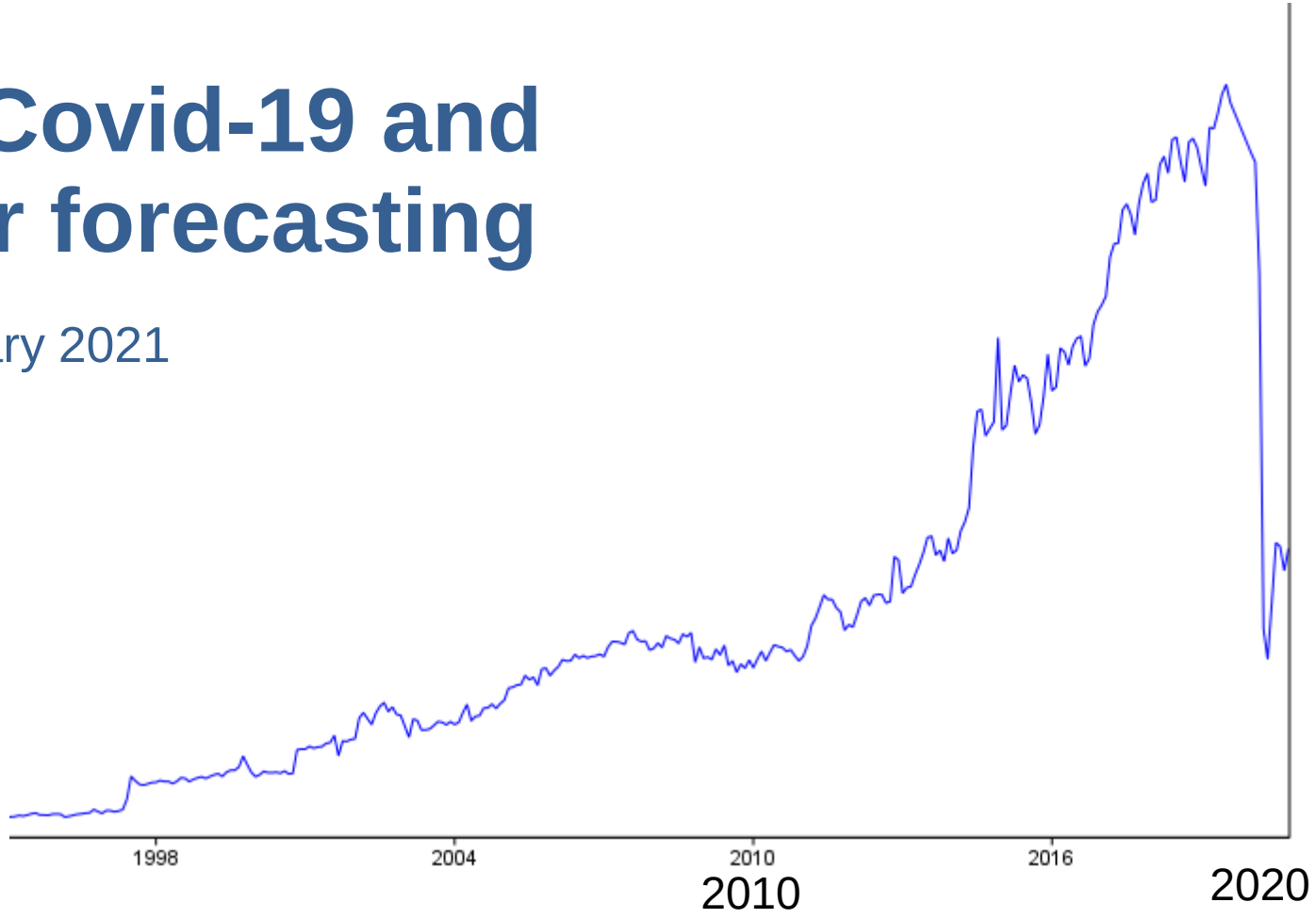
Aircraft data, Covid-19 and global weather forecasting

ECMWF webinar, 20 January 2021

Bruce Ingleby

ECMWF

Bruce.Ingleby@ecmwf.int



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Overview

- Impact of Covid-19 (via drop in aircraft numbers)
  - Impact of aircraft data (data denial experiment)
  - Forecast skill during 2020 (no clear drop)
- Changes to observation usage, mitigation attempts
  - Use of European Mode-S aircraft data
- Estimates of aircraft impact from FSOI

Part 1

- What do aircraft measure?
- Aircraft temperature biases
- Aircraft metadata
- Filling in the gaps

Part 2

- Summary

With thanks to

- ECMWF: Lars Isaksen, Mohamed Dahoui, Thomas Haiden, Martin Janouscek, Alan Geer, Cristiano Zanna, Marijana Crepulja, Tomas Kral
- ESoWC (2019): Mickey Yun Chan
- Met Office (UK): Stewart Taylor, Steve Stringer (E-AMDAR), Brett Candy, John Eyre, Warrant Tennant
- NOAA/NCEP (US): Chris Hill, Curtis Marshall (US-AMDAR), Daryl Kleist
- BoM (AU): Fiona Smith, Peter Steinle, Chris Tingwell
- KNMI (NL): Siebren de Haan, Jan Sondij (EMADDC Mode-S data), Jitze van der Meulen
- FLYHT (CA/US): Meredith Bell (AFIRS+TAMDAR data)
- Rockwell Collins (US): Alan Williard
- CMC (CA): Yulia Zaiseva
- NRL (US): Pat Pauley
- WMO: Dean Lockett
- Others…

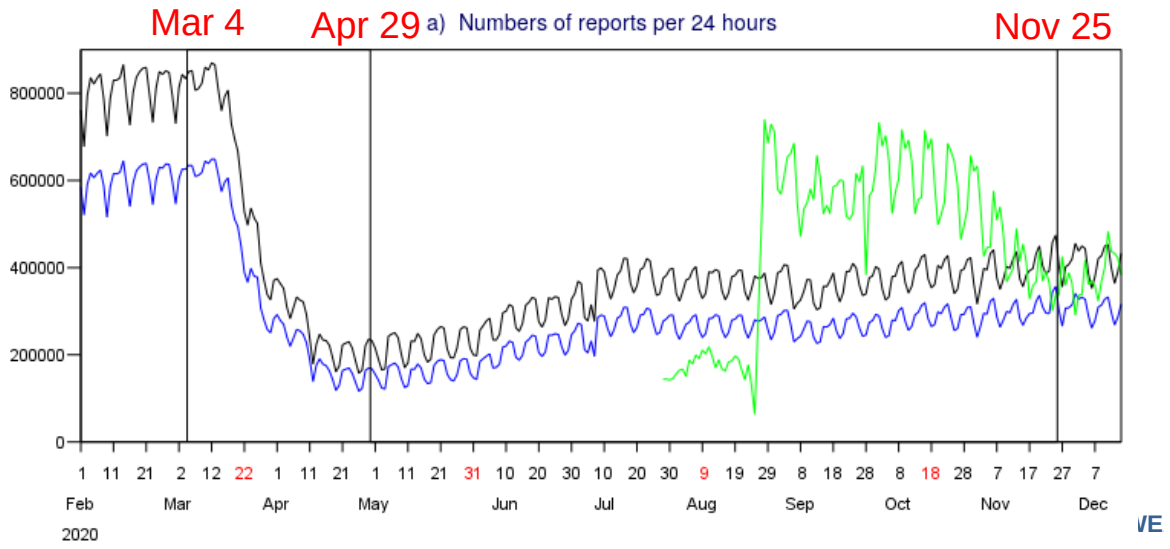
Flavours of aircraft data (use the same measurements)

- **AIREP**: Aircraft Report (alphanumeric), originally voice report to ATC *(Air Traffic Control)*
- **ADS-C**: Automated 'Contract' reports to ATC, oceanic/remote regions, from 2014
  - Some are converted to AIREPs, some to AMDAR BUFR format
- **AMDAR**: Aircraft Meteorological Data Relay, coordinated by WMO
  - Started in 1986, 12 programmes now, largest is U.S. program (MDCRS)
  - 43 airlines have agreements with NMSs to provide AMDAR reports
  - Many use ACARS transmission methods to reach the ground
  - GTS: (Older alphanumeric format.) New binary (BUFR) formats.
- **TAMDAR**: originally NASA+AirDat, then Panasonic, now FLYHT
  - Focus on short/medium-haul aircraft, includes RH sensor
- **AFIRS** (as AMDAR): satcomms system developed by FLYHT
- **Mode-S** (EHS): 'Broadcast' messages available in some ATC areas
  - All aircraft have to provide data if pinged

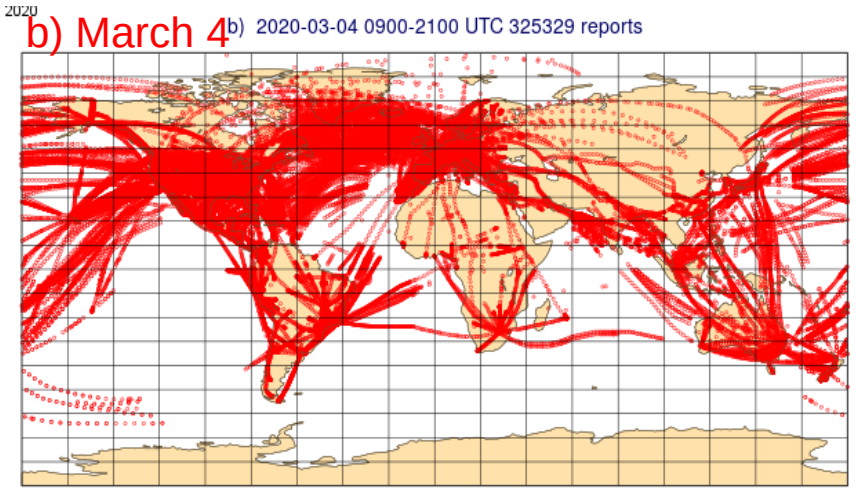
BUFR ADS-C were separated from AMDARs in July 2020 at ECMWF

Impact of Covid-19 on aircraft reports

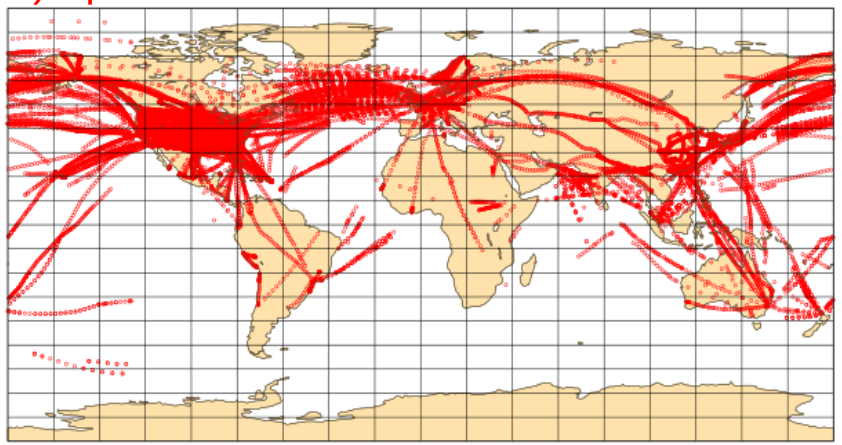
- Mid-March to Mid-April global numbers of AMDAR+ADS-C+AIREP dropped by 75%
- Long-haul very badly hit, cargo less so
- Back to almost 50% by July but ~constant since
- ECMWF started using Mode-S winds over Europe (green line below) – only about 5% of those available
- Recent months: European numbers declining again, numbers in Southern hemisphere increasing



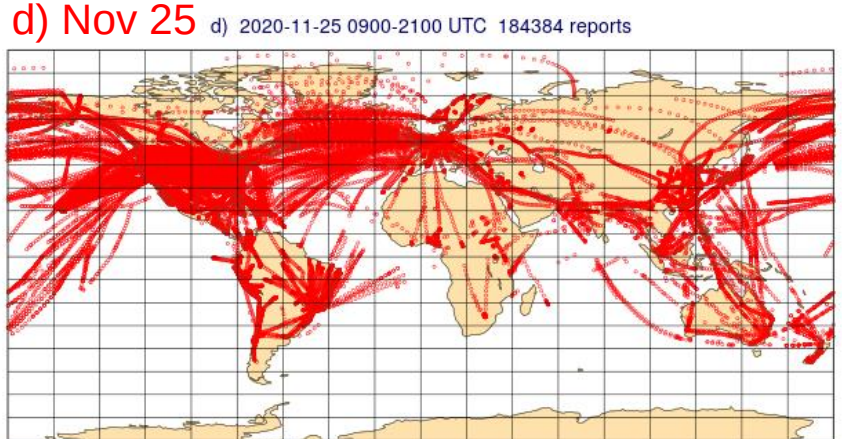
b) March 4



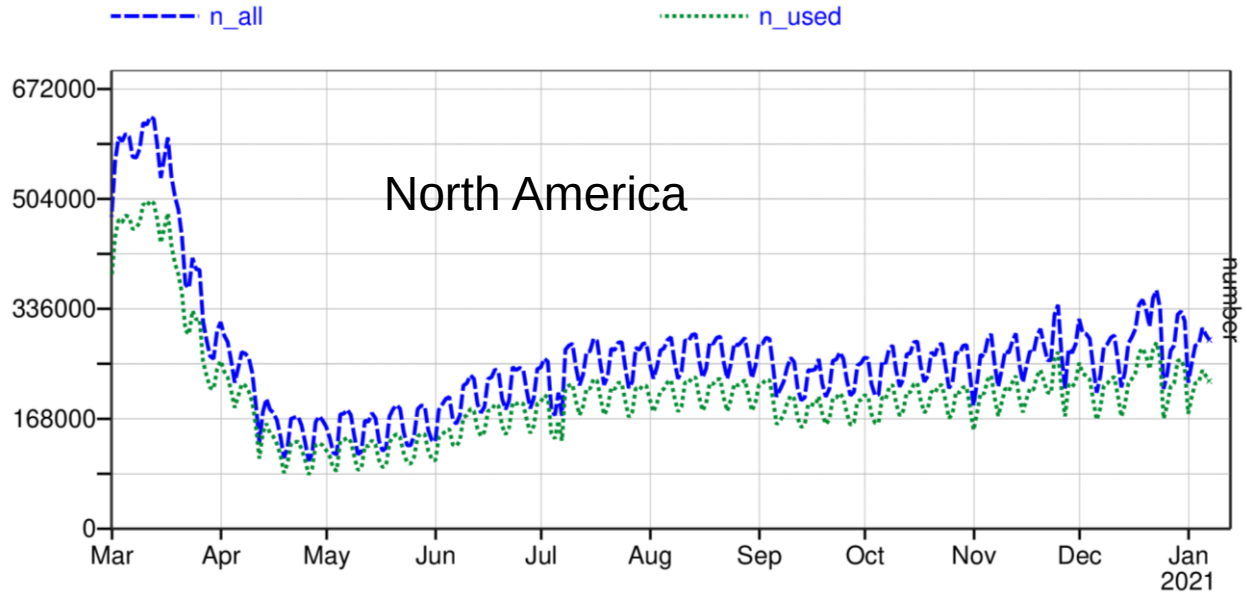
c) April 29

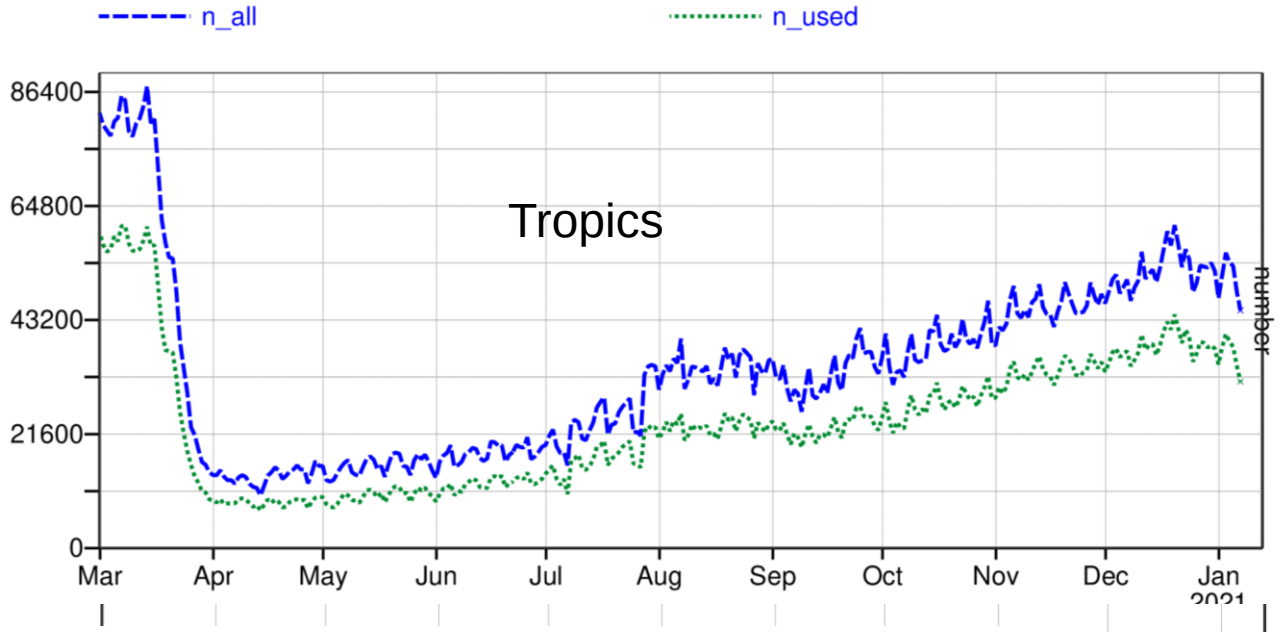


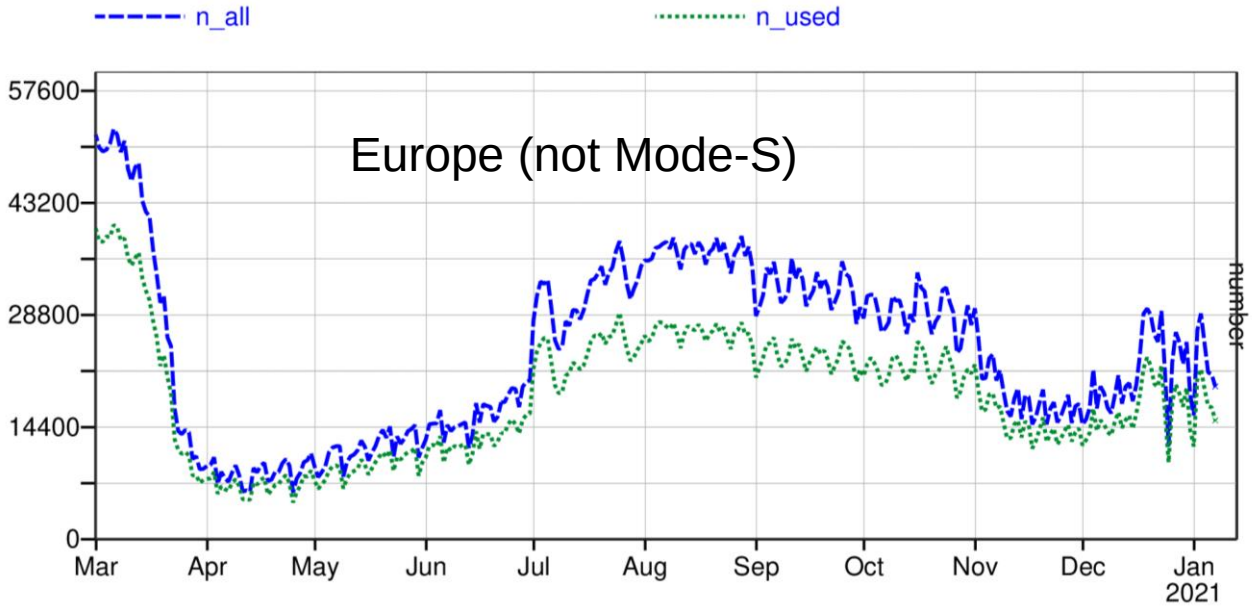
d) Nov 25



Aircraft reports by region

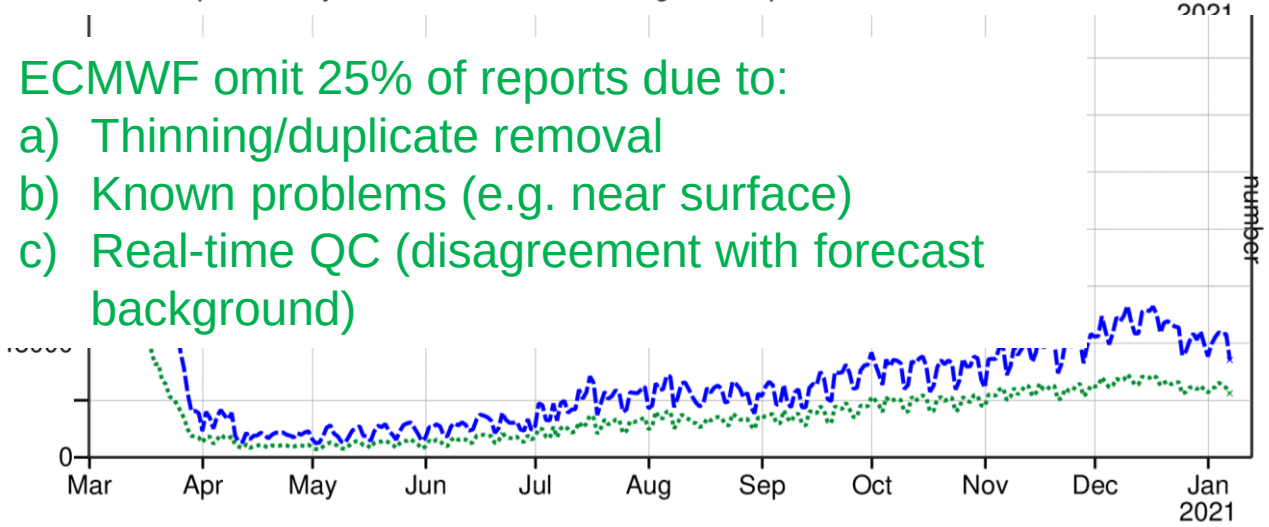






ECMWF omit 25% of reports due to:

a) Thinning/duplicate removal
b) Known problems (e.g. near surface)
c) Real-time QC (disagreement with forecast background)



Impact from aircraft data denial

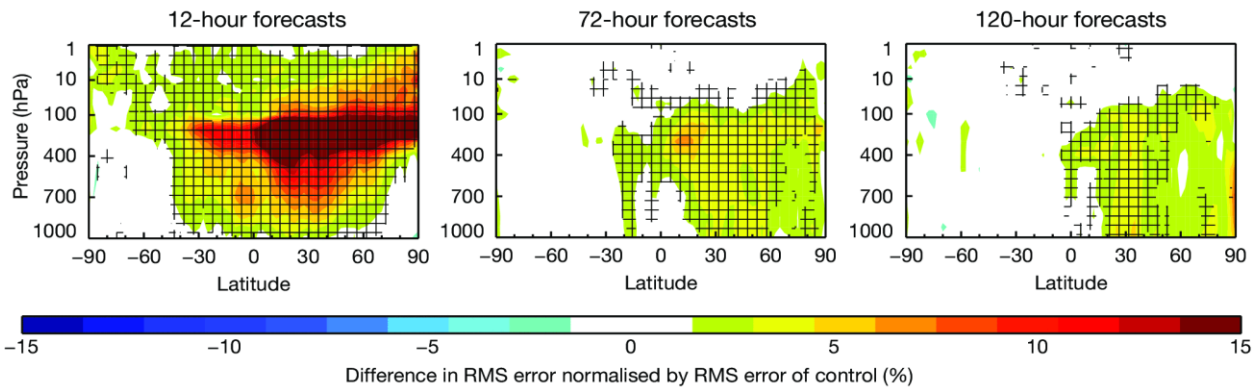
- OSE: Observing System Experiment
- ECMWF IFS, 3 months in 2019
- Control – all data
- NoAircraft: top plot and black line in b,c)
- NoAircraftT(emperature), red line in b,c)

- Biggest impact is ~250 hPa in NH almost 10% worse vs sonde T, 13% vs sonde wind
- Most of the impact (even on T) comes from the aircraft winds

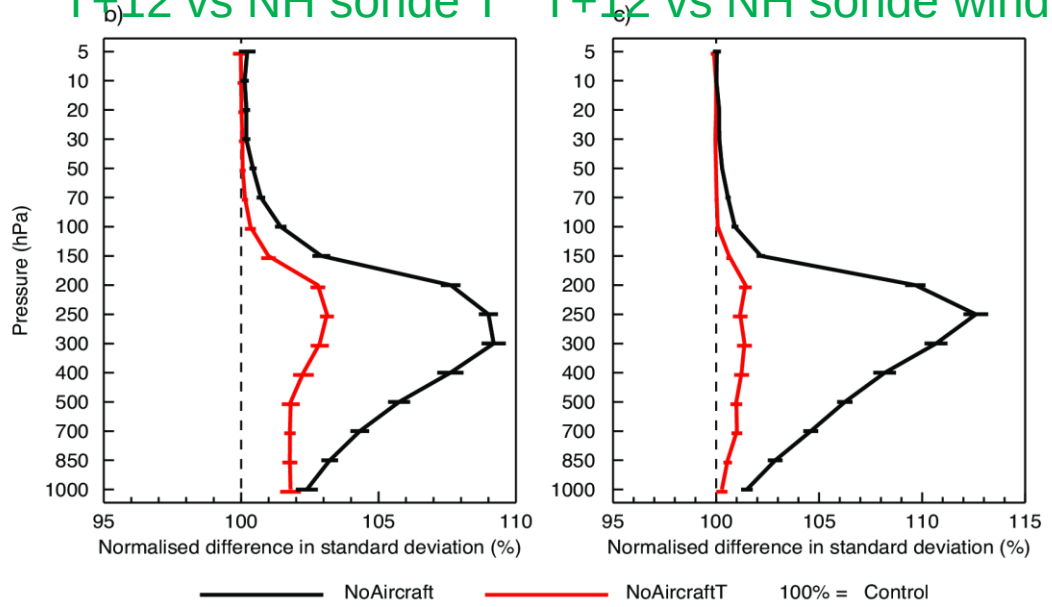
- Ingleby et al (2020, GRL)

Vs Analyses

T+12 T+72 T+120

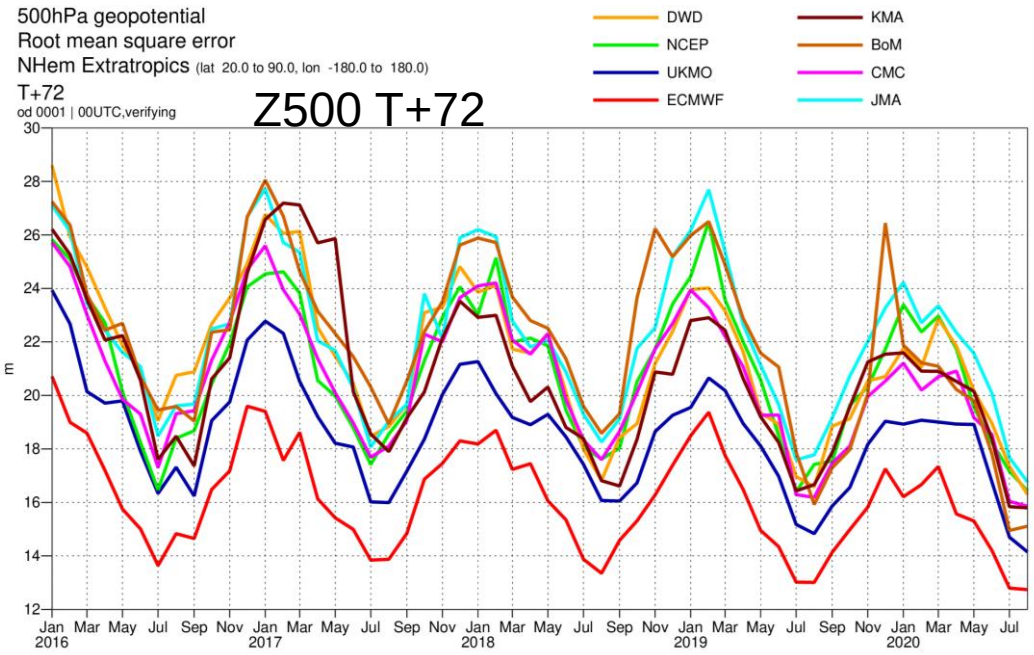


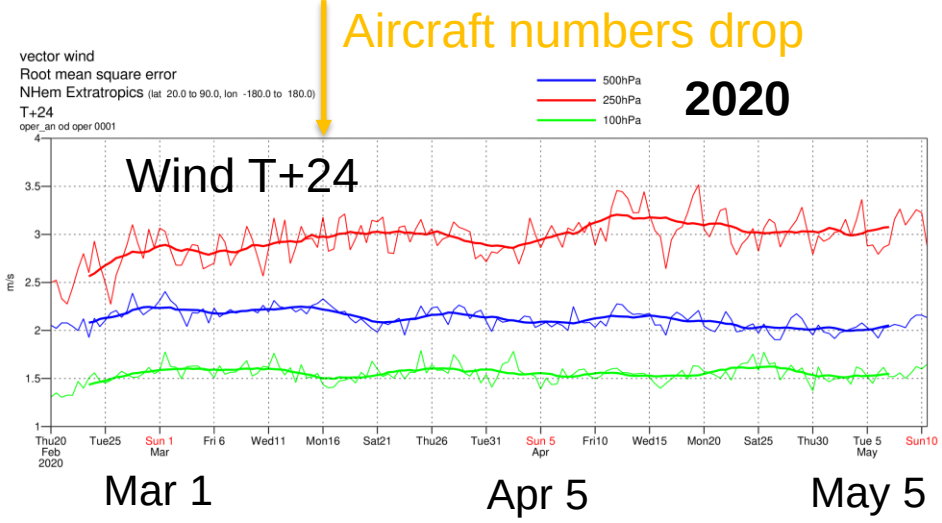
T+12 vs NH sonde T T+12 vs NH sonde wind

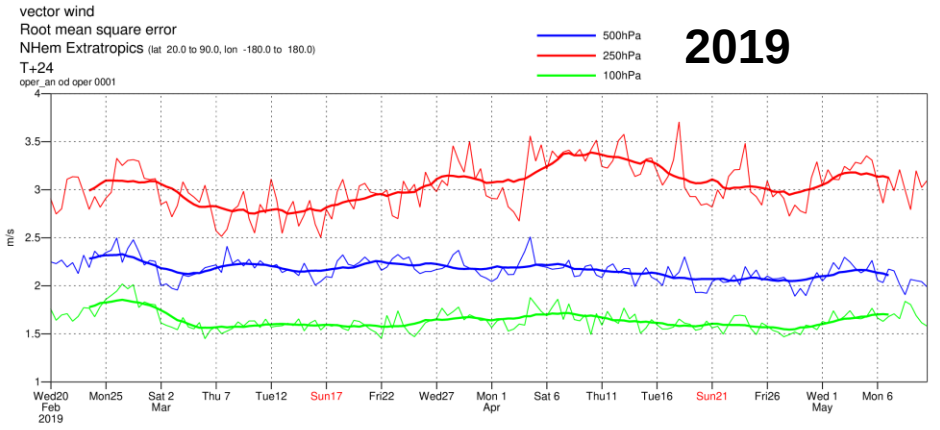


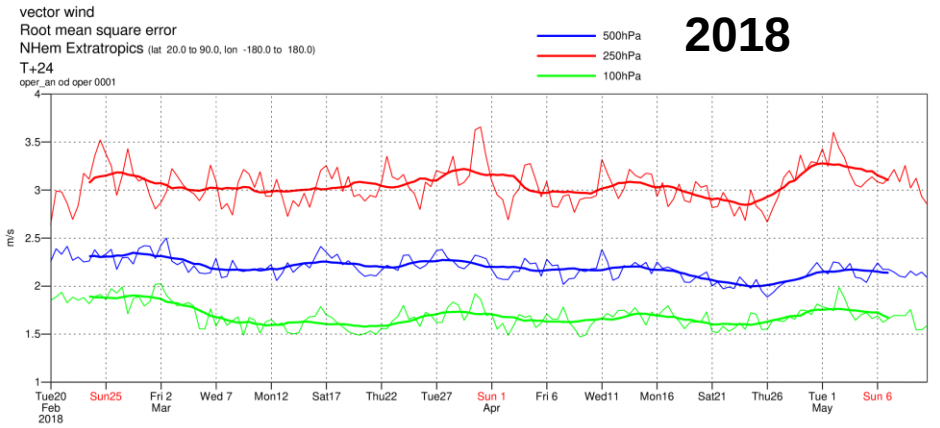
Can we see the impact in 2020?

- Not really in verification scores!?
  - Partly due to residual aircraft reports
- T+24 250 hPa NH vector wind rms in red
- 250 hPa is near jet level, lower errors at 500 hPa and 100 hPa
- Day-to-day noise plus seasonal/annual variations (2019 more predictable in NH?)









Discussion

- James & Benjamin (2017, MWR): aircraft data most important observations over North America (Rapid Refresh system)
- James et al (2020, JAMC): 20% of aircraft give >20% of impact of all aircraft
- Chen (2020, GRL) '*COVID-19 pandemic imperils weather forecast*'
- Ingleby et al (2020, GRL): '*The impact of Covid-19 …: a balanced view*'
  - Authors from ECMWF, Met Office (UK), NCEP (USA), BoM (Australia)
  - Chen's comparison of 2020 with previous years is 'oversimplistic'
  - Importance of satellite data, variations in forecast skill
- Riishojgaard (2020, WMO Bulletin, 69 (2)) '*Impacts of COVID-19 Restrictions*'
  - Minor reductions in surface and radiosonde reports in some regions
- Sorenson et al (2021, AMS101) *Effects on regional FSOI*

- Bauer et al (2015, Nature): '*quiet revolution*' – improvements in global NWP

Changes to ECMWF observation usage in 2020

- **Mid-January started using Aeolus wind data (Business As Usual)**
- **25 March started using COSMIC-2 Radio Occulation (RO) – BAU**
- April-August – extra radiosonde ascents from some European stations
- **13 May to end Sept use of Spire RO data**
- June started use of FLYHT aircraft data (AFIRS+TAMDAR)
- Mid-June started use of German radiosonde descent data
- **27 July started use of European Mode-S aircraft winds**
  - Pan-European ‘test’ product processed by KNMI (NL)
  - Both KNMI and ECMWF accelerated development/implementation
  - Air traffic control messages: De Haan (2011)
  - Wind: similar quality to AMDAR, temperature – more mixed
  - Also included ‘fix’ for ADS-C/AIREP B787 wind direction error

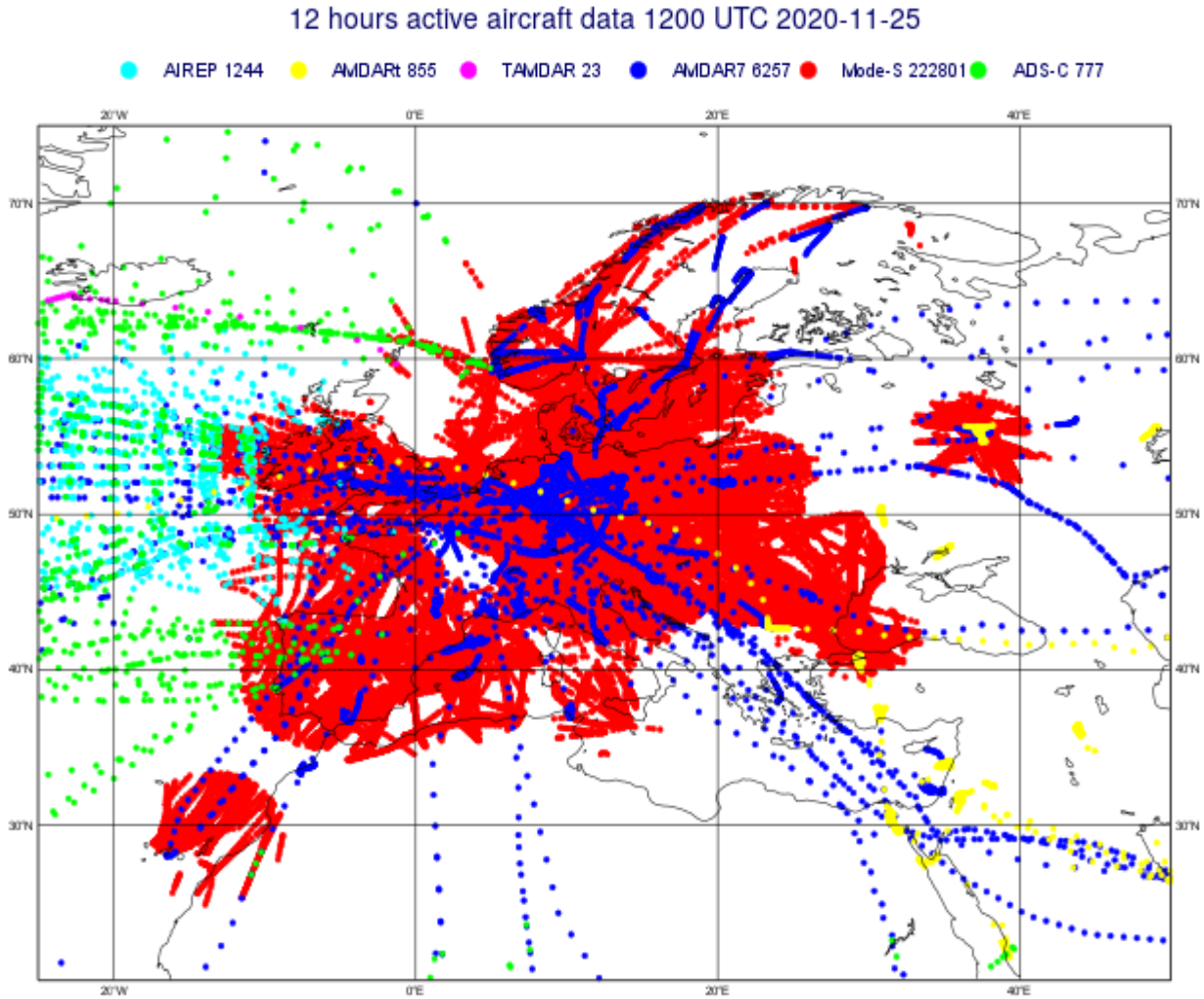
What is Mode-S?

- Mode-S EHS (De Haan, 2011; Sondij, 2020 EUMETNET/ECMWF workshop)
  - Some ATC systems ping aircraft for additional information
  - All aircraft have to respond (every 4-30 seconds): very dense data
  - Mode-S EHS was not designed for meteorological reporting
    - Temperature not included, can be derived from Mach number, but the precision is poor especially at low levels (can be mitigated by clever averaging – De Haan)
    - Aircraft heading (needed for winds) is reported wrt magnetic North* not true North (correction needed, *depends on date of aircraft look-up tables)
    - Despite this the wind quality is close to that of AMDAR reports

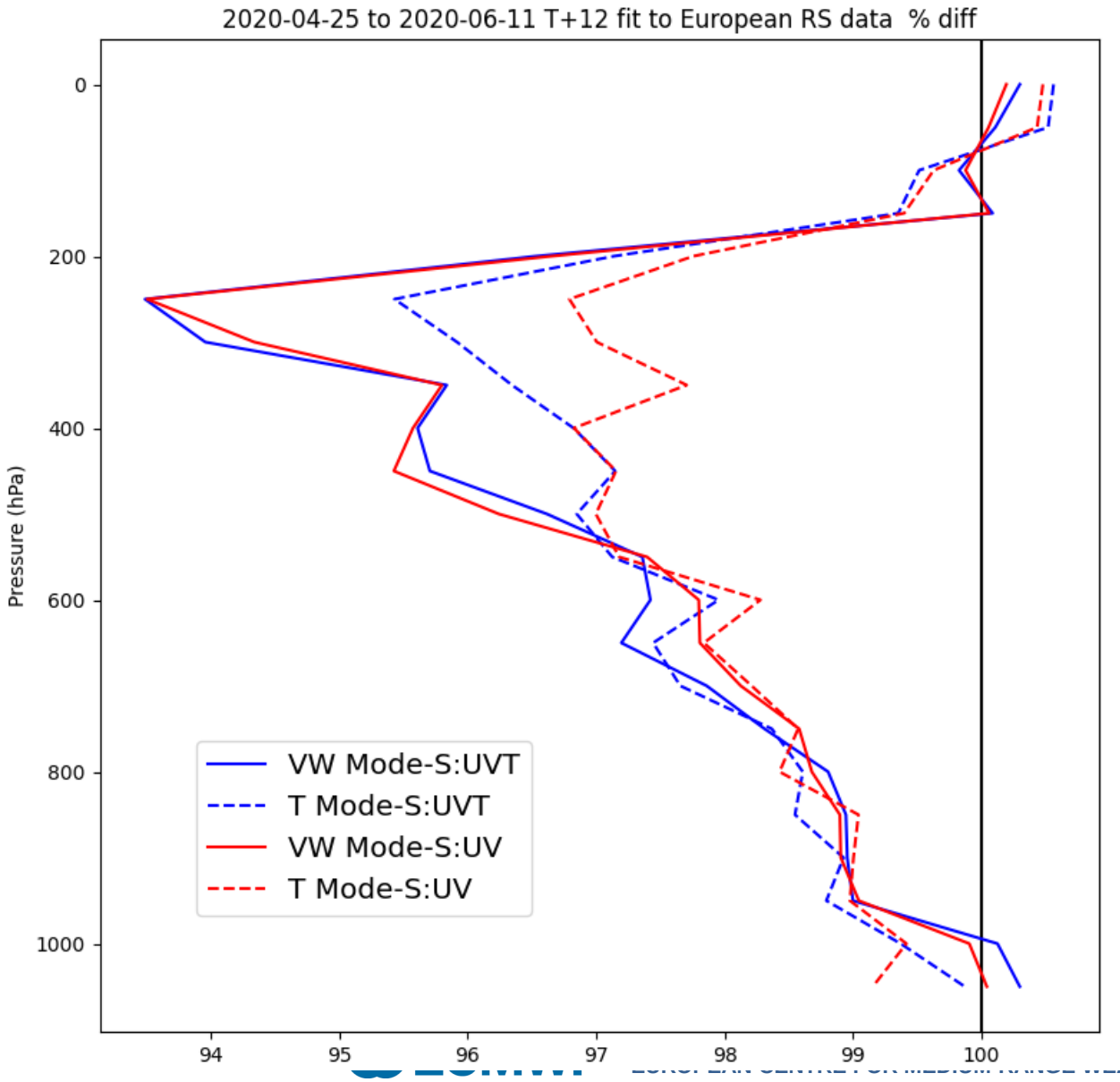
- Mode-S MRAR
  - These were designed as meteorological reports
  - Only available from limited number of aircraft in South-East Europe

European coverage including Mode-S

- November 25: 12 hours, used data
- AMDAR samples small % of flights
- Mode-S samples all flights within range (only 5% of reports used at ECMWF, still too many? Weighting?)
- Over N Atlantic most data provided by ADS-C/AIREP
- In last 6 months more Mode-S receivers have been set up (SE Europe, Norway, Moscow)



Impact of Mode-S: T+12 fit to European radiosondes

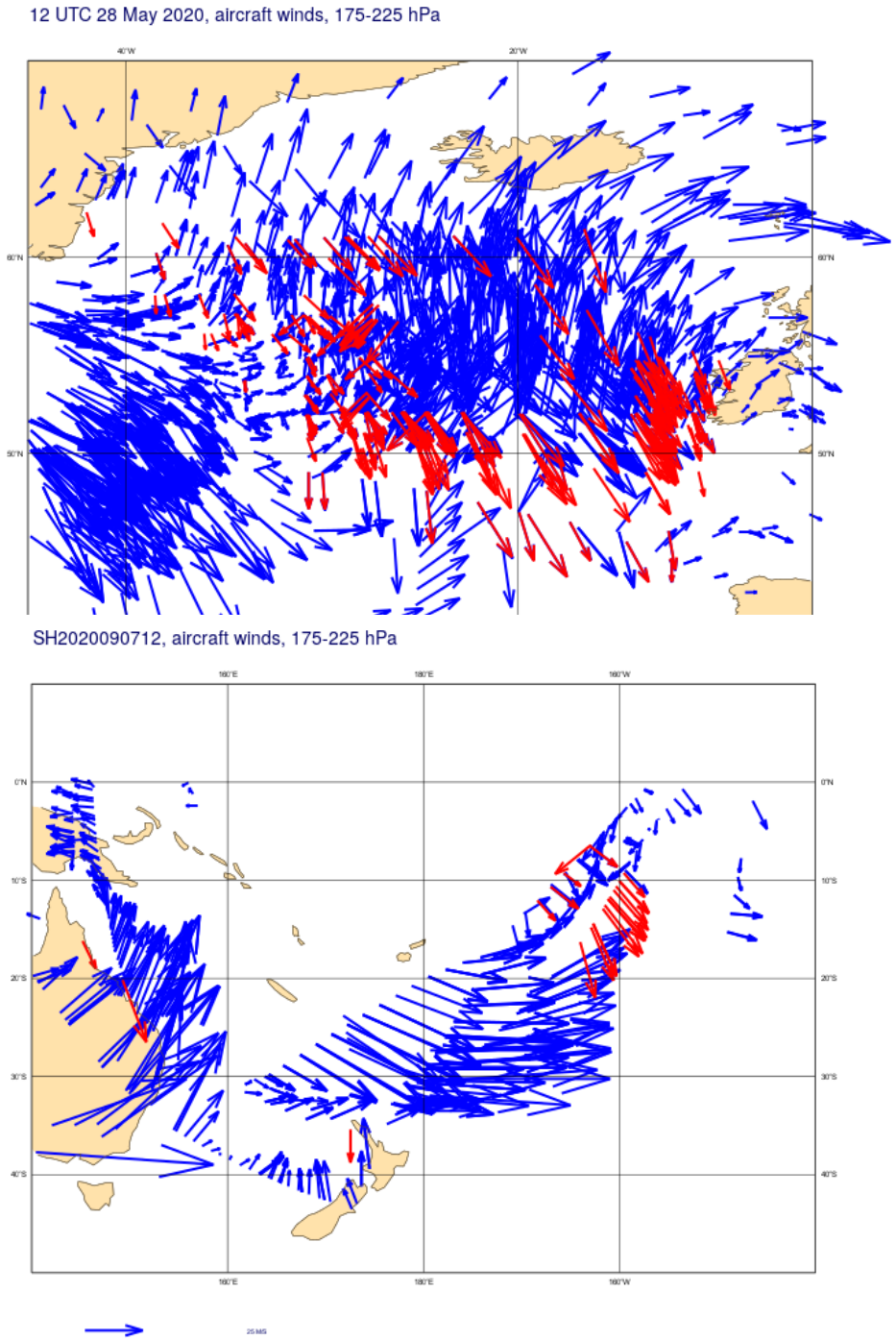


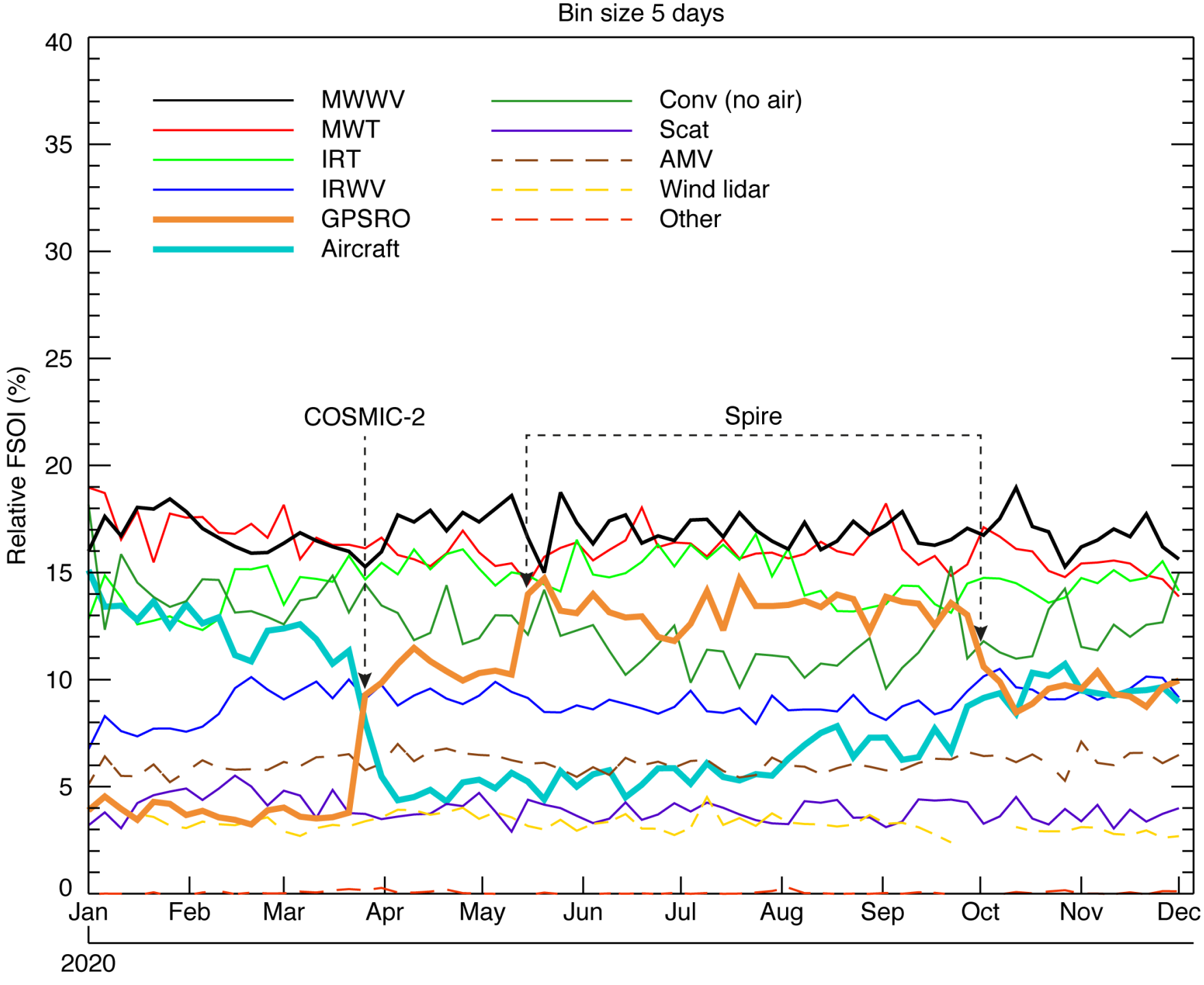
- Largest impact over Europe - expected
- Larger than seen in earlier LAM tests – partly because Mode-S is being used over a wider area

- Verification against analyses is ~neutral
- Minor bias effects and/or analysis increments outside an area with very dense observations??
- Biggest impact on winds at cruise level and less impact of T data – as seen for all aircraft data on hemispheric scale

B787 wind problem

- Error in ADS-C/AIREP wind direction (sign of v) for B787 winds from certain directions (details from C Hill, NOAA).
Nasty, frustrating QC problem ☹ ☹
- 2018 rejected wind from known B787s (550+ identifiers) – throws out good data too
- No metadata on aircraft type in reports: ☹ ☹ we now know type for a subset of aircraft
- Simple “correction” of v-winds (AIREP and ADS-C) implemented in 2020 - imperfect
- 90% of bad winds in North Atlantic – but little impact there – lots of good winds too
- More impact in South Pacific: fewer flights





FSOI % for 2020

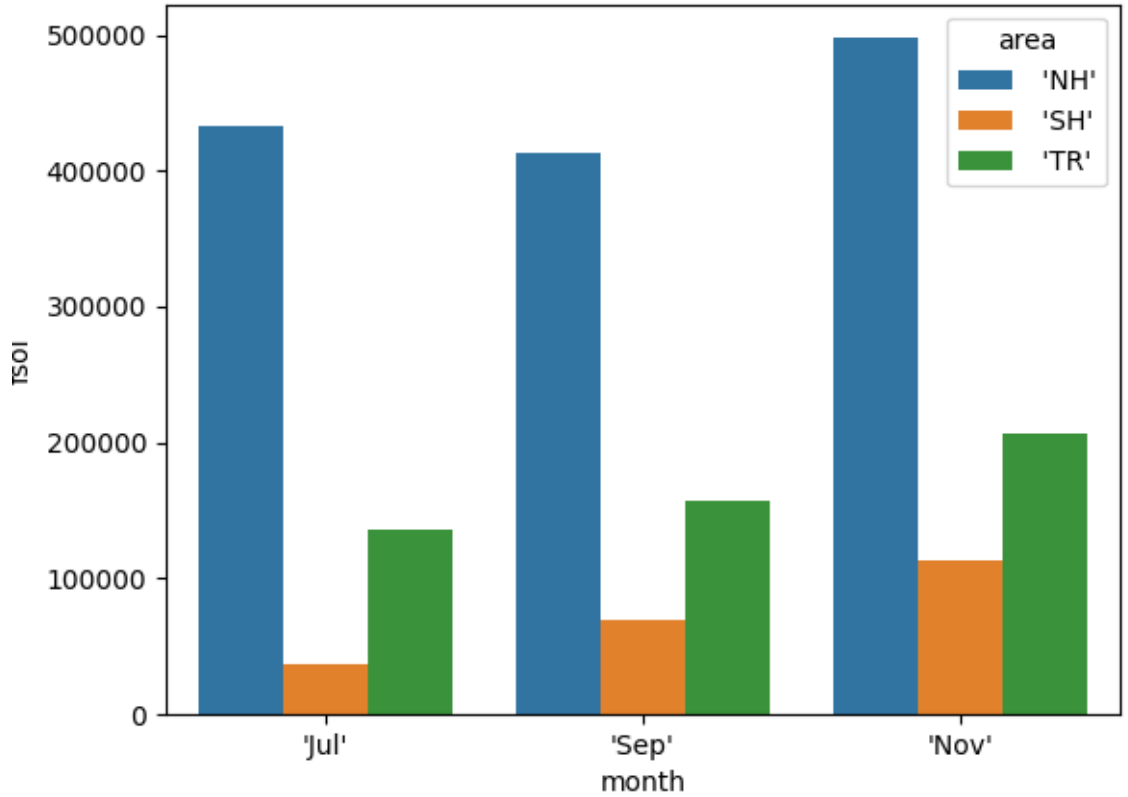
- Forecast sensitivity to observation impact: estimate of how important obs subsets are for T+24 forecast

- RO: steps from start of COSMIC-2+Spire, Spire stopped end Sept

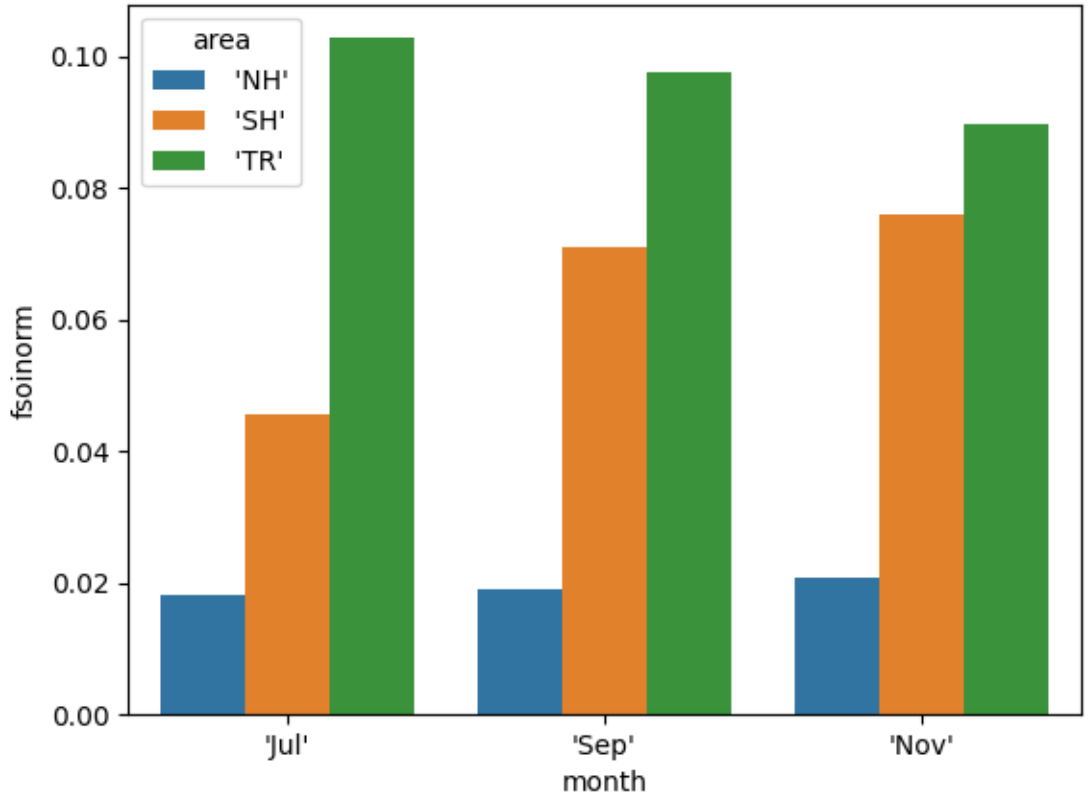
- Aircraft: drop in Mar/Apr then ~level
- Recent increase: seasonal or SH? (next)

- Aeolus: 3 or 4% (gaps)

Total (-)FSOI by region



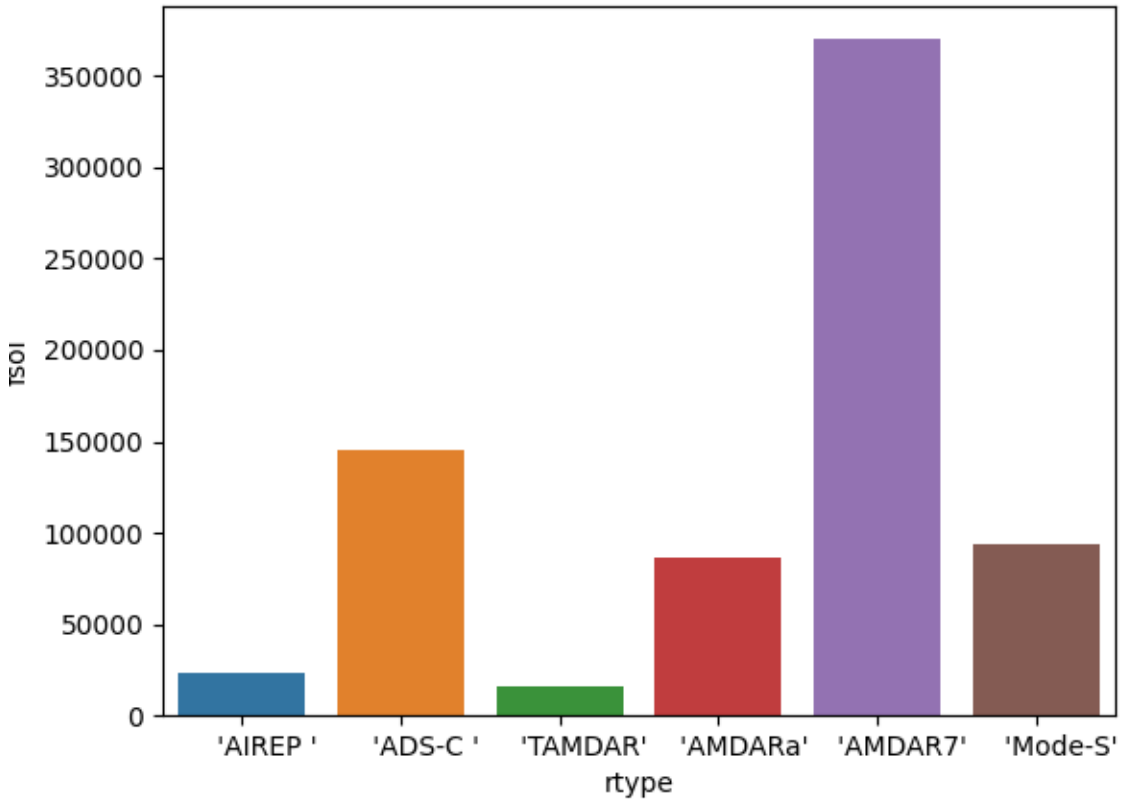
FSOI/datum by region

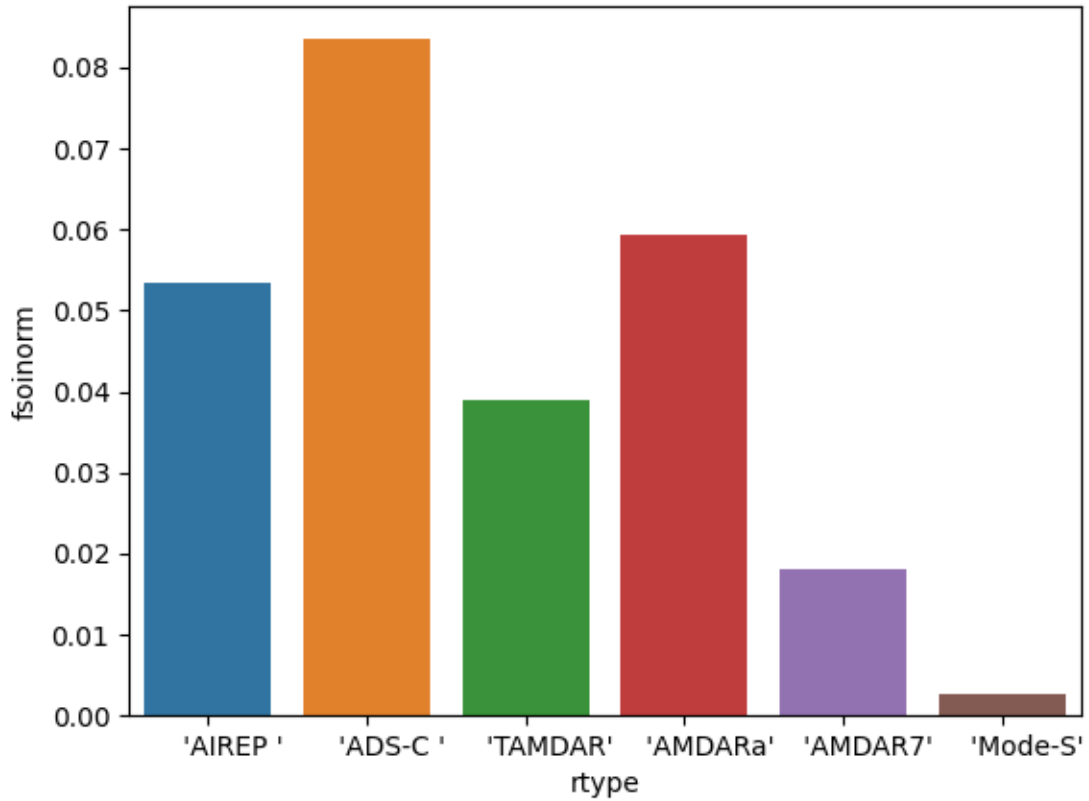


- **More impact per report in data sparse areas**
- Wind data particularly important in the tropics
- **Recovery in tropics + southern hemisphere has disproportionate impact**

- Mode-S (not included in figures): 12.5% of FSOI from ~50% of aircraft obs

Total (-)FSOI by type Sep 2020 FSOI/datum by type

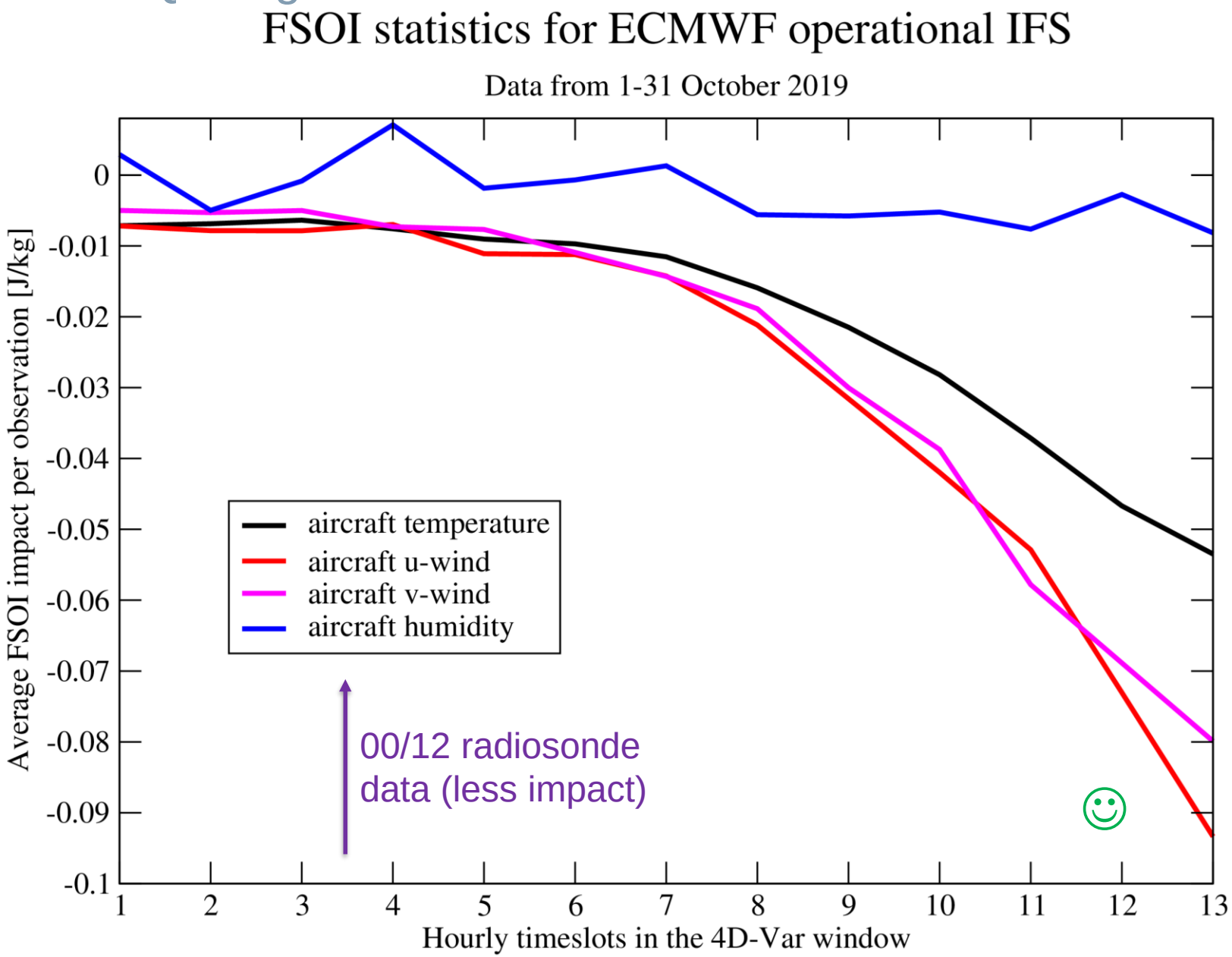




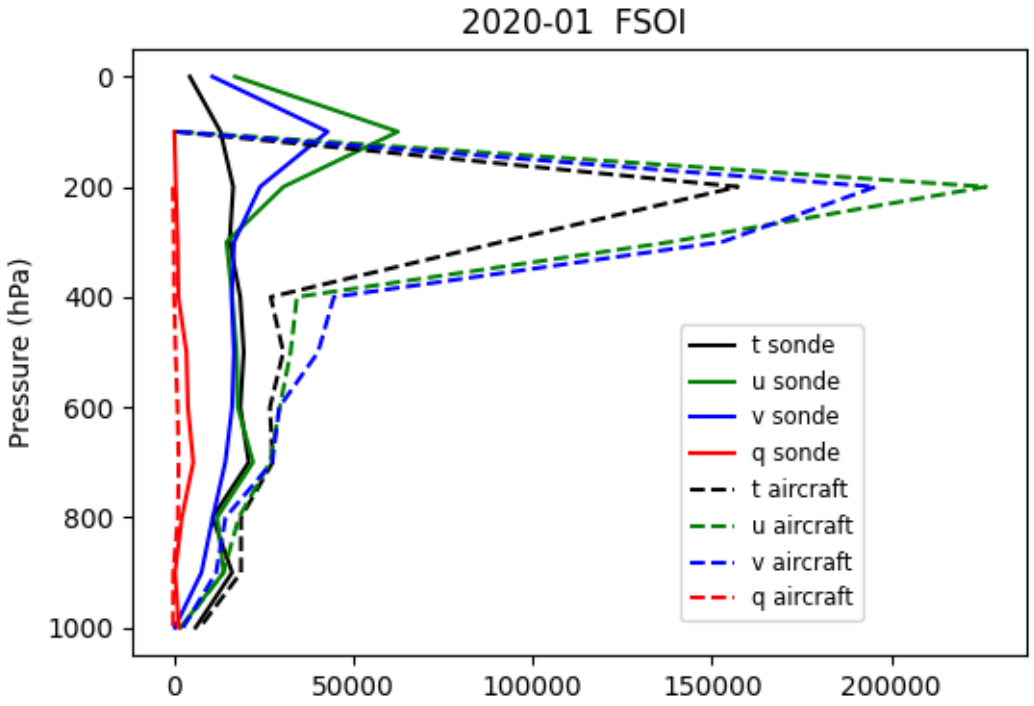
- Biggest contribution from AMDAR7: mainly Americas + Europe (dense)
- 2nd contribution from ADS-C (oceanic cruise data) – largest per datum
- AMDARa (old formats): AU, JP, CN, CA, ZA
- **Again impact per report is largest for data sparse regions**

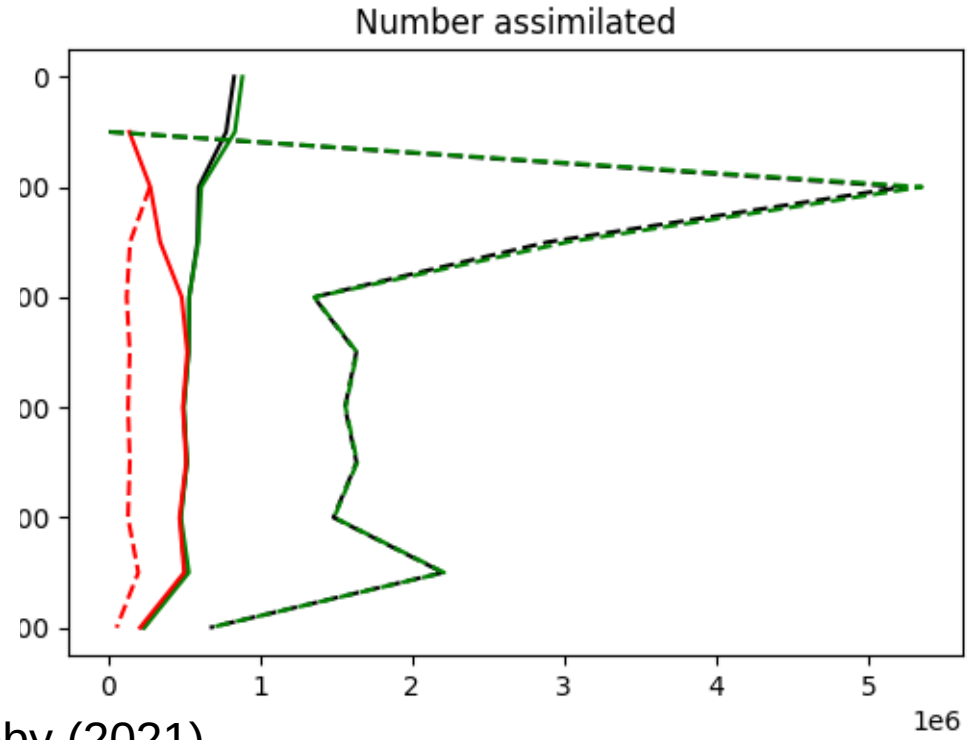
Timeliness is vital! Quite good for aircraft ☺

- ECMWF uses 4DVar with a 12 hour assimilation window
- Observations near the end of the window have more impact on forecast quality! See figure (from TM 855)
- This is a real effect, shown using satellite OSEs by McNally (2019)
- NWP centres need observations as early as possible



Aircraft and radiosonde FSOI: vertical profiles



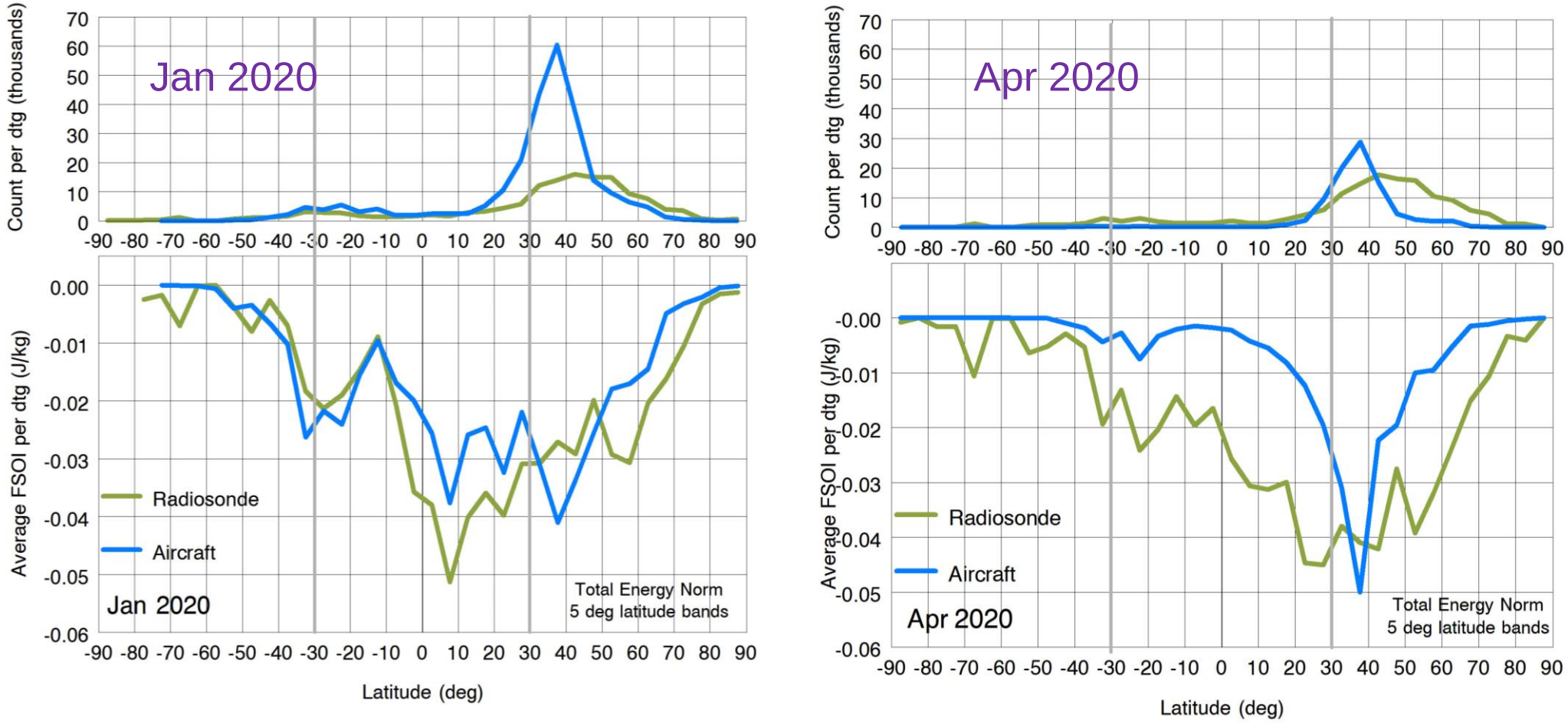


- ECMWF data (dry energy norm), Pauley and Ingleby (2021)
- Aircraft (dashed): biggest impact ~250 hPa from winds (as seen in OSEs)
- NOGAPS and Met Office have larger FSOI for radiosondes than aircraft

Aircraft and radiosonde FSOI by latitude

Count

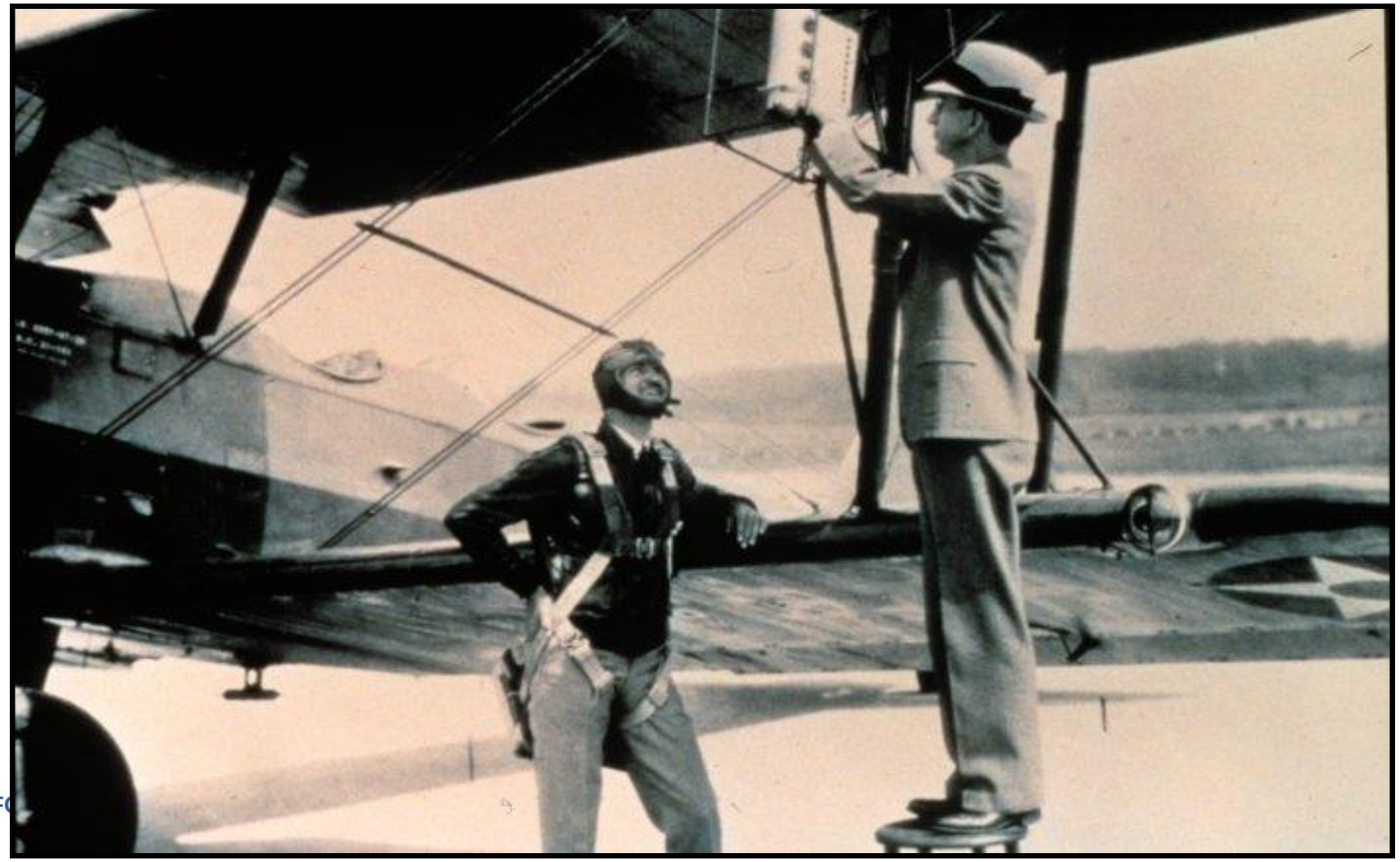
FSOI



- Data from NOGAPS (total energy norm), adapted from Pauley & Ingleby (2021)
- Jan 2020: moderate aircraft impact 40°S-20°N despite relatively few obs
- Apr 2020: aircraft numbers and impact collapse South of 25°N (and Arctic)

Part 2

- ‘Economics’ of aircraft observations
- What do aircraft measure?
  - Thanks to Steve Stringer (EUMETNET) for slides
- Aircraft temperature biases
- Aircraft metadata
- Filling in the gaps



Economics of Aircraft Based Observations (ABO)

- Aircraft measure wind and temperature for their own purposes
- AMDAR: meteorological services only pay communication costs
  - Reports are relatively cheap (especially over land, need satcomms over ocean)
  - U.S. takes all reports, Europe/others select e.g. 1 profile per airport per 3 hours
  - NMSs have limited control over metadata and quality
    - Can block particularly poor data and feedback to airlines
- Airlines benefit from improved weather forecasts:
  - Safety aspects (e.g. turbulence, take-off and landing, icing)
  - Efficiency: where possible routes are chosen to maximise tail-winds and minimise head-winds
    - 9 Feb 2020: fastest subsonic New York to London flight, 4 h 56 min (80 min early)
  - Fuel load chosen to match forecast flight time (+safety margin)

Global ABO: What is actually measured & reported by aircraft?

- TAT probes (temperature)

- Pitot-static tubes (pressure)

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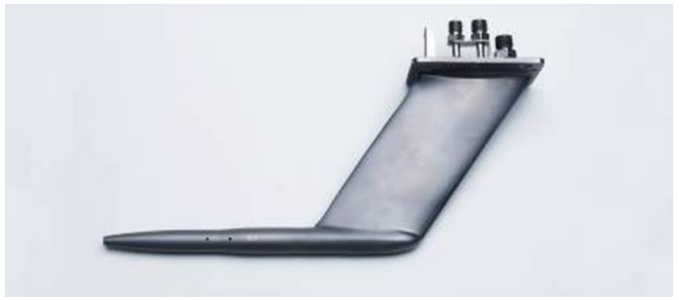
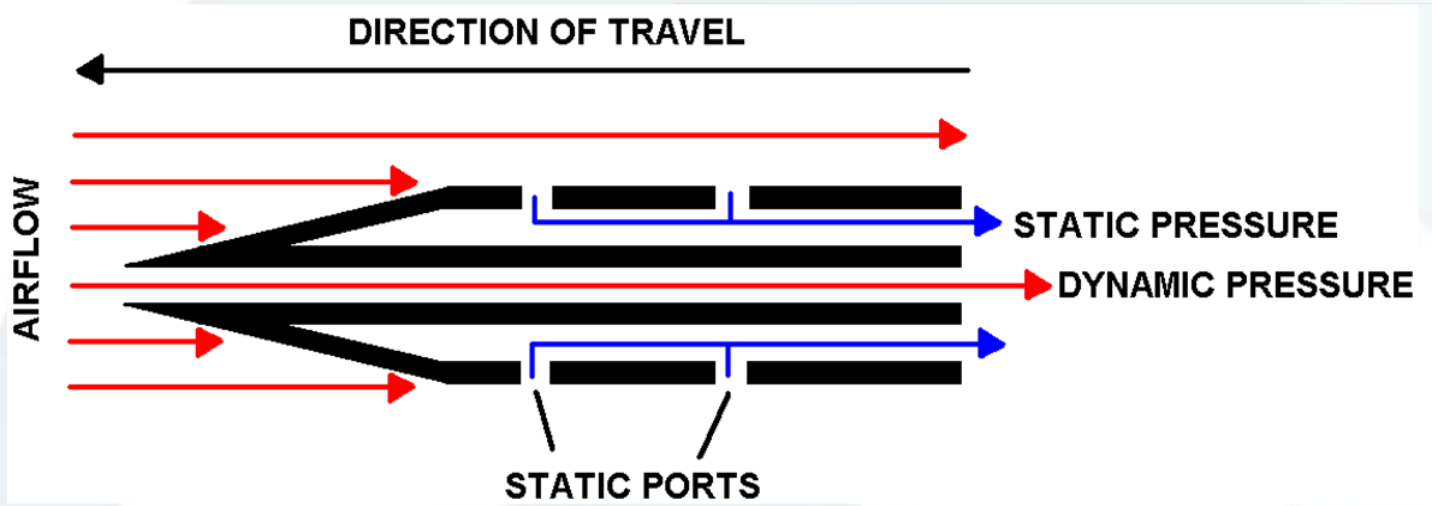
What is measured: Pressure

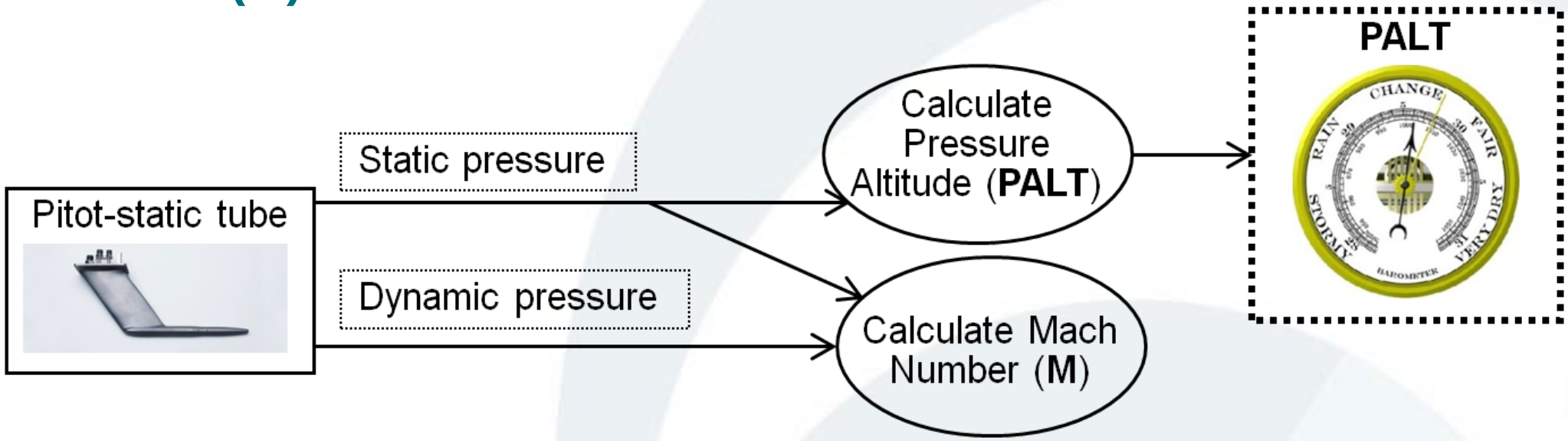
Pressure (and speed) is measured by standard aircraft sensors known as Pitot-static tubes





What is measured: Pressure (Altitude)

- Static pressure is used to calculate pressure altitude (**PALT**)
- Static pressure (normal air pressure) and dynamic pressure (caused by flight) can be used together to calculate the aircraft's speed as a **Mach number (M)**



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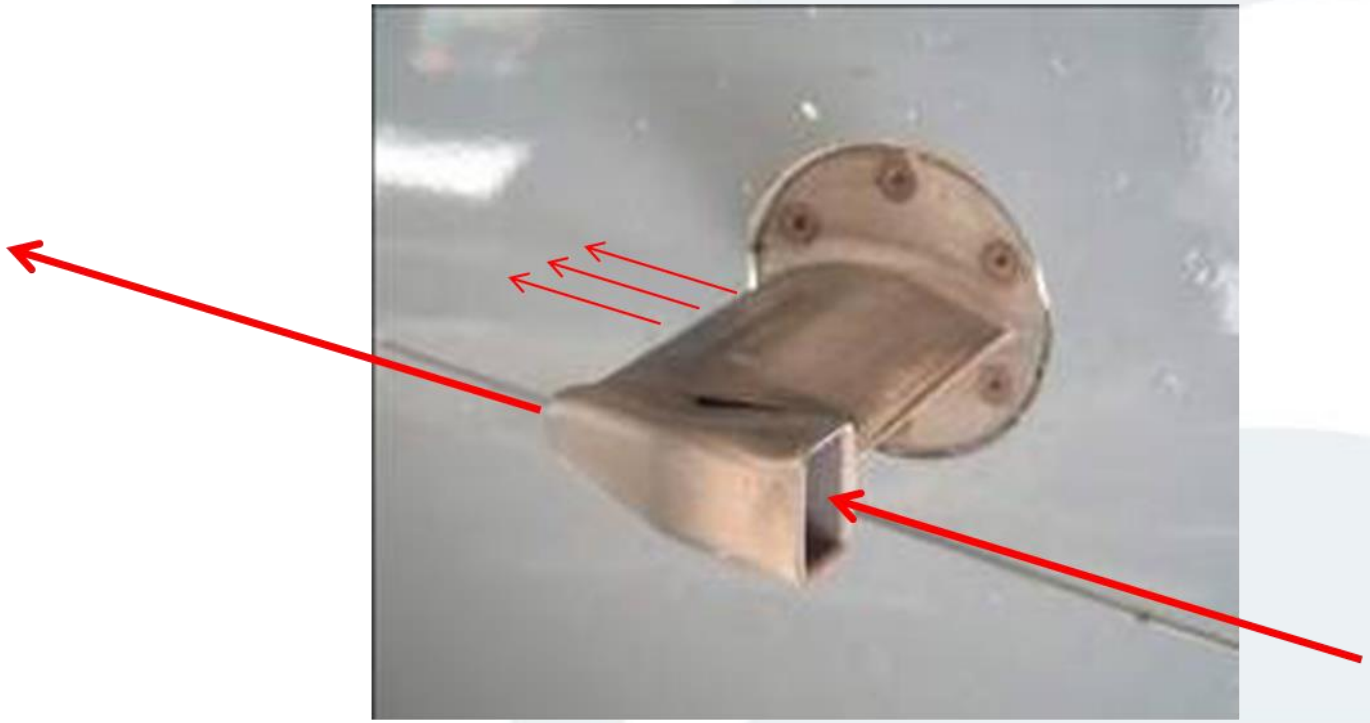
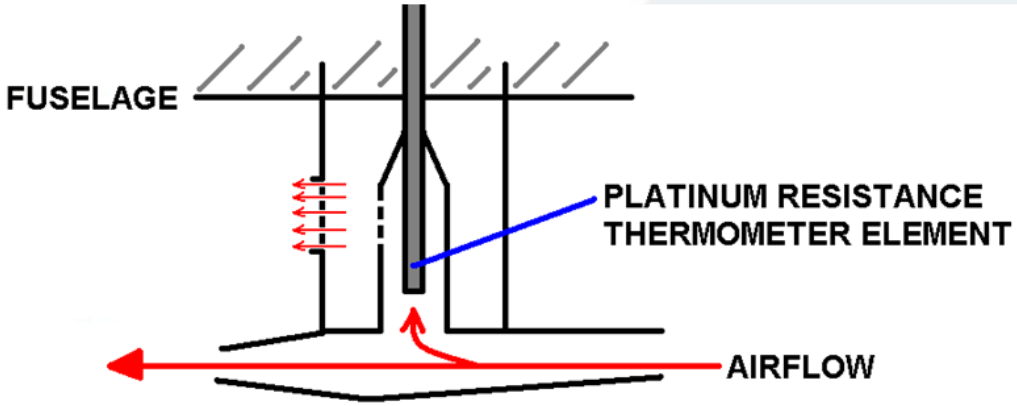
- Temperature is measured by a Total Air Temperature (**TAT**) probe
- Sensor faces into the airflow and brings air to a stop inside the sensor where its temperature is measured



What is measured: Temperature

Conversion of kinetic energy causes the air to warm (20° or more).
This warmer value is known as the **T**otal **A**ir **T**emperature (**TAT**)



This is then converted into **S**tatic **A**ir **T**emperature (**SAT**) by onboard software, which is equivalent to the true external air temperature (Complications/less accuracy during turns or turbulence)

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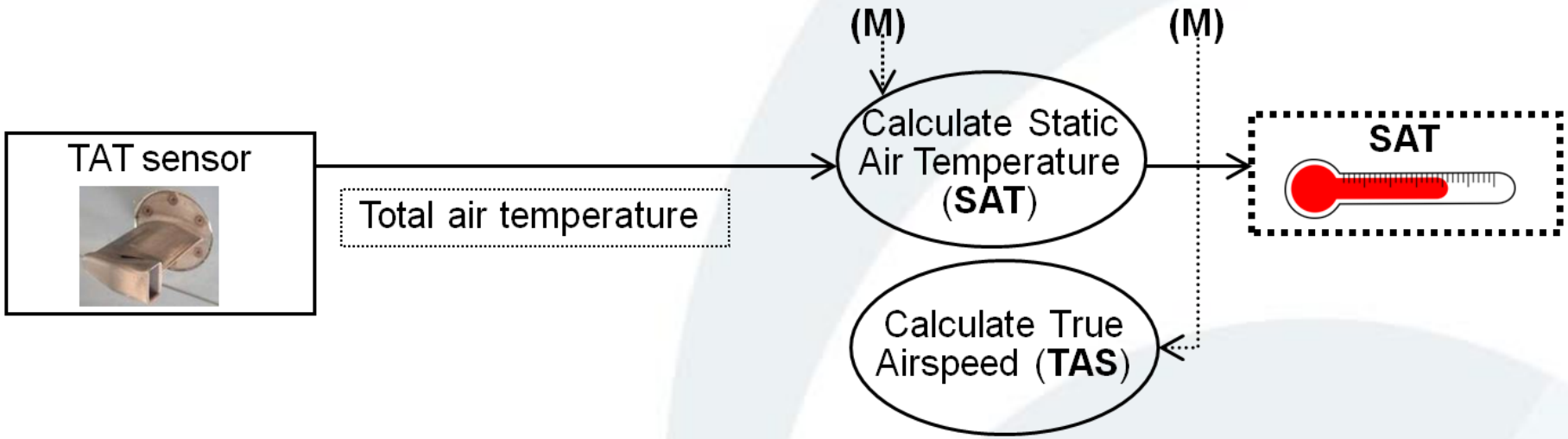
Static Air Temperature (SAT) is a function of sensor probe and Mach Number (aircraft speed relative to the speed of sound).

Mach Number is derived from total and static pressures



The measurement of the three-dimensional wind vector from an aircraft is a complicated problem!

Using the aircraft navigation system and the airspeed system (Pitot-static tubes) together with the TAT sensors, it is possible to estimate – to a high enough degree of accuracy:

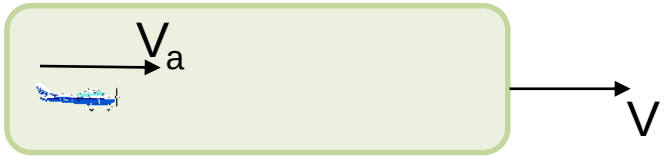
The velocity of the aircraft with respect to the ground below it

(V_g = ground speed)

The velocity of the aircraft with respect to the air around it

(V_a = airspeed).

Wind Vector (V) is then given by: $V = V_g - V_a$.



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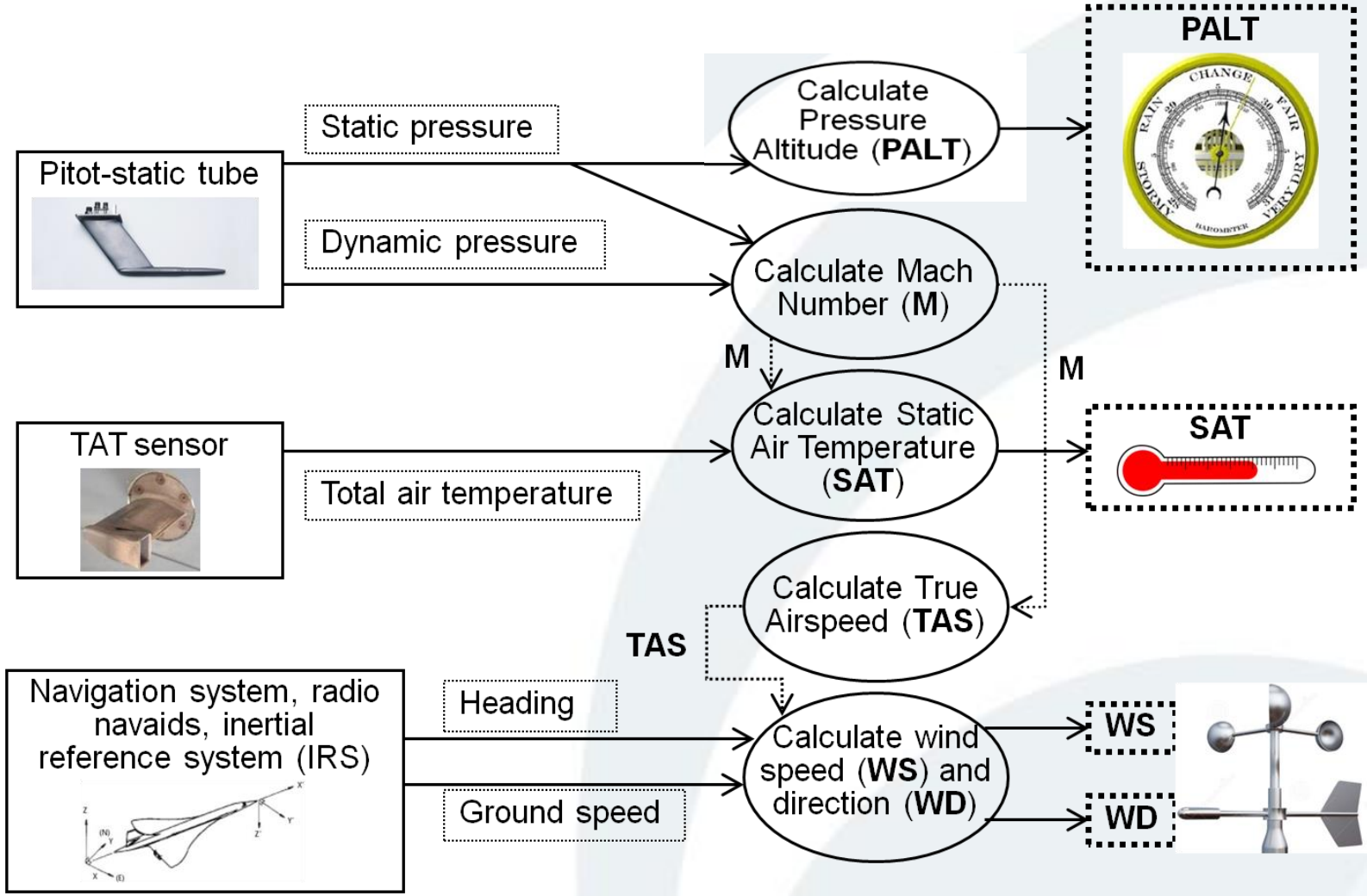
What is measured: Sensor Interdependencies



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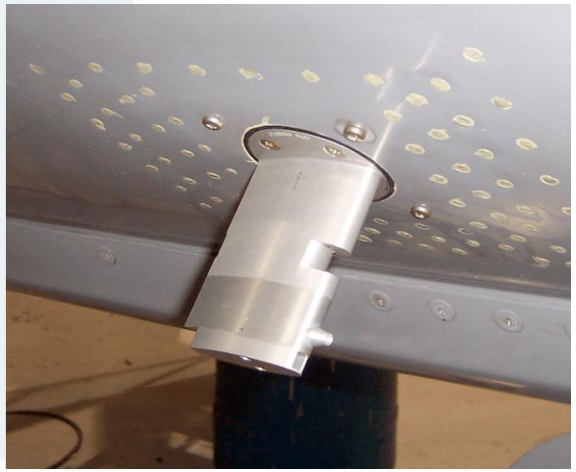
Water Vapour measurements

- Unlike T and wind, humidity is not required for aircraft operations
  - Need fast response sensor
- AMDAR: WVSS-II, laser sensor measuring specific humidity
  - Installed on ~150 U.S. aircraft, 9 German aircraft (some currently inactive)
- TAMDAR: capacitive sensor measuring relative humidity

- Petersen et al (2016, BAMS) overview
- Hoover et al (2017, W&F) impact of WVSS-II on NCEP system
- Ingleby et al (2019, EC TM 855) impact of WVSS-II and TAMDAR on ECMWF system

WVSS

1. System Electronics Box (SEB)
2. Air Sampler
3. Hoses
4. Standard Aircraft Power/Data Connector



TAMDAR

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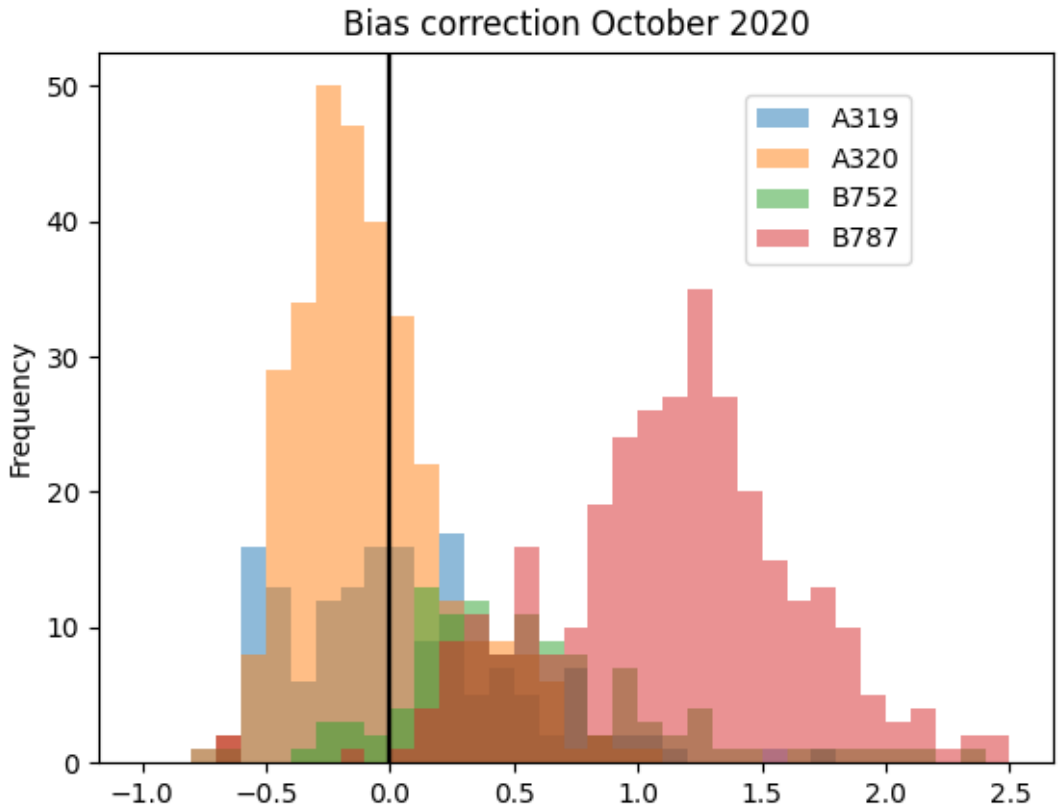
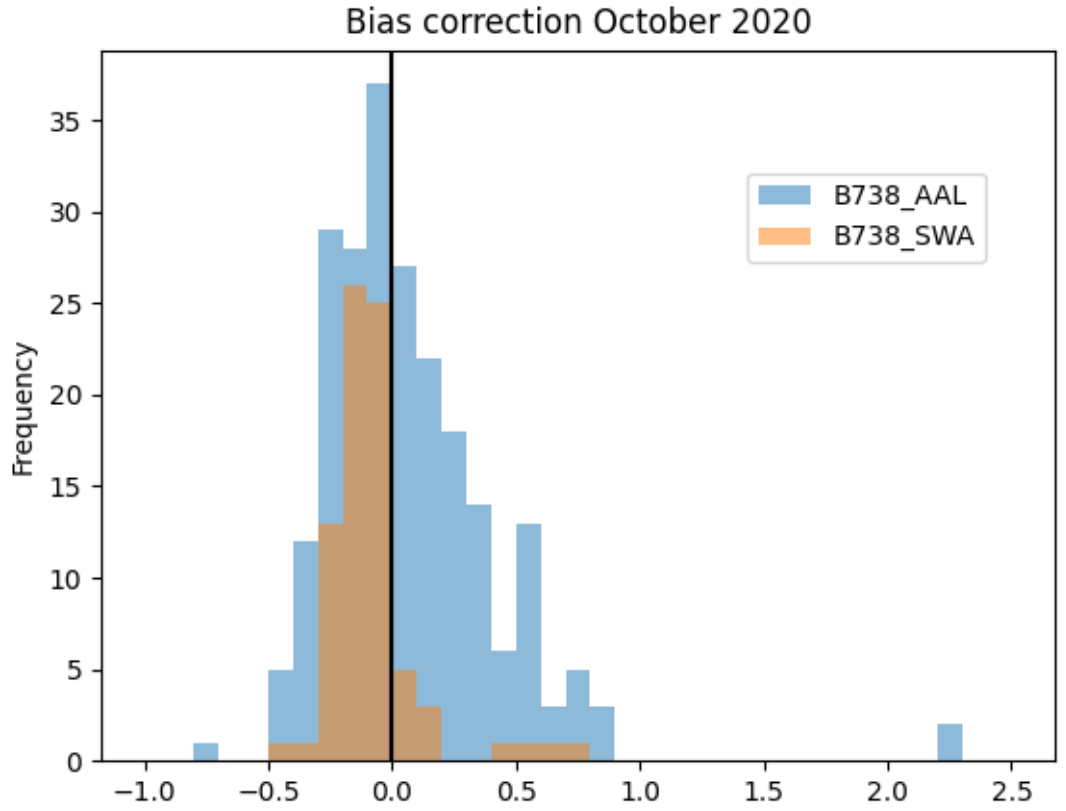
Aircraft temperature biases

- Ballish and Kumar (BAMS, 2008), Petersen (BAMS,2016): aircraft biased warm by 0.3-1.0K on average
- Drüe et al (QJRMS, 2008): bias as fn(aircraft type)? Just part of story?
- De Haan et al (2020, EUFAR meeting): convergence of M and T
- Use of VarBC to "correct" the data: ECMWF: Isaksen et al (2012, Newsletter), NCEP: Zhu et al (2015, MWR)
  - Typical fn each aeroplane: Constant + c_1*ascent rate + c_2*descent rate
  - VarBC works somewhat better for satellite data than in situ observations – primarily due to much larger data volume for a satellite data channel than for one aeroplane

- VarBC – Is it the best method?
  - Better if NWP centres don't have to bias correct data

October 2020 ECMWF mean bias correction by type*

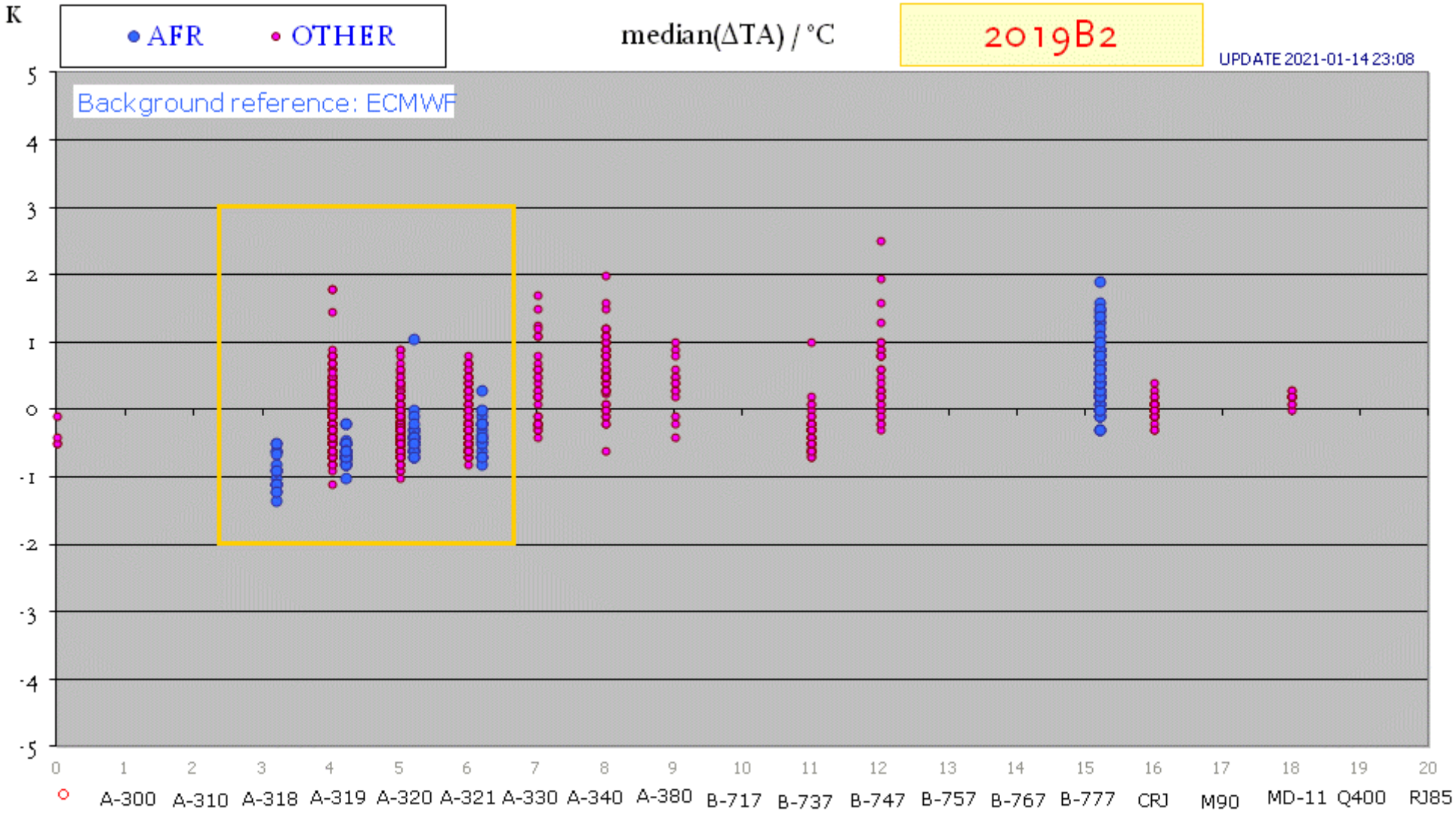




*Type information is incomplete but comes from either a) US/EU AMDAR programs or b) ESoWC 2019 study (with M Chan, M Dahoui) matching flightradar24 to AMDAR tracks. NOT used in ECMWF VarBC, which uses aircraft identifier, ascent rate and O-B.

Bias is linked to aircraft type (even if the details aren't clear)

E-AMDAR statistics Apr-Sep 2019 (Jitze van der Meulen)



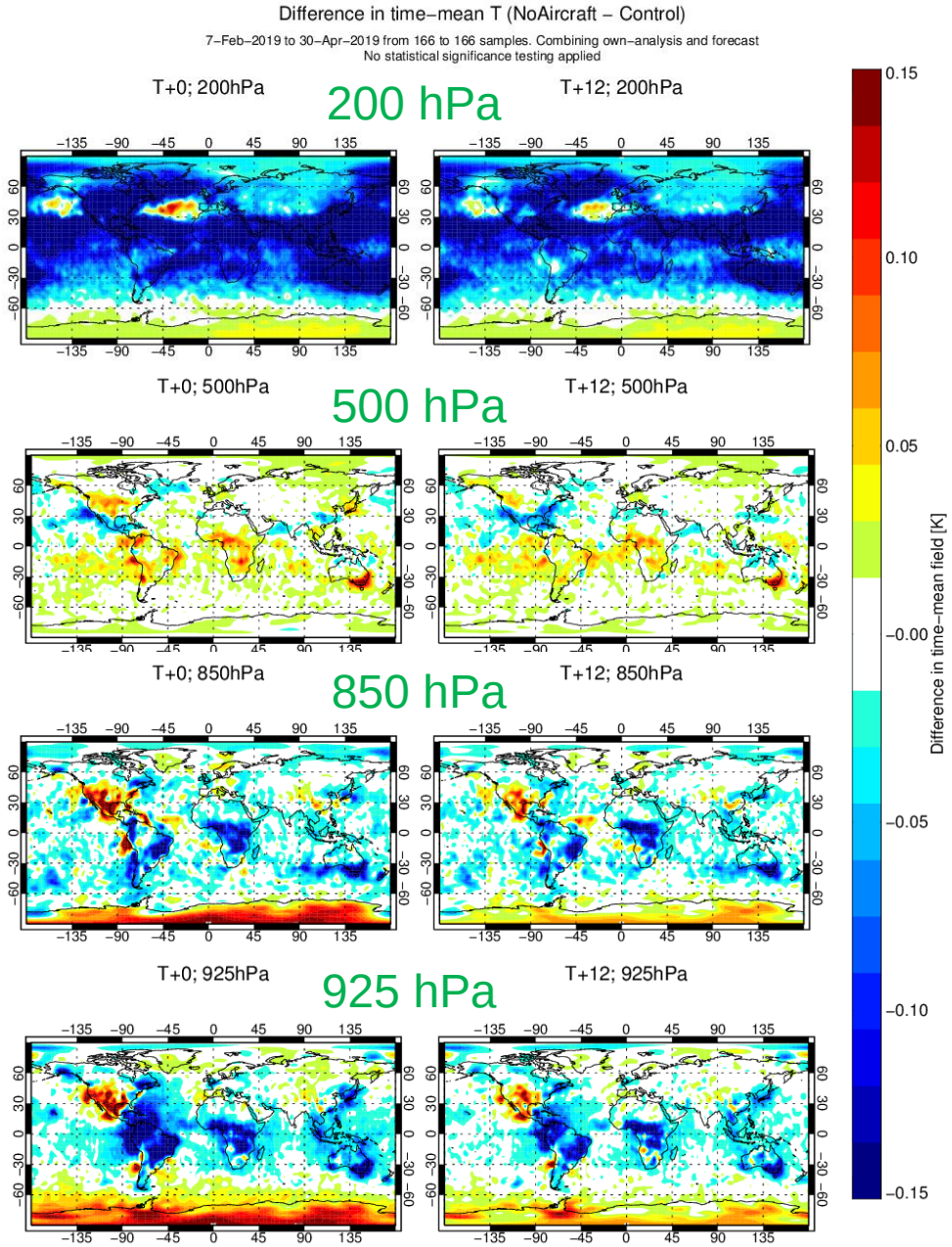
- **T biases:** individual aircraft by type, no QC
- Some differences between Air France and other airlines
- AFR: tighter clusters
- Jitze had access to airline metadata for all E-AMDAR aircraft

Bias correction methods are useful but imperfect

- Eyre (2015, QJRMS) in the presence of model biases NWP bias correction schemes work best when there is a large proportion of “anchor” observations
- For temperature radiosondes and GPS-RO form the anchor observations: up to end of 2019 these data sources were ~constant whereas the data needing bias correction (satellite soundings and aircraft data) was increasing
  - In 2020 the number of aircraft reports crashed and GPS-RO increased significantly
- Even with VarBC assimilation of aircraft data causes a residual bias (next slide)
  - Laloyaux et al (2020, QJ) have introduced ‘weak constraint’ in ECMWF stratosphere
  - Attempts to use it in troposphere confused aircraft bias with model bias – especially above (U.S.) airports with lots of reports – slowing forecast improvements
- Can something be done to improve aircraft temperatures “at source”?
  - Current accuracy is good enough for airlines but not for NWP and climate

OSE with no aircraft data

- Mean differences between NoAircraft and Control (T+0 and T+12)
- Largest, most widespread difference at 200 hPa (top) – as expected
- Magnitude ‘only’ 0.15° - but a problem, despite VarBC
- More localised impacts at lower levels
- Interaction with model bias at low levels in tropics?



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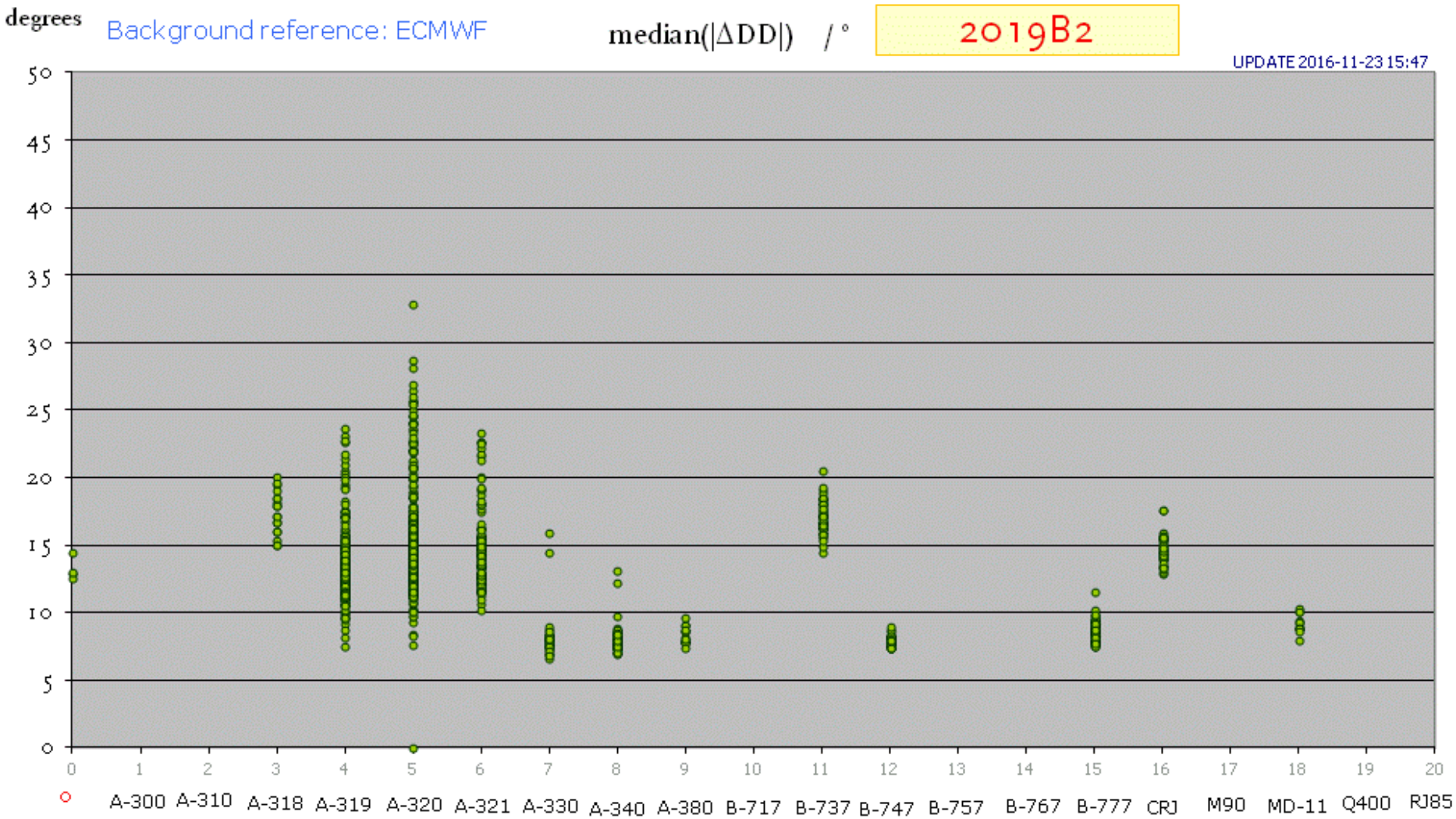


- **Wind direction stats** by aircraft type
- Vector wind shows some variation by aircraft type – but less marked
- Geographic/height sampling?
- Wind direction very variable at low speeds
- Scope for lots more investigation

Aircraft identifiers and anonymisation

- AIREP identifier is flight number (eg BA123 returns as BA124)
  - Often the same aircraft type does the same route but not guaranteed
- When AMDAR was set up users wanted aircraft specific ids
- Airlines+pilots didn't want users to track e.g. delays: anonymisation
- E-AMDAR: EU0001 etc, US-AMDAR/ADS-C: BYBS340A etc (8 characters, end A or Q)
  - Over 10000 aircraft identifiers
- One European aircraft can have 3 identifiers (E-AMDAR, ADS-C & Mode-S) 
- Anonymisation makes it more difficult to know aircraft type + airline 
-
- Since ~2006 the flightaware, flightradar24 etc have provided flight/delay information openly – nullifying original argument for anonymisation
- **Please can airlines provide more metadata** (even if not tail numbers)

Improved AMDAR metadata – ESoWC challenge

ECMWF Summer of Weather Code, 2019, with Micky Chan and Mohamed Dahoui

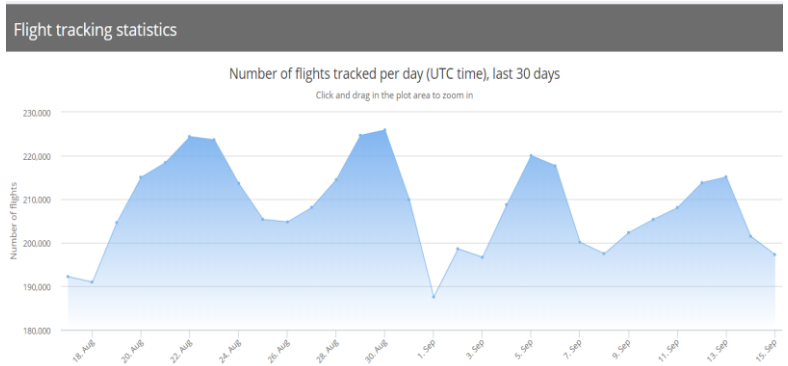
- AMDAR reports use an anonymised identifier, eg EU0001
  - No information on aircraft type or airline
  - A minority of AMDAR reports give departure/arrival airports
  - In 2018 ECMWF received E-AMDAR type list + NOAA B787 list
- Can we match online information (eg flightaware.com, available since ~2006) to AMDAR data to provide some of the “missing” metadata?
  - We can obtain flight summaries, but only start/end points
    - Full flight information N/A unfortunately (could try OpenSky Network)
  - AMDAR reports sometimes start/stop in mid-air: makes it difficult or impossible to deduce the airports (varies by airline/program)
  - Extra problems around cities with multiple major airports
  - Despite this some progress has been made
    - Make AMDAR data look like online lists
    - Look at 5-7 days rather than individual flights

FlightRadar24 – on average 200,000 flights are tracked each day

Free data for past 7 days with tail number of aircraft.

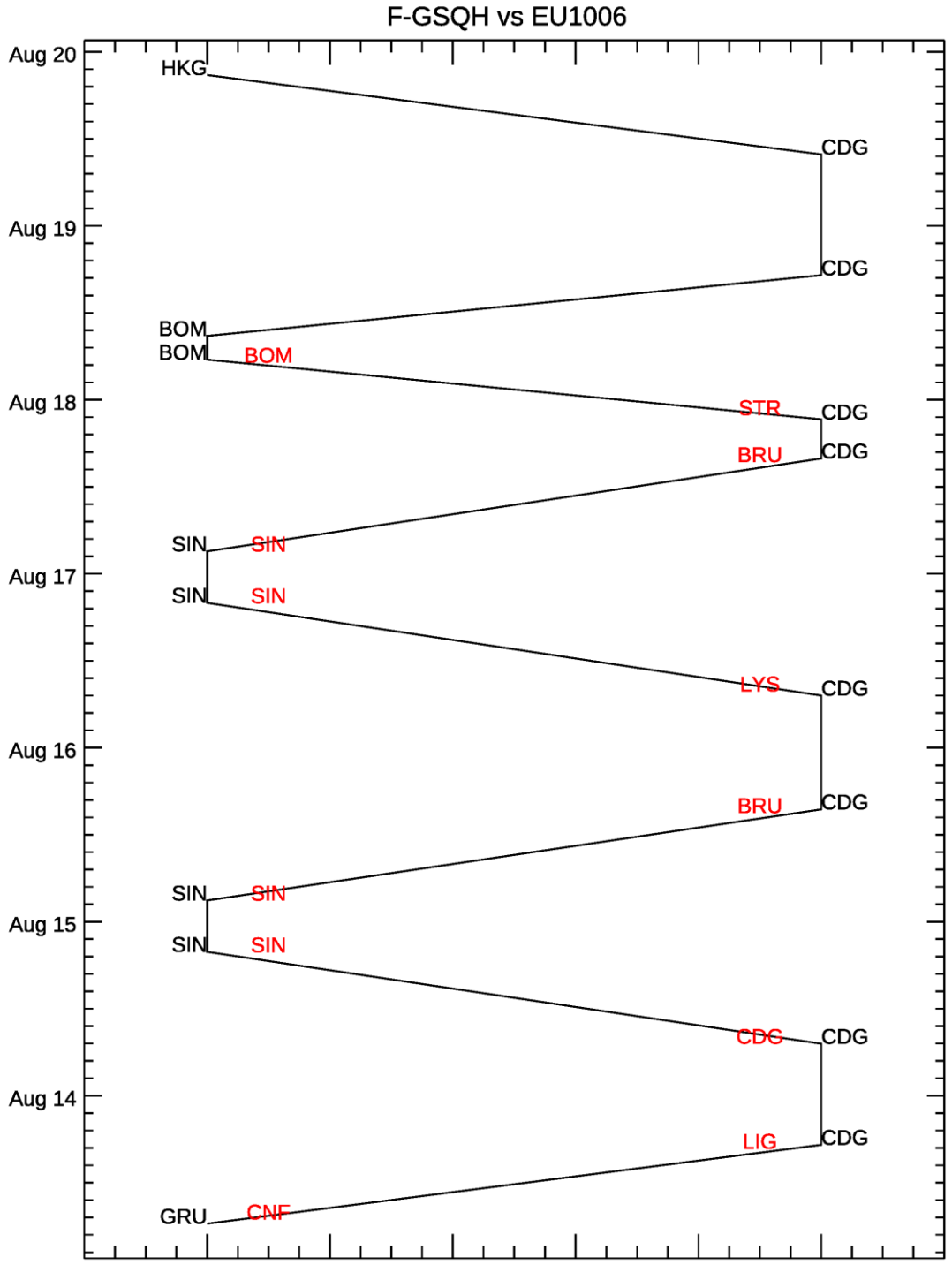
FlightAware

Challenge – We expected to compare en route positions and tried both flightradar24 and flightaware, but had to rely on departure and arrival airport for matching.



Example schematic

- An aircraft operating from Charles De Gaulle airport, Paris (CDG)
- Long-haul: Singapore, Bombay, …
- Estimated airports: mostly the ascent/descent is missing so another airport (eg Brussels) is the closest to first/last AMDAR
- In some cases it is difficult to determine from the AMDARs where one flight stops and another starts
- Know/guess an airline that provides AMDAR and scrape flight lists for all the tailnumbers from that airline
- Compare with likely AMDARs
- Visual check for now (automate?)



Preliminary results (for a week in August 2019)

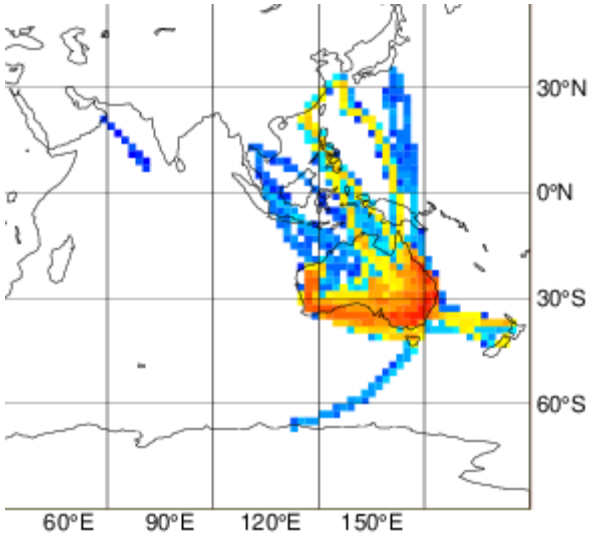
- USA: 1062 aircraft matched (1 wrong – C Hill), ~50% (ADS-C not matched)
- Europe: 505/1186 matched
- Japan: 142/252 matched … (6 other national/regional programs)
- AMDAR: ~50% matched, from 19/19 South Korea (id=tailnumber!) to 0/12 for Canada
- Different matching parameters work best for different programs

• Possible improvements

- Cut down list of airports
- Use machine learning to auto-tune parameters or clever user interface
- Use different sample periods (how to combine results?)
- “Fuzzy matching” of airports round major cities? AI/ML?

Potential uses of metadata

- Quality control (eg B787 wind problem)
- Bias correction (temperature)
- Real time warning systems (ADS-C data missing for 2 days in January 2020, noted by ECMWF and others, but not by some with ADS-C as subset of AMDAR)
- General monitoring: want meaningful subsets larger than individual aircraft but smaller than whole AMDAR programme
- Late 2019: realised that ECMWF wasn't using Hong Kong AMDARs
  - Non standard format, now have fix to cope



ECMWF has just started monitoring regional programmes

e.g. # of reports from Australian AMDAR programme

Filling in the gaps?

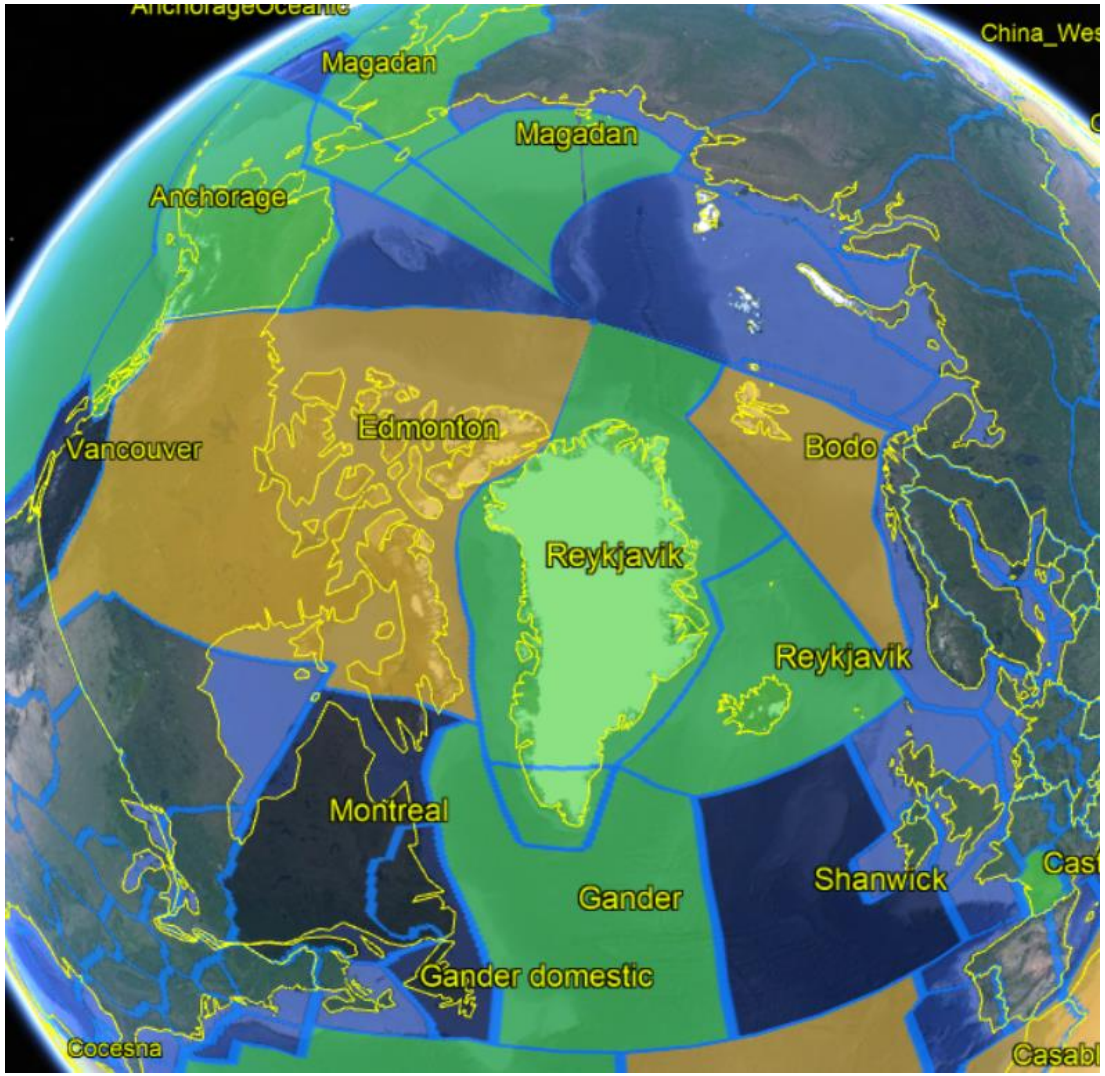
- Global NWP priority (1 report over remote/ocean worth several over USA/Europe)
- 2020: WMO and IATA Collaborative AMDAR Programme (WICAP) established, they hope to double the numbers of airlines participating
- Early morning gap in flights (some airports considering use of drones during gap)
- In last few years there were short-lived pilot programmes providing AMDAR data from Papua New Guinea and Leeward Islands, data sparse ☺ – quality OK ☺
  - Sadly, both stopped due to lack of funding ☹
  - Similar programmes might be supported by new WMO SOFF in future?
- Continued access to TAMDAR+AFIRS?
- Mode-S in remote areas? From satellite??
- ADS-C: globally there are 65 Air Navigation Service Providers (ANSPs)
- 39 provide meteorological reports, 26 do not (Alan Williard, Collins, next slides)
  - Technical issues in 5 ANSPs, see Williard presentation (EUMETNET/ECMWF workshop)

Arctic ANSPs supporting ADS-C protocol

ANSP regions with periodic ADS-C contracts enabling MET group

ANSP regions with periodic ADS-C contracts ***NOT*** enabling MET group

Exception regions: ADS-C present, but not available to AMDAR

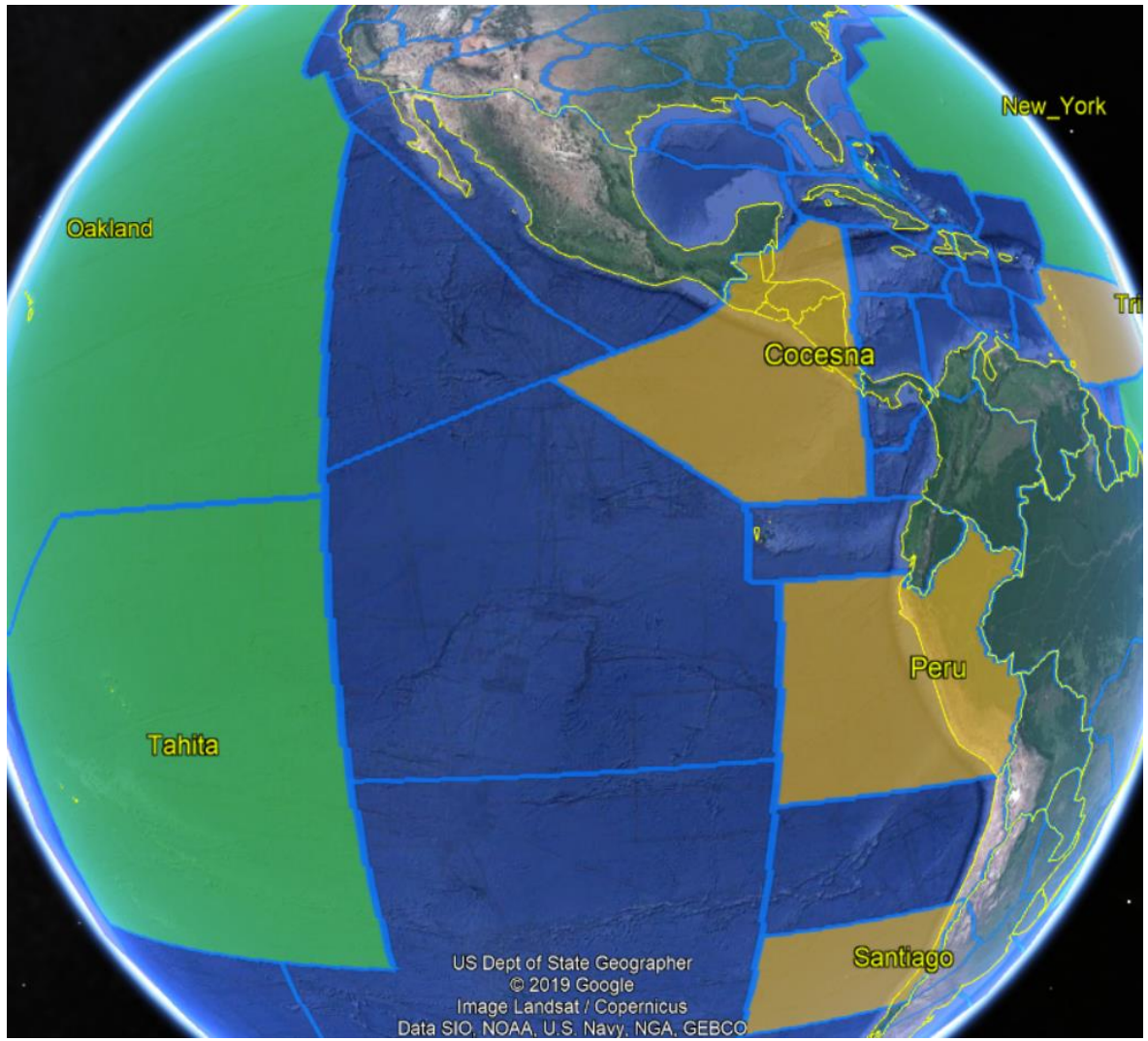


Google Earth
US Dept of State Geographer
http://gis.icao.int/GEOPDF/FIR2013.kml

Pacific Ocean ANSPs supporting ADS-C protocol

ANSP regions with periodic ADS-C contracts enabling MET group

ANSP regions with periodic ADS-C contracts ***NOT*** enabling MET group



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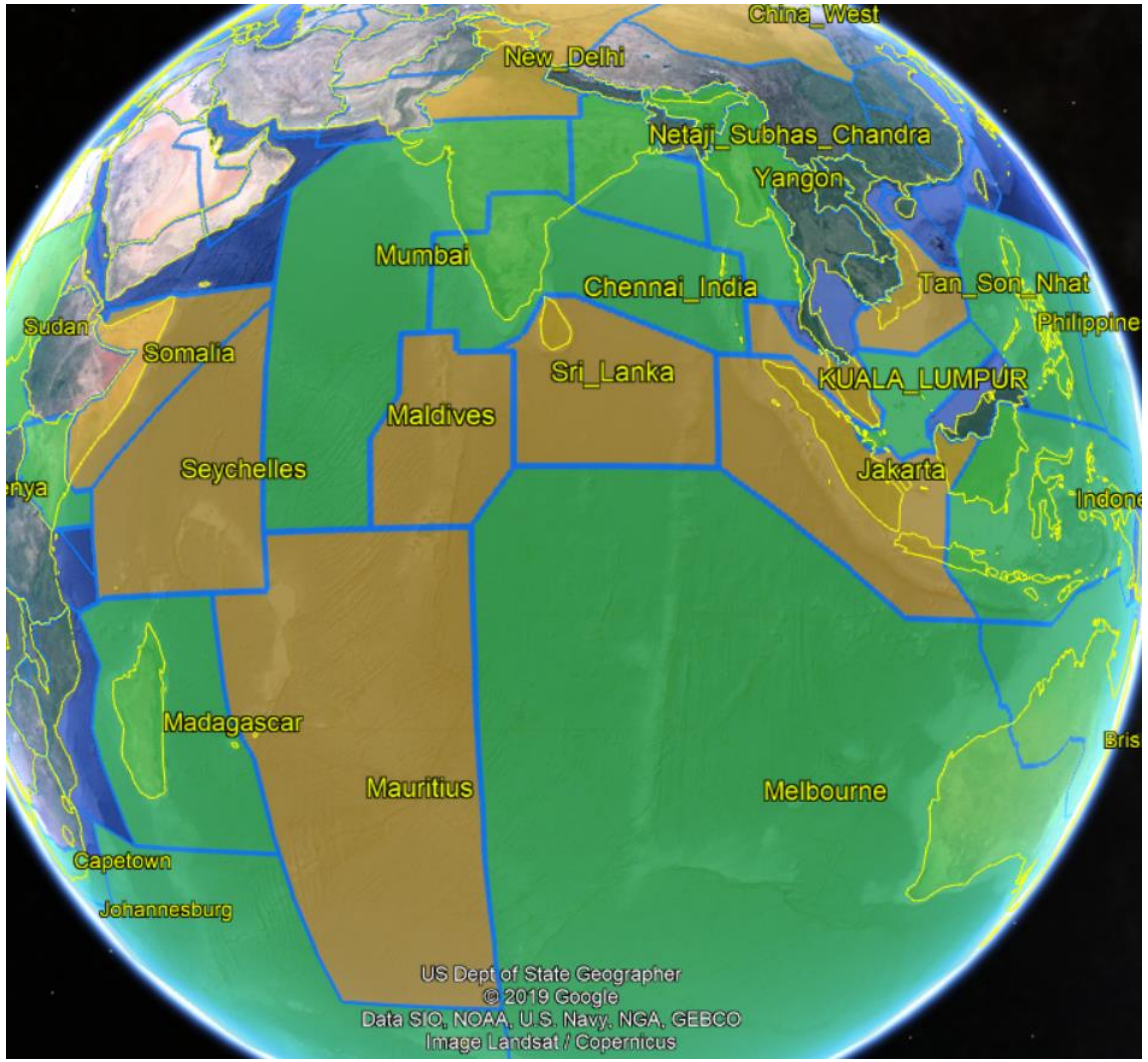
Indian Ocean ANSPs supporting ADS-C protocol

ANSP regions with periodic ADS-C contracts enabling MET group

ANSP regions with periodic ADS-C contracts ***NOT*** enabling MET group



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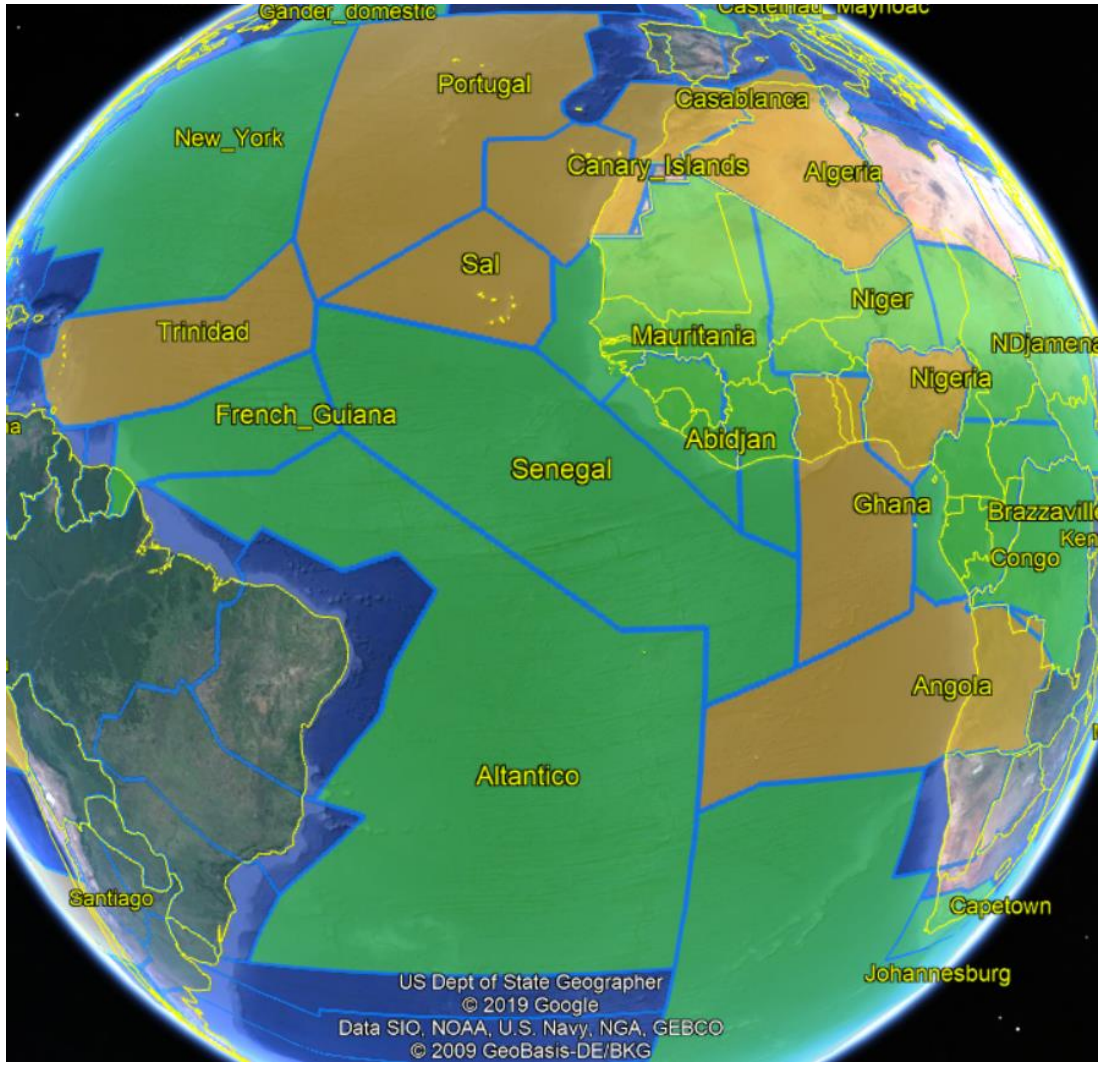
Atlantic Ocean ANSPs supporting ADS-C protocol

ANSP regions with periodic ADS-C contracts enabling MET group

ANSP regions with periodic ADS-C contracts ***NOT*** enabling MET group



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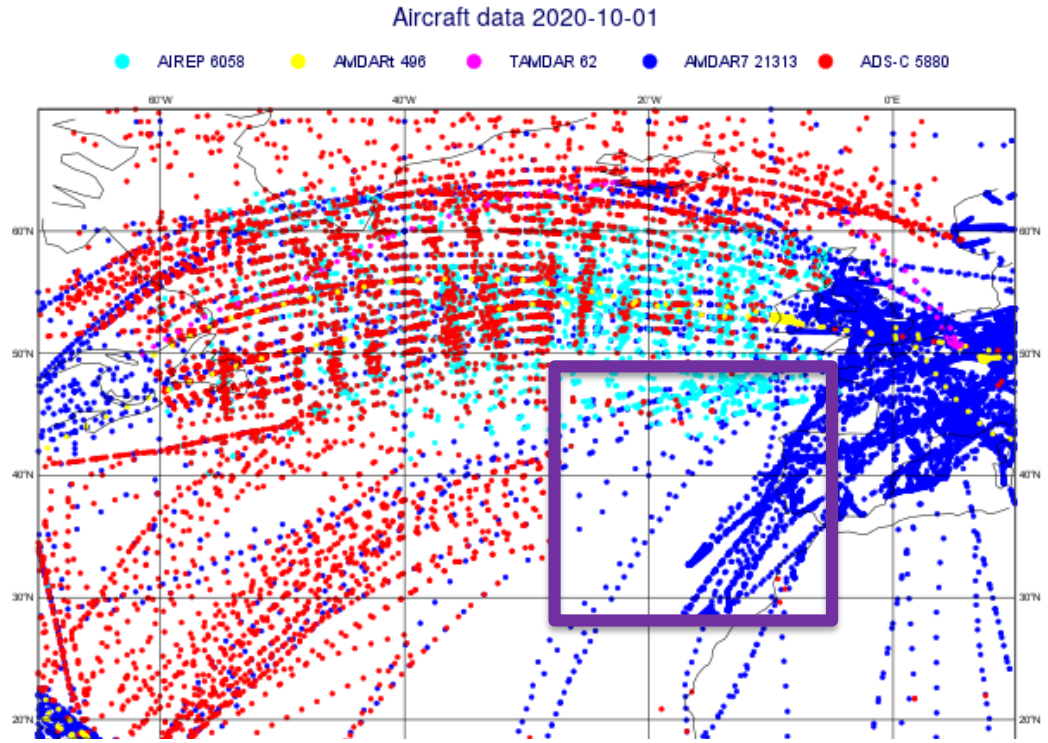
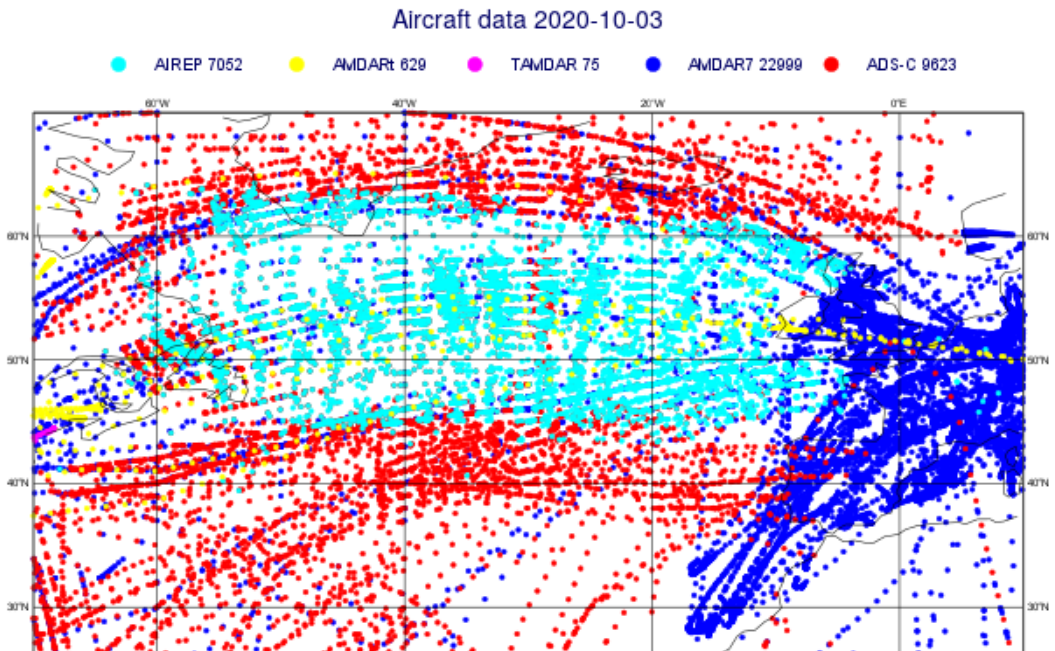




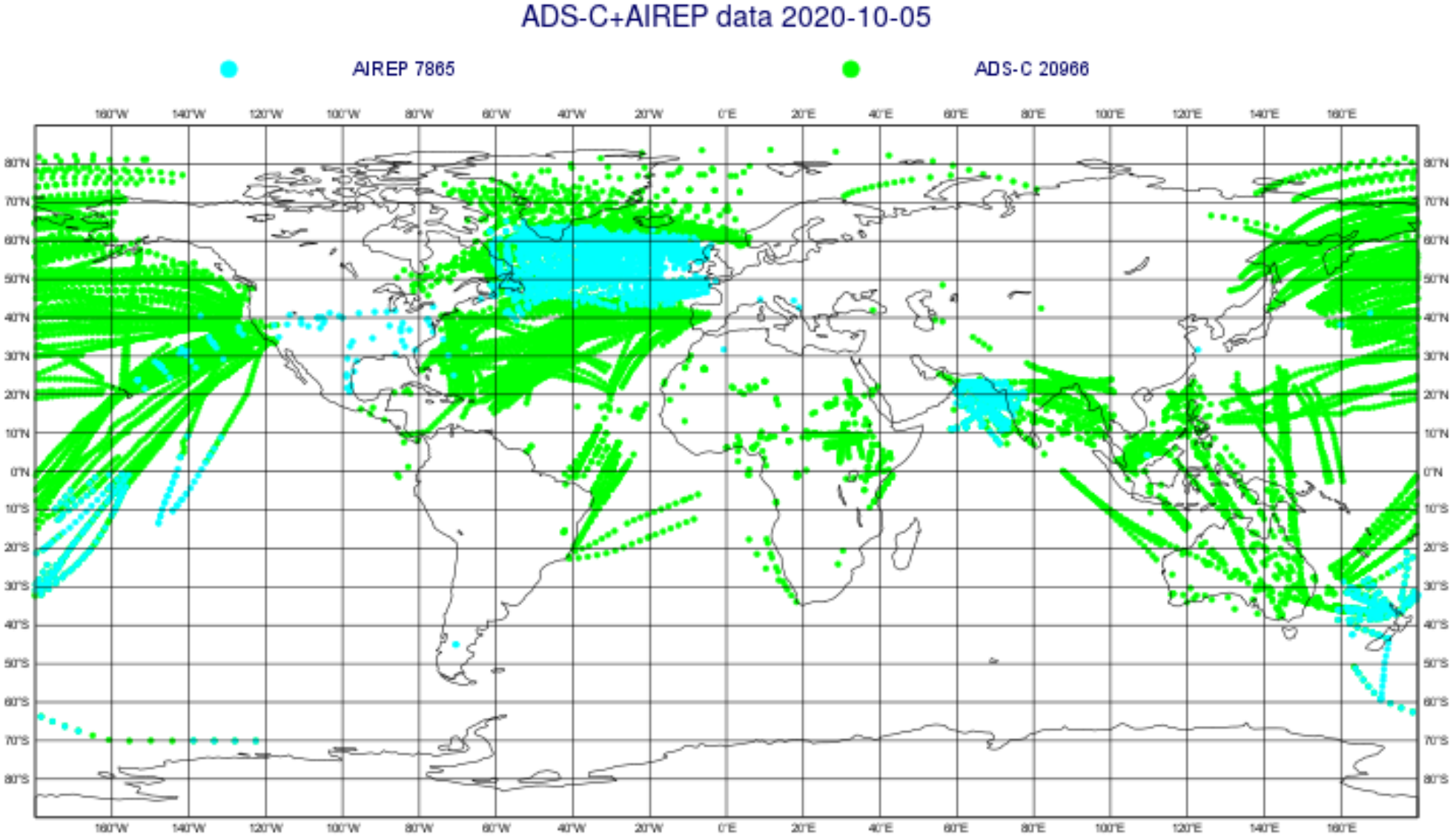
A gap in the North Atlantic

- 2 years ago we noticed a gap in N Atlantic west of Europe
- Tracks started/stopped 30-40°W
- AMDAR problem? No: ADS-C problem.
  - At that time ADS-C was treated as AMDAR
- Spoke to EUMETNET, Steve Stringer
- 'Santa Maria' flight information region
- Steve spoke to NavPortugal – outcome unclear
- Early October we started getting ADS-C from that region

- Only 26 more ANSPs to go!

ADS-C+AIREP data for 5 October 2020

- Cases where tracks stop mid-ocean may be due to non-request of MET data



Summary (I)

- Covid-19 reduced the number of aircraft reports by 75% for ~2months
  - Partial recovery to ~50% of pre-Covid levels
  - Autumn 2020: European reports decreased, S Hem. reports increased
- Aircraft data are valuable for NWP, biggest impact is on wind at ~250 hPa
  - Winds give more impact than temperatures
  - More impact in N Hem. where most reports are
- Cannot see a decrease in forecast quality in 2020 (multiple centres):
  - Satellite data more important – some increases in 2020
  - Aircraft data didn't drop to zero (more impact per report if data are sparse)
  - Day-to-day and year-to-year variations in forecast skill complicate the picture
- Mitigation attempts include use of Mode-S aircraft winds at ECMWF
- B787 wind problem – very frustrating issue - partially corrected at ECMWF now

Summary (II)

- Most aircraft have warm temperature bias
  - NWP centres apply bias correction (or don't use the temperatures)
  - Would be better if bias was addressed at source
  - Some ideas (EUFAR meeting) but need airline involvement
- Metadata: would be useful to know aircraft type and airline
  - Found these for 50% of AMDARs but better to get metadata from airlines
  - Multiple identifiers for the same aircraft ☹
- Filling in the gaps
  - # of reports increased dramatically to 2019
  - Hope for further expansion of AMDAR (WICAP)
  - Some avoidable gaps in ADS-C; Mode-S expansion?
- Aircraft data are valuable for NWP – could be even more so!

Resources

- WMO overview and description of AMDAR https://community.wmo.int/activity-areas/aircraft-based-observations
- Petersen (2016, BAMS), “impact and benefits of AMDAR observations”
- Ingleby et al (2020, GRL), “impact of Covid-19 on weather forecasts”
- Pauley and Ingleby (book chapter, soon), “assimilation of *in situ* data”
- EUMETNET/ECMWF workshop on ‘Aircraft Weather Observations and their Use’, February 2020, https://www.ecmwf.int/en/learning/workshops/workshop-aircraft-weather-observations-and-their-use
- EUFAR workshop on aircraft temperature measurement, Nov 2020, https://www.eufar.net/event/event/atmospheric-temperature-measurement-from-research-and-operational-aircraft-an-online-workshop-324457/
- ECMWF daily data coverage charts https://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring-observing-system