In situ and actively sensed observations

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Saleh Abdalla, Giovanna De Chiara, Sean Healy, Bruce Ingleby, Mike Rennie, Alan Geer, Cristina Lupu, Mohamed Dahoui, Stephen English and Adrian Simmons

Overview of lecture

- Why observations are essential for data assimilation
- Overview of in situ observations and some actively sensed observations
- Impact of in situ and actively sensed observations in global NWP
- Further aspects on assimilating in situ and actively sensed observations

Data Assimilation

- Primary goal of Data Assimilation:
  - To make the best estimate of the initial state of the atmosphere-land-ocean system based on the available information:
    Short-range model forecast + boundary constraints + observations
  - Main purpose (at ECMWF) is to ensure accurate NWP forecasts
- Secondary goal of Data Assimilation:
  - To quantify the uncertainty of our estimate of the initial state
    - This is used during the data assimilation process
    - It is also used to initialise the ensemble forecast

Extension to Multiple Dimensions

A slide from the previous talk by Sebastien M.

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{K}(\mathbf{y} - \mathcal{H}(\mathbf{x}_b))$$

Analysis = Background + “gain matrix” * innovation

- Remember that in the scalar case, we had

$$\begin{aligned} T_a &= \alpha T_o + (1-\alpha) T_b \\ &= T_b + \alpha (T_o - T_b) \end{aligned}$$

- We see that the matrix **K** plays a role equivalent to that of the coefficient α.
- **K** is called the gain matrix.
- It determines the weight given to the innovation $\mathbf{y} - \mathcal{H}(\mathbf{x}_b)$
- It handles the transformation of information defined in “observation space” to the space of model variables.

Comparing model and observations

- The forecast model provides the background (or *prior*) information to the analysis
- Observation operators allow observations and model background to be compared in “observation space” – “o-b”
- The differences are called departures or innovations
- They are central in providing observation information that corrects the background model fields
- These corrections, or increments, are added to the background to give the analysis (or *posterior estimate*)
- Observation operators also allow comparison of observations and the analysis (analysis departures “o-a”)

Example: Statistics of departures

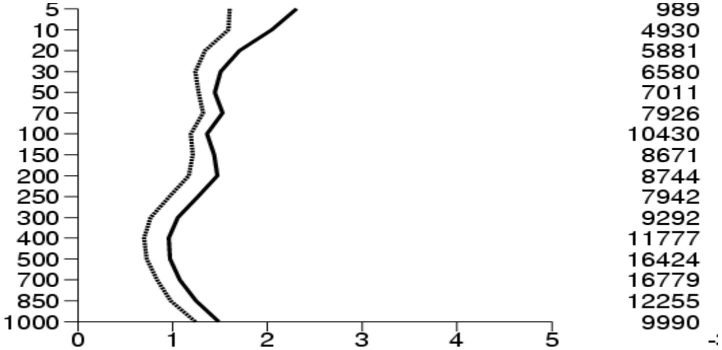
Background departures: $y - Hx_b$ (o-b)

Analysis departures: $y - Hx_a$ (o-a)

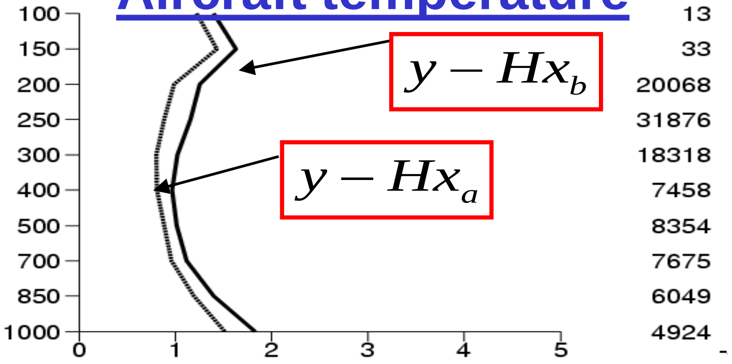
y = observations
x_a = analysis state
x_b = background state

Radiosonde temperature

Pres-sure (hPa)



Aircraft temperature

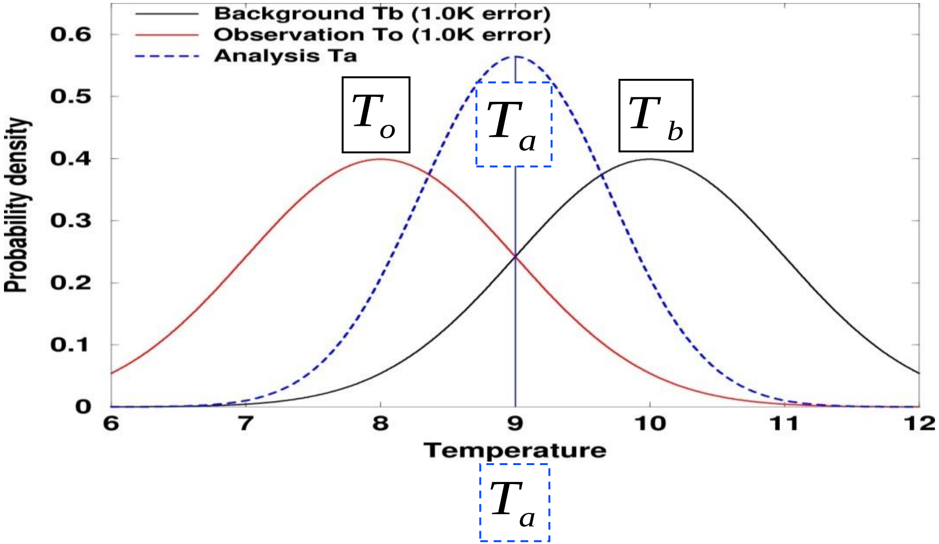


Number of obser-vations

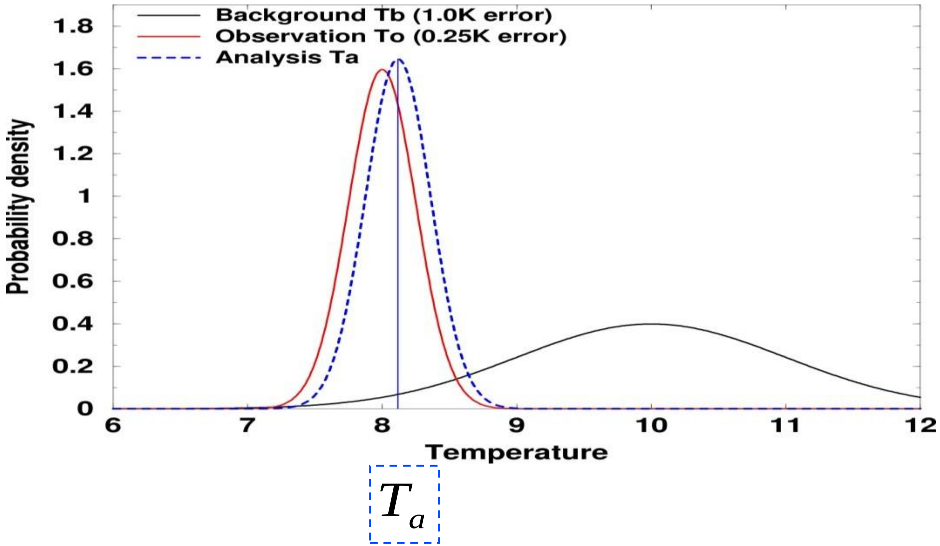
- The standard deviation of background departures for both radiosondes and aircraft is around 1-1.5 K in the mid-troposphere.
- The standard deviation of the analysis departures is here approximately 25% smaller – the analysis has “drawn” to the observations.

Observations and model background have errors
It is important to specify them accurately

Observed temperature (T_o): 8˚C
Background forecast temperature (T_b): 10˚C
Analysis (T_a): x˚C



9˚C



8.1˚C

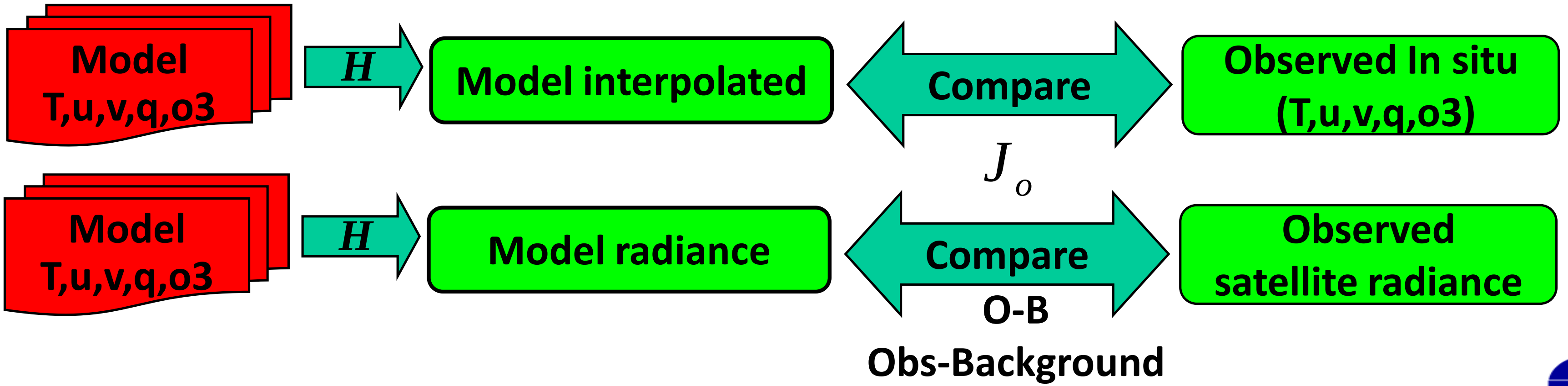
The observation operator "*H*" for in situ and satellite data

For in situ observations *H* typically only involves horizontal/vertical interpolation.

But satellites measure radiances/backscatter/radar reflectivity – NOT directly T,u,v, and q

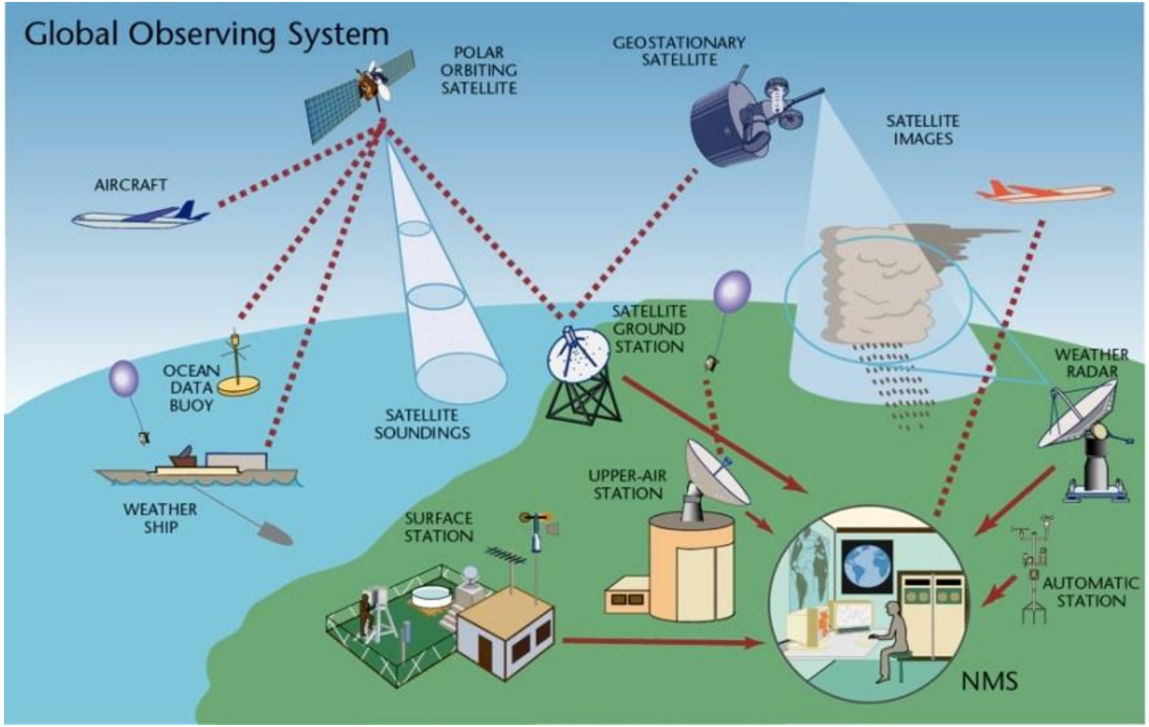
A model equivalent of the observation needs to be calculated to enable comparison in observation space (or related model-equivalent space).

For most satellite data *H* must perform transformations of model variables, e.g., to the radiative transfer operator for satellite radiances (see Tony McNally's talk tomorrow)



WMO Integrated Global Observing System

Observations are essential for data assimilation

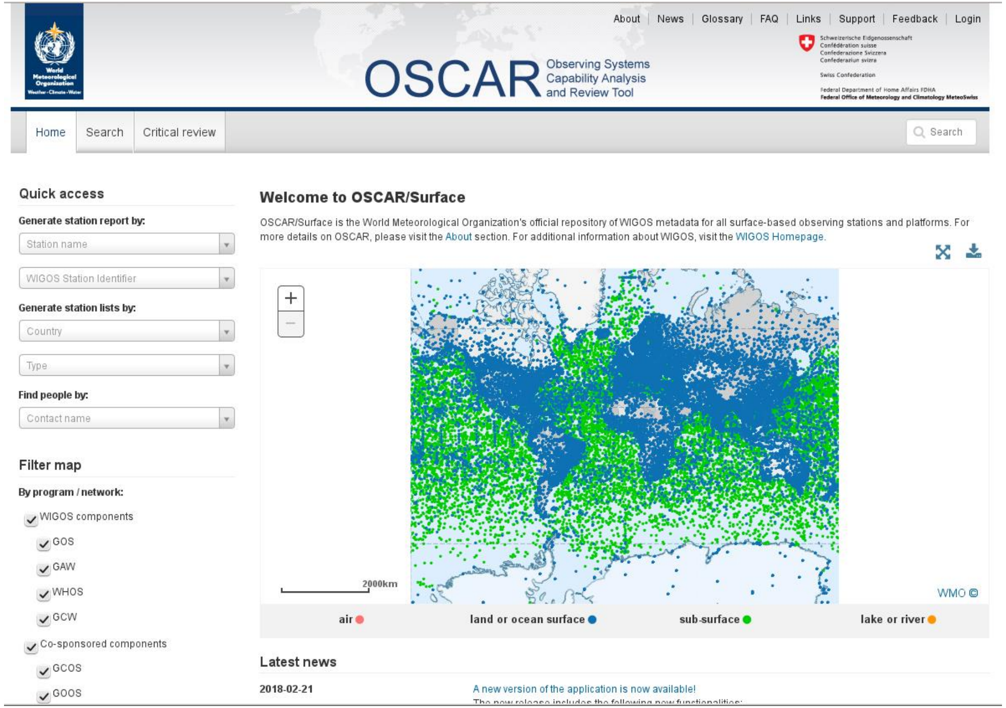


Courtesy: WMO

https://oscar.wmo.int/surface//index.html#/

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

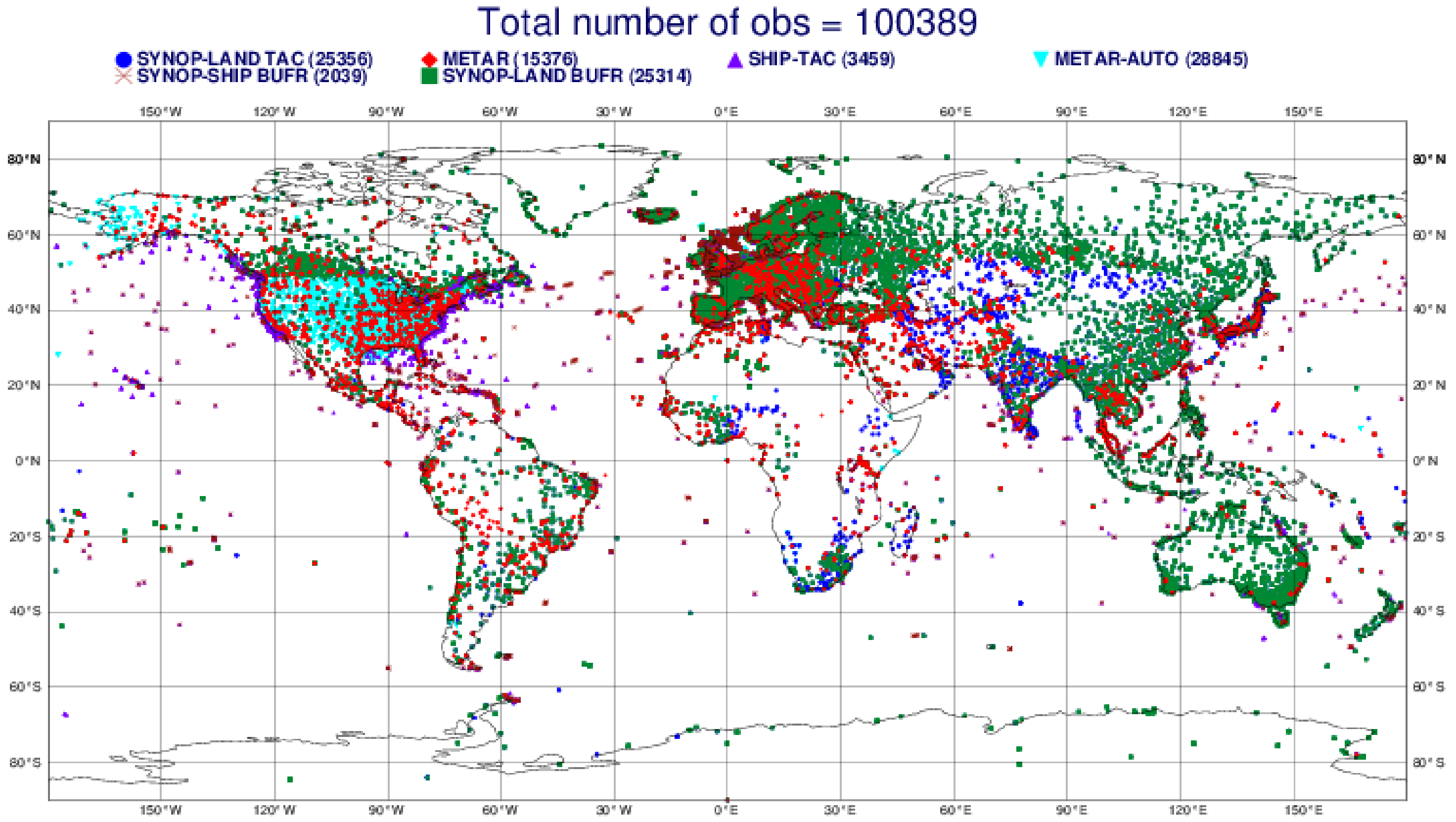
WMO OSCAR (Observing Systems Capability Analysis and Review Tool)



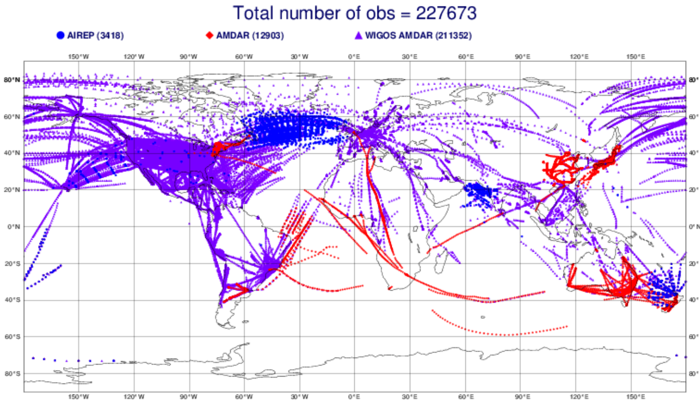
https://oscar.wmo.int/surface//index.html#/

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

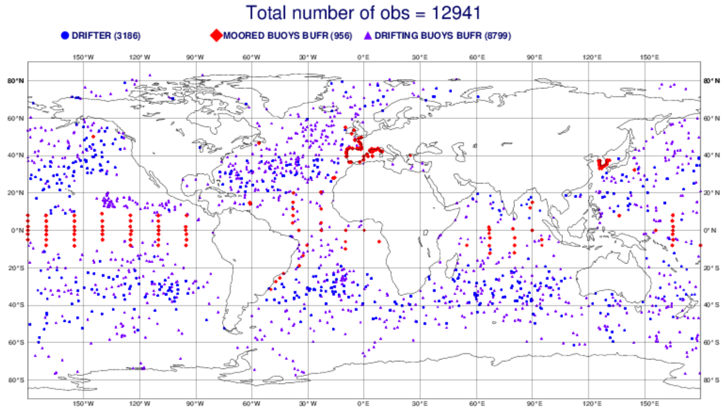
Example of 6hr SYNOP, METAR and SHIP data



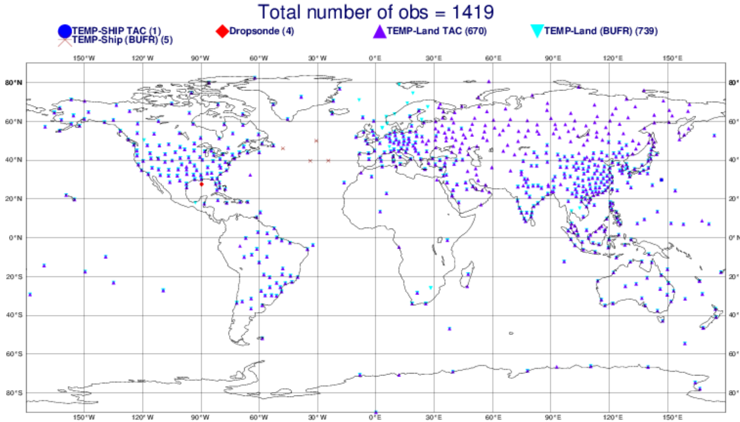
Example of 6hr of other in situ observations



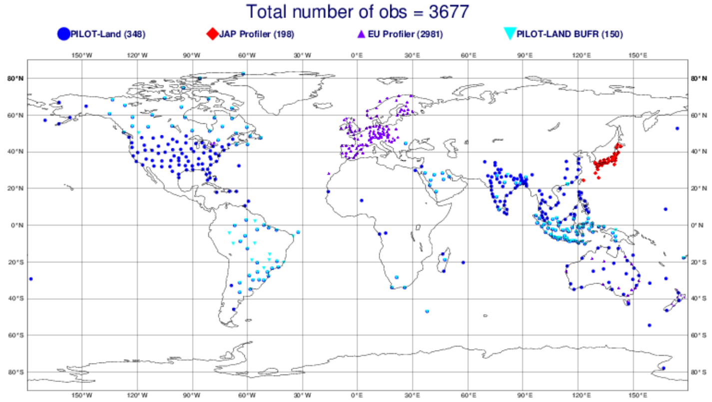
Aircraft



Drifters and moored buoys



Radiosondes



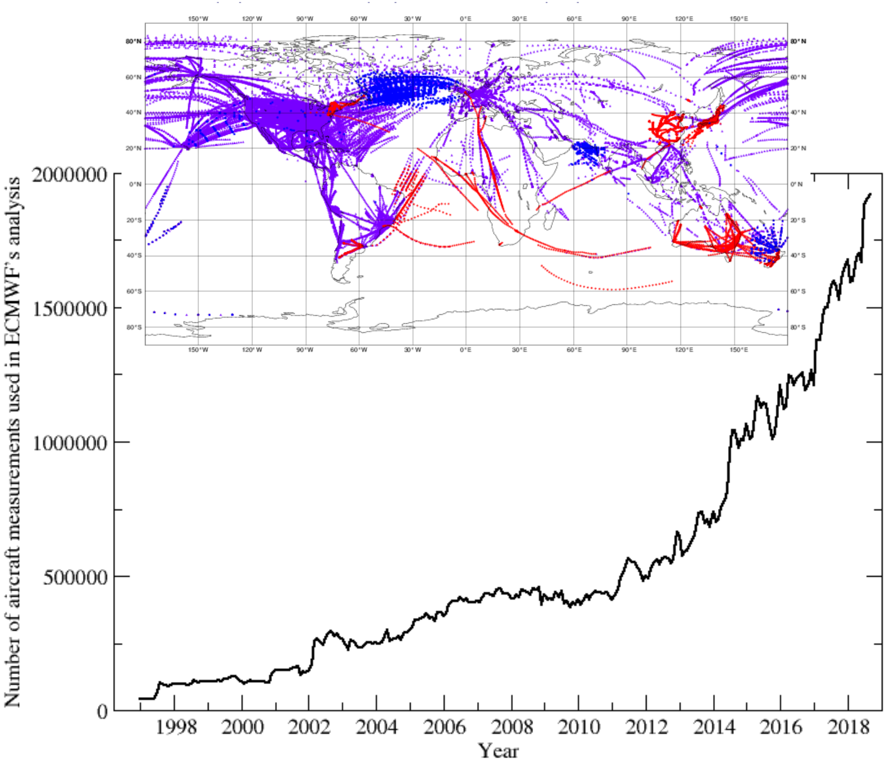
Wind profilers

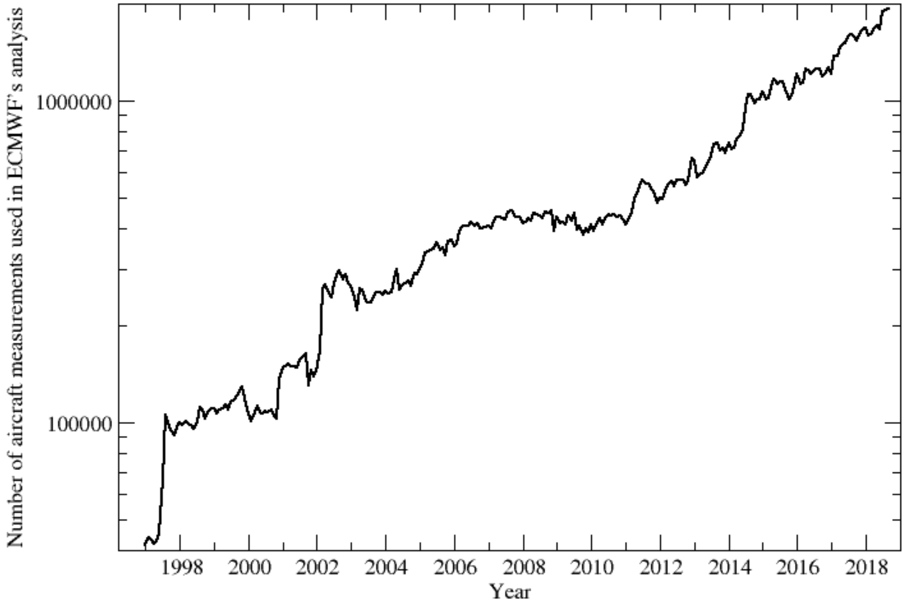
In situ data: which parameters are assimilated in atmosphere analysis?

Instrument	Parameters	Height
SYNOP **SHIP** **METAR**	pressure, dew-point temperature pressure, wind pressure	Station altitude, 2m Ships ~25m Station altitude
BUOYS	pressure, wind	MSL, 2-10m
TEMP **TEMPSHIP** **DROPSONDES**	temperature, humidity, wind	Profiles
PROFILERS	wind	Profiles
Aircraft	temperature, wind, humidity	Profiles near airports + Flight level data

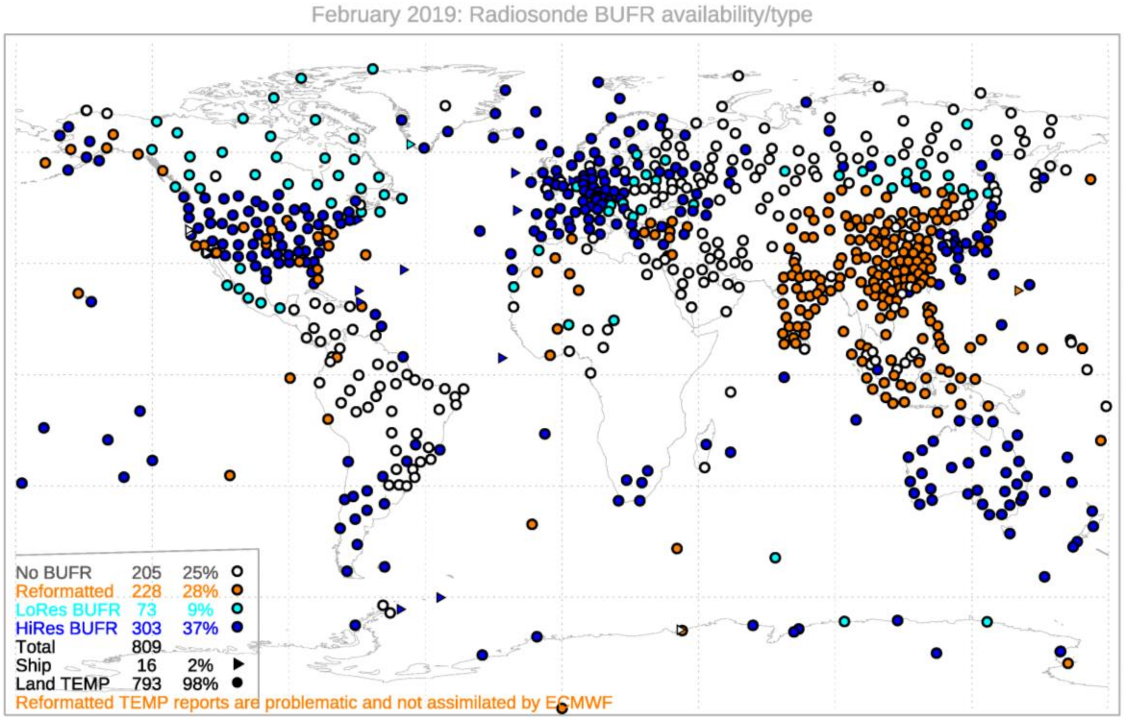
The number of aircraft observations have increased very significantly the last 20 years.

ECMWF used 42,000 aircraft measurements per day in 1996, we now use 1,900,000 aircraft measurements per day



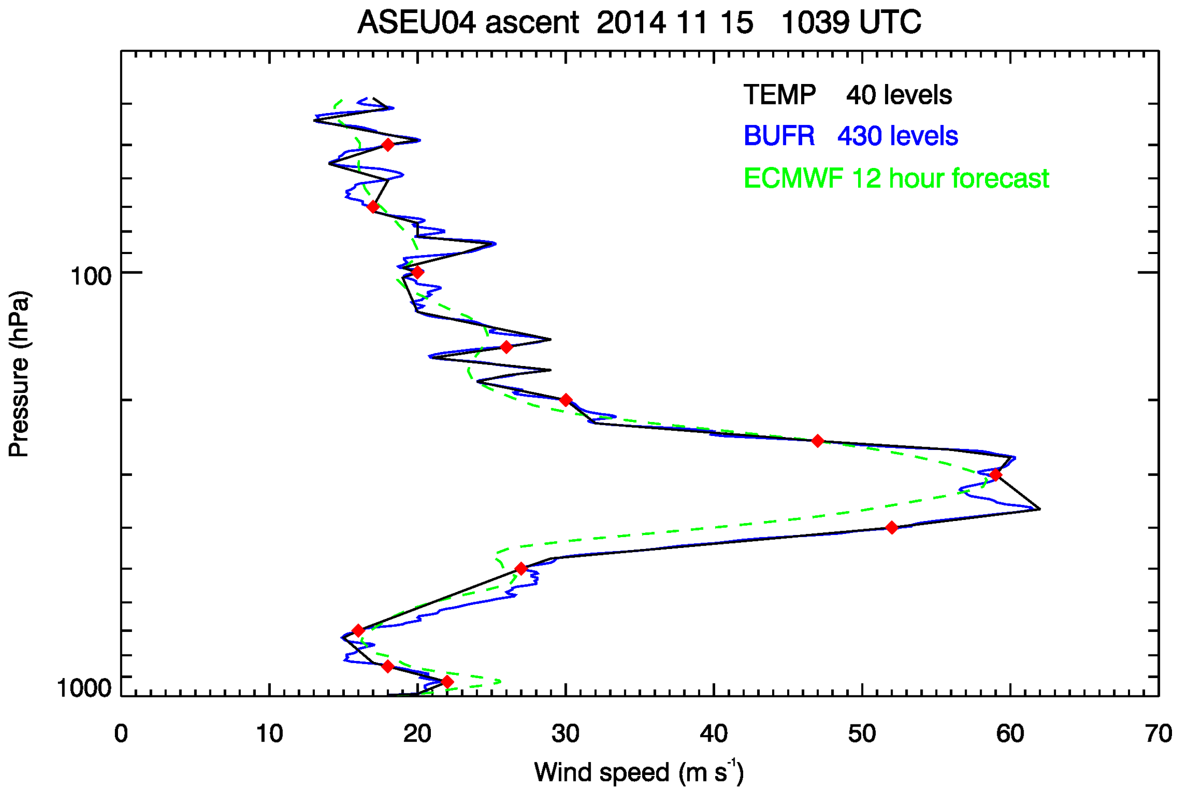


Migration to radiosonde BUFR format



- The proportion of native high-resolution reports is growing in fits and starts
- Recently USA (2017), Japan (July 2018), parts of South America (2018) and some Russian stations (~Nov 2018)
- https://software.ecmwf.int/wiki/display/TCBUF Ingleby et al (2016, BAMS)

BUFR radiosondes provide up to 8000 levels of measurements compared to less than 100 levels for TAC TEMP reports. A valuable improvement for data assimilation.



Bruce Ingleby, ECMWF

ECMWF

Accounting for radiosonde drift in data assimilation

- “Old style” radiosondes only provide the balloon launch location
- Native BUFR reports provides accurate location/time for each measurement
- The location/time information can be used to account for balloon drift in data assimilation

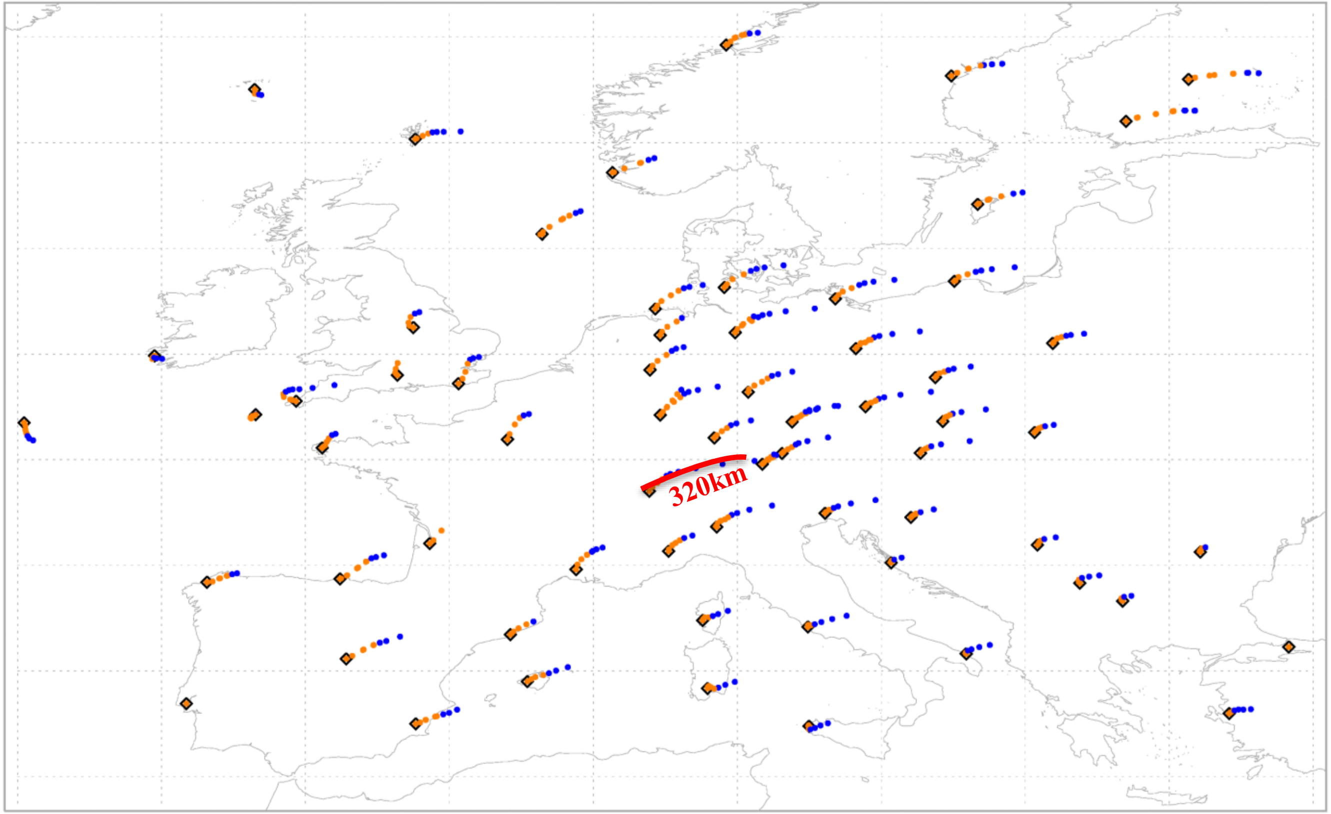
- We split the ascent into 15 minute chunks
- Was implemented at ECMWF in IFS Cycle 45r1 in June 2018

- BUFR DROP (high-resolution dropsonde data is coming soon)
- Descent data from BUFR radiosondes available from Germany and Finland

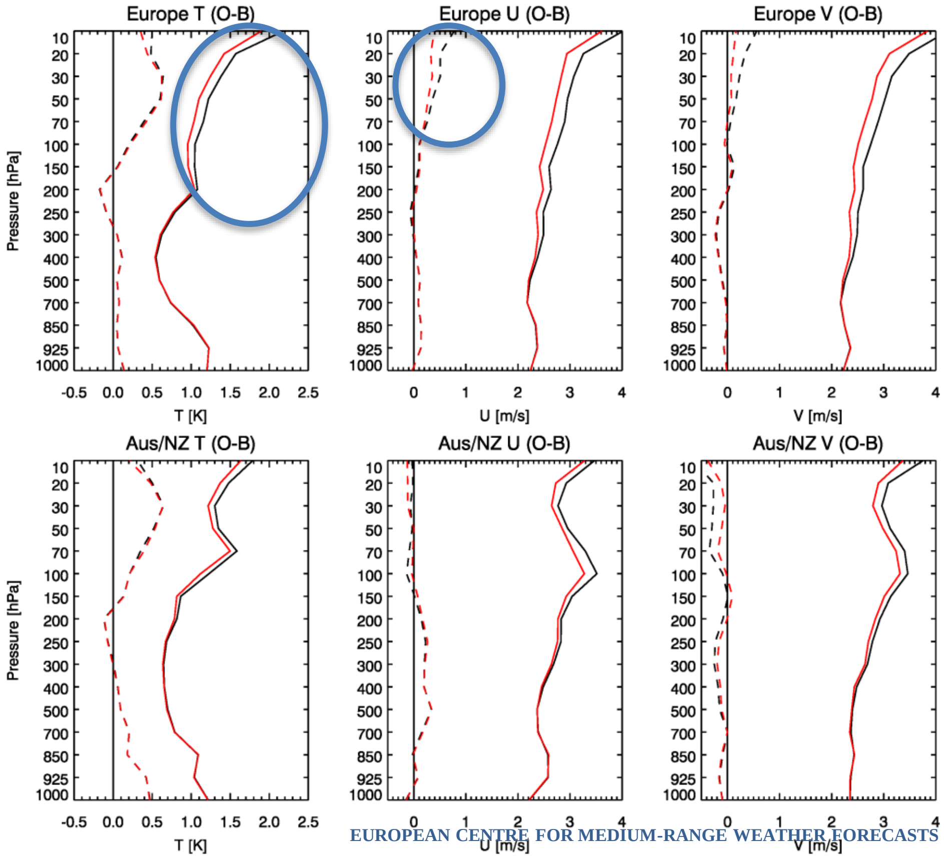
Example of large drift of radiosonde on a windy day

- Black diamonds – launch, levels to 100 hPa, levels above 100 hPa
- French (LoRes) and Polish (just upgraded) BUFR not used at the time

2016-11-21 12 radiosonde drift (15 minute intervals)



Impact of accounting for radiosonde drift in data assimilation
Mean and rms O-B statistics: Nov 2016



- Assimilated BUFR TEMP standard levels only (to get clean comparison)
- Good improvements at 200 hPa and above – including wind biases

Crowdsourced observations –potential for use in NWP

Three main categories:

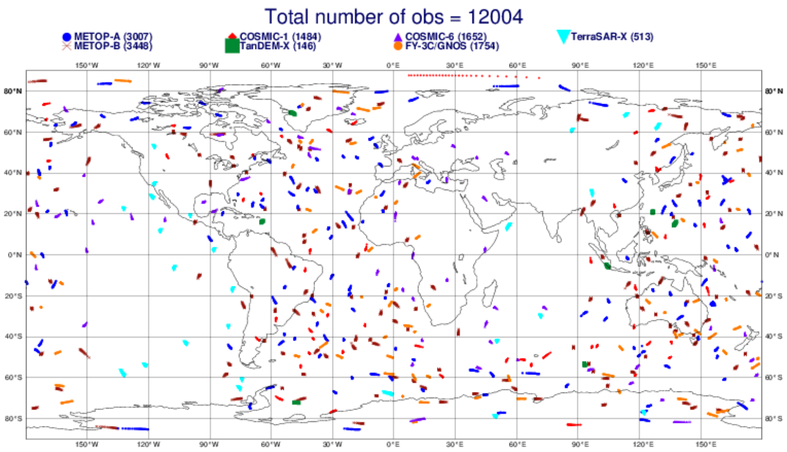
- ***Private sector and Third-party public organisations:*** *Not necessarily compliant with WMO regulations but the ones most similar to traditional meteorological networks.* ***Great potential for use in NWP***

- ***Automated amateur weather stations:*** *Huge increase in recent years. Large diversity in types and operating environments (*maintenance, operability, siting and exposure issues). Mainly private companies responsible for measurements/distribution chain. **Potential for use in NWP, if good collaboration is pursued.**

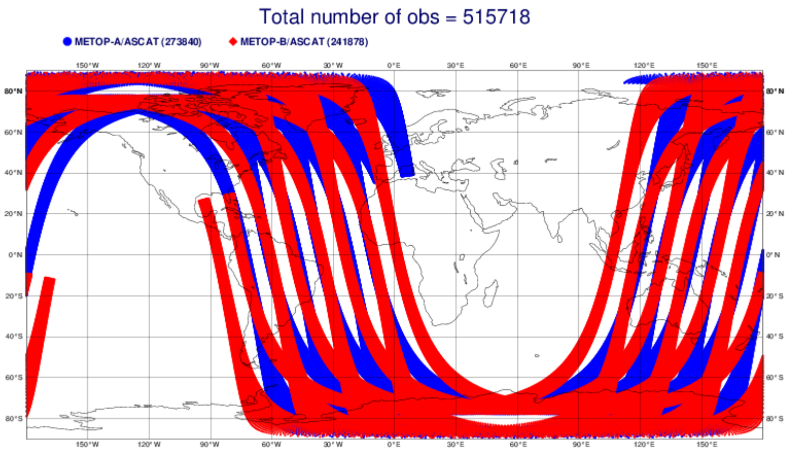
- ***Smart devices:*** *M*ass availability of meteorological parameters from internet connected smart devices: smartphones (e.g. atmospheric pressure combined with GPS data). Potentially useful, mainly in remote areas. Privacy issues. **Very challenging to use for NWP due to their rapidly changing positions.**

Advanced quality control essential for the use crowdsourced observations in NWP

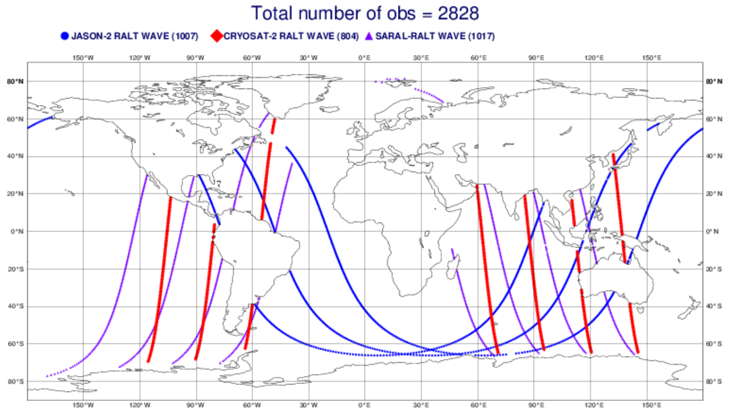
Example of 6hr actively sensed data



Radio occultation data



Scatterometer



Altimeter (wave height, wind speed)

Adjoint-based diagnostic methods (FSOI)

Slide from Cristina Lupu's presentation on Thursday

- Estimates of observation impact using the **adjoint** (transpose) of the data assimilation system have become increasingly popular as an alternative/complement to traditional OSEs.
  - Enable a simultaneous estimate of forecast impact for any and all observations assimilated.
  - Impact assessed without denial - FSOI measures the impact of observations when the entire observation dataset is present in the assimilation system
  - Used at several centres now for routine monitoring or experimentation: ECMWF, Met Office; Meteo France, JMA, NRL, GMAO
  - Implemented at ECMWF by *C. Cardinali (2009)*; FSOI statistics are published on the ECMWF monitoring website.

http://www.ecmwf.int/en/forecasts/charts/obstat/

Two methods to evaluate impact of observations: FSOI versus OSEs

FSOI **Forecast Sensitivity Observation Impact**	**OSE** **Observing System Experiment**
Measures the impact of obs when entire observation dataset is present using an adjoint based var. method	Observing system modified
Measures the response of a single forecast metric to all perturbations of observing system	Effects of a single perturbation on all forecast metrics
Short-range forecast (24-48hr) due to tangent linear assumption restrictions	Can measure data impact on long-range forecast
Measures impact of all observations assimilated in a single analysis time Further details by Cristina Lupu on Thursday	Accounts for effects of observations assimilated in previous analyses: compare modified Kalman gain matrix Further details by Tony McNally tomorrow

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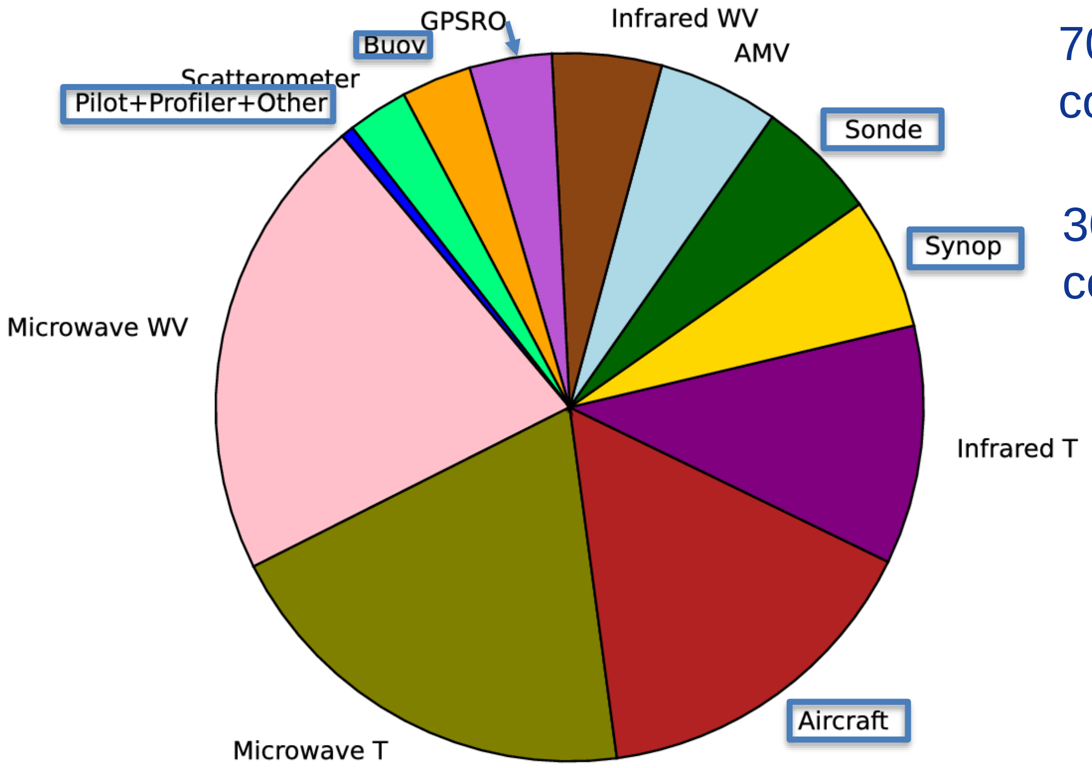


ECMWF FSOI February 2018:

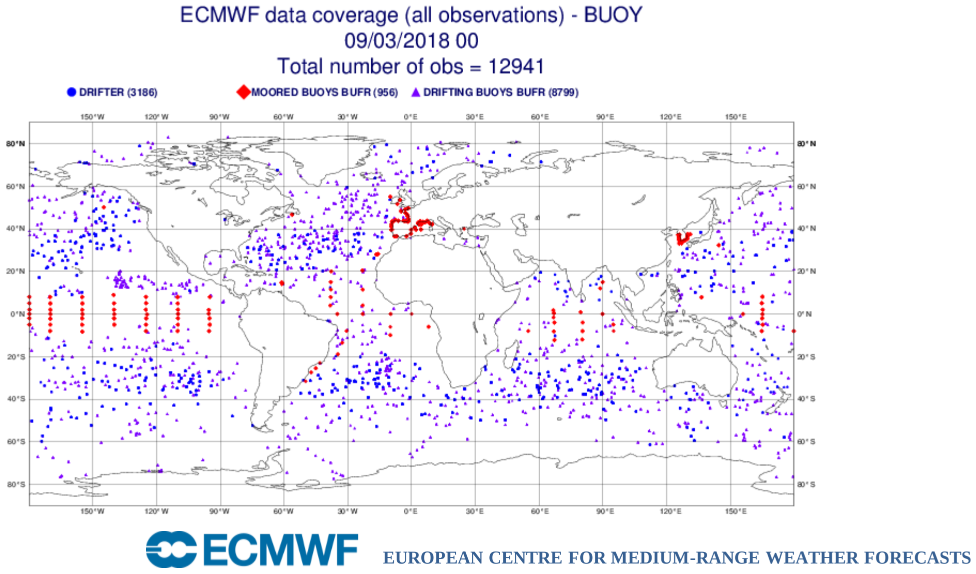
70% of 24h forecast impact comes from satellite data

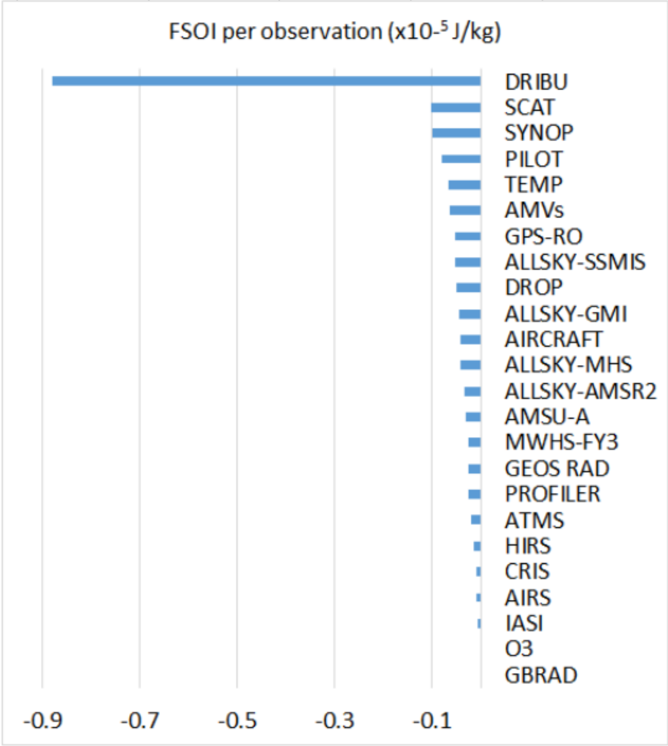
30% of 24h forecast impact comes from in situ data

Adapted from Alan Geer’s ECMWF Annual Seminar 2018 talk

Forecast sensitivity per observation

- FSOI: Forecast Sensitivity to Observation Impact
- Drifting buoys have largest FSOI per observation
- Good quality data from remote areas, means high value





C Lupu, ECMWF

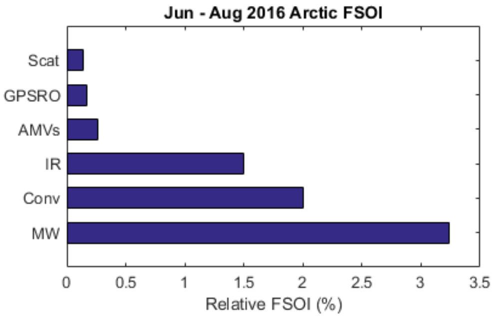
FSOI: Forecast Sensitivity to Observation Impact

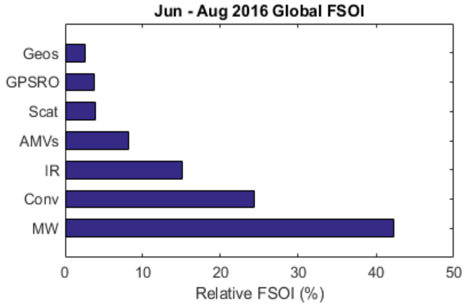
Adjoint-based method of measuring observation impact (Cardinali, 2009)

Arctic:

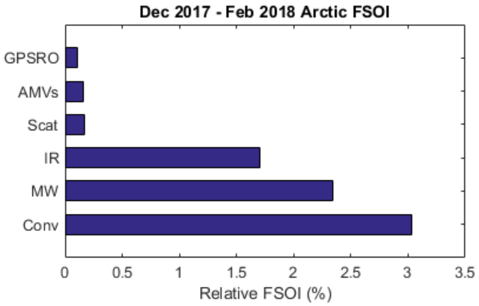
Global:

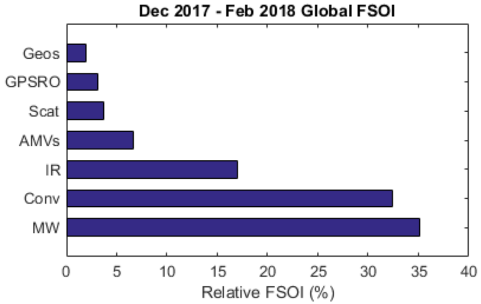
summer





winter





Globally:
1. Microwave
2. Conventional
3. IR

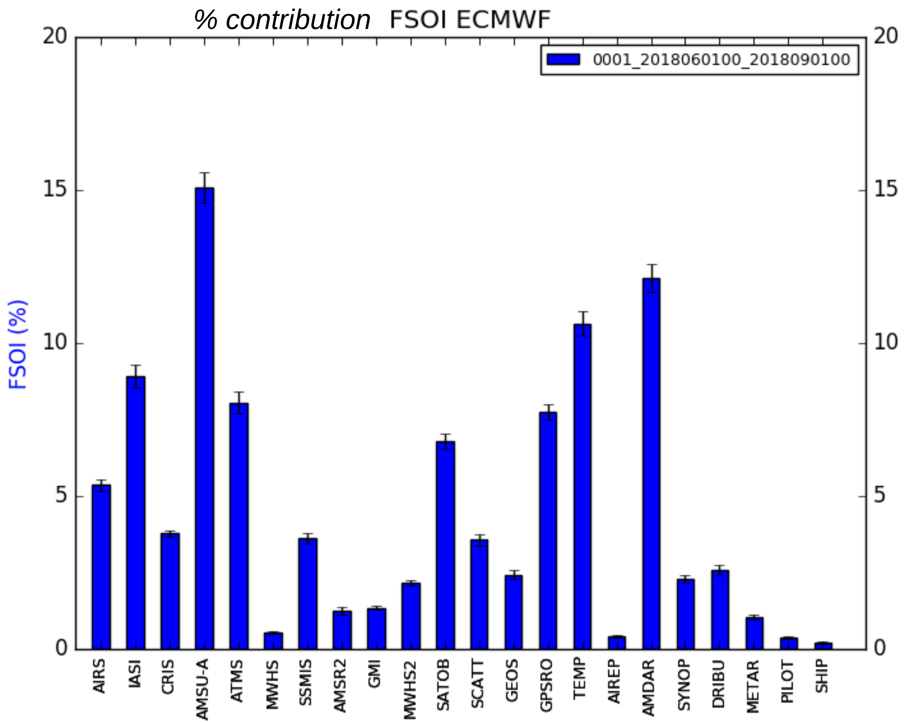
Arctic summer:
1. Microwave
2. Conventional
3. IR

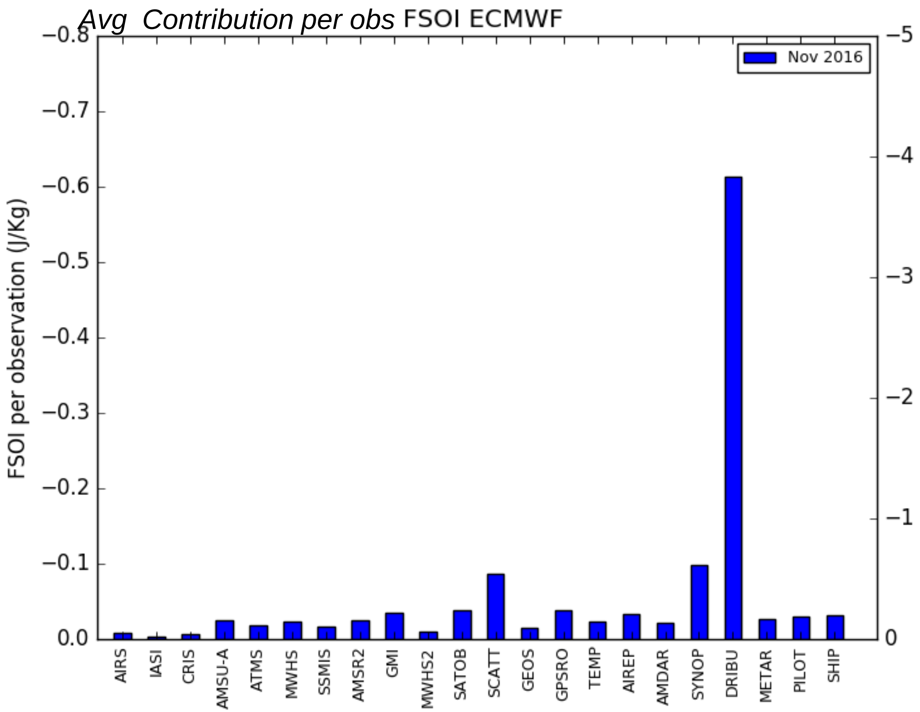
Arctic winter:
1. Conventional
2. Microwave
3. IR

H. Lawrence et al, 'Evaluation of Arctic Observation Forecast impact in the ECMWF Numerical Weather Prediction System," in preparation

Impact of observations (FSOI)

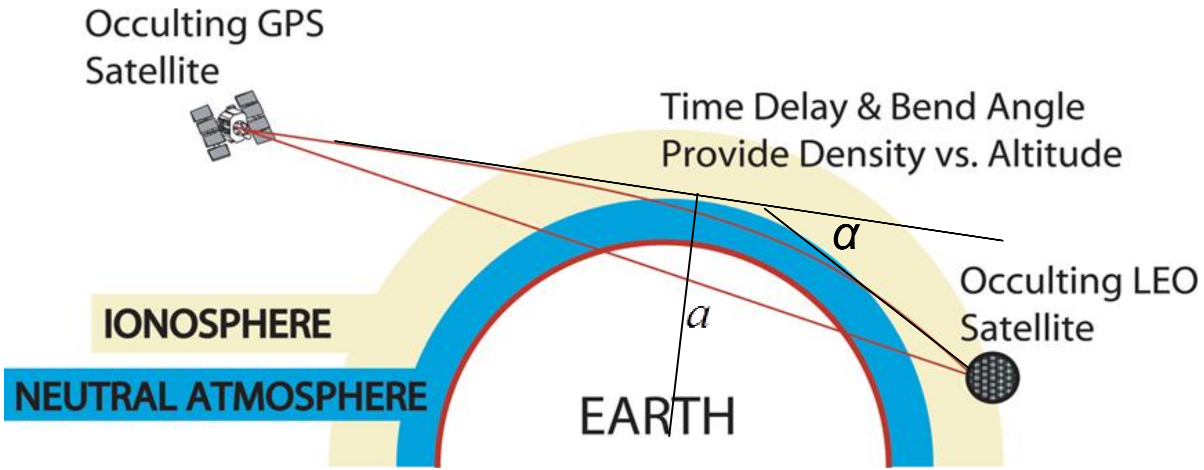
Surface observations have significant impact despite their small numbers





GPS RO geometry

(Classical mechanics: Compare this picture with the deflection of a charged particle by a spherical potential!)

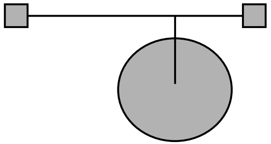


Setting occultation: as the LEO moves behind the earth we obtain a profile of bending angles, α, as a function of impact parameter, a. *The impact parameter is the distance of closest approach for the straight line path. It is directly analogous to angular momentum of a particle.*

Sean Healy, ECMWF

1D bending angle assimilation at Met Office, NCEP, MF, ECMWF (until 2014)

- Most centres assimilate bending angles with a 1D operator: ignore the 2D nature of the measurement and integrate



$$\alpha(a) = -2a \int_a^\infty \frac{d \ln n / dx}{\sqrt{x^2 - a^2}}\, dx$$

*Convenient variable (x=nr) (refractive index * radius)*

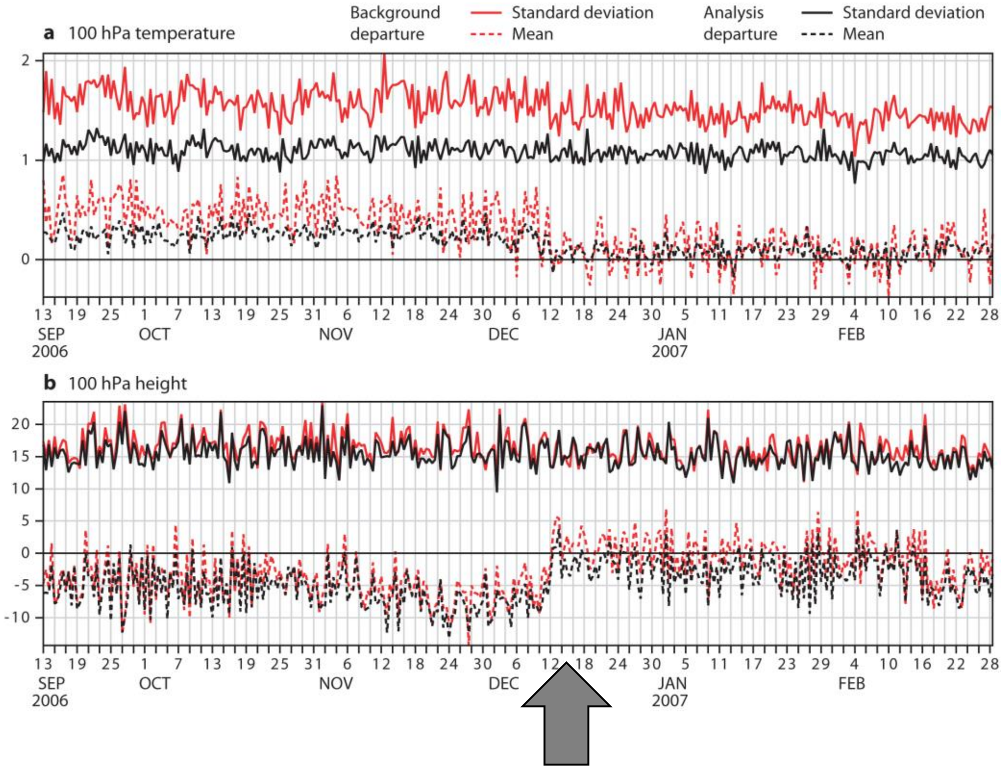
- The forward model is quite simple:
  - **evaluate geopotential heights of model levels**
  - convert geopotential height to geometric height and radius values
  - evaluate the refractivity, N, on model levels **from P,T and Q**.
  - Integrate, assuming refractivity varies ~(*exponentially*quadratic*) between model levels. (*Solution in terms of the Gaussian error function*).

GPS-RO data primarily improve temperature analysis in the upper troposphere and in the stratosphere –

Resulting in reduce background field biases measured against radiosondes

100hPa temperature O-B departures

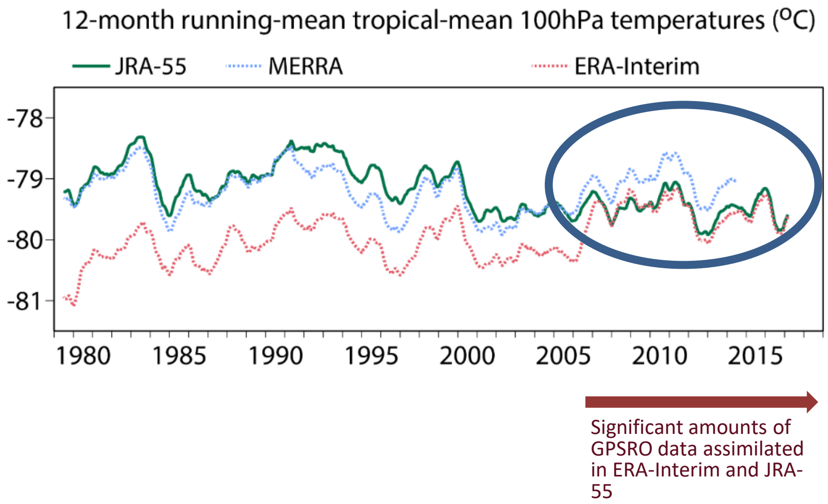
100hPa geopotential height O-B departures



Operational implementation

Tropical tropopause temperature

Using GPSRO data to anchor reanalysis temperatures, especially for upper troposphere and stratosphere

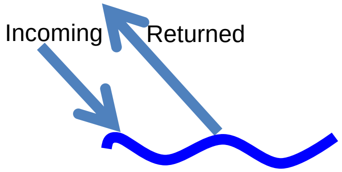


MERRA is warmer than ERA-Interim throughout.

ERA-Interim and JRA-55 assimilate GPSRO data, and come together in 2006. ERA-Interim warms and JRA-55 cools when significant amounts of GPSRO data start to be assimilated.

Scatterometer

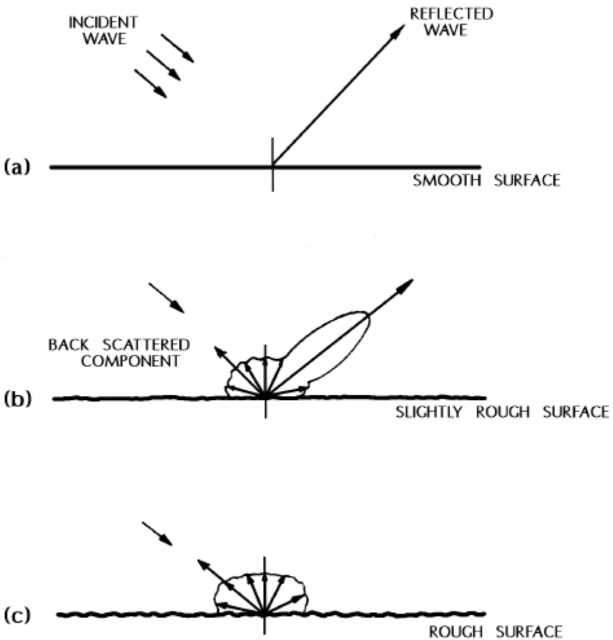
- A Scatterometer is an active microwave instrument (side-looking radar)
  - Day and night acquisition
  - Not affected by clouds



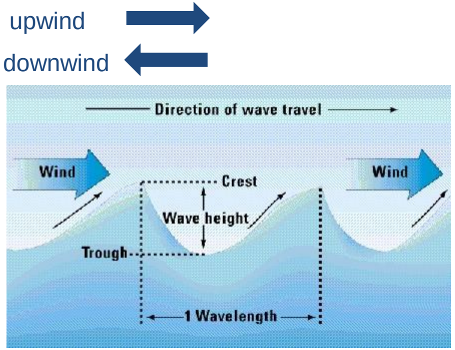
- The return signal, *backscatter* (σ_0 *sigma-nought),* is sensitive to:
  - Surface wind (ocean)
  - Soil moisture (land)
  - Ice age (ice)

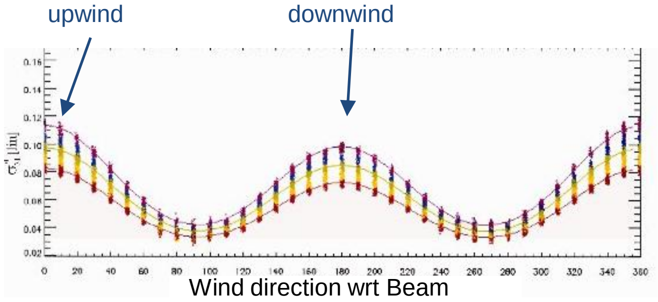
- Scatterometer was originally designed to measure ocean wind vectors:
  - Measurements sensitive to the ocean-surface roughness due to capillary gravity waves generated by local wind conditions (surface stress)
  - Observations from different look angles: wind direction

Dependency of the backscatter on... Wind speed



Dependency of the backscatter on... Wind direction





How can we relate backscatter to wind speed and direction?

The relationship is determined empirically by developing a Geophysical Model Function

- Ideally collocate with *surface stress* observations
- In practice with buoy and 10m model winds

$$\sigma_0 = GMF(U_{10N}, \phi, \theta, p, \lambda)$$

U_{10N}: equivalent neutral wind speed
ϕ: wind direction w.r.t. beam pointing
θ: incidence angle
p: radar beam polarization
λ: microwave wavelength

Past, present and future scatterometers

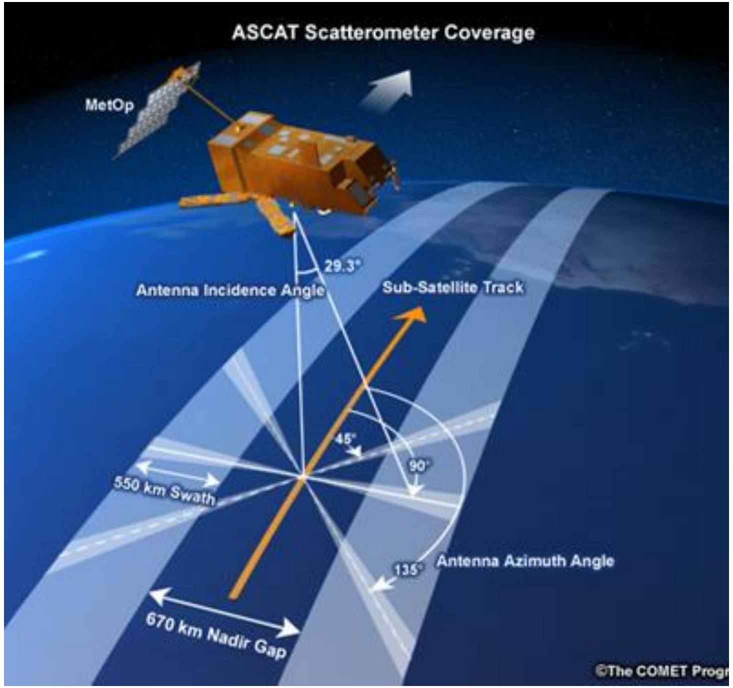
Used on European platforms (1991 onwards):

- ✓ SCAT on ERS-1, ERS-2 by ESA
- ✓ ASCAT on Metop-A/B/C by EUMETSAT
- ✓ ASCAT on future Metop planned until 2040

- Frequency ~5.3 GHz
- Wave length ~5.7 cm
- Three antennae
    - Enables estimation of both wind speed and wind direction

Also Indian and Chinese scatterometer data available now:

- ✓ OSCAT
- ✓ SCATSAT-1
- ✓ CFOSAT

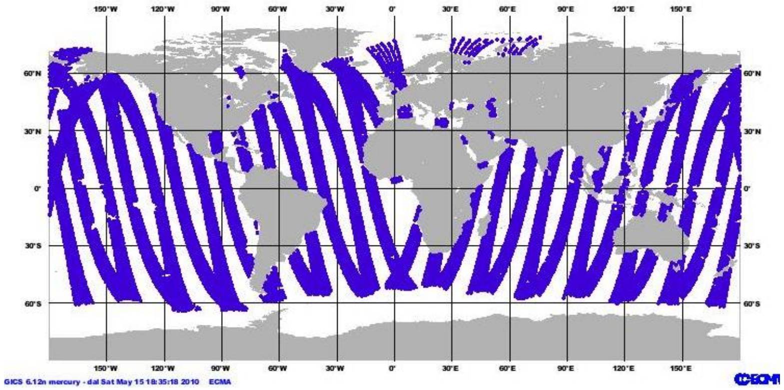


Why is Scatterometer important?

The scatterometer measures the ocean surface winds (ocean wind vector).

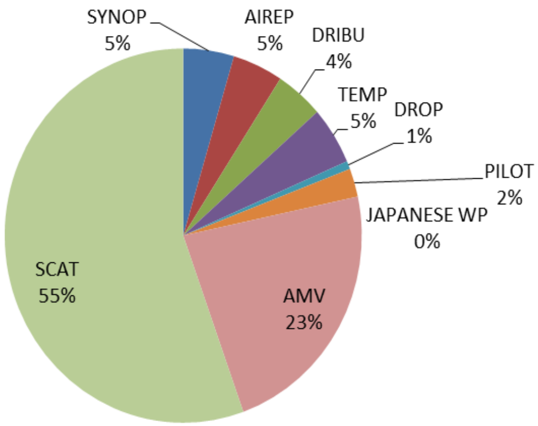
Ocean surface winds:

- affect the full range of ocean movement
- modulate air-sea exchanges of heat, momentum, gases, and particulates
- direct impact on human activities



Daily coverage of ocean surface winds
Example: 1 day of ASCAT-A data

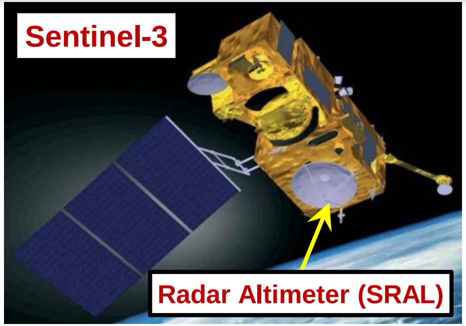
Wind observations below 850 hPa
FSOI values relative quantities (in %)



[Horanyi et al., 2013]

Giovanna De Chiara, ECMWF

Radar Altimeters



✓ Radar altimeter is a nadir looking instrument.

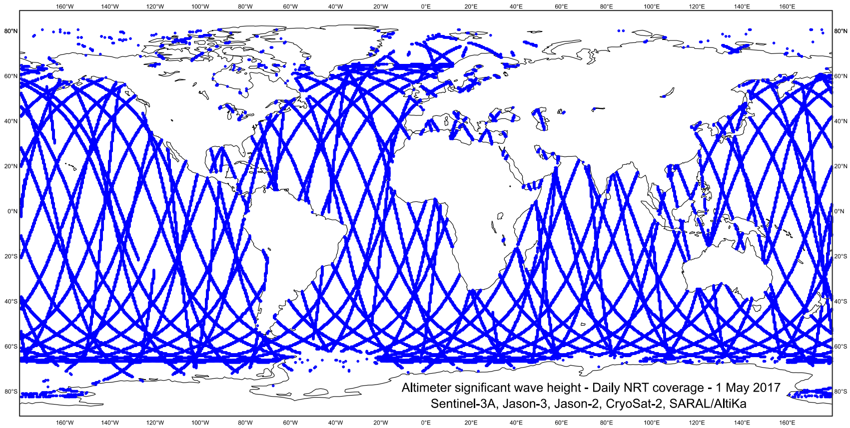
✓ Specular reflection.

✓ Electromagnetic wave bands used in altimeters:

- Primary:
  - Ku-band (~ 2.5 cm) – ERS-1/2, Envisat, Jason-1/2/3, Sentinel-3
  - Ka-band (~ 0.8 cm) – SARAL/AltiKa (only example)
- Secondary:
  - C-band (~ 5.5 cm) – Jason-1/2/3, Topex, Sentinel-3
  - S-band (~ 9.0 cm) – Envisat

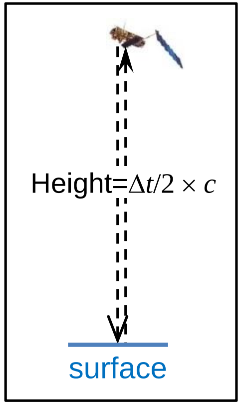
✓ Main parameters measured by an altimeter:

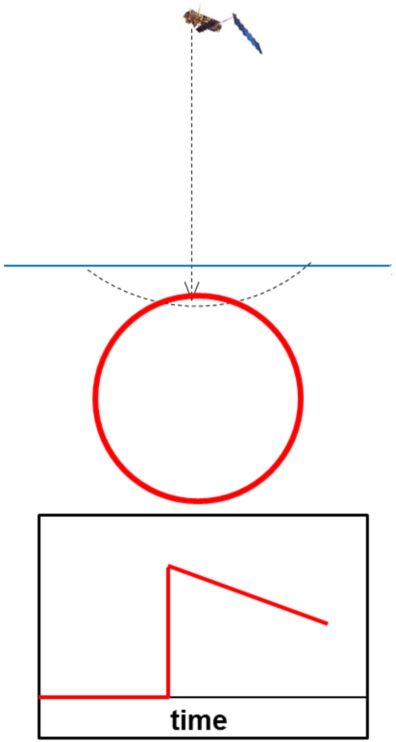
- Sea surface height (*ocean model*)
- Significant wave height (*wave model*)
- Wind speed (*used for verification*)

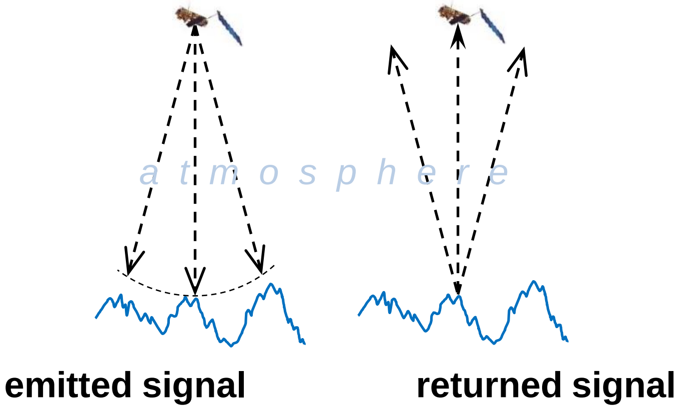


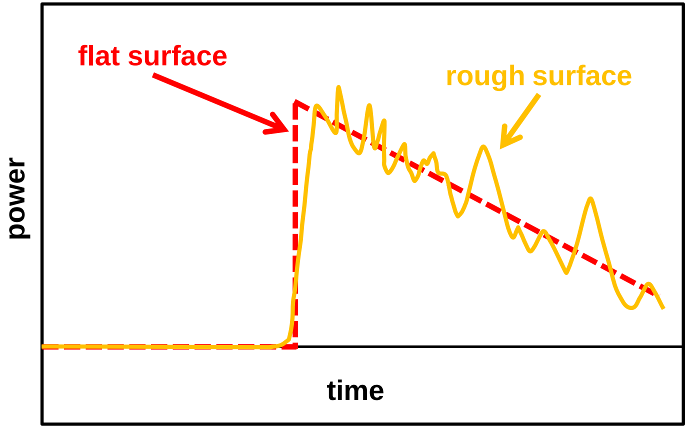
Saleh Abdalla, ECMWF

How Altimeter Works

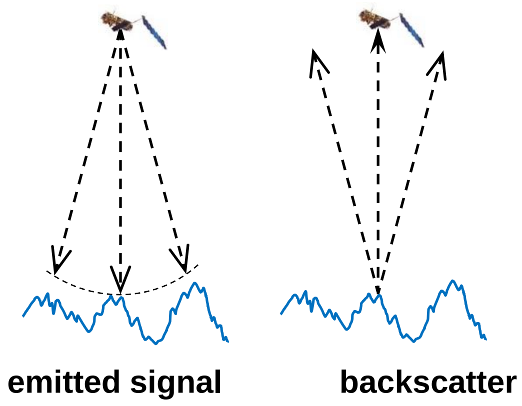


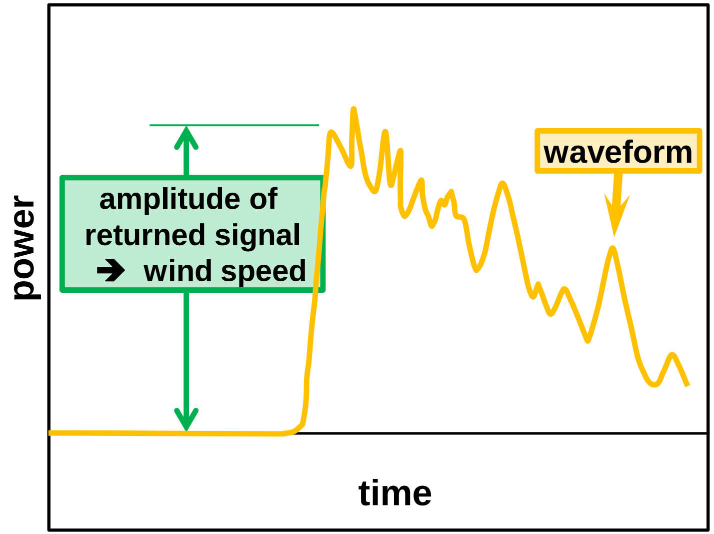






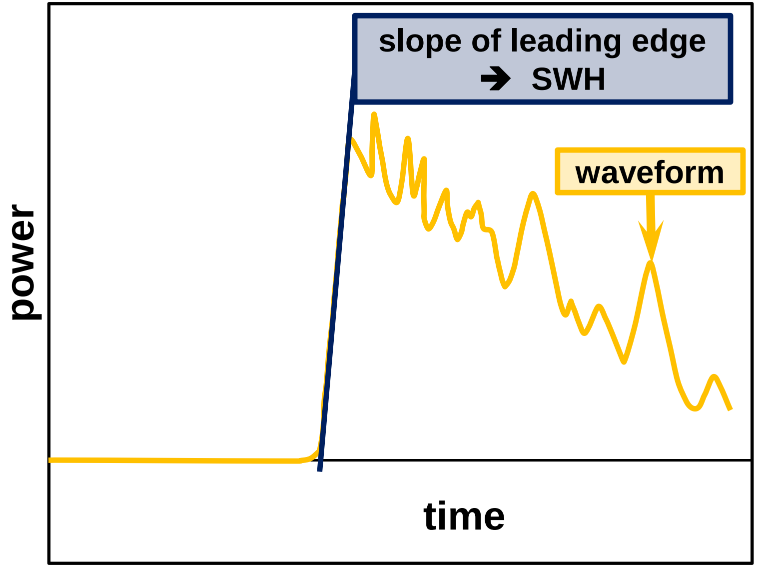
Surface wind speed





- ✓ Backscatter is related to water surface Mean Square Slope (MSS)
- ✓ MSS can be related to wind speed
- ✓ Stronger wind → higher MSS → smaller backscatter
- ✓ Errors are mainly due to algorithm assumptions, waveform retracking (algorithm), unaccounted-for attenuation & backscatter.

Significant Wave Height (SWH)



- ✓ SWH is the mean height of highest 1/3 of the surface ocean waves
- ✓ Higher SWH → smaller slope of waveform leading edge
- ✓ Errors are mainly due to waveform retracking (algorithm) and instrument characterisation.

Altimeter SWH data available from five satellites – nice synergy!

Plot shows random error reduction of SWH compared to model only.

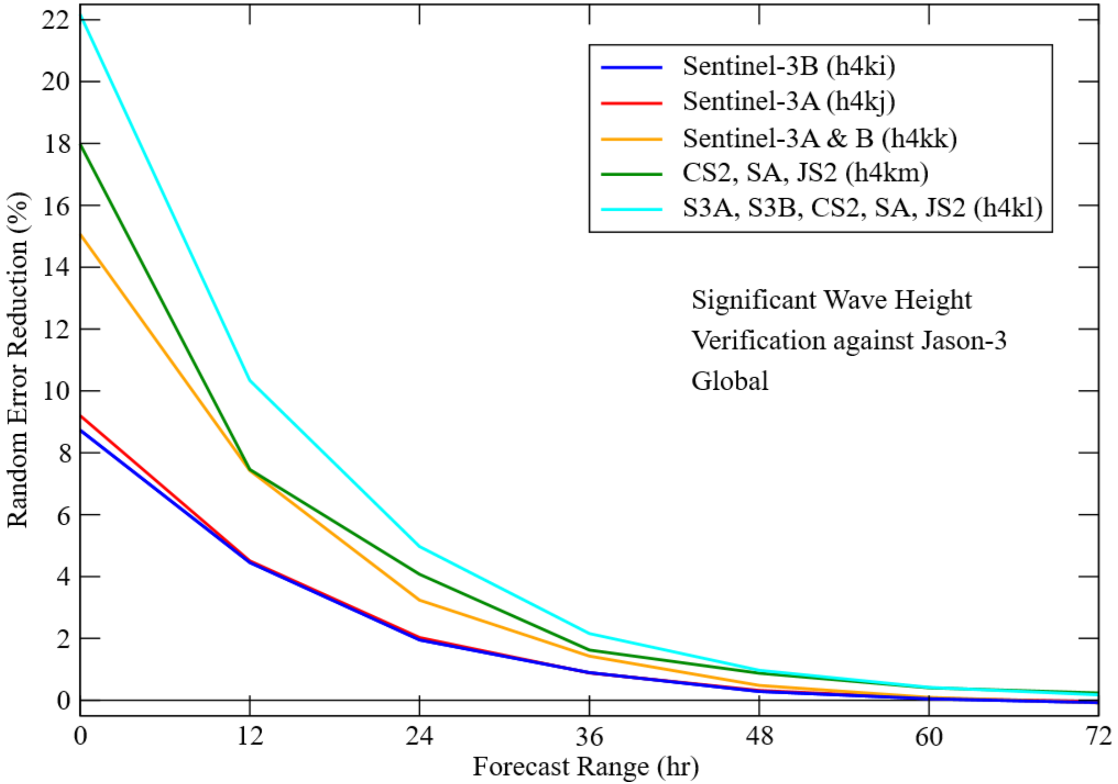
All the five altimeter instruments listed below

Cryosat-2 (CS2)+
SARAL AltiKa (SA)+
Jason-2 (J2)

Sentinel-3A&B

Sentinel-3A

Sentinel-3B



Altimeter summary

- **Radar Altimeter →**
  - Significant wave height (SWH);
  - Surface wind speed (U10);
  - Sea surface height (SSH);
  - Sea ice, … etc.

- **Altimeter wind and wave data are used for:**
  - Wave data assimilation;
  - Monitoring the model performance;
  - Assessment of model changes;
  - Use in reanalyses (assimilation and validation);
  - Estimation of effective model resolution;
  - Estimation of absolute random model error;
  - Long-term assessments and climate studies.

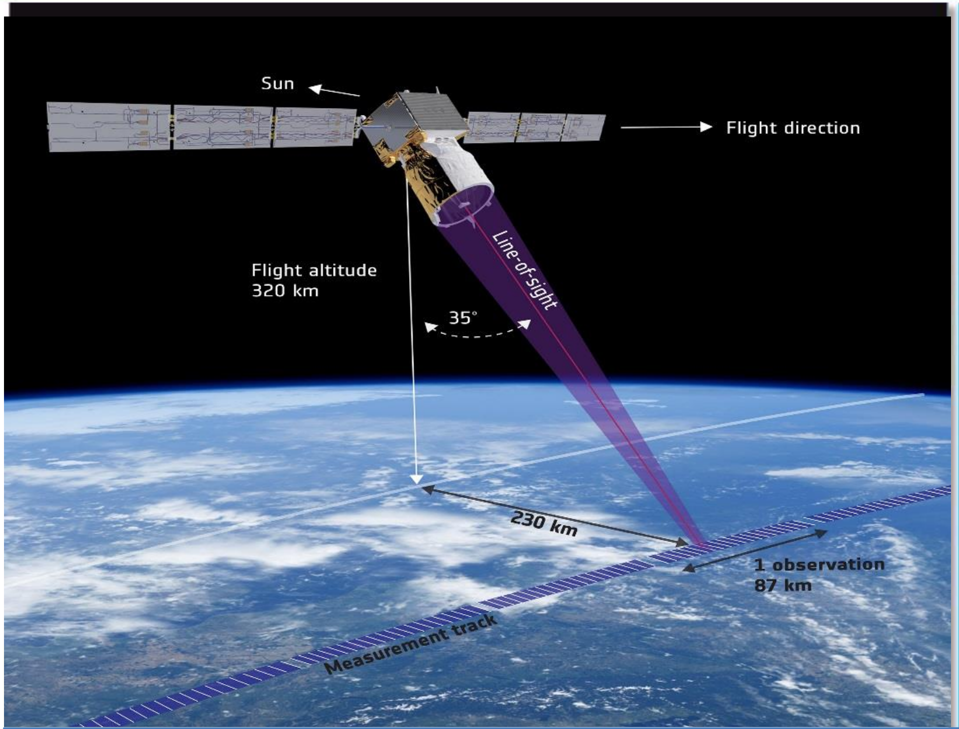
Aeolus Doppler Wind Lidar

- ESA Earth Explorer Core Mission
  - Chosen in 1999
  - Part of ESA's Living Planet Programme
- Technology demonstration; designed to be a 3 year mission

Mission status

- **Launched on 22/8/2018!** *delayed by a decade*
  - *First* European lidar in space, after 20 years of development challenges
  - *First* wind lidar in space
  - *First* high-power UV lidar in space, with stringent frequency stability requirements
- **Aeolus has been technically proven to work as the first wind lidar in space**
  - Over 5 months of wind data available now

Aeolus: Measurement Principle



- Direct detection UV Doppler wind Lidar operating at 355 nm and 50 Hz PRF in continuous mode, with 2 receiver channels.
- Mie receiver to determine winds from aerosol & cloud backscatter.
- Rayleigh receiver to determine winds from molecular backscatter.
- The line-of-sight is pointing 35° from Nadir to obtain horizontal backscatter component
- The line-of-sight is pointing orthogonal to the ground track velocity vector to minimize contribution from the satellite velocity.

Aeolus: Mission Objectives

esa

Scientific objectives

- To improve the quality of weather forecasts;
- To advance our understanding of atmospheric dynamics and climate processes;

Explorer objectives

- Demonstrate space-based Doppler Wind LIDARs potential for operational use.

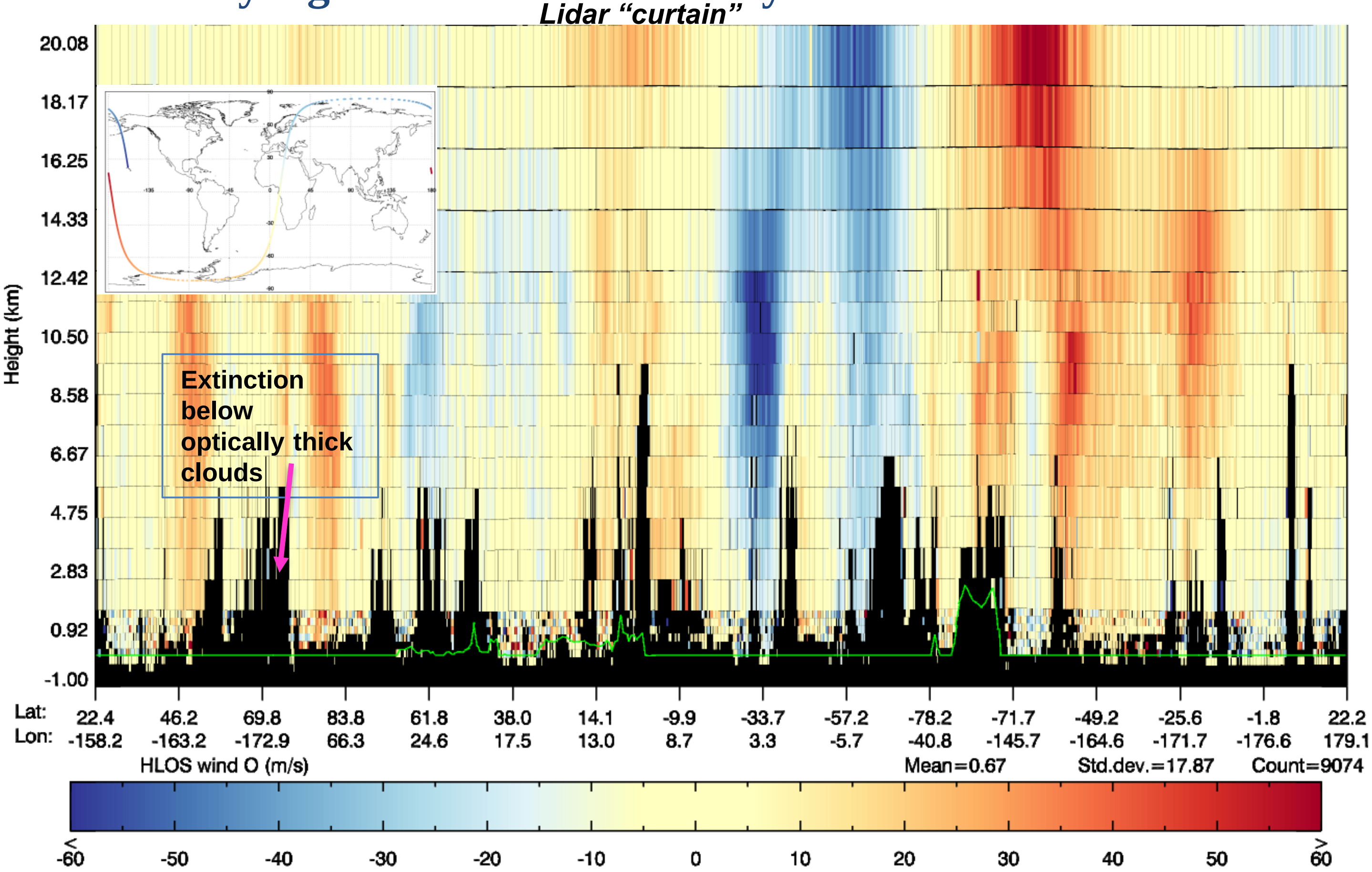
Observation means:

- Provide global measurements of horizontal wind profiles in the troposphere and lower stratosphere

Payload

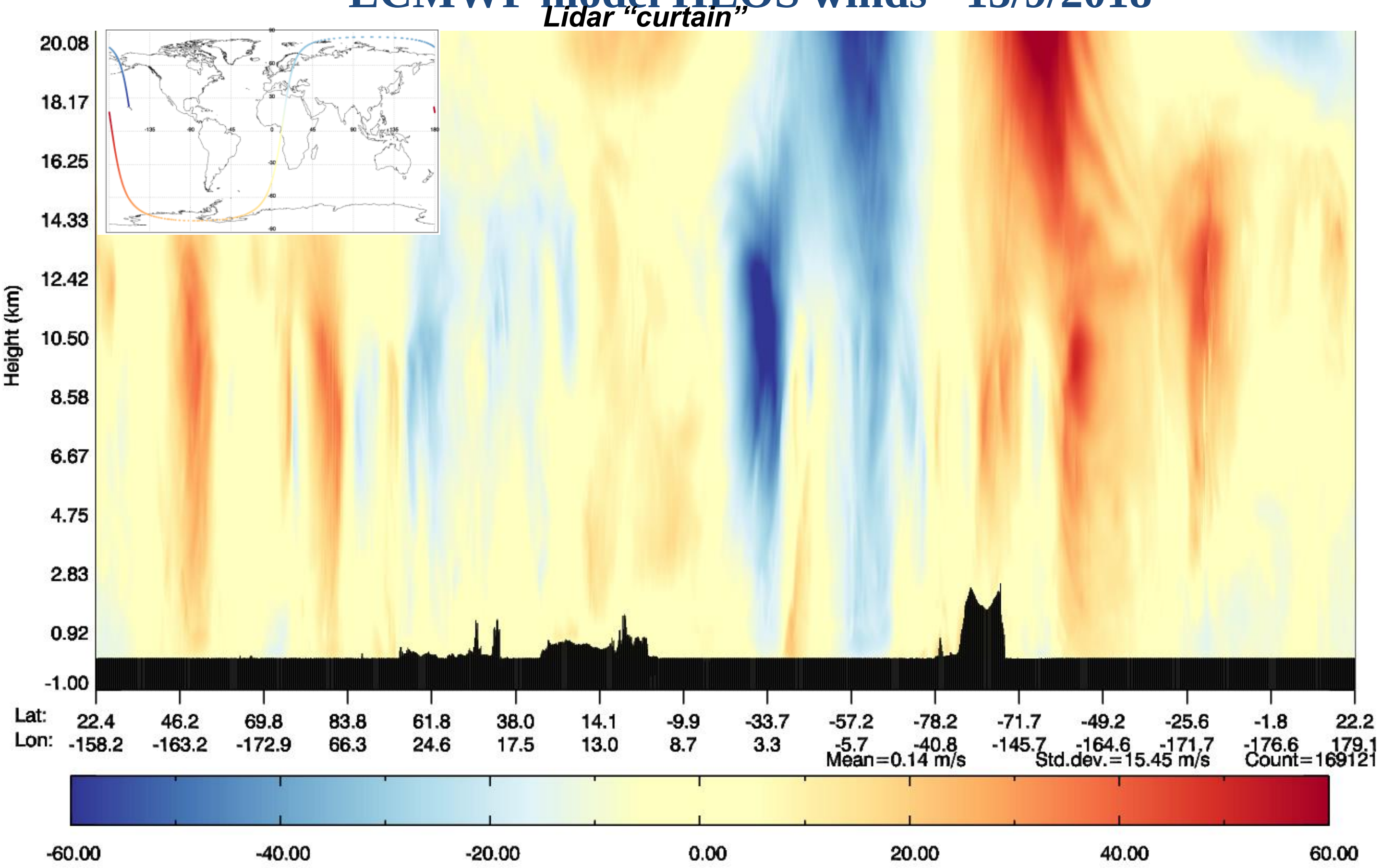
- ALADIN: Atmospheric LAser Doppler INstrument

L2B Rayleigh-clear and Mie-cloudy HLOS winds – 15/9/2018



ECMWF

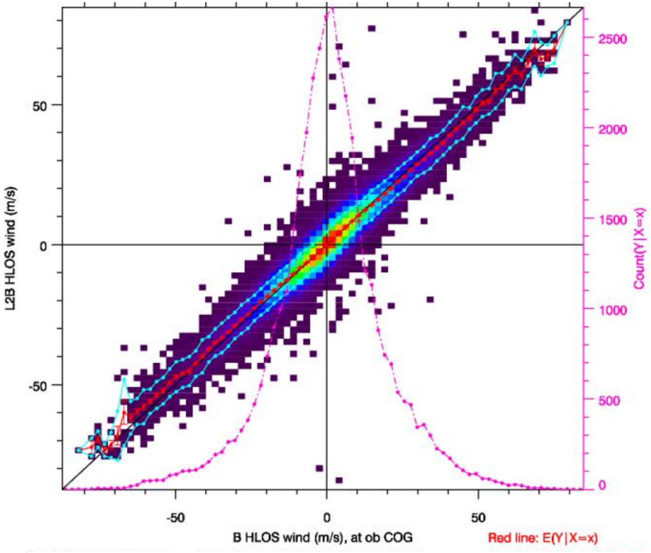
ECMWF model HLOS winds - 15/9/2018

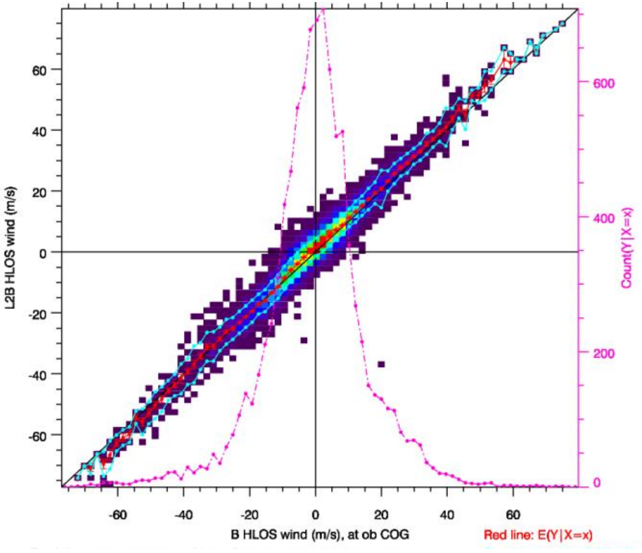


ECMWF

Aeolus HLOS winds compare very well with ECMWF's model winds

L2B Rayleigh-clear HLOS winds L2B Mie-cloudy HLOS winds





Topics covered in today's lecture

- Why observations are essential for data assimilation
- Overview of in situ observations and some actively sensed observations
- Impact of in situ and actively sensed observations in global NWP
- Further aspects on assimilating in situ and actively sensed observations

Thank you for your attention!

Any questions?