Assimilation of in-situ observations

Annual Seminar 2026
Advancing the assimilation of Earth system observations with new methodology and Machine Learning

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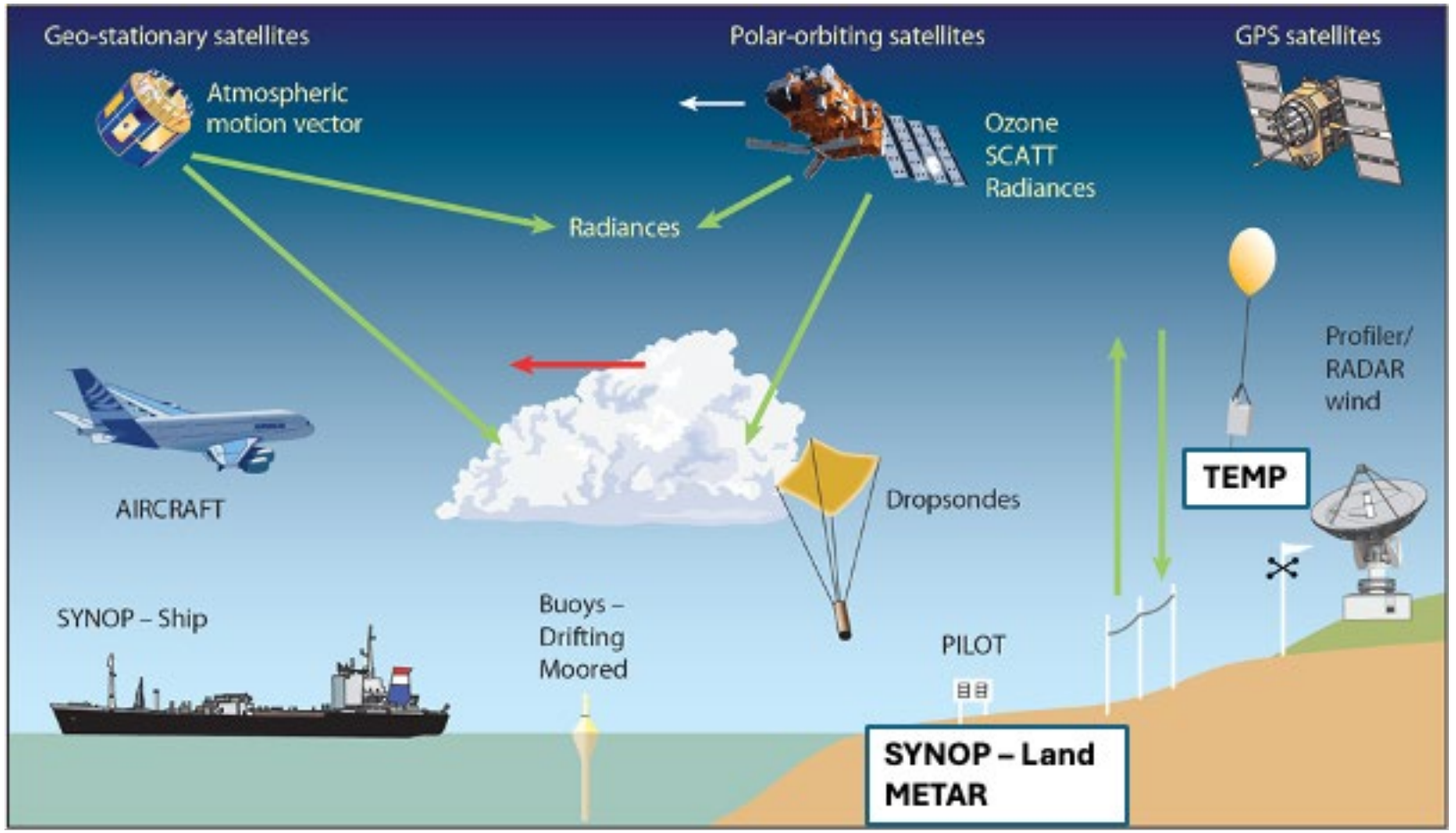
Structure

- Introduction
- Current use of in-situ measurements
  - Observation systems
  - Impact assessment
- On-going and future developments
  - Improved use of currently used observations
  - Extended observation use
- Summary and Conclusions

In-situ measurements

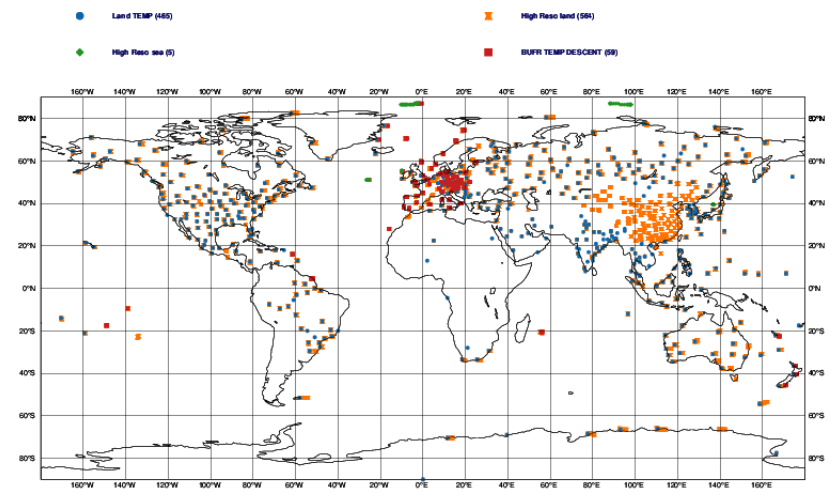
- In meteorology, **in-situ measurements** are observations made **directly at the location where the atmospheric variable exists**. This can be done either by sensors located within the atmosphere or at the **Earth's surface.**
- Often then in-situ measurements are referred to as conventional types of observations.
- Examples of in-situ measurements are: (1) a thermometer measuring air temperature, (2) a barometer measuring pressure, (3) a hygrometer measuring humidity, (4) an anemometer measuring wind speed and (5) a wind vane measuring wind direction.
- In contrast, **remote-sensing observations** of the atmosphere **are obtained from a distance** for example by various instruments on-board satellites or ground-based weather radars.

WMO Integrated Global Observing System

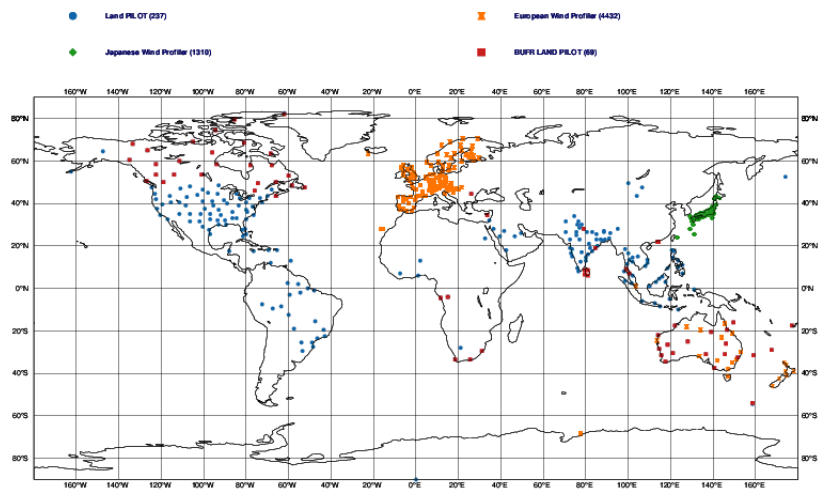


Conventional Observing systems assimilated in atmospheric part of ECMWF IFS

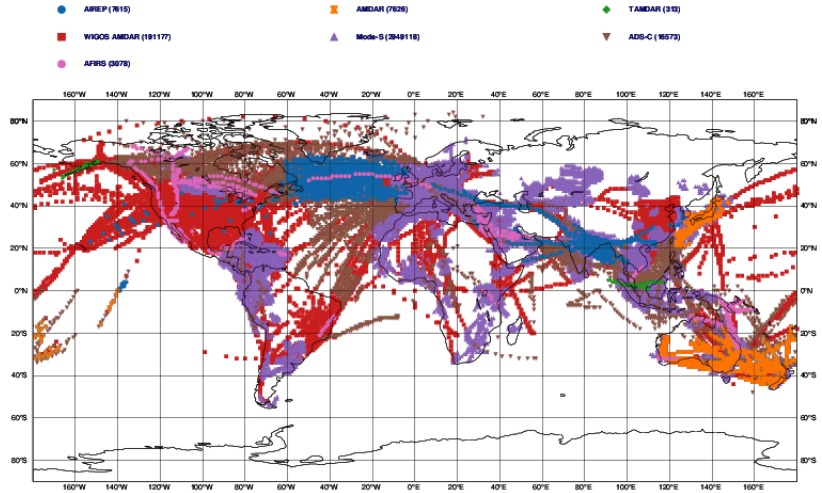
ECMWF data coverage (all observations) - RADIOSONDE
2026081921 to 2026082003
Total number of obs = 1093



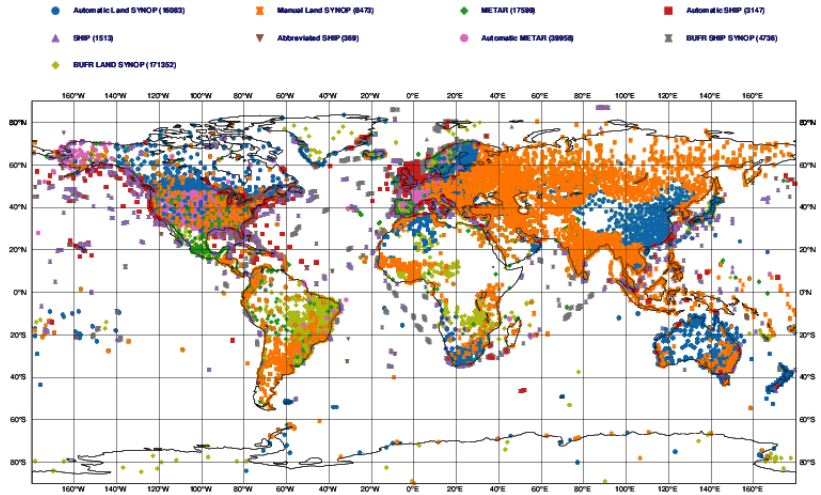
ECMWF data coverage (all observations) - PILOT
2026081921 to 2026082003
Total number of obs = 6048



ECMWF data coverage (all observations) - AIRCRAFT
2026081921 to 2026082003
Total number of obs = 3175500



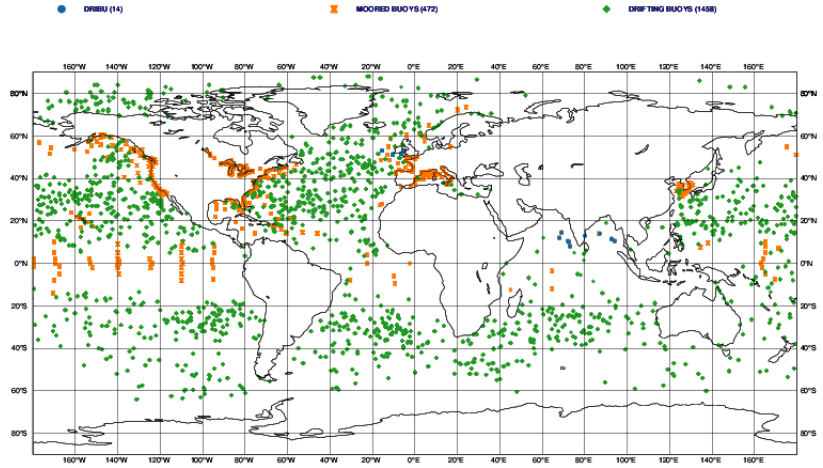
ECMWF data coverage (all observations) - SYNOP-SHIP-METAR
2026081921 to 2026082003
Total number of obs = 263230



2026-08-20 00 UTC

(GB GPS not covered here)

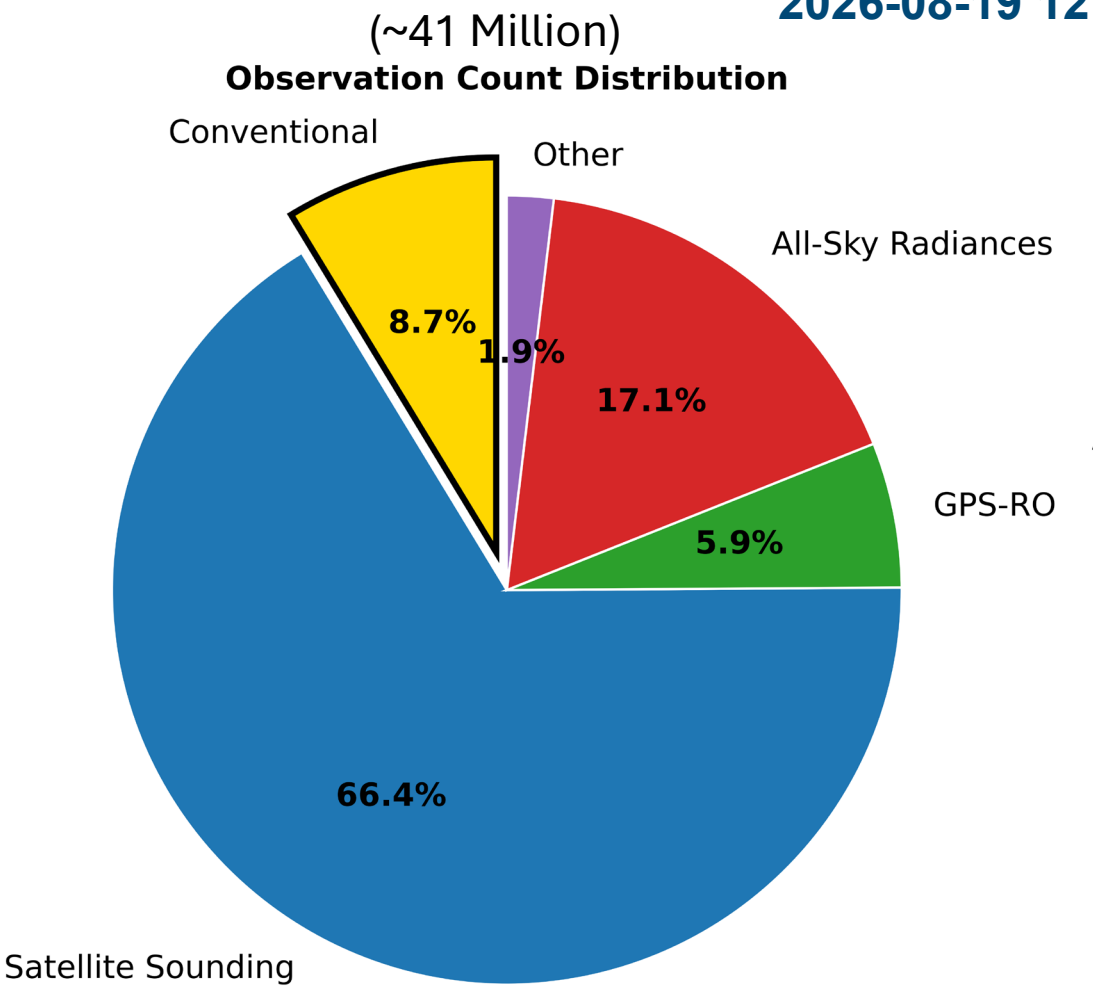
ECMWF data coverage (all observations) - BUOY
2026081921 to 2026082003
Total number of obs = 1944

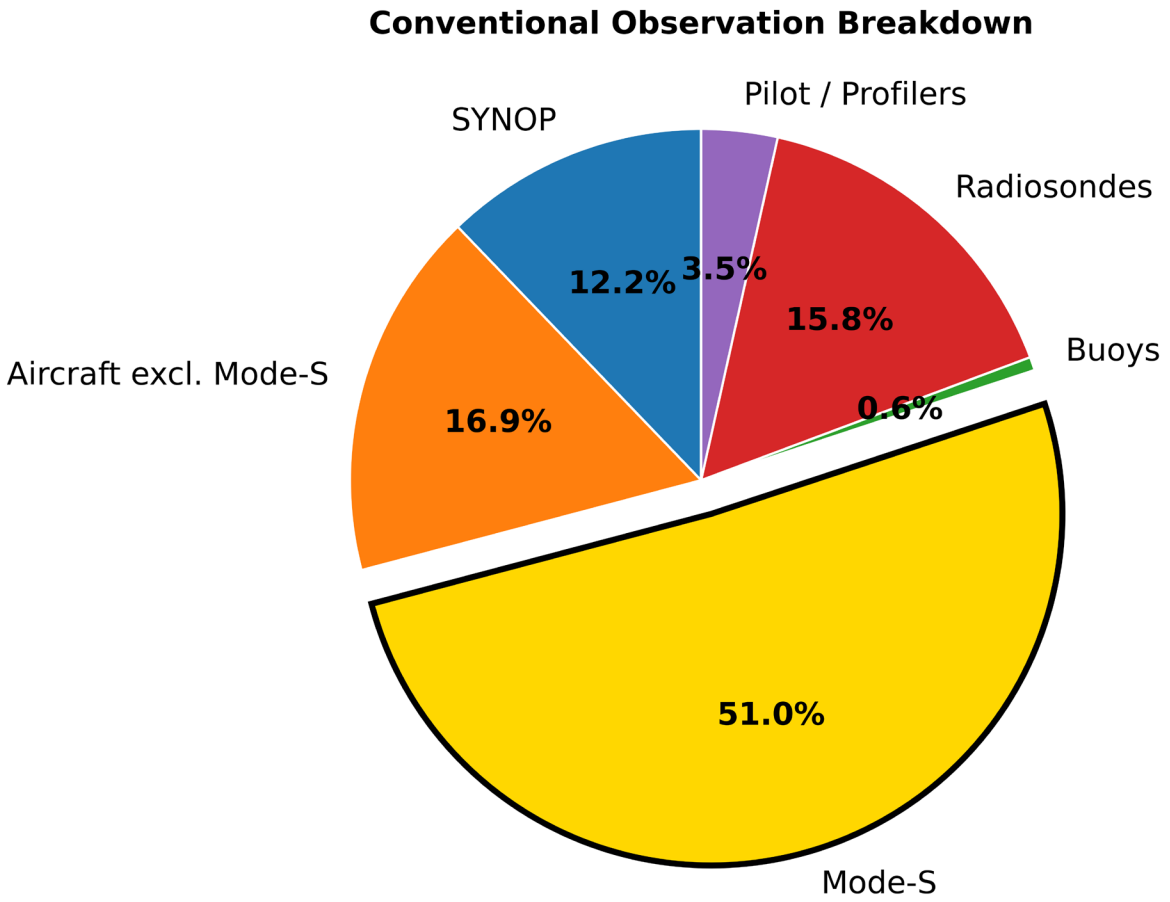


Data handling components for in-situ measurements

- Data monitoring, selection and thinning procedures.
- Quality control of observations.
- Handling of error characteristics including biases.
- Modelling of observation equivalents.

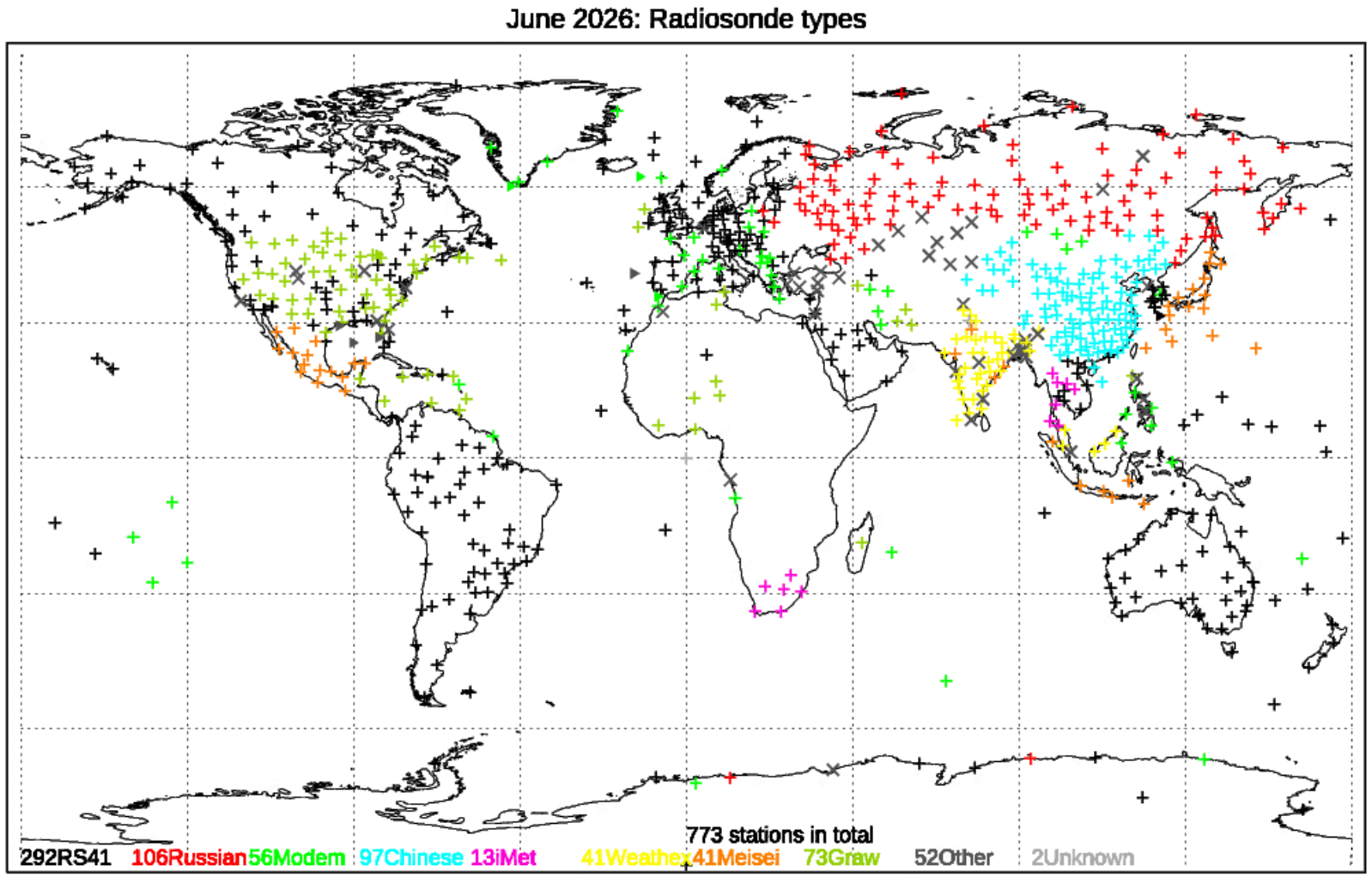
Conventional types of observations in single ECMWF IFS single data assimilation cycle 2026-08-19 12 UTC





In-situ measurements roughly 10 percent of total observation number assimilated.
How it translates into impact on analysis and forecast?

Radiosondes





Radiosonde

Various sonde types

(sensor package for observing pressure/height, temperature, humidity and winds)

RS41
Modem
Weathex
Meisei
Graw
Russian
Chinese
iMet

* Radiosondes are typically targeted for 00 and 12 UTC. Some countries also operates 06 and 18 UTC soundings.

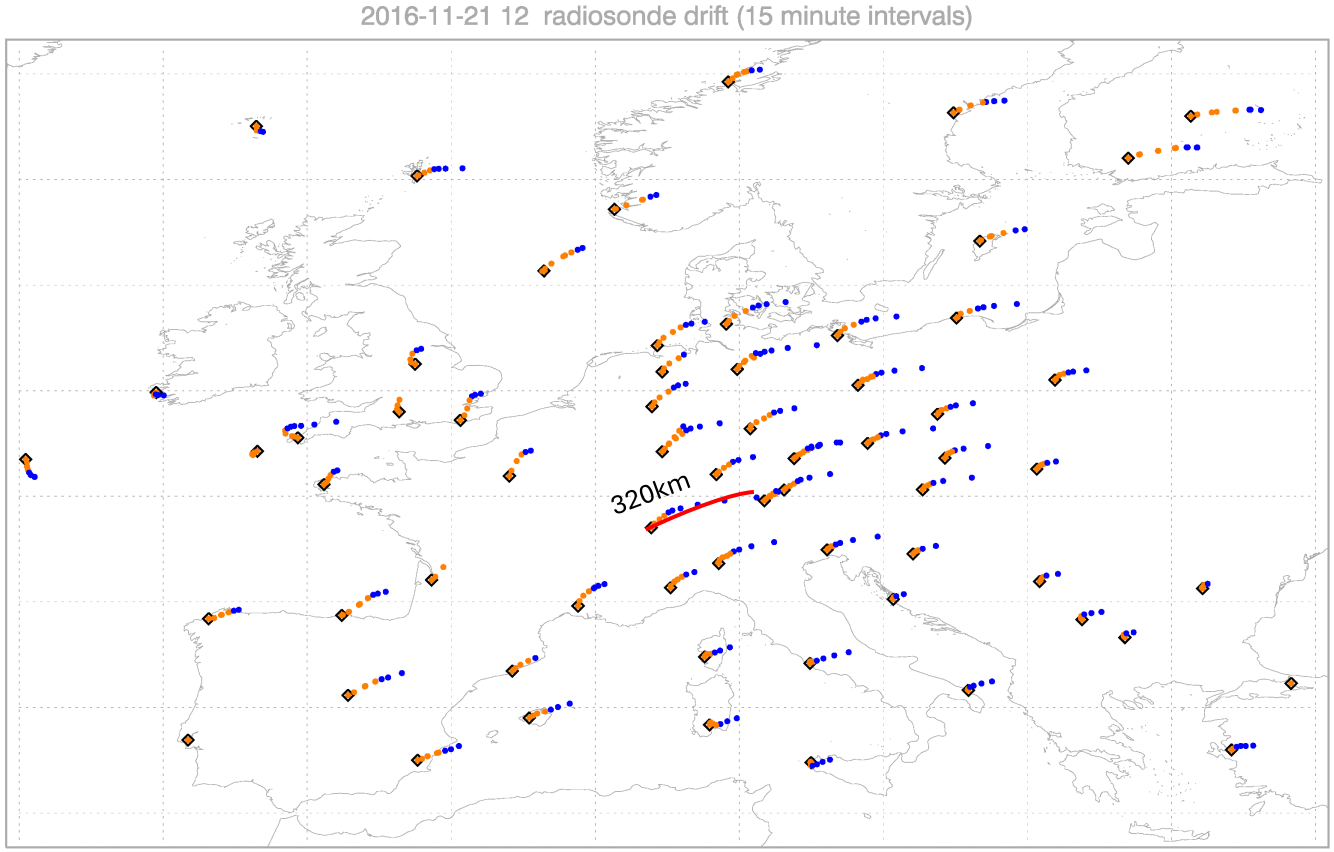
Radiosondes

Height and drift of ascents

- Most radiosonde launches worldwide are still performed manually, although automatic radiosonde are becoming more common.
- Ascent takes about 2 h on average.
- The balloon bursts at about 10-20 hPa.
- Horizontally drift up to ~100 km during ascent
- BUFR format needed to report all vertical levels, variation of time and horizontal position.
- Still 10% of the reports are in old TAC format.

Example of large drift of radiosonde on a windy day

- Black diamonds – launch, levels to 100 hPa, levels above 100 hPa



Statistics of radiosonde burst height

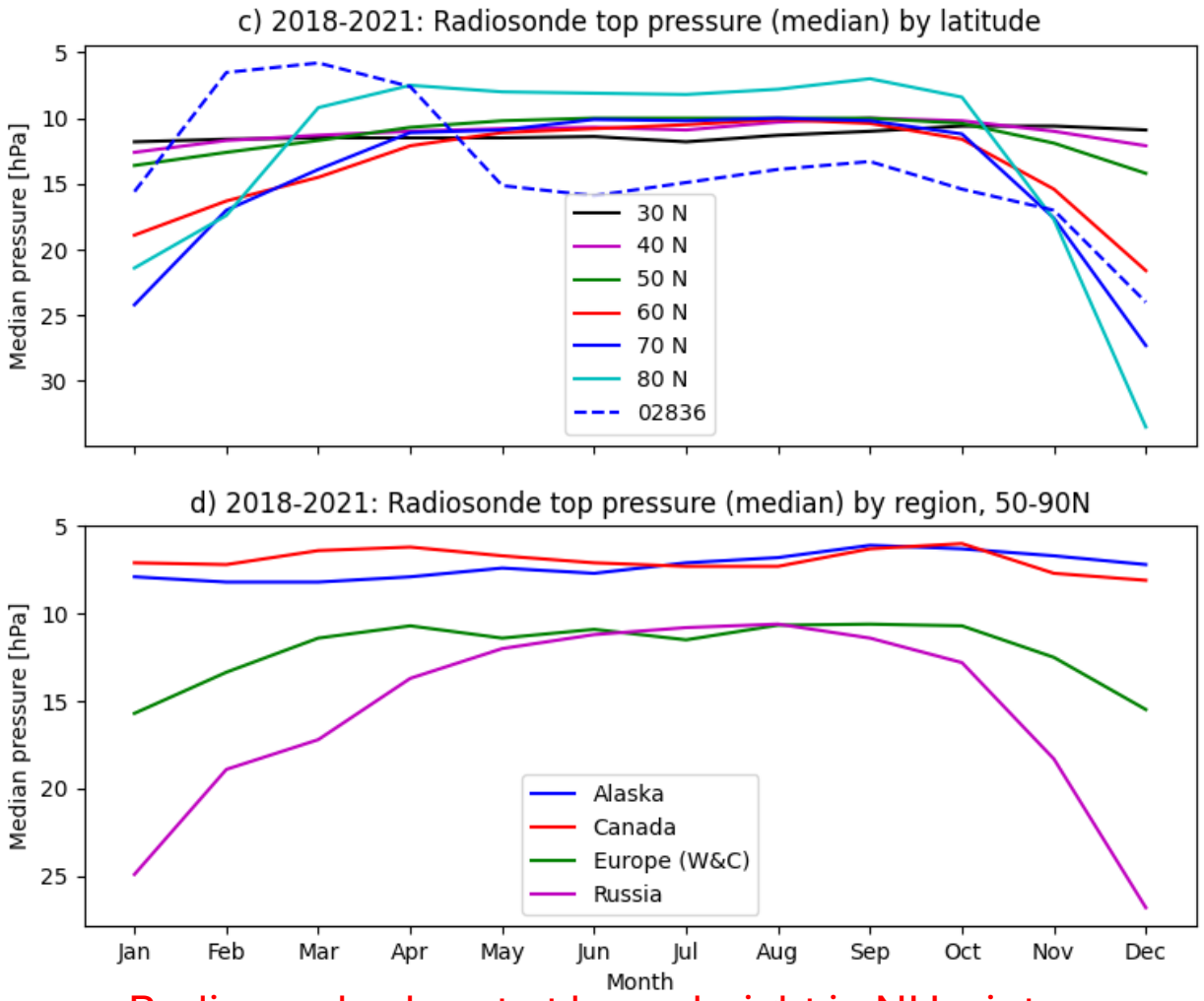
Ingleby and Policthchouk (QJRMS, 2026)

Upper: Burst height as function of month for various latitudes on NH

- Seasonality in burst height is largest at high latitudes, with lower burst heights during winter.
- Can see effect of larger balloon at Sodankyla station (blue dashed line) – selected months

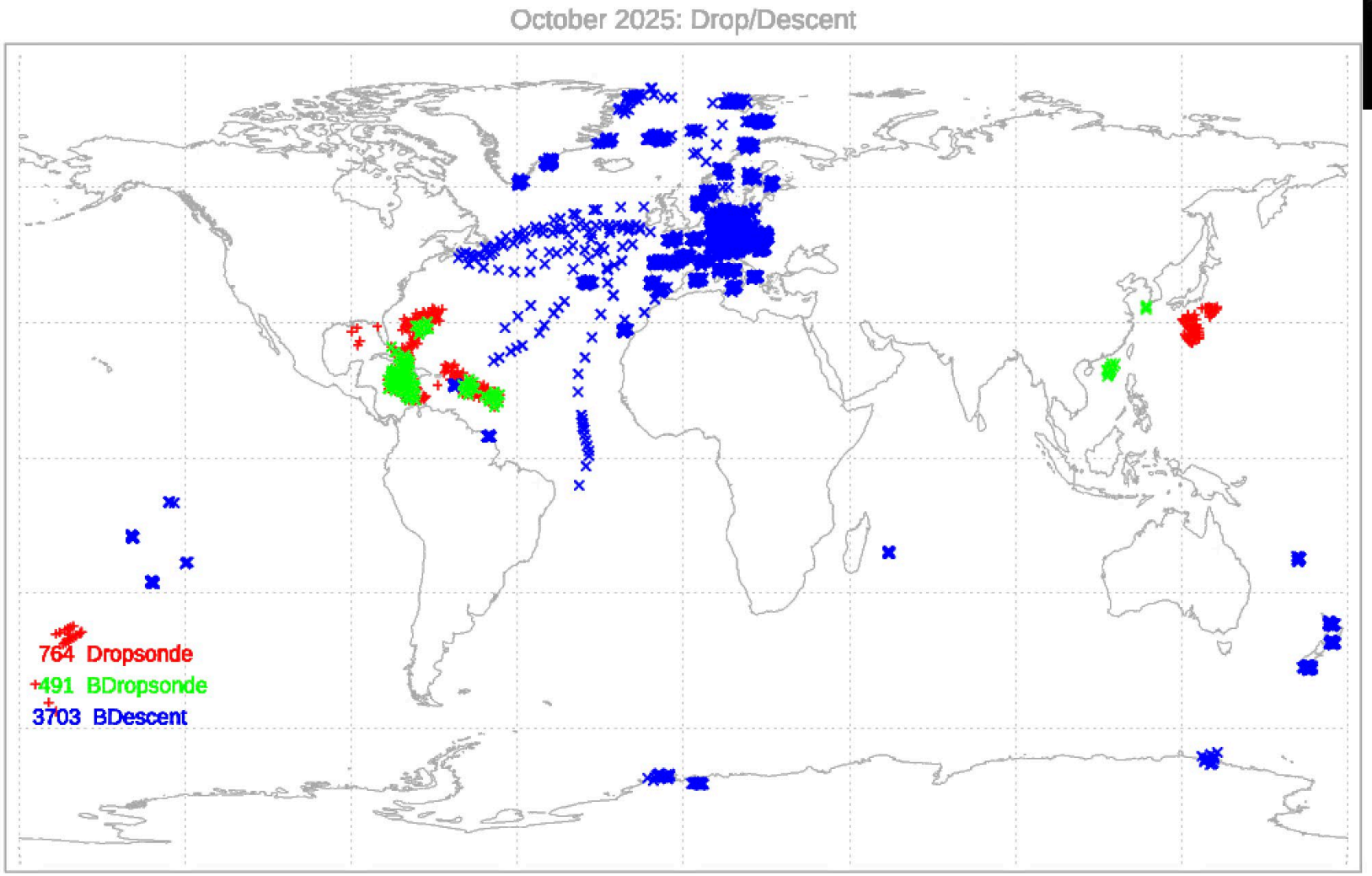
Lower: Burst height as function of month for various sonde weights

- Alaska: 600 g balloons
- Canada: 800 or 600 g
- Russia: 500 g
- Europe: varies, mainly 350 and 600 g

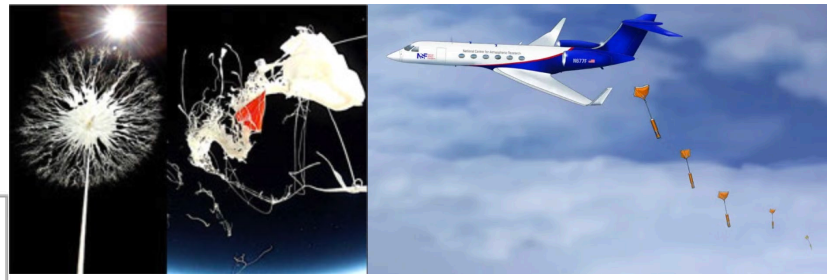


Radiosondes burst at lower height in NH winter.
Larger sondes bursts at higher altitudes.
Use larger balloons during winter?

Radiosondes



* Also Driftsondes and Long endurance balloons



Radiosonde descent (left) and dropsonde (right)

Descents and Dropsondes

- Today some 10% of the **radiosonde ascents** (BUFR) as well report **descent part**. This is the part when, after the balloon bursts, the instrument package is falling.
- Some of the radiosondes have parachutes for the descent part, others have not.
- A descent takes about 30 min.
- In case of Tropical cyclone / Hurricane / Typhoons there are additional aircraft-based **Dropsondes** are launched and reported in **BUFR** or **TAC** format.
- Dropsondes and some descents are assimilated in ECMWF IFS.

Aircraft

- **AIREP** Manual routine over-ocean reports required by Air Traffic control (ATC). Include temperature and wind at flight level give in pressure.
- **ADS-C** (Automatic Dependent Surveillance-Contract). Automated over-ocean reports required for ATC. Increasingly replacing AIREP.
- **AMDAR** (Aircraft Meteorological Data Relay). Automated meteorological reports containing observations of temperature, wind, pressure, turbulence, (few with humidity), some with height. From flight levels, ascents and descents,
- **AFIRS AMDAR** (Automated Flight Information Reporting System)/**TAMDAR** (Tropospheric Airborne Meteorological Data Reporting).
- **Mode-S** derived from information automatically downlinked from an aircraft's transponder in response to being queried by ATC.
- **ADS-B** (Automatic Dependent Surveillance-Broadcast), **UAV** Unmanned Aerial Vehicles (UAVs), **HDOB** (High Density Observations or high-density high-accuracy.)



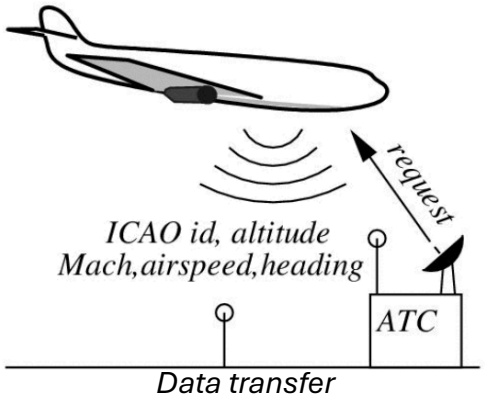
Aircraft

*Complex relation between sensor systems and meteorological variables (in particular for temperature and pressure).
**Bias correction generally needed for temperatures from AIREP/ADS-C/AMDAR
***Turbulence measurements are mainly for verification

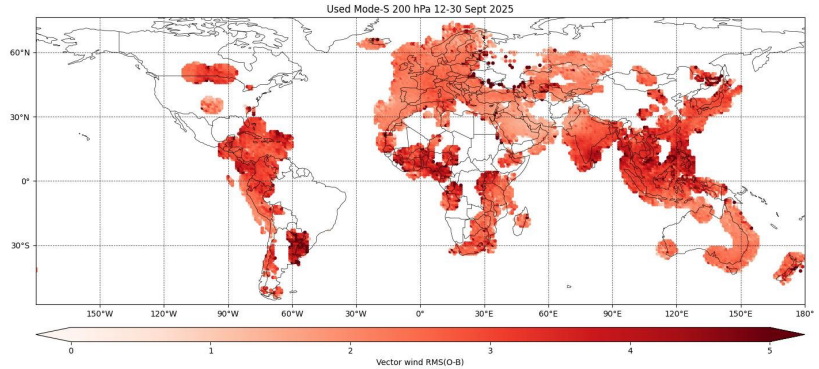


UAV

Mode-S



- Aircraft winds and temperatures derived from ATC messages.
- Mode-S EHS messages sent in response to ATC requests – in some regions:
  - In those regions there are data from **all** commercial aircraft (every 1 to 20 seconds!).
  - Need to have a receiver in the area – or to get the data from ATC.
  - Where present much more data than AMDAR: more aircraft, more frequent reports.
  - Mode-S wind quality similar to AMDAR, temperature worse (esp. low levels).
- Processing performed by EMADDC (KNMI), de Haan et al. (AMT, 2025).
- From Oct 2024 Global Mode-S data available:
- https://www.emaddc.com/participate/data+users/emaddc-met-office-global/default.aspx
- Data collected by Flightradar24 receivers, paid for by Met Office, processed by EMADDC.



Example of global data coverage

Land-based Surface observations

- Land-based observations for meteorology (SYNOP) and aviation (METAR).
- Surface land stations generally consist of a group of sensors that vary according to the requirements of their parent network (also siting requirements).
- In general, sensors include a barometer to measure pressure, temperature and humidity sensors (2 m) and wind speed and direction sensors (10 m). Also measurements of precipitation, as well as cloud and visibility data.
- For global NWP the most important variable from surface reports is the surface pressure.
- SYNOP reports can be 6-hourly, 3-hourly, or hourly. METAR reports are sent hourly or more frequently. Mainly automated observations but some manual.
- There are networks of crowd sourced observations which provide potential and a challenges.

*ECMWF started assimilating T2m in 2024



SYNOP station



METAR station

Marine-based surface observations

- Marine-based surface observation include networks of drifting and moored buoys as well as ships.
- For global NWP the most important marine data are the surface pressure reports from drifting buoys, because they sample some very data sparse areas. These buoys drift with the near-surface ocean currents.
- The moored buoys are attached to the bottom of the sea with a mooring line. There are two types of moored buoys: coastal and open-ocean tropical arrays. For the atmosphere we use surface pressure and winds (10m) observations.
- Volunteer Observing SHIP (VOS) reports provide measurements of surface pressure and wind speed. A problem is lack of metadata (ship identifier and station height) and reduction procedures of wind from station height to 10m. Station height change when ships load/offload cargo.



Drifting buoy



Moored buoy



SHIP

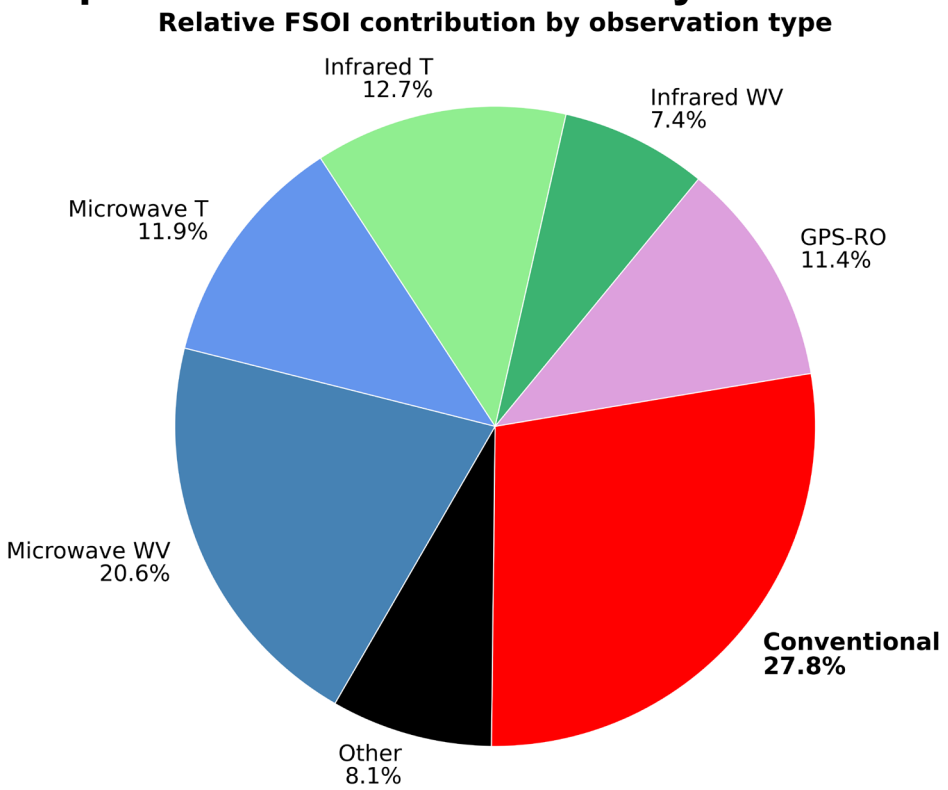
Which parameters are assimilated in ECMWF IFS atmosphere analysis?

Instrument	Parameters	Vertical
TEMP **TEMPSHIP** **DESCENTS** **DROPSONDES**	temperature, humidity, wind vector temperature, humidity, wind vector, low lev. Z	Profiles
PILOT BALLOONS (PROFILERS)	wind vector	Profiles
Aircraft Based Observations	temperature, wind vector, (humidity)	Profiles near airports + Flight level data
SYNOP **METAR**	pressure, temperature, humidity	Station altitude, 2m
BUOYS **SHIP**	pressure, wind vector (moored) pressure, wind vector	MSL, 2-10m ~30m

Impact assessment on forecasts

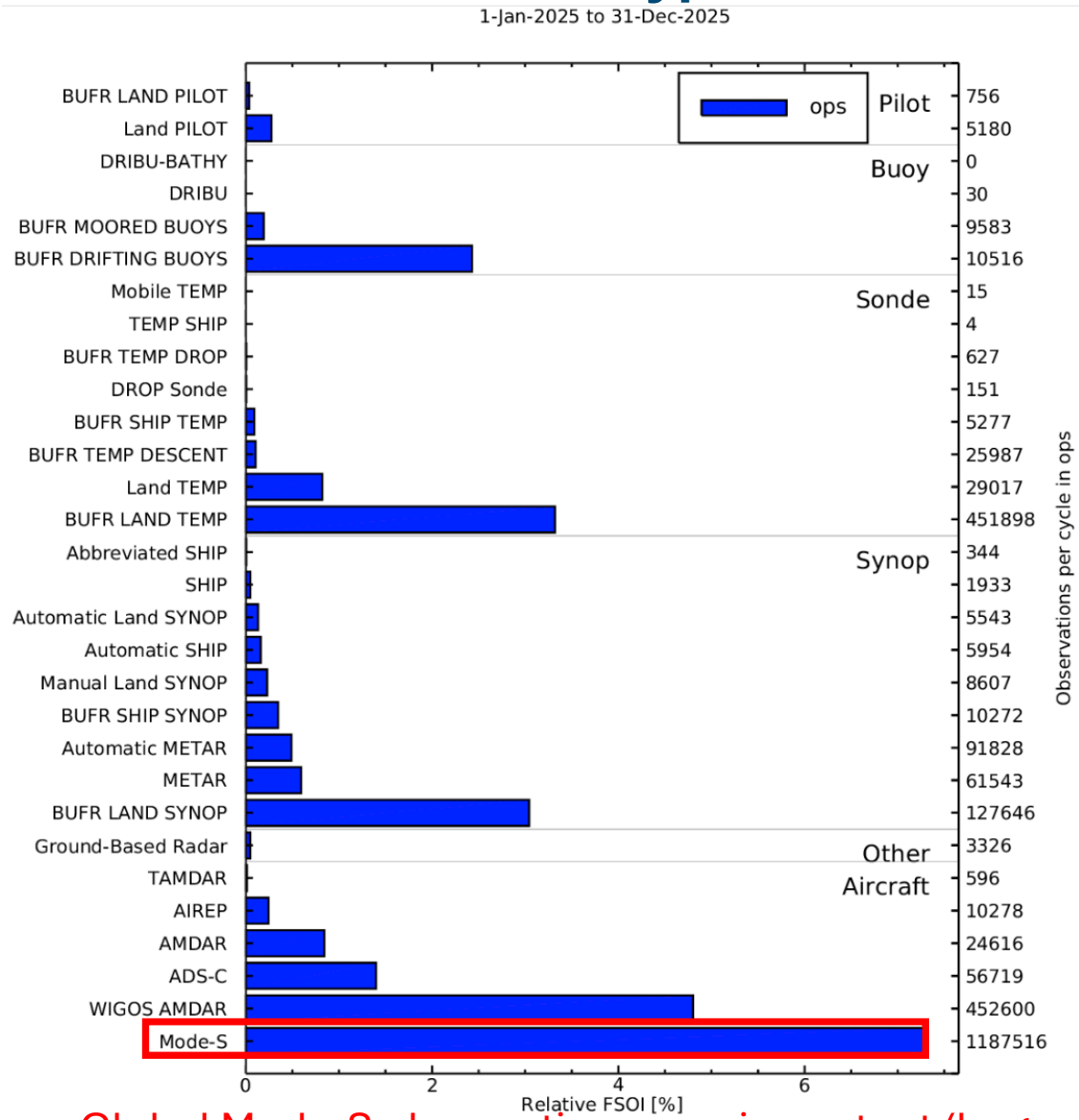
Forecast Sensitivity to Observations (**FSOI**)- An adjoint based method to measure the contribution from various observation types to reduce the errors of a 24 h forecast. (ECMWF use a dry energy norm)

ECMWF operational model 1 January to 31 December 2025



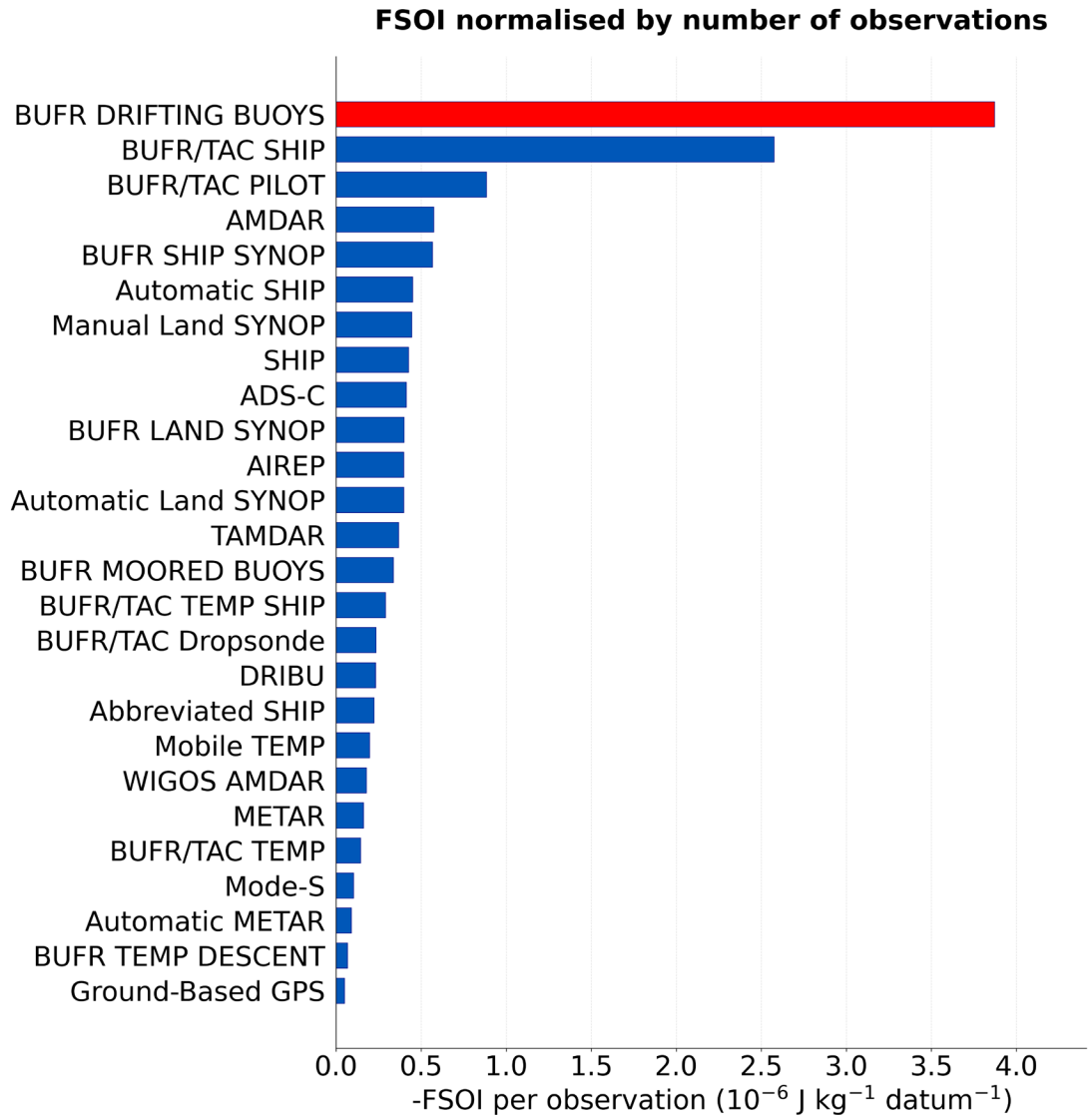
Conventional observations contributes on average with ~28% to reducing the forecast error (despite only contributing with about ~10% of the total amount of observations)

Contributions from various observation types to reduction of forecast error (FSOI)



Global Mode-S observations very important (large amount)

Contribution per datum from various observation types to reduction of forecast error (FSOI)

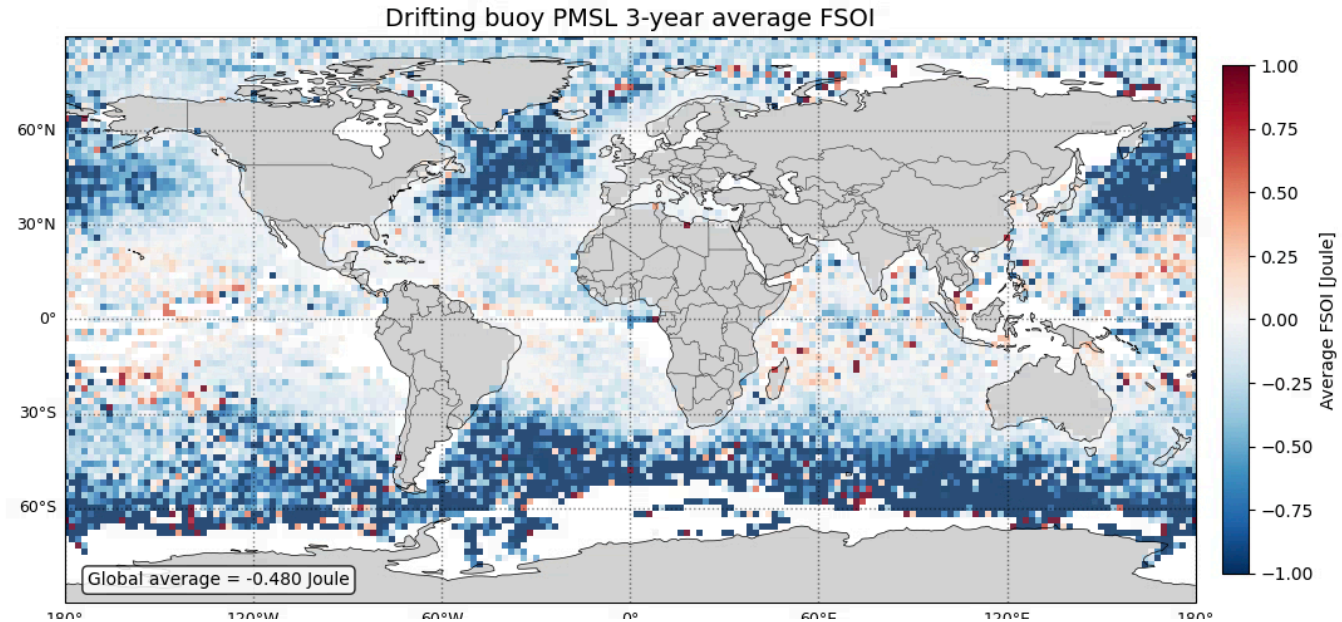


Per datum, drifting buoy observations most important.

Drifting buoys FSOI spatial variation

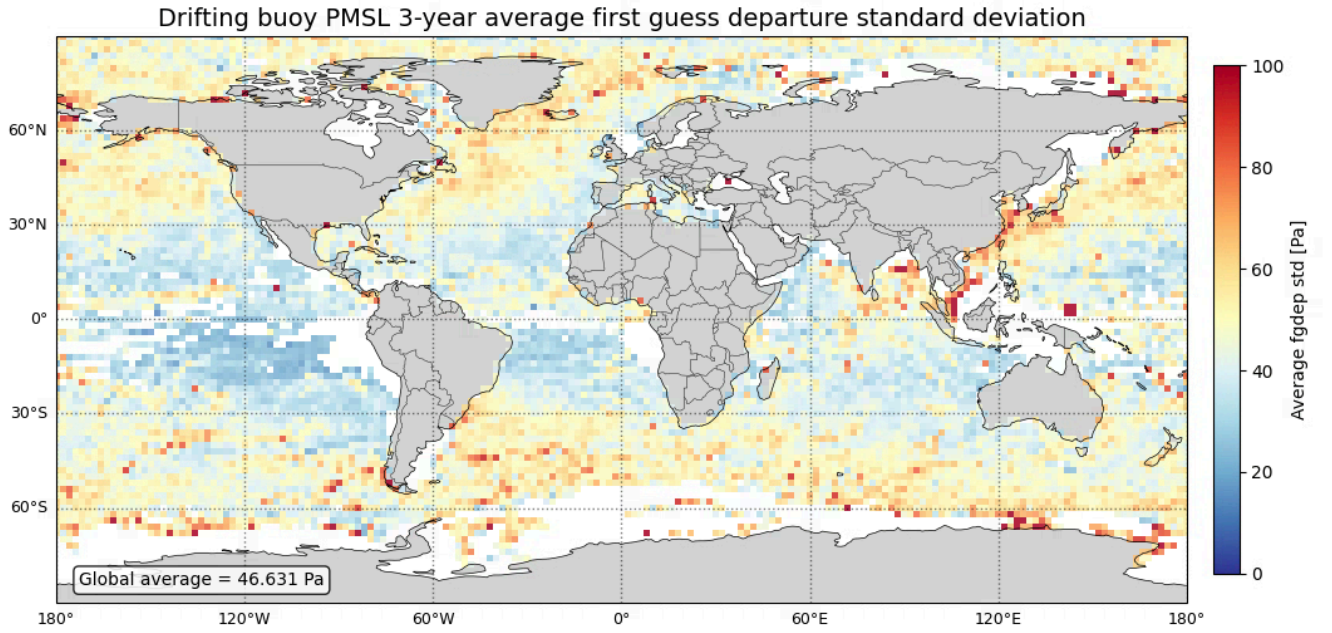
3-year average FSOI
(2023-05-01 to 2026-04-30)

Note that largest negative FSOI means biggest positive impact!
There is a clear latitudinal dependence of FSOI with minima at midlatitude storm tracks and maxima around the Equator.

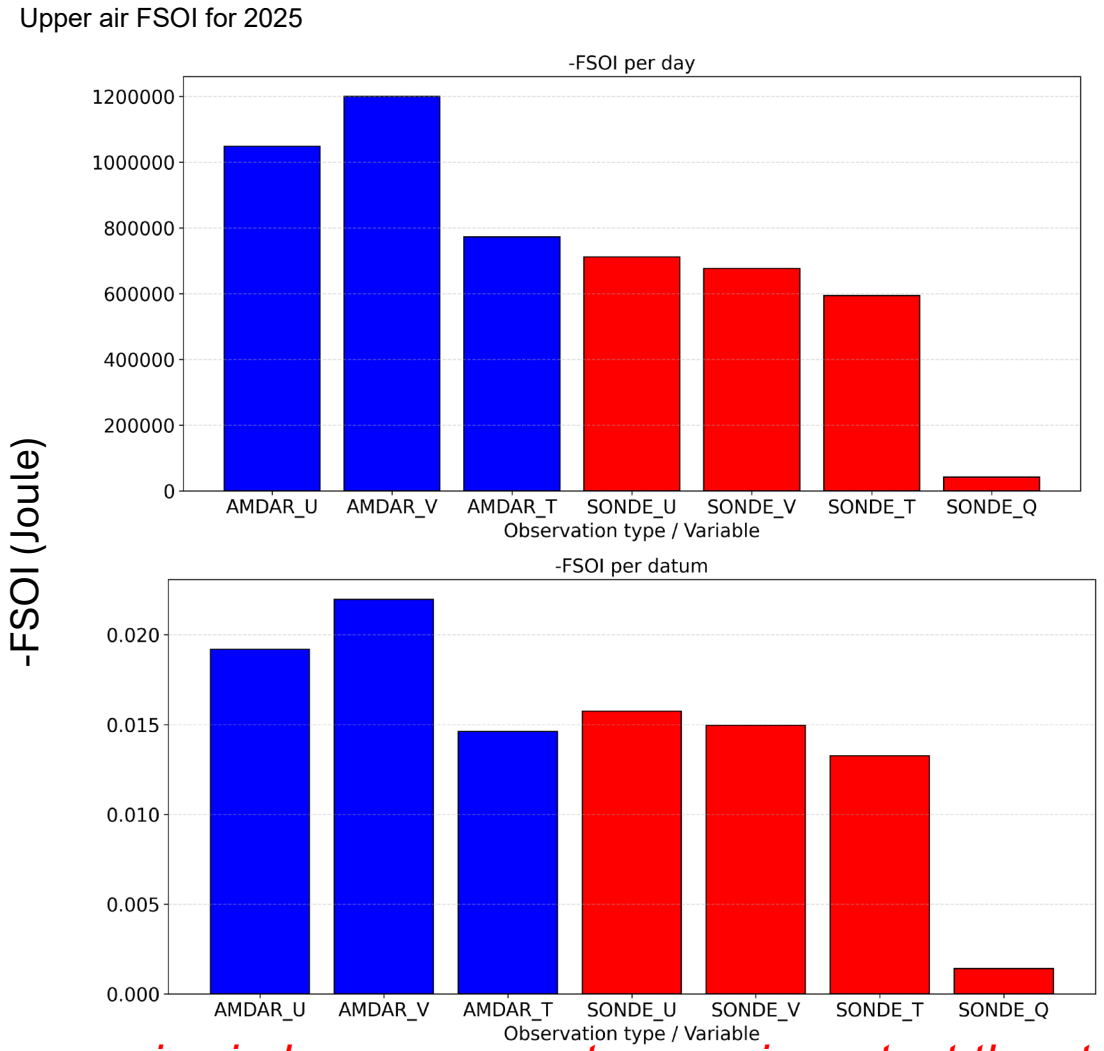


3-year average first-guess departure standard deviation
(2023-05-01 to 2026-04-30)

Large negative FSOI in areas with high background error standard deviations
(large uncertainties, not so many other observations and dynamical active areas)



FSOI Dependence on type of variable assimilated (upper-air)

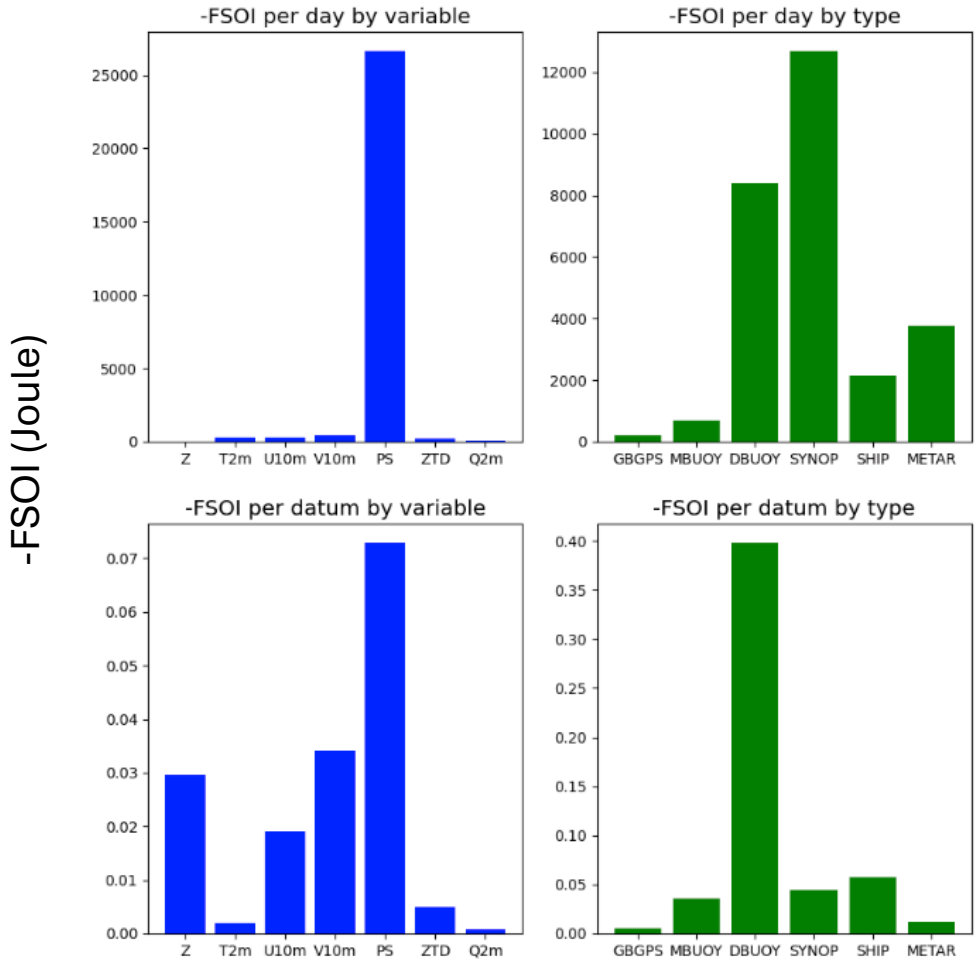


On average, in-situ upper-air wind measurements more important than temperatures (and humidity least). There are as well seasonal and spatial aspects, such that wind observations are particularly important in winter stratosphere.

FSOI Dependence on type of variable observed (surface)

Upper air FSOI for 2025

Surface FSOI for 2025



Surface pressure observations important variable to assimilate. SYNOP and Drifting buoy contribute most.

Impact assessment through Observing system Experiment

In a recent one carried out at ECMWF the impact of various observation types on both the physical based model (IFS cy49r1) and the ML/AI model (AIFS) was assessed.

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Experimental Design

Experiments

Control: Full observing system as used operationally at the time

No conventional: As Control, but with all in-situ data denied.

No MW radiances: As Control, but excluding all satellite radiances from passive MW sensors.

No IR radiances: As Control, but excluding all satellite radiances from passive IR sensors.

No GNSS-RO: As Control, but excluding all GNSS-RO data.

Time-period runs

1 June – 30 August 2022 and 1 December 2022 – 28 February 2023

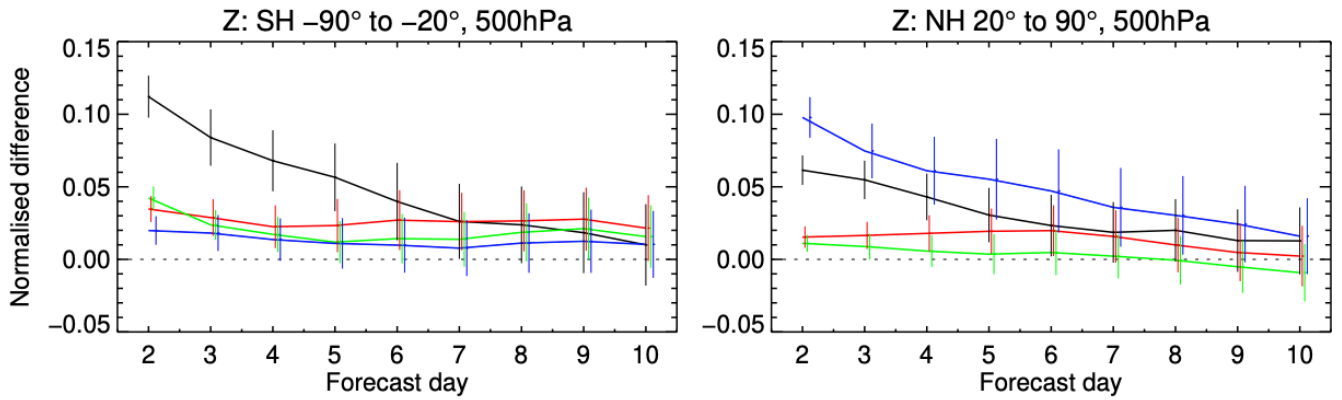
Bormann et al. (ECMWF Tech. Mem., 2026)

Impact on forecasts of not using in-situ measurements

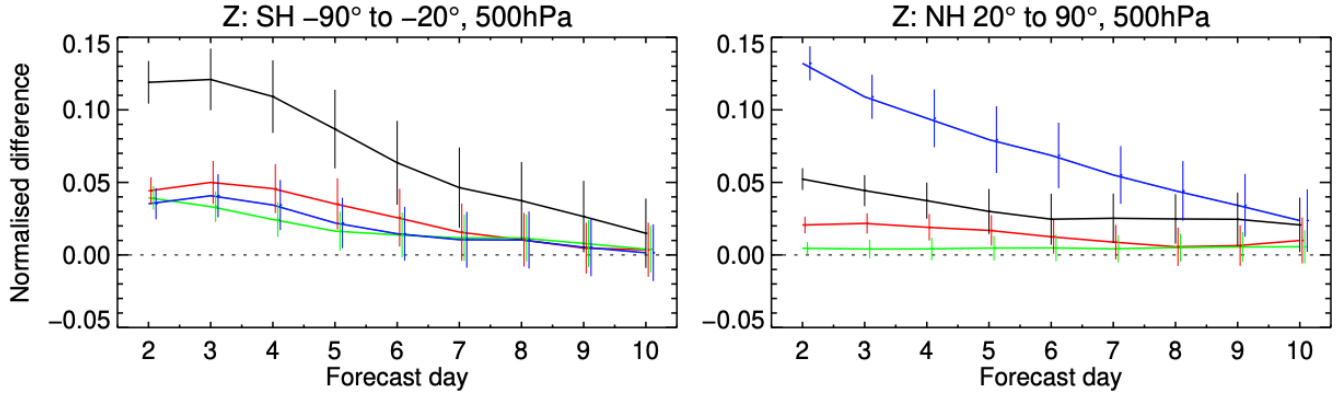
Geopotential Height at 500 hPa

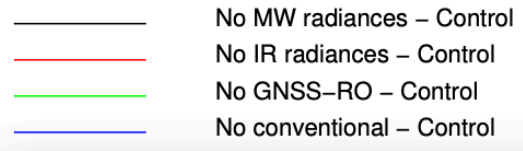
Normalised difference in standard deviation as compared with control of standard deviation. Verified against operational control analyses.

IFS:



AIFS:





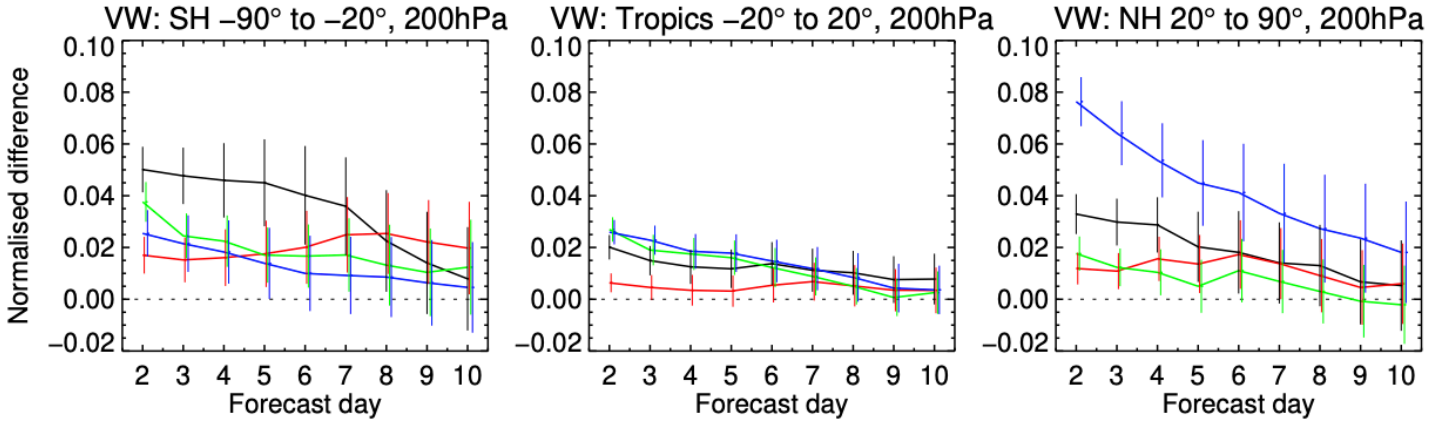
Impact on forecasts of not using in-situ measurements

Vector wind at 200 hPa

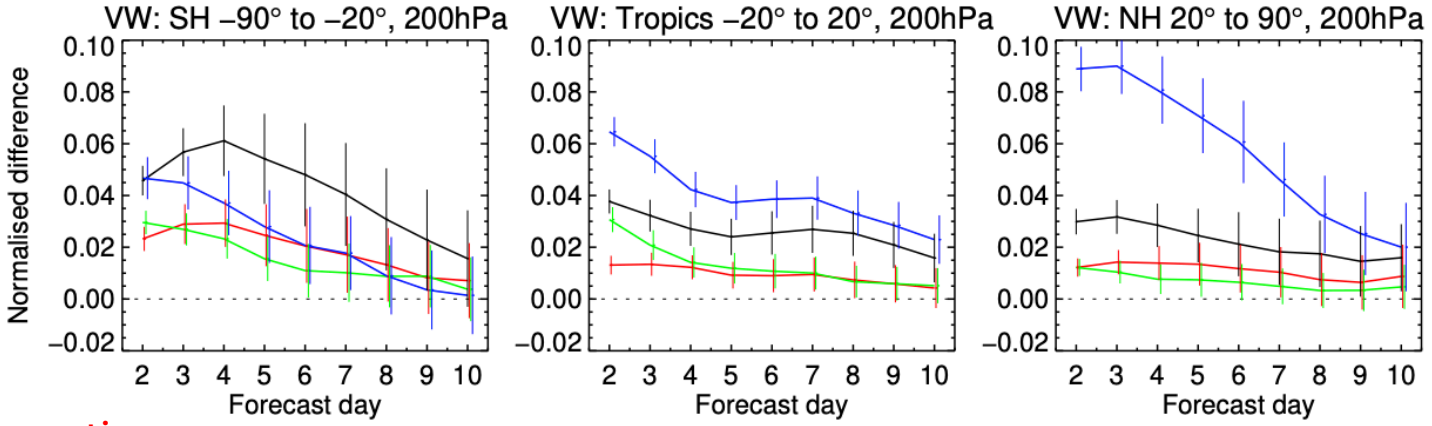
(Similar main signal at 850 hPa)

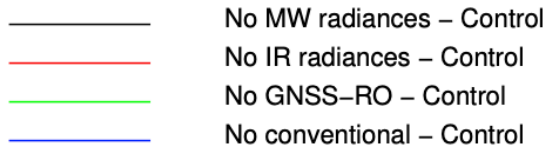
Normalised difference as compared with control of standard deviation. Verified against operational control analyses.

IFS:



AIFS:





In-situ measurements the most important observation type in Tropics and Northern Hemisphere.
For AIFS even slightly more important than for IFS

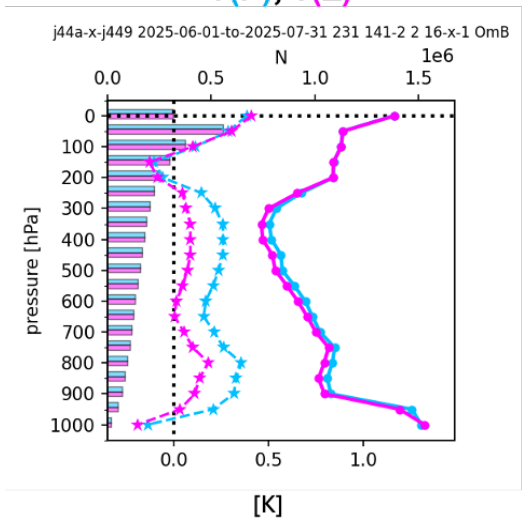
On-going developments

Additional quality and coverage of critical radiosonde data if we can use GPS heights and access descent information

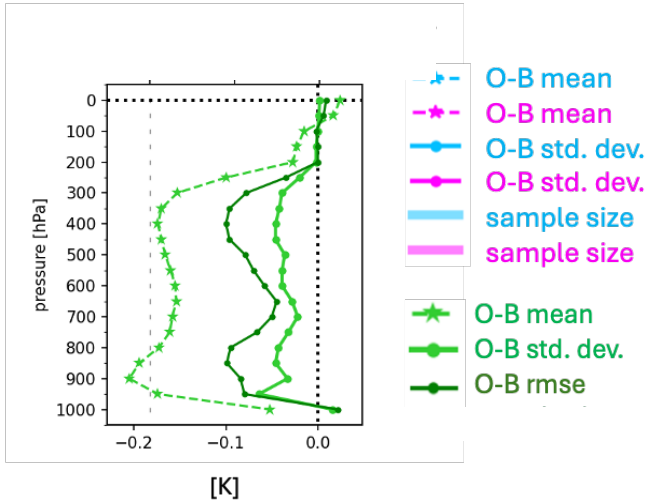
For many radiosonde types using the **GPS height information** as vertical coordinate instead of the reported pressures allows a more accurate treatment of the observation

RS41

T(P), T(Z)

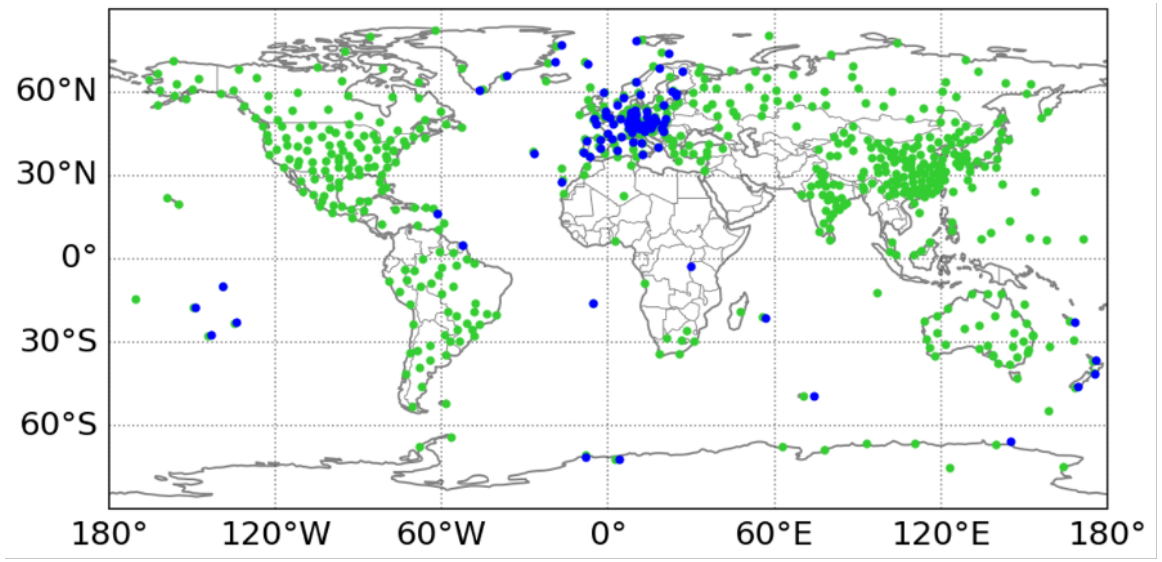


Tdiff(Z-P)



This could also allow us to assimilate significantly more **radiosonde descent observations** which currently cannot be used due to height errors.

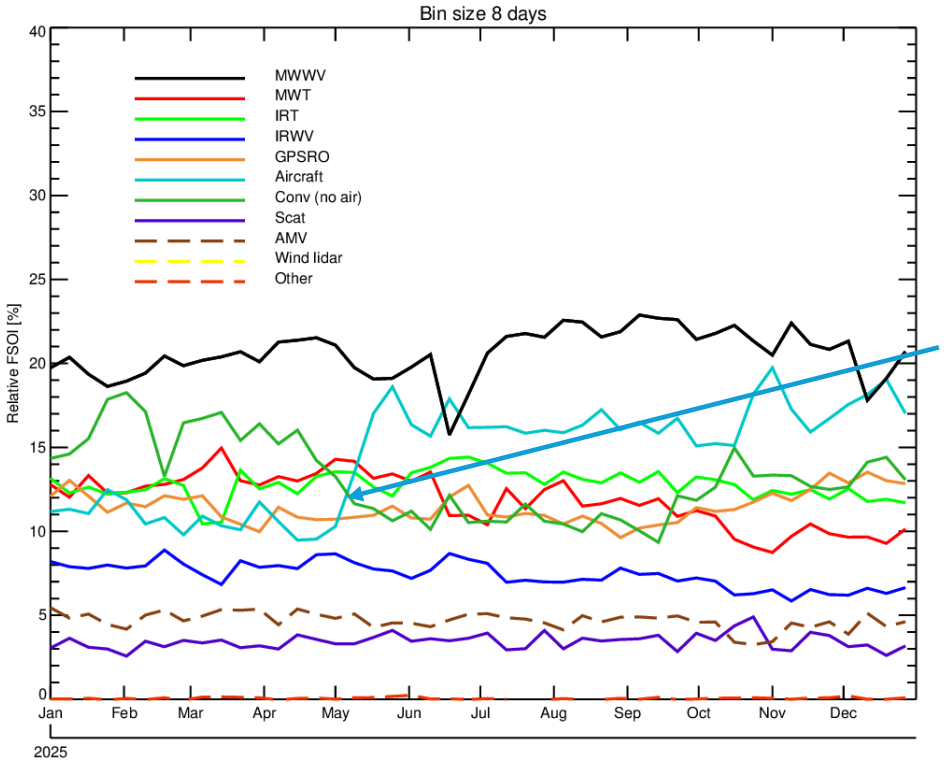
Blue below are the only locations where we currently assimilate descent data. But with GPS tracking and use of height vertical coordinate and also changes of reporting practice we could have data from the **entire sonde network** (in green) and and **significant additional information to improve forecasts!**



A next later step is to also use of geopotential height for Aircraft.

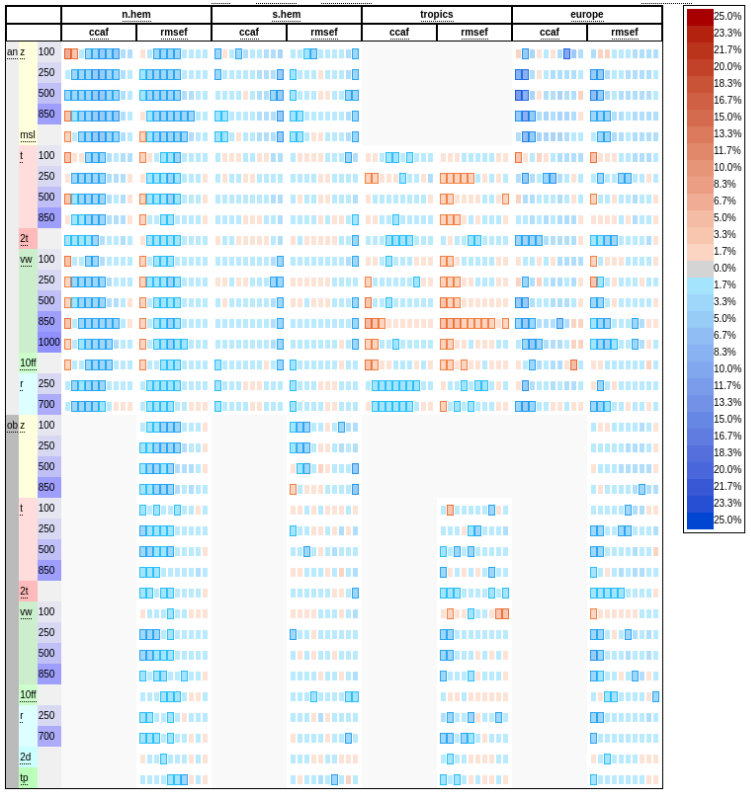
MODE-S winds give a huge positive impact…can we use temperature ?

FSOI 2025 Timerseries



Aircraft FSOI
Jump up in May 2025
When introducing
global Mode-S

“Two season” DJF 2024/2025+JJA 2025 Mode-S vs noMode-S
Impact study result in the form of a scorecard (rmse)



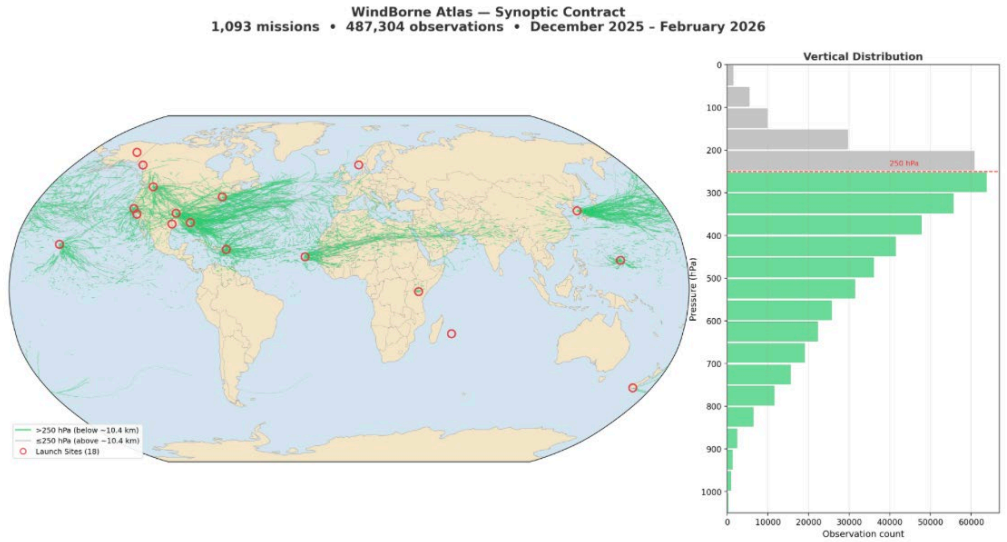
Large positive impact from Mode-S winds!

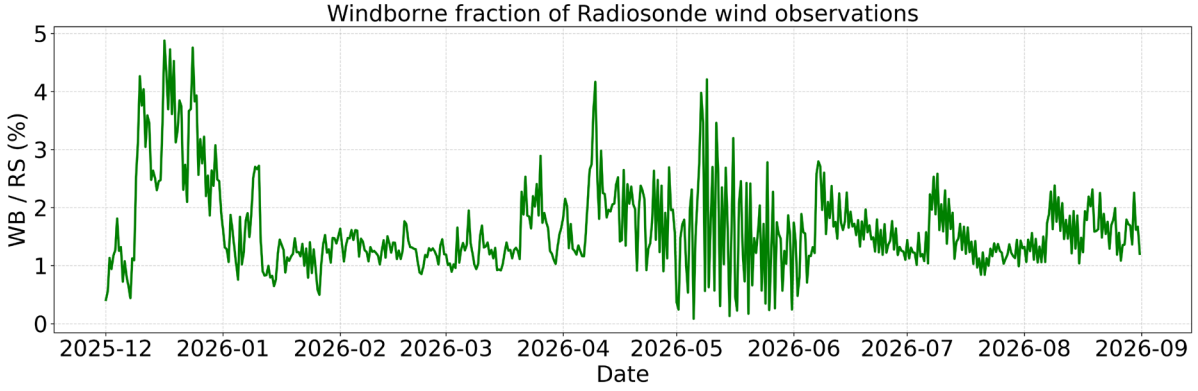
Acknowledgments to EMADDC/KNMI and Met Office

On-going studies with temperatures.

Long endurance balloons

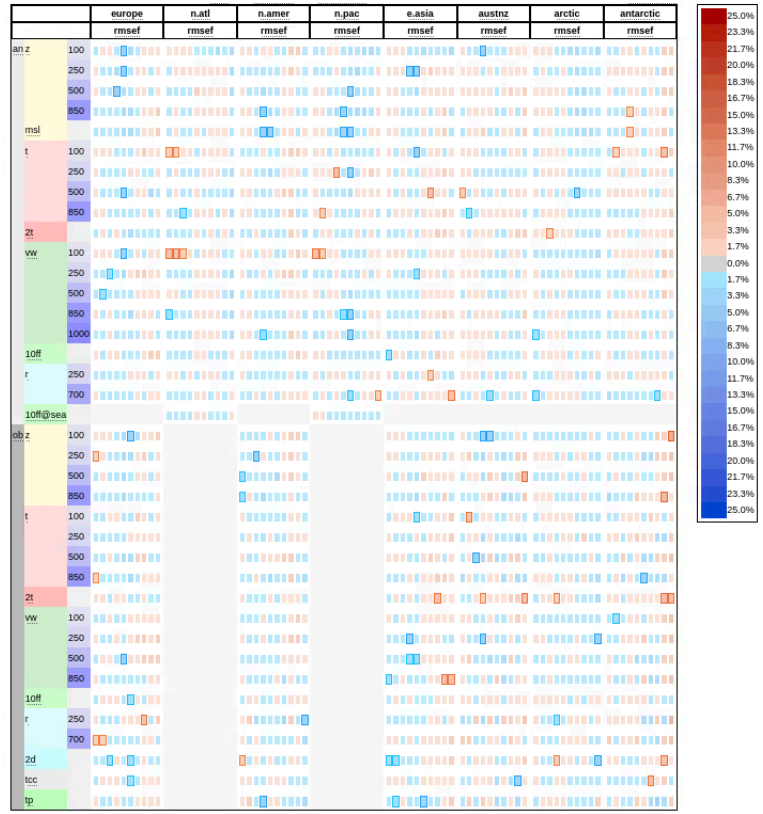
Windborne Launch sites and low as well as high altitude observations on GTS
DJF 2025/2026





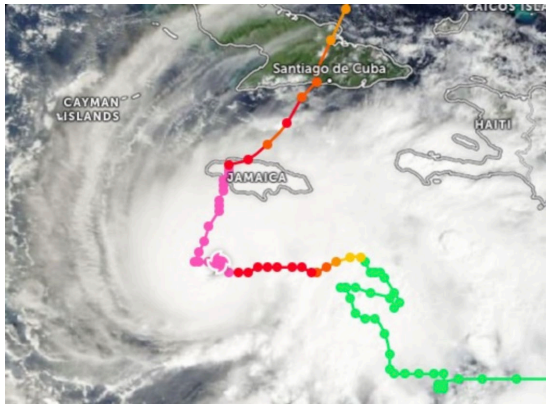
- Launched from sites along the world (mainly NH). Altitude can be controlled as the balloon is transported by the wind.
- Some Windborne observations put on GTS and are freely available (but more exist which are private)
- **These are a very small fraction compared to** radiosondes and mainly on NH.
- **Quality of temperatures and wind observations are good** and are being assimilated in research experiments.
- Neutral to slightly positive impact on forecast scores, expected from such a small number of data.

"Three season" DJF 2025/2026+MAM 2026 and JJA 2026 WB vs noWB Impact study result in the form of a scorecard (rmse)



Observation impact on Forecast for individual cases

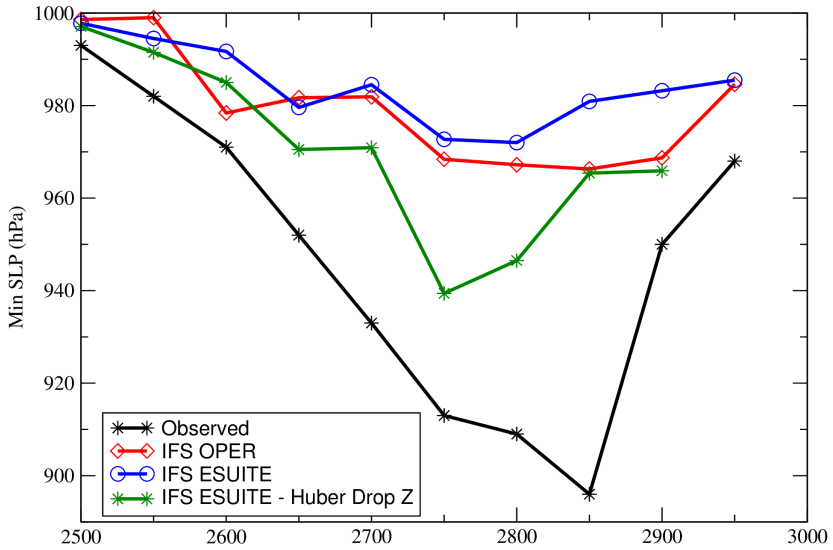
Dropsonde usage in high impact weather events



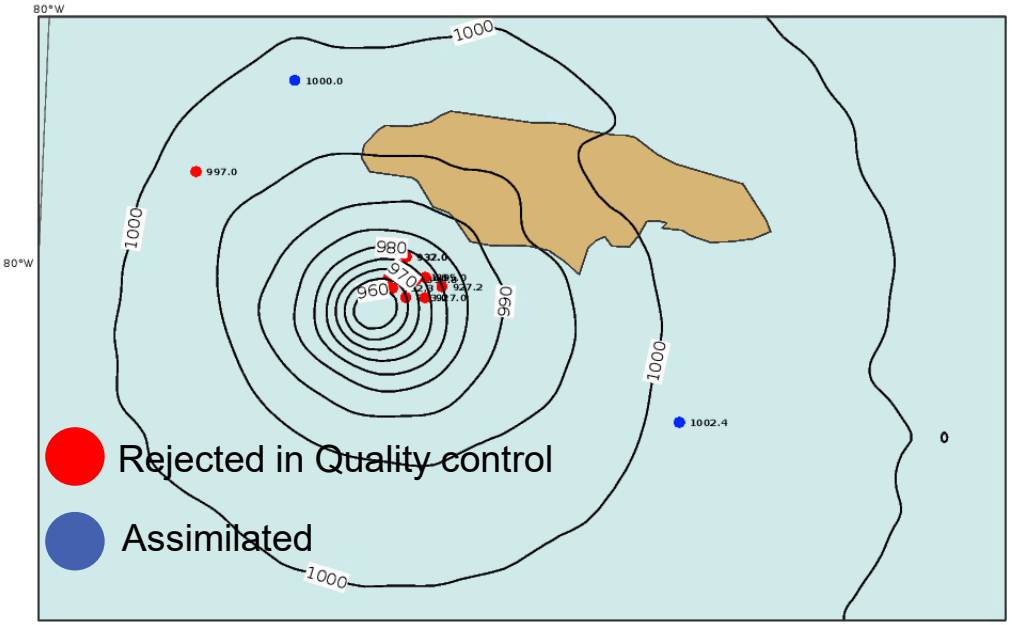
Tropical Cyclone Melissa

25-29 Oct. 2025

Observed cyclone depth (black) and analyses of runs with various QC revisions.



Operational MSLP analysis, Tuesday 28 October, 12 UTC



- Many potentially useful low-level geopotential Dropsonde observations were rejected by quality control.
- With a revised quality control forecasted depth of depth of cyclone closer to observed.
- Currently we are, to assure stability and improvement re-running the revised quality control over several Tropical cyclone cases.

Massimo Bonavita, Elias, Holm, Giovanna De Chiara, Ziga Zaplotnic

Future developments

- There is a wide range of emerging observing systems: Crowd-sourced surface networks, UAVs, Wind farm observations etc.. These might help to improve the lack of boundary layer observations (particularly winds) pointed out by WMO (Andersson et al., 2005).
- AI/ML methods enable possibilities to further improve quality control procedures and to also extend use of conventional observation types through improved representation of model equivalent of observations. Example cloud and visibility observations (although not strictly in-situ measurements).
- The merits, possibilities and requirements regarding in-situ measurements in AI Direct Observation Prediction system is an upcoming field to be fully exploited.

Summary and Conclusions

- In-situ measurements provide a backbone of the global observing system used for numerical weather prediction.
- These observations provide a heterogenous data set with a wide range of instruments and reporting practices.
- The in-situ measurements contributes significantly to forecast accuracy of global weather forecasts, regardless if physical based model or AI/ML based model is used.
- There is still room for improvements regarding handling of currently used observations.
- The emerging new observation networks and application of evolving AI/ML techniques allow for use also of new types of observations.

Thank You!

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