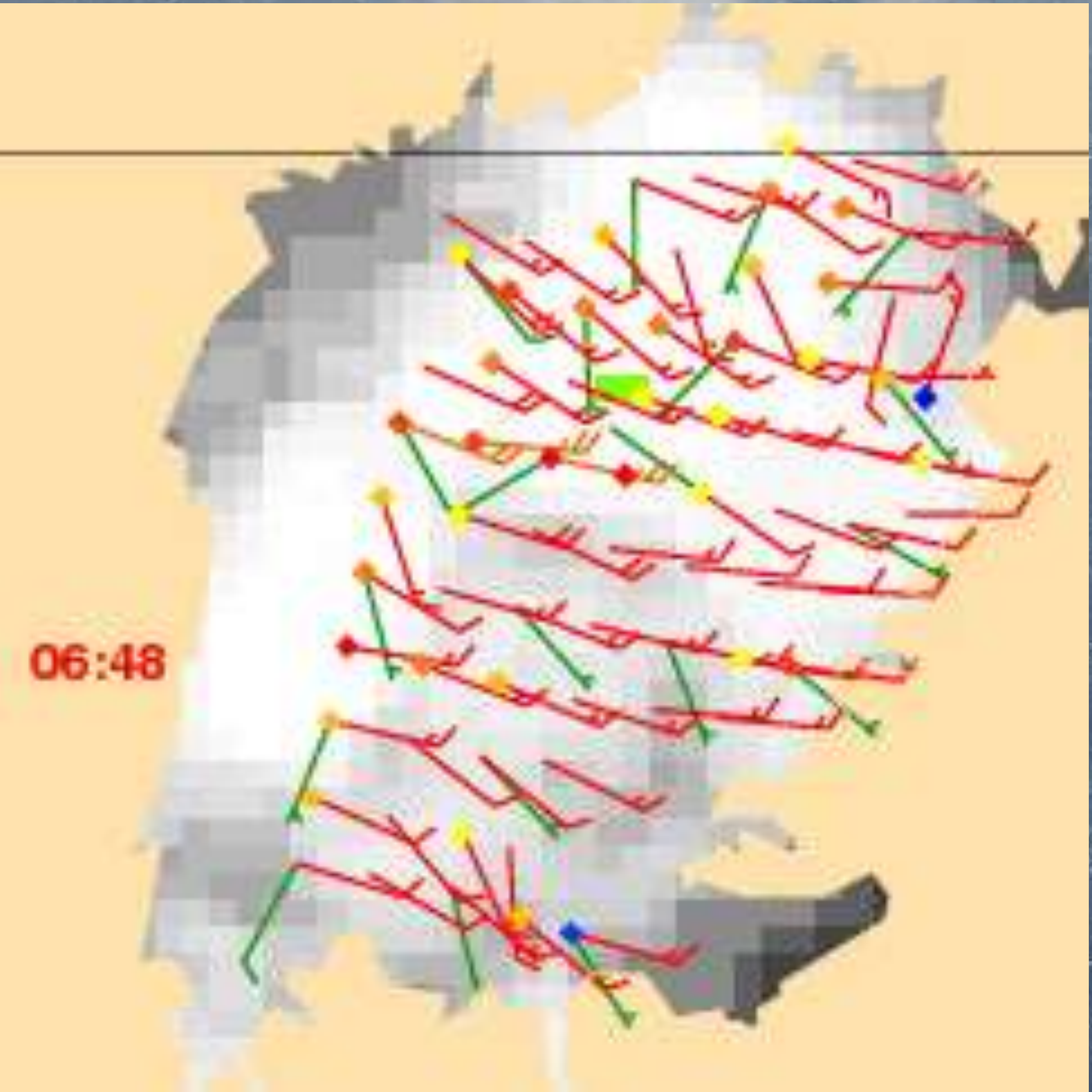
- "Forecast" F: SNREMO, reference "forecast" R: NRA, predictand/observation: gridded QuikSCAT L2B12 data



Nastrom & Gage Observed Spectrum

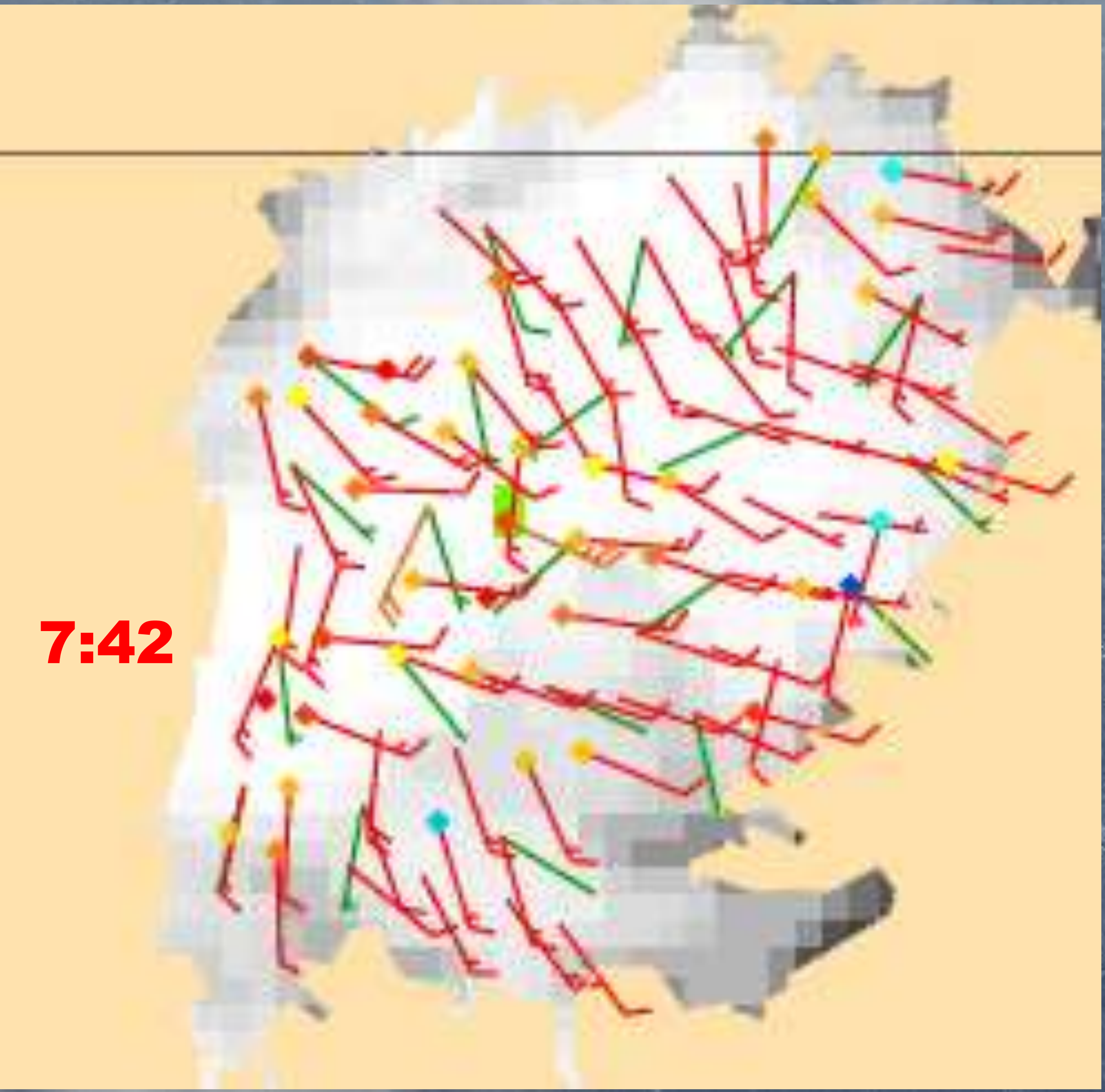


Lake Victoria

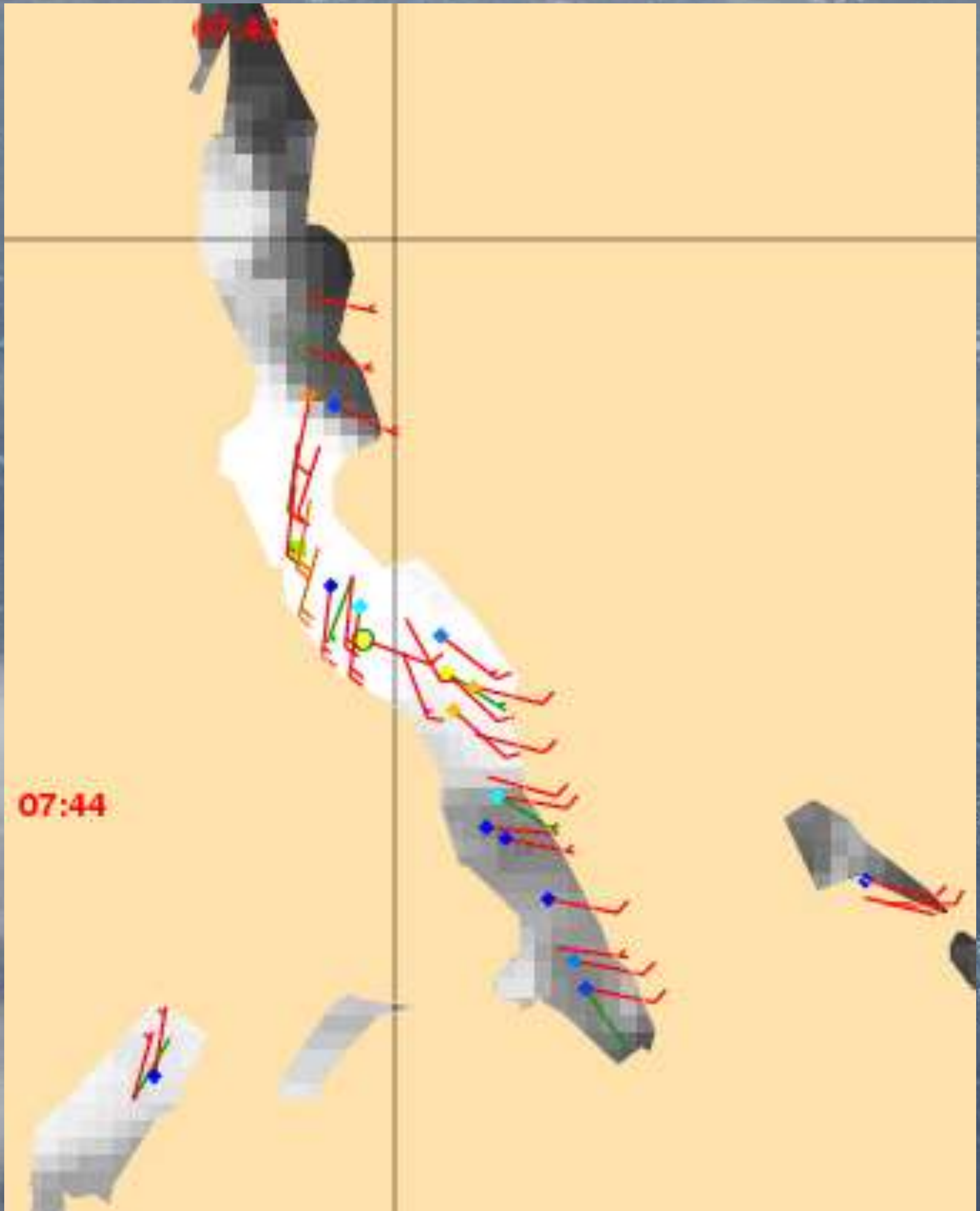


- 8 Dec 2016
- ASCAT-A
- Little wind in ECMWF (green)
- 25 knots in ASCAT (red)
- Moist convection

Lake Victoria



- 8 Dec 2016
- ASCAT-B, 50 min later
- Little wind in ECMWF (green)
- 25 knots in ASCAT (red)
- Moist convection
- Messy !

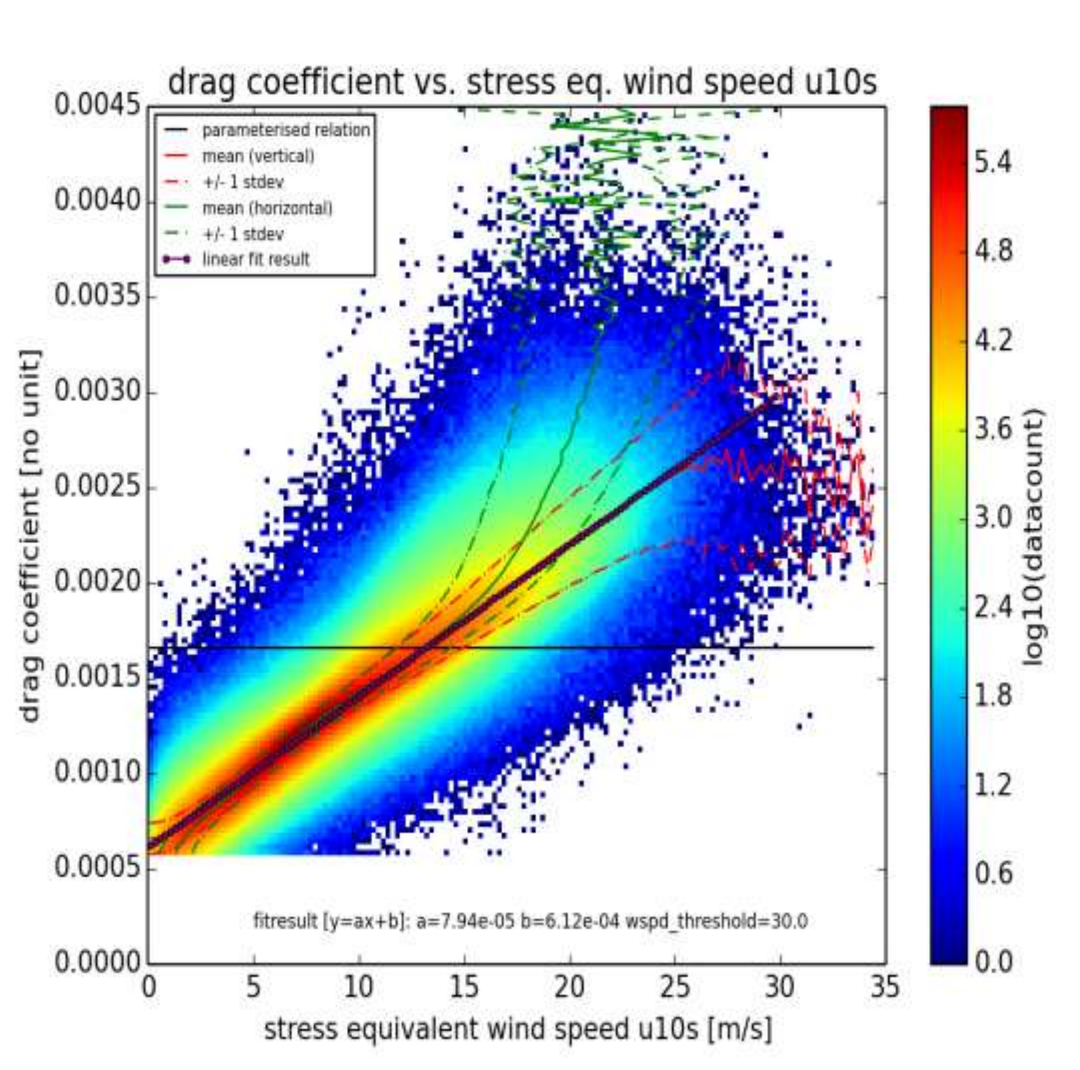


Lake Tanganyika

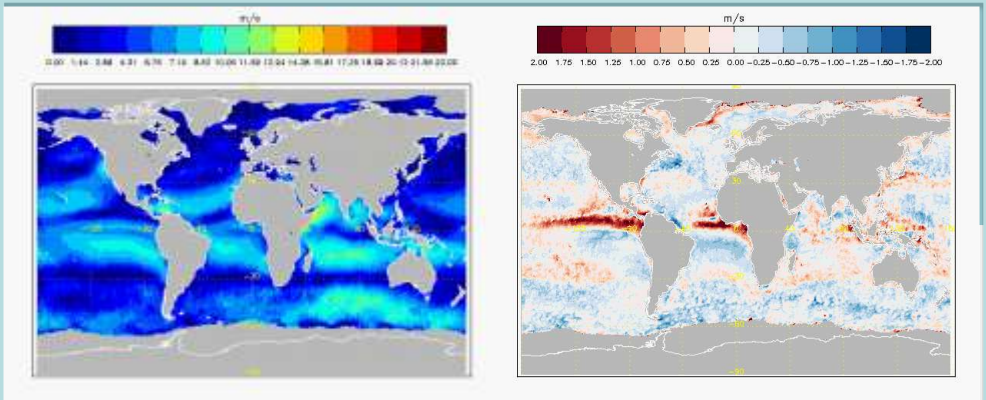
- 8 Dec 2016
- ASCAT-B
- Little wind in ECMWF (green)
- 20 knots in ASCAT (red)
- Moist convection

From U10S to stress: drag

- ❖ Stress-equivalent winds are computed for validation of scatterometer wind vectors: independent of atmospheric stratification and incl. air mass density
- ❖ Obtain drag to compute stress
- ❖ Is the NWP model drag correct ? If not, speed biases occur !

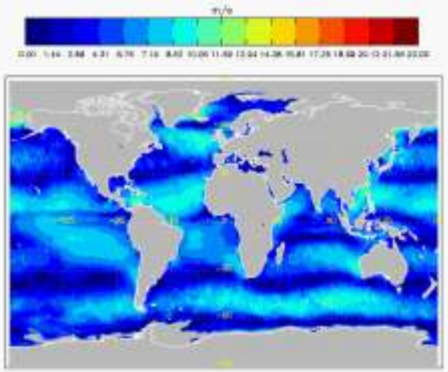


Wind Speed

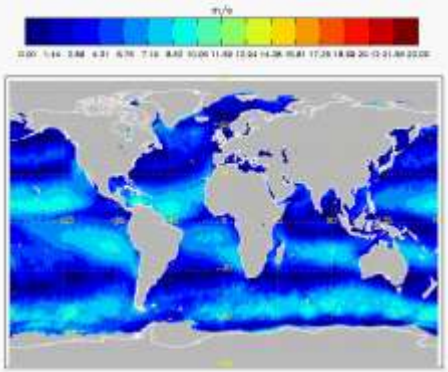


Annual 2014

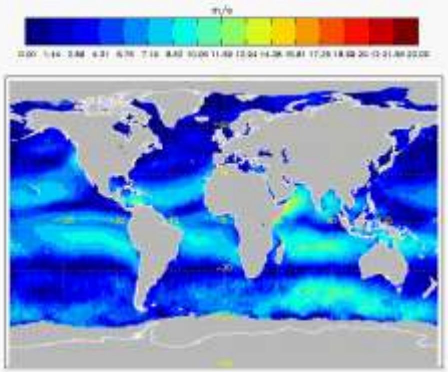
ASCAT



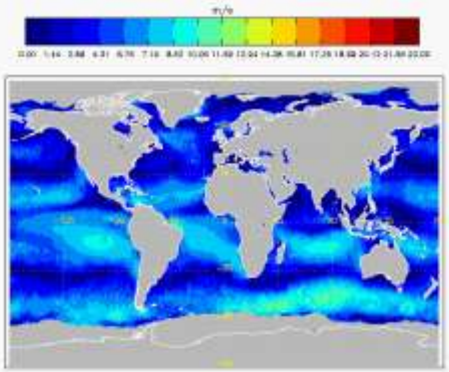
DJF



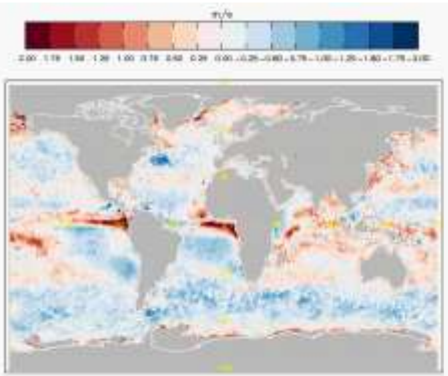
MAM

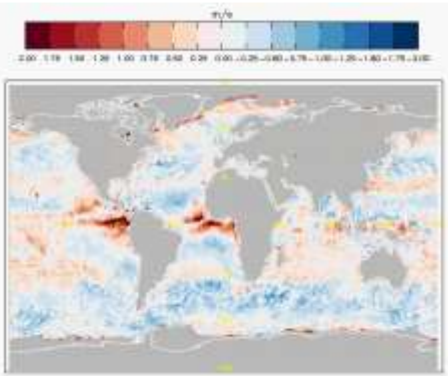


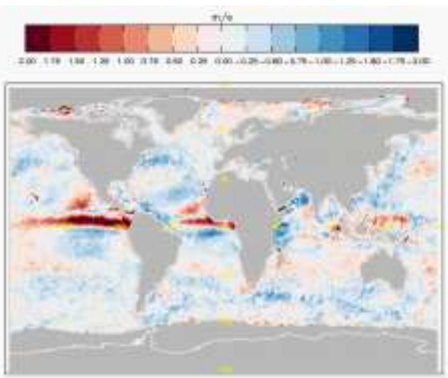
JJA

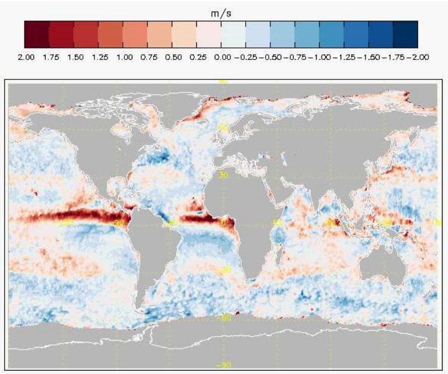


SON





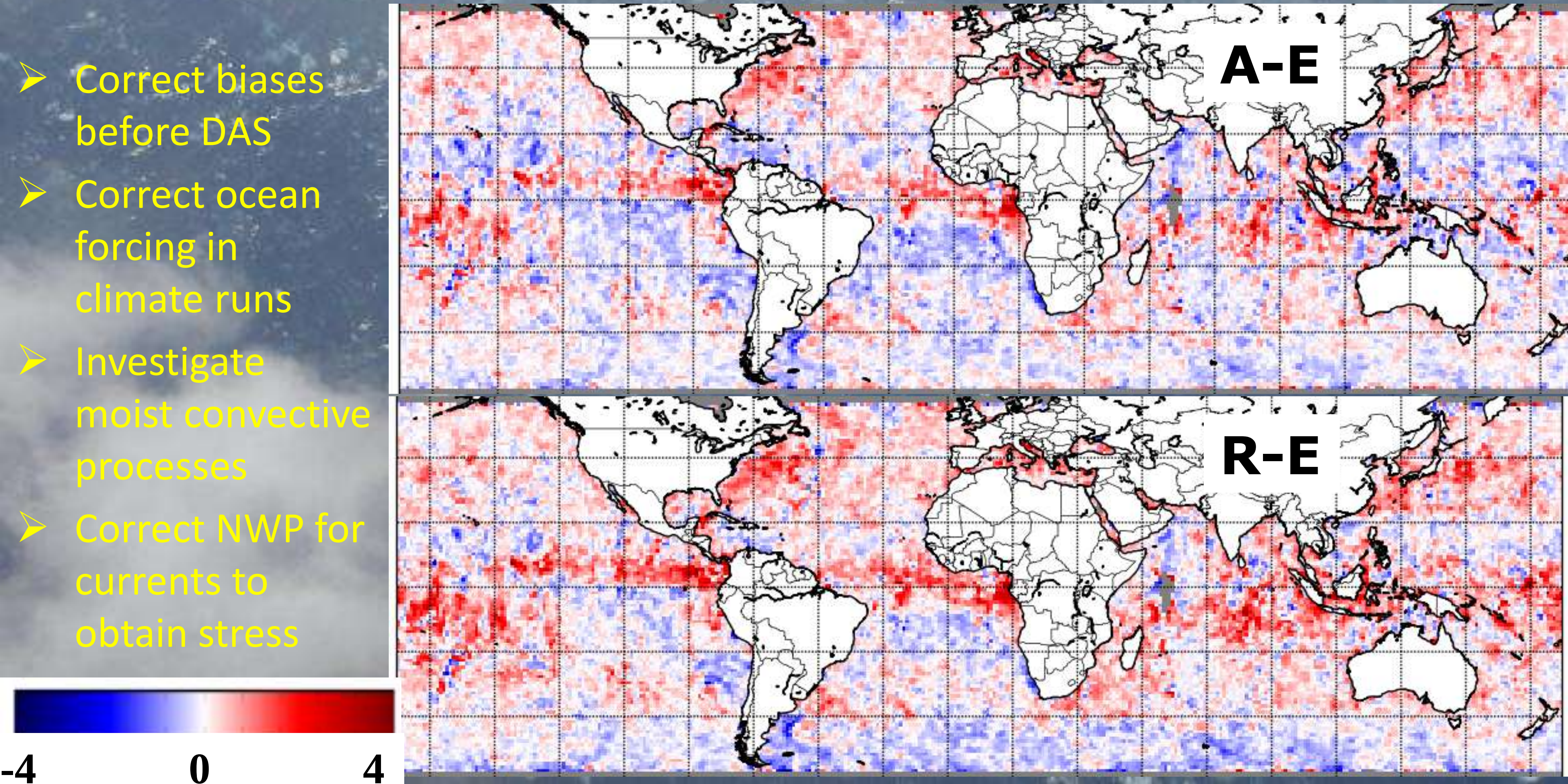




Anomaly (ASCAT-NWP)

Bias patterns with NWP

- Systematic wrong ocean forcing in the tropics
- Violates BLUE in data assimilation systems (DAS)
- Similar patterns every day, due to convection, parameterisation, ocean current



- ➢ Correct biases before DAS
- ➢ Correct ocean forcing in climate runs
- ➢ Investigate moist convective processes
- ➢ Correct NWP for currents to obtain stress

Triple Collocation at ASCAT scales

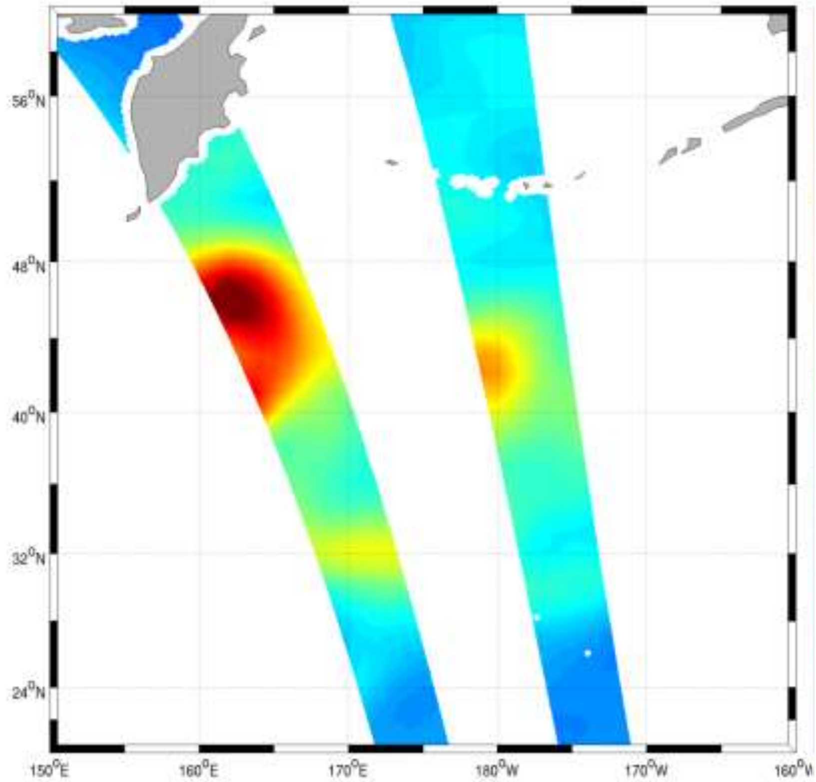
The error standard deviations at ***ASCAT*** scale of the triple collocation with **averaged buoy winds**; The accuracy of each estimated SD error is presented in parenthesis.

SD errors	Buoy (m/s)		ASCAT (m/s)		ECMWF (m/s)		Number
Categories	u	v	u	v	u	v	
95% stable winds	0.76 (0.01)	0.80 (0.01)	0.52 (0.01)	0.73 (0.01)	1.33 (0.01)	1.39 (0.01)	39293
2%-5% variable winds	1.1 (0.1)	1.1 (0.1)	0.9 (0.1)	1.4 (0.1)	2.1 (0.2)	2.1 (0.2)	1243
2% variable winds	1.5 (0.1)	1.1 (0.1)	1.4 (0.2)	2.0 (0.3)	2.5 (0.3)	2.5 (0.3)	828

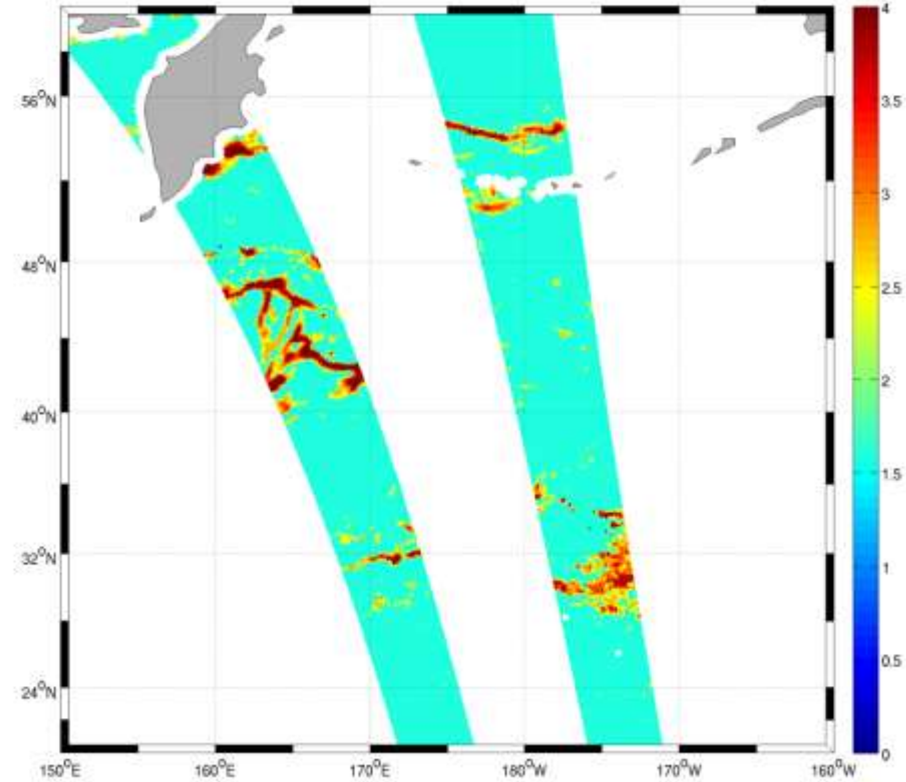
As expected, errors increase with increased wind variability

- ECMWF errors are the highest
- ASCAT and buoy errors are still reasonable quality for the highest wind variability category !

Estimated B error variances



ECMWF Ensemble Data Assimilation (EDA background error)



ASCAT-derived ECMWF background error by triple collocation in QC classes

- The structure and location of ECMWF errors is not well resolved in EDA

Statistics

QC-ed 2-solution cases with |MLE$_1$|<1

- New ASCAT winds fit buoys and ECMWF better
- New 2Dvar analysis fits ASCAT and buoys much better, but ECMWF worse

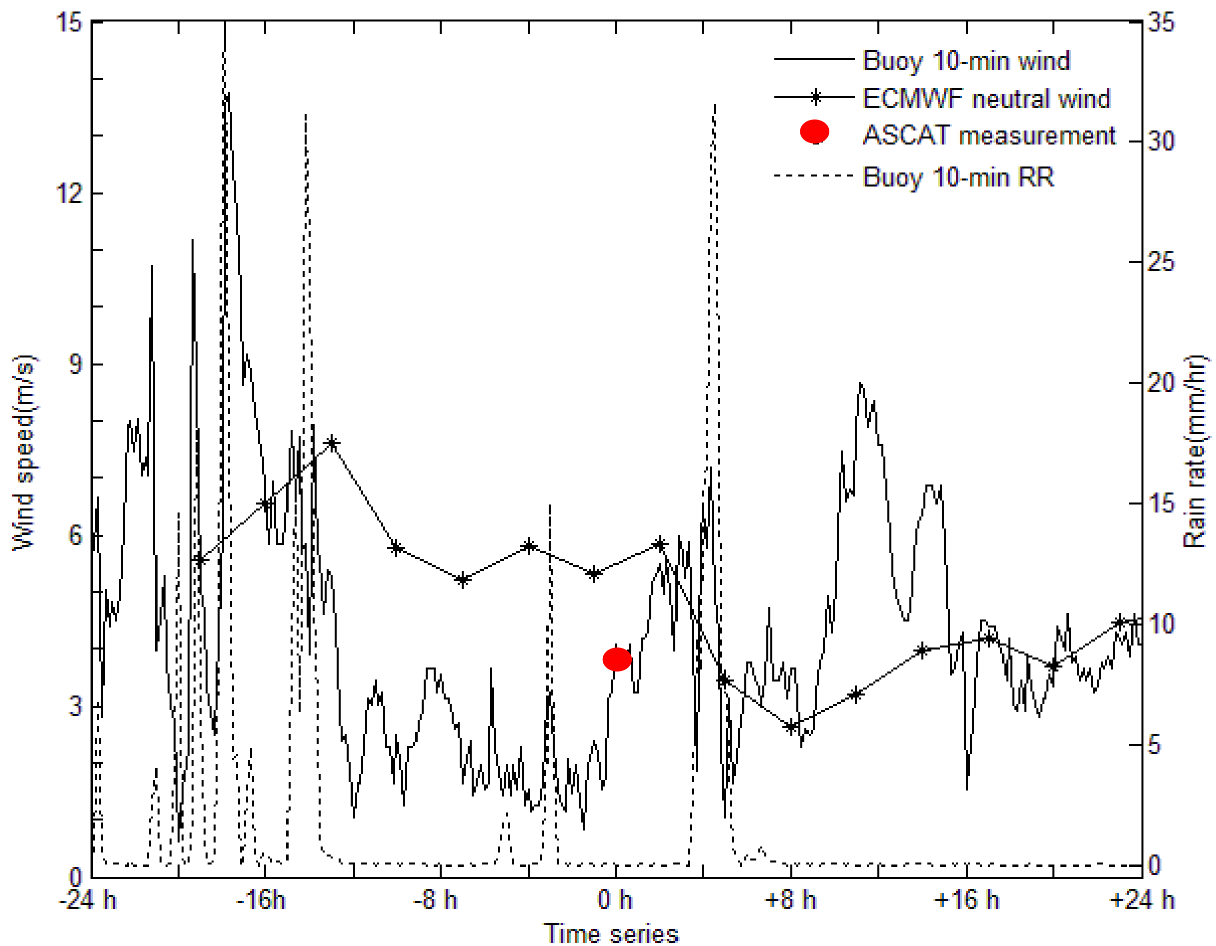
	ASCAT-ECMWF-buoy comparison (mean buoy winds)		
	ASCAT vs ECMWF	ASCAT vs buoy point wind	N
Default	2.19	1.74	5034
New	2.17	1.71	

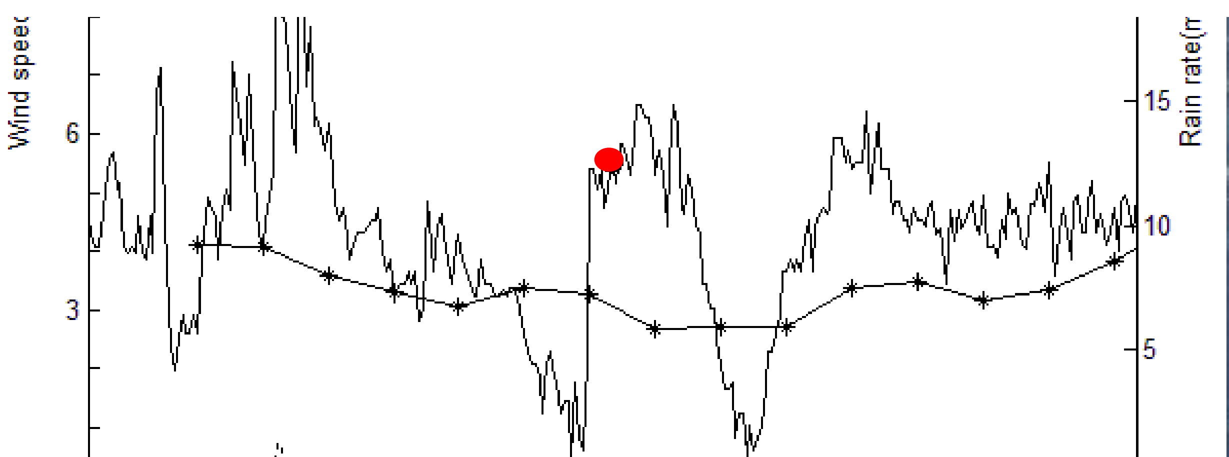
	ASCAT-ECMWF-buoy comparison (mean buoy winds)			
	2DVAR vs ECMWF	2DVAR vs buoy point wind	2DVAR vs ASCAT	N
Default	1.85	1.94	1.17	5034
New	2.00	1.76	0.74	

Tropical variability

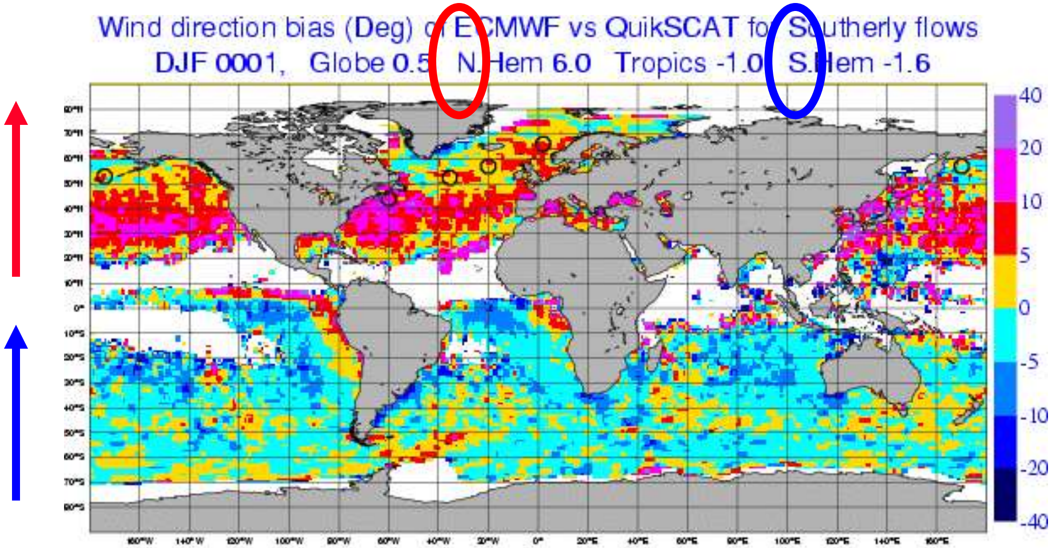
- Dry areas reasonable
- NWP models lack air-sea interaction in rainy areas
- ASCAT scatterometer does a good job near rain
- QuikScat, OSCAT and radiometers are affected by rain droplets

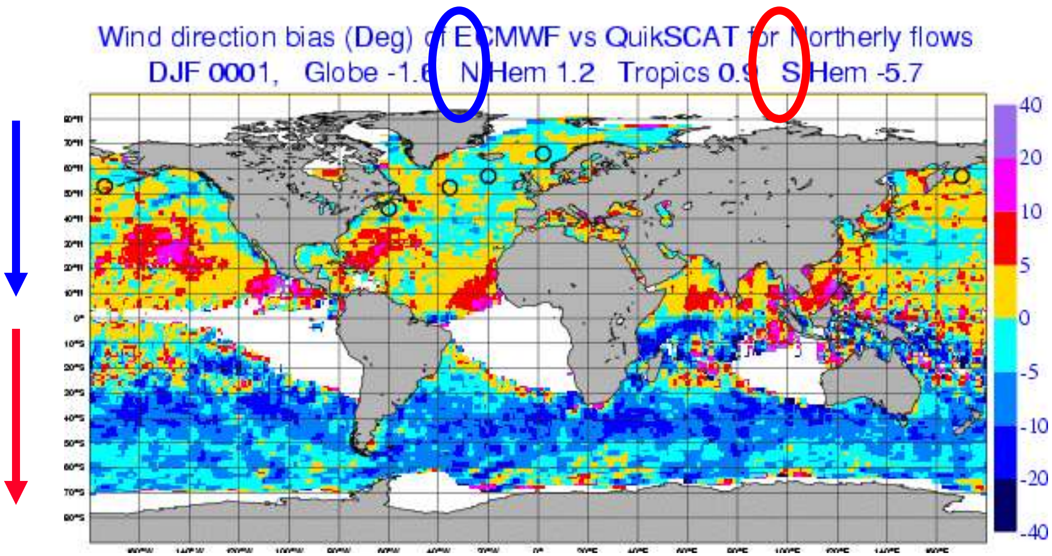
Portabella et al., Lin et al.





Lack of cross-isobar flow in NWP





QuikSCAT vs model wind dir
Stratify w.r.t. Northerly, Southerly wind direction.
(Dec 2000 – Feb 2001)

- **Large effect warm advection**
- **Small effect cold advection**
- **Similar results for NCEP**

A. Brown et al., 2005

I. Sandu et al., ECMWF (2013)

Model Winds

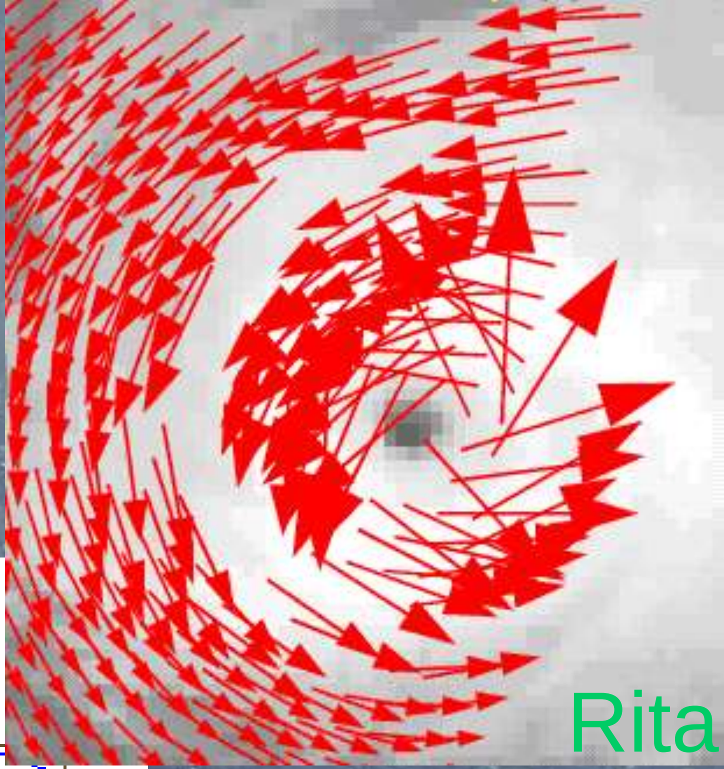
- Are initialized from observations in a DAS
- Are improving and any forecasters' reference
- Global models lack mesoscale variability
- Regional models lack true mesoscale variability over sea and in the upper air
- Regional models are seriously affected by lateral boundaries http://meteo.fmf.uni-lj.si/sites/default/files/MesoWindsWorkshopLjubljana2016_Summary.pdf
- Are not so good in the tropics or elsewhere near convection (e.g., polar lows)
- Have some systematic wind biases (in stable air, ocean currents, drag, diurnal cycle, ..)

Mesoscale Wind Data Assimilation

- What do we need ?
- Wind observations
- How well do we model ?
- How to assimilate observations ?

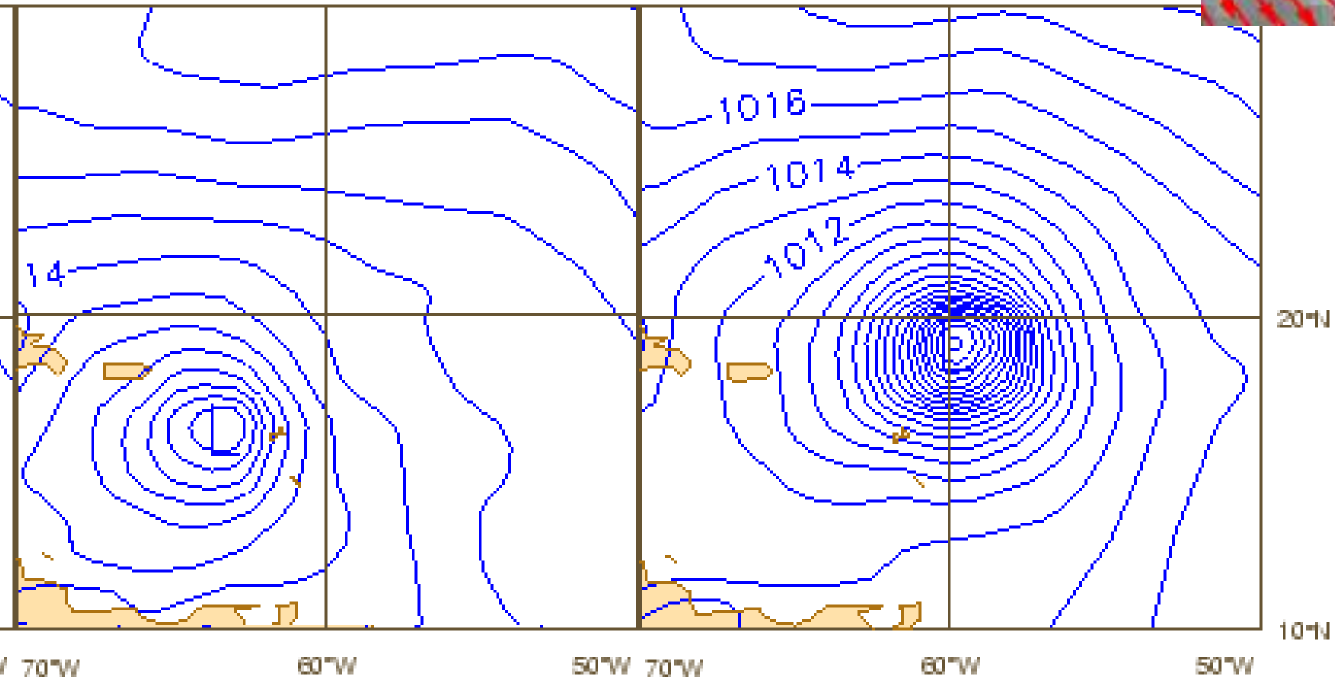
Scatterometer

- Improved forecasts of tropical hurricanes



Isaksen & Stoffelen, 2000

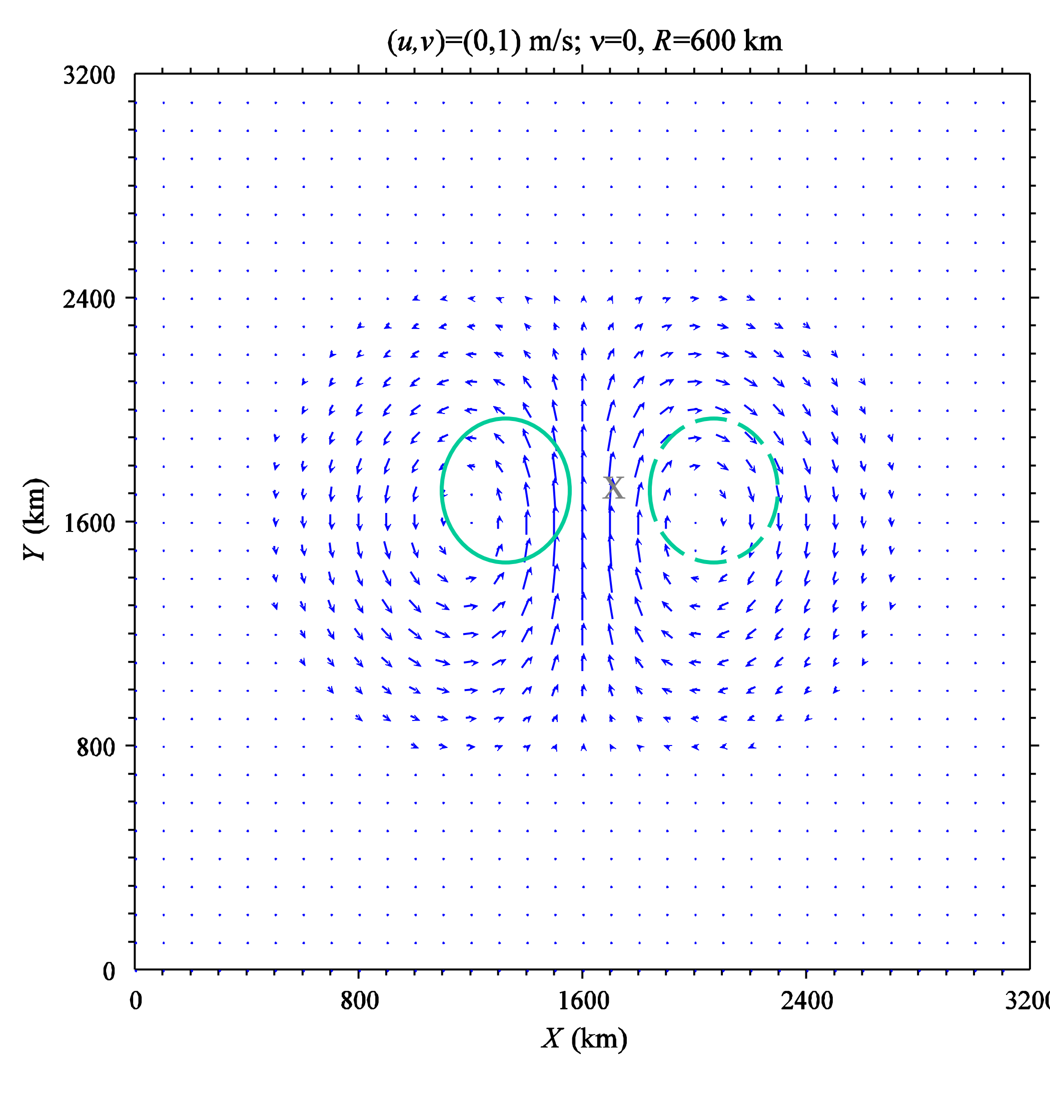
No ERS Scatterometer With ERS



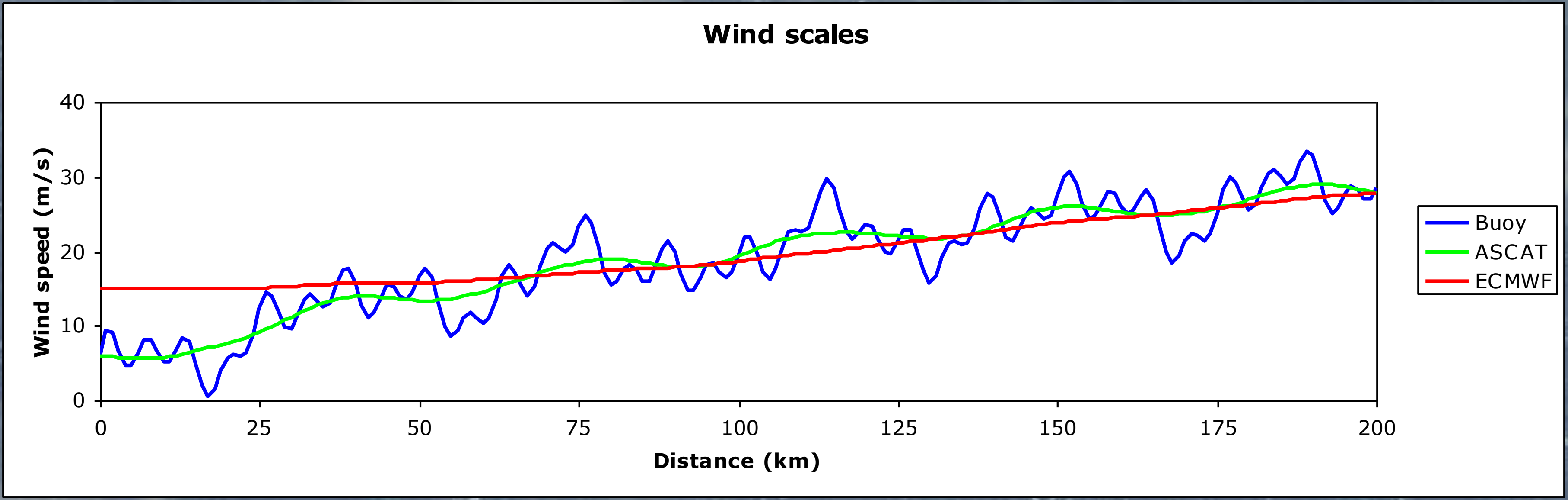
Mainly by improved vertical projection in 4D-VAR

Using observations

- Use of short-range forecast containing all observed information from the past
- One new observation influences a large area
- A change in the wind field by an observation implies a change in the mass field (balance mass/wind)
- Relatively few 4D observations determine the weather evolution
- Small scales remain the most difficult to determine due to the limited global observing system



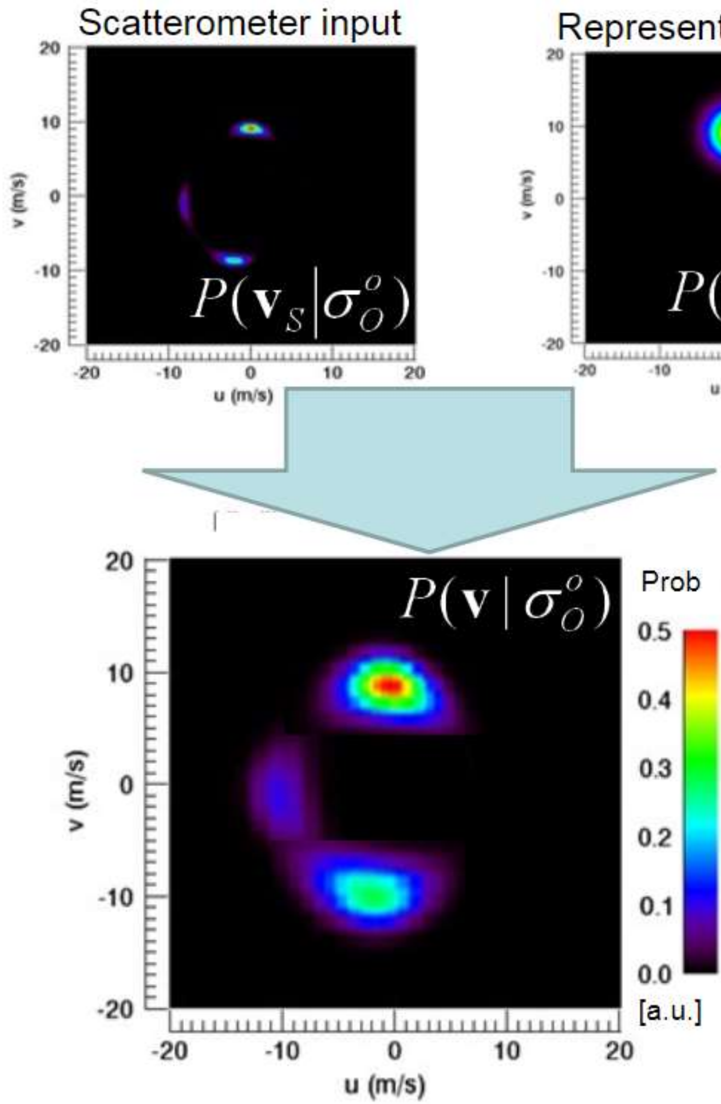
Spatial representation



- We estimate area-mean (WVC) winds using the empirical GMFs
- 25-km areal winds are less extreme than 10-minute sustained in situ winds (e.g., from buoys)
- So, extreme buoy winds should be higher than extreme scatterometer winds (allow for gustiness factor)
- Extreme global NWP winds are again somewhat lower due to lacking resolution ; all have different PDFs!

Scatterometer example

- Buoy errors are < 0.2 m/s, but in NWP σ_u = 1.5 m/s is used due to representation error
- Scatterometer winds are used with similar error
- But, thinned to 100 km to not oversample B spatial structure functions



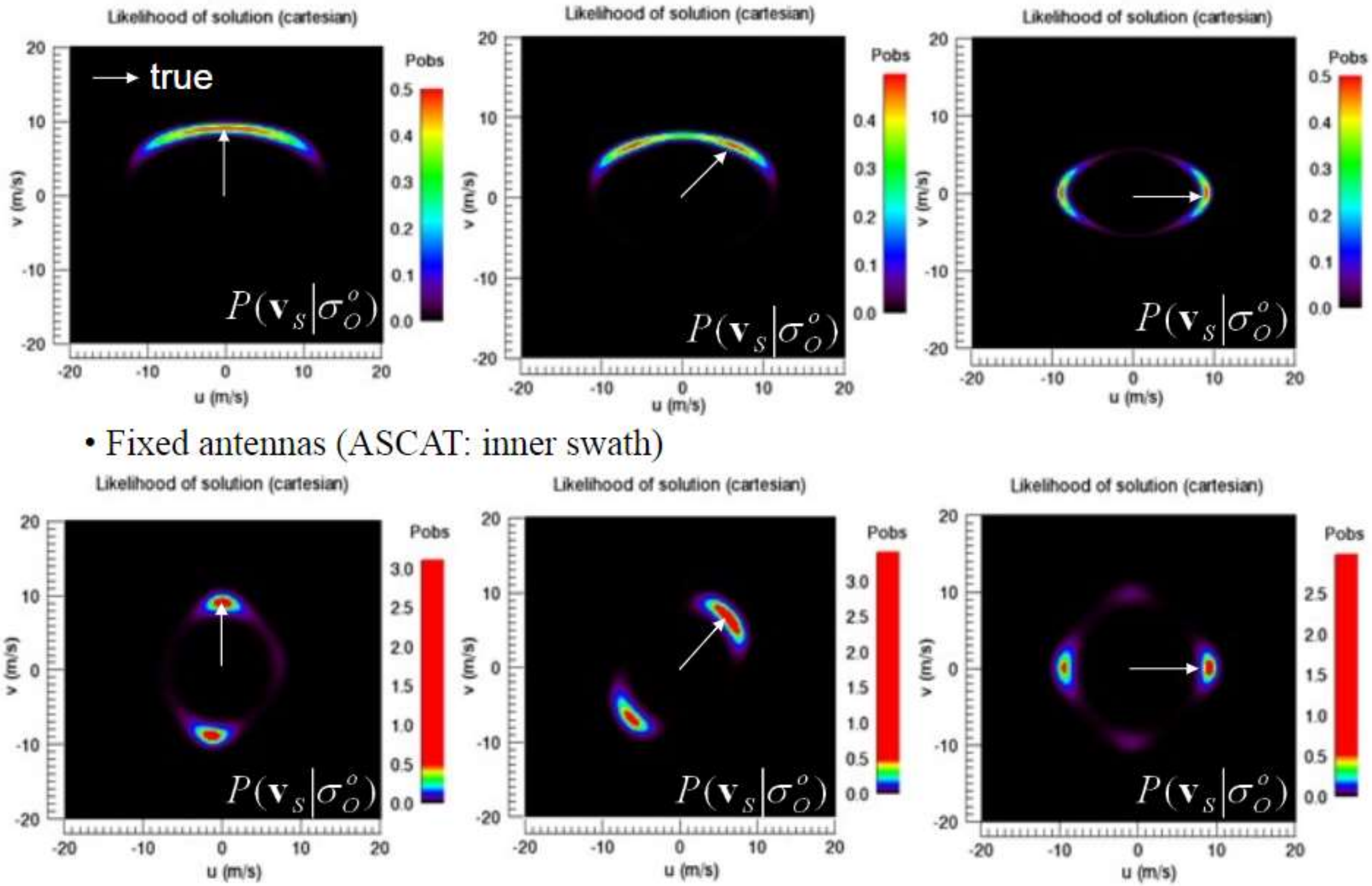
NWP
Scatterometer
Observation

Ku-band systems more complex

- Mid swath (nadir) data are rejected

• Rotating beam (SeaWinds, OSCAT: mid swath)

• Fixed antennas (ASCAT: inner swath)

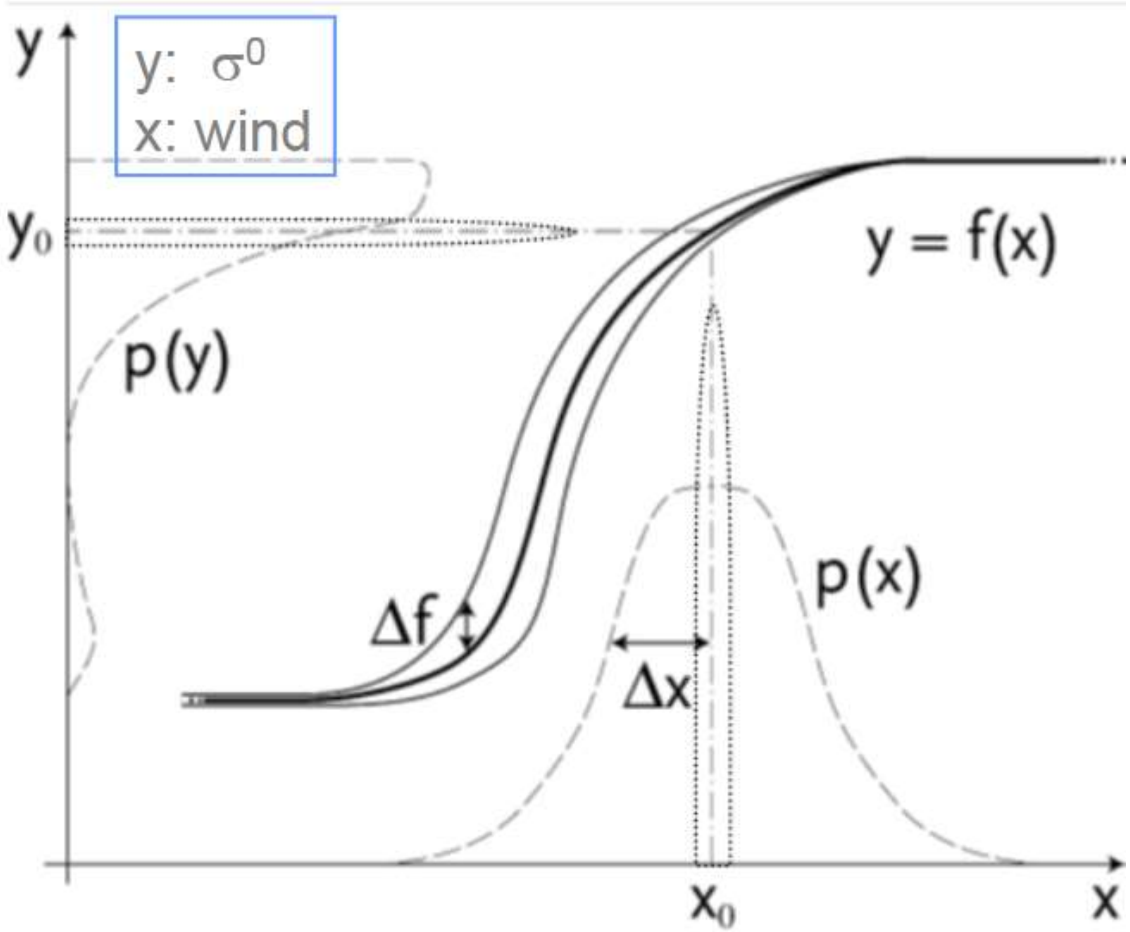


✖ Broad MLE minima and closeby multiple ambiguous solutions are complicating scatterometer wind assimilation

Direct assimilation of σ^0

- σ^0 noise is narrow leading to accurate wind retrieval
- Observation and background wind noise are relatively large leading to complex and skew error PDFs in measurement space
- Not compatible with BLUE, higher order statistics needed

➢ Wind assimilation appears simplest

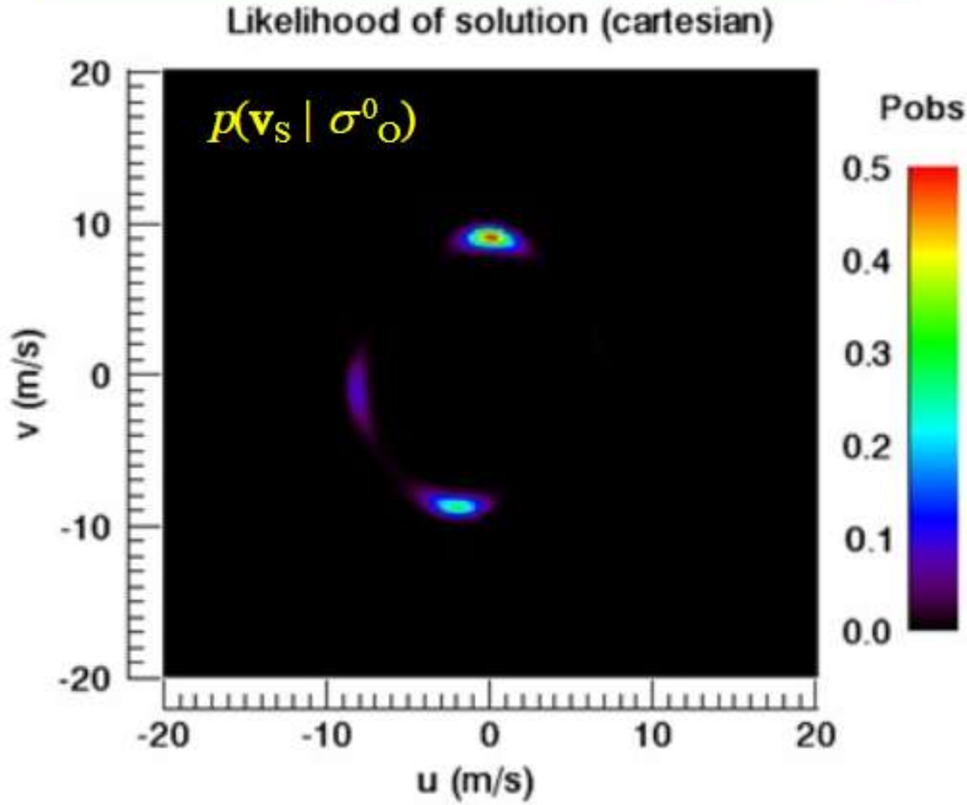


➢ Main uncertainty is in the wind domain (B, R)

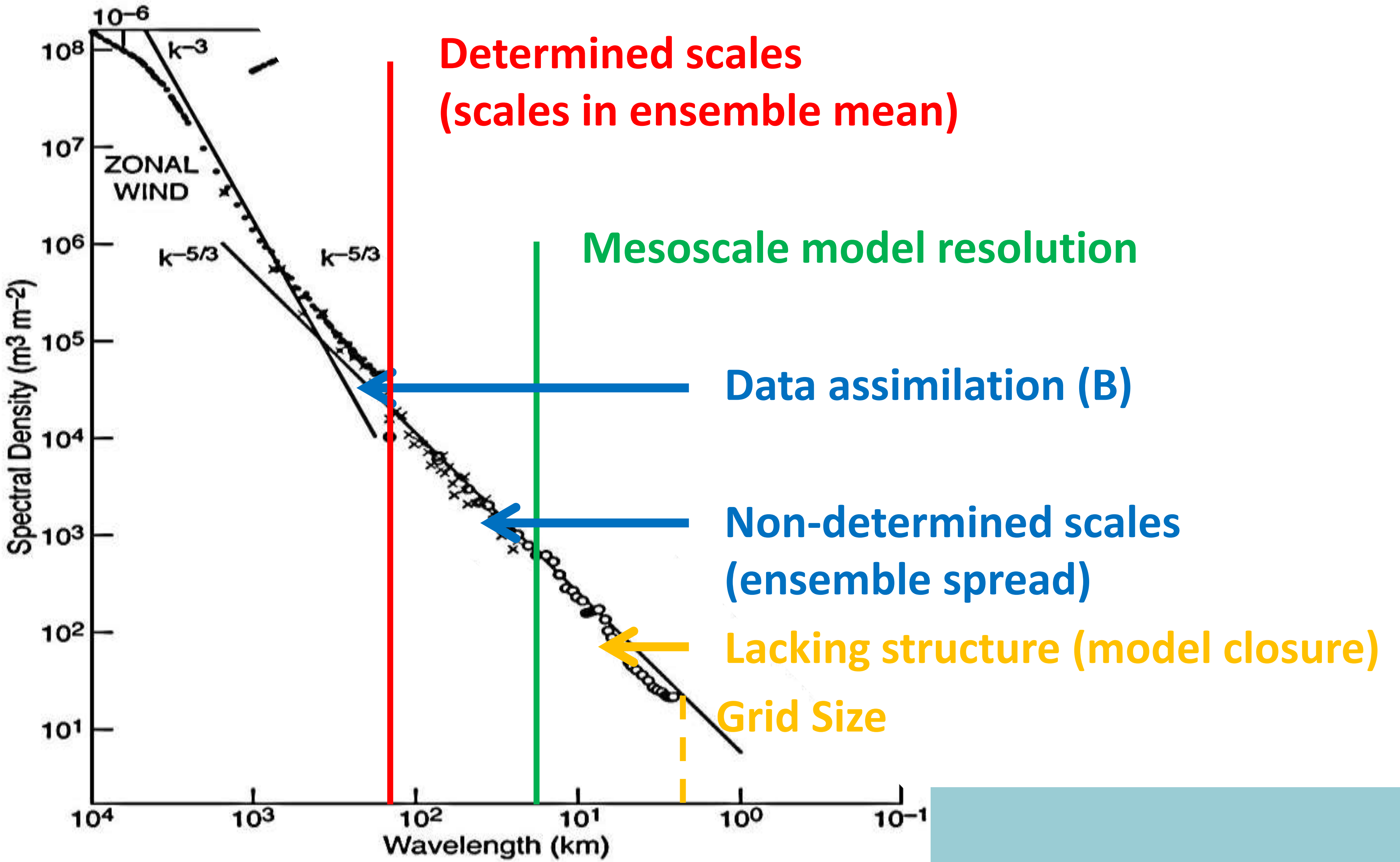
Scatterometer data assimilation

- J_O is a penalty term penalizing differences of the analysis control variables with the observations
- Choices:
  - Direct assimilation of σ^0_O
    - ✗ Complex error PDFs
  - Assimilate $p(\mathbf{v}_S \mid \sigma^0_O)$, like in MSS and 2DVAR
    - Needs p information
  - Assimilate ambiguities
    - ✗ Reduces wind solution space to max 4 points
  - Assimilate selected solution
    - ✗ Reduces wind solution space to one point, but 2DVAR skill may be better than 4Dvar

$$J_O^{SCAT} = -2 \ln \left\{ p\left(\sigma_O^0 \mid \mathbf{v} \right) \right\}$$



Nastrom & Gage Observed Spectrum



(o-b) diagnostic

Following Lorenc (1986): “t is the vector of coefficients obtained by projecting the true state of the atmosphere onto the model basis”

$$\begin{aligned} & o-b \\ &= t_o + \varepsilon_o - b \\ &= t_m + t_{o-m} + \varepsilon_o - b \\ &= t_{o-m} + \varepsilon_o + (t_m - b) \end{aligned}$$

t_o is the true state averaged over the sampling volume
t_m is the true state on scales that the model can determine

$$\left\langle (o-b)^2 \right\rangle = \left\langle t_{o-m}^2 \right\rangle + \left\langle \varepsilon_0^2 \right\rangle + \left\langle (t_m - b)^2 \right\rangle$$

repr. err + instr. err + backgr. err

Experiments show $<(o-b)^2>$ Harmonie larger than from ECMWF

Harmonie: $<(o-b)^2>$ = instr. error + repr. error + background error

$>$ $=$ $<$ $>>$

ECMWF : $<(o-b)^2>$ = instr. error + repr. error + background error

➢ Harmonie (small) scales do not verify with observations

HARMONIE from ECMWF

- HSCAT scatterometer 50 km
- HARMONIE effective resolution 25 km, grid 2.5 km

	(m/s)	bias u_{10m}	stdev u_{10m}	bias v_{10m}	stdev v_{10m}
	HSCAT	(23.961 collocations); $\overline{\Delta t} = -0.29$; $\overline{\lvert\Delta t\rvert} = 0.85$			
	$(o-b)$	-0.46	1.61	-0.24	1.57
Temporal interpolation:	$(o-b_t)$	-0.46	1.36	-0.22	1.29
+ spatial averaging:	$(o-\bar{b}_t)$	-0.45	1.25	-0.22	1.18

- ECMWF:

	t_f	bias u_{10m}	stdev u_{10m}	bias v_{10m}	stdev v_{10m}
HSCAT	5.6	-0.11	1.09	0.05	1.15

- ECMWF 6-hour forecast better than matched 50-km scale time-interpolated HARMONIE background
- ECMWF resolution is ~150 km over the open ocean
- Deterministic resolution HARMONIE ≈ ECMWF over sea

Small-scale data assimilation

- The amplitude spectrum of small-scale atmospheric waves can be well simulated in NWP models, but the determination of the phases of these waves will be problematic in absence of well-determined forcing (orography) or 4D observations (1 observation cannot determine structure)
- Undetermined phases at high resolution cause noise in data assimilation:
  - Increased NWP model error, **B'** > **B**
  - Model errors get more variable and uncertain since small scales tend to be coherent; coherence is of most interest meteorologically
  - **B** error structures will be spatially more sharp
  - Increased **o-b**, while the observation (representativeness) errors will be reduced; observations (should) get more weight, **O'** < **O**
  - Increments would be larger
  - When **O'** > **B**, the analysis error will be larger too ! **A'** > **A**
- Undertermined scales interfere with larger scales in DAS
  - On common scales **A'** may be deteriorated w.r.t. **A**

Mesoscale model noise

$o = t + \varepsilon_o + \varepsilon_r$; $<t\ \varepsilon_o>=0, <t\ \varepsilon_r>=0, <\varepsilon_o\ \varepsilon_r>=0$

$b = t + \varepsilon_d + \varepsilon_n$; $<t\ \varepsilon_d>=0, <t\ \varepsilon_n>=0, <\varepsilon_d\ \varepsilon_n>=0$

$o\text{-}b = \varepsilon_o + \varepsilon_r - \varepsilon_d - \varepsilon_n$; $<\varepsilon_o\ \varepsilon_d>=0, <\varepsilon_o\ \varepsilon_n>=0, <\varepsilon_d\ \varepsilon_r>=0, <\varepsilon_r\ \varepsilon_n>=0$

- Error r is real variability on scales of n
- We define n as realistic but not real (noise), i.e., undeterminable model scales
- Errors o and d as defined here do not include the geophysical variability in n and r at the intermediate scales

$<(o - b)^2> = \sigma_o^2 + \sigma_d^2 + \sigma_r^2 + \sigma_n^2$

$\mathbf{a} = \mathbf{W}.[\mathbf{o} - \mathbf{H}(\mathbf{b})]$; $\mathbf{H}$ interpolation operator

- Variances in n and r do not contribute constructively to **a** as we have too few observations for appropriate 4D initialization, “aliasing” will occur
- Aliasing on scales of n detriment **a** for scales in **b**; upscale errors occur
- Variances in n and r represent the same scales and a “double penalty”
- This “double” aliasing does also occur in each ensemble member of EDA

Deterministic scale ?

$<(o - b)^2> = \sigma_o^2 + \sigma_d^2 + \sigma_r^2 + \sigma_n^2$

- Consistent superobbing and supermodding reduces variance in all σ terms
- This is undesirable as the determined true variance should be maximized

$<b^2> - <(o - b)^2> = \sigma_T^2 - \sigma_o^2 - \sigma_r^2$

- Supermodding of b reduces σ_n which is not part of righthandsight terms
- Averaging deterministic scales reduces σ_T though

$<o^2> - <(o - b)^2> = \sigma_T^2 - \sigma_d^2 - \sigma_n^2$

- Superobbing of o reduces σ_r which is not part of righthandsight terms
- Averaging deterministic scales reduces σ_T though

- Spectral/spatial analysis of o, b and $o - b$ (Vogelzang et al., . . .)

Nyquist, Moiré & aliasing

- To determine a 4D structure, sufficient samples are required in time and 3D space
- Insufficient sampling leads to interference of the sampling pattern and the structure being sampled
- It leads to corrupted/artificial analysis structures
- Evolving artificial waves in NWP may degrade the short-range forecasts
- Determining scales that cannot be determined well provides a sincere risk in mesoscale (ensemble) data assimilation
- Nyquist suggests oversampling of 4D analysis structures by a factor of 2
- E.g., in the horizontal: a deterministic resolution of 150 km thus suggests sampling at 75 km

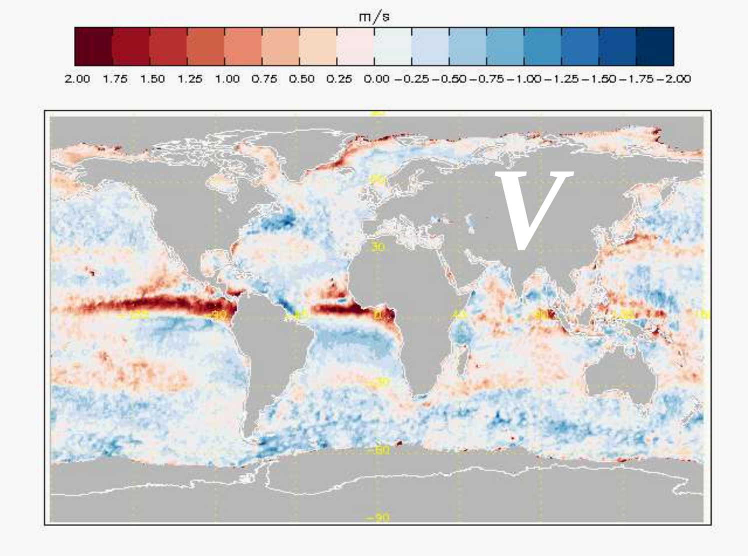
Challenges and Guidance

- Adaptive **B** covariances are difficult to estimate (slide 88)
- More (wind) observations are needed to spatially sample small-scale 4D **B** structures
- Observations need to be accurate, **O** < **B**
- How to prevent overfitting (uncertain **B**, small **O**) due to inaccurate and high innovation weights ?
- And spin-up due to more noisy analysis (statistical model **B**) ?
- Problems also exist in EDA

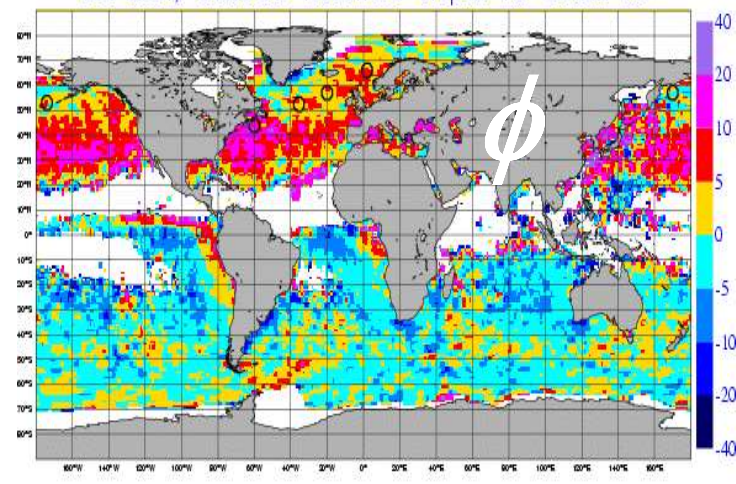
- Separate determined from undetermined scales in data assimilation, e.g.,
  - Data assimilation with ensemble mean / full ensemble (expensive!) ?
  - Maintain broad **B**, i.e., target deterministic scales ?
  - Average **b** up to determined scales ("SuperMod") in **H** operator ?

Best Linear Unbiased Estimate

- Common assumption in data assimilation
- NWP model biases exist due to drag, ocean currents, stable PBL, moist convection, diurnal cycle, . . .
- Biases are not only speed dependent, but also air mass dependent
- Correcting parameterizations may detriment forecasts (Sandu, 2013)
- Correct model in $\mathbf{H}$ operator to follow BLUE ?
- Local bias contributions are not negligible in o-b, but of the order of the innovations !
- Biases probably severely detriment scatterometer impact in NWP
- Most biases are stable in time -> apply VarBC



Wind direction bias (Deg) of ECMWF vs QuikSCAT for Southerly flows
DJF 0001, Globe 0.5 N.Hem 6.0 Tropics -1.0 S.Hem -1.6



Effect of bias

- Bias reduces the dynamical innovation

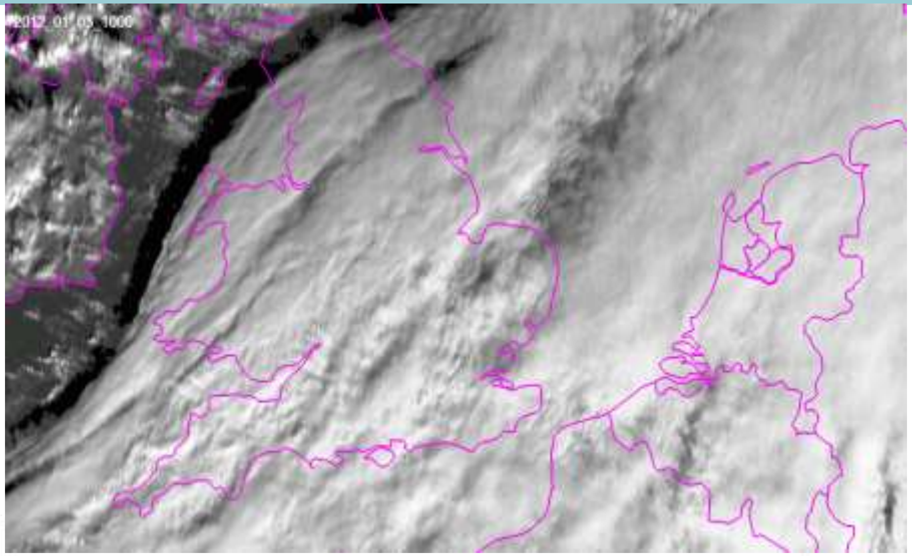
$<(o - b)^2> = \sigma_o^2 + \sigma_b^2 + \text{bias}^2$

$\mathbf{a} = \mathbf{W}.[\mathbf{o} - \mathbf{H}(\mathbf{b})]$; $\mathbf{H}$ interpolation operator

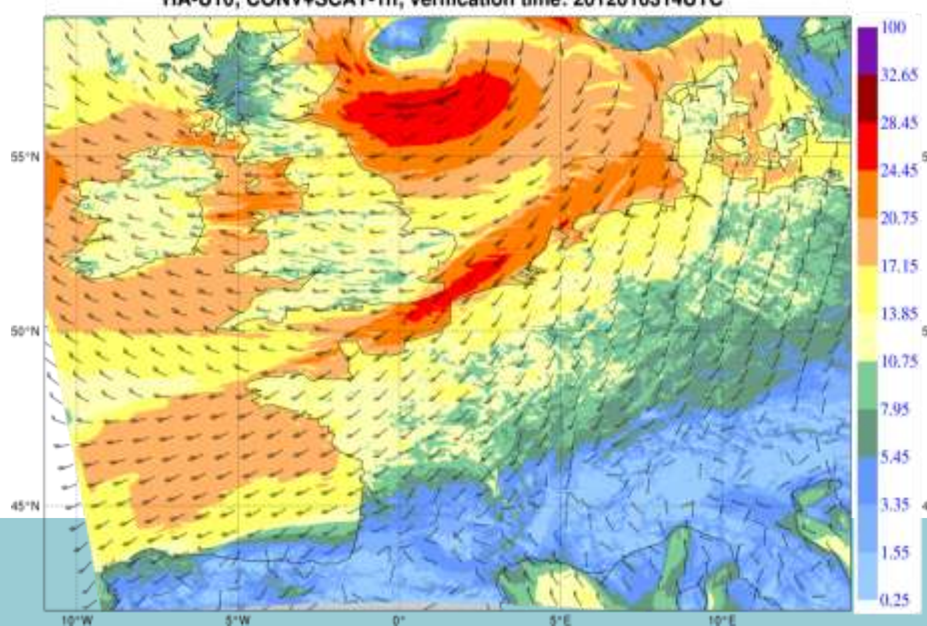
- Biases are caused by dynamical closure (smoothing), parameterization error, missed processes (moist convection downdrafts, ocean currents)
- Assimilation of a bias does NOT correct the model's dynamical balance
- Model biases are the same every cycle and corrected over and over again in every analysis cycle without much beneficial effect
- Improving the dynamical closure, physics and resolution of a model is a long-term project
- Bias is detrimental for analyzing evolving dynamical structures, which is however what we need to better forecast the weather

Model bias example: Storm Ulli

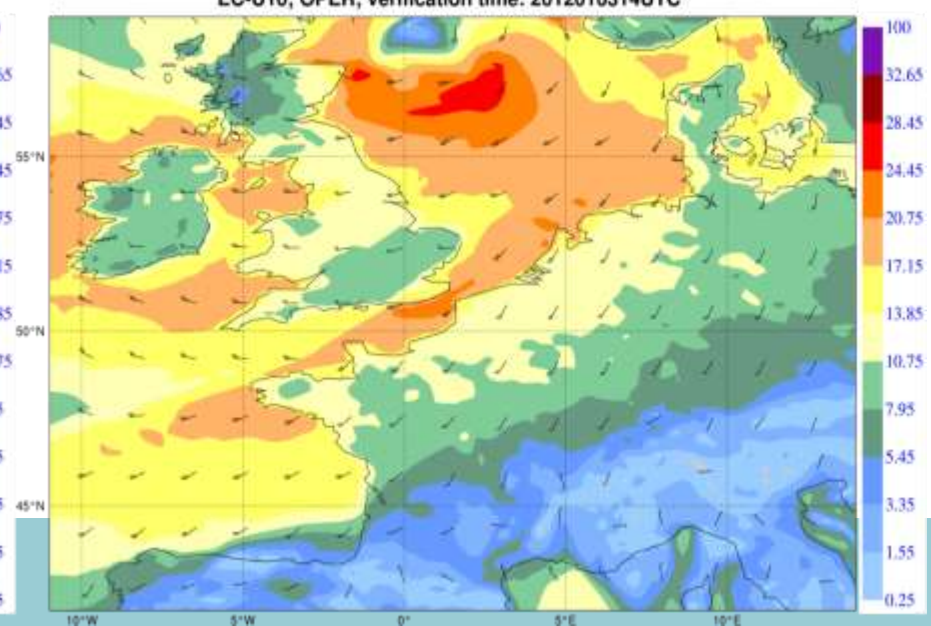
3 Jan. 2012 ~ 13UTC. In the strong westerly flow, a cold front rapidly moved across the North Sea, passing the Dutch coast. The front was accompanied with a squall line. The coastguard ('Rijkswaterstaat') reported a so called meteotsunami at the coast at Ijmuiden, with a sea level change (rise and fall) of over 1.5 meters in 30 minutes.



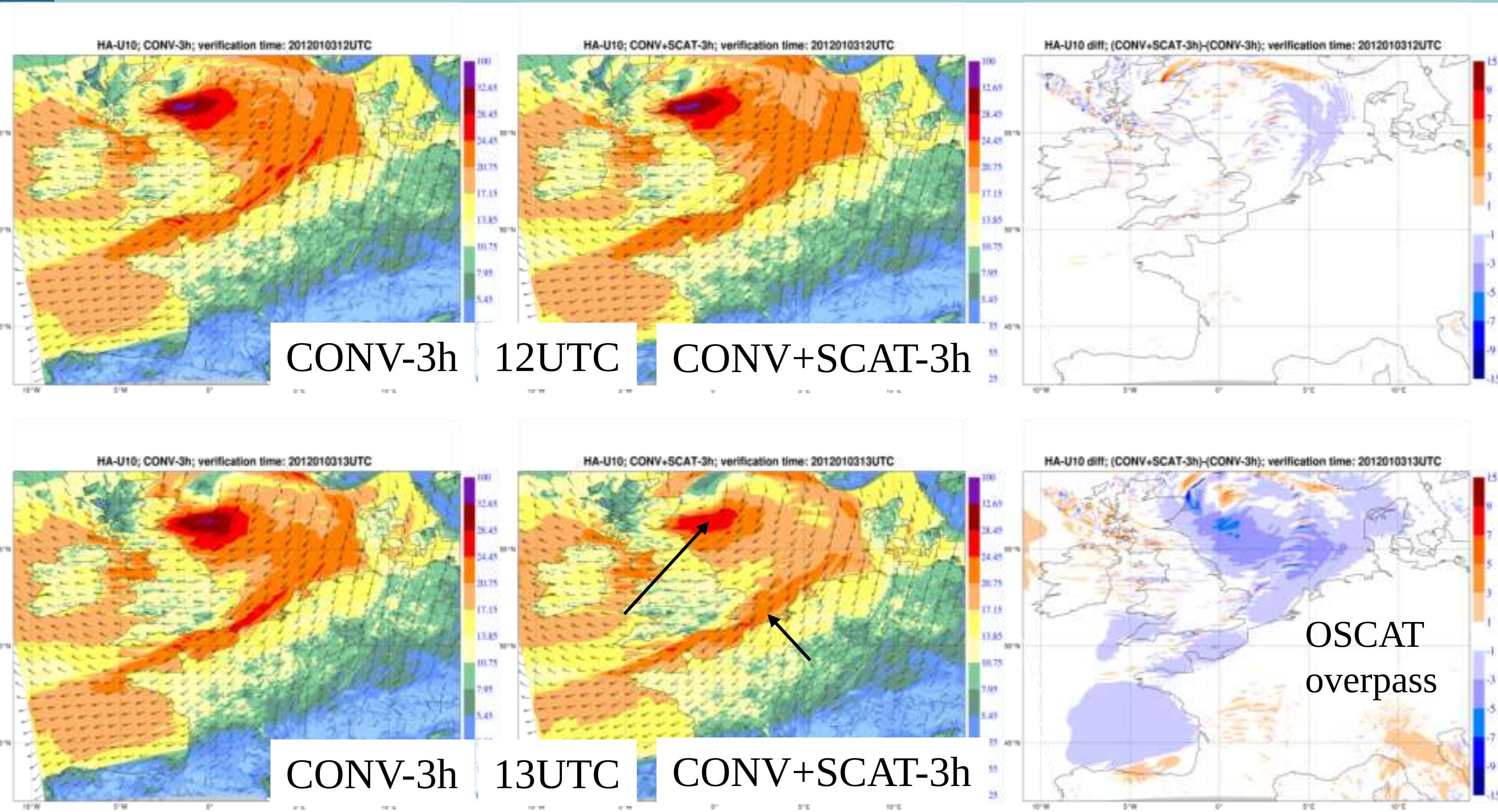
HA-U10; CONV+SCAT-1h; verification time: 2012010314UTC



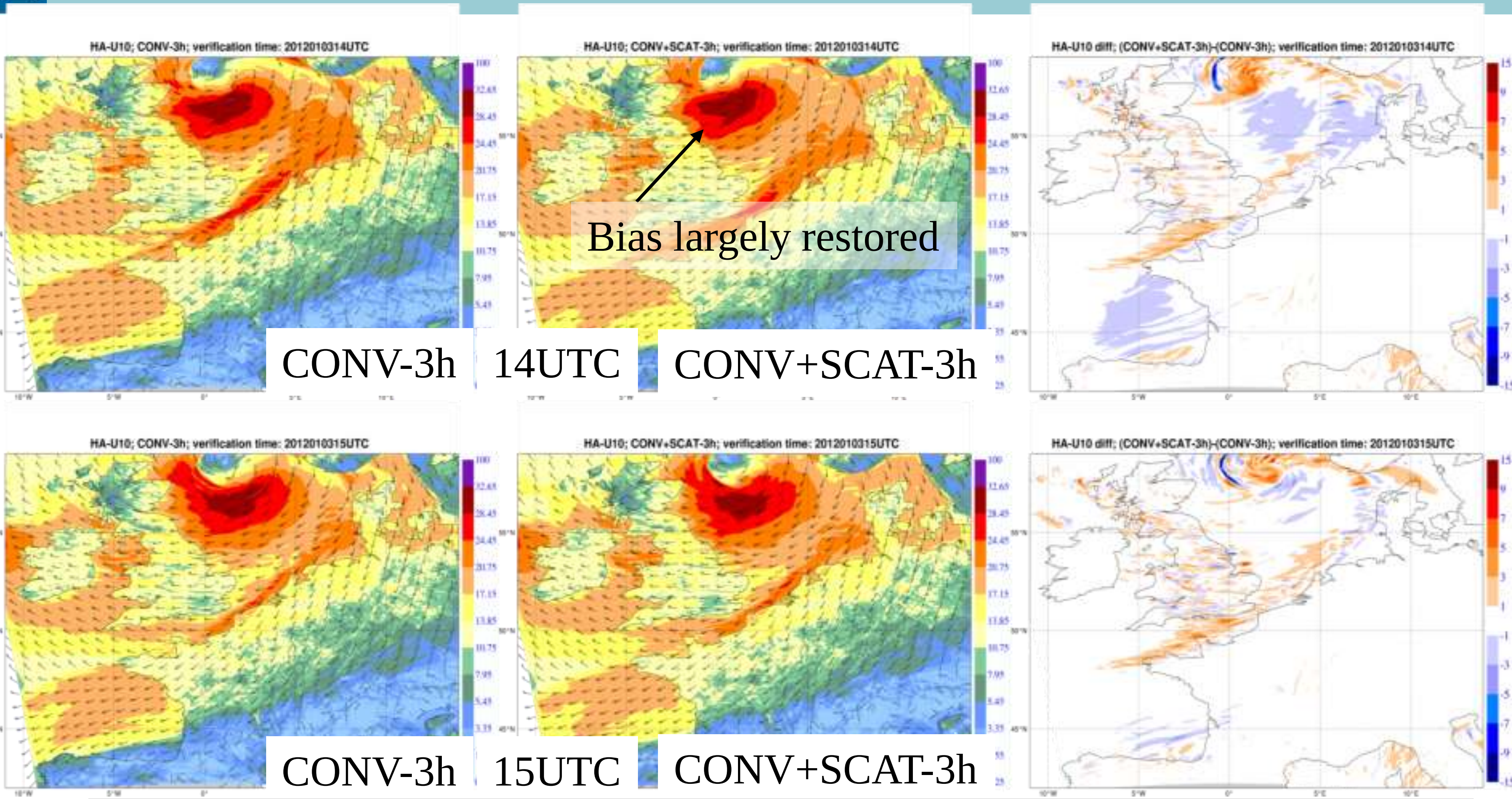
EC-U10; OPER; verification time: 2012010314UTC



Harmonie 3 January around 13 UTC

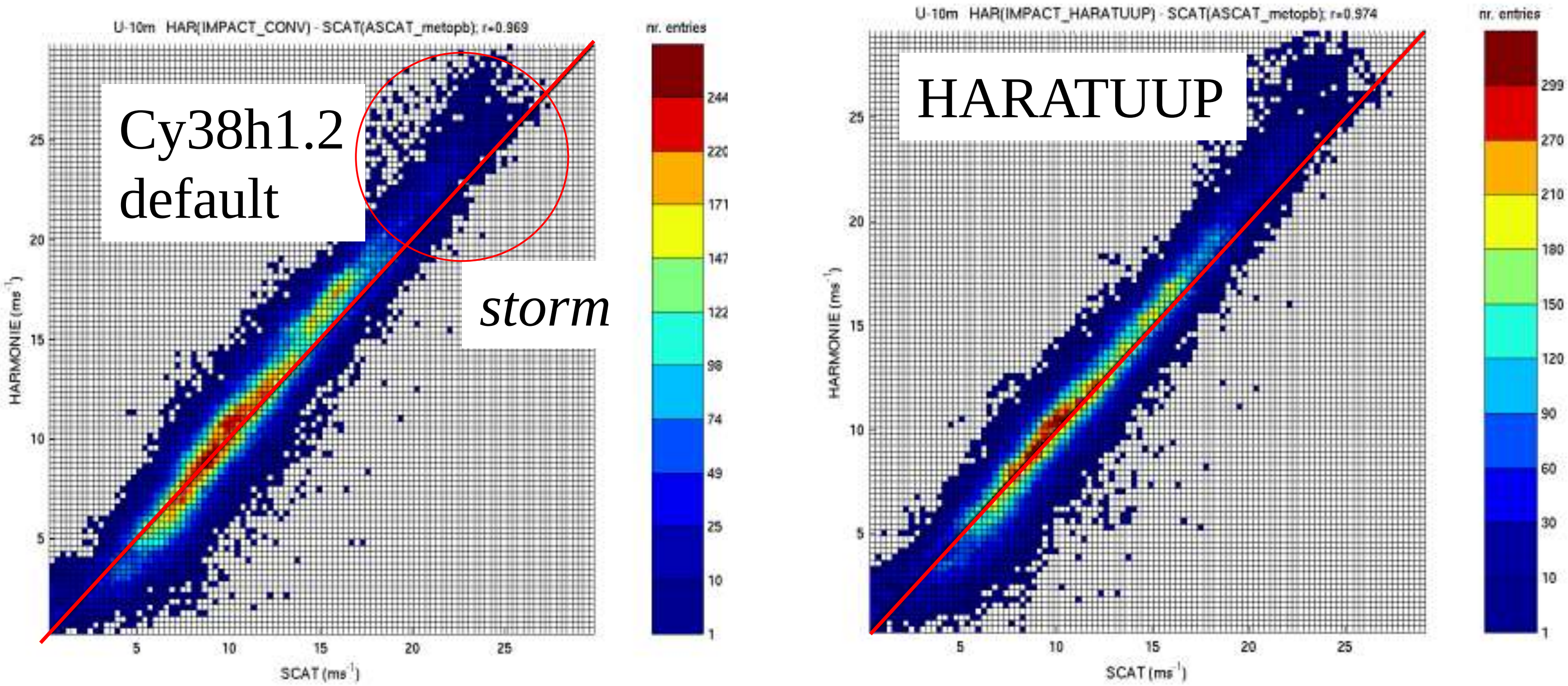


Harmonie 3 January around 13 UTC



Large impact of SCAT on analysis but forecast skill is limited to a couple of hrs (biased model)

New turbulence scheme: HARATUUP



- HARATUUP shows smaller biases and spread
- But still substantial model biases for strong winds
- HARMONIE coupling with ocean model may further help
- Bias correction in speed at global NWP centres, but not yet

Conclusions

- Mesoscale data assimilation is a new paradigm
- Many accurate 4D wind observations are needed to initialize 3D turbulence and convection in the atmosphere
- NWP models are locally substatially biased over long periods -> VarBC needed
- Undetermined scales cause headaches and destroy the analysis of the larger scales potentially
- It is possible to determine small observed scales in the analysis, even if they did not exist yet (2DVAR)
- Weather models return to their dynamical balance very quickly though
- Seek ways to avoid analyzing non-deterministic scales and to avoid their detriment as model noise:
  - Ensemble mean ?
  - Broad B (low pass filter) ?
  - Supermod and superob up to deterministic scales ?

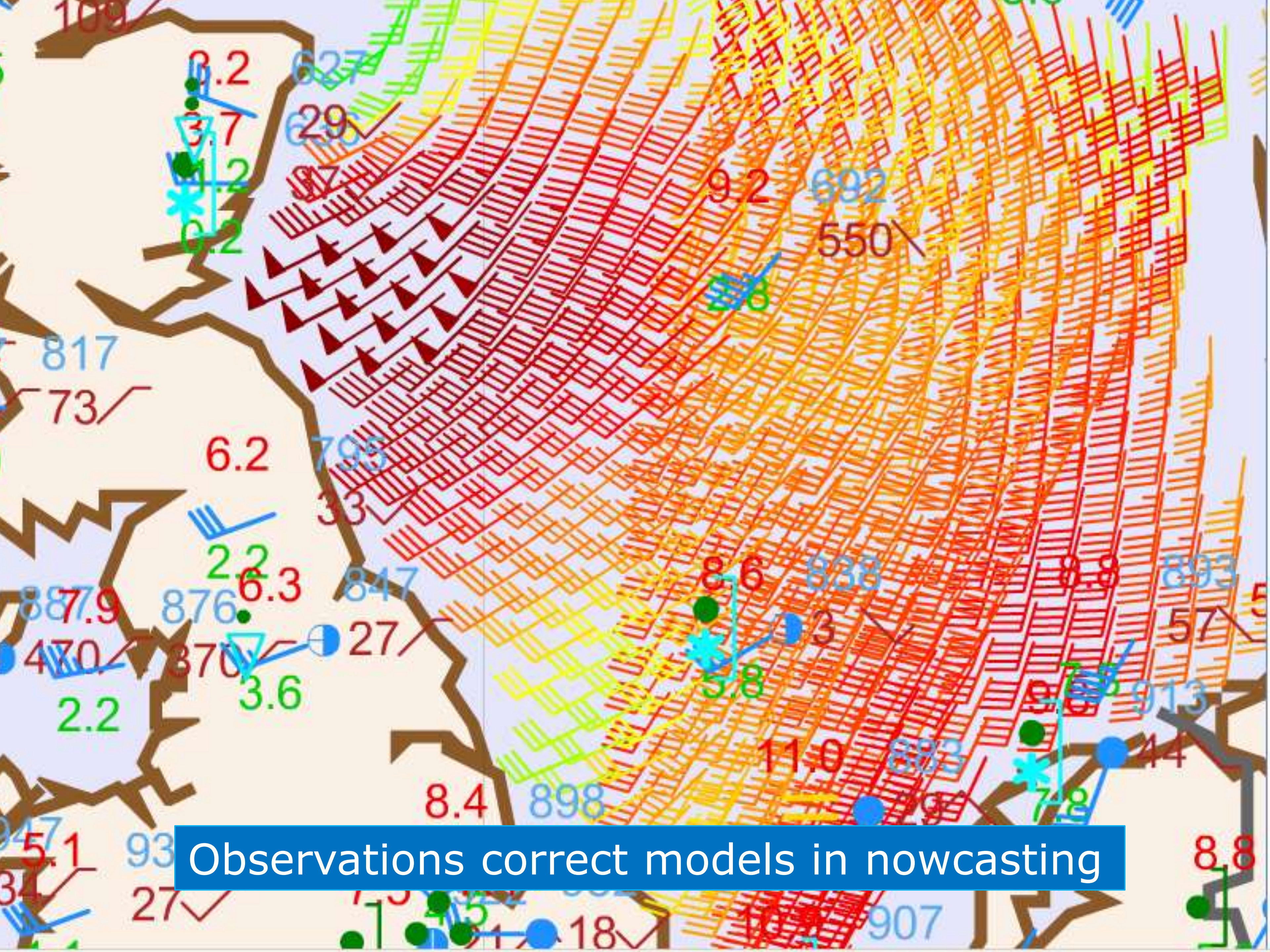
Related EUMETSAT2018 talks

Hi-res NWP and nowcasting session:

- Saleh Abdalla, NRT winds and waves from S3, Monday 15:30
- Giovanna De Chiara, Impact ASCAT winds at ECMWF, Monday 17:15
- Giovanna De Chiara, Assimilation of new ASCAT products, Wednesday 10:30
- Ad Stoffelen, Summary of this workshop, Wednesday 11:00
- Yan Liu, Impact scatterometer winds in GRAPES, Thursday 10:30
- Isabel Monteiro, Impact ASCAT in HARMONIE, Thursday 11:00
- Ralph Peterson, gNWP and rNWP impact of winds, Thursday 11:15
- Jur Vogelzang, Impact observed flow-dependent errors, Thursday 11:45

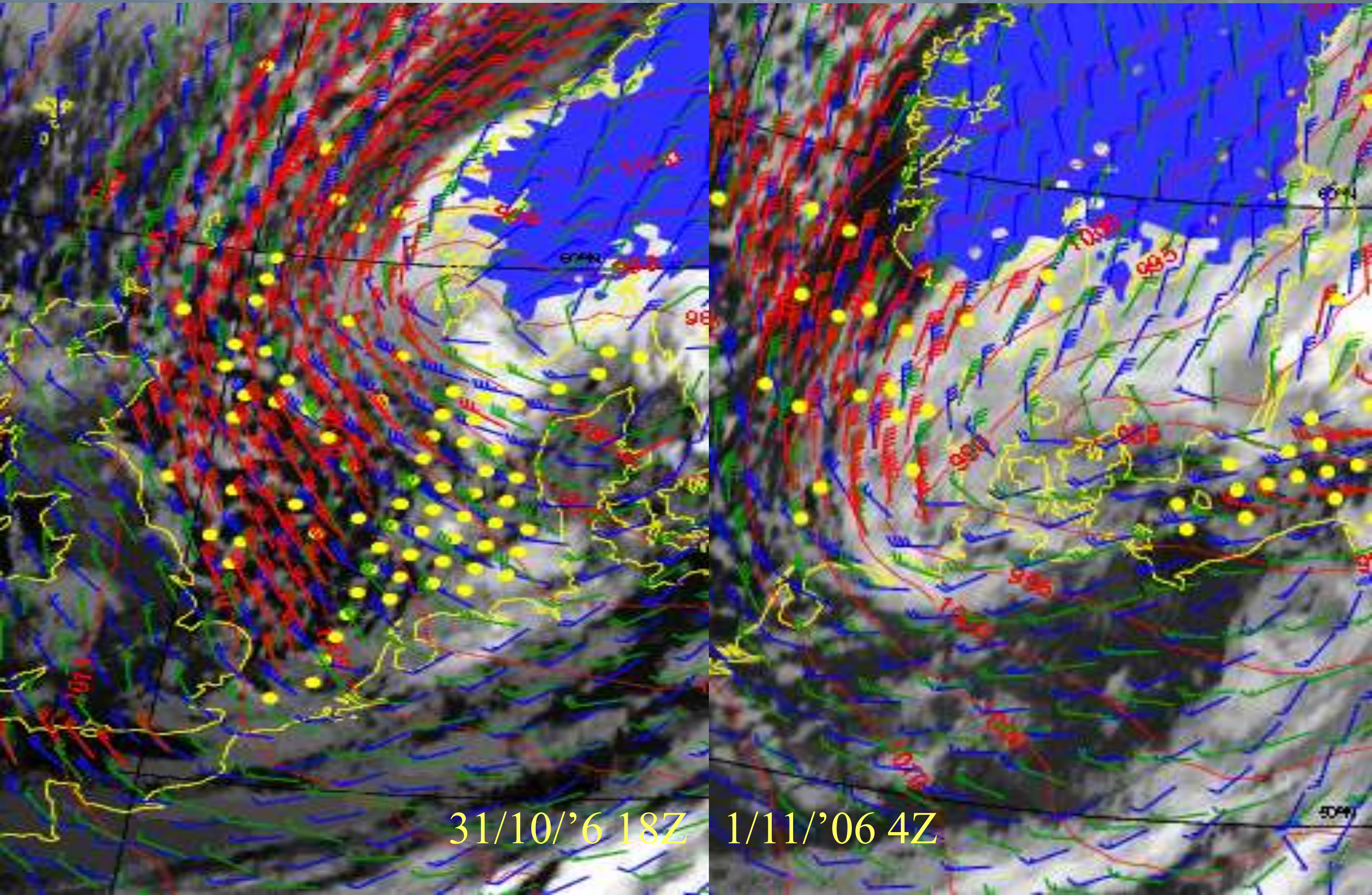
Session on Monitoring Climate and Oceans, Wednesday 16:15-17:30

Plenary Gunnar Noer, Thursday 9:00



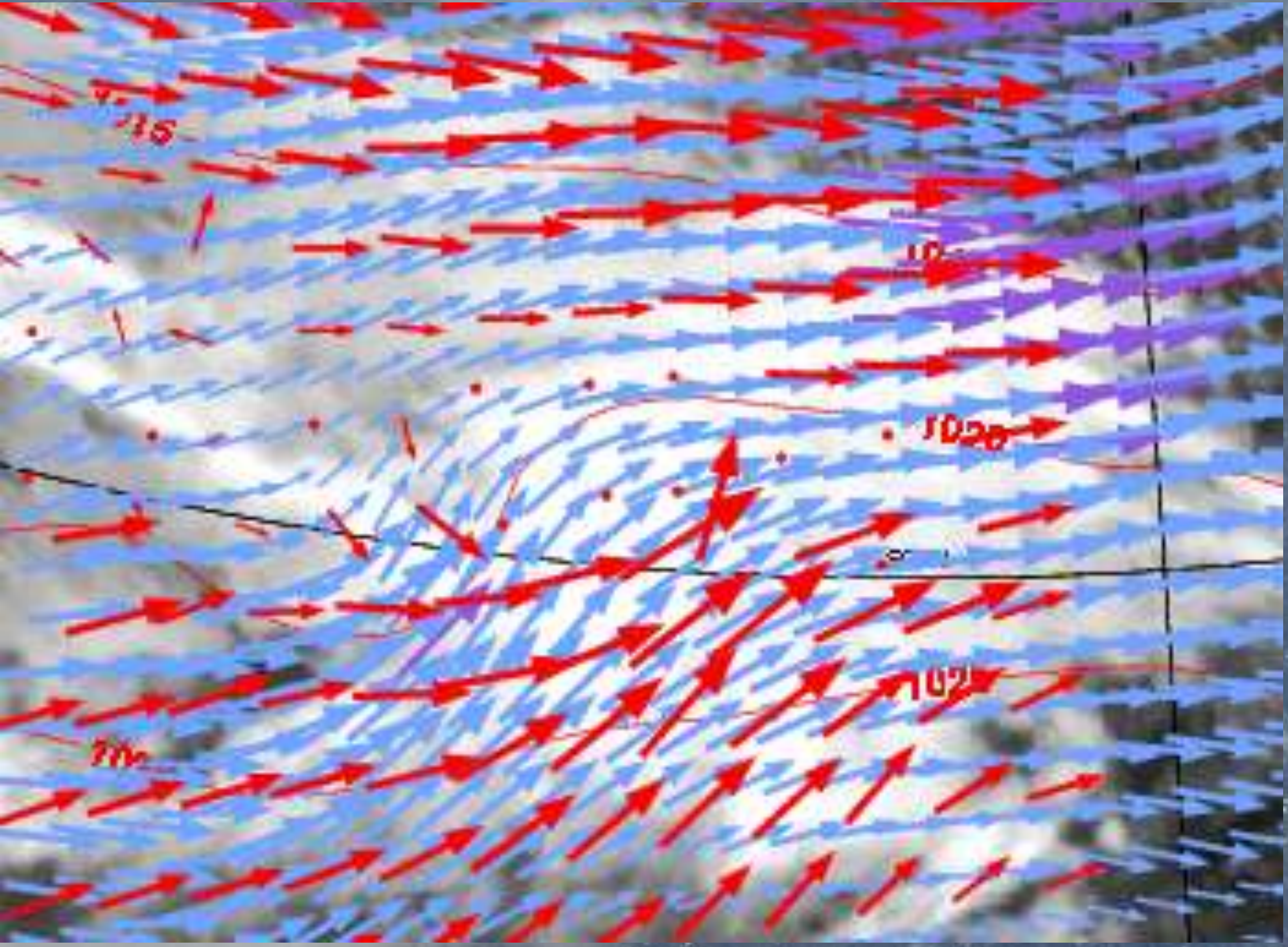
Observations correct models in nowcasting

Storm surge Delfzijl



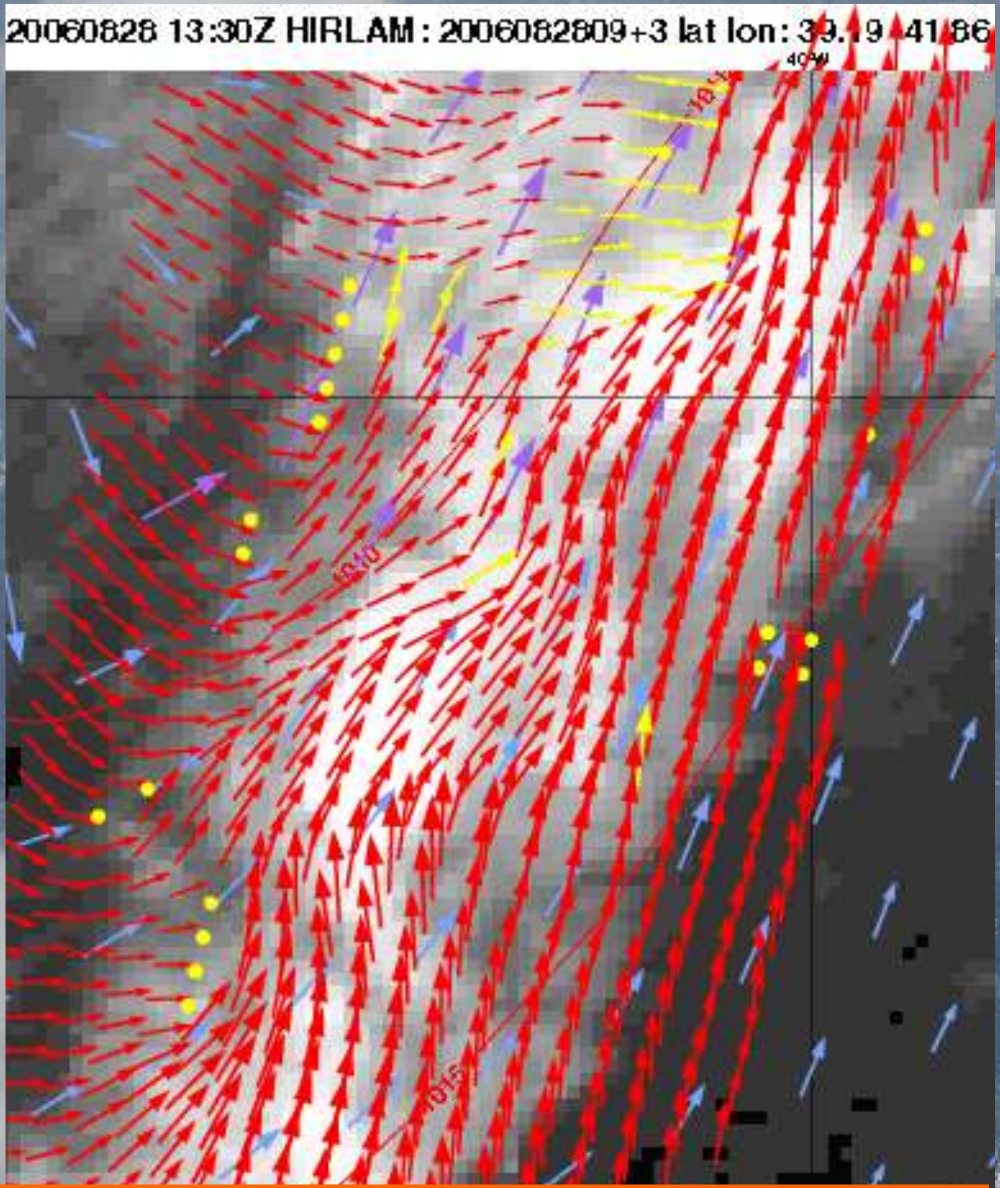
NWP Impact @ 100 km

29 10 2002

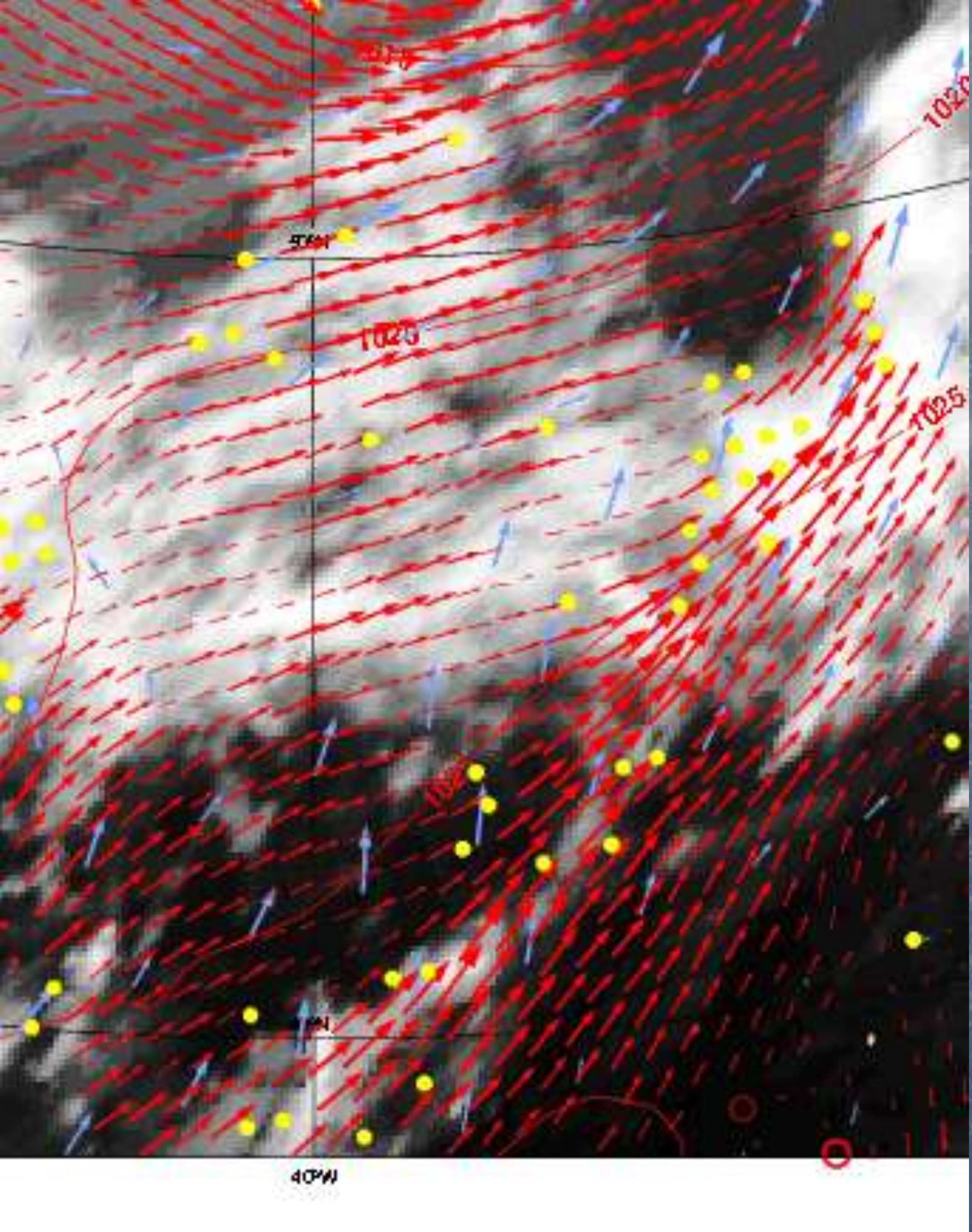


Storm near

HIRLAM misses wave; SeaWinds should be beneficial!



ERS-2 scatterometer wave train; missed by HiRLAM



1020
1025
1025
50N
40W

Missed wave train in QuikScat

Further references

- scat@knmi.nl
  - Registration for data, software, service messages
  - Help desk
- EUMETCAST, RMDCN, KNMI FTP
- www.knmi.nl/scatterometer
  - Multiplatform viewer, tiles!
  - Status, monitoring, validation
  - User Manual
- EUMETrain forecasters forum
- NWP SAF monitoring www.metoffice.gov.uk/research/interproj/nwpsaf/monitoring.html
- Copernicus Marine Environment Monitoring Service marine.copernicus.eu/

Training/interaction

- Training Course Applications of Satellite Wind and Wave Products for Marine Forecasting
  vimeo.com/album/1783188 (video)
- Forecasters forum
  training.eumetsat.int/mod/forum/view.php?f=264
- Xynthia storm case
  www.eumetrain.org/data/2/xynthia/index.htm
- EUMETrain ocean and sea week
  eumetrain.org/events/oceansea_week_2011.html (video)
- NWP SAF scatterometer training workshop
  nwpsaf.eu/site/software/scatterometer/
- Use of Satellite Wind & Wave Products for Marine Forecasting
  training.eumetsat.int/course/category.php?id=46 and others
- Satellite and ECMWF data vizualisation
  eumetrain.org/eport/smhi_12.php?
- MeteD/COMET training module
  www.meted.ucar.edu/EUMETSAT/marine_forecasting/

Ocean references

- CMEMS, marine.copernicus.eu/
- PODAAC, podaac.jpl.nasa.gov/
- eSurge, www.storm-surge.info/
- MyWave
- 2016 scatterometer conference, www.eumetsat.int/Home/Main/Satellites/Metop/index.htm?l=en
- IOVWST, coaps.fsu.edu/scatterometry/meeting/