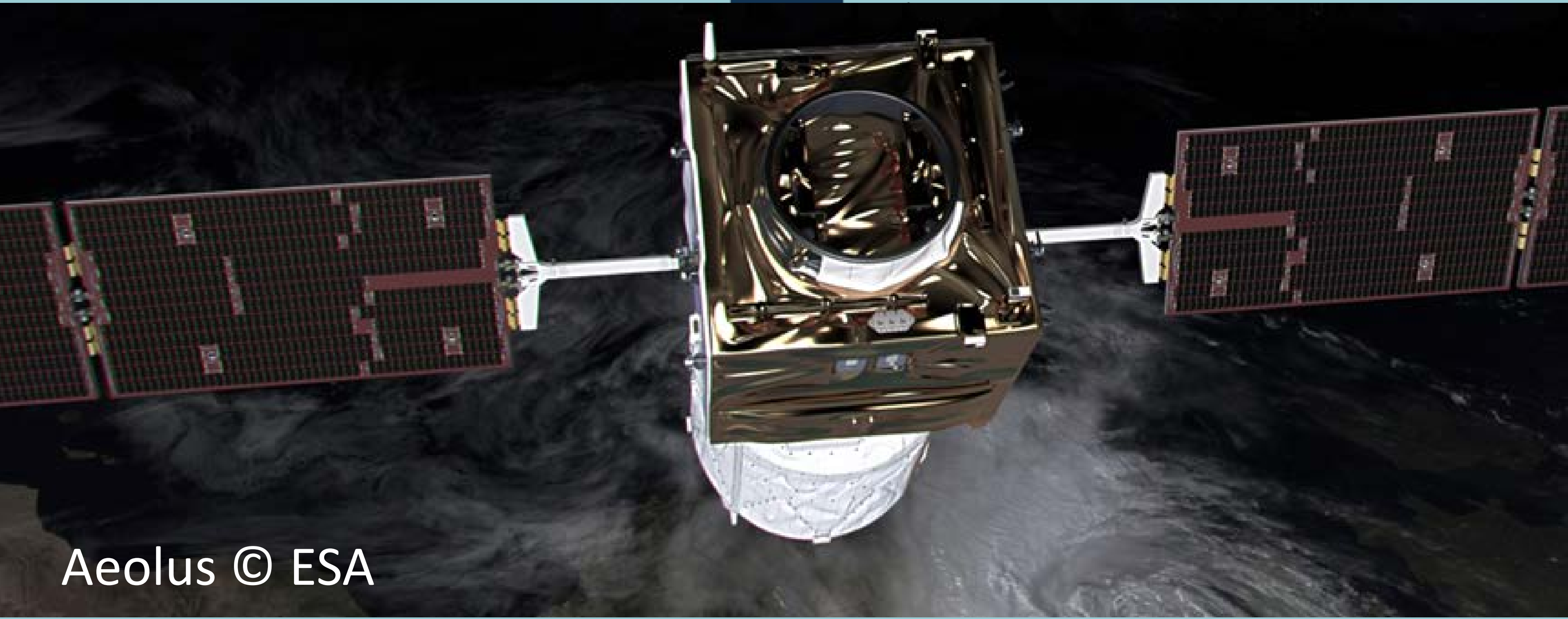
Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the



Wind profile satellite observation requirements and capabilities

Ad Stoffelen
ESA Aeolus MAG
(Gert-Jan Marseille)

White paper

- Motivation: initiate preparations for Aeolus follow-on as soon as possible

- ESA Aeolus MAG white paper
  - Draft version prepared by Ad Stoffelen
  - Submitted to the ESA MAG for feedback

- This presentation: summary of major items white paper

- Take home message. A UV Doppler wind lidar is the only option on the table to meet the WMO requirements on winds (OSCAR database)

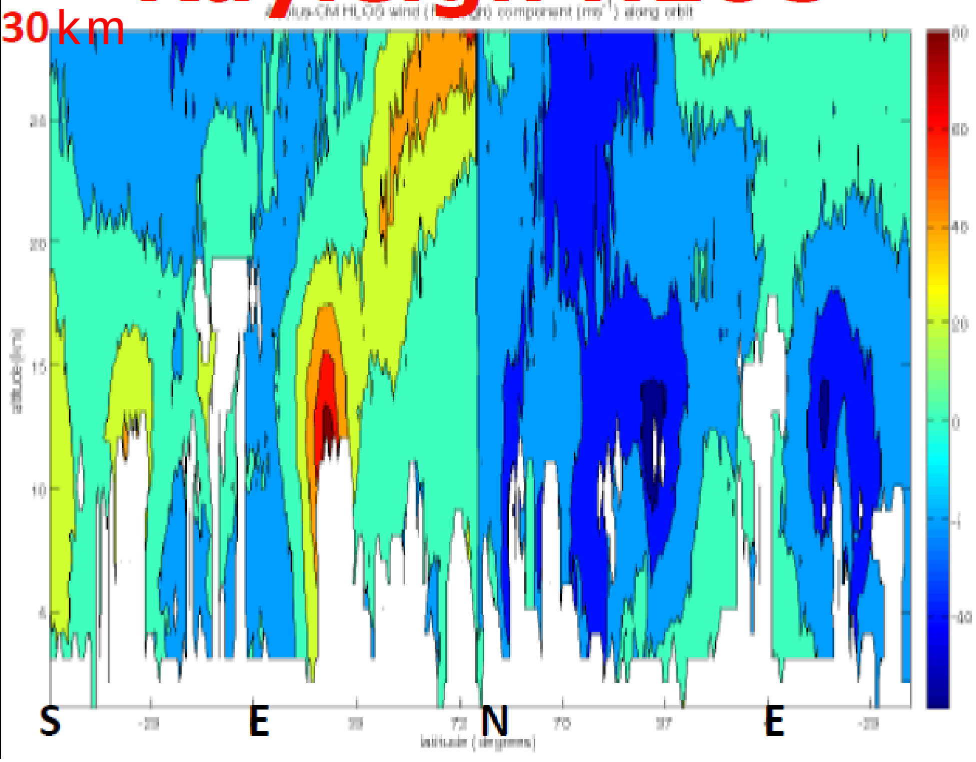
Overview

- What will Aeolus see?
- Winds from clouds?
- What do we need beyond 2020?
- What is possible from satellites?
- How to proceed after Aeolus?

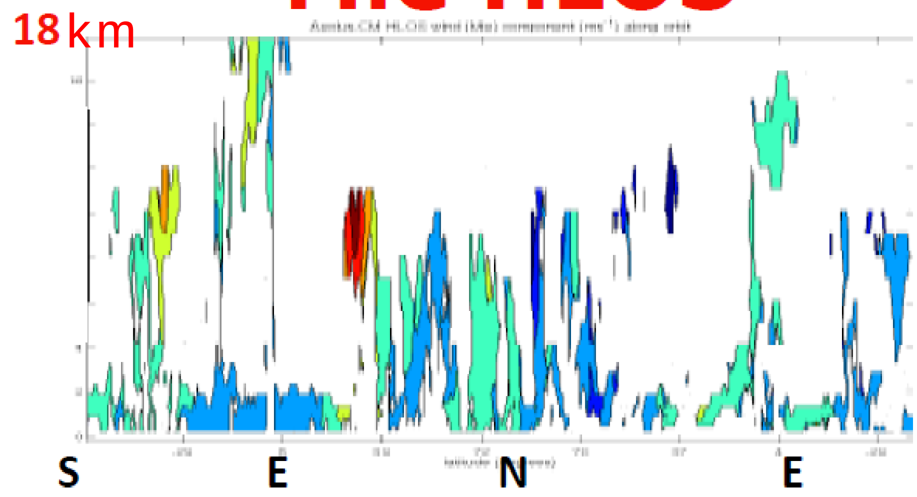
What will Aeolus see?

✓ One simulated orbit
✓ LIPAS

Rayleigh HLOS



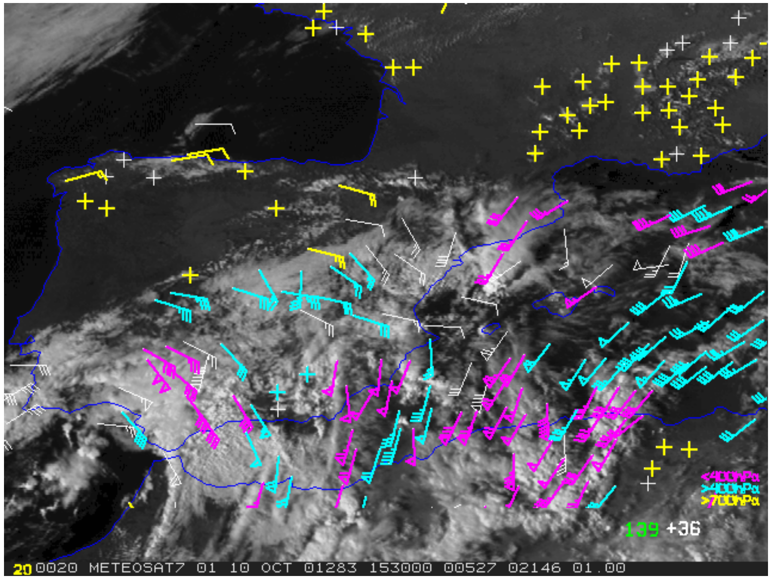
Mie HLOS



- Rayleigh signal in clear air is most abundant and will have most impact
- Cloud and aerosol observations are sparse and affected by cloud

➢ UV DWL is very favorable to obtain wind profiles everywhere

Winds from clouds?



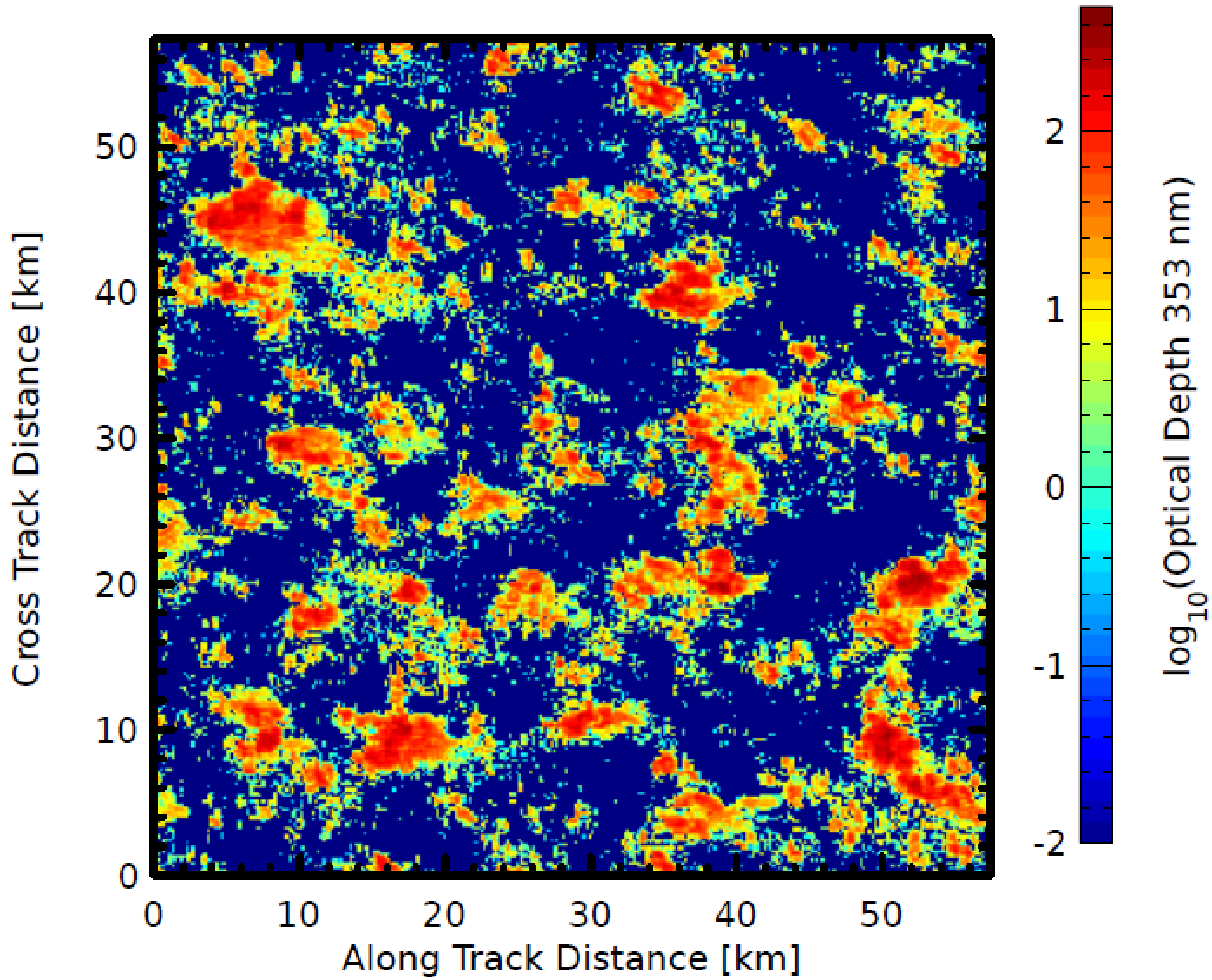
- Yes, that’s possible
  - This workshop
  - e.g. upper cloud motion winds
- But, clouds are tough
  - They move, grow and transform, due to heat, radiation, turbulence and mixing
- Far from trivial to retrieve atmospheric dynamics from cloud displacements

CRM

A spatial plot of the CRM cloud field

t = 0

CRM grid at 200m and 30s over 8 minutes (after spin-up)



CRM

A spatial plot of the CRM cloud field

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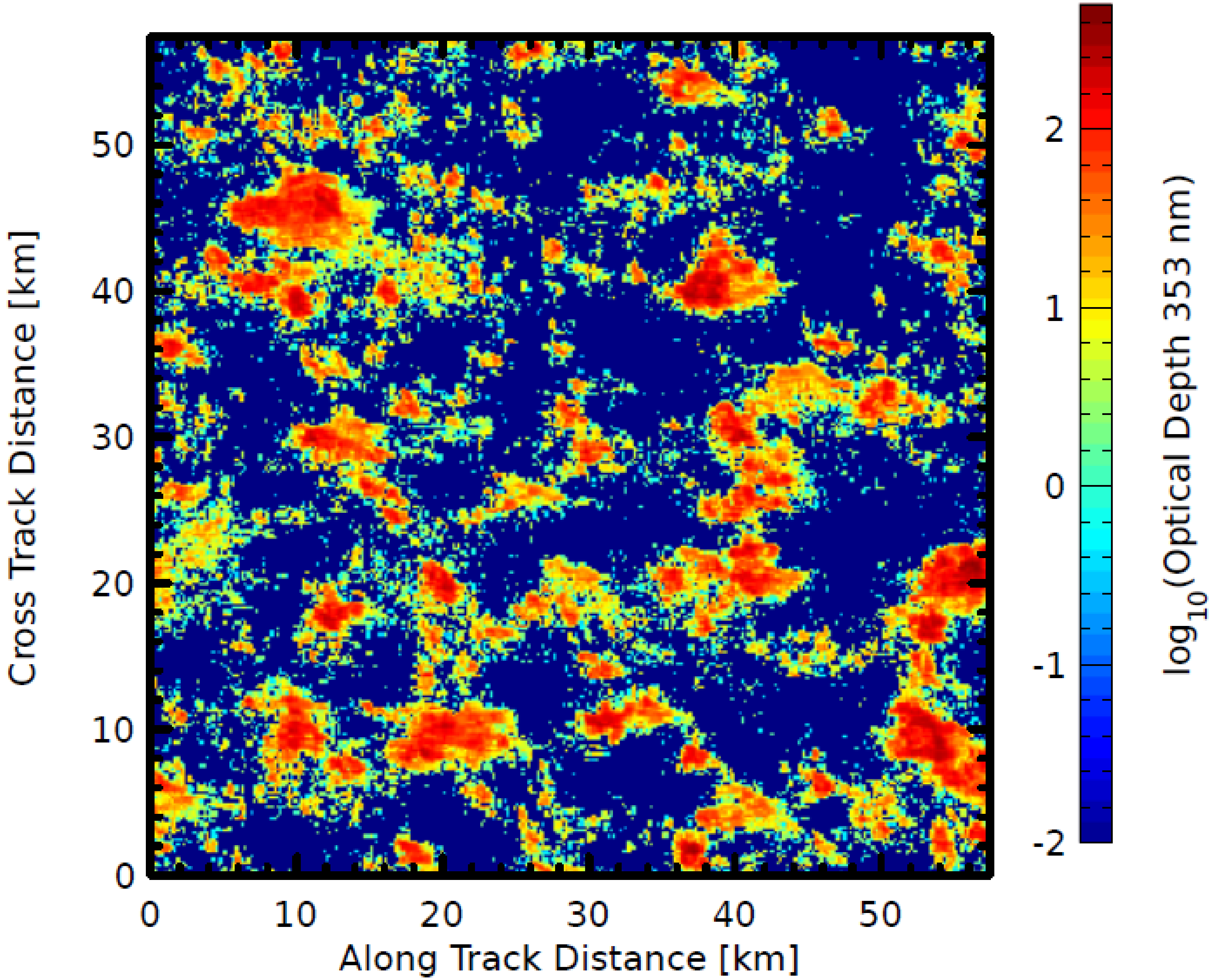
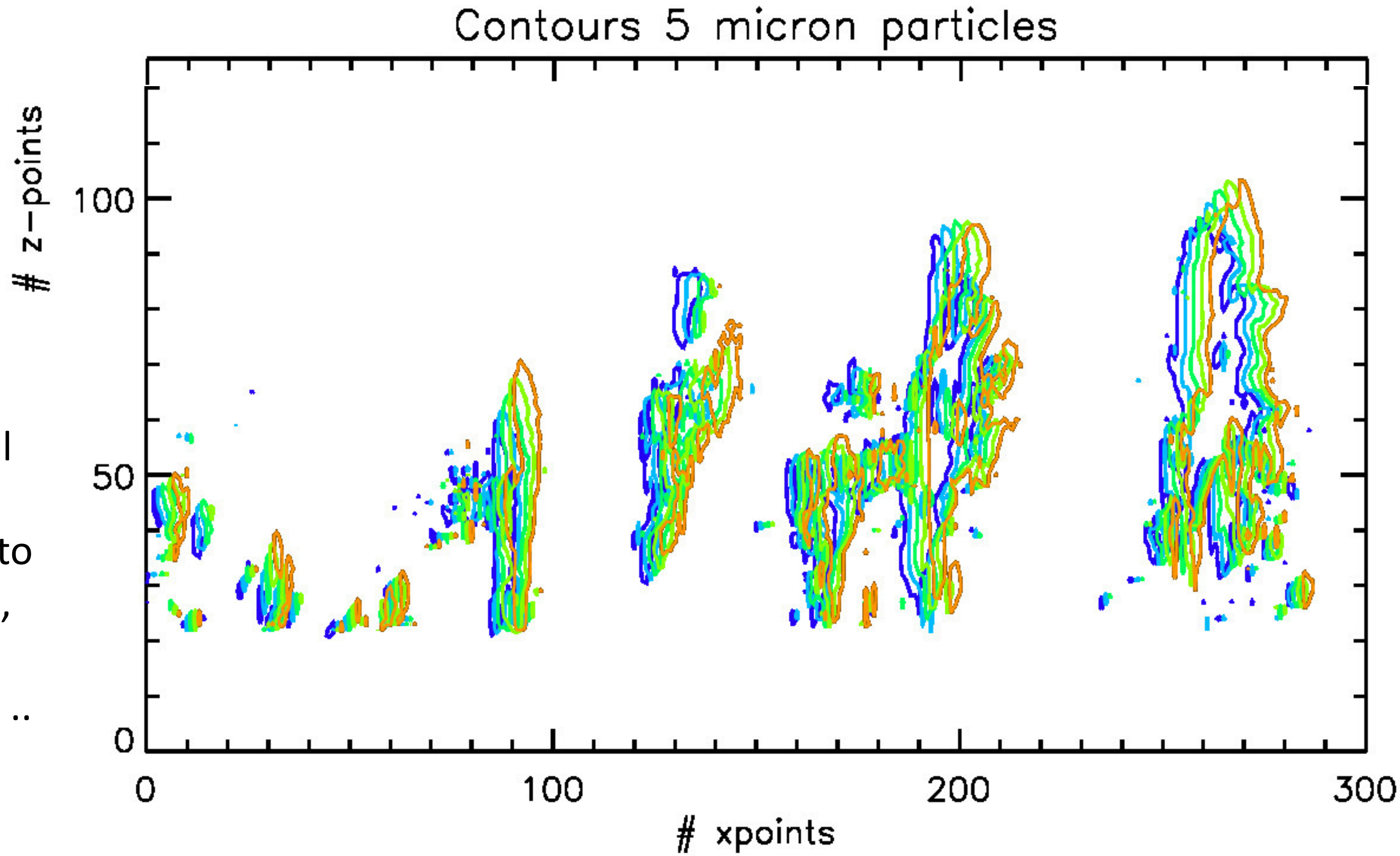


Vertical view

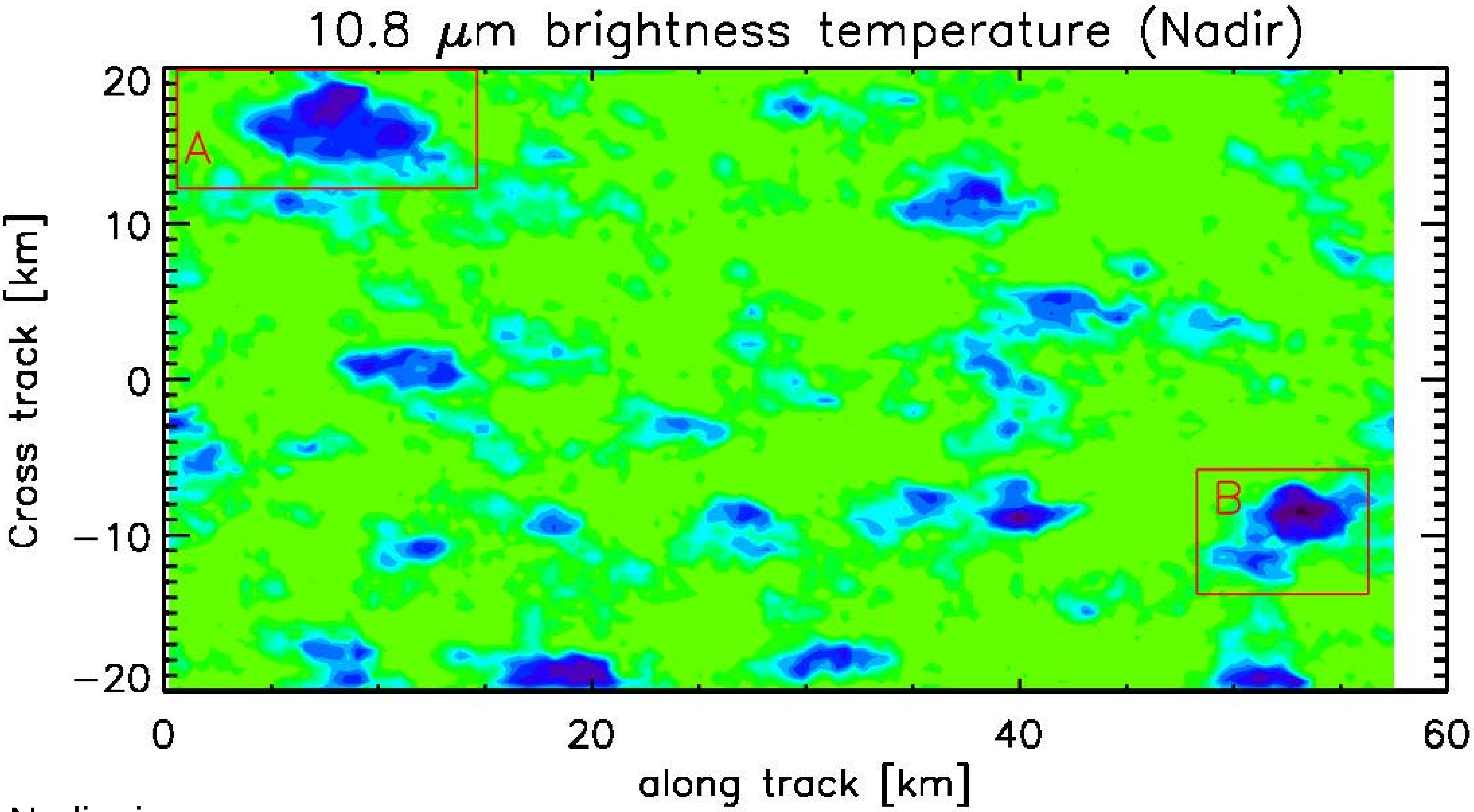
Colors in 1-minute steps

u = 3.3 m/s; v = 0

- Clouds move, grow and transform, due heat, radiation, turbulence and mixing
- NWP models will NOT capture this for decades to come
- Many cloud missions will fly over this time frame to obtain wind, Tb, dBz, w, BRDF, BPDF, ..

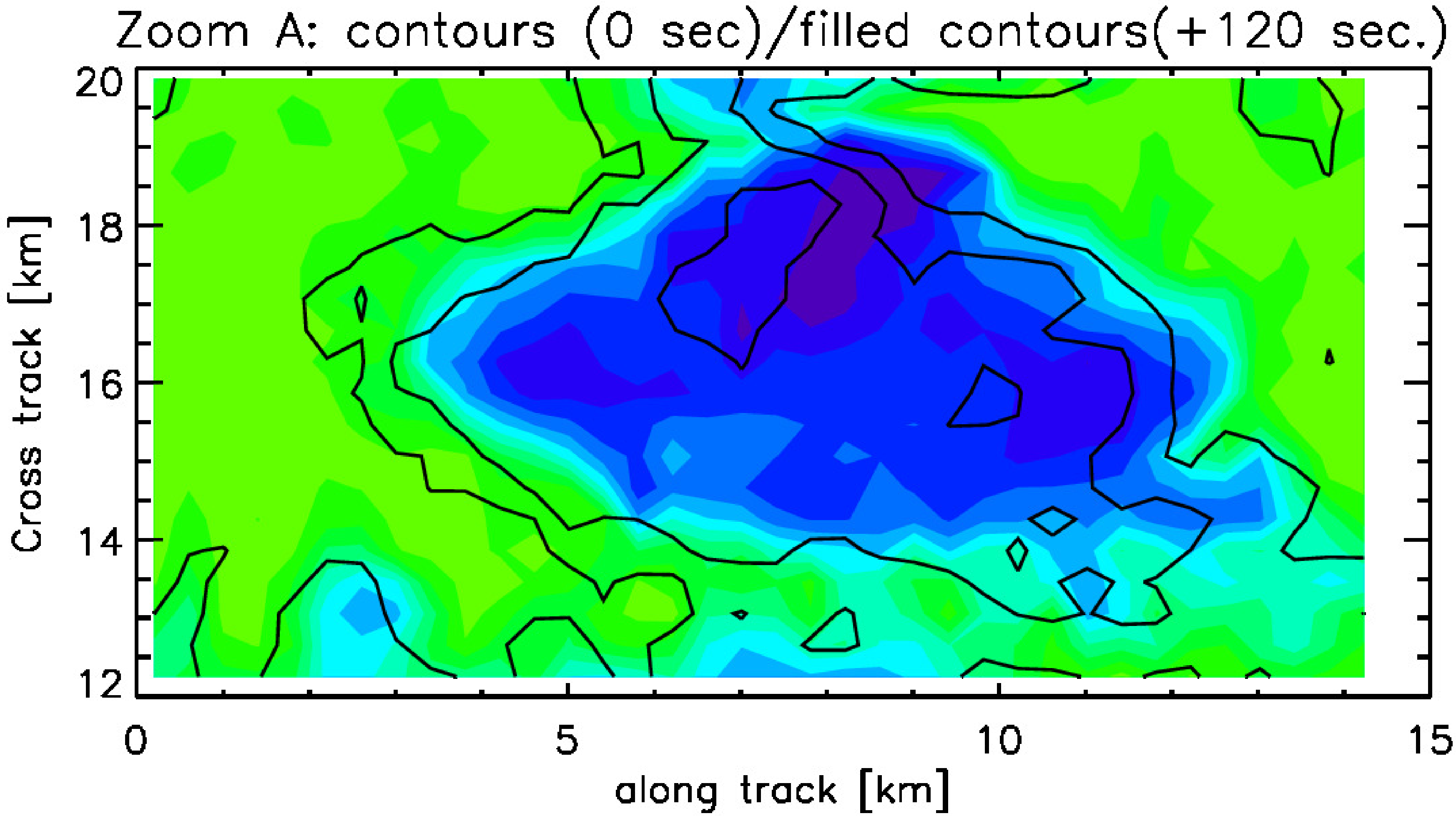


Images



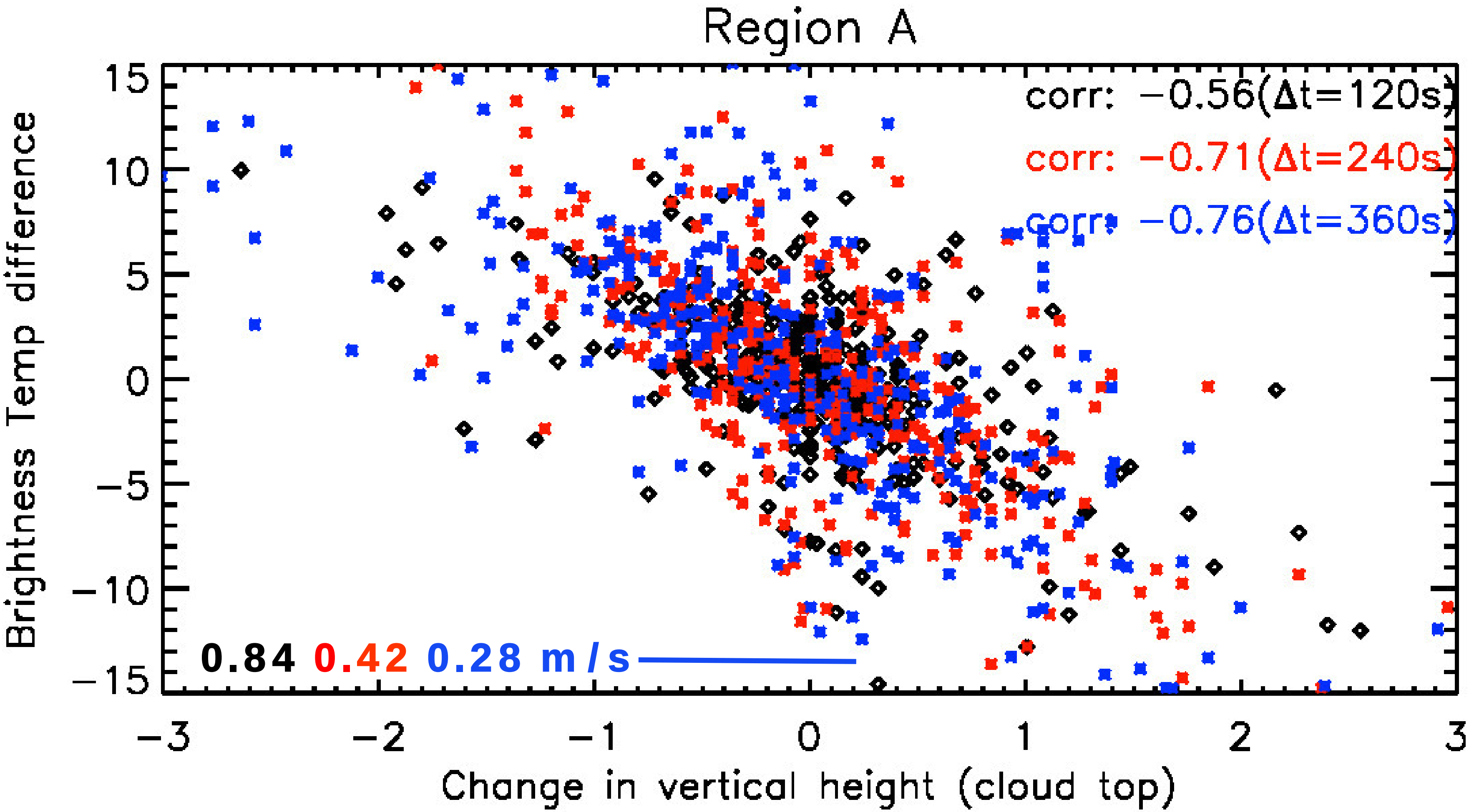
Nadir view

A



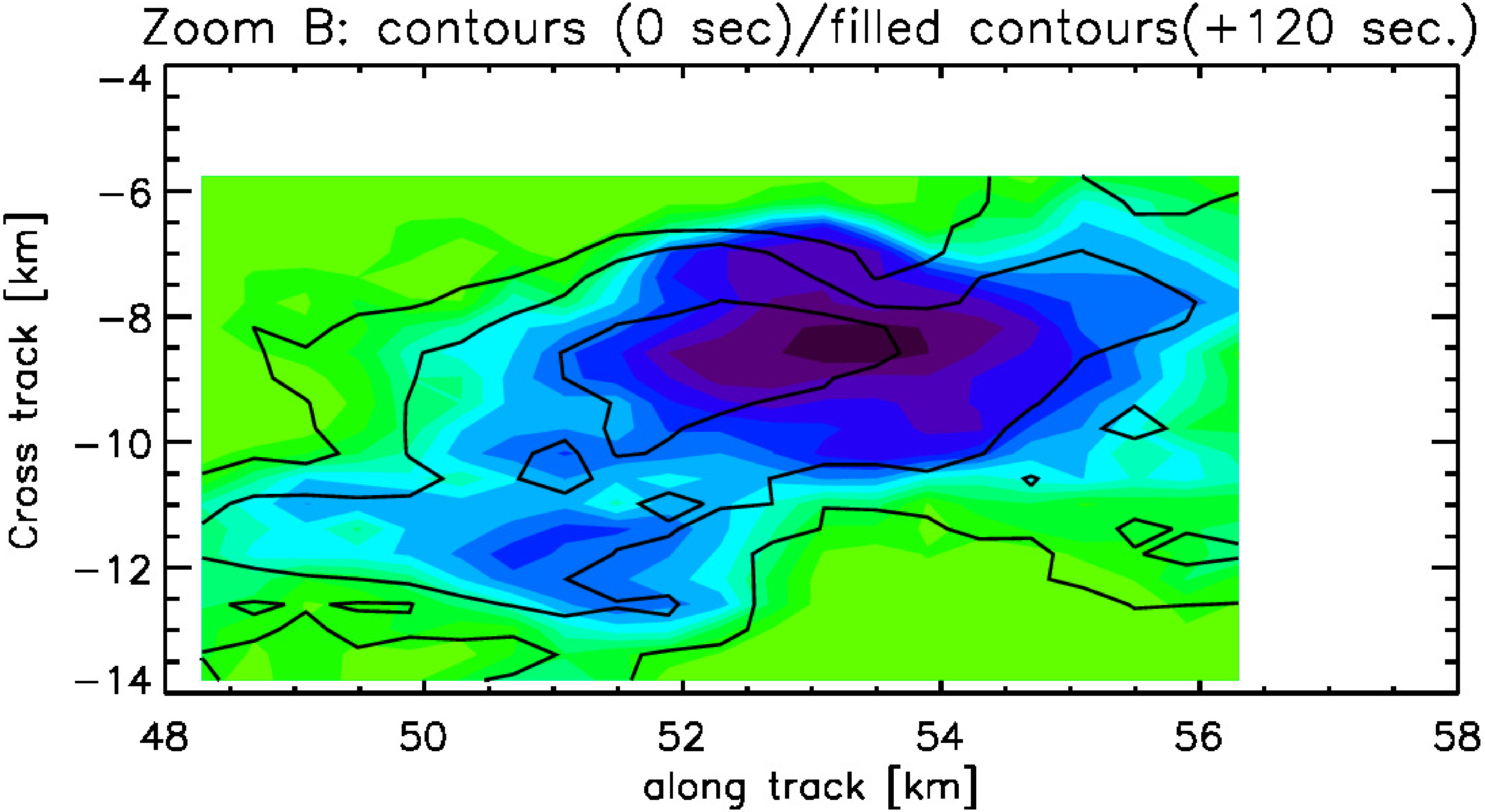
➢ The mean horizontal motion has been fully and exactly compensated

Tb is no good proxy for height



- Vertical speed is not a perfect proxy for vertical wind
- A single MISR compromises both the temporal CTH an Tb changes

B



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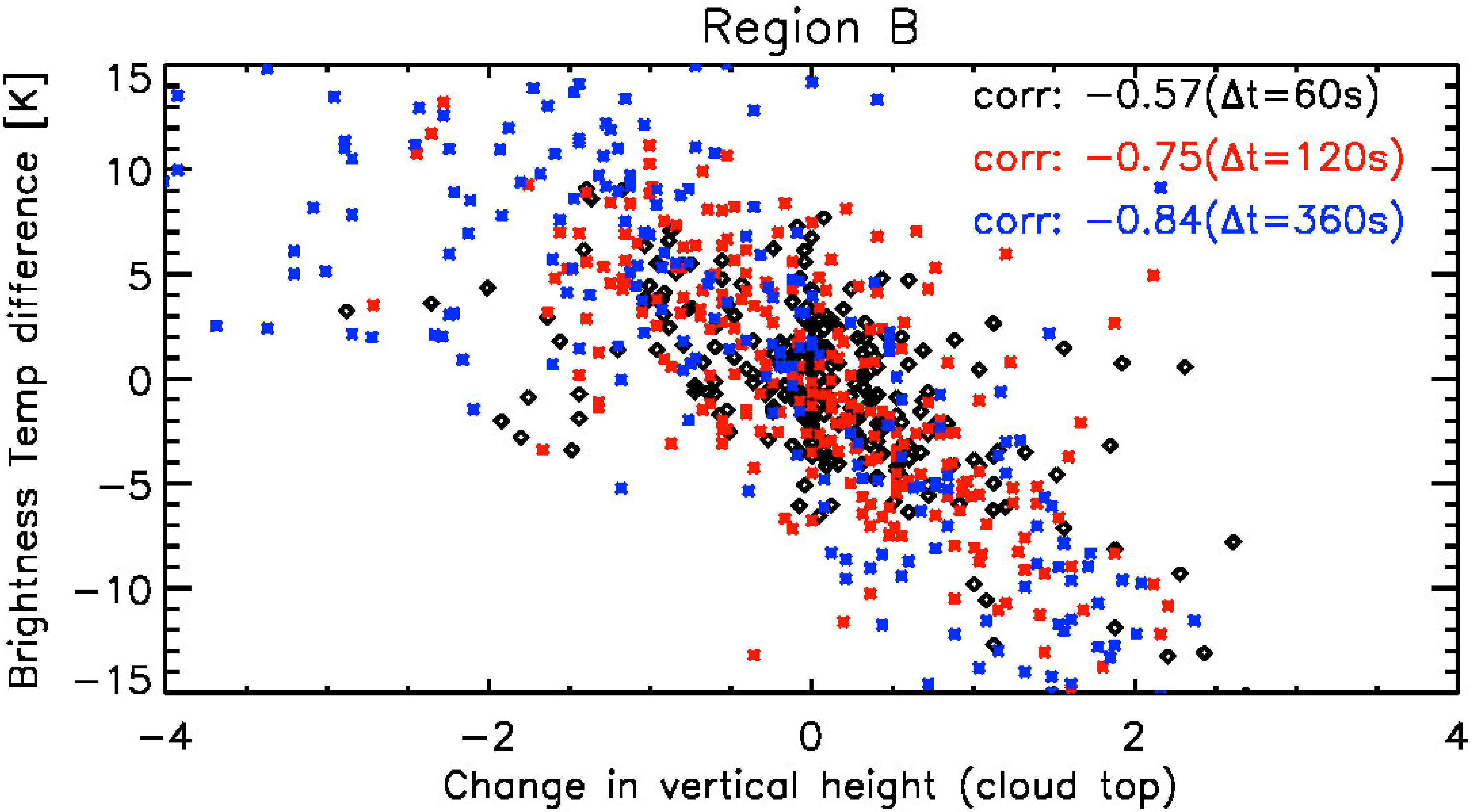
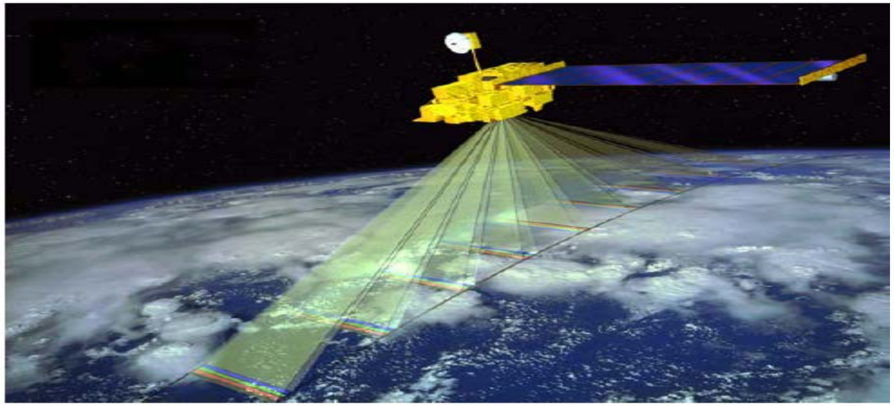


How do clouds look like and behave?

- Single-satellite multi-angle imagers do not resolve the time or dynamic aspects of cloud development and deformation.

- Therefore height, vertical and horizontal wind components are aliased in the resulting wind products.



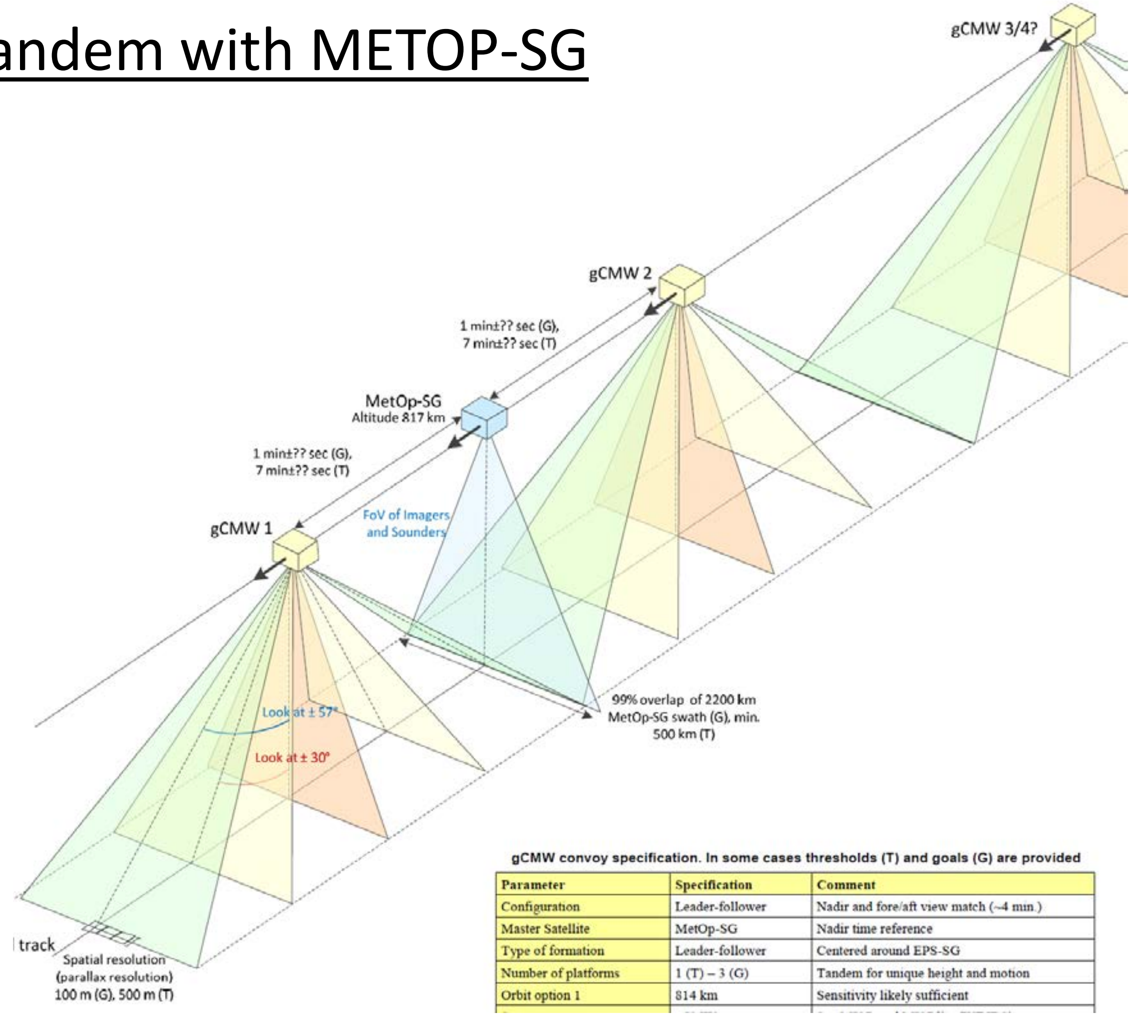
The solution is: tandem

- Synergy between various instruments
- Sample fast developing processes; avoid aliasing

gCMW - tandem

MISR-like, but tandem with METOP-SG

- Cloud top heights, height resolved winds, vertical motion, aerosol, humidity and cloud structures
- Needed for mesoscale NWP



gCMW convoy specification. In some cases thresholds (T) and goals (G) are provided

Parameter	Specification	Comment
Configuration	Leader-follower	Nadir and fore/aft view match (~4 min.)
Master Satellite	MetOp-SG	Nadir time reference
Type of formation	Leader-follower	Centered around EPS-SG
Number of platforms	1 (T) – 3 (G)	Tandem for unique height and motion
Orbit option 1	814 km	Sensitivity likely sufficient

- Proposal EE9 in 2015 (rejected)
- Being proposed for H2020 in 2018

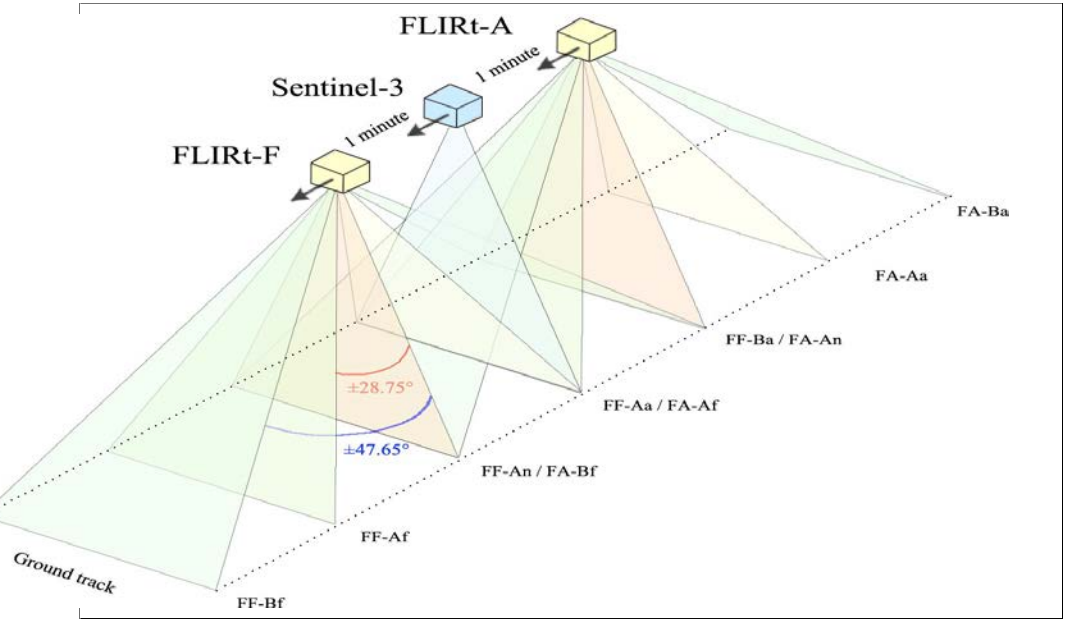
FLIRt

FLIRt: Flow by IR tandem

Accurate 4D wind observations from a tandem mission in convoy with Sentinel-3 to answer the key missing link in global climate change: aerosol and cloud interactions in vertical updrafts and improved representation in climate and NWP atmospheric circulation models

ESA – EE09 proposal

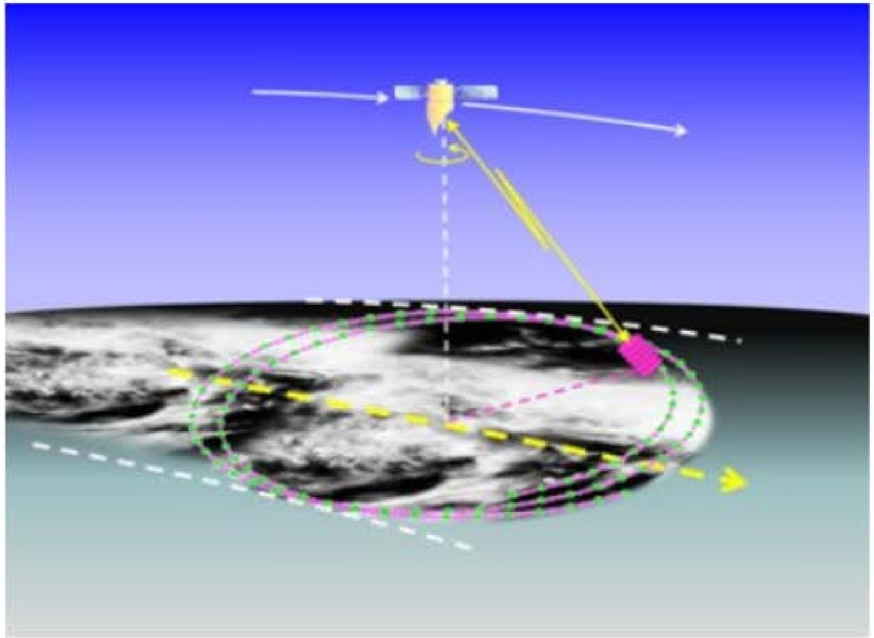
The driving requirement is the need to obtain vertical cloud surface motion at an accuracy of 1.0 ms^{-1} and also u and v wind-speed of 1.0 ms^{-1}.
This value is near the lower bound of vertical motions of highly convective clouds, such as Cumulo-Nimbus, and at the high end of marine stratocumulus.



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

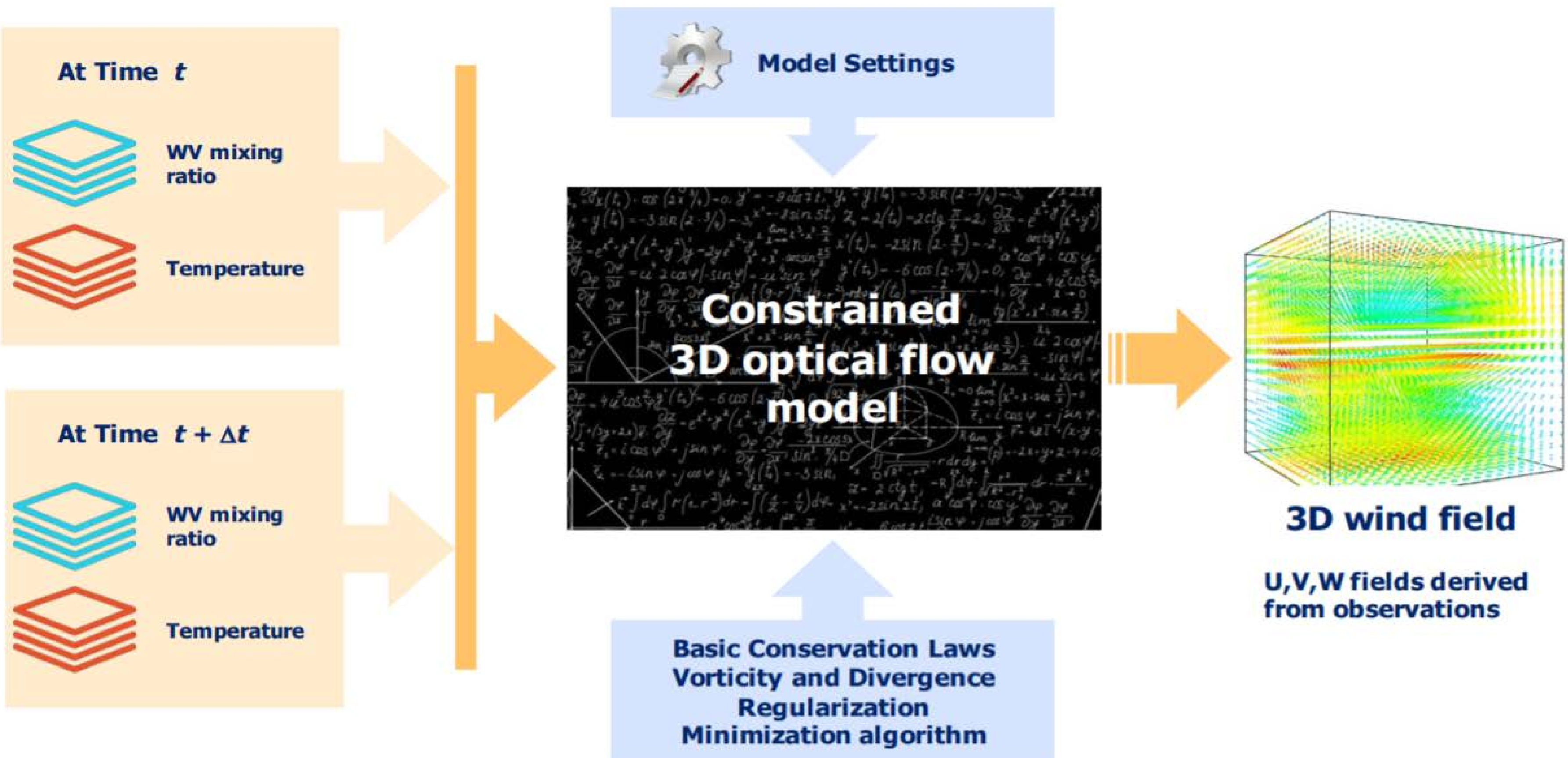
NARROW BEAM - must use 94GHz – 2.9m elliptical antenna
- 3dB two-way beamwidth 0.001rad - pulse length 500m,

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

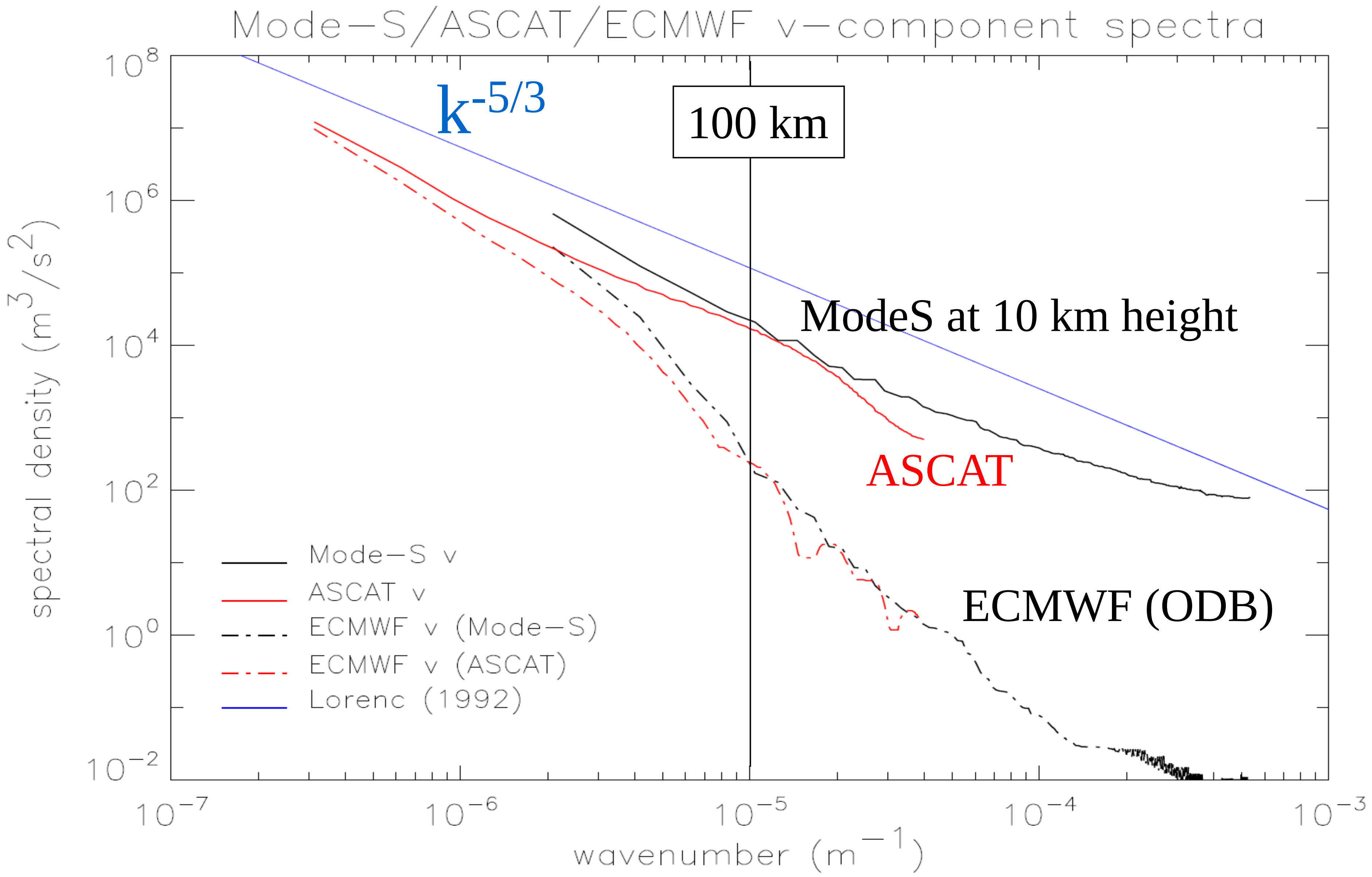
3D IASI winds from WV mixing ratio

The concept

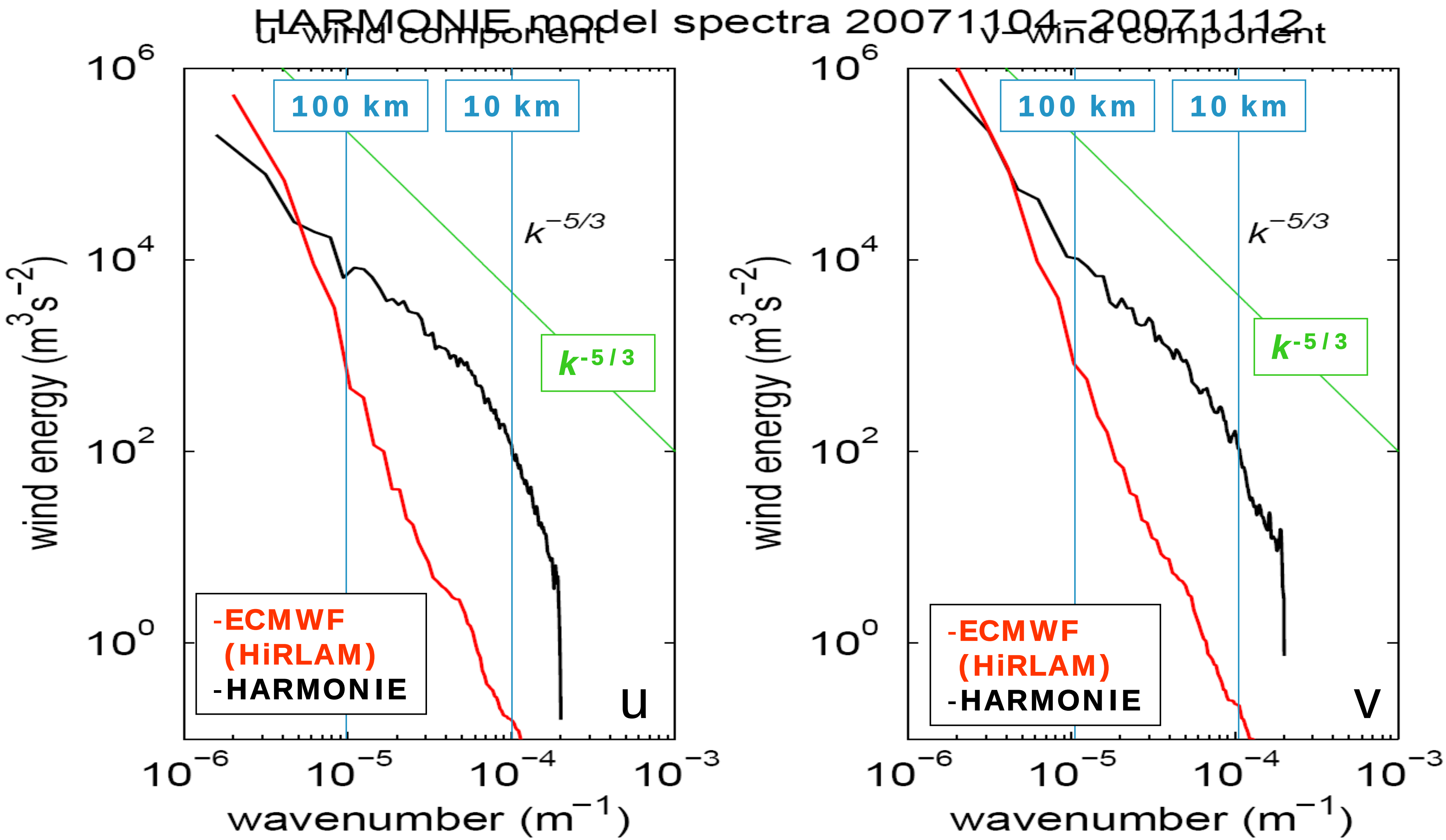


Hautecoeur et al.

Small scales



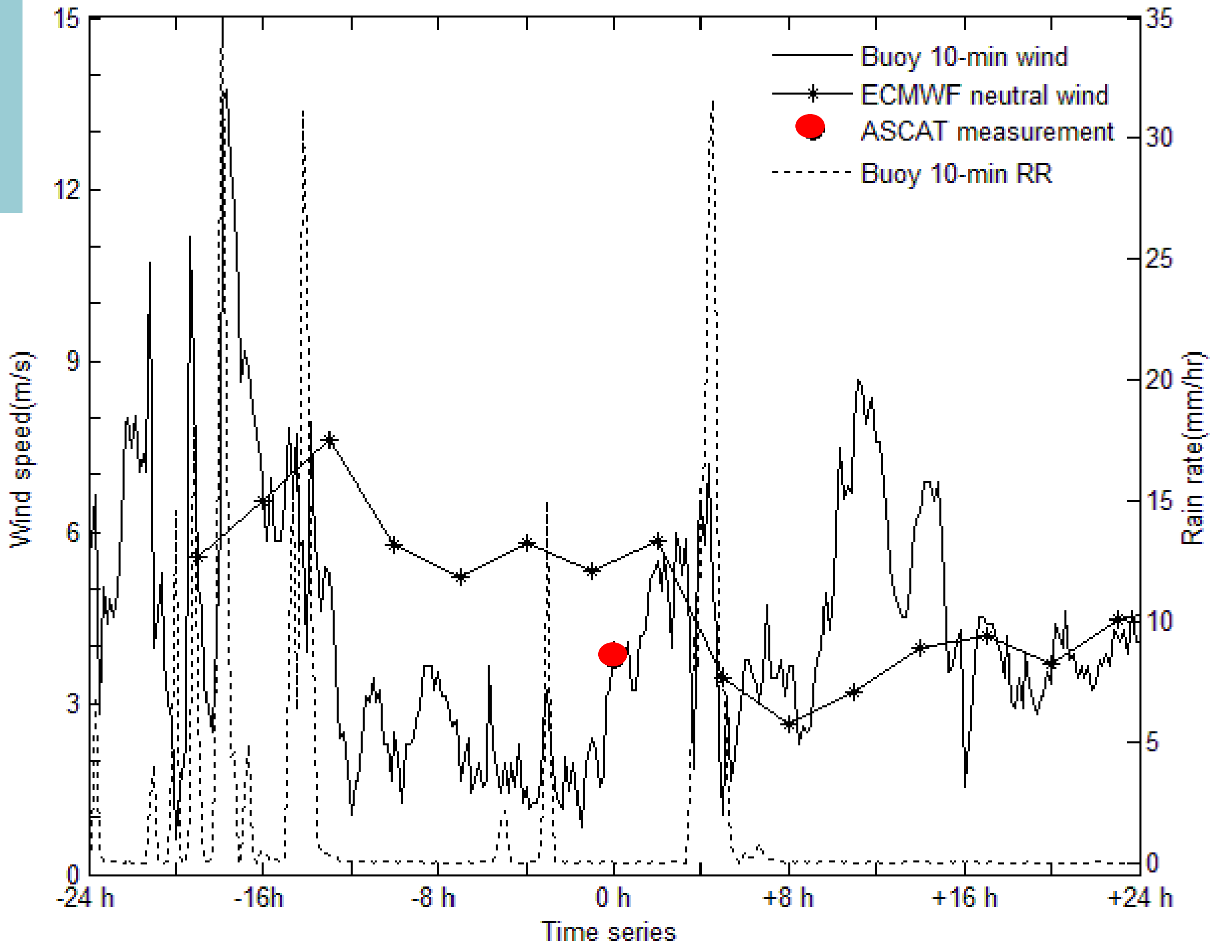
Regional NWP progress

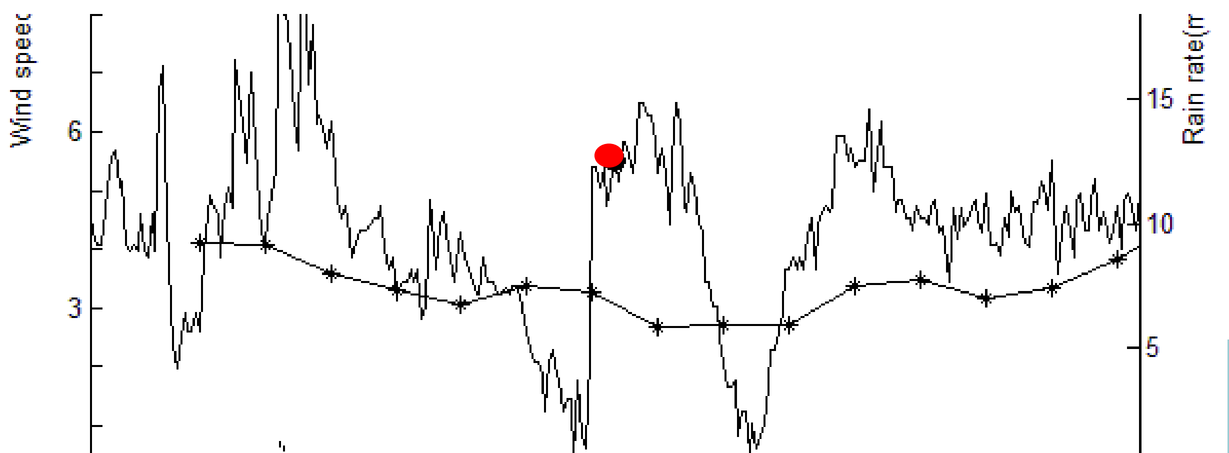


Tropical variability

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

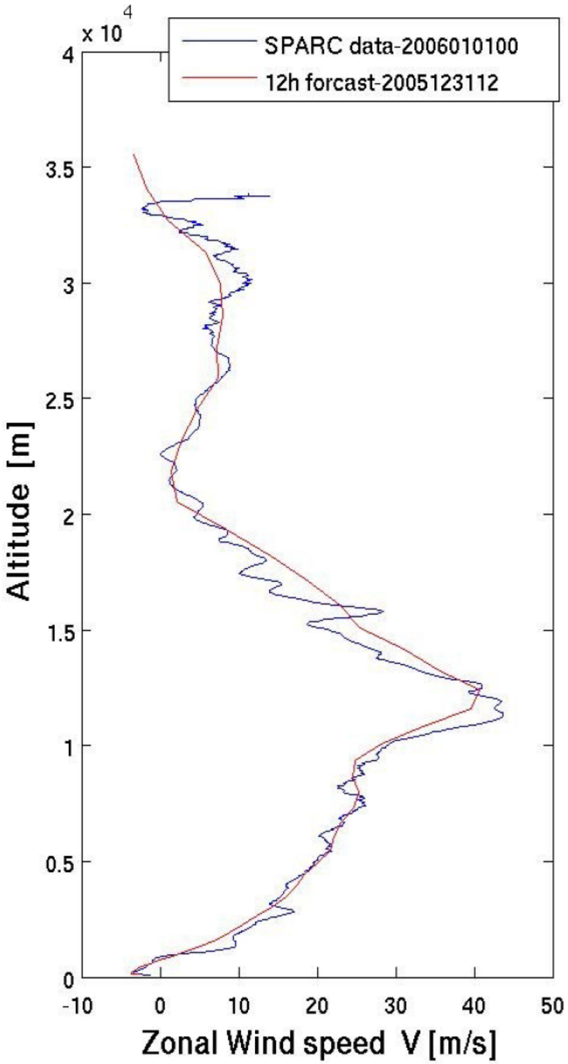
➢ Portabella et al.,
Lin et al.



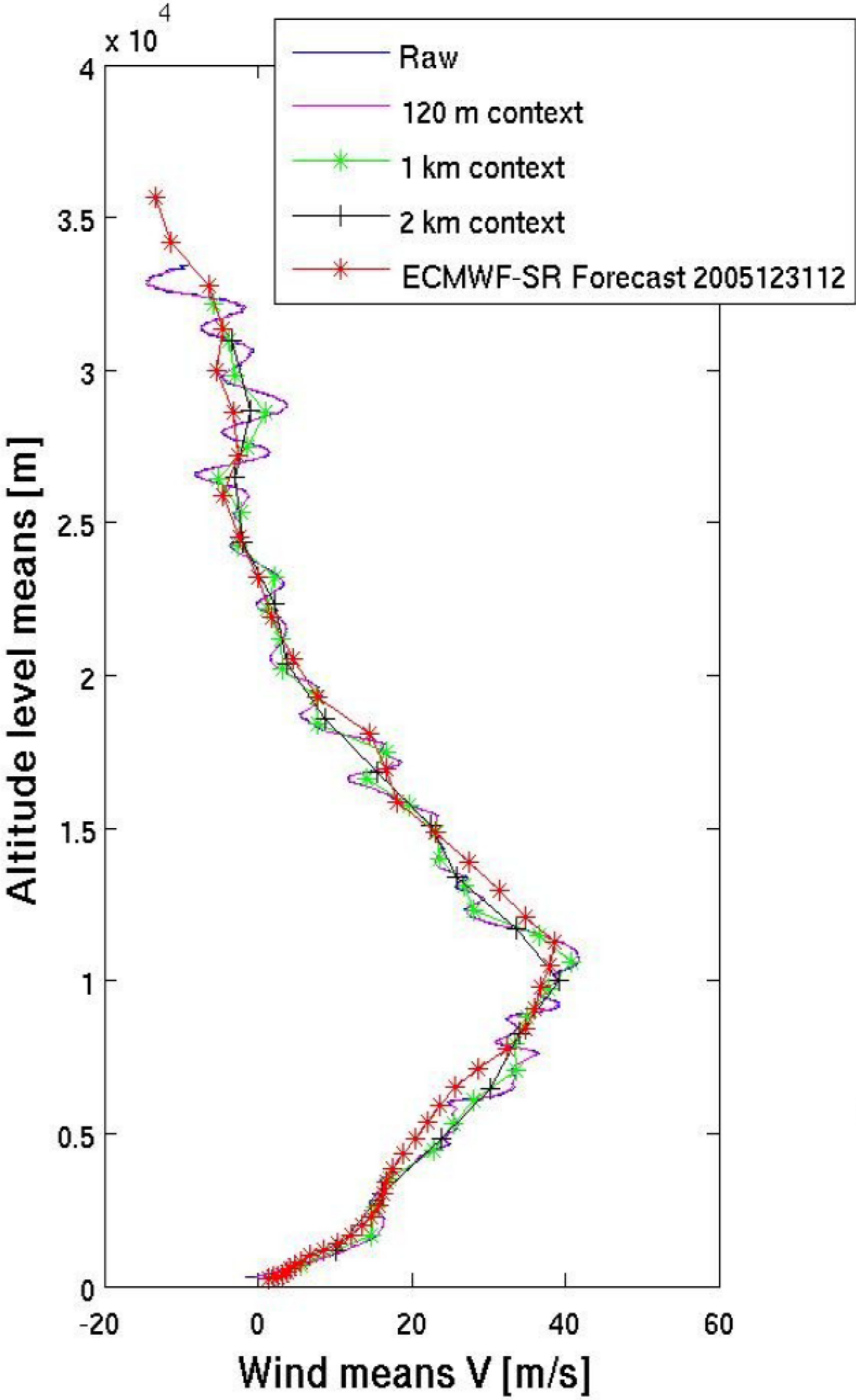


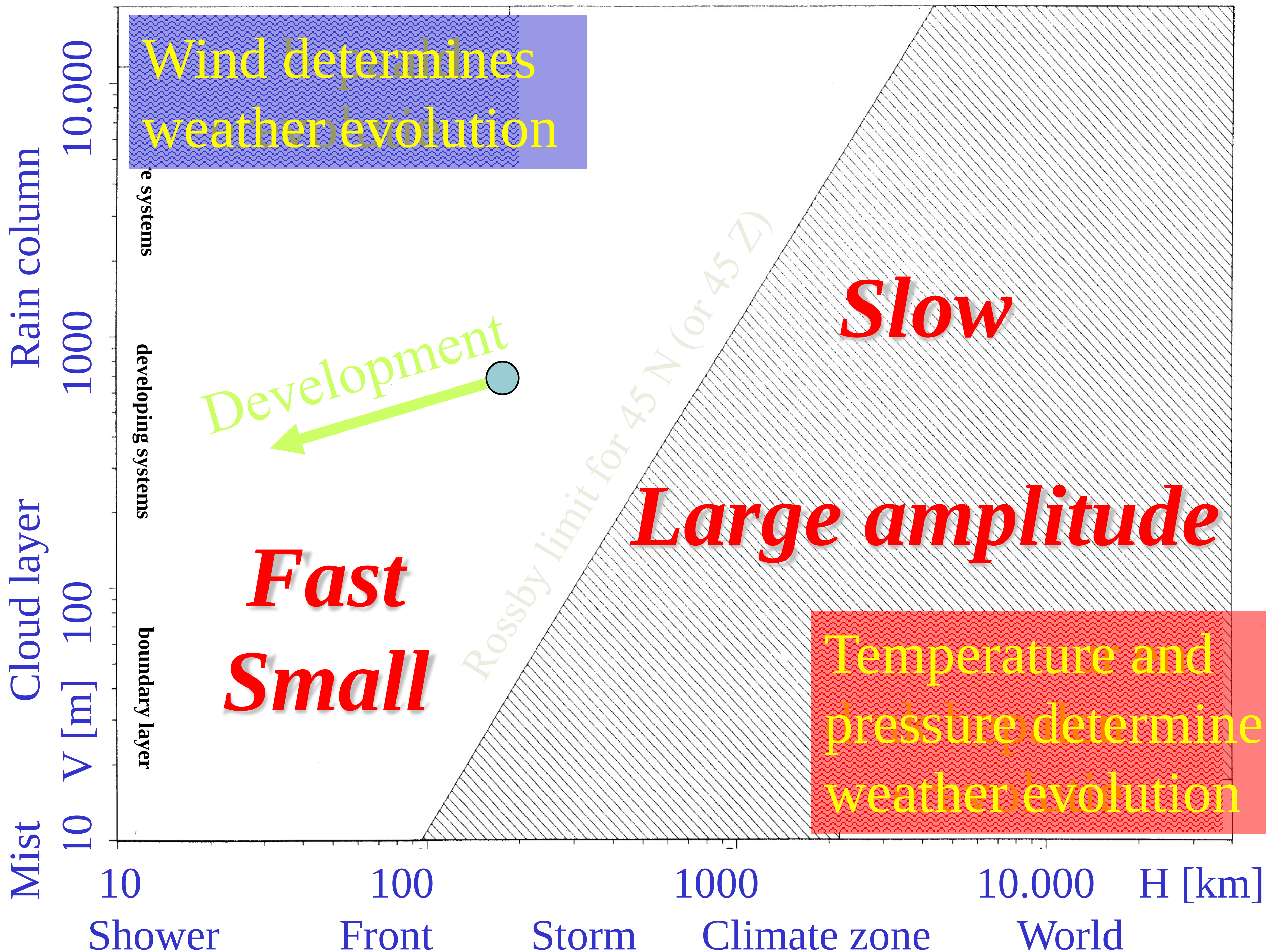
NWP model versus hi-res SPARC radiosondes

Houchi et al., 2010



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





Wind determines weather evolution
Temperature and pressure determine weather evolution
Slow
Large amplitude
Fast
Small
Development
Rossby limit for 45 N (or 45 Z)
developing systems
boundary layer
Rain column
Cloud layer
Mist
V [m]
10.000
1000
100
10
10
100
1000
10.000
H [km]
Shower
Front
Storm
Climate zone
World

WMO OSCAR

Observing Systems Capability Analysis and Review Tool

- Quantitative user-defined requirements for observation of physical variables in application areas of WMO
- Detailed information on all earth observation satellites and instruments
- Expert analyses of space-based capabilities
- Facilitates the Rolling Requirements Review process, comparing "what is required" with "what is, or will be available", in order to identify gaps and support the planning of integrated global observing systems (2040 vision)
- Future objective is to automatically generate first-level analyses of compliance between the quantitative requirements and the actual capabilities (space- or surface-based)

- Observation Requirements
- Satellite Capabilties
- **Surface-based capabilities** (future module, not yet available)

http://www.wmo-sat.info/oscar/

So what if Aeolus is a sucess?

- The technology of obtaining molecular winds has been demonstrated
- But, Aeolus does not meet NWP data assimilation practice, which needs (e.g. from OSCAR database)
  - 100-km density and every 3 hours
  - Increased vertical sampling

Considerations for post-Aeolus spaceborne DWL

- Constellation of several DWLs (similar to scatterometer)
- For instance through international collaboration
- Aeolus UV lidar is favourable for winds in clear air
  - Stick to 355 nm wavelength
- Evaluate improved technology on solid state physics, detectors and efficiency => improved wind quality and resolution
- Evaluate the additional option for optical profiles, besides winds
- During design phase: lessons learnt from Aeolus, e.g. Cal/Val and data processing

Conclusions

- UV lidar will provide clear air winds and is currently the only potential candidate to meet the WMO requirements on wind coverage and quality (OSCAR database).
- Cloud dynamics are poorly described in models, also in relation to aerosol
- Many potentially capable cloud/aerosol missions exists and may fly > 2020
- Tandem missions exploit synergy to yield height resolved horizontal and vertical wind, cloud structure and dynamics, aerosol and humidity which are needed for further advances in mesoscale NWP

➢ The white paper provides a clear overview of requirements for wind profiling and satellites capabilities; soon available for a wider audience

➢ We will start a discussion on technologies, but with Aeolus we will have a space heritage soon hopefully!

Why wind profiles ?

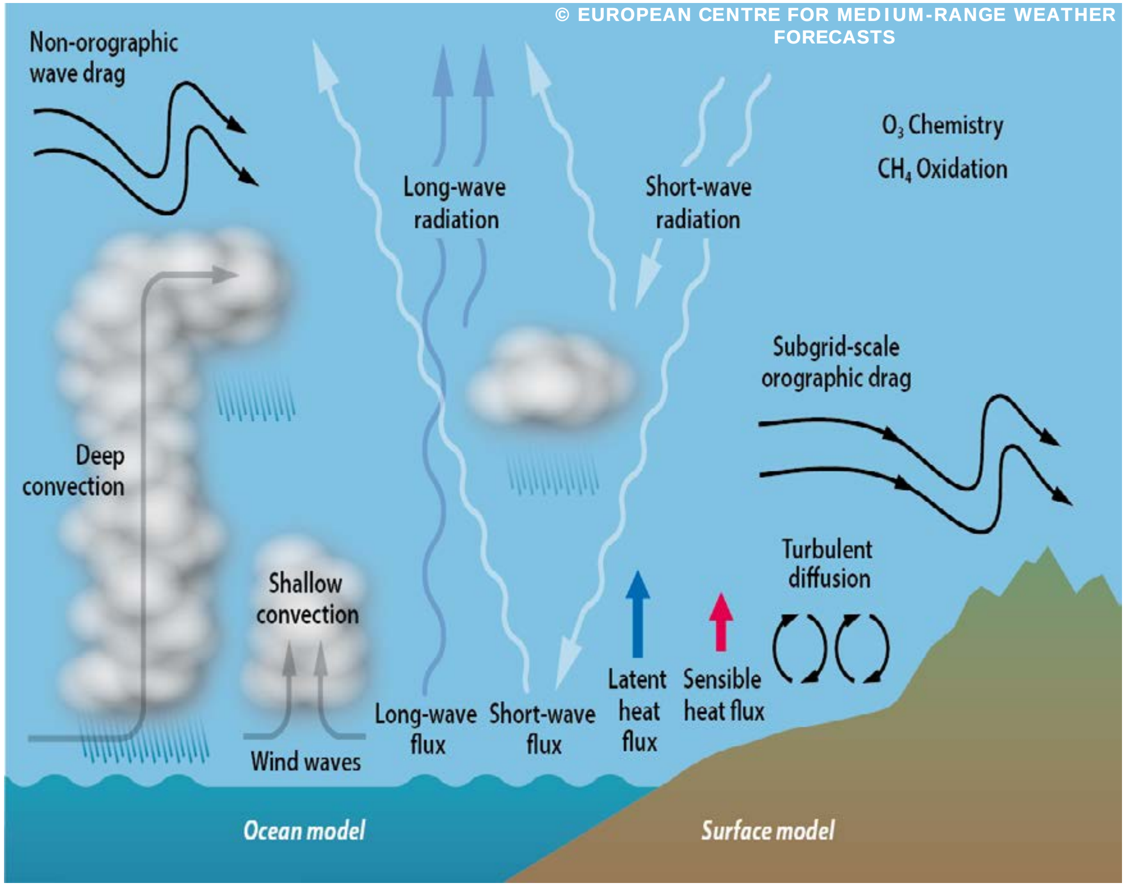
Extend the G(C)OS to fill spatial and temporal gaps of wind profiles in the vertical and provide shear observations

- Improved initialisation for weather forecasting, leading to improved weather forecasts and transport of constituents
- Weather and circulation model improvement
- Quality reference for existing wind observations
- Better resolve 3D turbulence (< 500 km), convection and processes

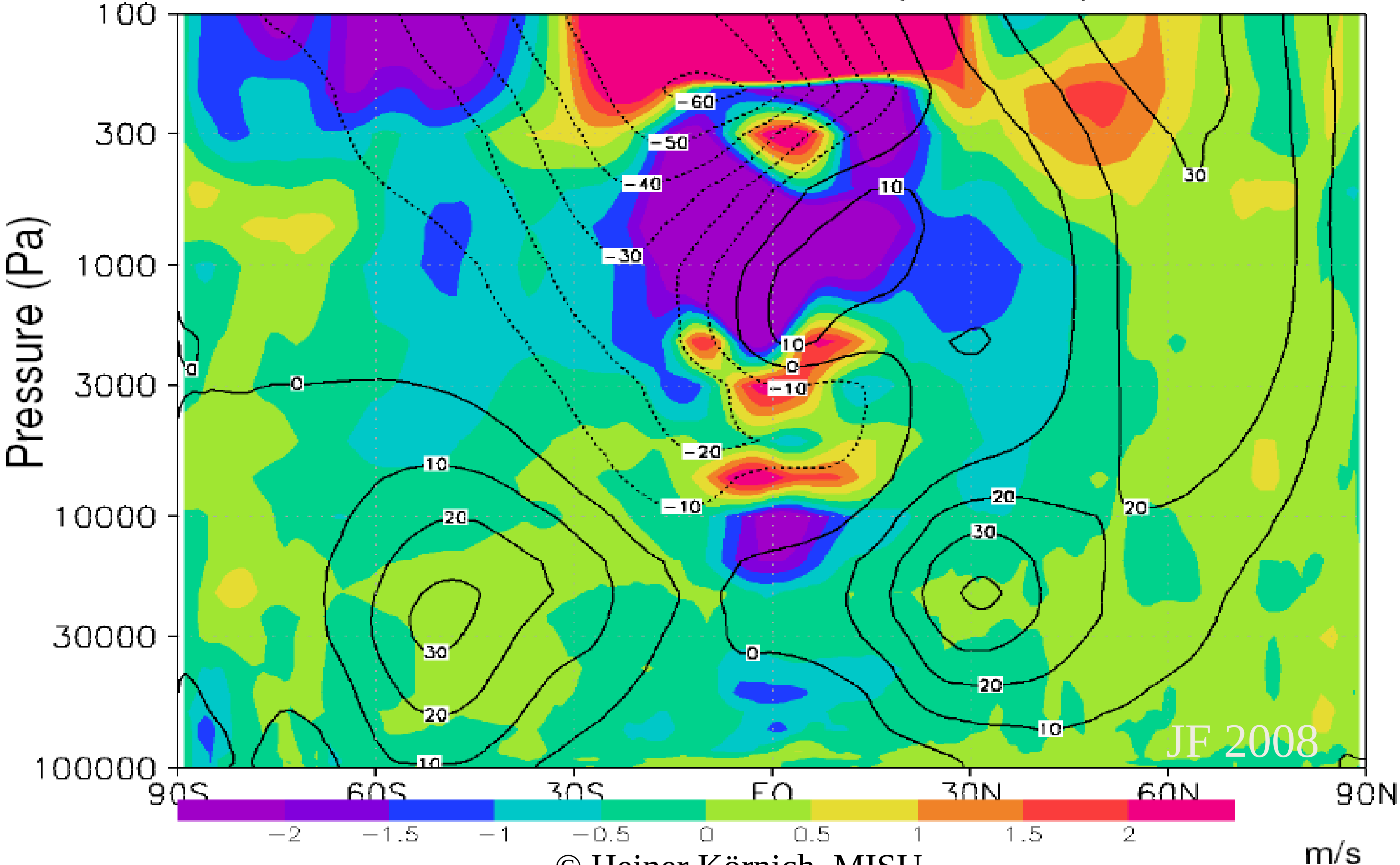
Physical processes in a NWP model

- Many small-scale processes have interaction with the 3D turbulence spectrum, which dominates atmospheric dynamics in the tropics and elsewhere on scales below 500 km

- Yet, few 3D wind observations exist

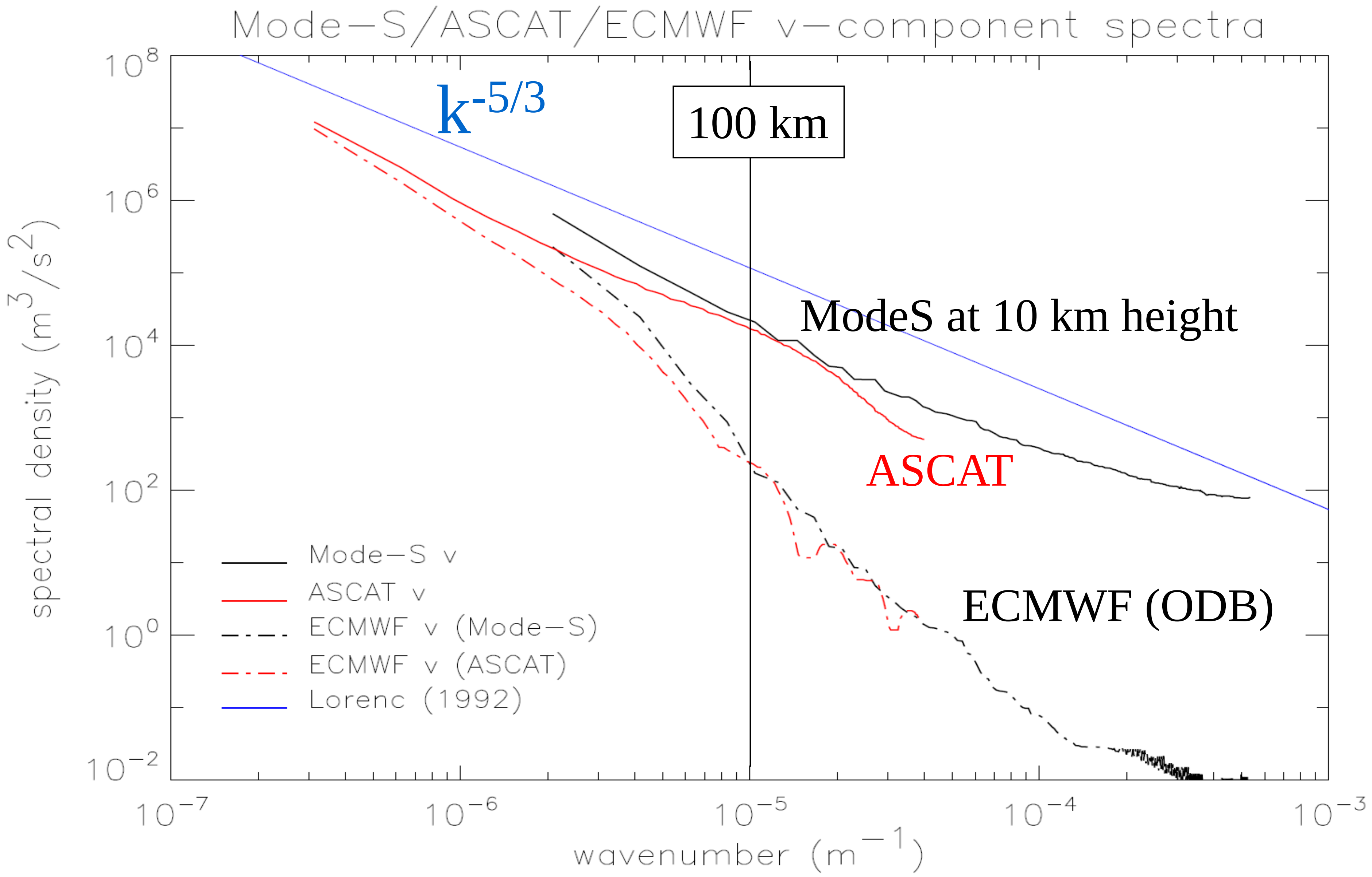


Time and zonal mean u-wind in ECMWF (contours) and difference with UKMO (shaded)



☞ Large uncertainty in tropics on seasonal flow affects climate processes

Small scales

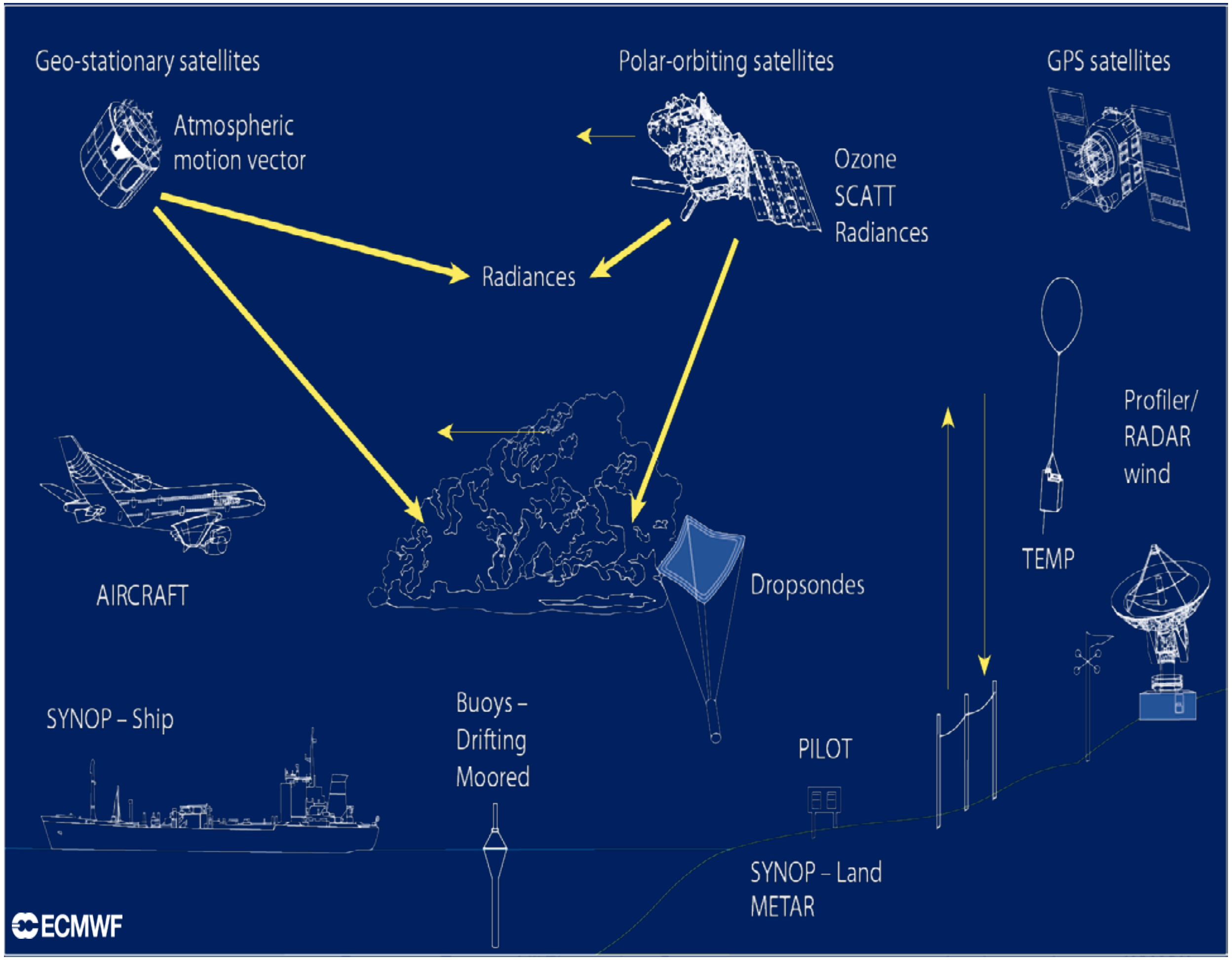


Initialisation of weather forecasts

40 million observations processed every day

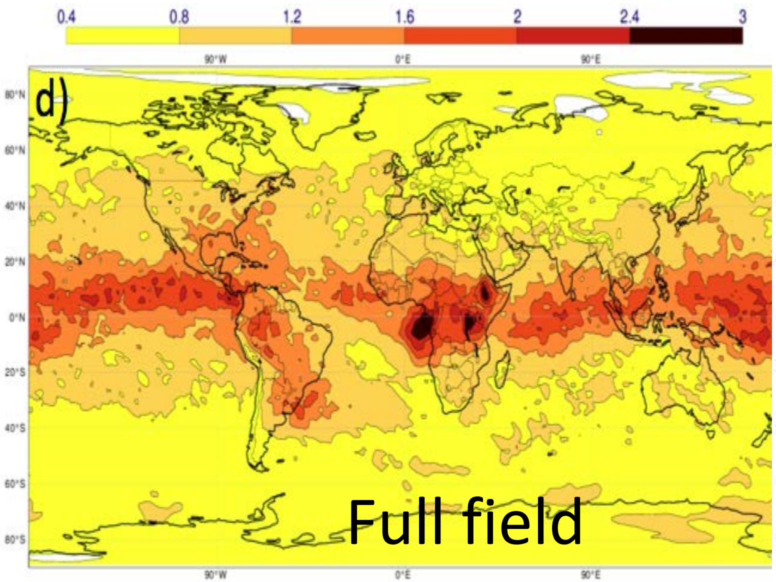
- Data assimilation in NWP to initialize model dynamic state

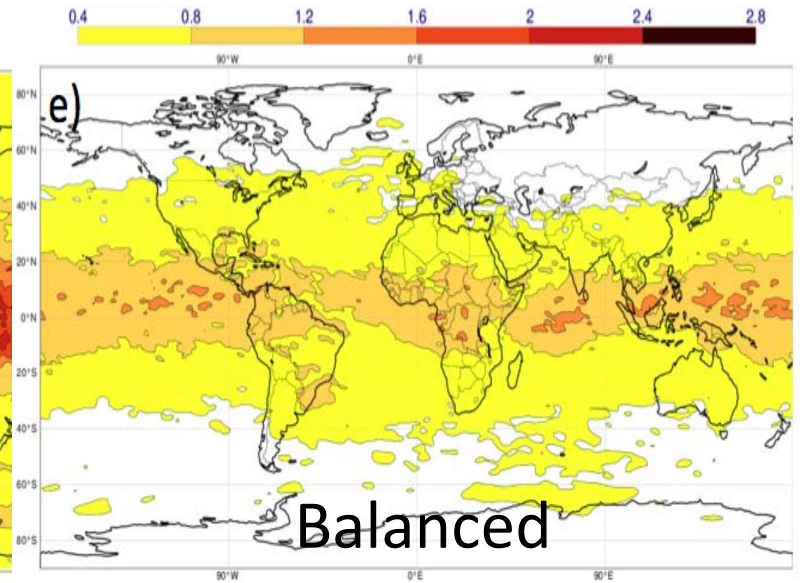
- Also basis for climate reanalysis (ERA)



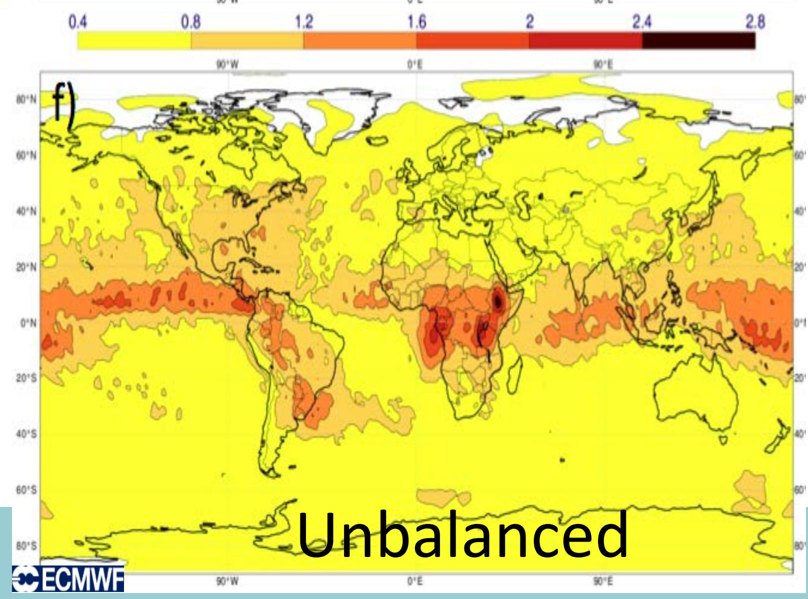
Absolute analysis increments u_{150}

18UTC average for Sept-Nov 2015

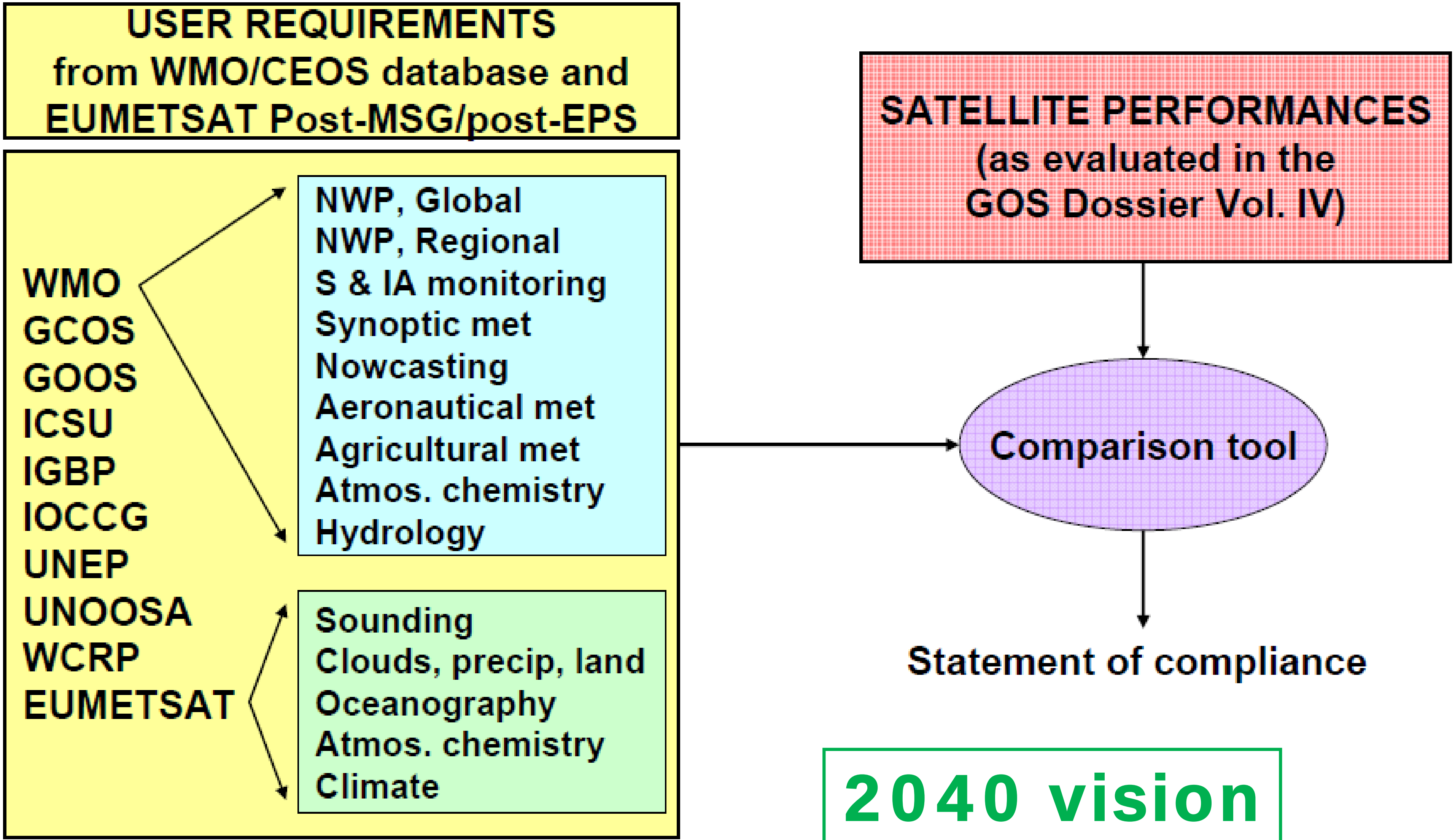




- Dynamical errors in the tropics and in moist convection are mostly unbalanced and 3D winds are needed to observe them, hence Aeolus



WMO G(C)OS gap analysis



2040 vision

All instruments for measuring *Wind (horizontal)*

Instruments	Relevance of Measurement	Processing Maturity	Operational Limitations
ALADIN	Primary	Methodology to consolidate	Non-scanning, radial viewing, Cloud
GIIRS IRS HIS	Primary	Methodology to consolidate	From humidity profile and tracers
HRDI TIDI WINDII	High	Methodology being tuned	Mesosphere and lower thermosphere
ABI AHI FCI AGRI AMI MSU-GSM	High	Consolidated methodology	Tracers needed
MSU-GS SEVIRI MSU-GS/A ISR	High	Consolidated methodology	Tracers needed
IMAGER (GOES 8-11) IMAGER (INSAT-3D) IMAGER (MTSAT) JAMI MI IMAGER (GOES 12-15) S-VISSR (FY-2C/D/E)	Medium	Consolidated methodology	Tracers needed

www.wmo-sat.info/oscar/gapanalyses?view=179

S-VISSR (FY-2C/D/E)	3-Medium	FY-2E	105°E	X	X	X	X	X																
S-VISSR (FY-2F/G/H)	3-Medium	FY-2G	105°E				X	X	X	X	X													
GIIRS	1-Primary	FY-4B	105°E								X	X	X	X	X	X	X							
GIIRS	1-Primary	FY-4D	105°E												X	X	X	X	X	X				
GIIRS	1-Primary	FY-4F	105°E																			X	X	X
S-VISSR (FY-2F/G/H)	3-Medium	FY-2F	112°E			X	X	X	X	X														
S-VISSR (FY-2F/G/H)	3-Medium	FY-2H	123.5°E						X	X	X	X	X											
AMI	2-High	GEO-KOMPSAT-2A	128.2°E								X	X	X	X	X	X	X	X	X	X	X	X		
MI	3-Medium	COMS-1	128.2°E	X	X	X	X	X	X	X	X													
AHI	2-High	Himawari-8	140°E					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
AHI	2-High	Himawari-9	140°E							X	X	X	X	X	X	X	X	X	X	X	X	X	X	
JAMI	3-Medium	Himawari-6 (MTSAT-1R)	140°E	X	X	X	X	X	X															
IMAGER (MTSAT)	3-Medium	Himawari-7 (MTSAT-2)	145°E	X	X	X	X	X	X	X	X													
MSU-GS	2-High	Electro-L N3	166°E						X	X	X	X	X	X	X	X								
MSU-GS/A	2-High	Arctica N1	63.4 °					X	X	X	X	X	X											
MSU-GS/A	2-High	Arctica N2	63.4 °					X	X	X	X	X	X											
ISR	2-High	PCW-1	63.4 °									X	X	X	X	X	X	X	X					
ISR	2-High	PCW-2	63.4 °									X	X	X	X	X	X	X	X					
TIDI	2-High	TIMED	74 °	X	X	X	X	X																
VIIRS	4-Useful	Suomi-NPP	13:25 asc		X	X	X	X	X	X														
MODIS	4-Useful	EOS-Aqua	13:30 asc	X	X	X																		
VIIRS	4-Useful	JPSS-1	13:30 asc							X	X	X	X	X	X	X	X							
VIIRS	4-Useful	JPSS-2	13:30 asc												X	X	X	X	X	X	X	X		
MERSI-2	4-Useful	FY-3D	14:00 asc						X	X	X	X												
MERSI-2	4-Useful	FY-3F	14:00 asc										X	X	X	X								
MSU-MR-MP	4-Useful	Meteor-MP N1	15:30 asc								X	X	X	X	X	X								
VIIRS	4-Useful	DWSS-1	05:30 desc									X	X	X	X	X	X							
VIIRS	4-Useful	DWSS-2	05:30 desc													X	X	X	X	X	X	X		
ALADIN	1-Primary	ADM-Aeolus	06:00 desc				X	X	X															
MSU-MR-MP	4-Useful	Meteor-MP N2	09:30 desc									X	X	X	X	X	X							
MetImage	4-Useful	MetOp-SG-A1	09:30 desc											X	X	X	X	X	X	X	X	X		
MetImage	4-Useful	MetOp-SG-A2	09:30 desc																		X	X	X	X
MERSI-2	4-Useful	FY-3E	10:00 desc								X	X	X	X										
MERSI-2	4-Useful	FY-3G	10:00 desc												X	X	X	X						
MODIS	4-Useful	EOS-Terra	10:30 desc	X	X	X																		

Summary observational needs

Topic	Observational needs
Dynamics, transport	• Spatially resolved, particularly vertically, and high accuracy measurements of wind and humidity. • Particularly, UTLS (clear, cloudy and aerosol)
Physical processes	• 3D turbulence on scales < 500 km • Vertical mixing of air • 3D or 4D measurements of convective, cloud, radiative and precipitation processes involving wind, humidity, clear air, aerosol, cloud and radiation parameters, aerosol and precipitation forms • Improved observation techniques and algorithms to measure and retrieve these physical properties • Compare physical properties / processes with weather or atmospheric circulation models
Satellite product	• Spatially resolved, particularly vertically, and high accuracy measurements of wind, humidity and clear/aerosol/cloud process properties, collocated with existing (operational) LEO and GEO instruments for validation, e.g., (Doppler) lidar, radar, multi-angle

References

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[1] www.wmo.int/pages/prog/sat/Refdocuments.html#spacebasedgos

[2] www.wmo-sat.info/oscar/

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Aeolus MAG White Paper

Wind Profile satellite observation requirements and capabilities

Ad Stoffelen[1], Angela. Benedetti[2], Regis Borde[3], Alain Dabas[4], Pierre Flamant[5], Mary Forsythe[6], Mike Hardesty[7], Lars Isaksen[2], Erland Källén[2], Heiner Körnich[8], Oliver Reitebuch[9], Lars-Peter Riishøjgaard[10], Harald Schyberg[11], Anne-Grete Straume[12], Michael Vaughan[13]

Comment [Ad1]: As I was asked by the MAG to set this paper up, I included all of the MAG, observers and secretary. Further suggestions are welcome.

Abstract:

Context and needs of the numerical weather prediction community.

The nature of user requirements. Model application. Dynamical weather, transport, climate, circulation.

Data assimilation.

Rolling Review of Requirements and Task Team on Observational Requirements and Satellite Measurements.

Accuracy/uncertainty, Spatial resolution and sampling, Temporal distribution and sampling, timeliness

Capabilities; what for what purpose. Operational: Sondes/planes., AMV, research: DWL, WIVERN, FLIRT.

Operations and resilience. Way forward.

1. Introduction

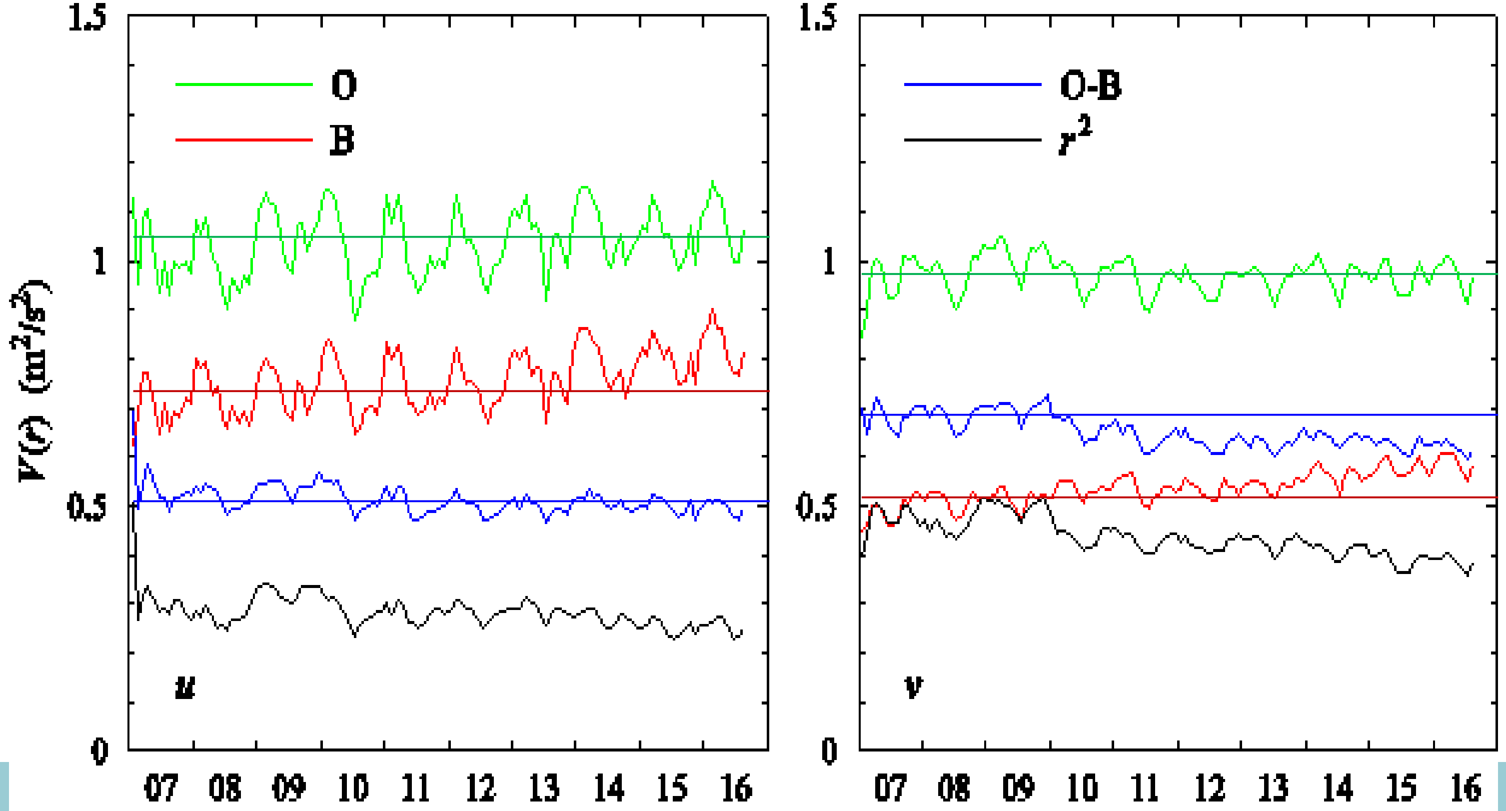
Weather forecasting and reanalyses, using methods developed for Numerical Weather Prediction (NWP), have seen unprecedented improvements in skill in the past decades (Bauer et al., 2015; Dee et al., 2011). Basic predictability was achieved in the early days of NWP by following the relatively slow large-scale dynamical modes on the synoptic scale, but today's models may capture fast-evolving mesoscale convective complexes rather well. These improvements have been possible due to increased

Way Forward

- Complete draft
- Present at LWG
- Present at EUMETSAT workshop, 1st European lidar workshop, EUMETSAT conference
- Submit

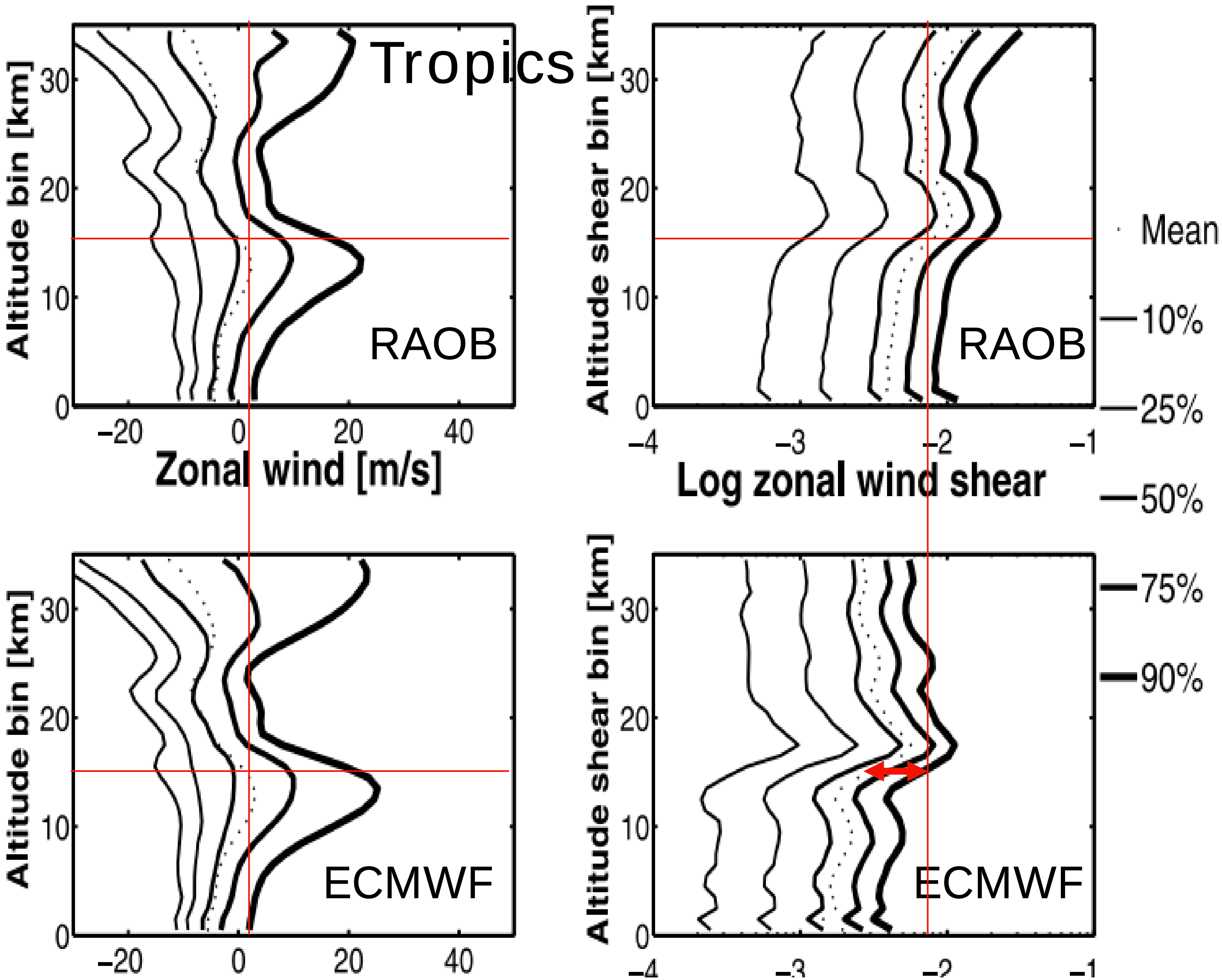
ECMWF OPS improves slowly

- Let's look at progress!
- 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



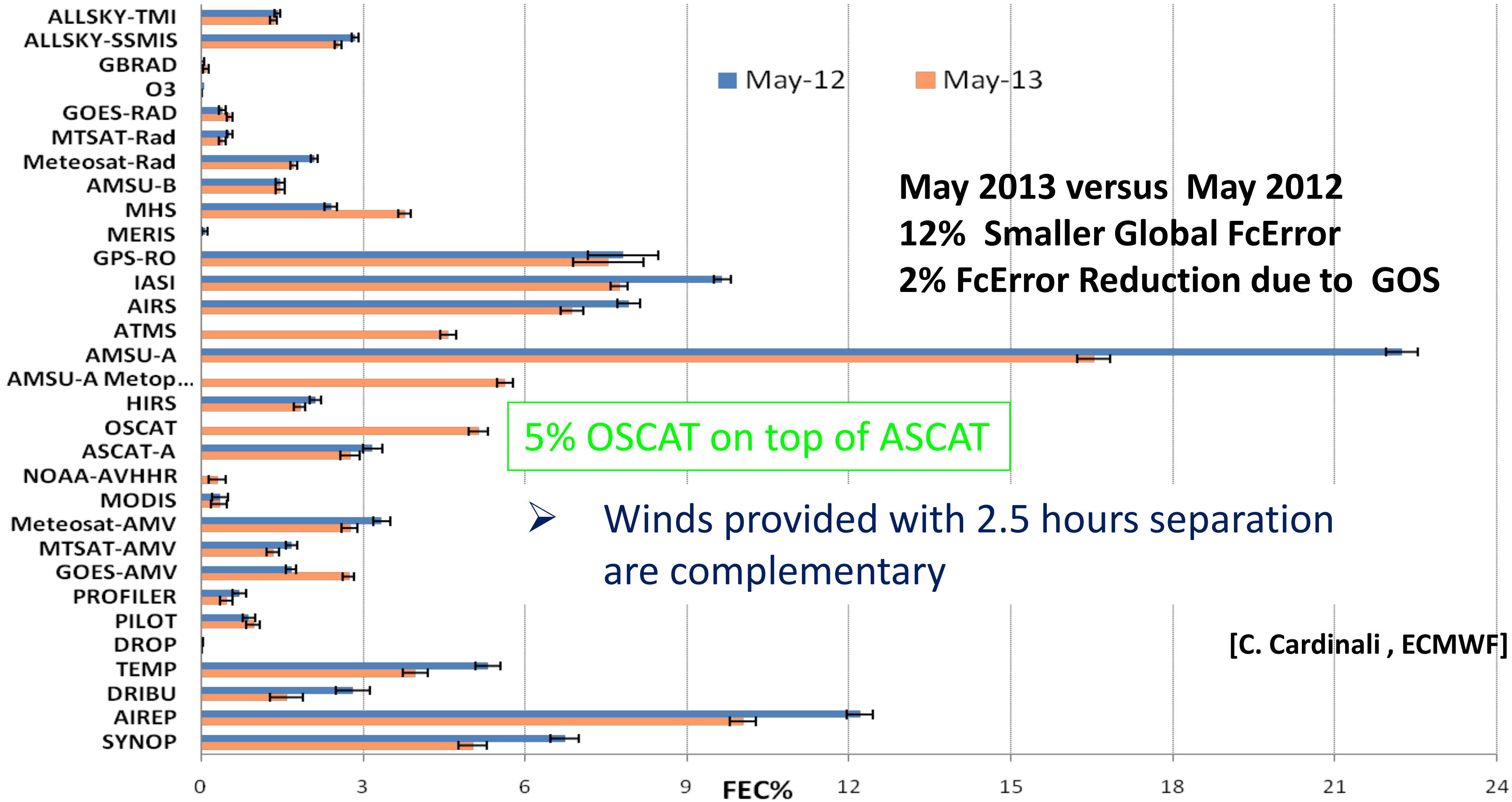
Hi-res radiosonde shear

- ✓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

Forecast Error Reduction of assimilated observations



May 2013 versus May 2012
12% Smaller Global FcError
2% FcError Reduction due to GOS

5% OSCAT on top of ASCAT

- Winds provided with 2.5 hours separation are complementary

[C. Cardinali , ECMWF]

Conclusions

- Aeolus will provide clear air winds
- Clear air constitutes 3/4 of the tropospheric volume
- Upper tropospheric winds are clearly lacking and therefore needed
- Global wind vectors every 3 hours would be needed at 100 km/1 km
- Accurate surface level winds and low-level AMVs do/will exist > 2020
- Existing upper air winds are relatively poor
- Cloud dynamics are poorly described in models, also in relation to aerosol (recognized as DS focus)
- Many potentially capable cloud/aerosol missions exists and may fly > 2020

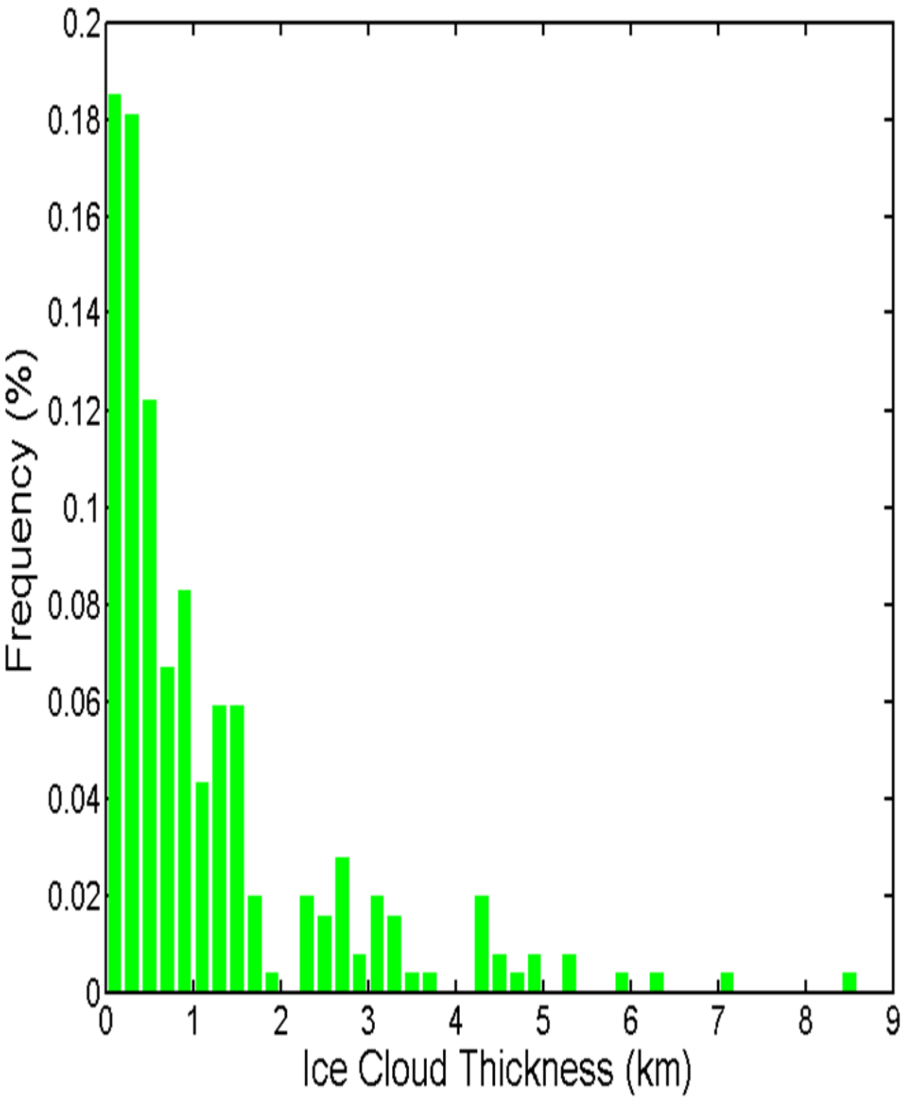
➢ The white paper will likely recommend enhanced capability of clear air wind profiles using molecular responses for operational NWP

➢ We will start a discussion on technologies, but with Aeolus we will have a space heritage soon hopefully!

Cloud heterogeneity (stratiform)

- Example radiosonde study: 1/3 of cloud layers are thinner than 400m
- Such layers cause non-uniform Mie backscatter and extinction
- Mean backscatter height will be uncertain
- Wind and wind shear will be biased (mean shear = 4 m/s per km height)
- Not sure about 3D heterogeneity of other particle distributions
- Advanced 3D spatial resolution and retrieval methods will be needed for any cloud wind sensor

➢ Molecular scattering is homogeneous and easy to control



Sun et al., 2014

How do clouds look like and behave?

- We propose a tandem imager convoy (stereo) to assess cloud dynamics and thermodynamics and seek design trade-offs by using CRMs
- Effectively addresses key priority M-G5, but NOT M-G1; needs different missions!
- Herewith we present a (limited) attempt at KNMI to illustrate aspects of improvements in cloud observation by the tandem configuration we propose

- Idea in ESA Atm. Convoy project in 2012 due.esrin.esa.int/stse/page_stse_project165.php
- Proposal EE9 in 2015 (rejected)
- Being proposed for H2020 in 2018

CRM work by:
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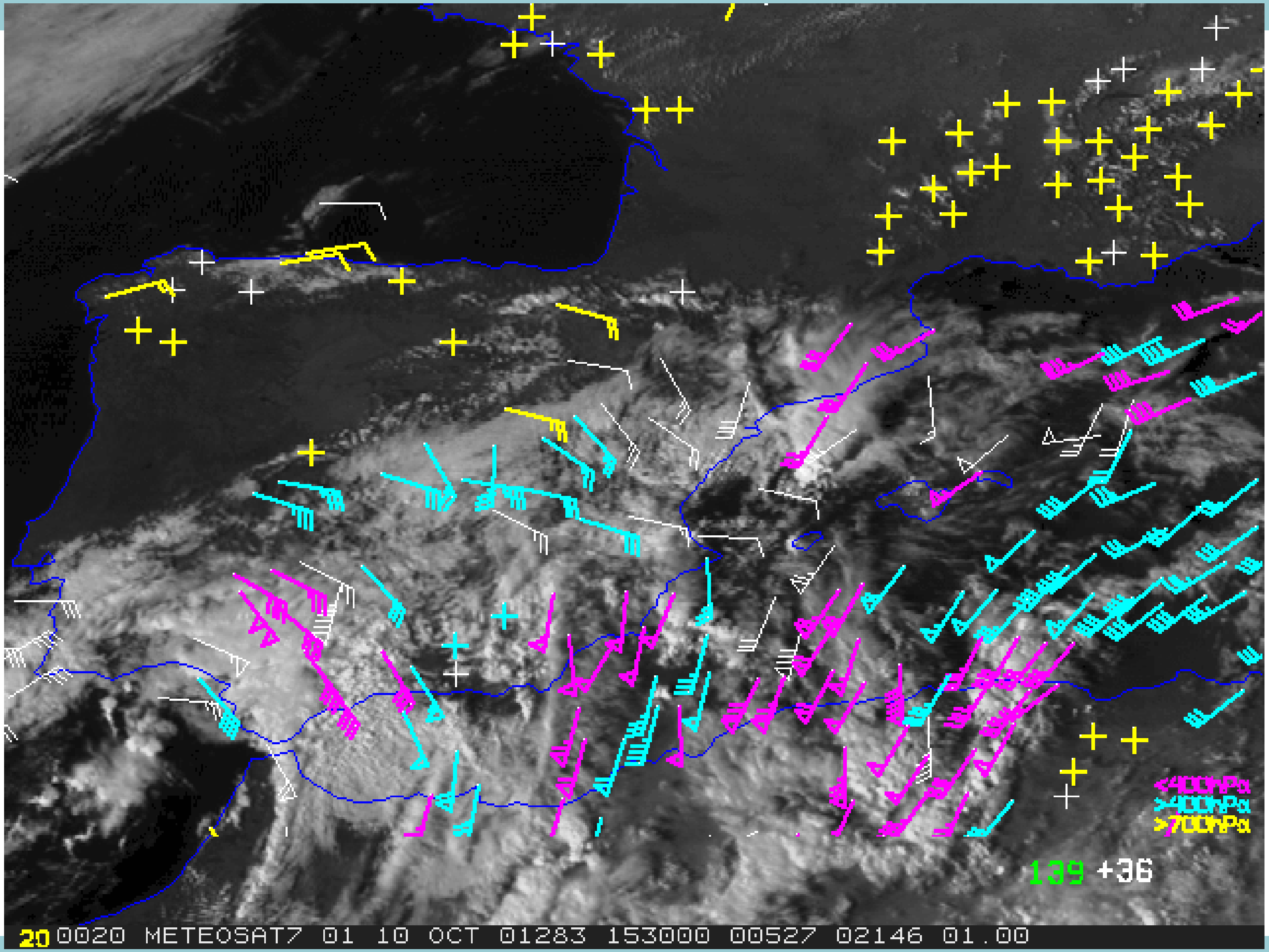
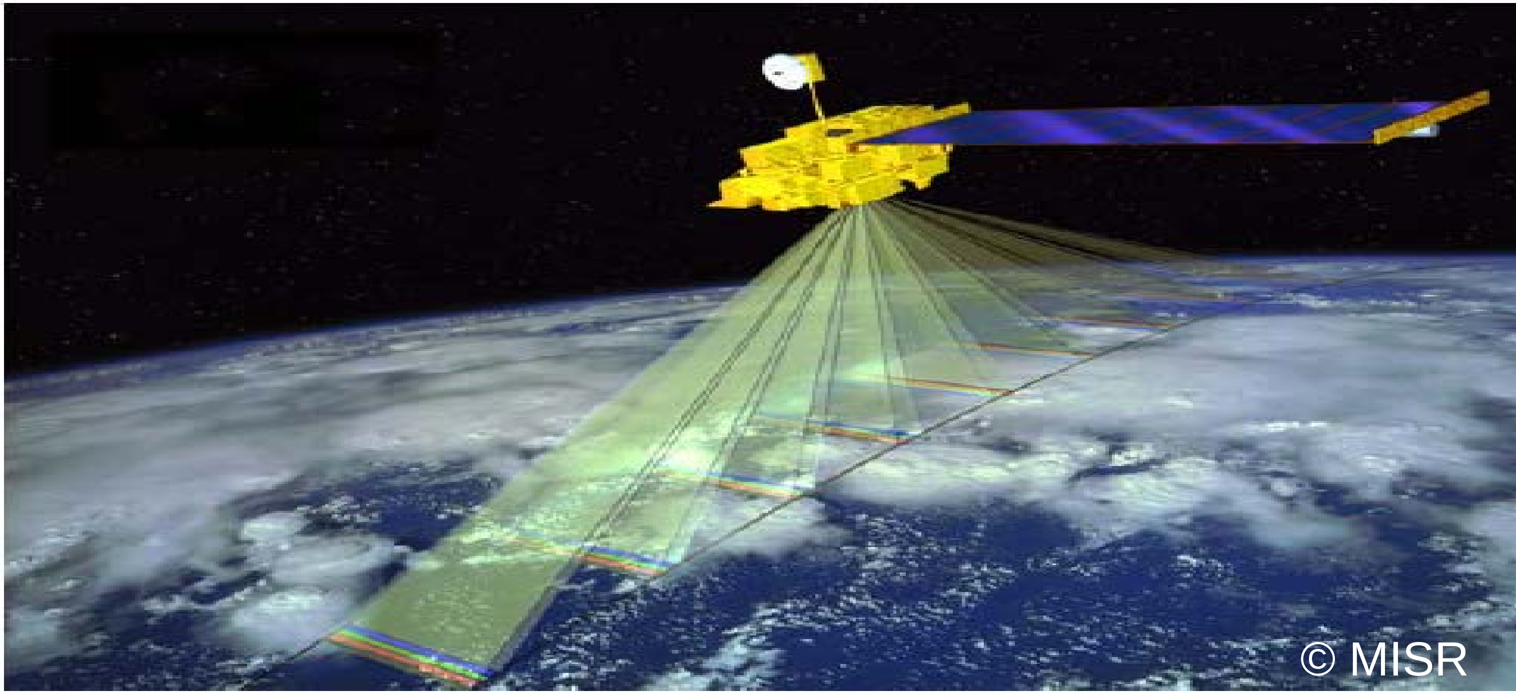
Priority	Gap ID	Application Description	Notes/Technique
Key	M-G1	Initialisation of NWP models, both regional and global. Particularly wind. Improved weather forecasts	Improved winds will in particular improve short-term (extreme) wind forecasts and tropical initialisation of convection.
	M-G1	Improved global and regional circulation models on both small and large scales; improved climate predictions.	The tropical circulation, convective processes and UTLS dynamics are poorly known and key in climate prediction. This is synergistic with the above application.
	M-G1	Quality Control and cal/val of satellite observations	Better use of existing satellite observations, particularly AMVs
	M-G5	Modelling of cloud-scale processes	Combined knowledge of cloud and wind to model convection; one of the forthcoming main challenges in NWP
Secondary	M-G4	Aerosol distribution modelling	Little 3D information due to horizontally uniform targets
	M-G5	Cloud distribution modelling	3D cloud structure (by geometrical techniques)

Summary of the primary mission objectives for the gCMW convoy in formation with MetOp-SG

Upper Cloud Motion Winds



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

Knowledge gaps in processes

- Atmospheric dynamics
- 3D turbulence (scales < 500 km)
- Vertical mixing (shear)
- Convection
- Cloud dynamics and radiation, precipitation
- Circulation

All these are interrelated, but each may need different missions to proceed