# Scientific preparations for Aeolus and Aeolus follow-on

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1. Optical and dynamical variability and Aeolus errors

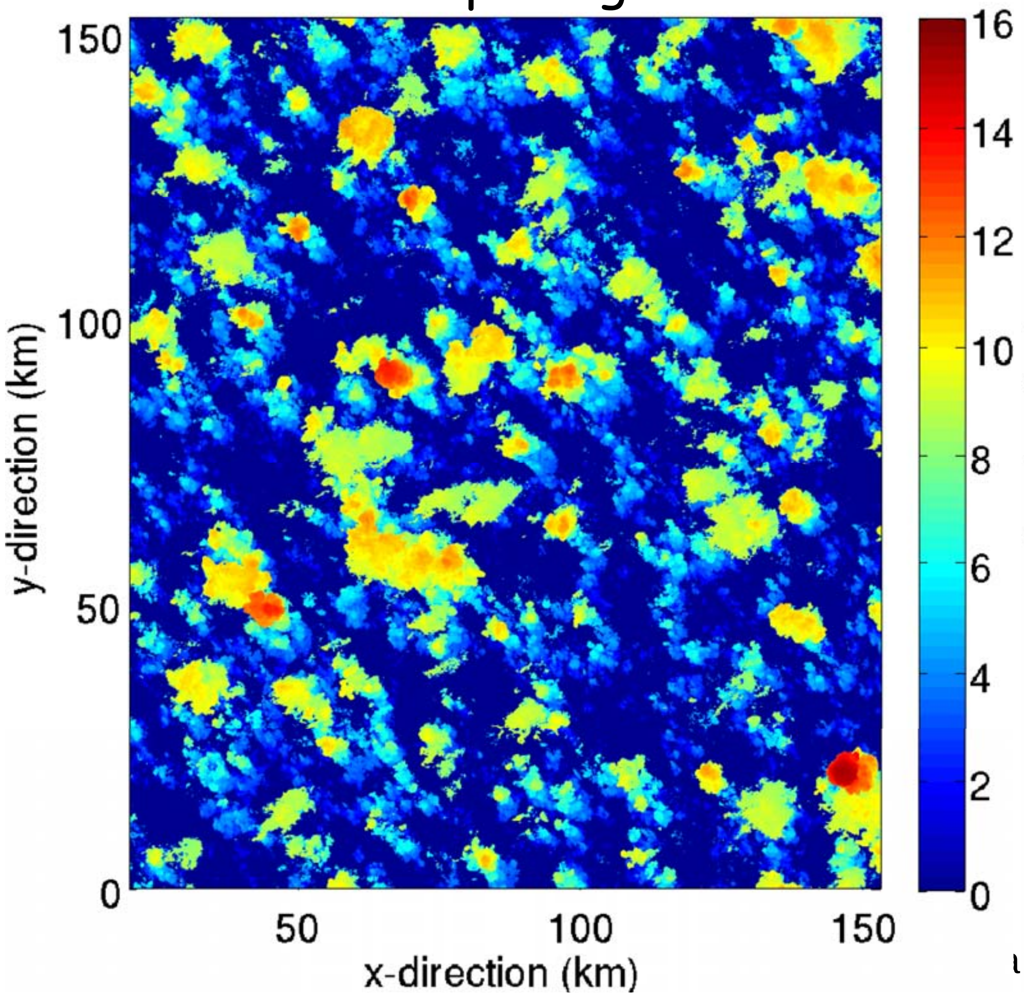
2. Studies for Follow-on Missions

3. Conclusions, Way Forward

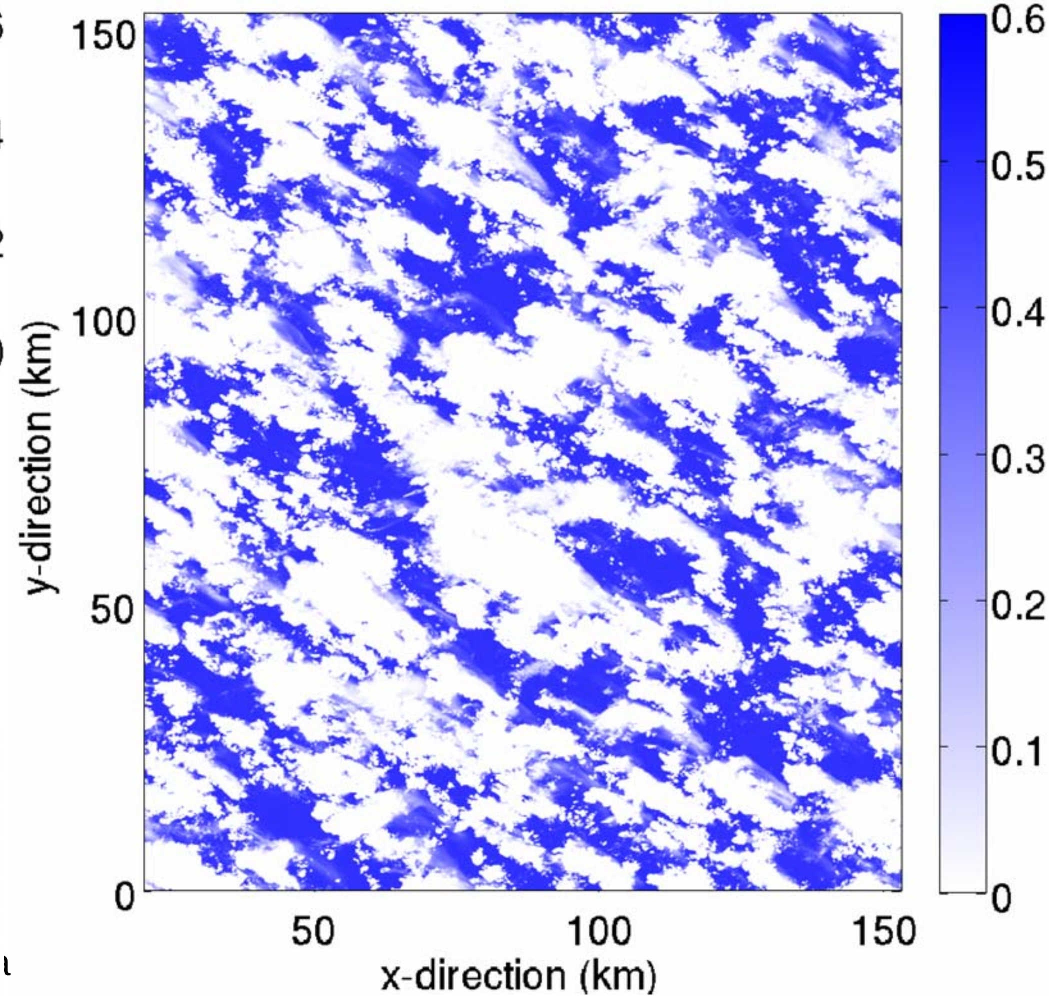
# Optical variability Cloud Resolving Model

- SAM; 154kmx154km; 100m; Khairoutdinov and Randall (2006)
- 14:00 LST tropical cloud field (no cirrus)

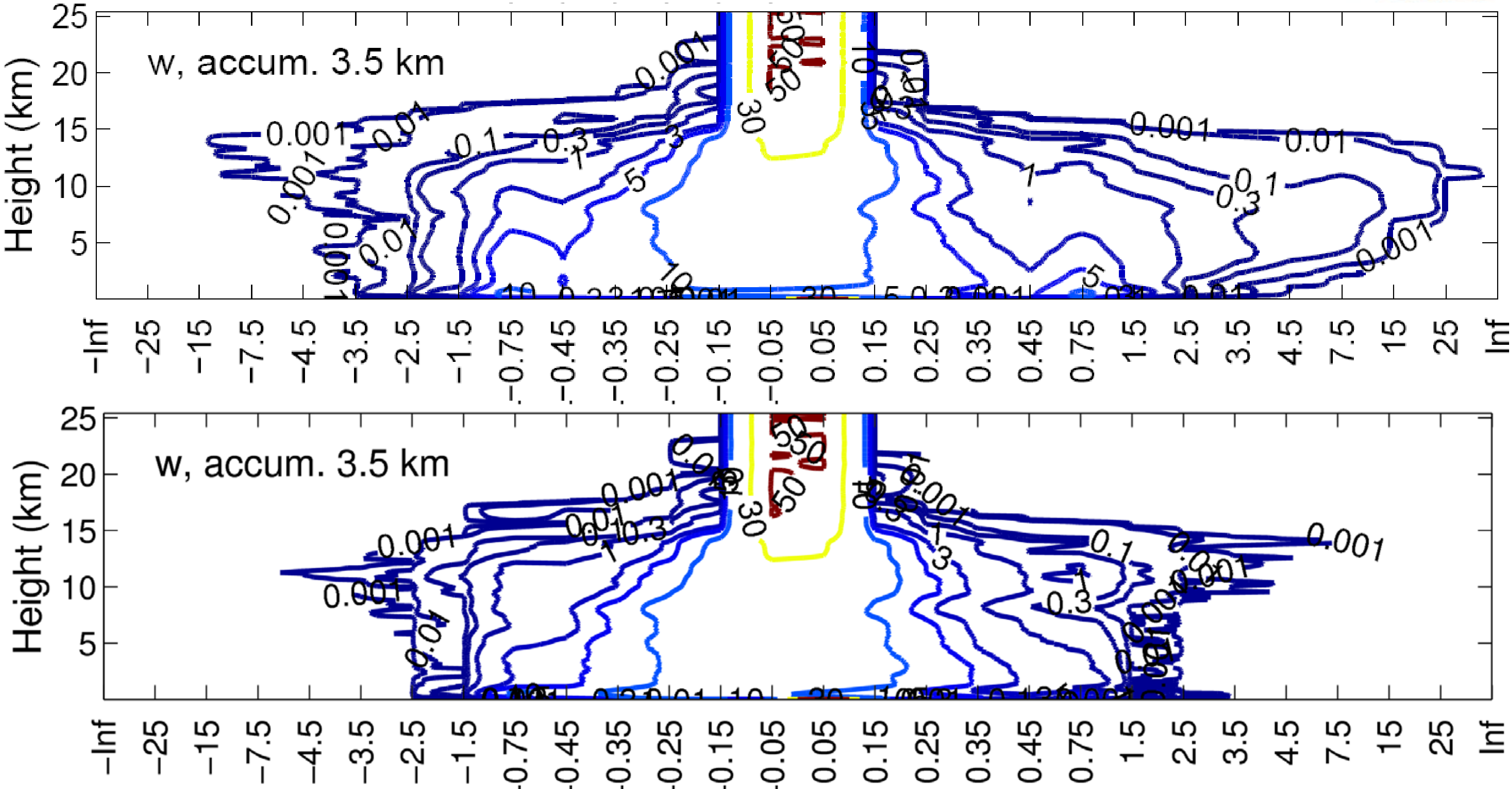
Cloud top height




Transmission at 37.5 degrees

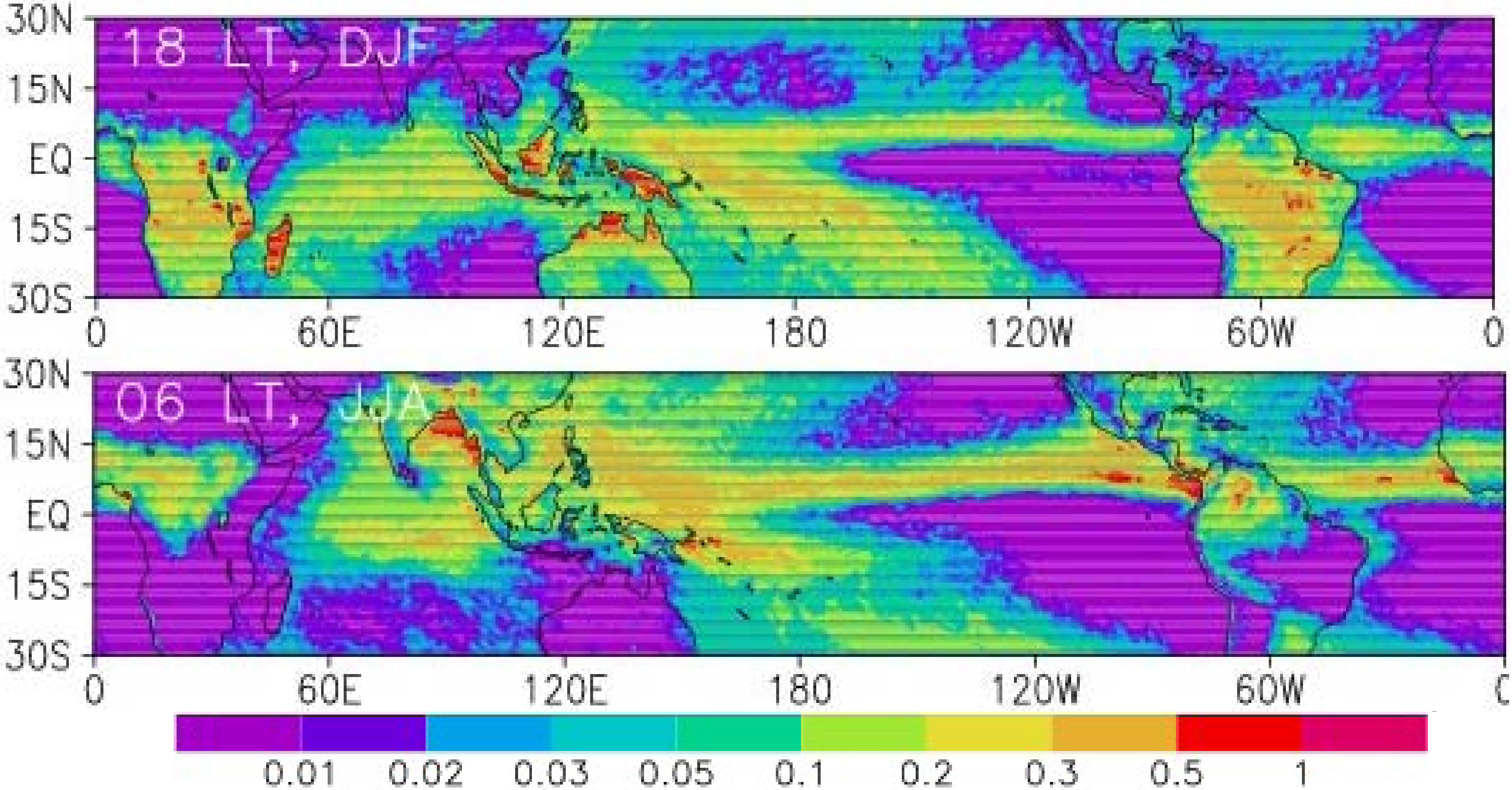


# Vertical wind histogram

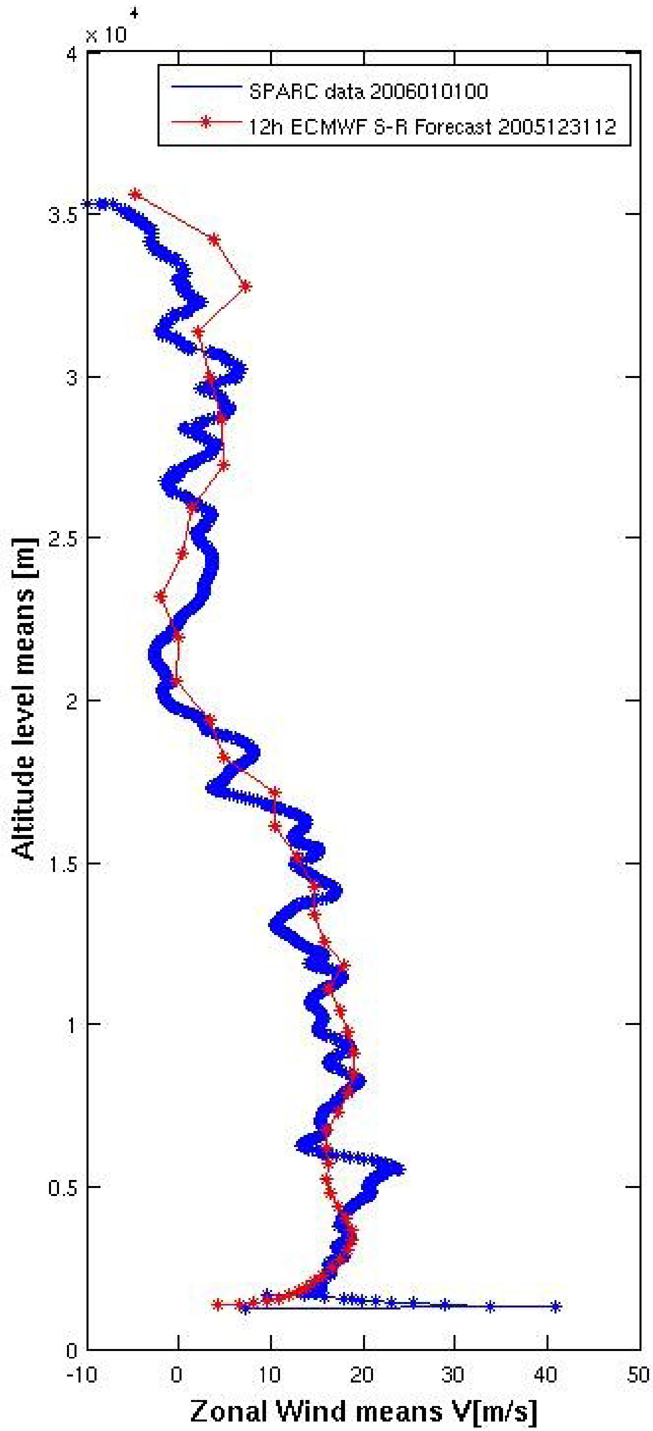



- Extreme vertical winds > 25 m/s occur in clouds

# Estimated % of vertical wind w > 1 m/s




- QC needs to flag these cases since w unpredictable



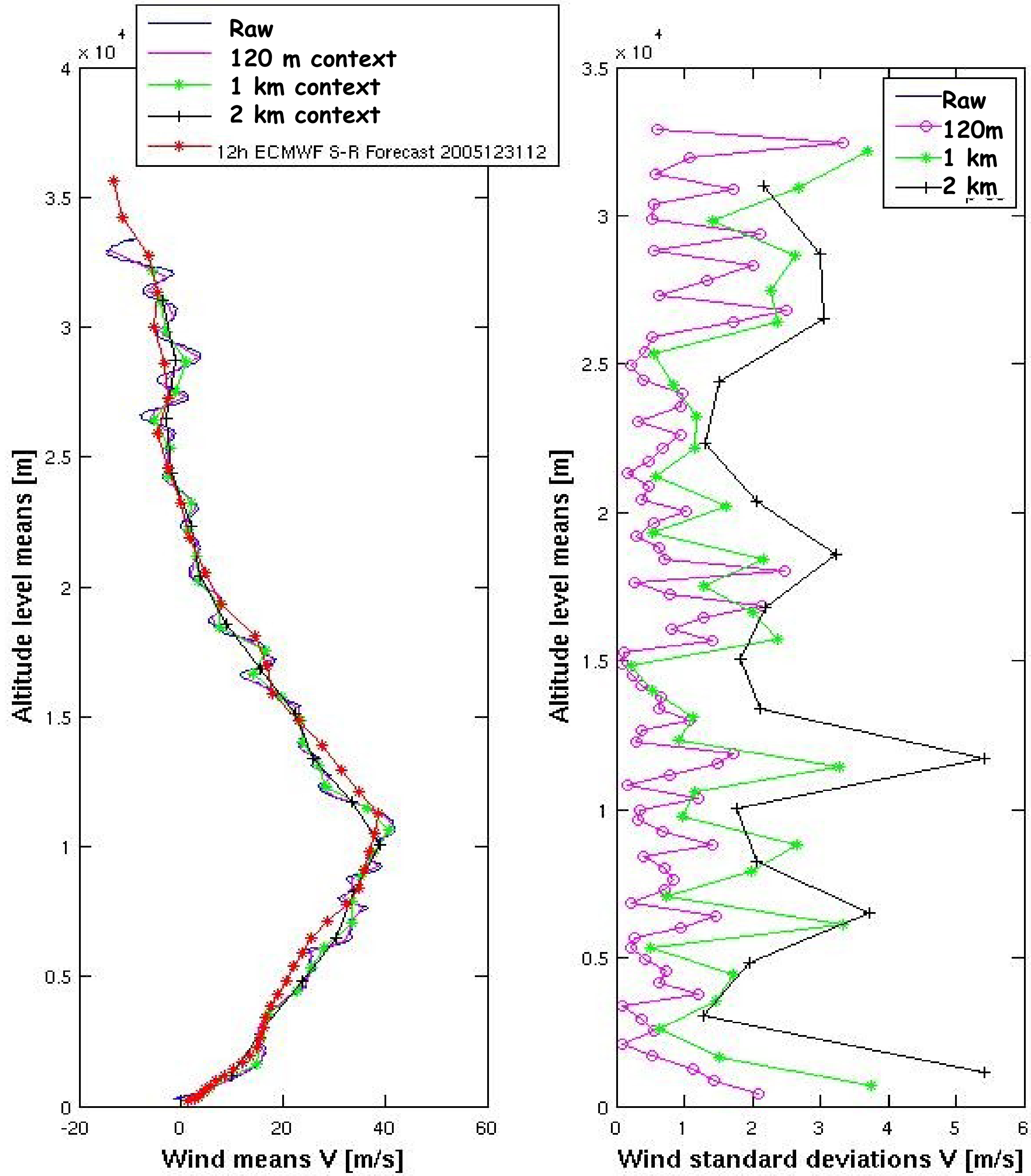

# Hi-res radiosondes

- Variability of the horizontal wind is large in the vertical
- What is the effect of this variability on Aeolus sampling ?

- ECMWF is smooth as compared to the hi-res radiosonde

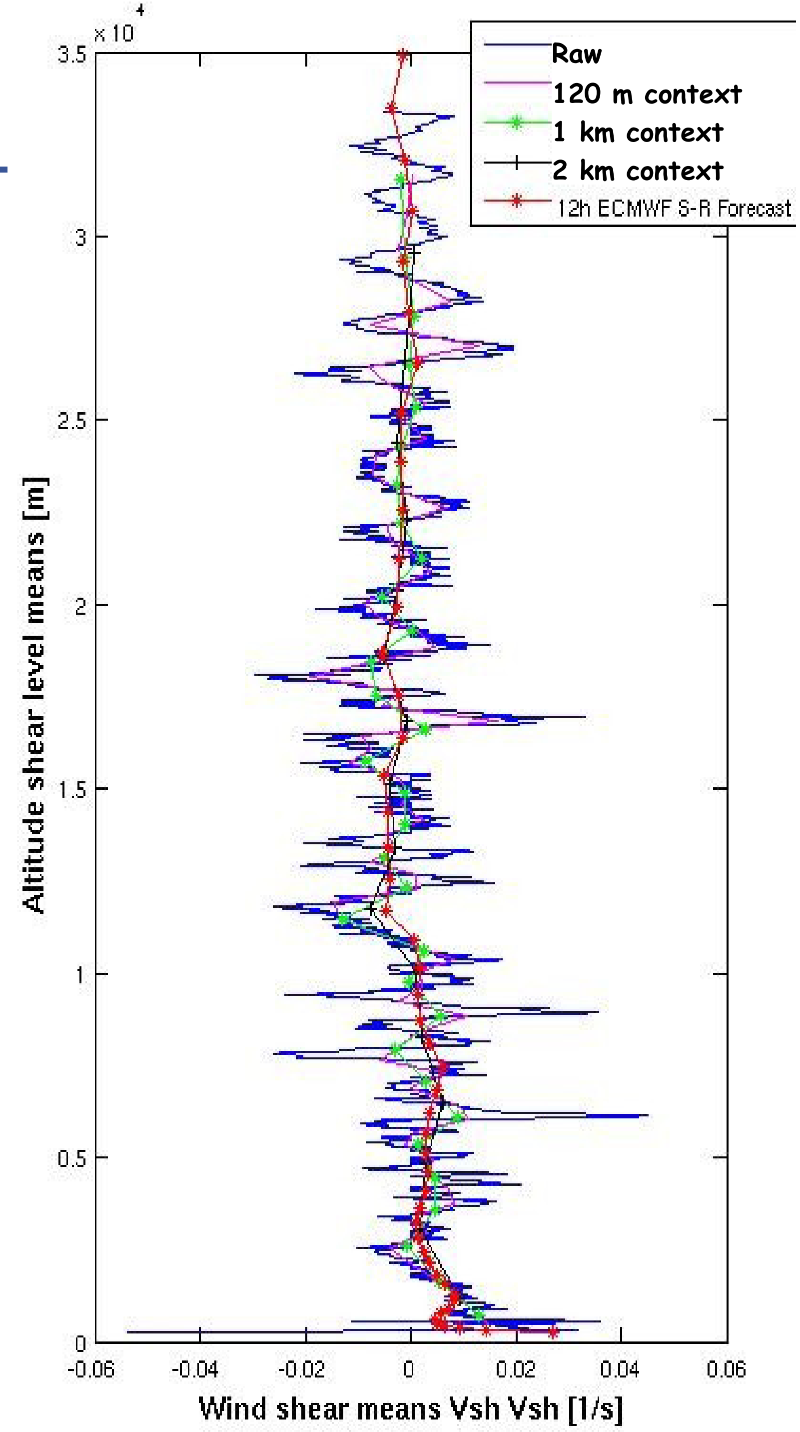
# Vertical Variability

- Example 90.6W 41.6N
- 2 km vertical context resembles ECMWF resolution
- Within 2 km context the variability of the horizontal wind is about 2 m/s
- Within Aeolus resolution (1 km) it is about 1 m/s
- This causes noise



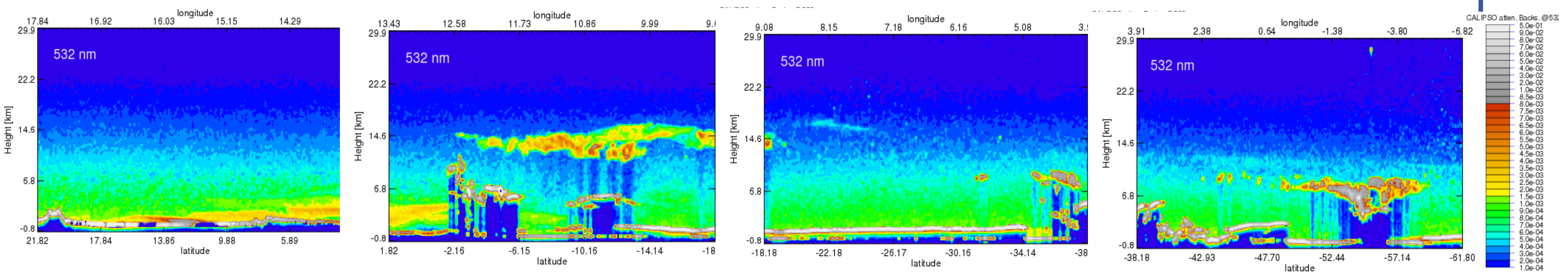
# Vertical shear of V

- Example 90.6W 41.6N
- ECMWF << 10 m/s per km
- RaSonde ~ 10 m/s per km with sharp peaks of 30 m/s per km
- Shear causes vertical height assignment problem in case of optical variability in the vertical
- Denser particle channel sampling in the vertical to obtain a heterogeneity measure or QC measures may prevent biases
- Cloud/aerosol (q) analysis TBDone

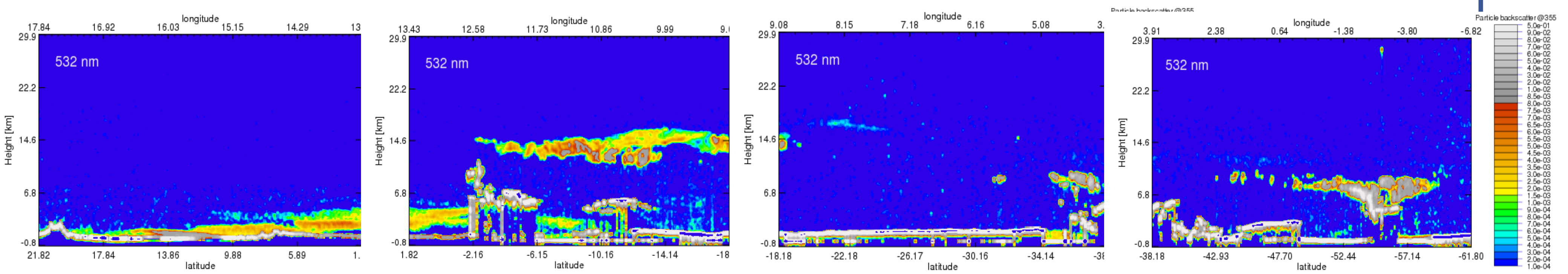


# CALIPSO β′ @532nm ⇒ β @355nm

CALIPSO β′ @532nm at 3300 m horizontal and 125 m. vertical resolution



β @355 nm at 3300 m horizontal and 125 m. vertical resolution

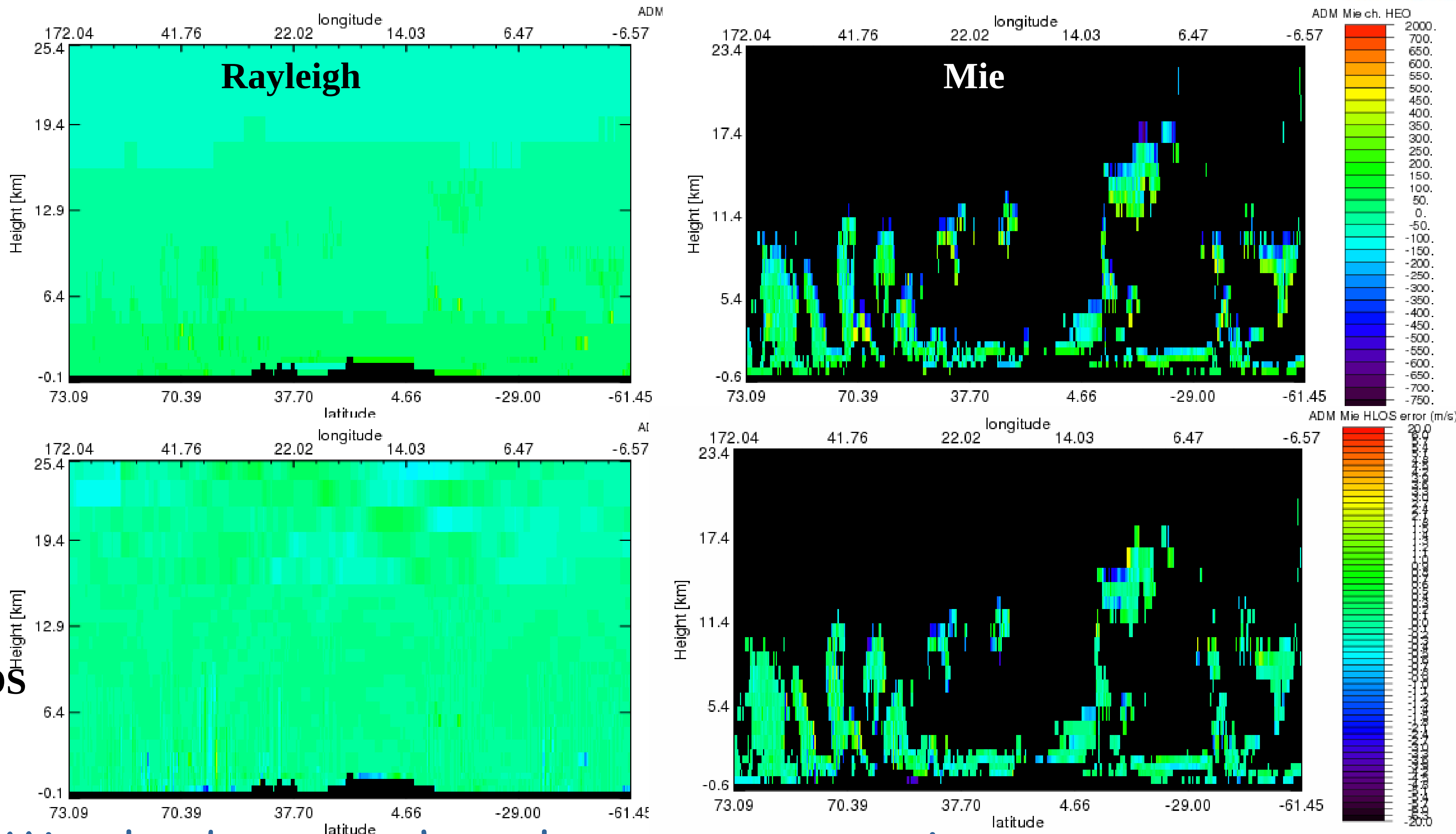


- Nighttime, since daytime is noisy; Aeolus is dawn/dusk

# ADM height and HLOS wind error

ΔH

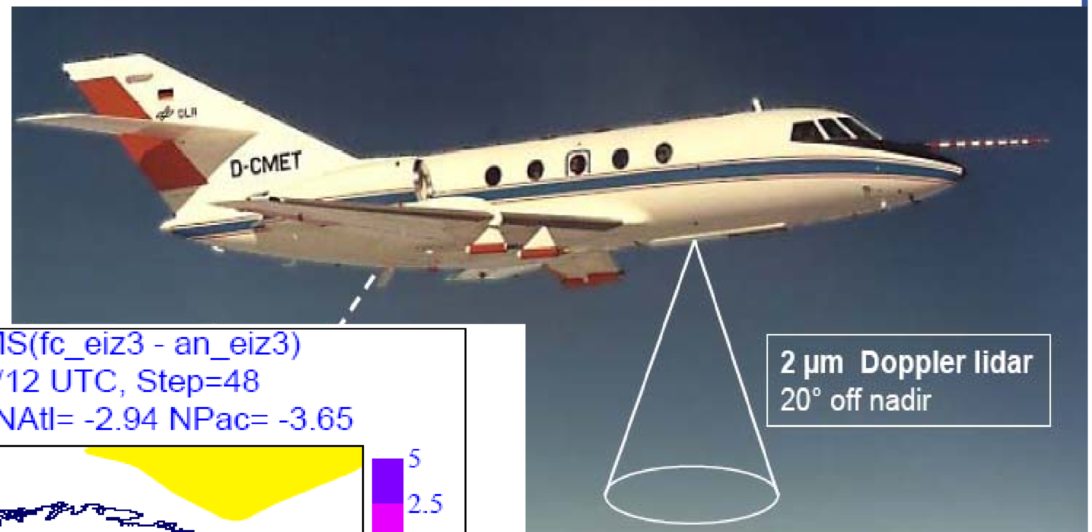
Δ HLOS

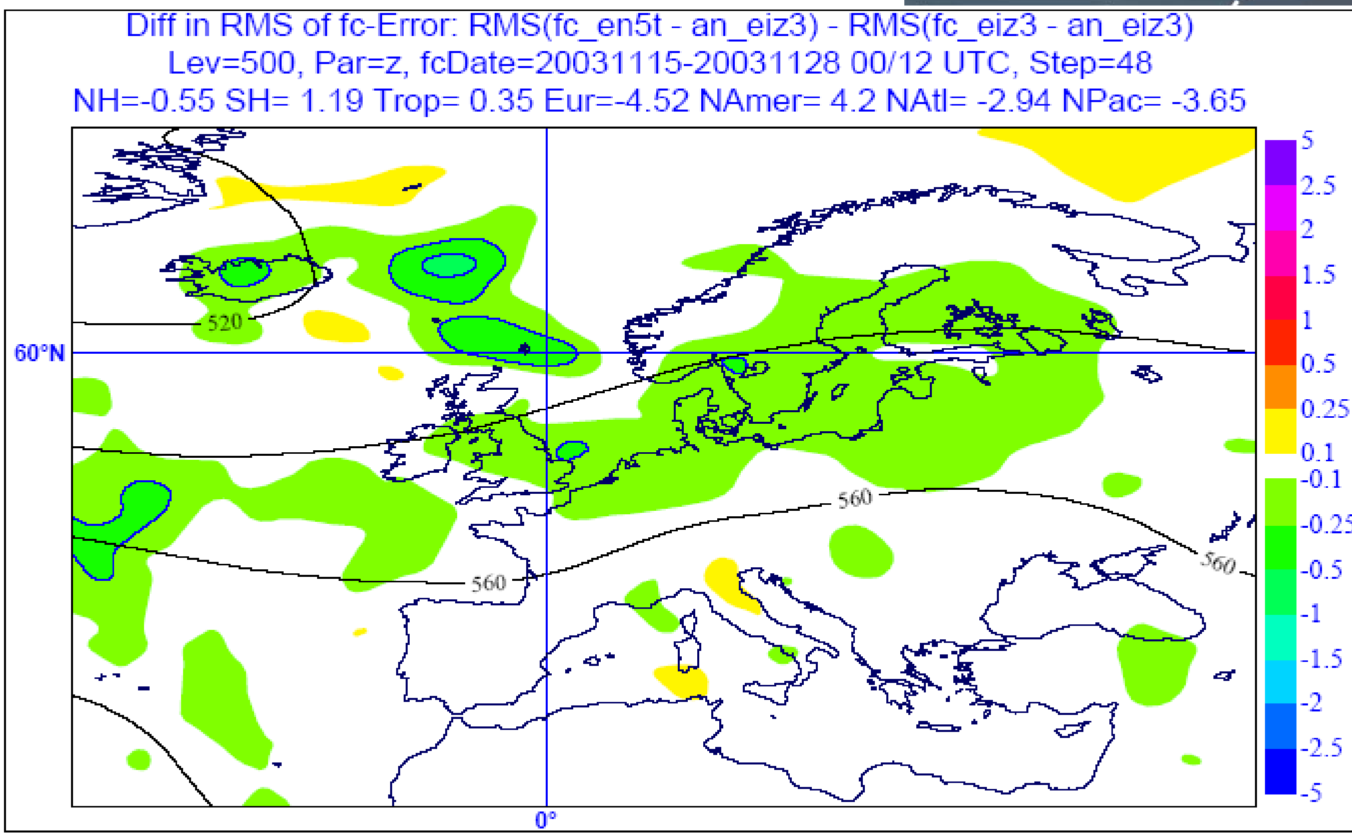



- Mie cloud returns have largest systematic errors
- Subsample variations not accounted for (ECMWF winds)

# Impact of DLR 2 μm DWL

ECMWF T511, two weeks
3000 DWL observations
**0.005% of all used observations**
Better winds than Sonde and AIREP
*Weissman et al, Aeolus Workshop*




First assimilation of real Doppler lidar observations (dense vertical sampling)

**Average 48 - 96 h forecast error reduction over Europe ~3%**

# Aeolus follow-on

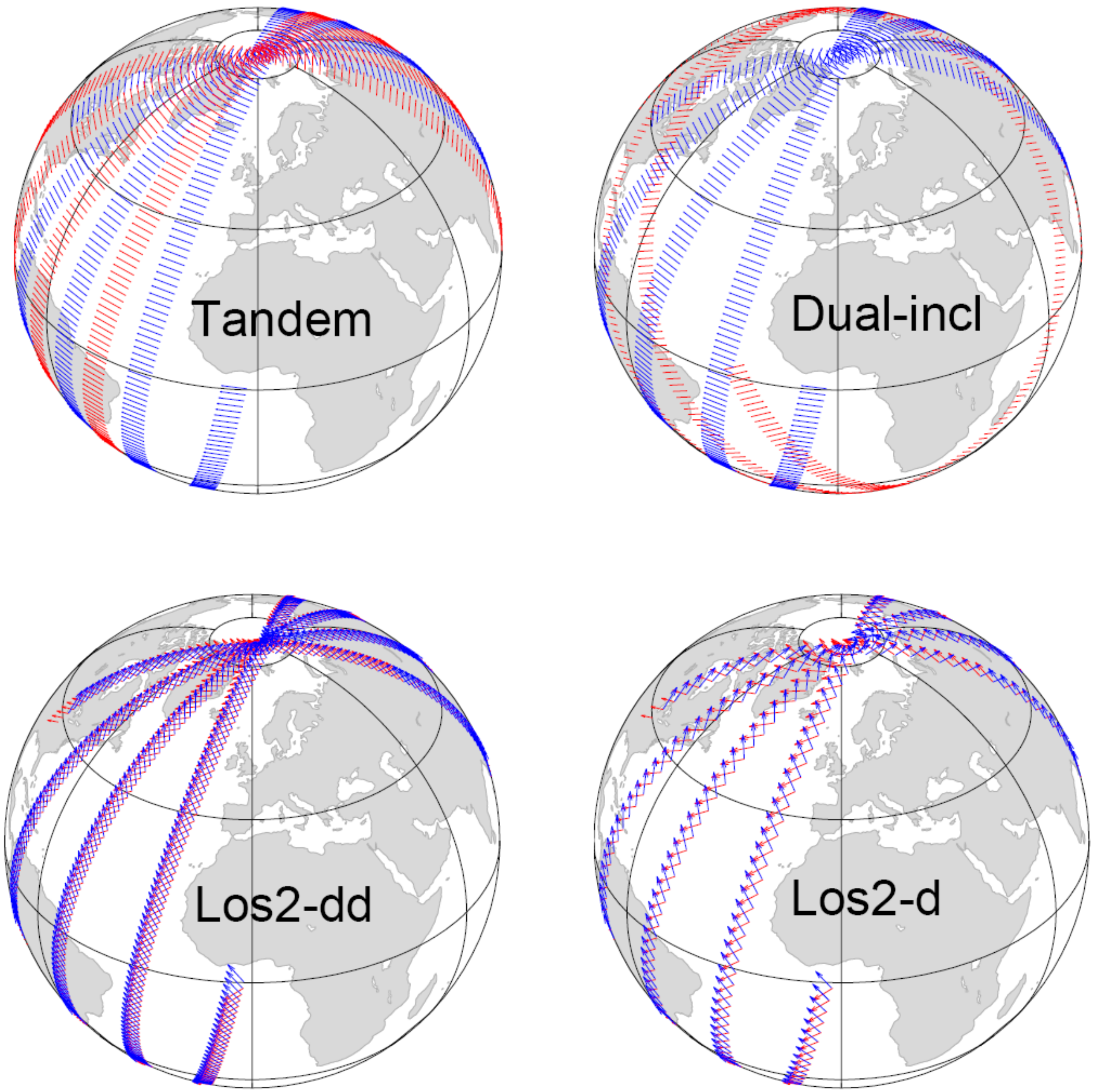
ESA-project PIEW:

**Prediction Improvement of Extreme Weather**

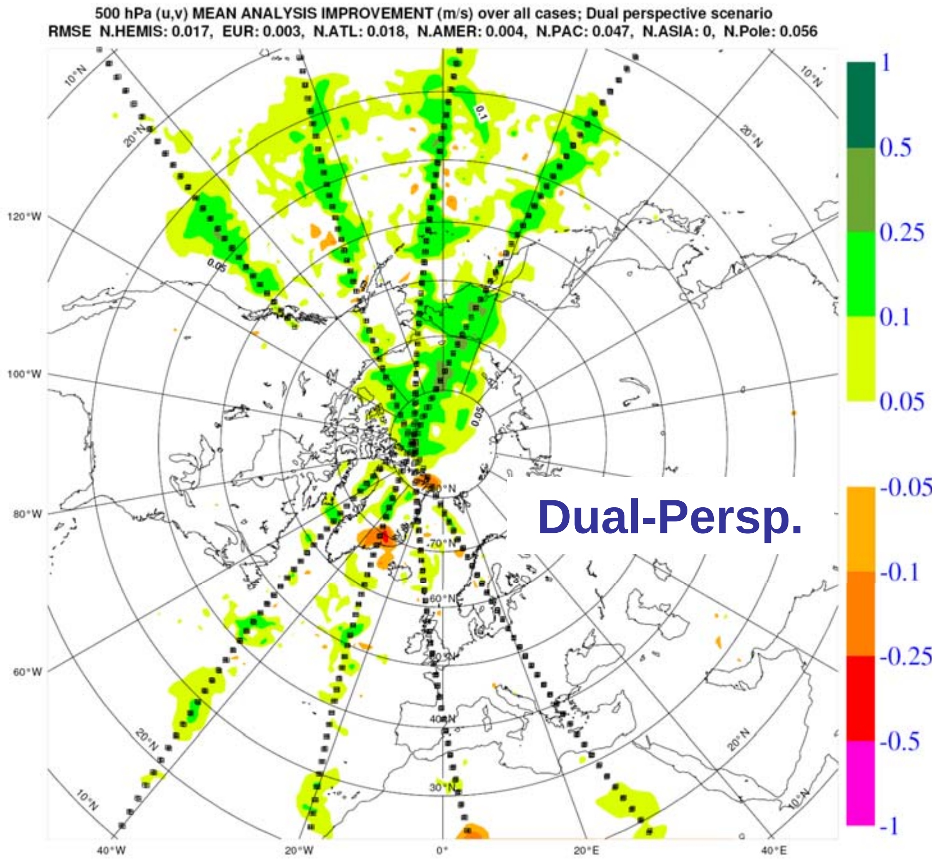
- Assess the added value of space-borne DWLs in NWP systems to enhance the predictive skill of high-impact weather systems
- What DWL coverage and quality is needed to capture rapidly-evolving sensitive structures, which are otherwise not observed?
- Capability requirements for ADM follow-on system

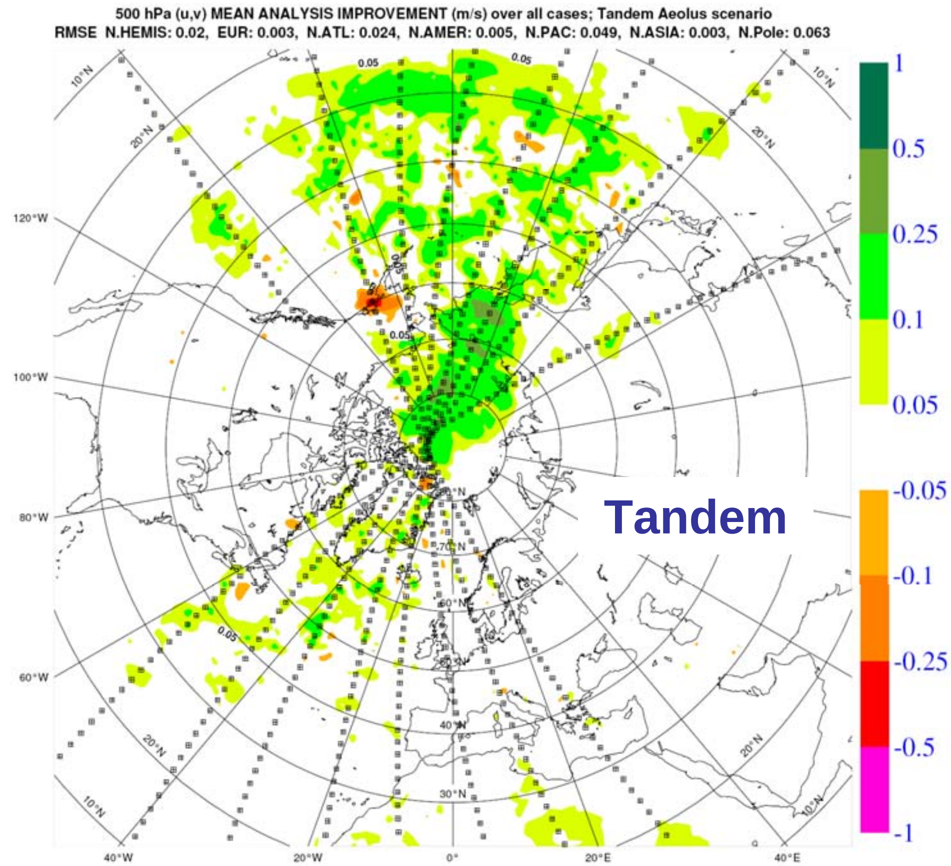
# Tested scenarios

- Tandem: 2x coverage
- LOS2-d: Aeolus tracks but vector
- LOS2-dd: double density along track of LOS2-d
- Dual inclination: 2 coverage Aeolus and vector in storm tracks



# Mean DWL Analysis Impact (per cycle)



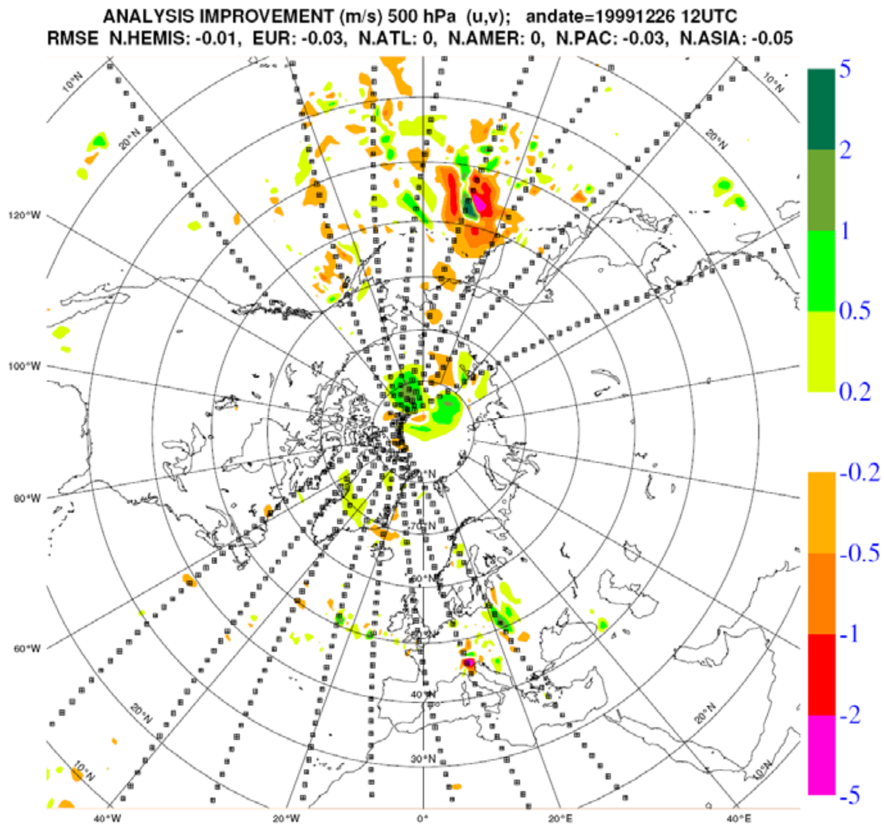




- Dual-perspective better than single LOS (Aeolus), but still gaps between tracks
- Tandem-Aeolus scenario has reasonably spatially uniform improvements

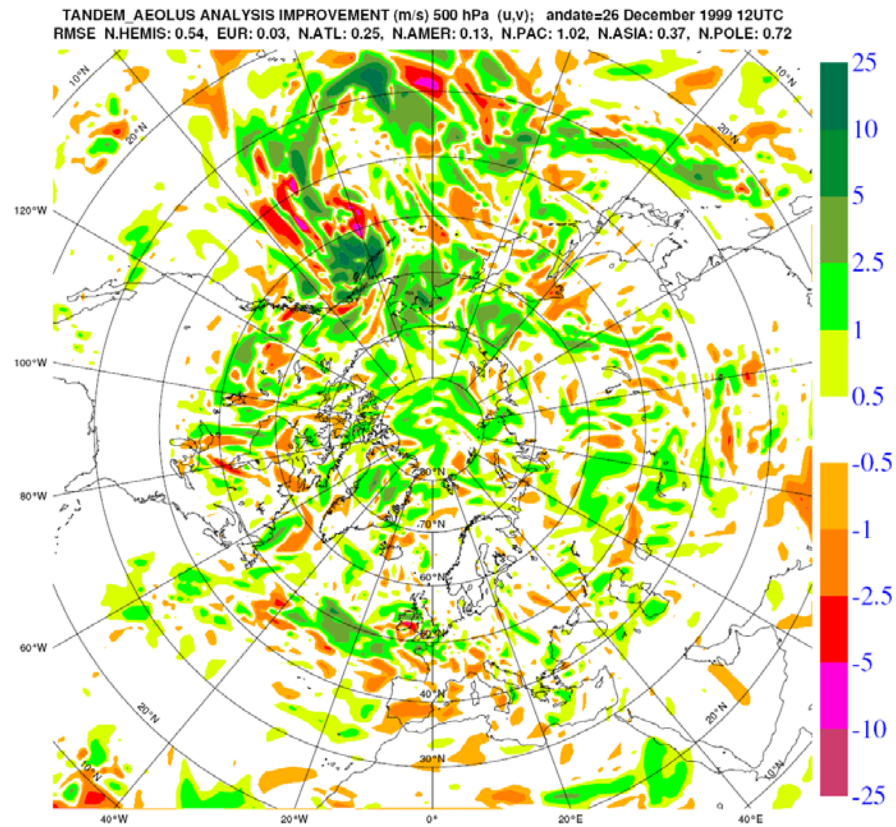
# Tandem-Aeolus impact on analyses

Analysis improvement at forecast initial time of '99 Christmas storm Martin (26 Dec 1999 12:00 UTC) for the Tandem-Aeolus scenario

***Single-time SOSE; 6 hours DWL obs.***




***SOSE – cycling; 84 hours DWL obs.***



# EPS storm probability forecast

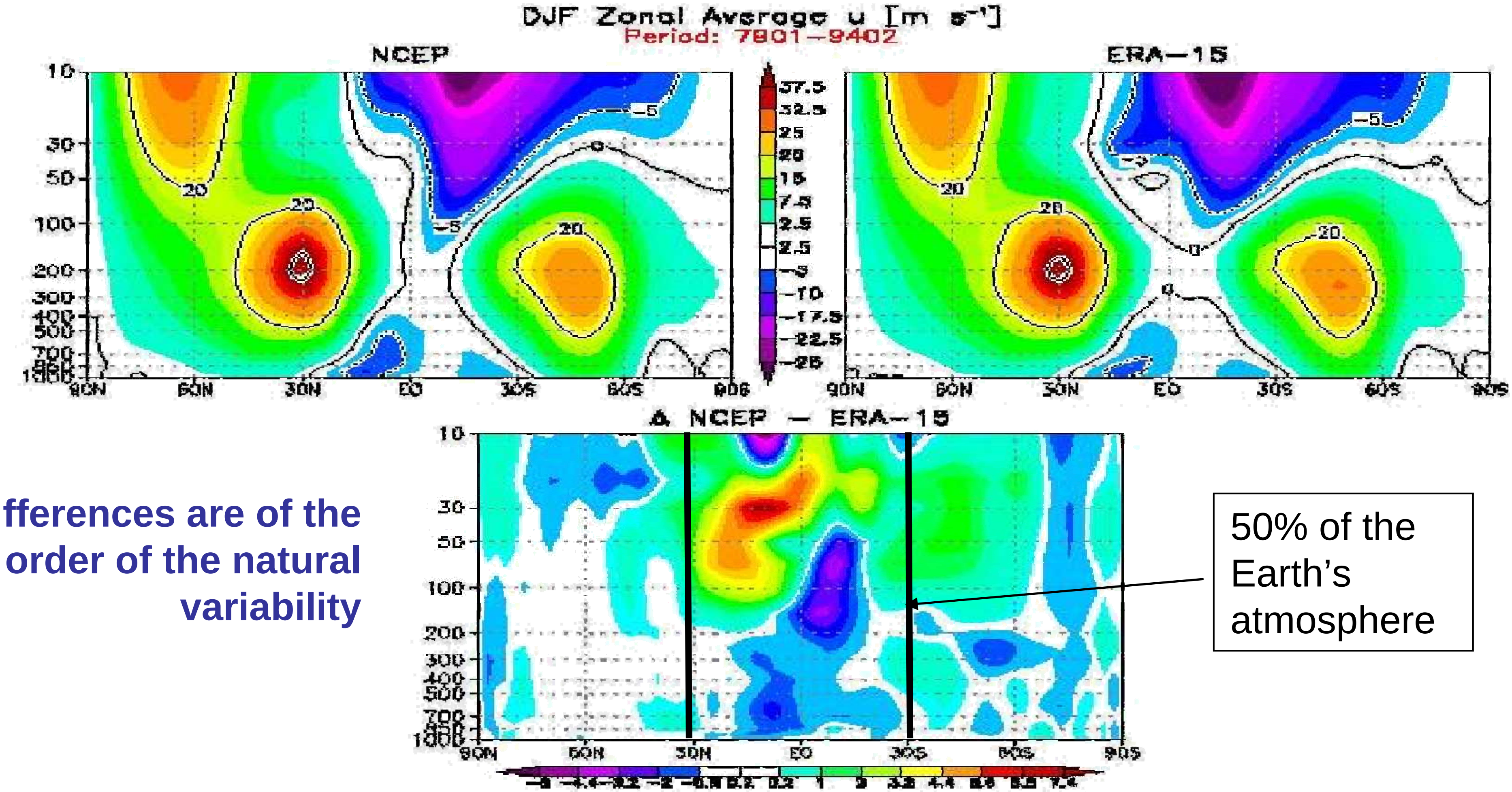
| *Verification 00 Z 28 Dec 1999 +54-h forecasts* | # Members of 50 ff > 10 Bft or PMSL < 980 hPa |
|---|---|
| NoDwl | 5 |
| DWL | 15 |
| Pseudo-truth | 38 |

- Three times more storm members in DWL (30%) than in noDWL (10%) over France and Gulf of Biscay
- DWL storm locations are better situated than noDWL

See Aeolus special issue in Tellus: Marseille, Stoffelen and Barkmeijer (3x)

# Tropics: Largest Uncertainties

**An example** (Kistler et al., 2001):
Zonal mean winds in NCEP and ERA-15 re-analyses




**Differences are of the order of the natural variability**

50% of the Earth's atmosphere

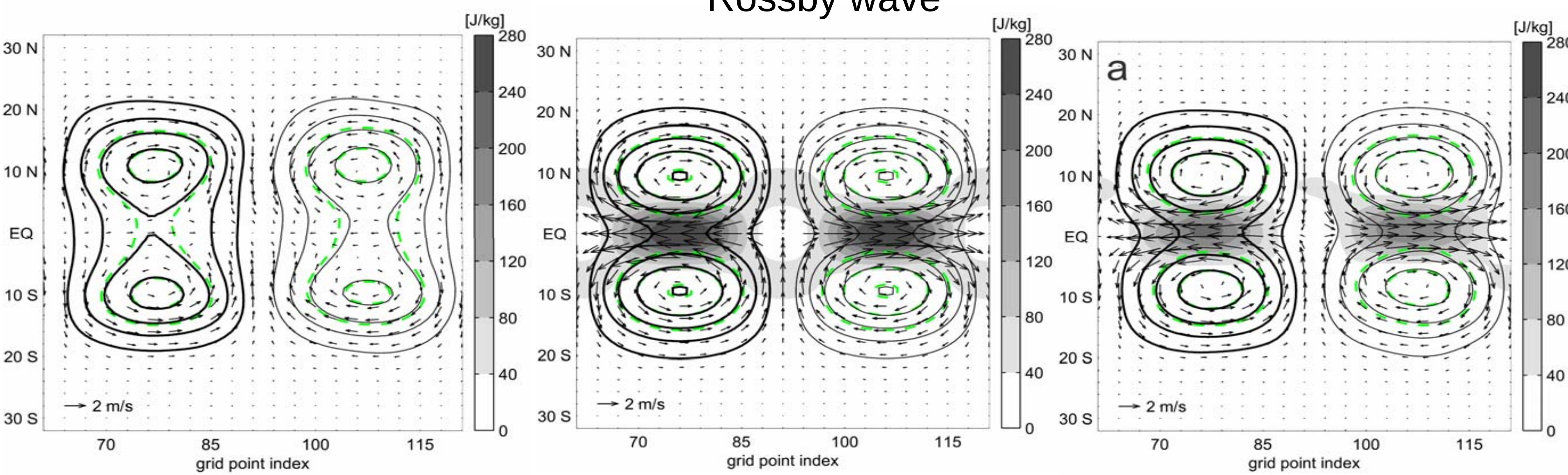
# Tropics:
# Potential impact of Aeolus winds

A shallow water model example (Žagar, 2004): Spreading of the observed information was modelled, largest weight given to Equatorial Rosby waves and large scales, Equatorial Inertial Gravity waves given little importance.

**Mass-field data**

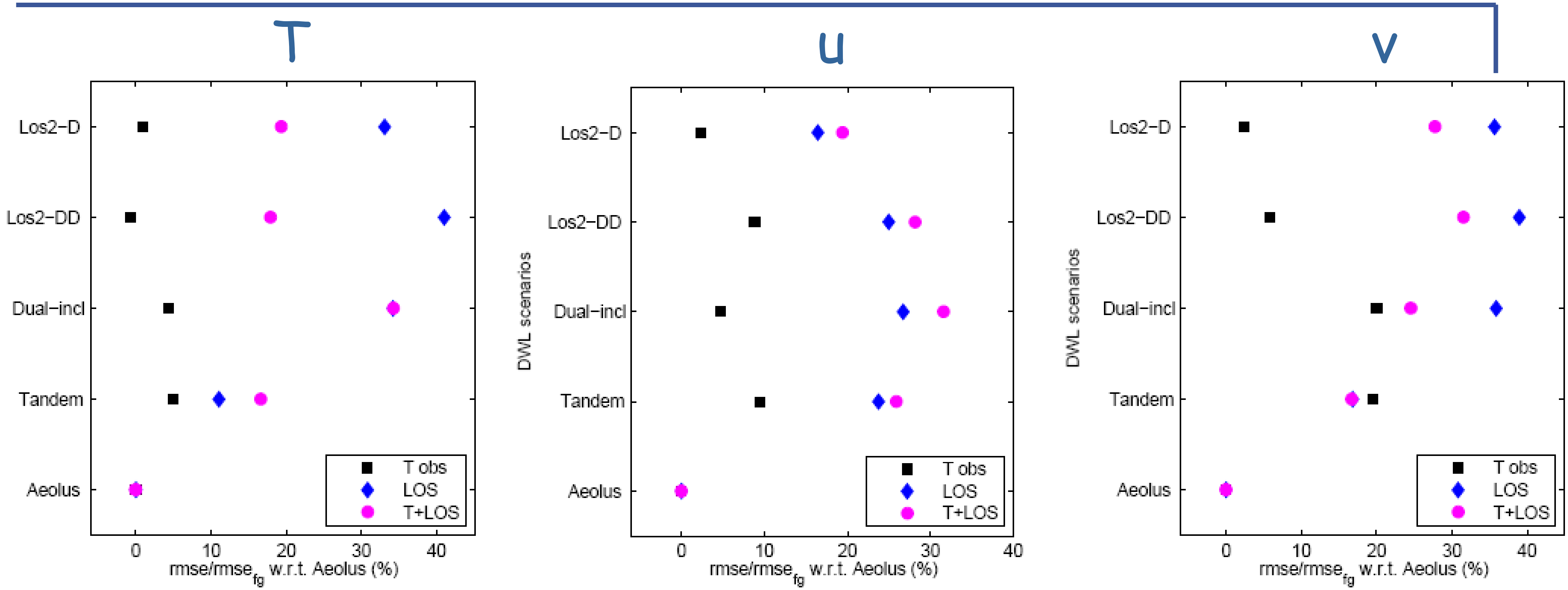
**"Truth":** equatorial Rossby wave

**ADM winds & mass-field data**

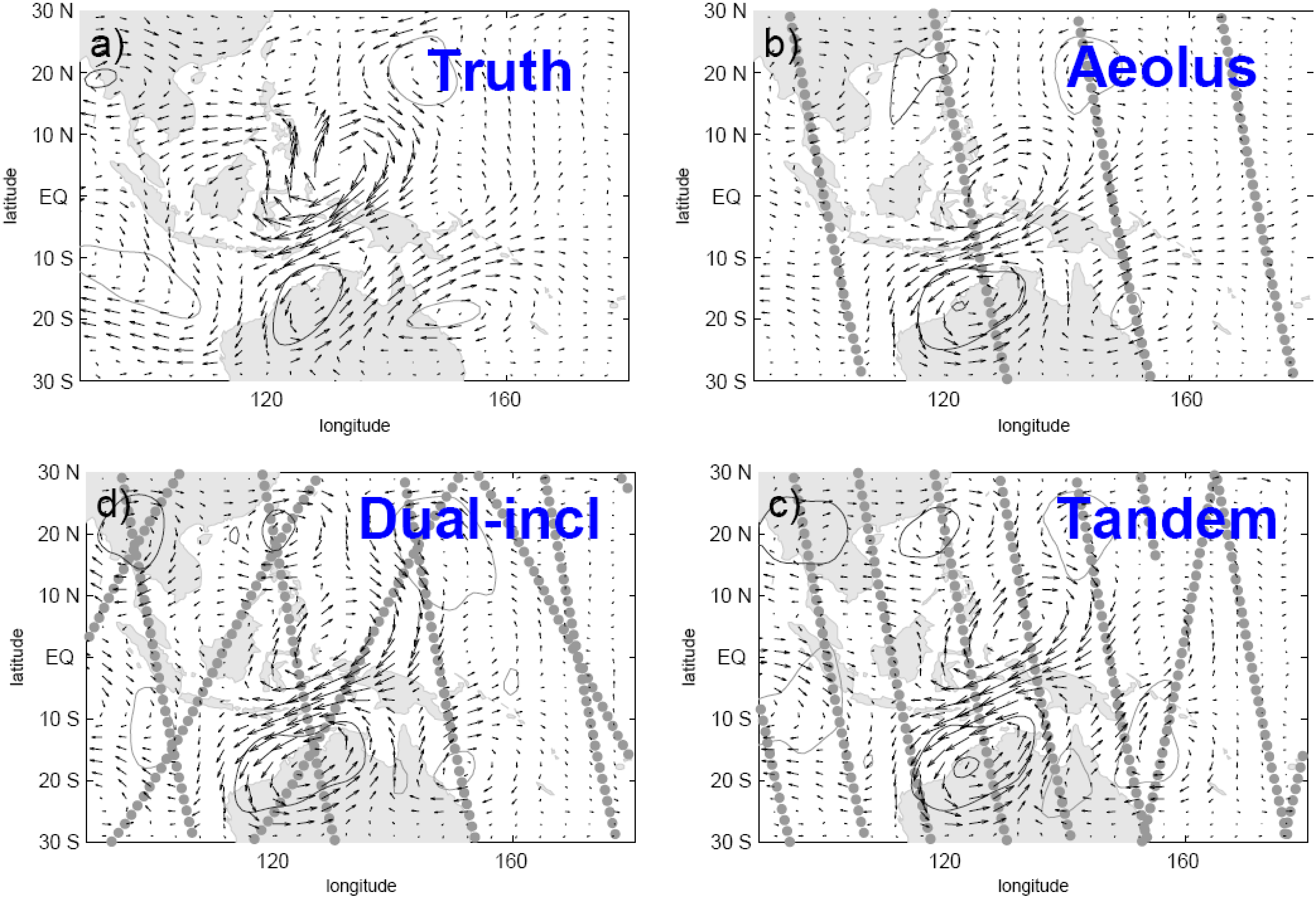



**Grey scales is kinetic energy, isobares are potential energy**

# 4D-Var




- Coverage beneficial for all scenarios; DD > D
- Dual perspective provides best v; dual inclination best overall score
- B error causes V, T conflict



a)
Truth
b)
Aeolus
d)
Dual-incl
c)
Tandem
30 N
20 N
10 N
EQ
10 S
20 S
30 S
latitude
120
160
longitude

# Summary for Aeolus Follow-on

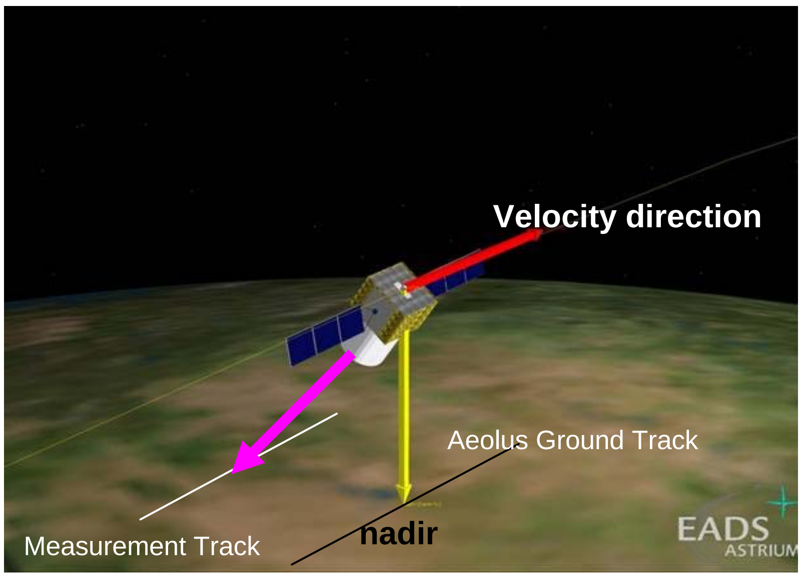
- Aeolus is expected to improve NWP analyses and forecasts in the tropics and extra tropics
- Aeolus improvements result from uniform sampling and provide a similar relative improvement in extreme and less extreme weather cases
- Increased coverage from two satellites is clearly beneficial
- Single perspective measurements appear effective in the extra tropics, but dual perspective measurements are advantageous in the tropics

➢ Aeolus follow-on is recommended with increased coverage and perspective

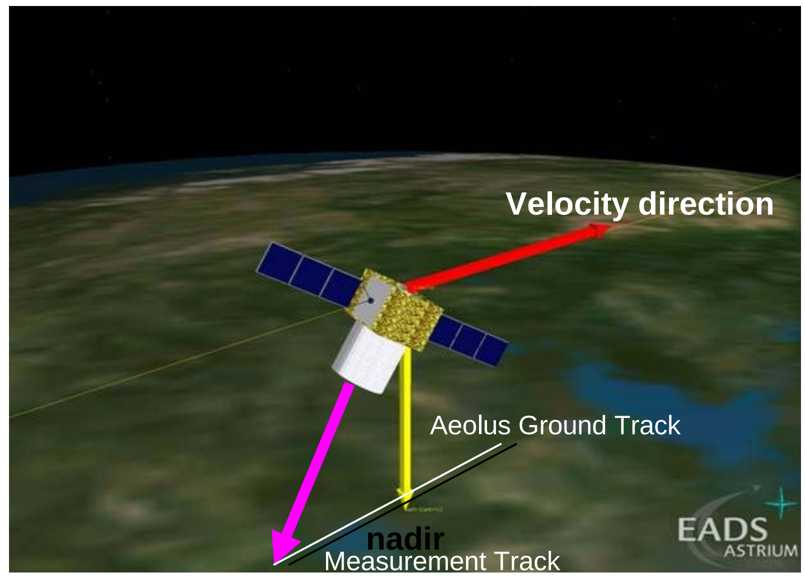
# Follow-on: Second Line of Sight

A modification of the Aeolus concept to sense "backwards" along the track is possible using most of the same building blocks as the existing design

- *Receiver would need to operate at different multiples of Free Spectral Range*
- *Some changes to thermal design of spacecraft*
- *Pointing requirements not significantly more stringent than for Aeolus*



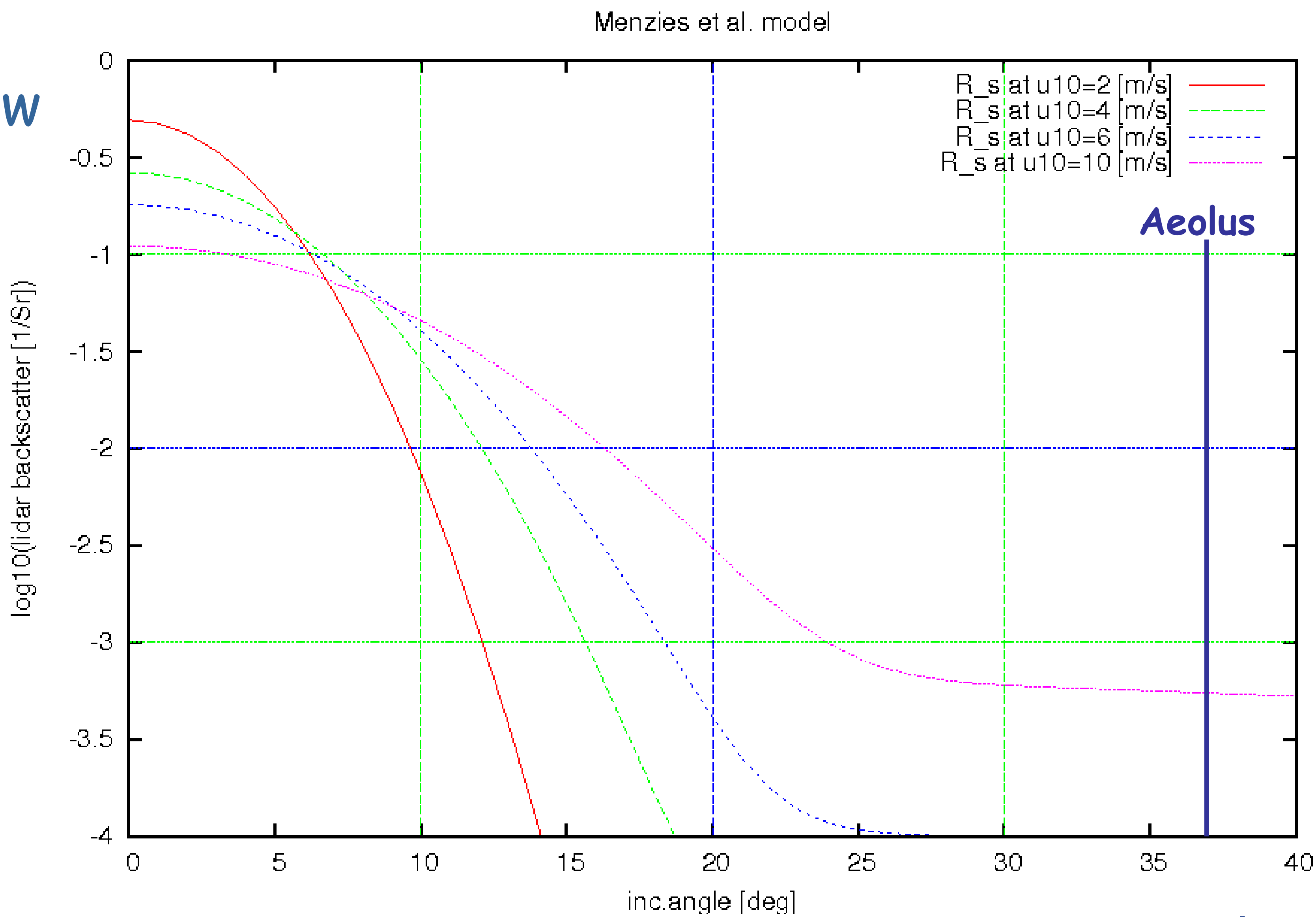

Nominal (sideways) Aeolus observation scenario




Orthogonal (backwards) Aeolus observation scenario

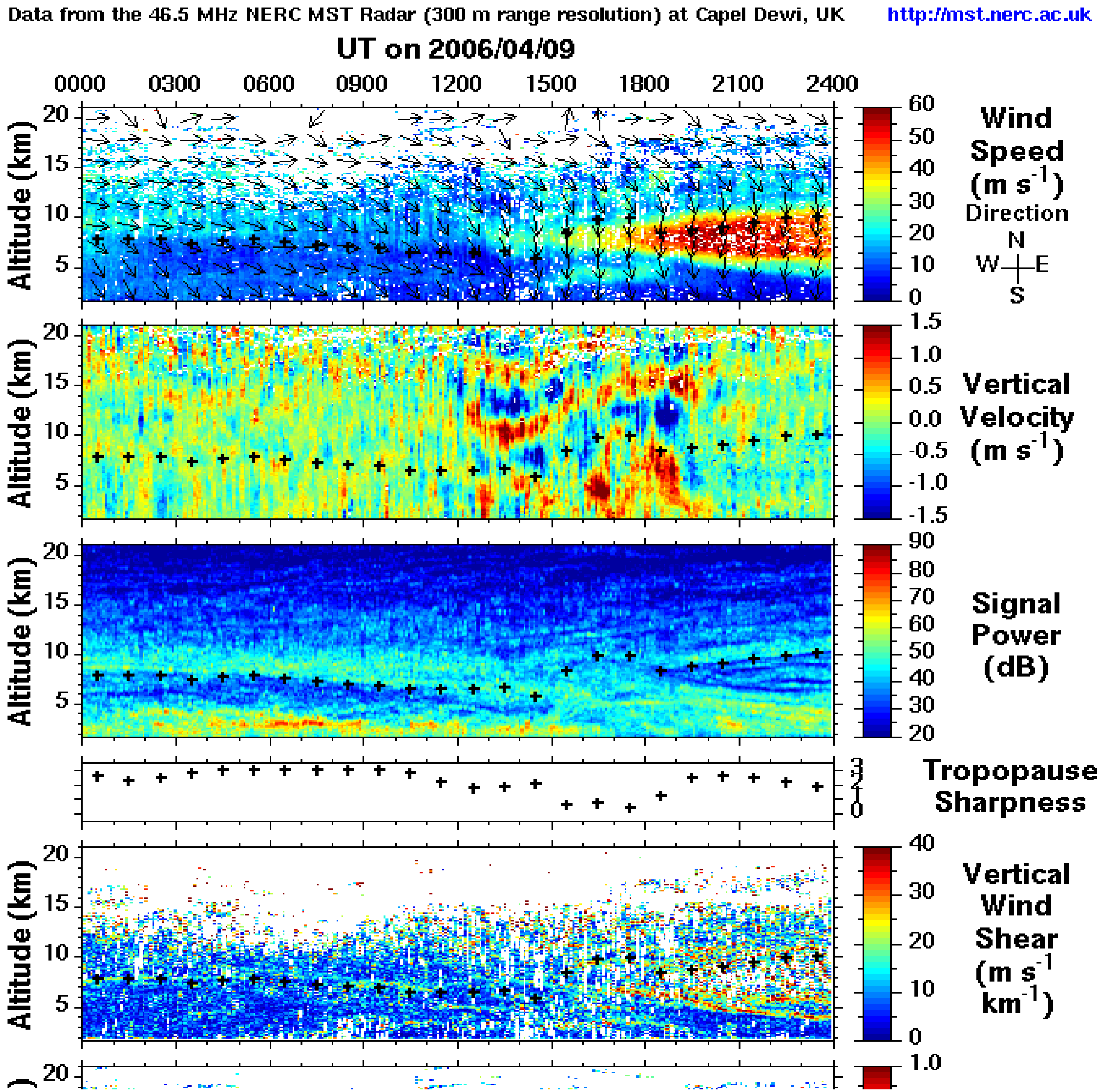
# Ocean calibration in WVM

- Not at low winds
- Ocean moves and drifts

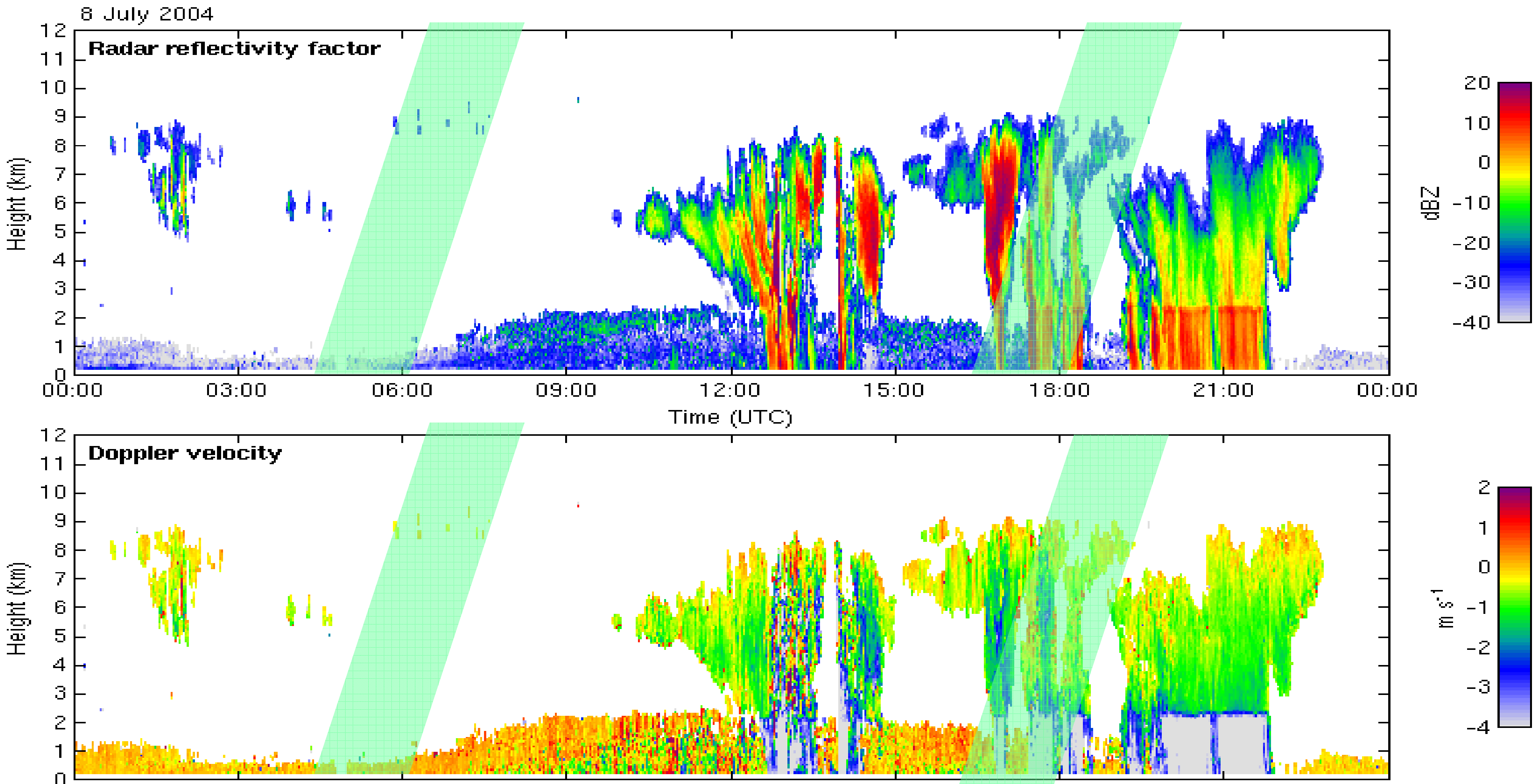


# Variability

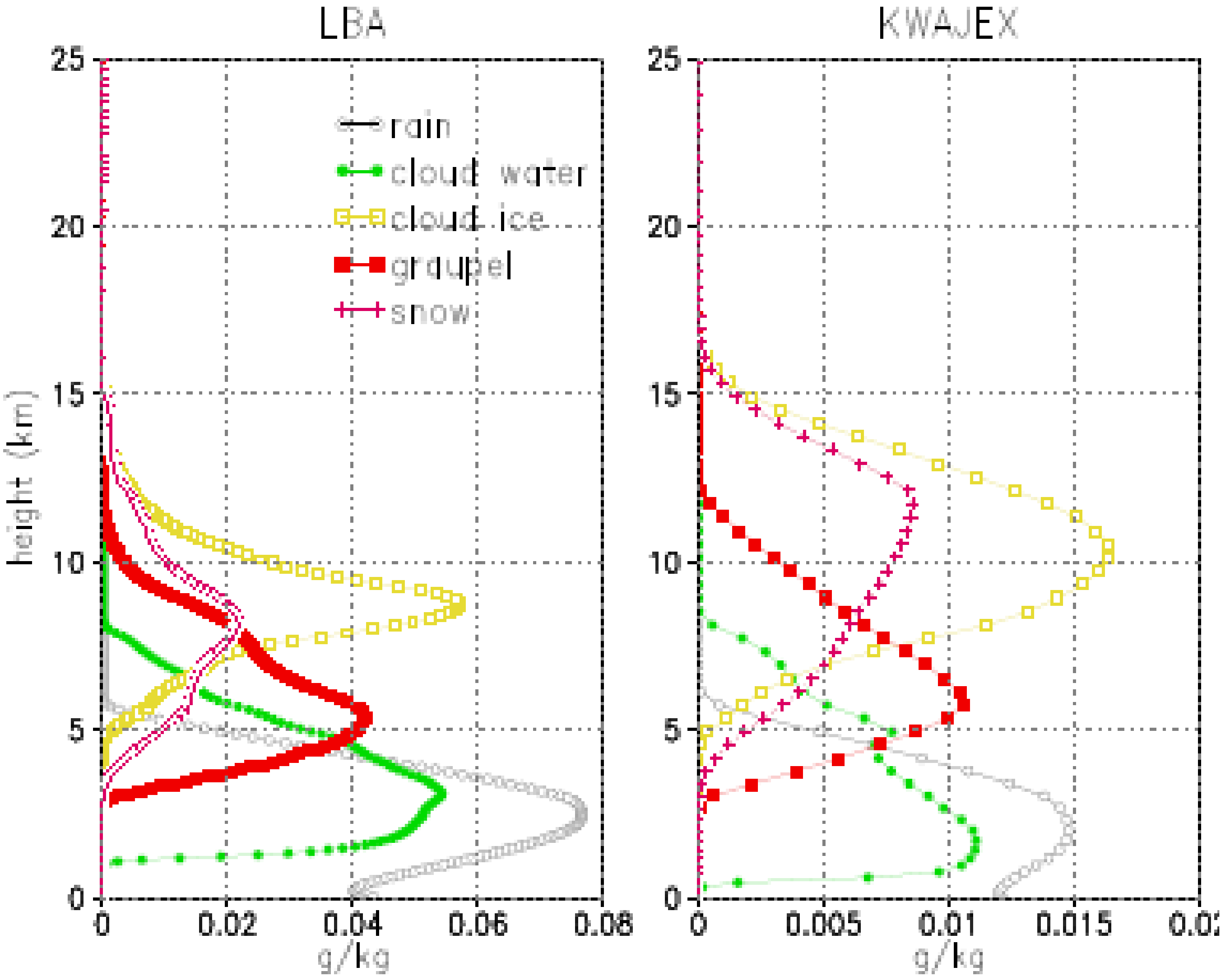
- Horizontal wind variability may be controlled by oversampling
- Vertical wind variations can be substantial; see common scale
- Mans Hakansson challenges vertical sampling of 1 km
- Control by Mie oversampling as suggested in MERCI and tested in L2B
- Where?



# Doppler on clouds with radar

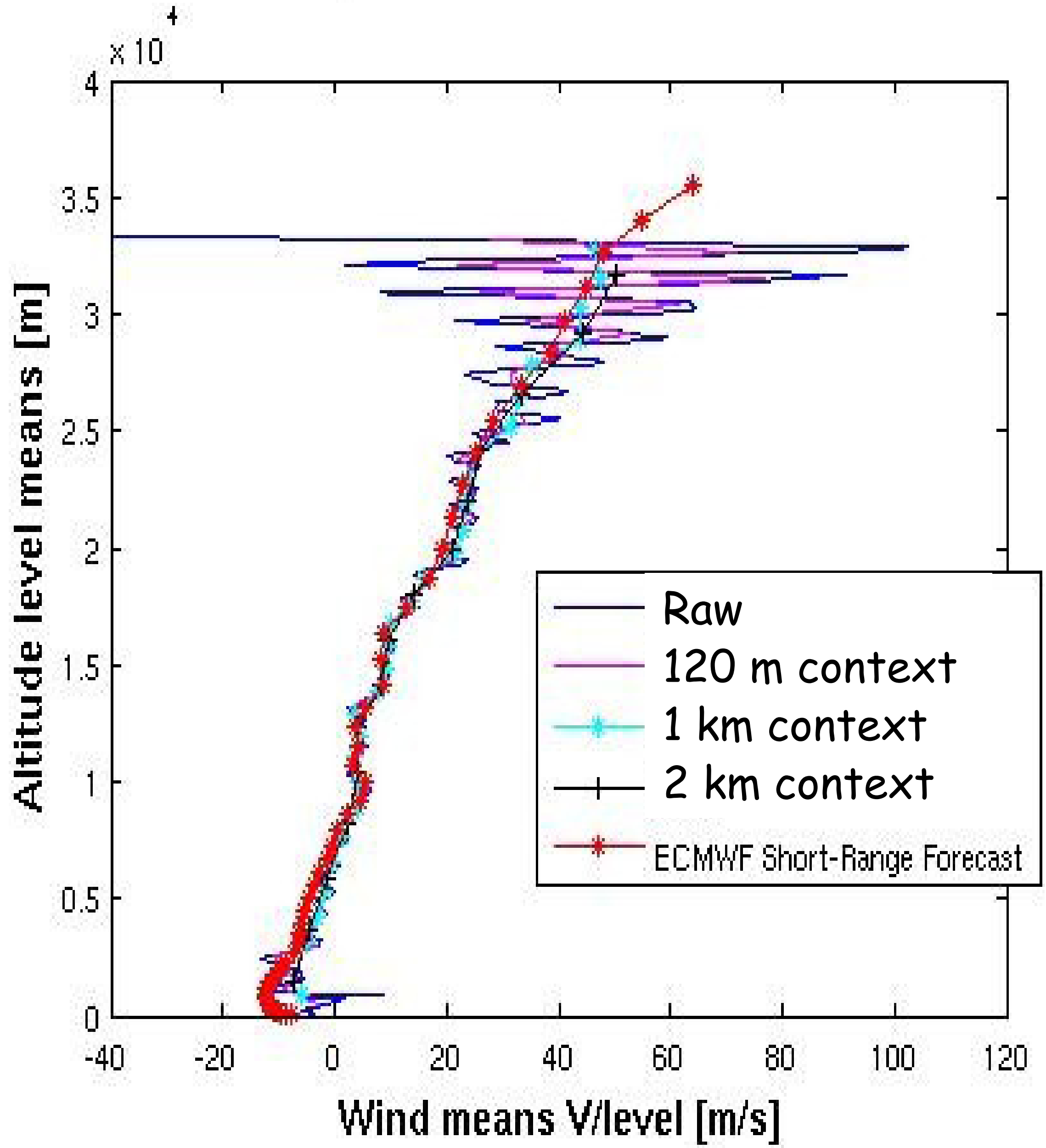



- Heterogeneous scenes; spatial representativeness? QC ?


LBA
KWAJEX
rain
cloud water
cloud ice
graupel
snow
height (km)
g/kg
g/kg
0
5
10
15
20
25
0
0.02
0.04
0.06
0.08
0
0.005
0.01
0.015

# Gravity waves

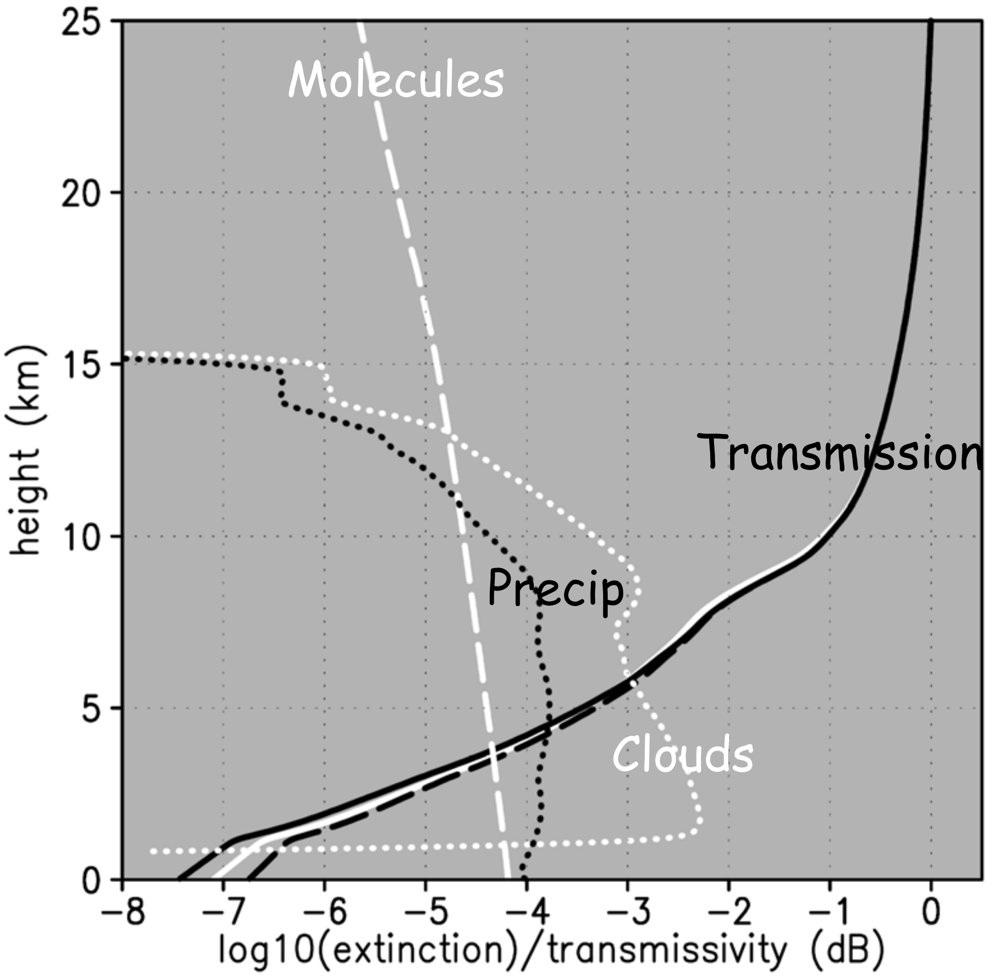
- 2 km or 1 km vertical context well smoothes a gravity wave
- Due to bin position biases of a few m/s may result



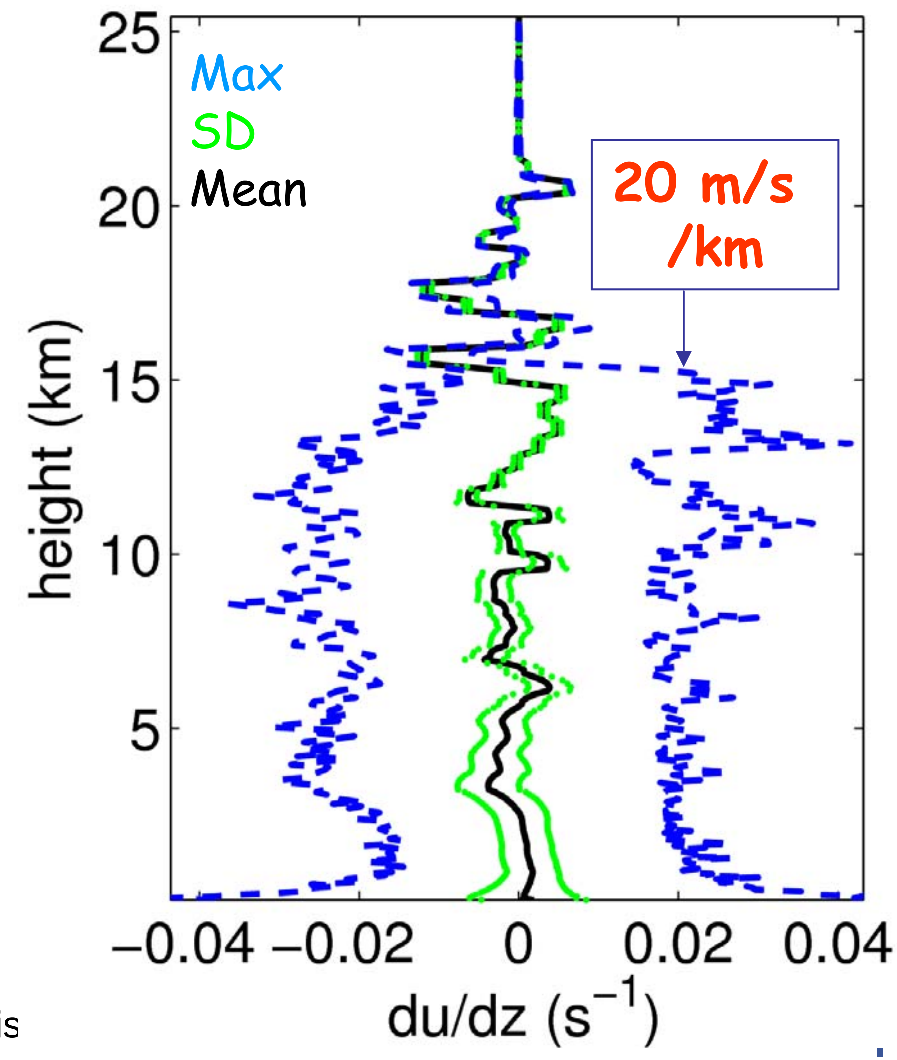
# Optical variability Cloud Resolving Model

- Precip causes vertical motion

Tranmission

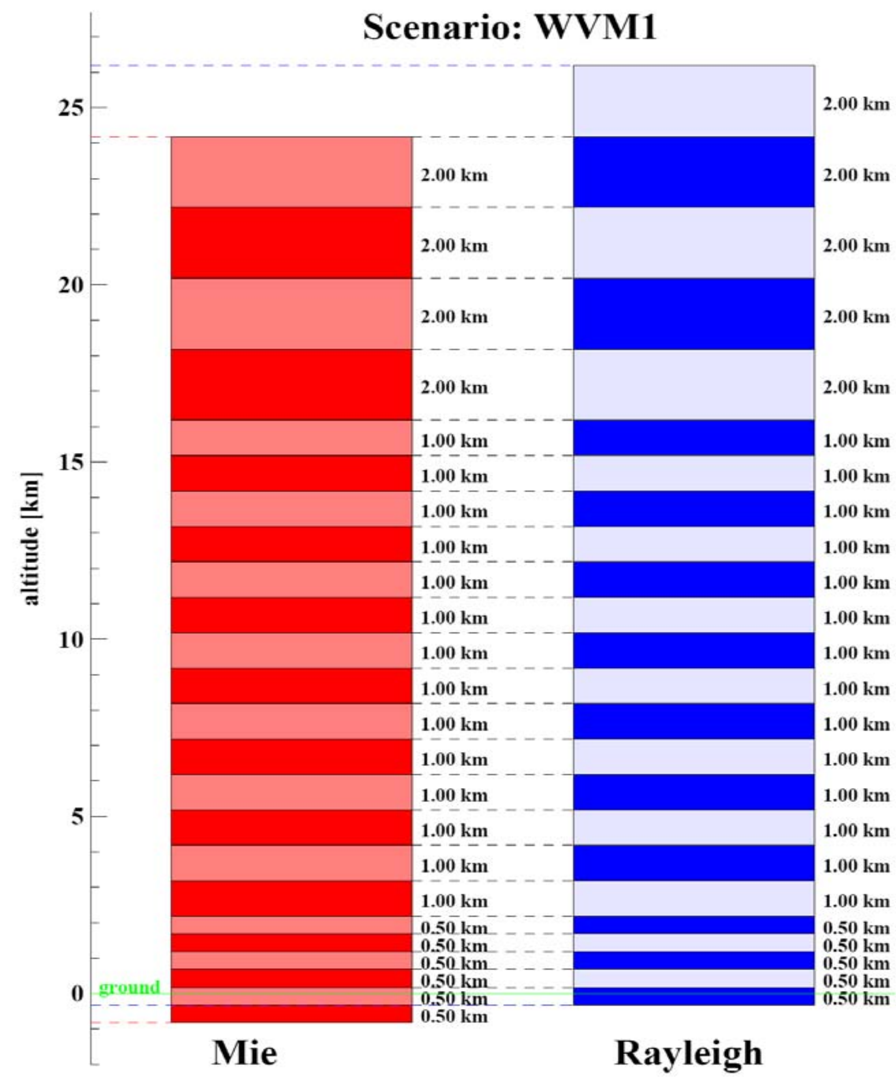



Vertical shear of horizontal wind

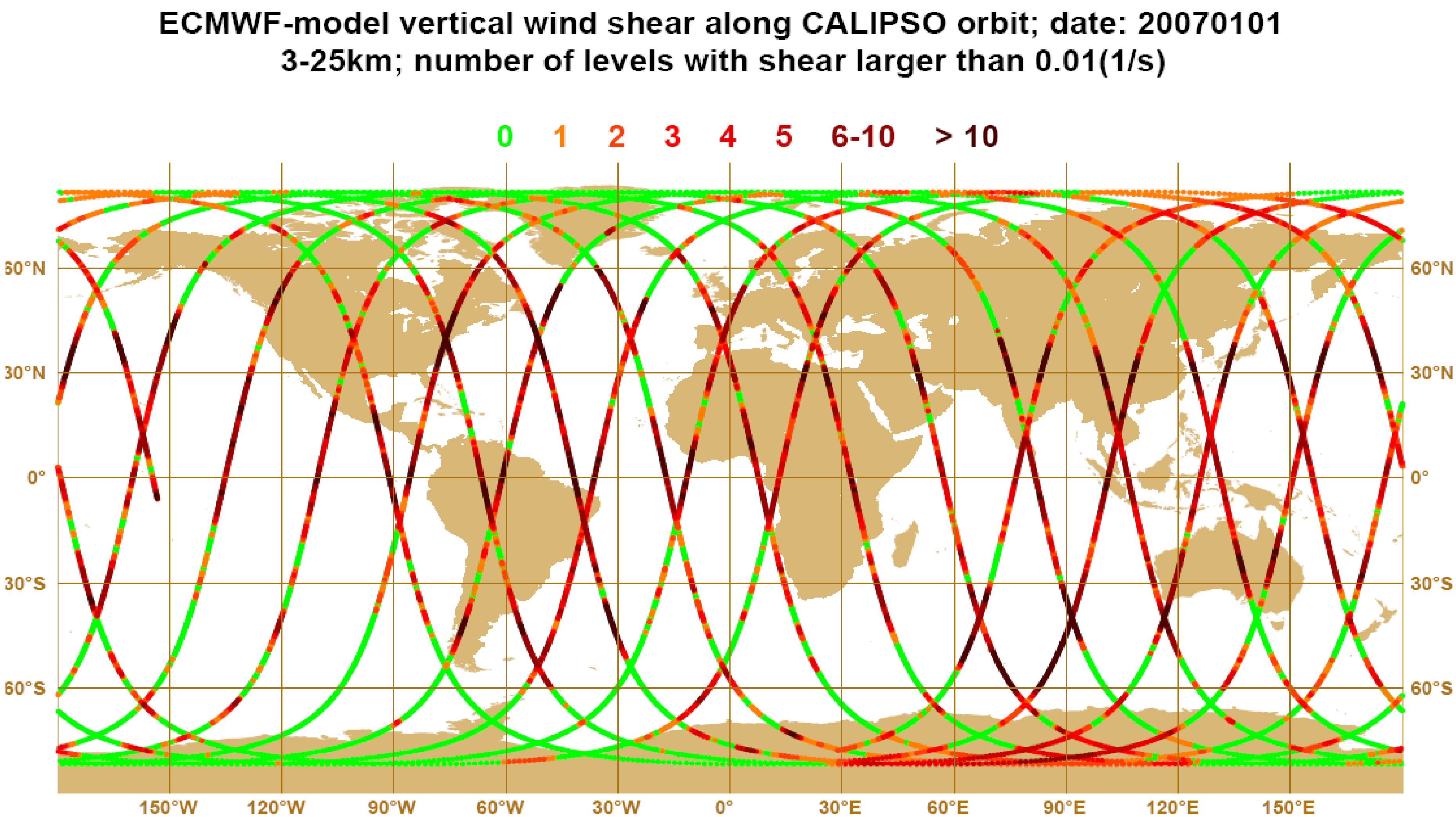


# Aeolus vertical sampling scenario

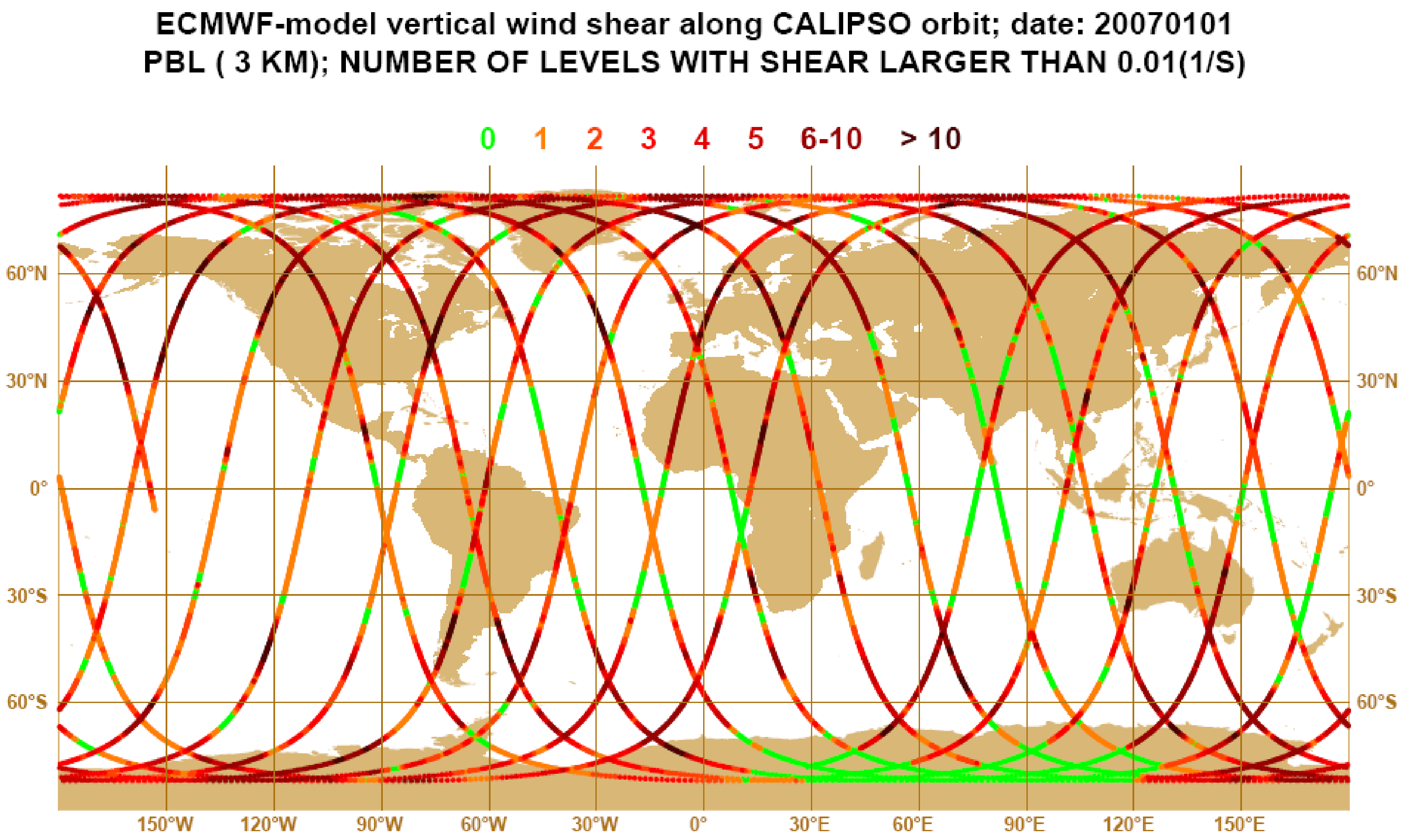
- Limited number of vertical levels for molecular and particle channel (24 each)
- How to distribute these in the vertical ?
  - ➢ Ground motion calibration
  - ➢ Wind computation, QC
  - ➢ Contamination molecular channel with particle backscatter
  - ➢ Height assignment in case of shear and optical heterogeneity
  - ➢ Climate zone
  - ➢ Land/sea



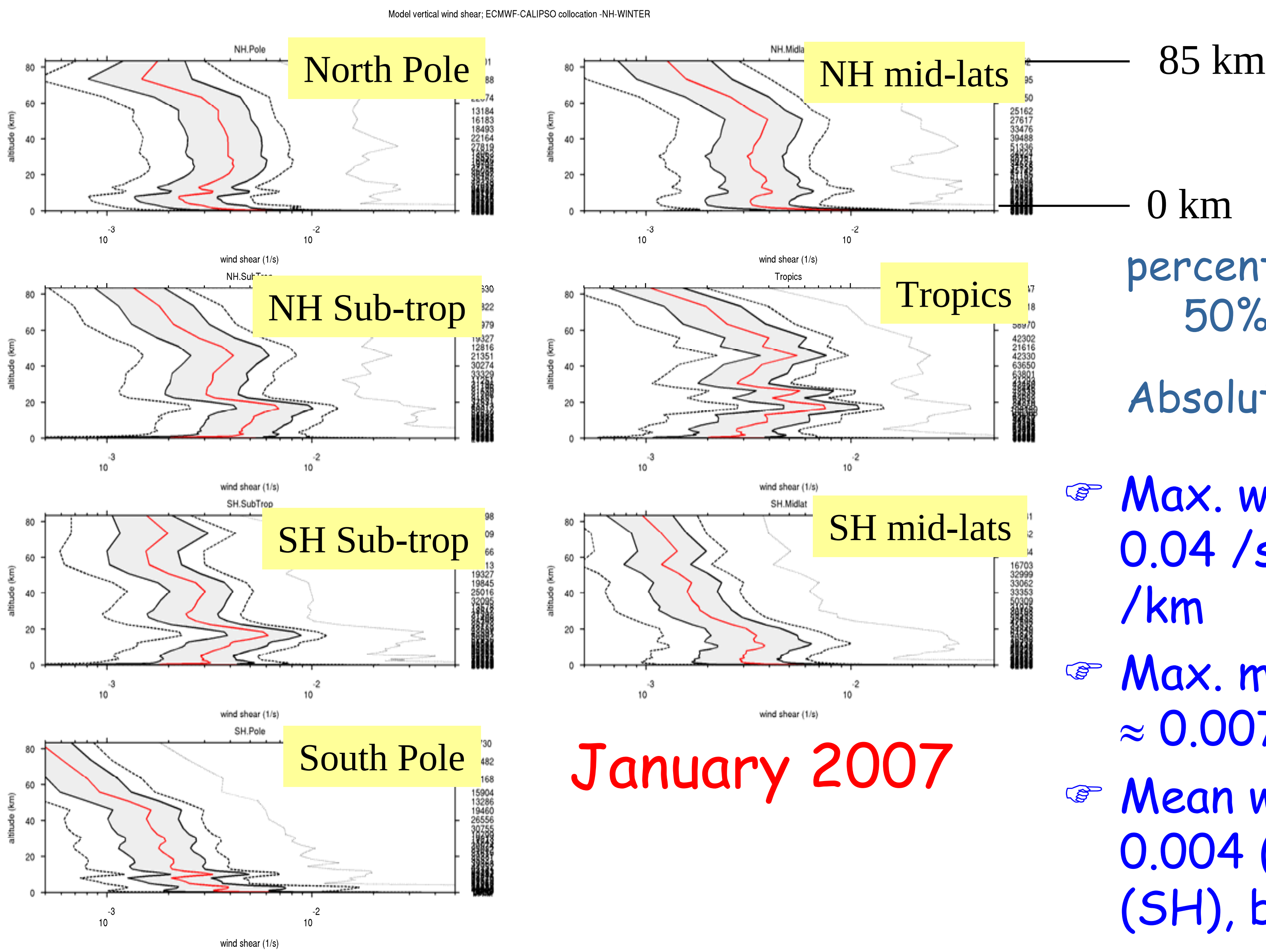
# Free-troposphere wind-shear



# PBL wind-shear



# ECMWF wind-shear statistics



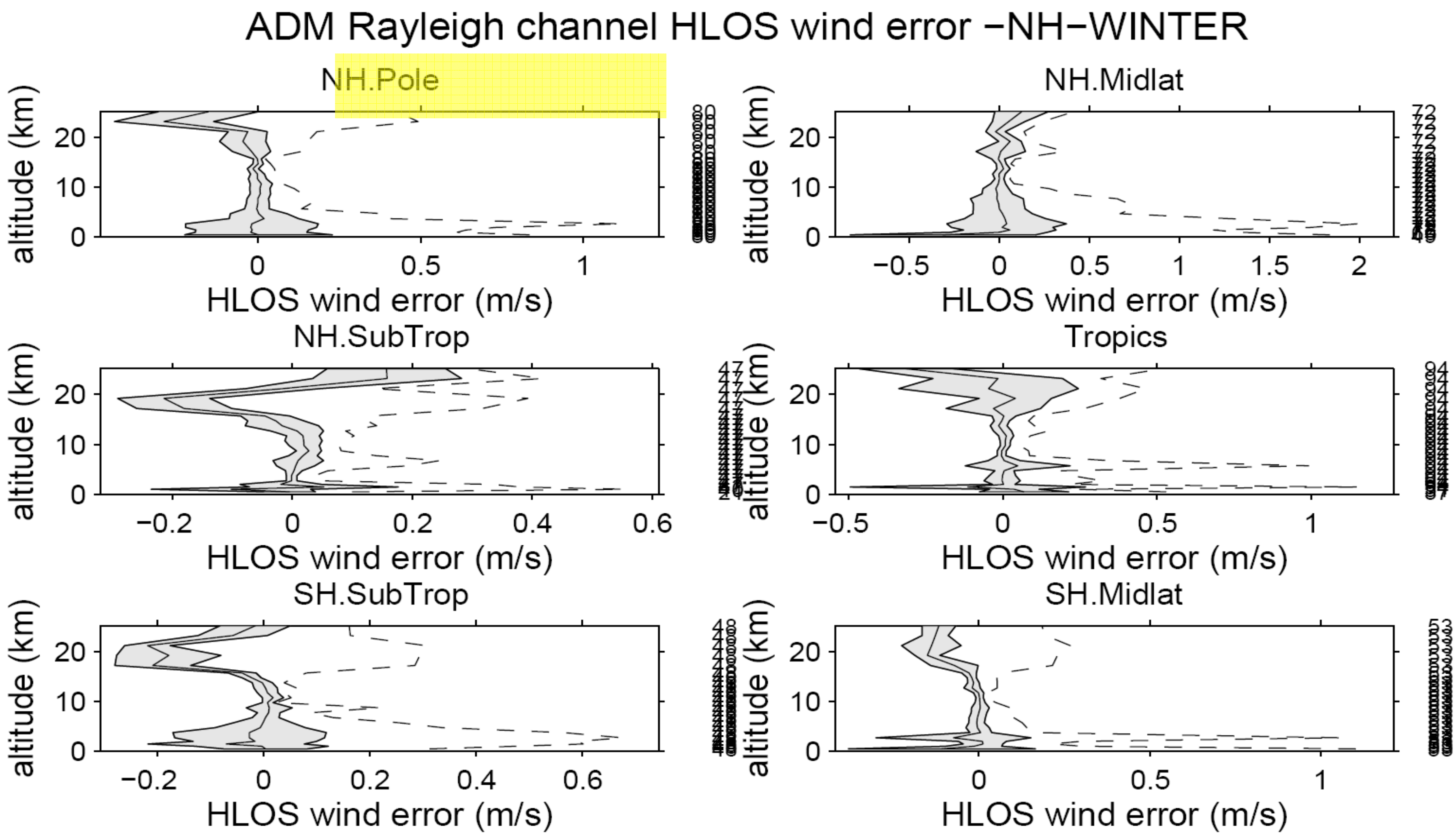

percentiles: 10%, 25%, 50% (red), 75%, 90%

Absolute maximum value

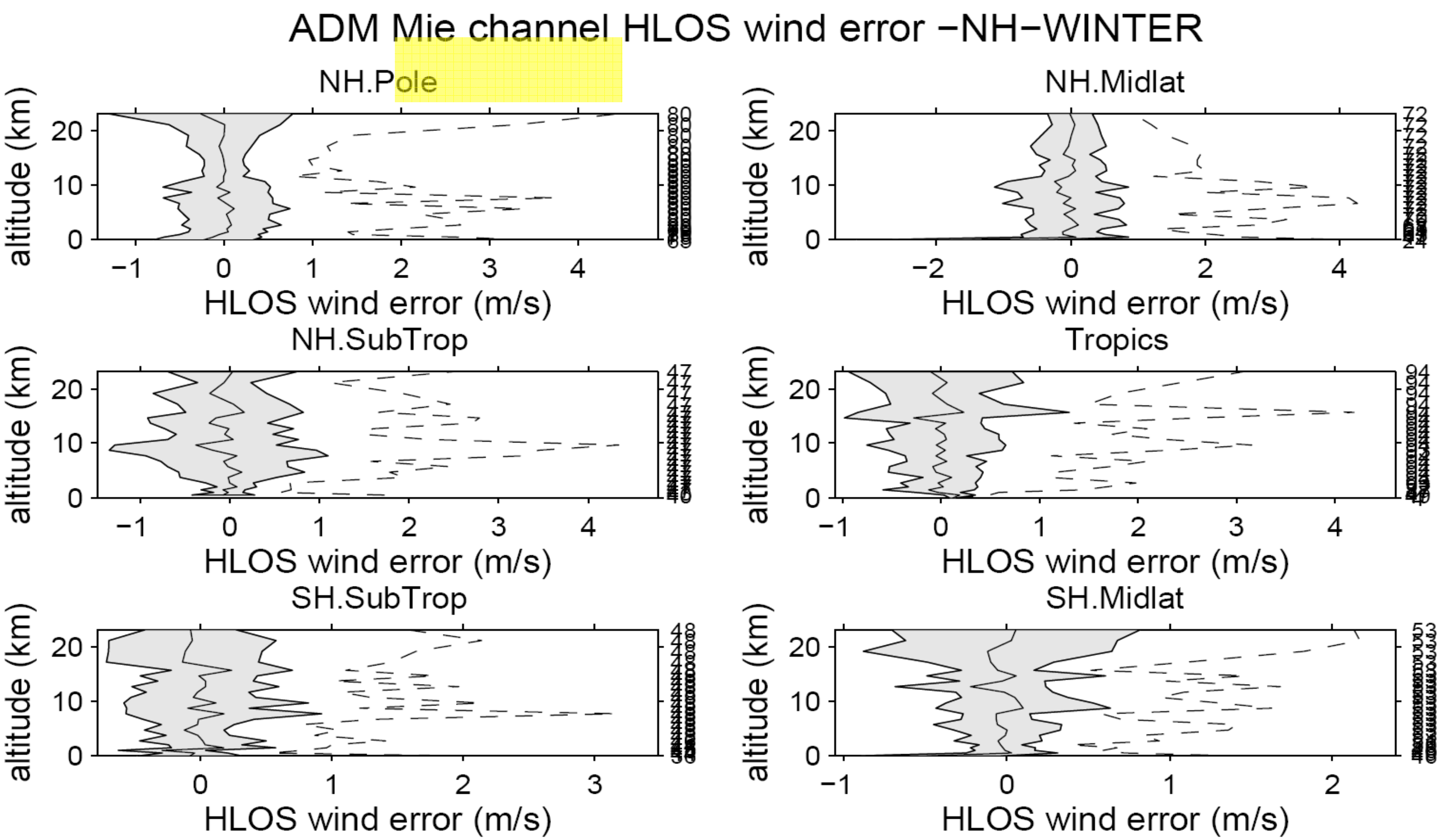
January 2007

- Max. wind shear ≈ 0.04 /s, i.e. 40 m/s /km
- Max. mean wind shear ≈ 0.007 1/s
- Mean wind shear ≈ 0.004 (NH), ≈ 0.003 (SH), below 30 km

# HLOS wind error statistics (1 orbit only)



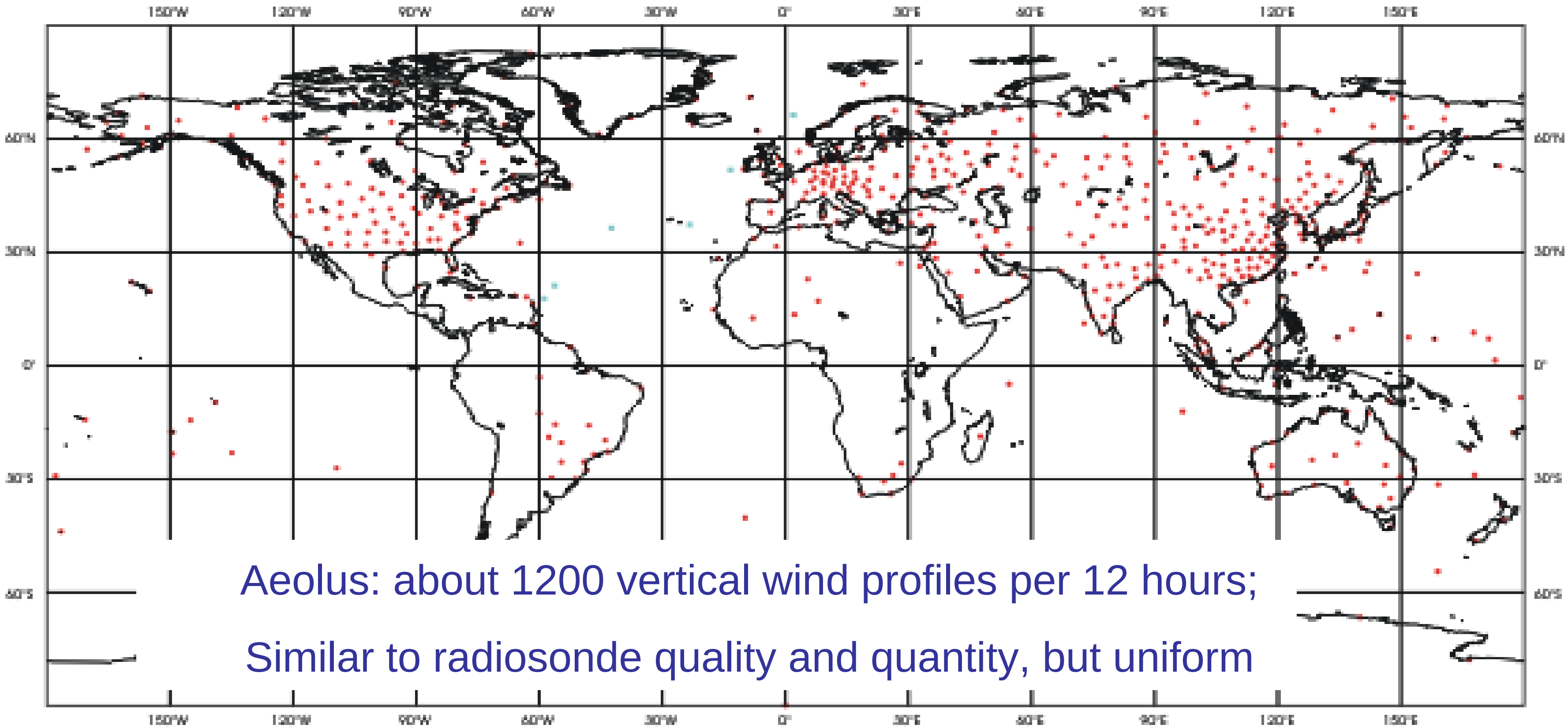
# HLOS wind error statistics (1 orbit only)




- Mie cloud returns have largest systematic errors
- Subsample variations not accounted for yet (ECMWF winds)

Wind profiles are the main missing component of the global observing system over ocean, tropics and Southern Hemisphere

Total number of vertical wind profiles on 25 Sep 2005, 00 UTC: 613



Aeolus: about 1200 vertical wind profiles per 12 hours;

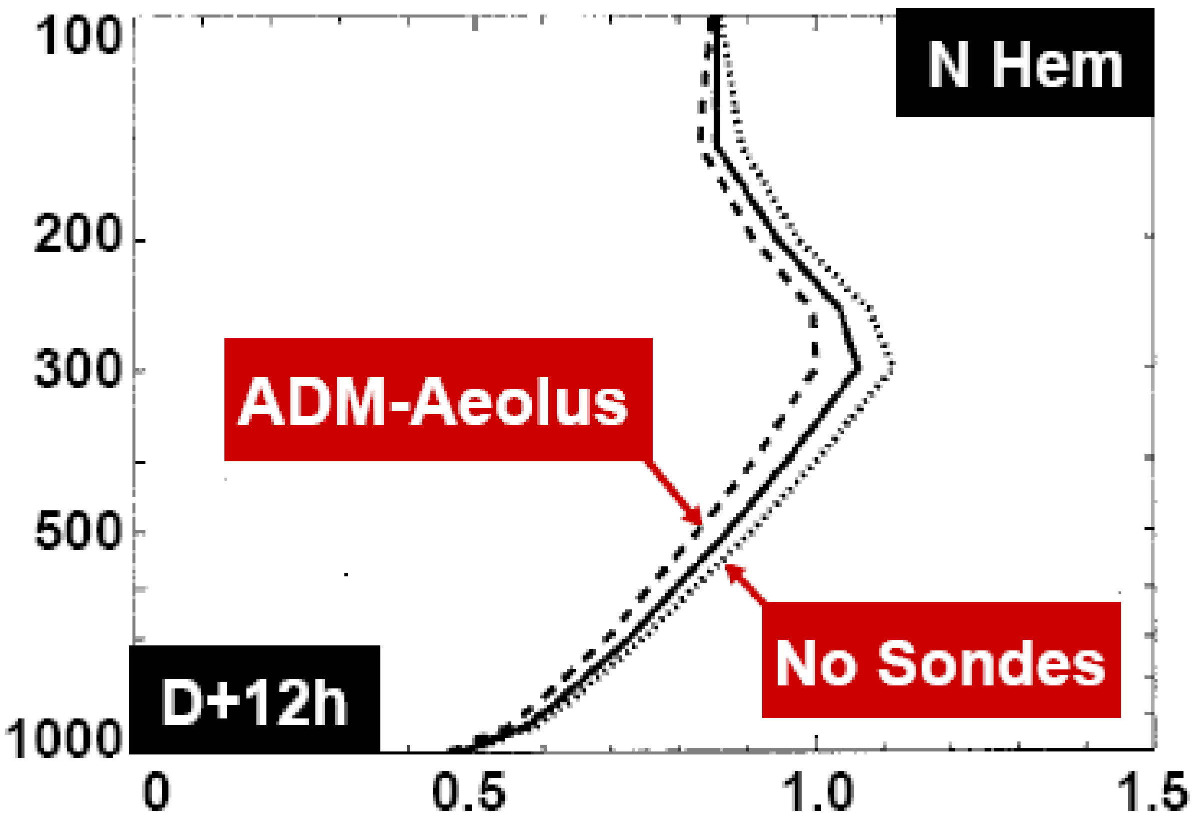
Similar to radiosonde quality and quantity, but uniform

# 3.2 Aeolus User Workshop

Workshop proceedings at www.esa.int/esaLP/LPadmaeolus.html :

- ECMWF: Based on the positive results of ADM-Aeolus and DWL follow-on impact experiments so far, we should start planning a DWL follow-on (Simmons)
- JCSDA: Significant benefit of wind in NWP is well established … well prepared to use LOS wind data (LeMarshal)
- SPARC: Data assimilation as vehicle for exploitation of DWL data and climate analysis (O'Neill)
- GOS: CBS implementation plan item S10 on LEO DWL: a long-standing technological programme is solicited for operational implementation (Hinsman) WMO's top priority for Global NWP
- GCOS: Call for planning Aeolus follow-on missions (Sommeria)
- WMO: unparalelled international cooperation is maturing (Hinsman)
- NOAA/NASA: set up European collaboration for follow-on

## ECMWF Analysis Ensemble Results

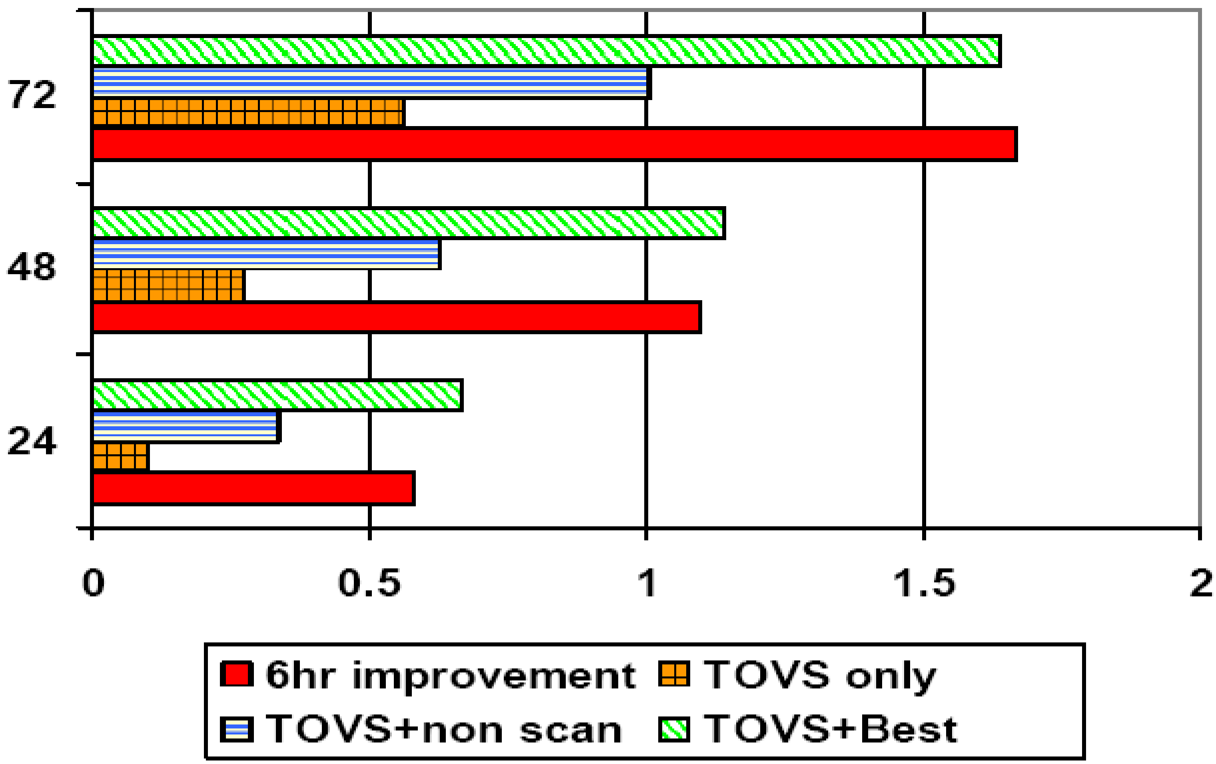



Profiles of zonal-wind forecast impact (m/s)

Ensemble spread used as proxy for analysis and forecast error, and spread difference as proxy for analysis and forecast impact of the assessed observations

**Direct impact of ADM-Aeolus data on forecast accuracy may be comparable to that of radiosonde data.**

# Stare versus Scan DWL OSSE (NCEP)



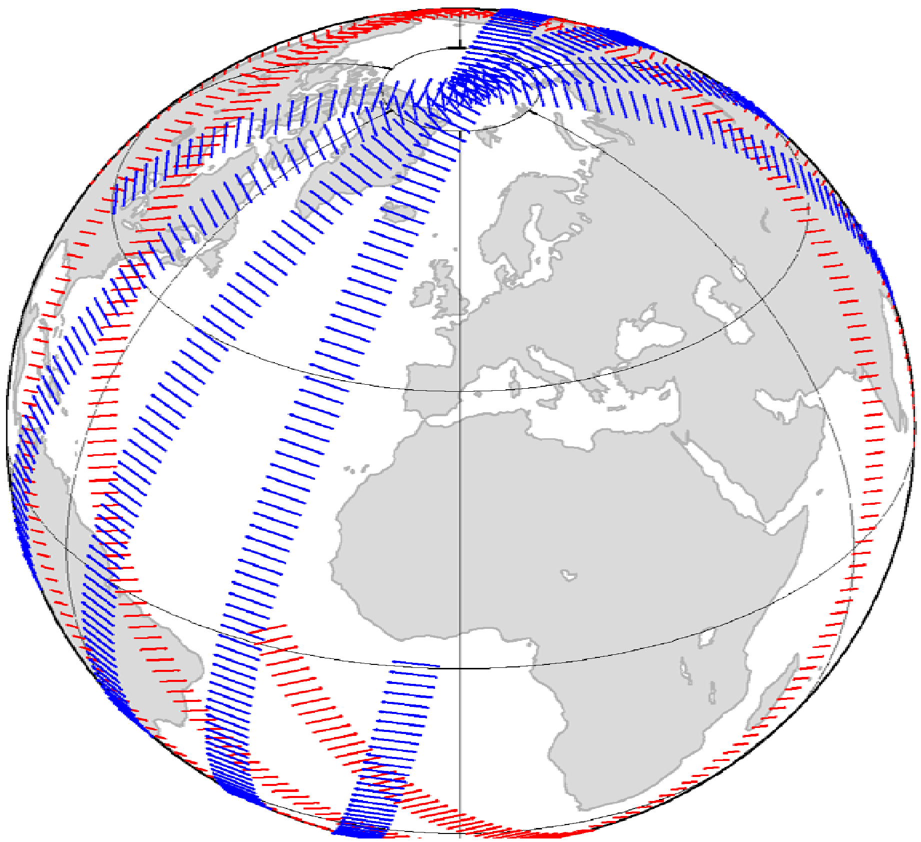

Northern Hemisphere Anomaly Correlation difference with respect to control

GMAO/NCEP
Global Forecast System T62
*Masutani et al, ADM Workshop*

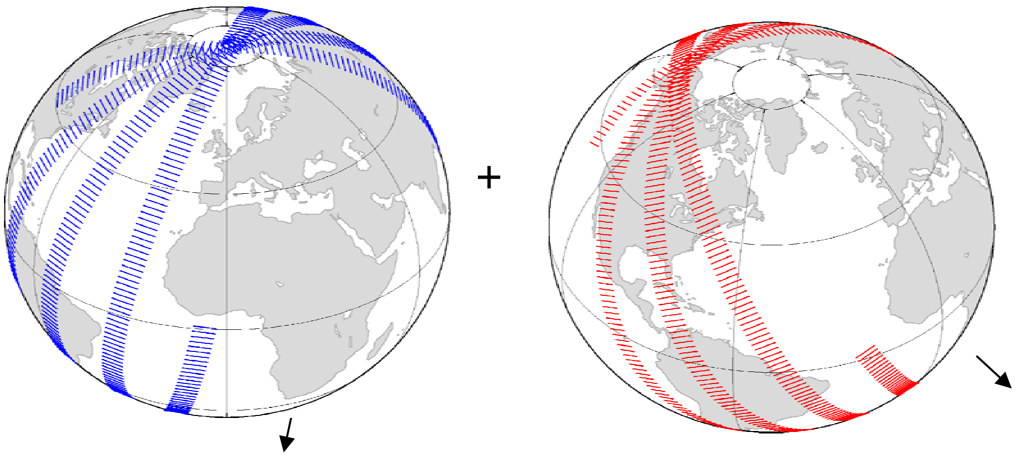
- ***Scan "best" DWL costly***

- JCSDA: Significant benefit of wind in NWP is well established … well prepared to use LOS wind data (LeMarshal)

# Dual Orbit Inclination Scenario



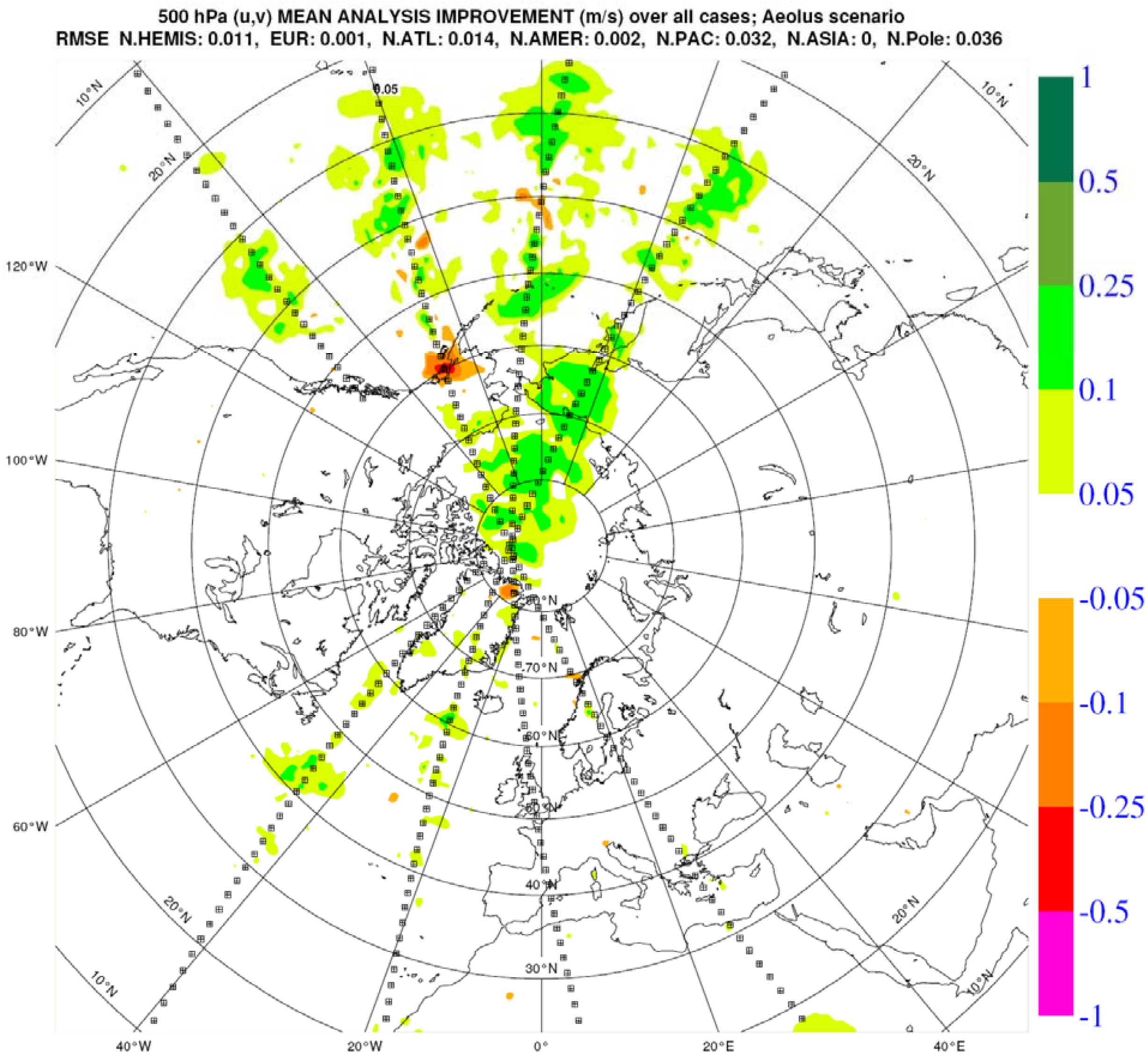
6-hour orbit started at the equator




- Two Aeolus-type instruments with different orbit inclination angles, to get both dual perspective and increased coverage
- e.g. inclination angles of 97º and 70º
- Orbits tuned to provide the best coverage in the storm track regions
- Twice the number of Aeolus profiles

**Courtesy N. Žagar**

# PIEW: Mean DWL Analysis Impact

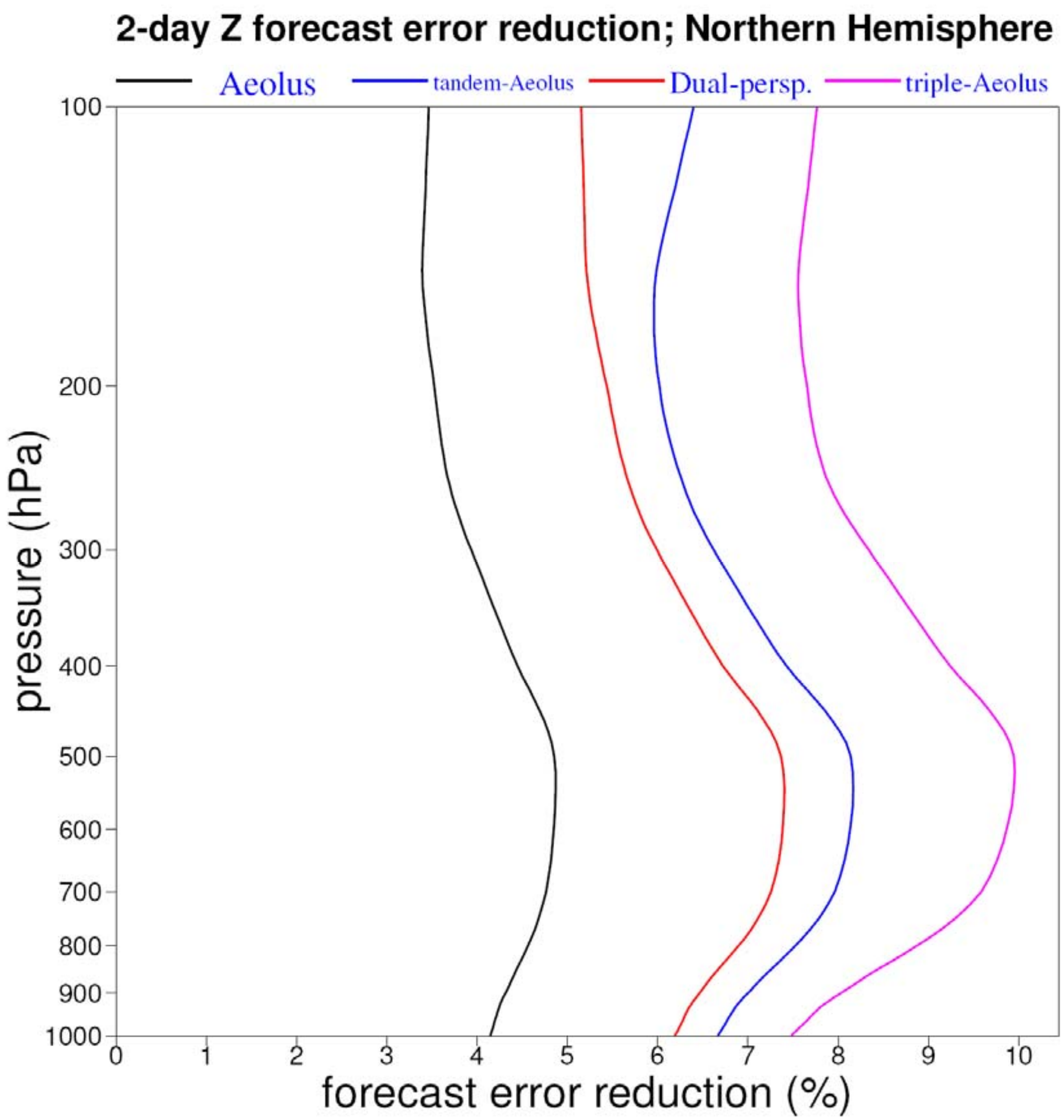



**Aeolus scenario**

- 38 cases at 12:00 UTC
- Covering all seasons
- Impact scale in m/sec

**Gaps between tracks**

# PIEW: Mean DWL Forecast Impact




- Analysis and forecast impacts are vertically consistent and well distributed
- Benefit over multiple cycles larger

# PIEW: Conclusions

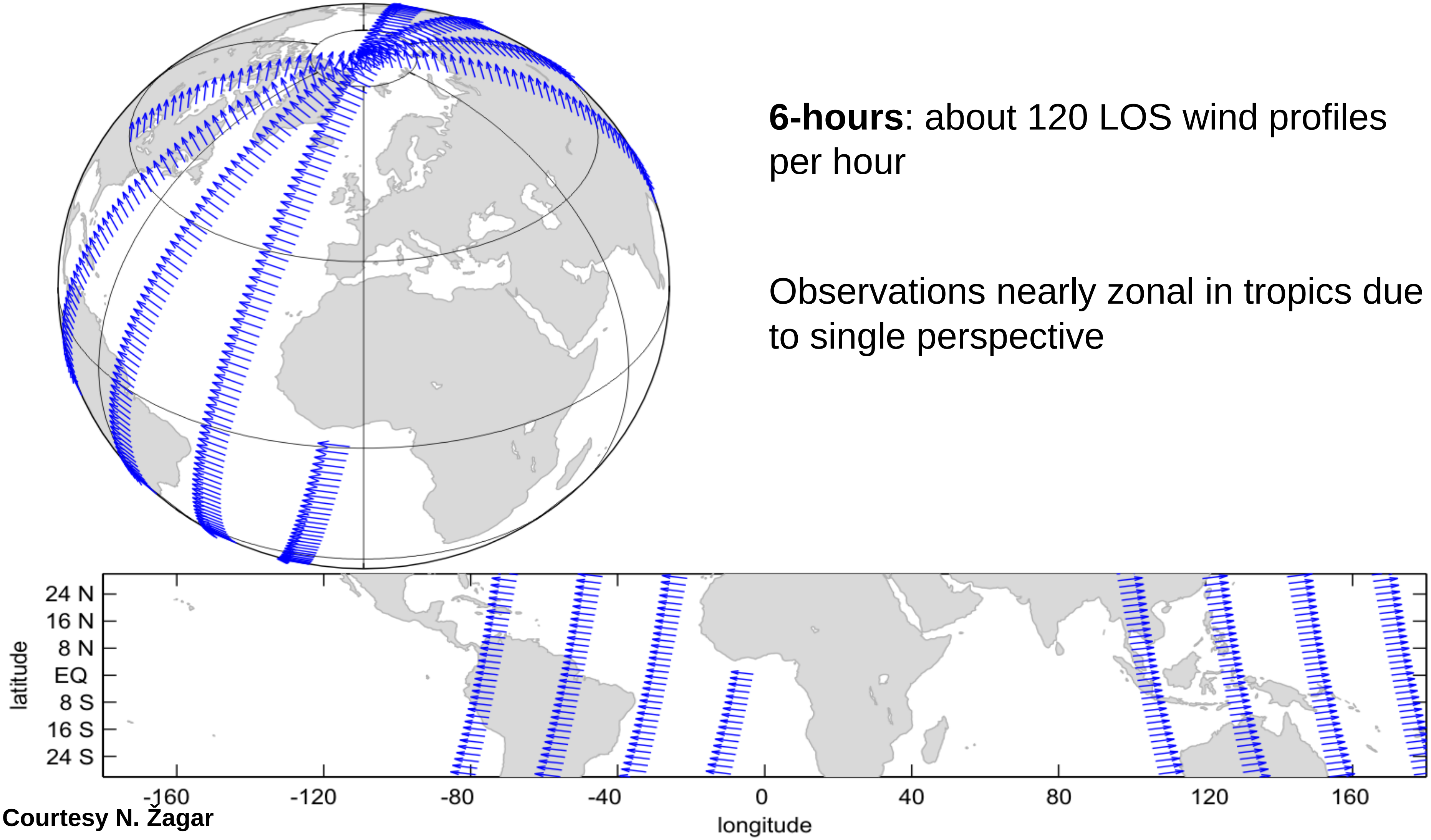
- Aeolus is capable of resolving analysis error structures in data sparse areas and improving state-of-the-art forecasts
- Measuring wind vector profiles instead of LOS components over the Northern Hemisphere oceans gives "only" a 50% forecast improvement
- A larger and more uniform improvement of 70% is achieved by a more uniform distribution of single-LOS wind observations (Tandem Aeolus)
- A third Aeolus in orbit gives still additional substantial improvement, in particular over the North Atlantic
- The results apply for precursor regions for extreme weather as well as for regions of common extra tropical weather

## Objectives

- Address dynamical issues of assimilating ADMAeolus winds in the tropics. Analysis increments due to LOS winds are more dependent on *a priori* information than the full wind-field information (Žagar, JAS, 2004)
- Compare potential impact of several Aeolus follow-on scenarios with two spaceborne DWLs

A study by Nedjeljka Žagar, now at NCAR

# PIEW Reference Scenario: Aeolus

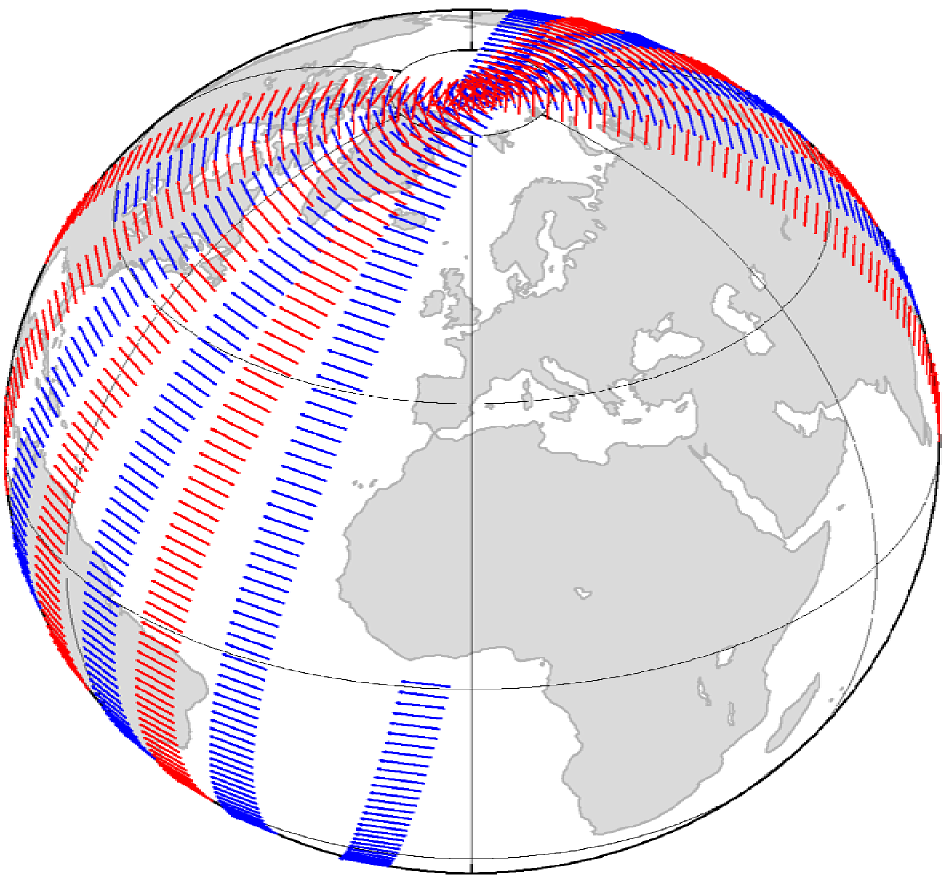



**6-hours**: about 120 LOS wind profiles per hour

Observations nearly zonal in tropics due to single perspective

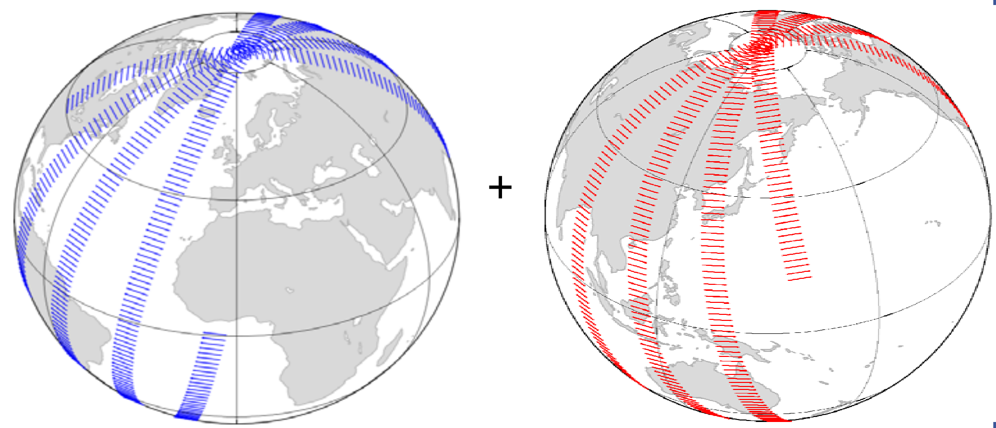
**Courtesy N. Žagar**

# Tandem Aeolus Scenario



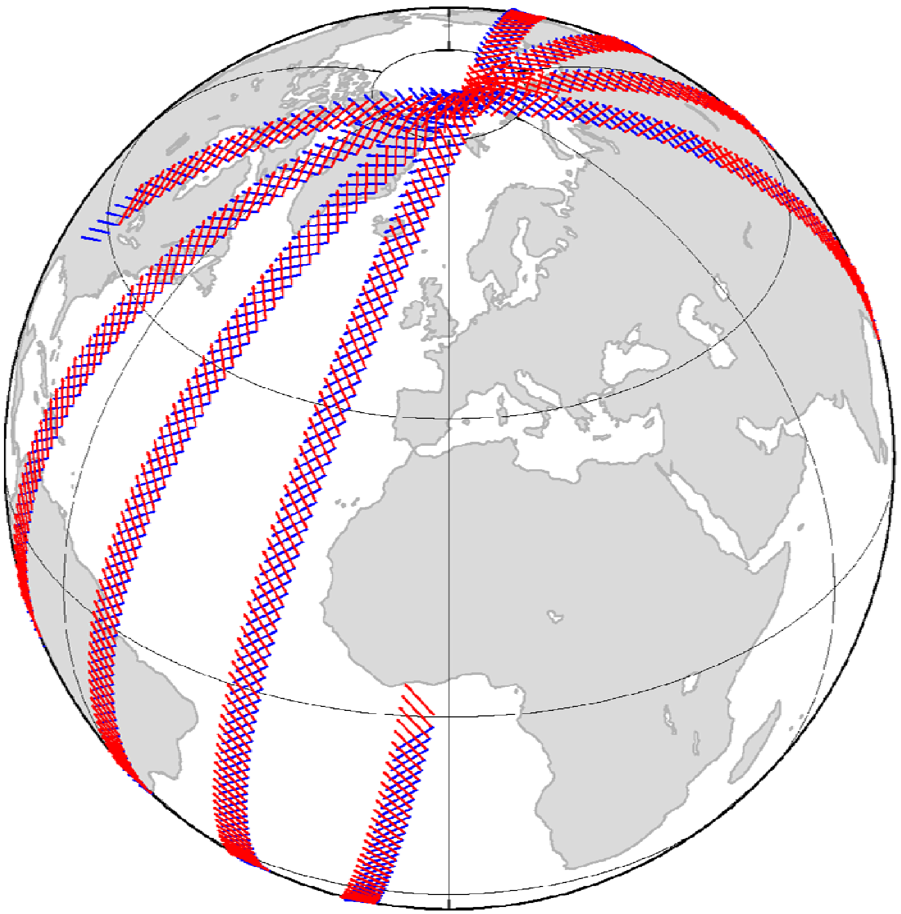
6-hours of sampling

**Courtesy N. Žagar**



- Same dawn-dusk orbit and instrument, but phase difference 180 degrees (45 minutes)
- Minimum of observation coverage redundancy; great heritage (low cost)
- Twice as many LOS wind profiles as Aeolus

# Dual Perspective Scenario



**6-hours orbit started at the equator**

**Courtesy N. Žagar**

- Two LOS on the same satellite or two satellites in similar orbits
- 90 degrees between the pointing directions
- Twice as many LOS wind profiles as Aeolus

# Tropics:
# Analysis Procedures Balance Criteria?

- **Mid-latitude Analysis:**
  Rossby waves
  Quasi-geostrophic balance
  $\Rightarrow$ multivariate assimilation

- **Tropical Analysis:**
  Rossby, Kelvin, mixed Rossby-gravity and equatorial inertio-gravity waves
  No obvious dominant balance relationship
  $\Rightarrow$ univariate assimilation (ECMWF)
  $\Rightarrow$ direct wind observations needed

## Tropics: Conclusions

- It is difficult to make use of balance relationships in the tropics. Wind measurements are crucial for the reduction of uncertainties in the tropical analysis fields.

- A second satellite can reduce the analysis error by an additional 50% w.r.t. Aeolus. In the case of poor background-error makes orthogonal observations of wind vectors better than the same number of observations along a single Line-of-Sight.

- Among three scenarios, dual-inclination scenario provides on average best scores. This is due to the combination of more spatial coverage and the information brought by measuring both wind components.

- Due to the weak mass-wind coupling in the tropics, 4D-Var cannot extract information on the meridional wind component from the Tandem-Aeolus winds to the same  extent as in the extra-tropics.