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The Use of High Vertical-Resolution Radiosonde Data (HVRRD) in U.S. Navy NWP: Characteristics and Quality Control of Operationally Available HVRRD

Patricia Pauley and Justin Tsu

Naval Research Laboratory, Monterey, California, USA

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(What could possibly go wrong?!)

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Outline

- Background: traditional vs. high (vertical) resolution radiosonde data
- Radiosonde data in U.S. Navy numerical weather prediction
- Examples of errors in high resolution radiosonde data
- Upcoming changes

Outline

- Background: traditional vs. high (vertical) resolution radiosonde data
  - Focus on data operationally available on the Global Telecommunications System (GTS)
  - TAC to BUFR migration and its impact on vertical resolution
  - Examples of high and low vertical resolution from BUFR messages
- Radiosonde data in U.S. Navy numerical weather prediction
- Examples of errors in high resolution radiosonde data
- Upcoming changes

TAC to BUFR Migration

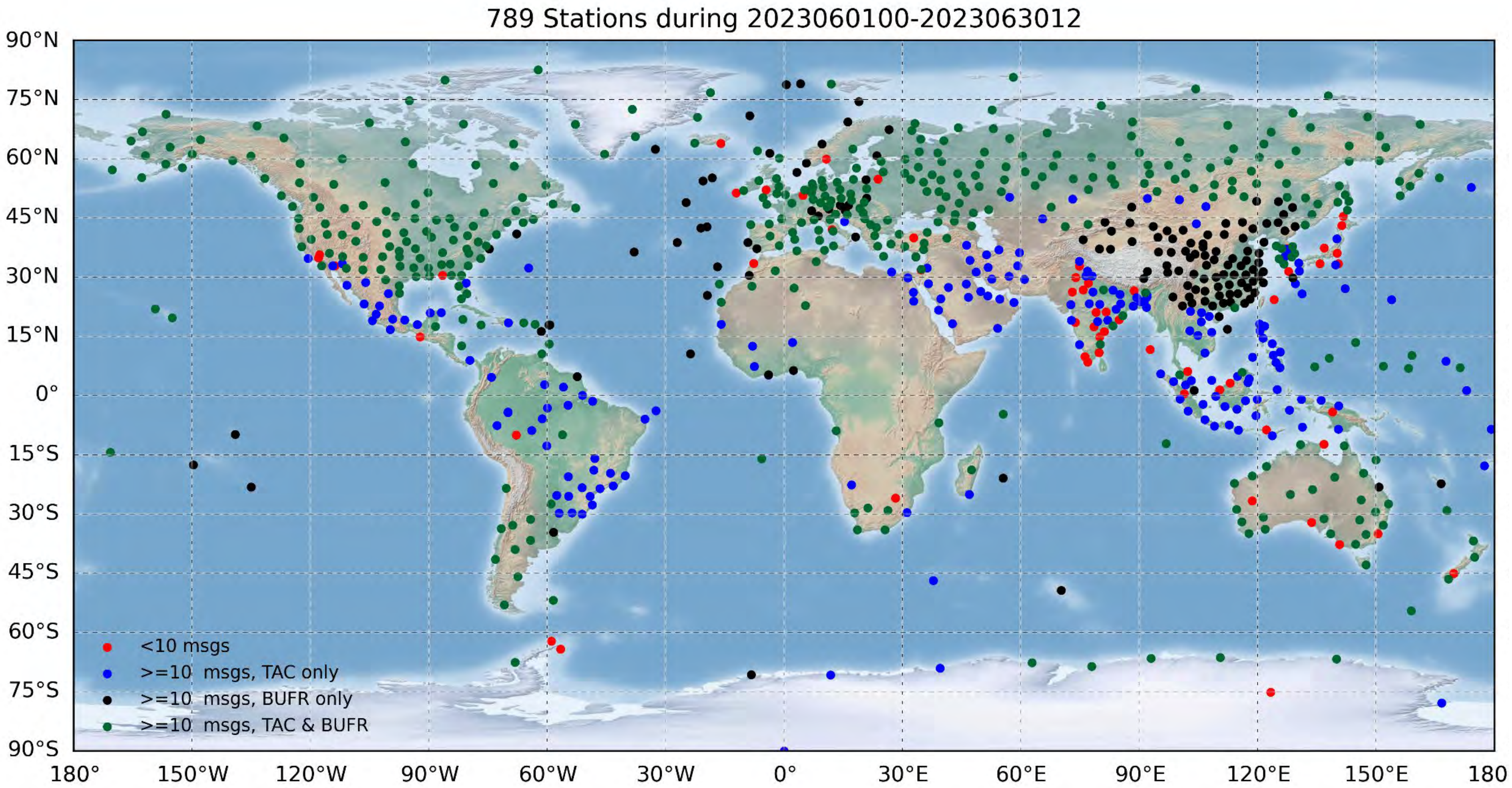
TTAA 56121 72662 99892 12262 27505 00047 32078 40729 25560 33077 30931 41356 34104 25052 51159 35120 20195 58557 35127 15374
59362 33588 10628 59368 34058 88181 ///// ///// 92717 ///// ///// 85430 11263 32026 70018 00058 32553 50563 13557 63356 34622
77207 35129 40716 31313 58208 81109 51515 10164 00009 10194 32034 32054=

- **Traditional Alphanumeric Codes (TAC)**
  - TEMP radiosonde format developed for teletype era in 1940’s
  - Groups of 5 digits—no decimals or negative signs, some leading/trailing digits omitted
  - Station latitude, longitude, and elevation not in message—must supply from external station list
  - Four unique messages—mandatory or significant levels, above or below 100 hPa

4255465200070E040000160000FF000000000201FF0E0007E10C080C000000000900000180C9330006E3008FDEFFFFFFFFFFFFFFFFFA808793F0E10B3EC78C97708DCD401
38D09D40113FC01C100041000044F44AA2022551023C02E401804000121D12A7F48953EA15C219013800100519 44AA11225496074071406404000155112A8C28951F41F81C
502B01000061E44AA90225424C7A04B40BE00040192912AA6889505D9D41050330100006714 4AAA9A2540C46E03B40E0040001A9112AA9C894FF39940F504C00010077A44A
ADC2253B567D04C418C0400021B112AD50894D70A5C12D0690001008AB44AB7522535049404E41DE80000250D12AF70894C8DA381790A1010000B0544ACC6A2526F0700484

- **BUFR (Binary Universal Form for the Representation of meteorological data)**
  - Binary format approved in 2003 as a replacement for TAC for international exchange
  - TAC distribution originally scheduled to end by November 2014, but migration is still underway
  - Messages include launch location and time as well as drift offsets
  - Two overlapping messages—”early” (surface to 100 hPa) and “late” (surface to balloon burst)
    - The “early” (“late”) BUFR messages are in GTS bulletins starting with “IUK” (“IUS”).
  - Possibility of descent message with observations from balloon burst to near-surface

TAC to BUFR Migration



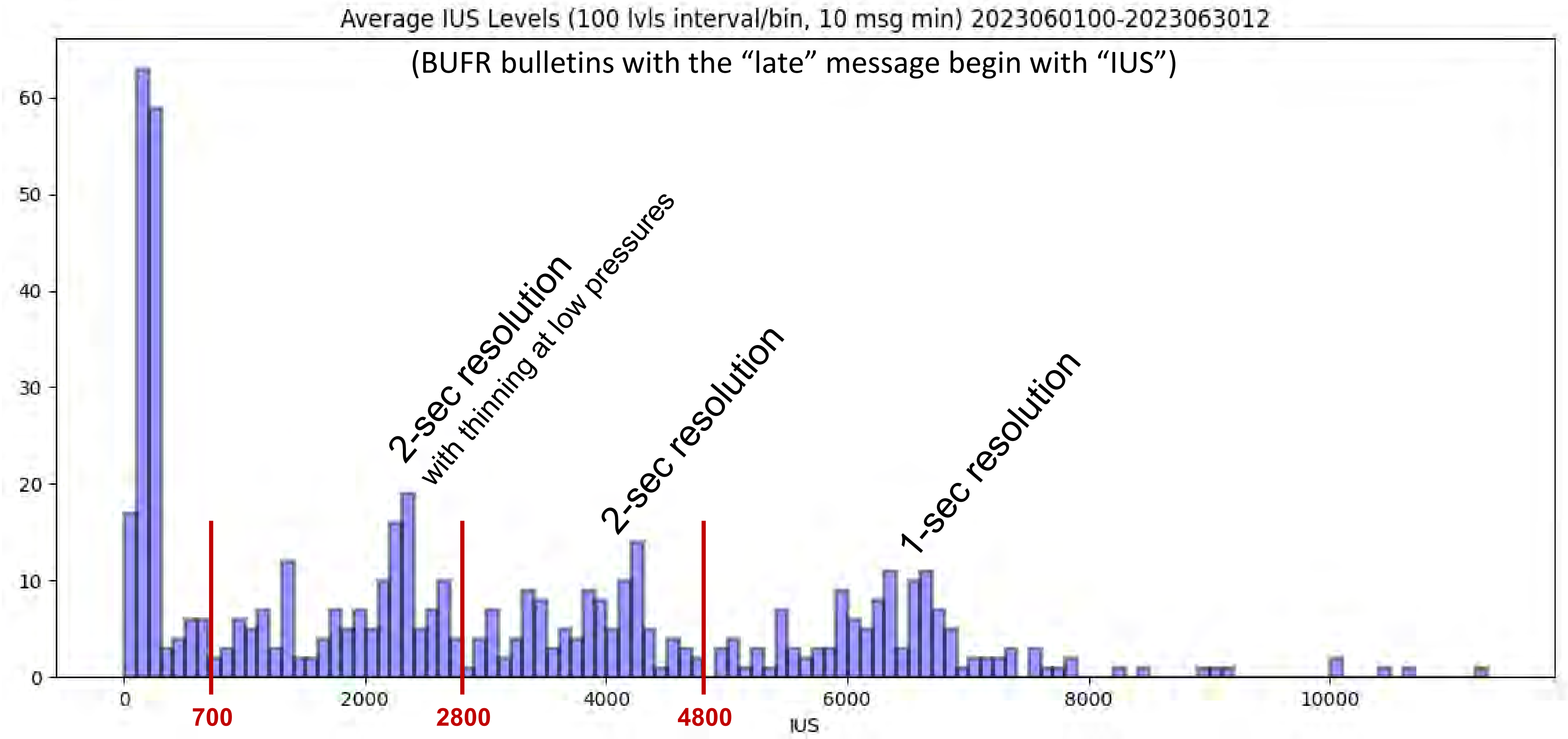
Most stations report twice per day (00Z, 12Z), some once per day, some four times per day

- Data for June 2023 as received and decoded at FNMOC
- Many stations still report in TAC only, especially in the tropics (blue dots)
- Most stations report in both BUFR and TAC (green dots) => need selection process or duplicate check
- Some stations report in BUFR only (black dots)
  - China
  - Ships
  - Some sites in Europe
  - Some islands

Vertical Resolution

- **Level selection for TAC**
  - Mandatory levels—specified values of pressure
    - e.g., 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10, 7, 5 hPa
    - Each level includes pressure, geopotential height, temperature, humidity, winds
  - Significant levels—levels needed to reconstruct the profile piecewise linearly within a tolerance
    - Determined separately for temperature/humidity and wind speed/direction
- **Level selection for BUFR**
  - Levels typically spaced by time—1 sec (~5 m), 2 sec (~10 m), etc.
  - Some BUFR messages originally reformatted from TAC
    - not as commonly done now, but some countries send both high-res BUFR and BUFR reformatted from TAC
  - Each level includes all variables--pressure, geopotential height, temperature, humidity, winds
  - Most include a level type designator corresponding to mandatory or significant levels (or "other")
  - Most also include drift times and latitude/longitude offsets
    - Added to launch time and location to use the actual location of the balloon in time and space

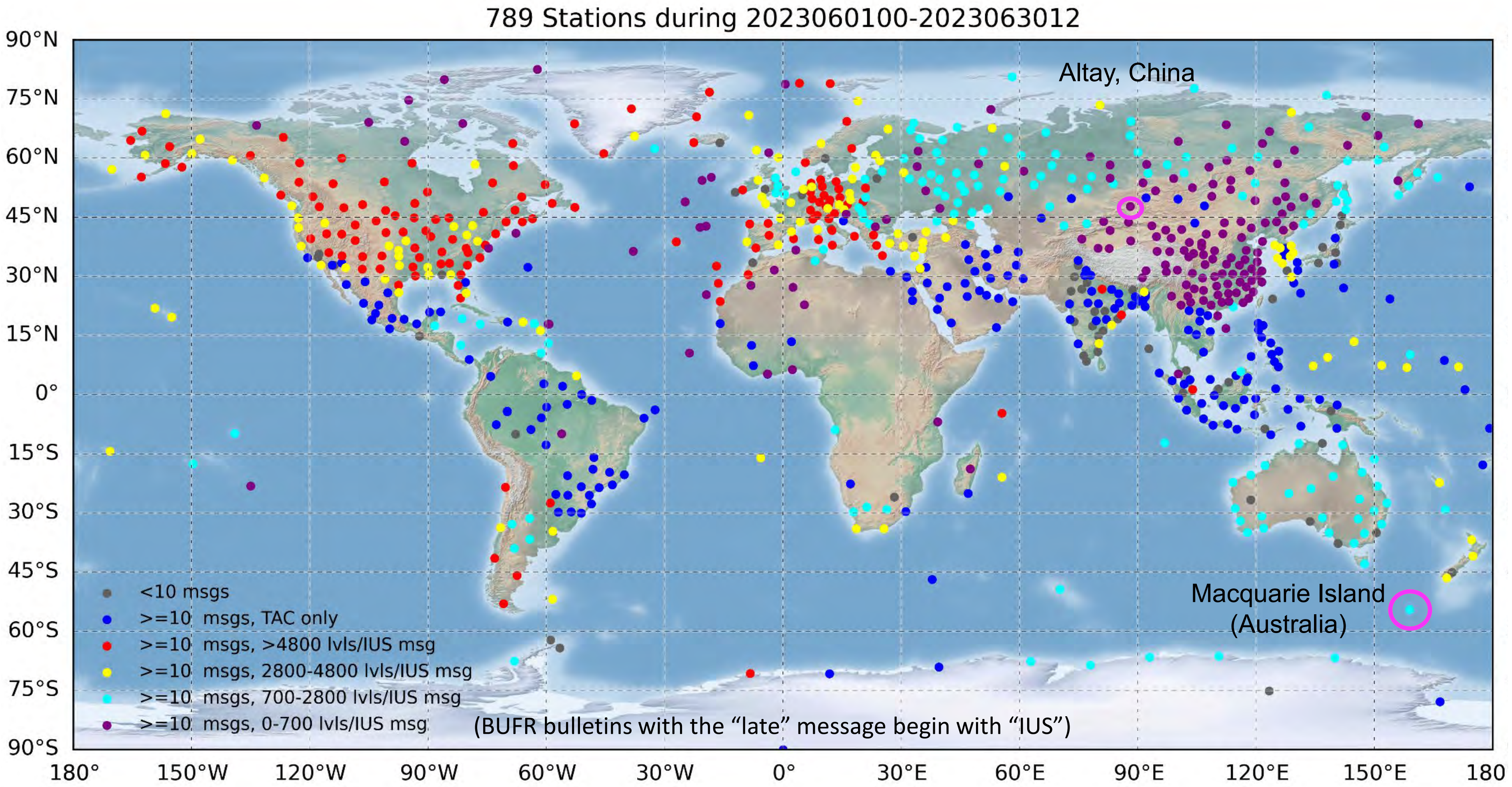
BUFR Vertical Resolution



Average number of BUFR levels by station is related to vertical resolution and extent

Usually related to radiosonde type or country

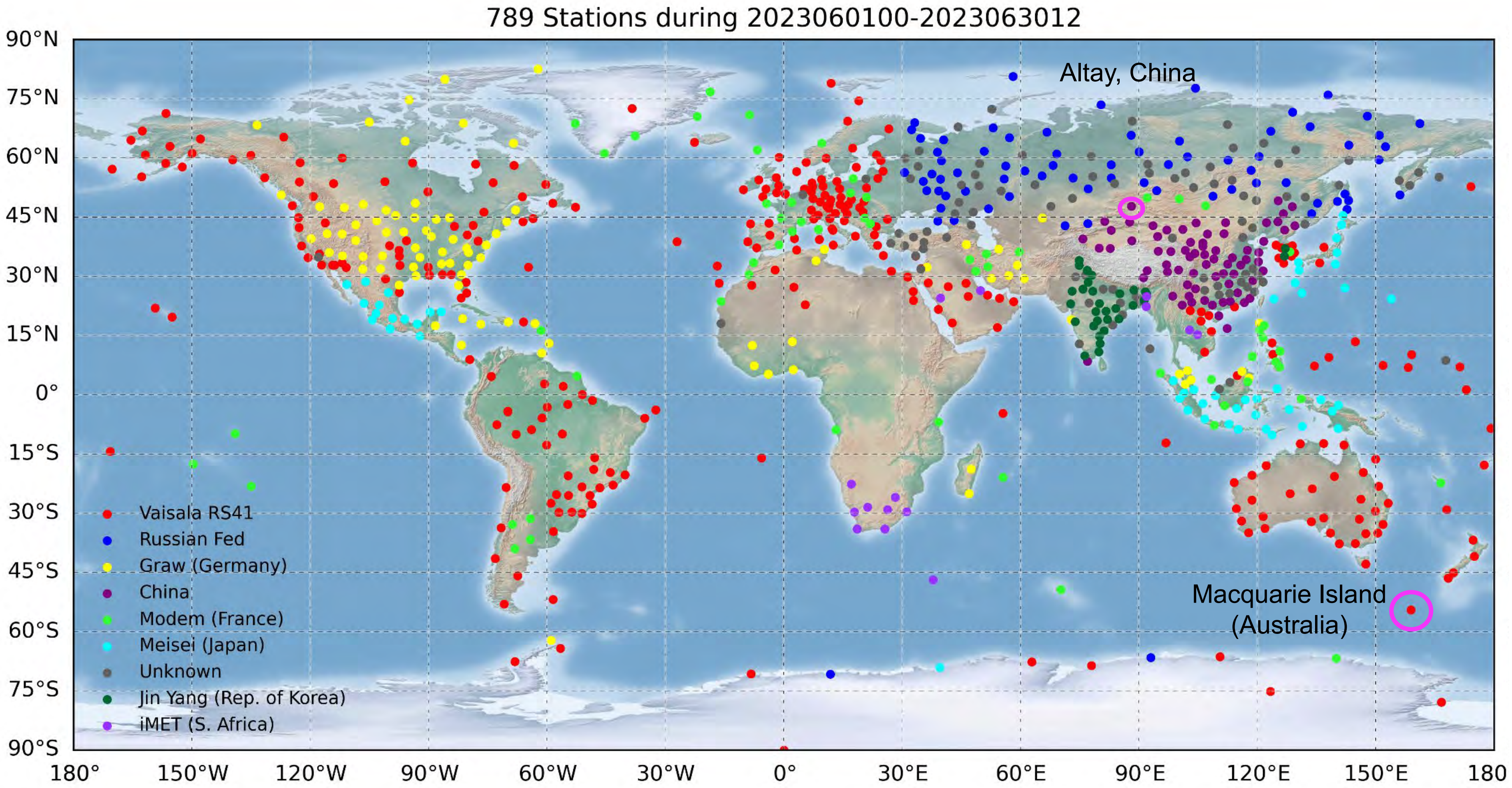
BUFR Vertical Resolution



- Highest vertical resolution (red or yellow) concentrated in North America, Europe
- Soundings from Russia, Australia, Caribbean still considered high resolution (light blue)
- Soundings from China, some Russian stations, the Canadian Arctic, and some ships considered low resolution (purple) but typically still higher resolution than TAC

Examples shown for RS41 sounding from Macquarie Island, Australia (94998) and GTS13 sounding from Altay, China

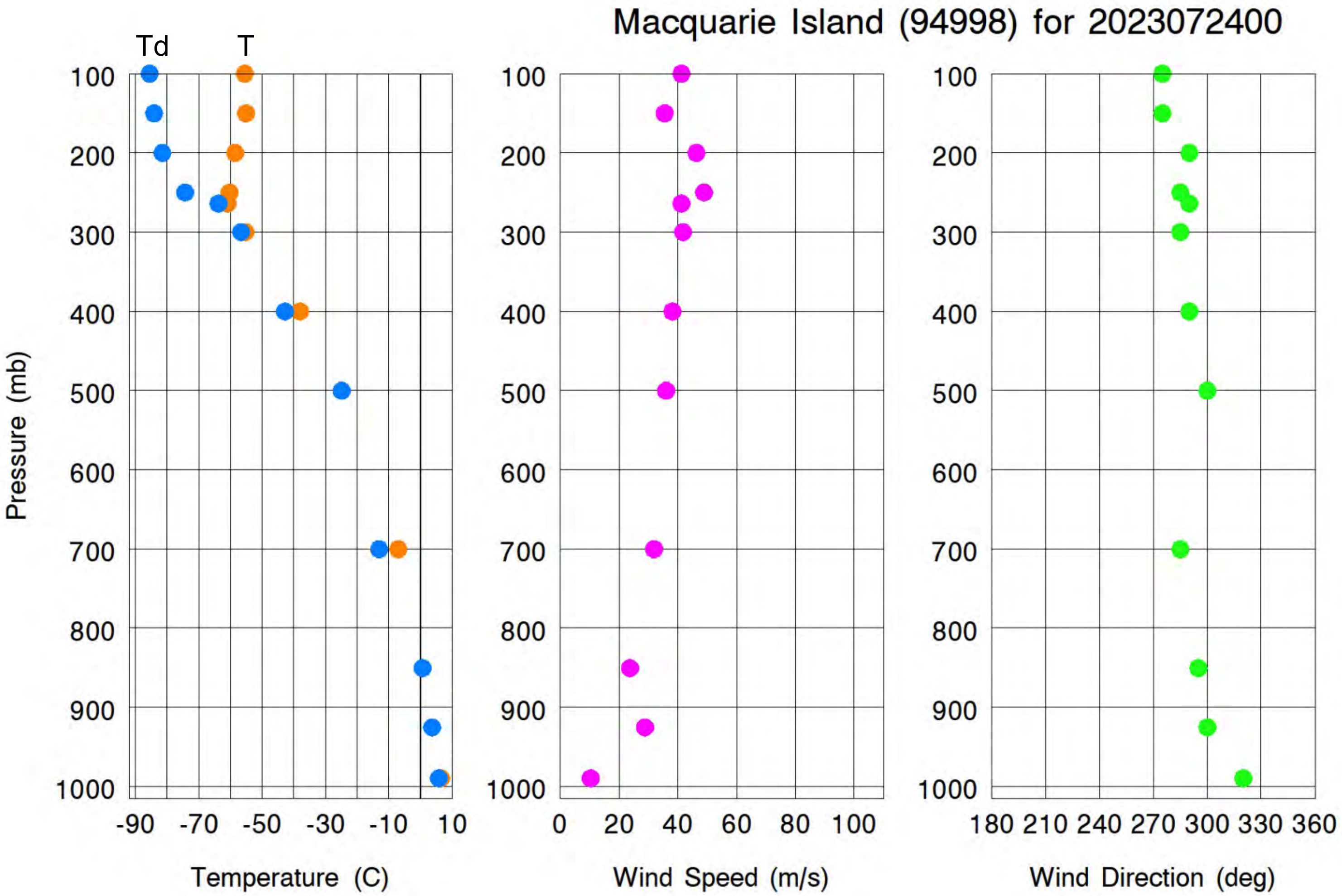
Radiosonde Types



- Vaisala RS41 sondes most widely used—can be configured in various vertical resolutions
- Graw, Modem, Meisei, Jin Yang sondes used in multiple countries
- Multiple types used by Russian Federation and China, including some radar-based sondes
- Many stations in Russian Federation and in China report missing or unknown values for radiosonde type

Examples shown for RS41 sounding from Macquarie Island, Australia (94998) and GTS13 sounding from Altay, China

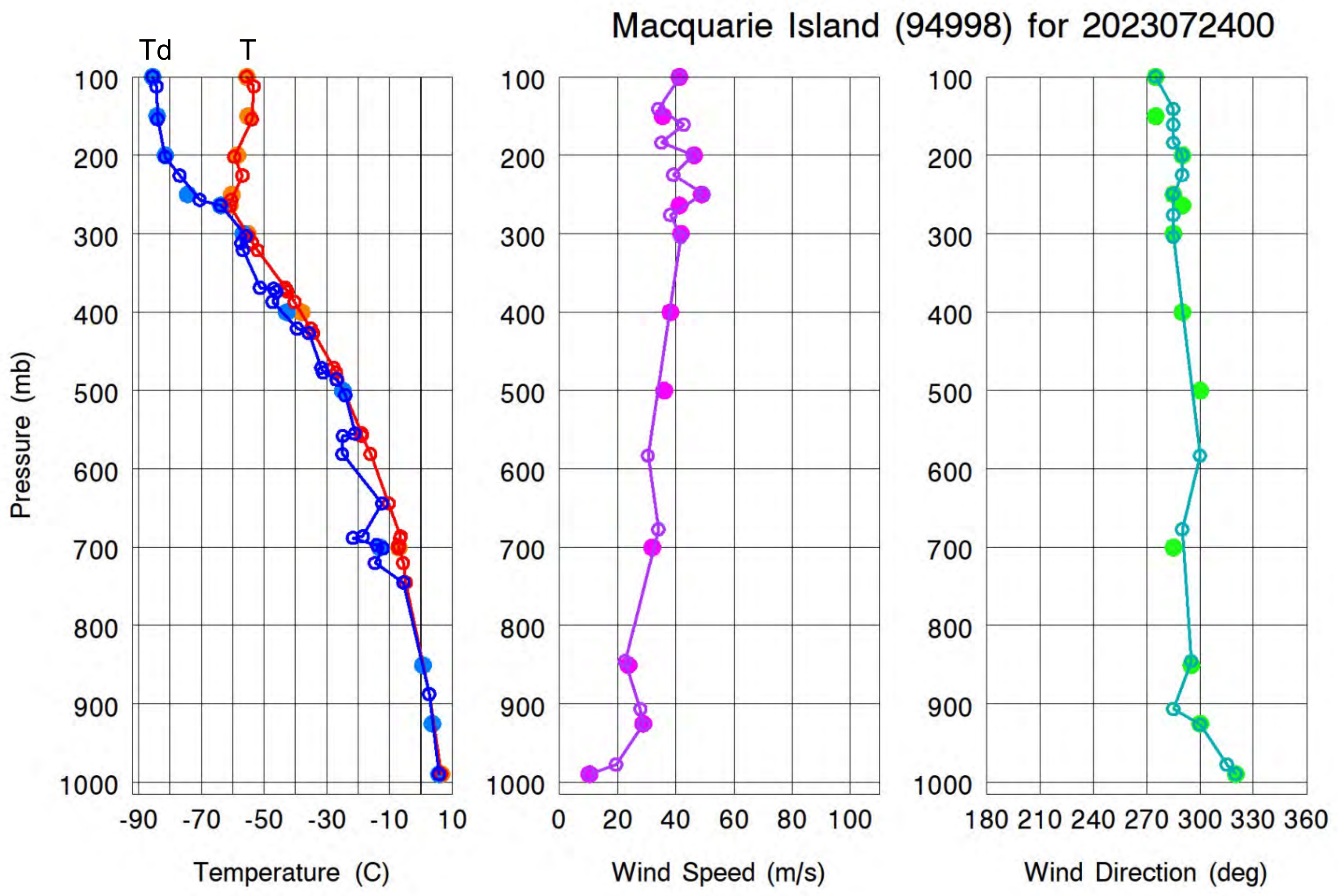
Sounding Example



- Mandatory levels at specified pressures (~20 levels total)

Below 100 hPa: Mandatory-level data

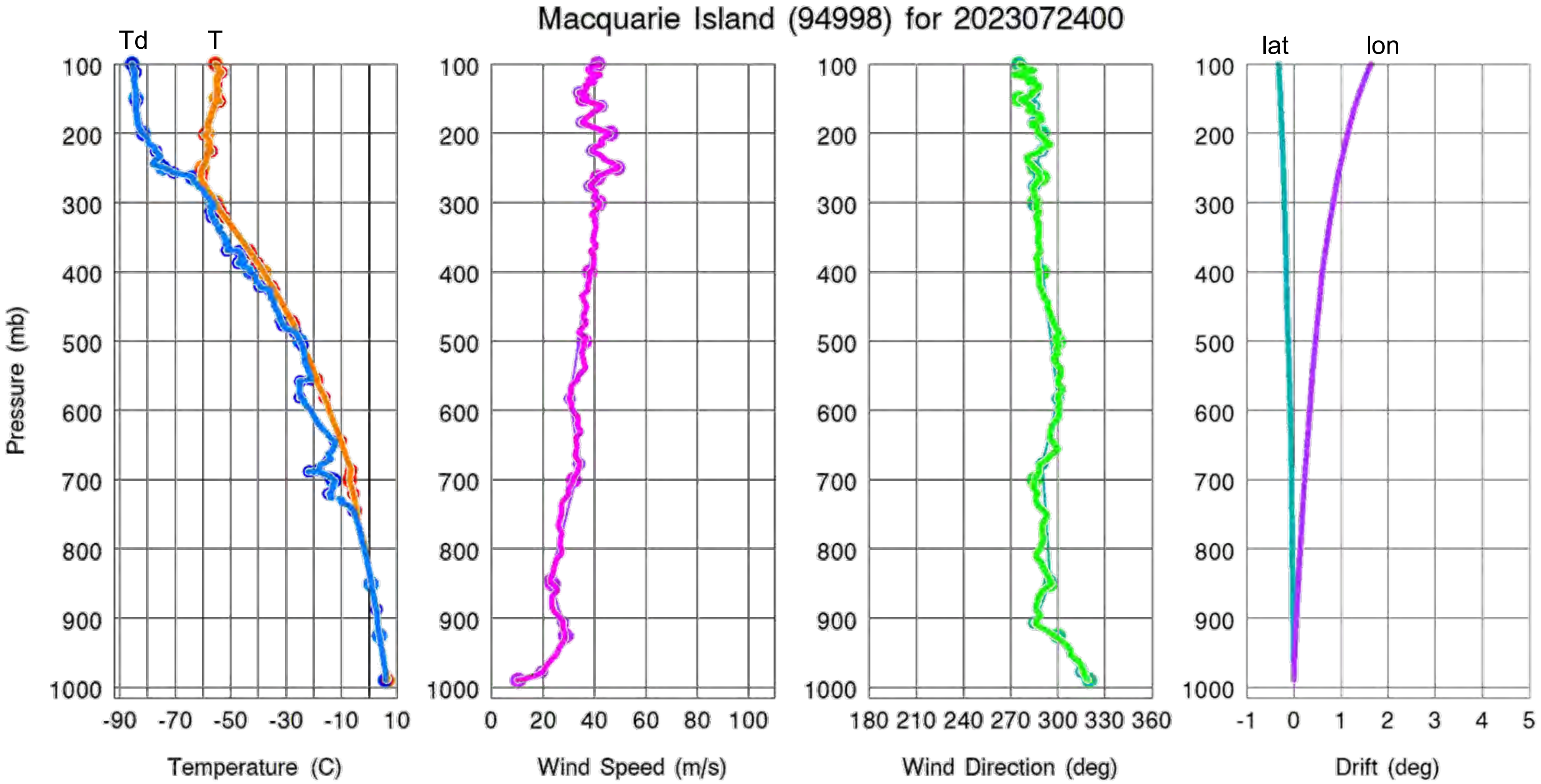
Sounding Example



- Mandatory levels at specified pressures (~20 levels total)
- Significant levels add change points (~100 levels total)

Below 100 hPa: Mandatory-level data + significant-level data

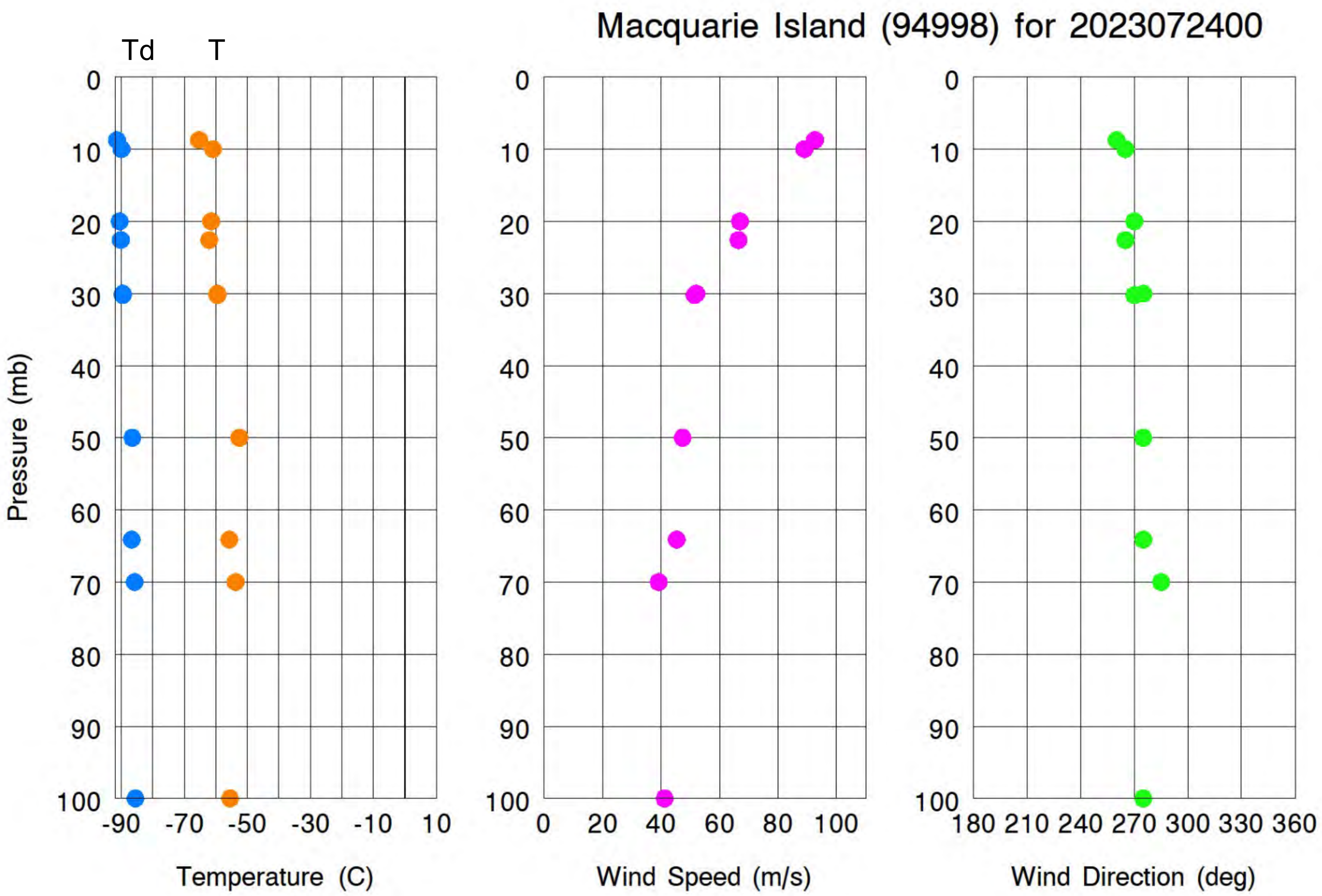
Sounding Example



- Mandatory levels at specified pressures (~20 levels total)
- Significant levels add change points (~100 levels total)
- BUFR levels at 2-sec intervals up to ~70 hPa and 0.1 hPa intervals above that (~2500 levels total)

Below 100 hPa: Mandatory-level data + significant-level data + BUFR data

Sounding Example



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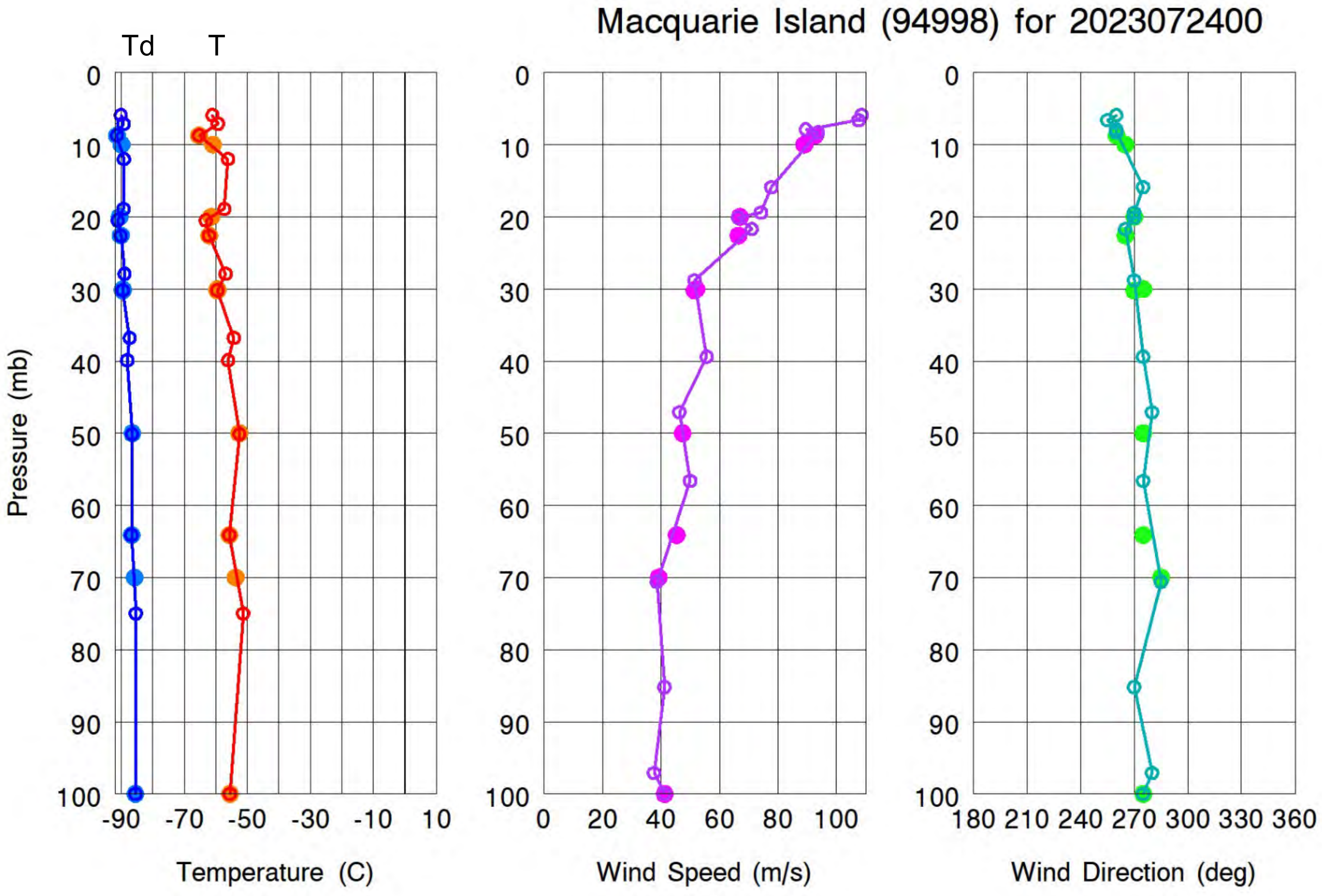

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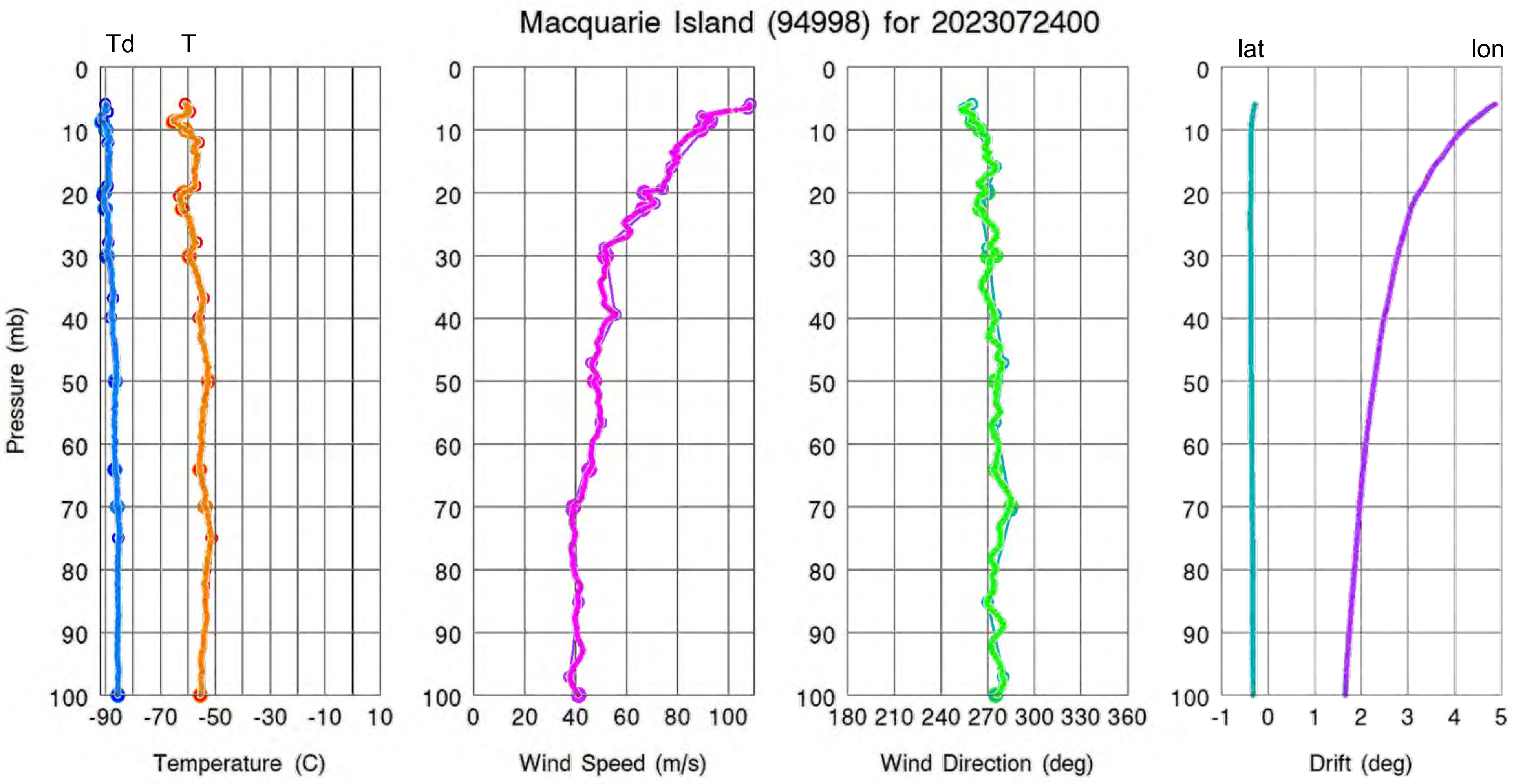

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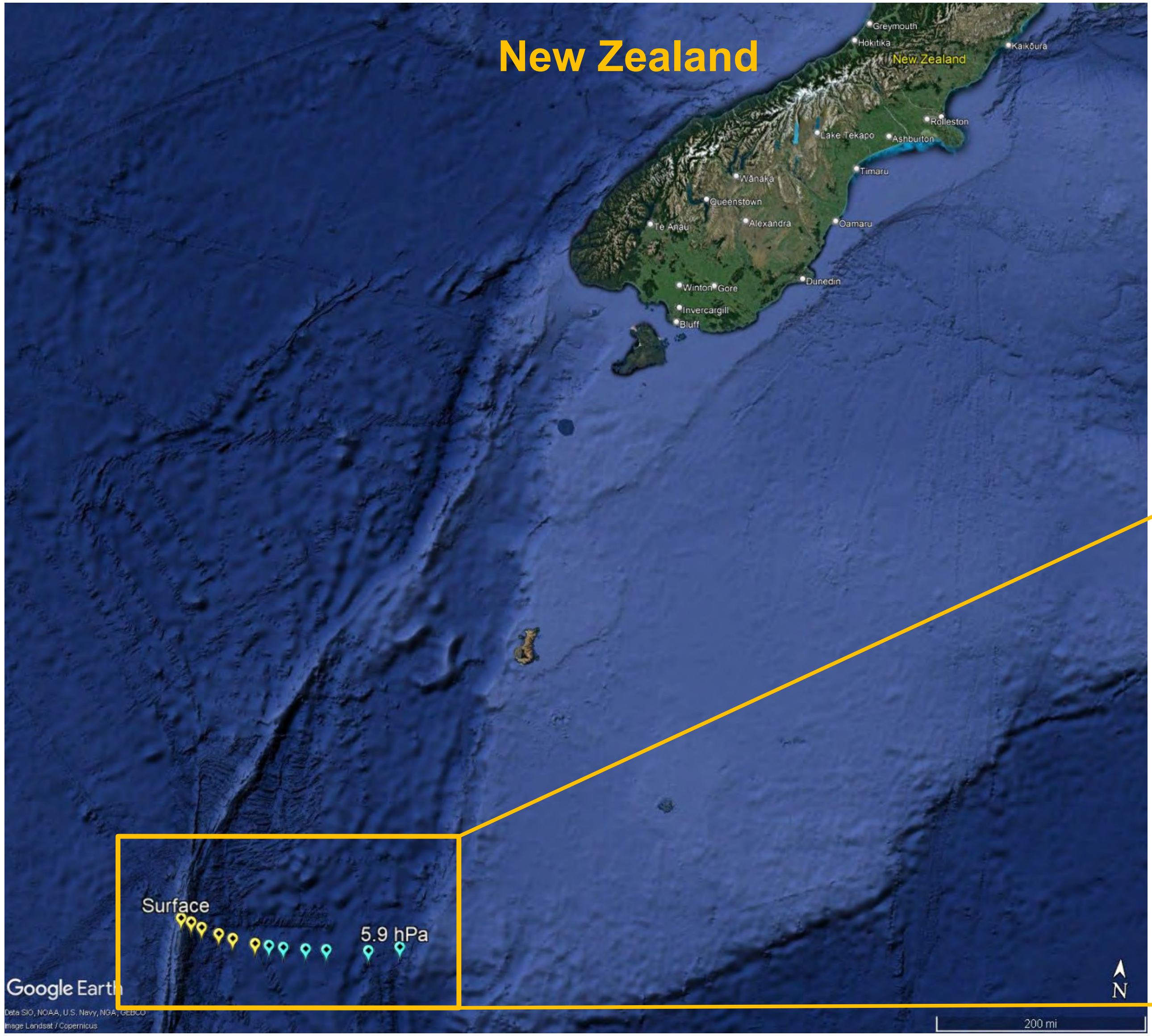
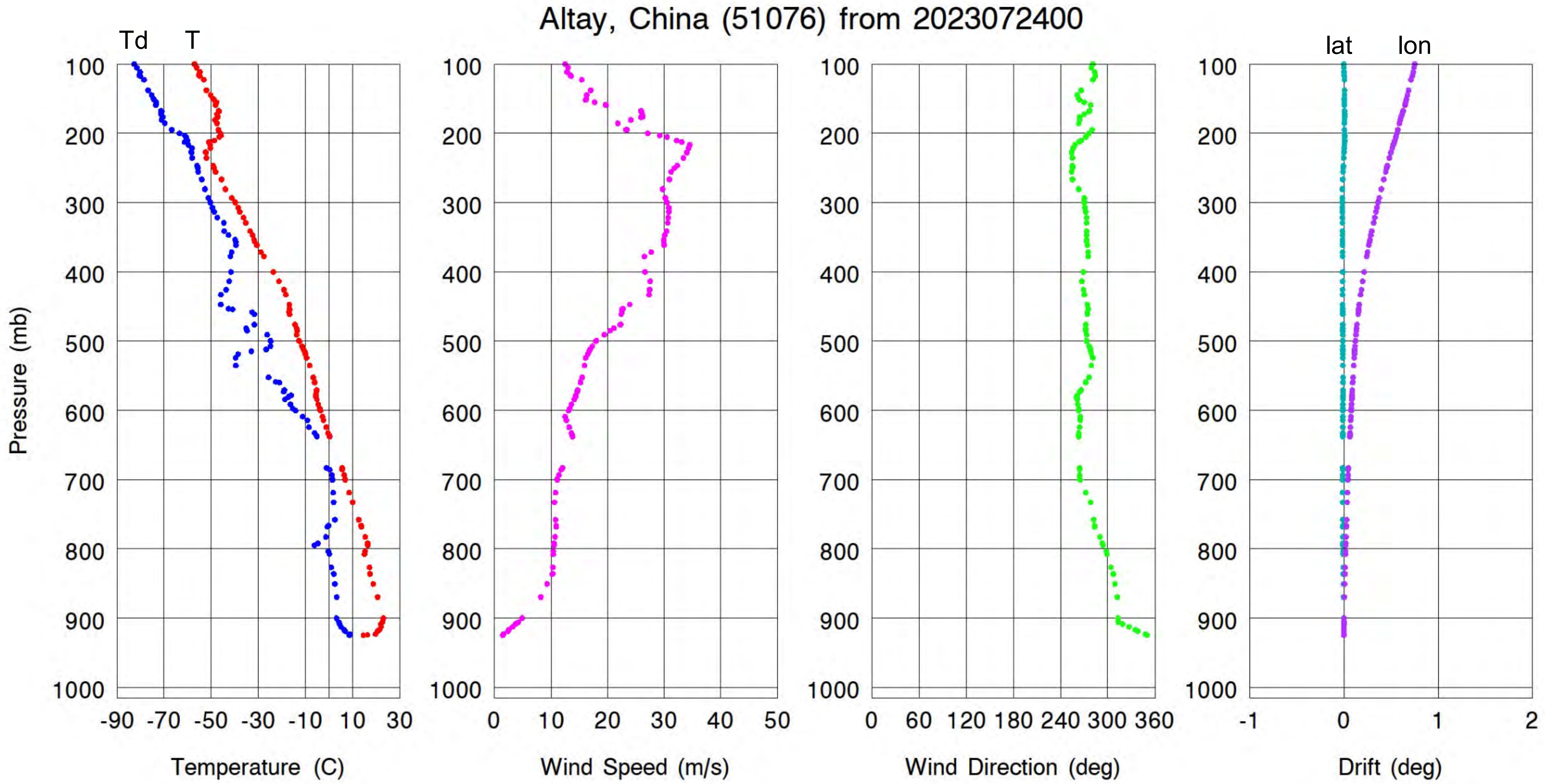


- Macquarie Island (94998) sounding at 2023072400
- Selected mandatory levels plotted from BUFR
  - Levels at and below 100 hPa in yellow
  - Levels above 100 hPa in blue
- Total drift distance ~310km

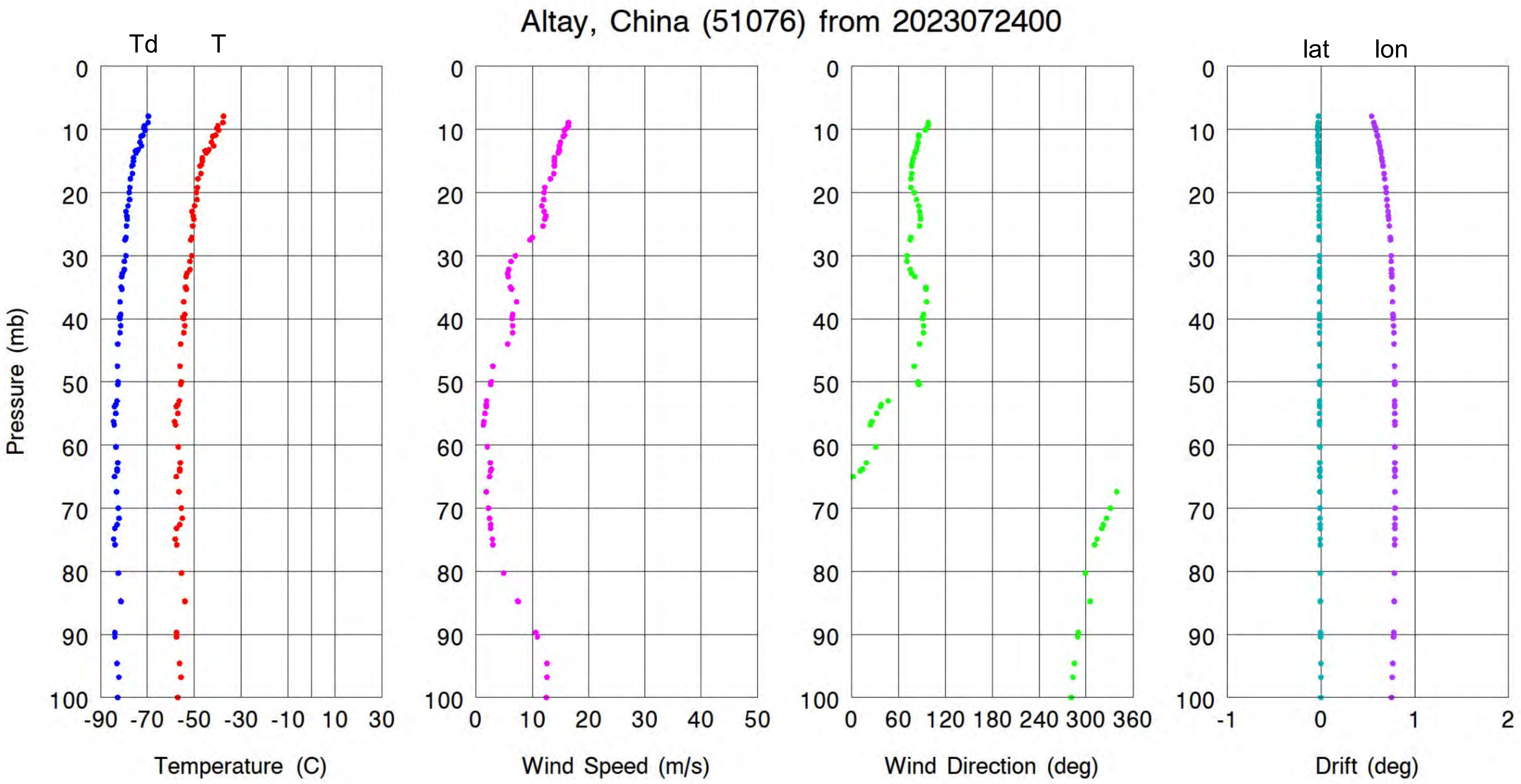
Sounding Example



- BUFR levels at uneven intervals (~200 levels total)

Below 100 hPa: Only low-resolution BUFR data available

Sounding Example



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Outline

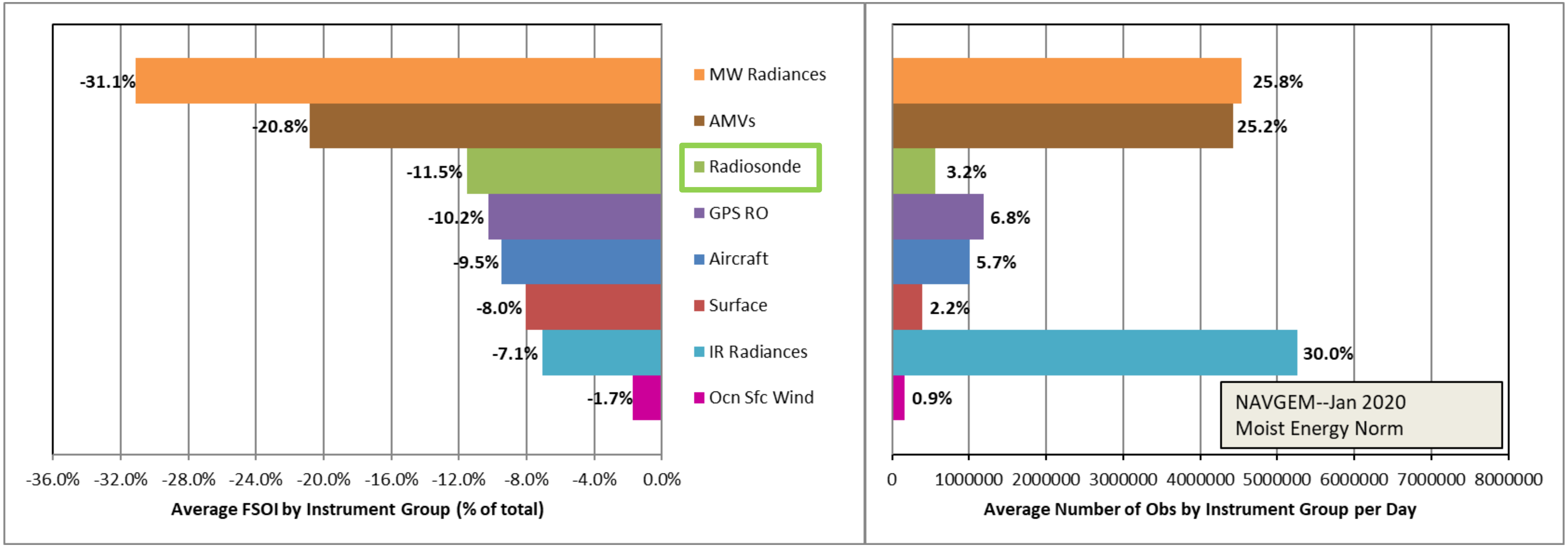
- Background: traditional vs. high (vertical) resolution radiosonde data
- Radiosonde data in U.S. Navy numerical weather prediction
  - NAVGEM characteristics
  - Radiosonde data quality control and thinning
  - Example of thinning
  - Impact of radiosonde observations
- Examples of errors in high resolution radiosonde data
- Upcoming changes

NAVGEM

NAVGEM: Navy Global Environmental Model

- Operational model resolution: T681L60
- Data assimilation system: Hybrid 4DVAR
  - “NAVDAS”—NRL Atmospheric Variational Data Assimilation System
- Observations assimilated—over 90% are satellite-based
  - Satellite radiance and GPS radio occultation observations
  - Satellite-derived winds (atmospheric motion vectors and scatterometer winds)
  - Aircraft observations (temperature, humidity, winds)
  - Land and marine surface observations (temperature, humidity, winds)
  - Radiosonde observations (temperature, humidity, winds)
    - High-resolution BUFR radiosonde data used operationally since Sept 2015
    - Radiosonde drift locations used operationally since Dec 2019

NAVGEM



FSOI (Forecast Sensitivity to Observation Impact)

- Measure of error reduction in 24 hr forecasts associated with assimilating observations
- Negative FSOI => beneficial impact
- In Jan 2020, radiosondes gave 3.2% of observations but 11.5% of error reduction in NAVGEM

Radiosonde Processing

- FNMOC retrieves and decodes data from the GTS
- Automated radiosonde quality control
  - **Duplicate checks**—BUFR retained over TAC, “late” message retained over “early” message
  - **Reject list checks**—data from problematic stations rejected outright (by variable)
  - **Gross error checks**—large departures from climatological values, excursions from physical limits
  - **Known error checks**—various checks by country or radiosonde type for known errors
  - **Complex Quality Control**—hydrostatic and other checks developed by Gandin and Collins in the 1980s
  - **Metadata checks**—BUFR launch locations compared to FNMOC Master Station List locations
  - **Three-sigma check**—check against model background inside 4DVAR—”failsafe”

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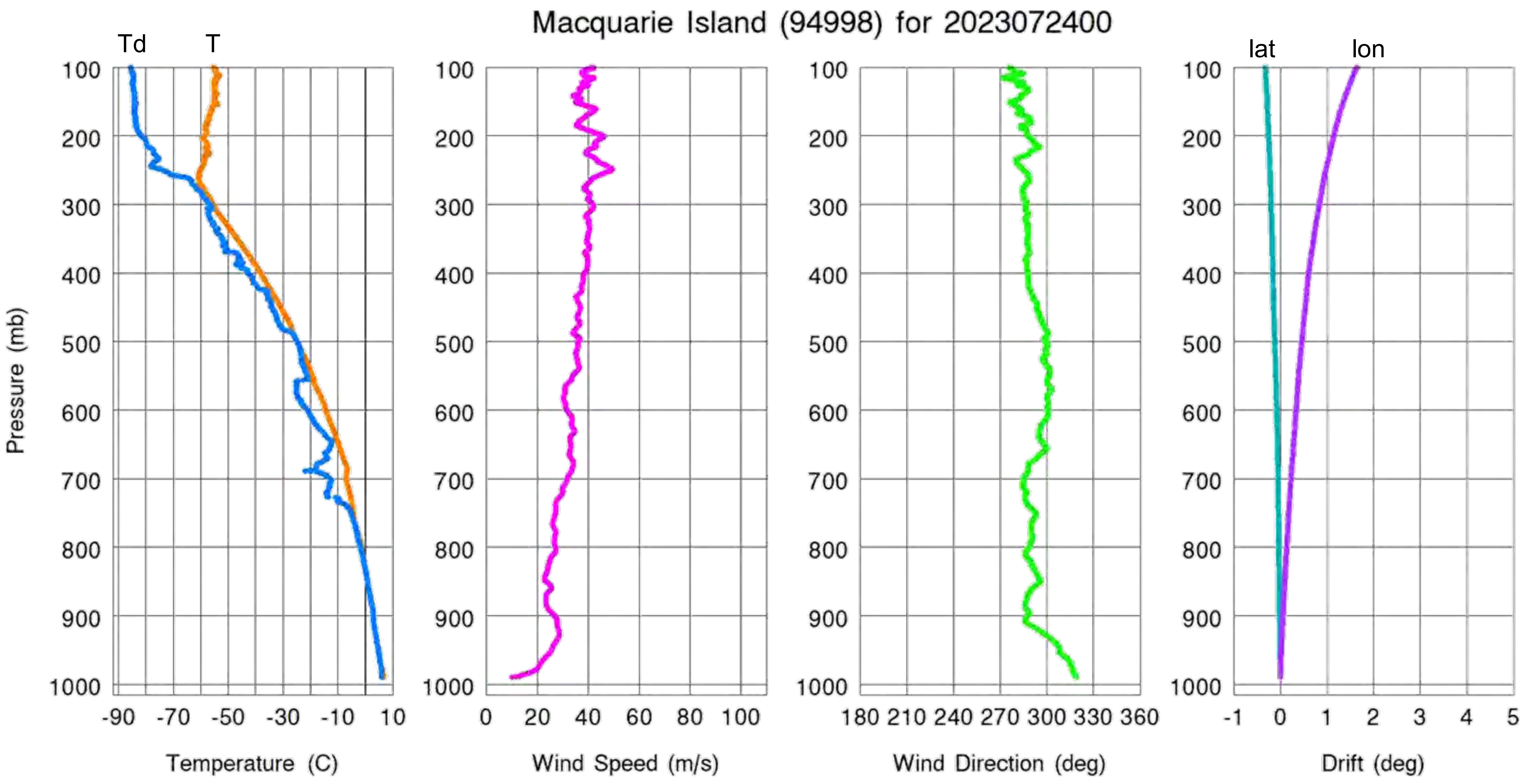
  - **Three-sigma check**—check against model background inside 4DVAR—”failsafe”
- Vertical thinning for soundings with more than 250 levels
  - Levels thinned to a minimum vertical separation of 130m, retaining mandatory levels

Sounding Example



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Below 100 hPa: BUFR data

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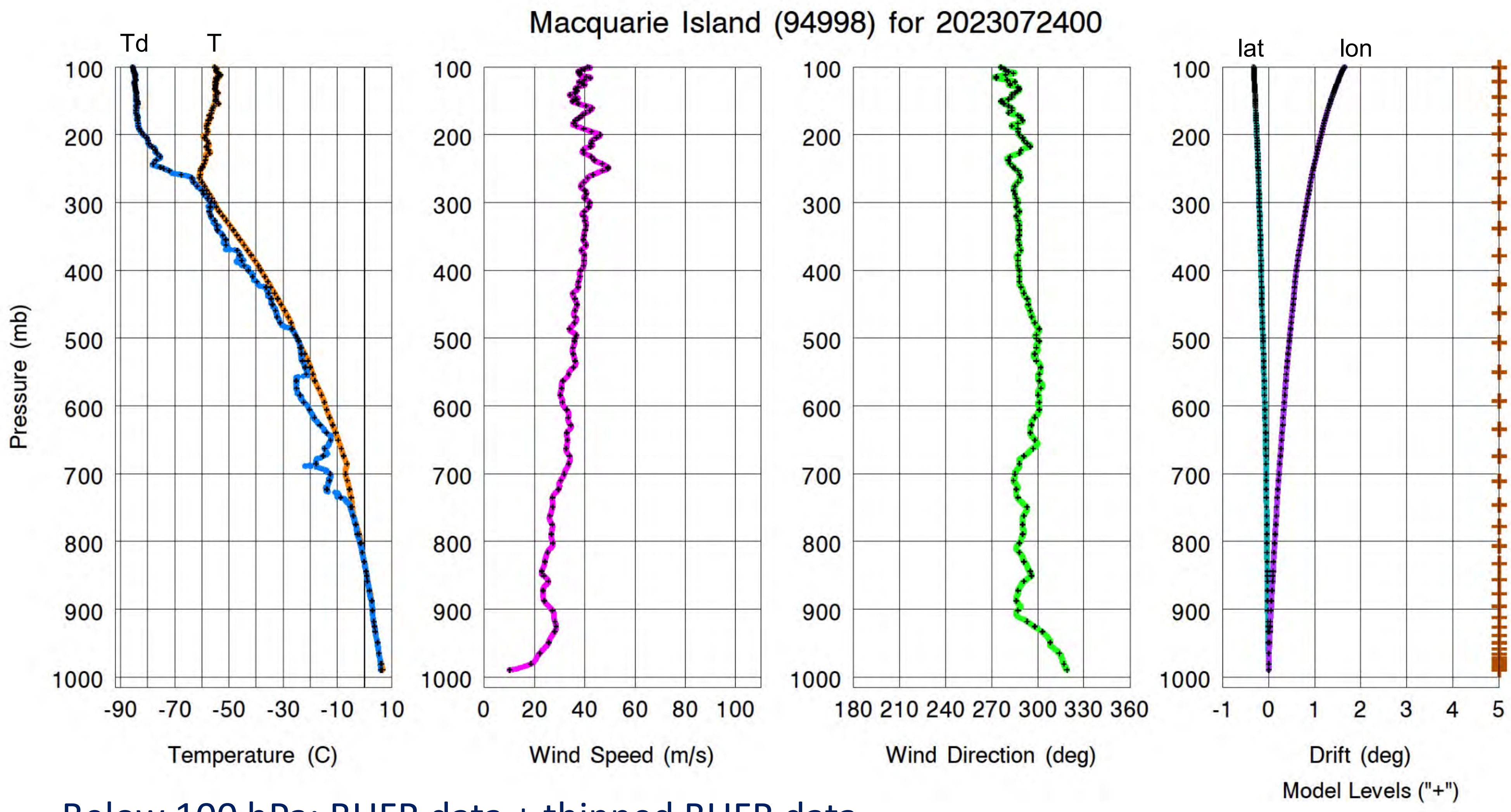

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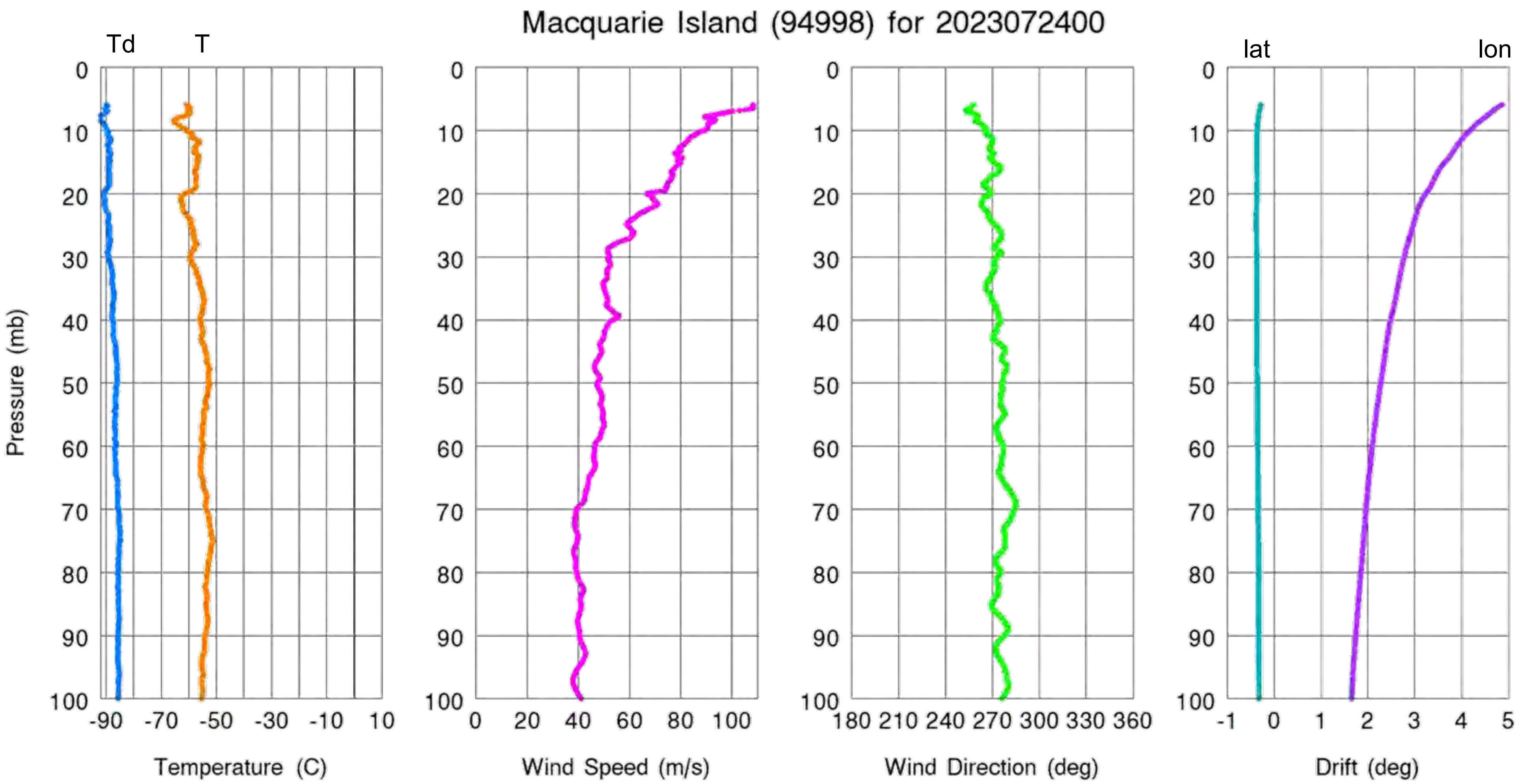
- BUFR levels at 2-sec intervals up to ~70 hPa and 0.1 hPa intervals above that (~2500 levels total)
- Thinned BUFR at ~130m intervals + mandatory levels (~250 levels total)
- 60 model levels (“+”)

Below 100 hPa: BUFR data + thinned BUFR data

Sounding Example



Above 100 hPa: BUFR data

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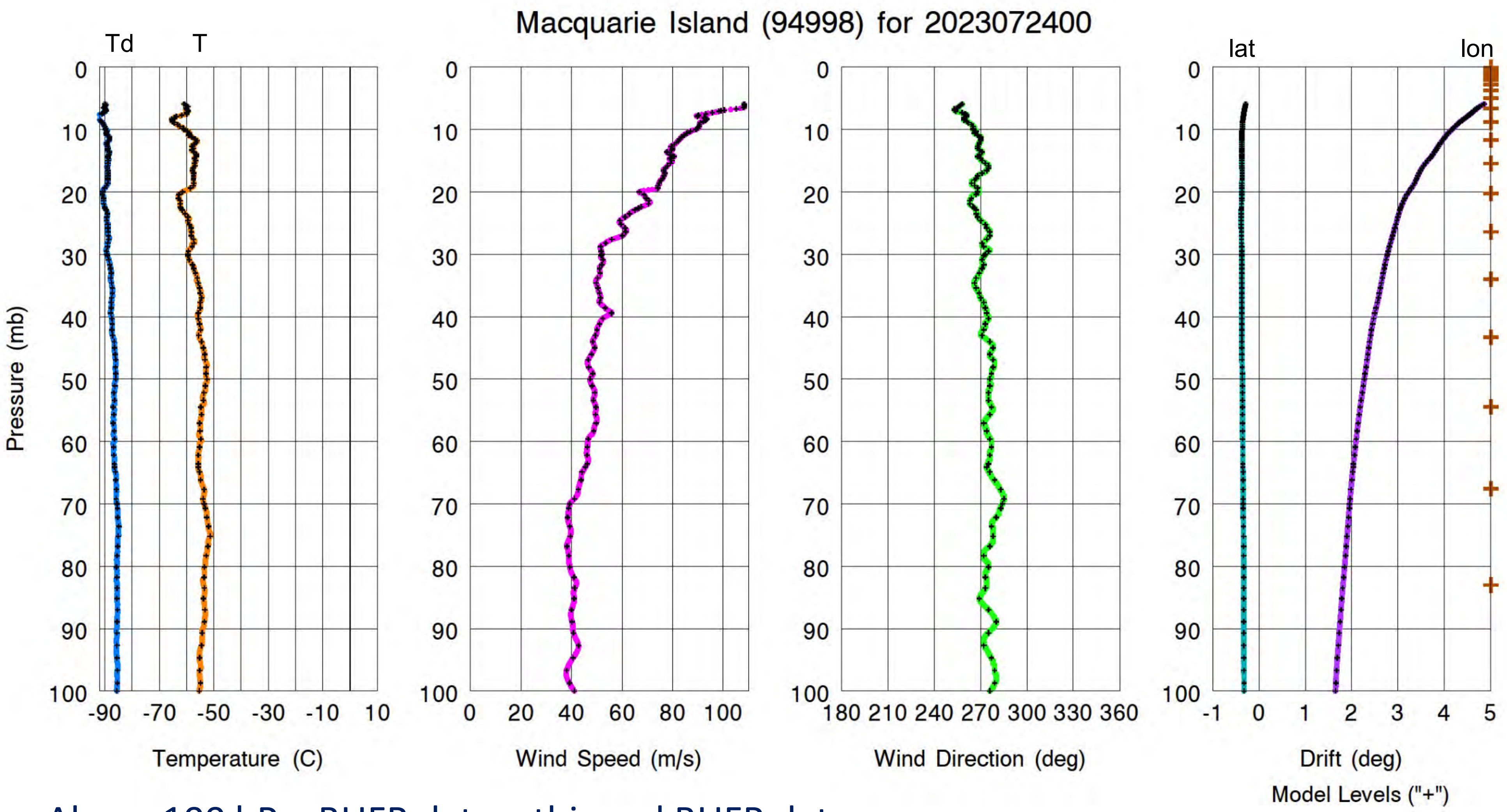

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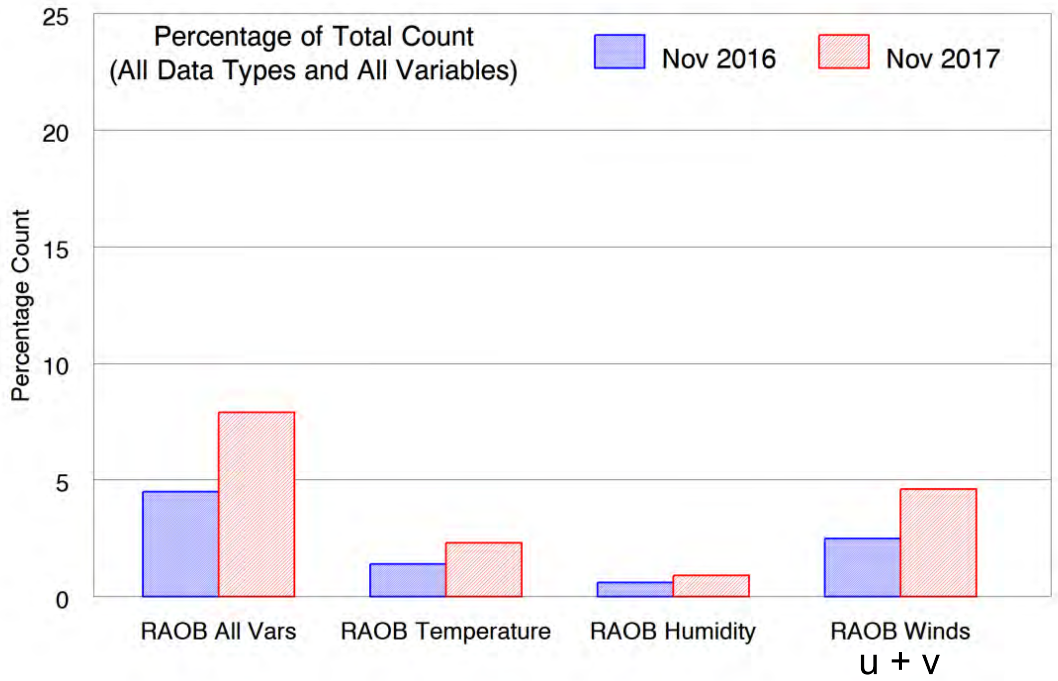
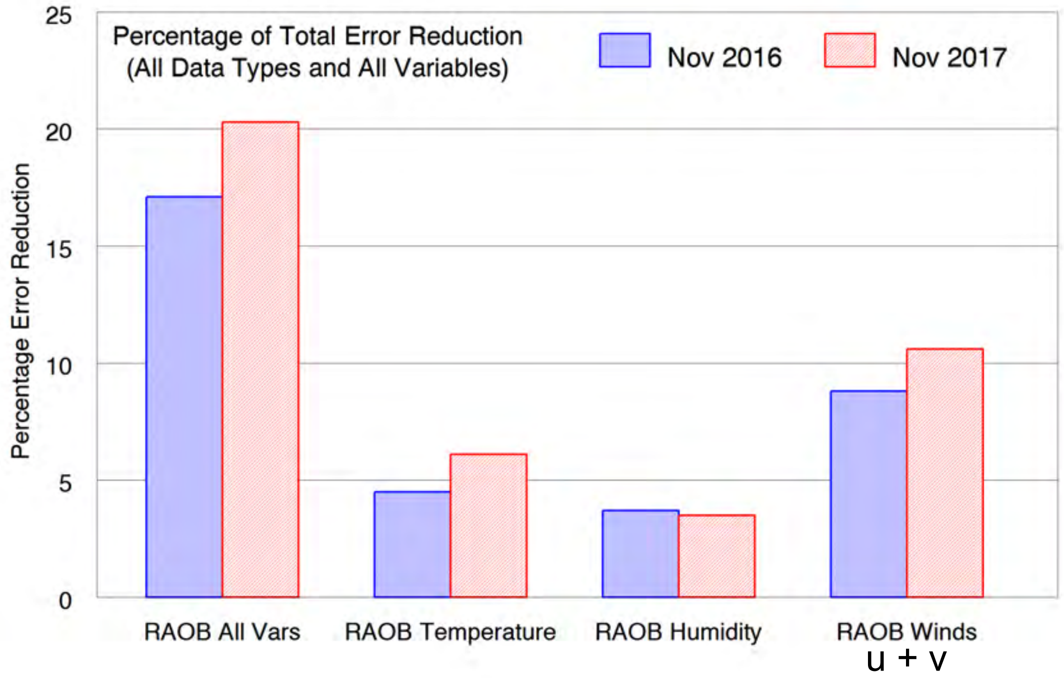
Impact of U.S. Radiosonde Data

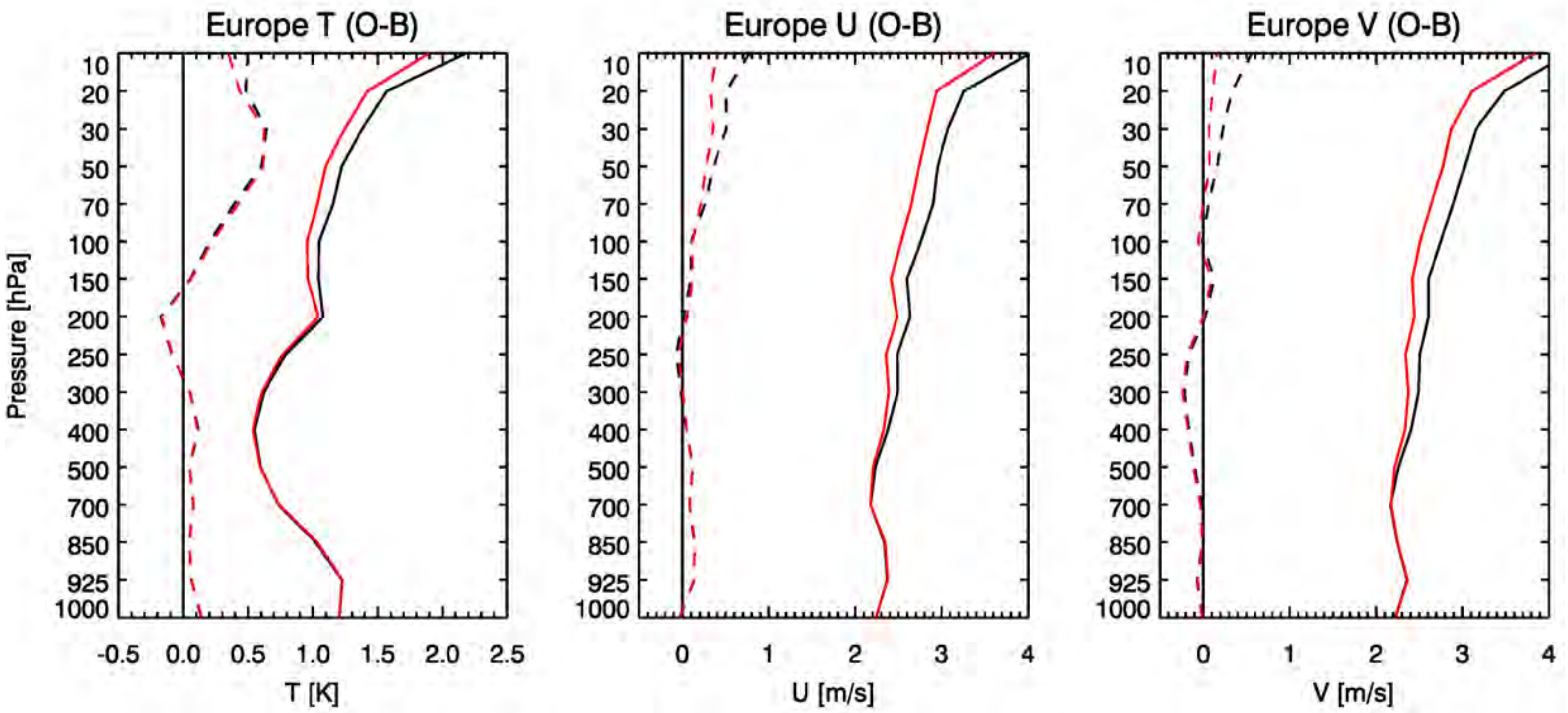




Contribution to global FSOI from the contiguous U.S. for NAVGEM

- Looking at the regional contribution to FSOI from CONUS to isolate impact of U.S. radiosondes
- Left: Increase in counts associated with the implementation of high-resolution software by the NWS
- Right: Increase in percentage error reduction
  - nearly equal increase for temperature and winds, little change for humidity

Impact of Drift in Europe



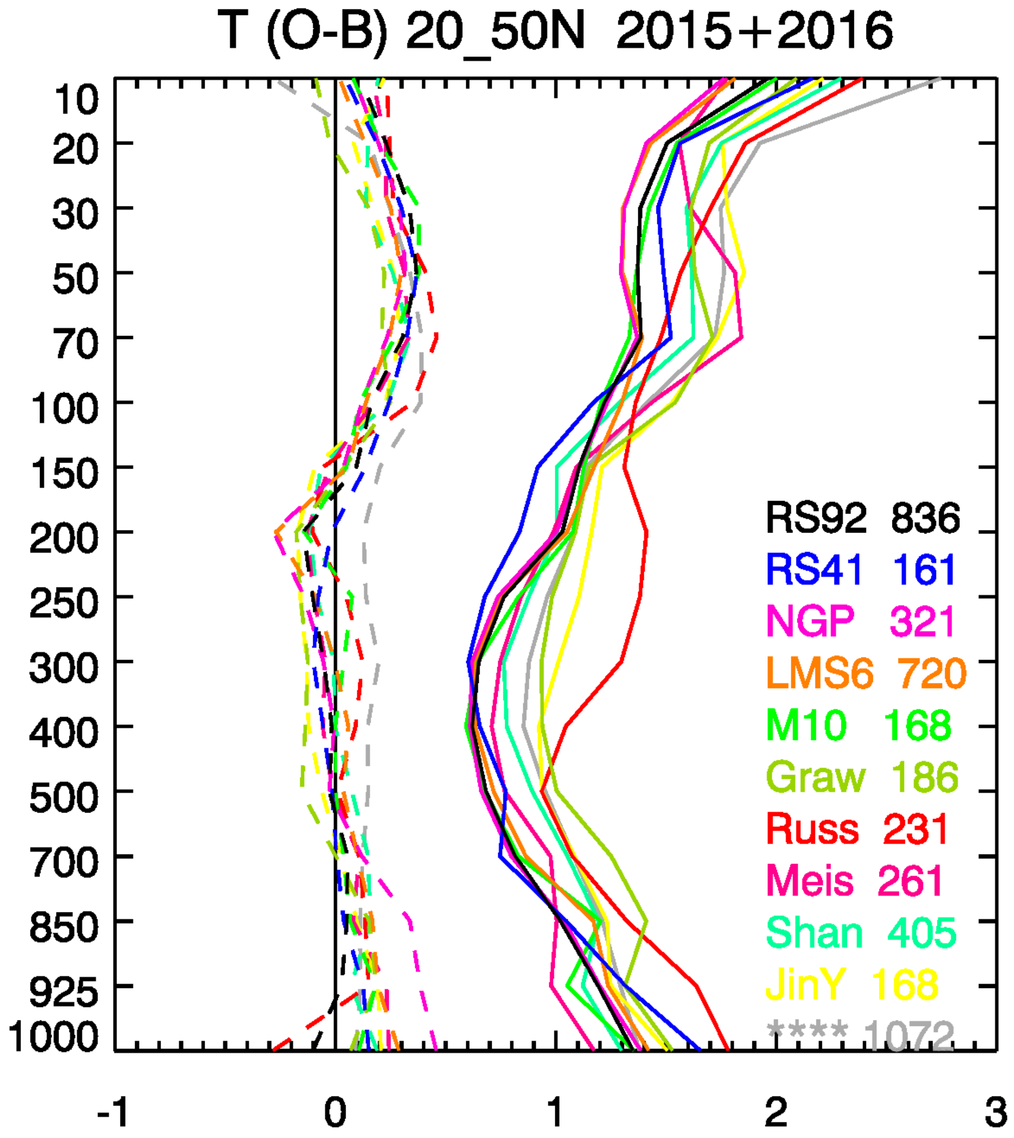
ECMWF O-B statistics for Europe for Nov 2016-Feb 2017 (from Ingleby et al. 2018)

- NWP centers use “O-B” (Observation minus Background) statistics as a proxy for errors
  - Radiosondes used to verify forecasts
  - Short-range forecasts (“background”) used to verify radiosondes
- Using radiosonde data at drift locations improves both the mean (dashed) and standard deviation (solid)

Outline

- Background: traditional vs. high (vertical) resolution radiosonde data
- Radiosonde data in U.S. Navy numerical weather prediction
- Examples of errors in high resolution radiosonde data
  - Data assimilation typically assumes errors are:
    - Random
    - Normally distributed
    - Unbiased
    - Uncorrelated in time and space (including in the vertical)
    - Uncorrelated with the model background
  - Actual errors often violate these assumptions
  - Observations should be viewed with suspicion—most are good, some are not!
- Upcoming changes

ECMWF O-B Statistics



- Example from Ingleby (2017) shows northern hemisphere mid-latitude temperature O-B mean (dashed) and RMS (solid)
- Many of the listed types are no longer in use (e.g., Lockheed-Martin LMS6), but widely used Vaisala RS41 is shown
- Radiosonde data are heterogeneous but often treated in NWP as a homogeneous dataset
- Vertical variation in “errors” handled through specification of observation error in DA system

Error Example

Error in BUFR latitude

- Incorrect launch latitude encoded in BUFR for Lord Howe Island, Australia (94995), presumably from ground station entry
  - FNMOC: -31.5330, 159.0670, 7m
  - OSCAR/Surface: -31.5422, 159.07861, 5m
  - BUFR (Jan 2023): -31.54170, 159.07680, 5m
  - BUFR (July 2023): **10.18716**, 159.07854, 5m
  - Distance ~4,650km
  - Initial latitude drift of 63.08348° indicates error
- **QC solution:** Compare BUFR locations with locations from an external station list
- Reported error to BOM on 7/31; error corrected for 00Z 8/2 launch

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Error Example

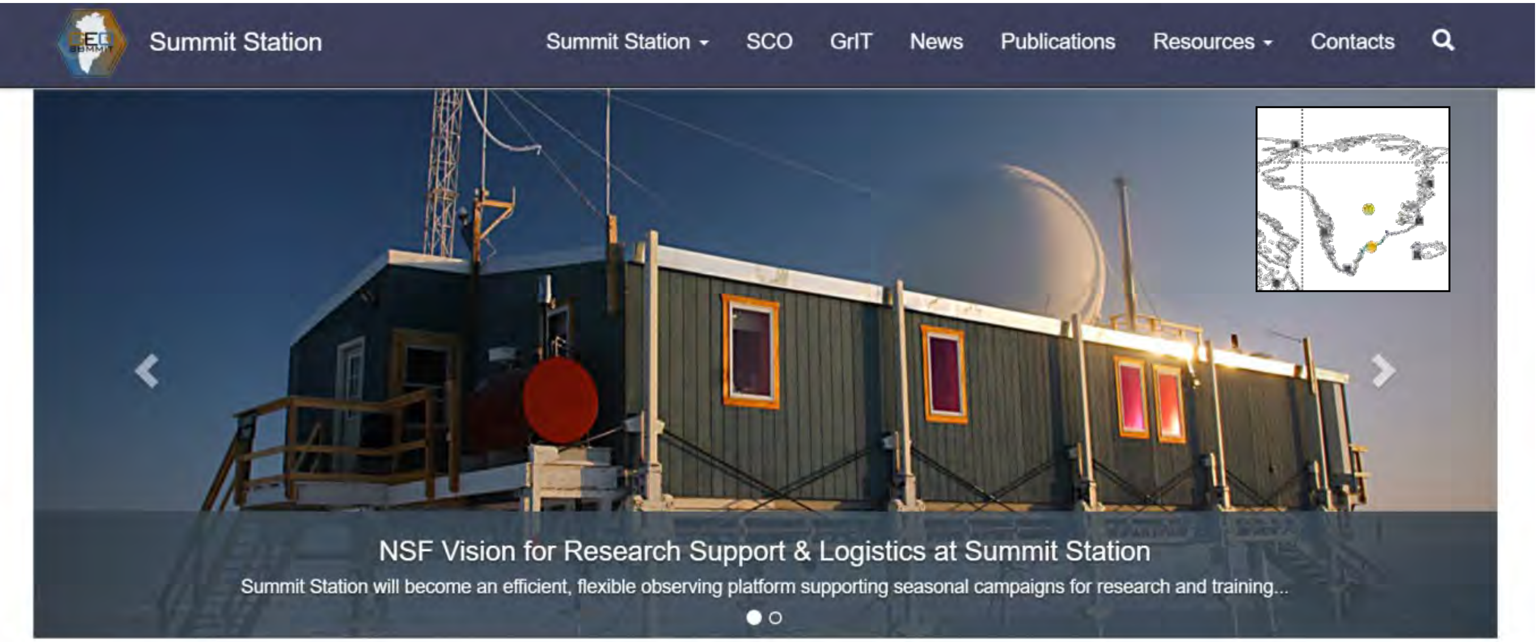
Error in BUFR longitude

- Incorrect launch longitude in BUFR for Taiyuan, China (53772), presumably from ground station entry
- **QC solution:** Compare BUFR locations with locations from an external station list

- FNMOC: 37.7830, 112.5500, 779m
- OSCAR/Surface: 37.62056, 112.57667, missing
- BUFR (July 2023): 37.62000, **106.2000**, 776m
- Distance ~560km
- Radar-based sonde—no indication in drift
- Elevations agree with Google Earth for location near Taiyuan; elevation ~1400m at BUFR location

Error Example

Error in BUFR release height

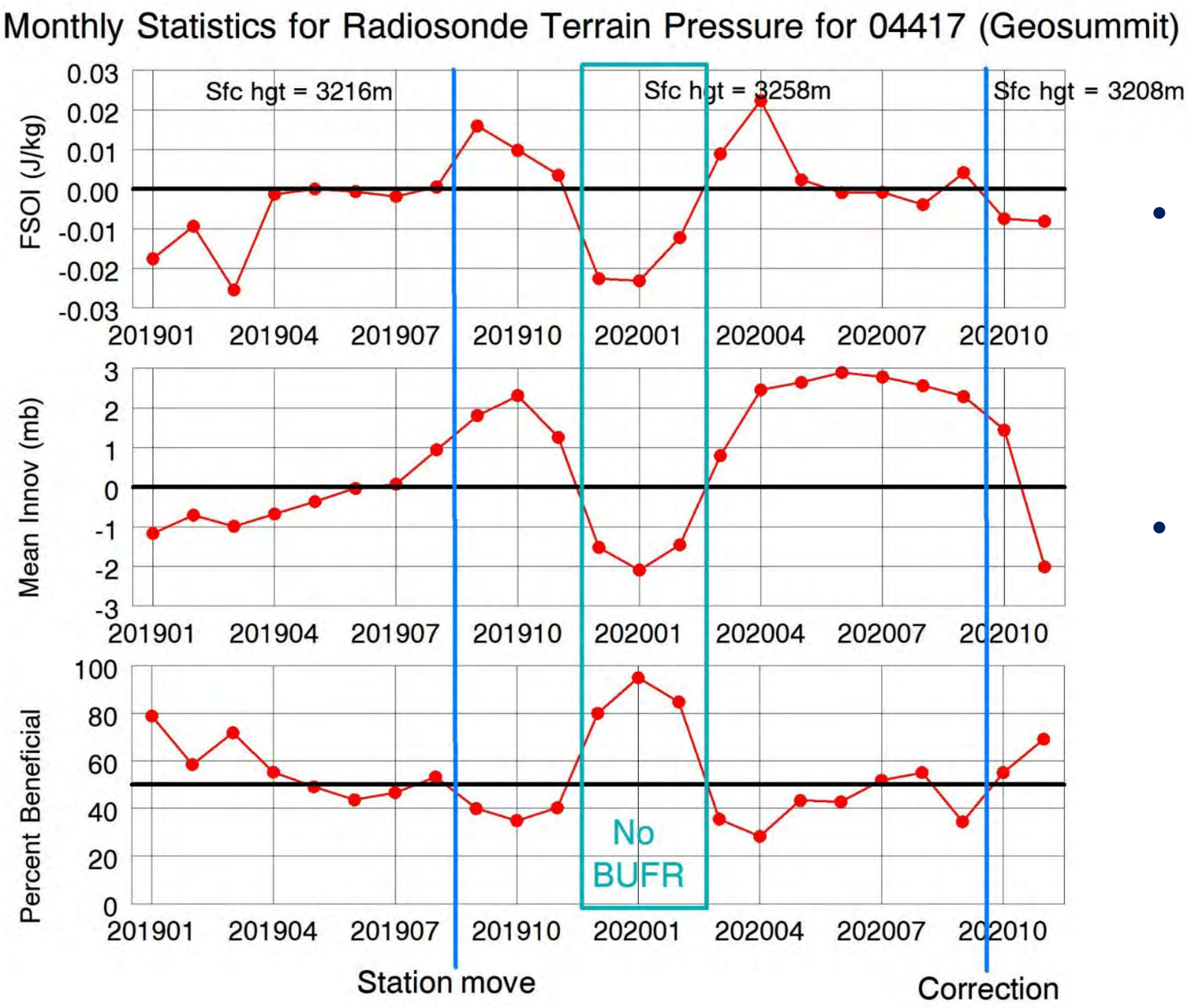


Summit Station, Greenland (04417)

Summit Station is the only high altitude, high latitude, inland, year-round observing station in the Arctic. Summit Station offers immediate access to the free troposphere and is relatively free of local influences that could corrupt atmospheric observations. As such, it is ideally suited for studies aimed at identifying and understanding long-range, intercontinental transport and its influences on the ice sheet surface, boundary layer, and overlying atmosphere. The pristine and remote location in a year-round dry snow and ice region provides an optimal facility for energy and surface mass balance, radiation measurements, and remote sensing validation studies. Summit Station is also a prime site for astronomy and astrophysics research due to its high altitude and dry and stable atmosphere.

- Confusion about elevation
- ECMWF found 35m height bias in O-B statistics in early 2016
  - 3255m unadjusted GPS height
  - Changed to 3216m in July 2016
- Station moved, BUFR release height reset to GPS value of 3258m in Aug 2019
- After many emails, BUFR release height corrected to 3208m in Oct 2020

Error Example

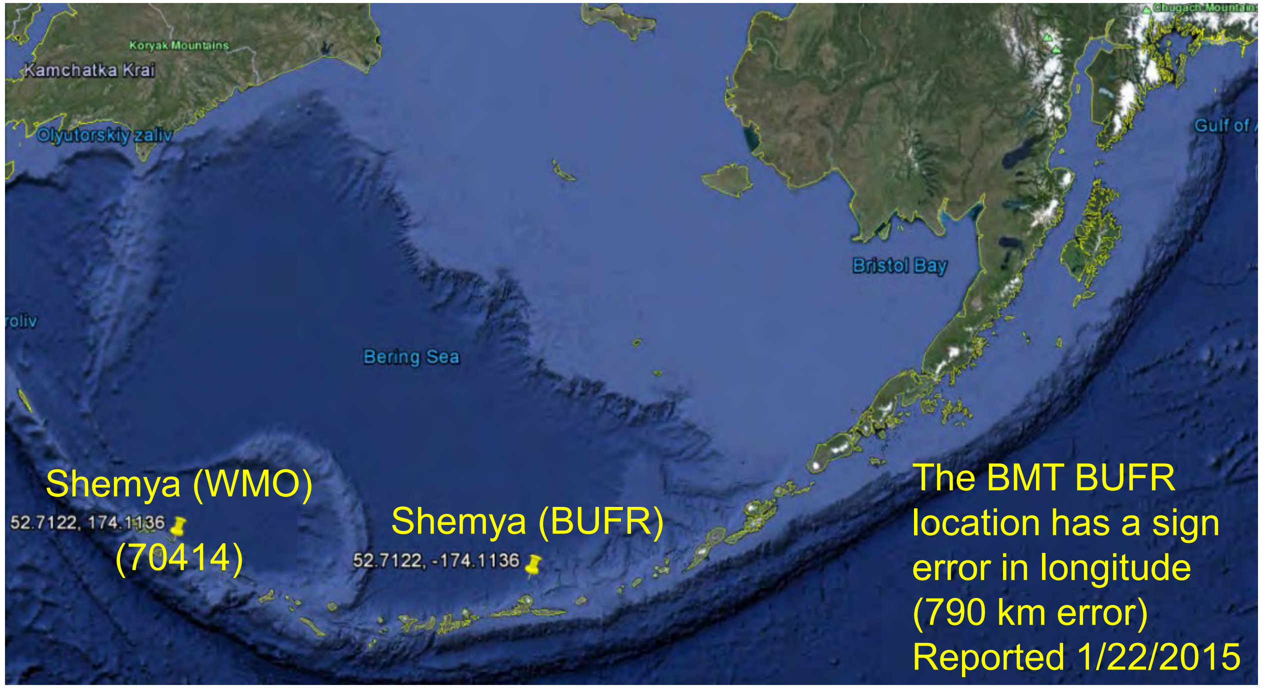


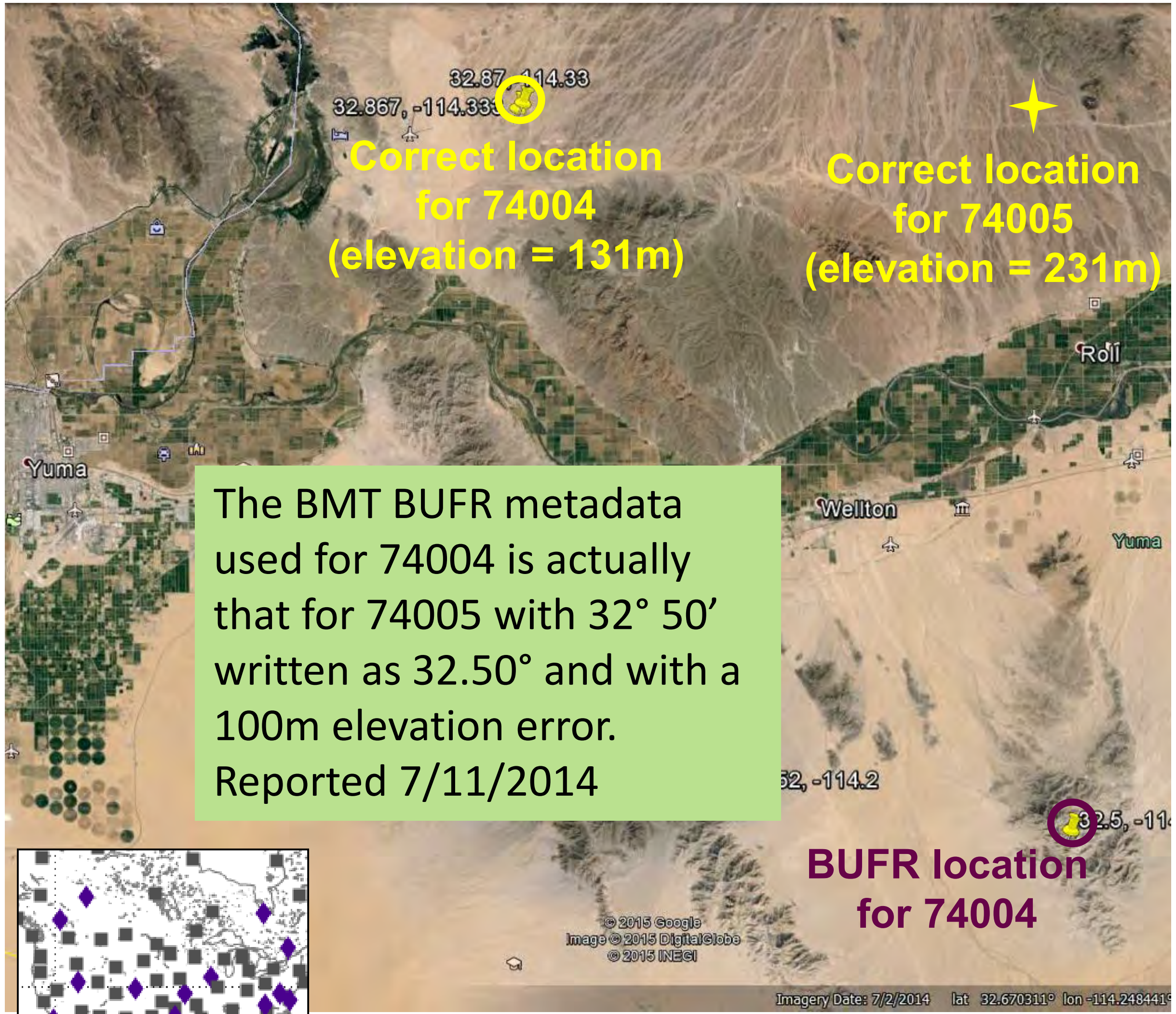
- Change to GPS elevation of 3258m affected the radiosonde terrain (surface) pressure
  - Non-beneficial (positive) overall FSOI
  - Less than 50% of obs with beneficial FSOI
  - Large positive bias in O-B ("innovation")
- BUFR radiosonde data not received at FNMOC in late 2019 and early 2020
  - TAC radiosonde data used with correct elevation from the FNMOC station list
  - Beneficial FSOI for terrain pressure
  - Negative bias in O-B

Error Example

NCEP Central Operations (NCO) generates BUFR radiosonde messages reformatted from TAC for U.S. stations, including military sites with no "native" BUFR

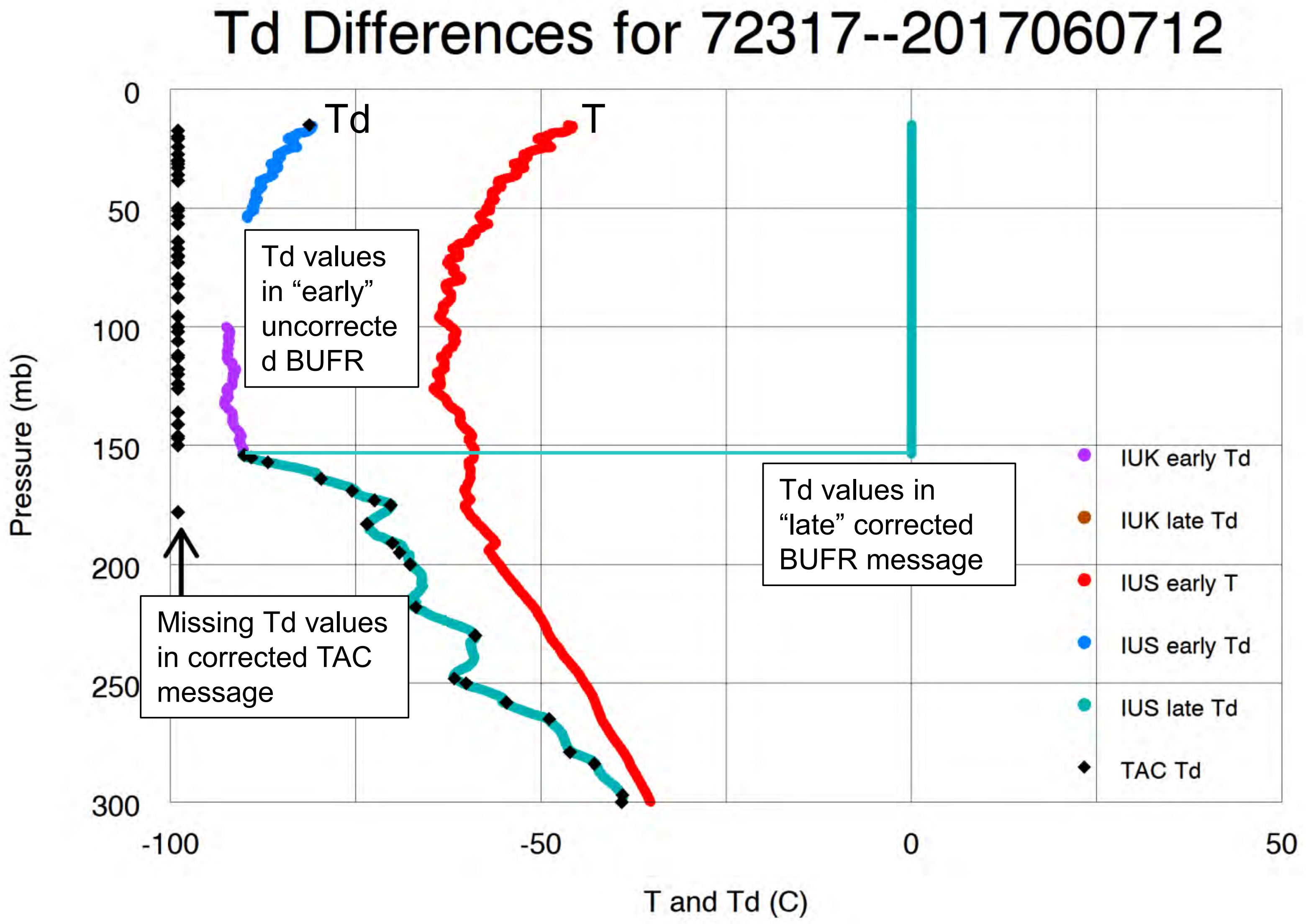
- No improvement over TAC
- Most NWP centers do not subscribe to these bulletins
- Station metadata supplied by station list internal to the "BUFR Migration Tool" (BMT)—source of error





Yuma Proving Ground has three sites: 74004 (most used), 74005, 74006

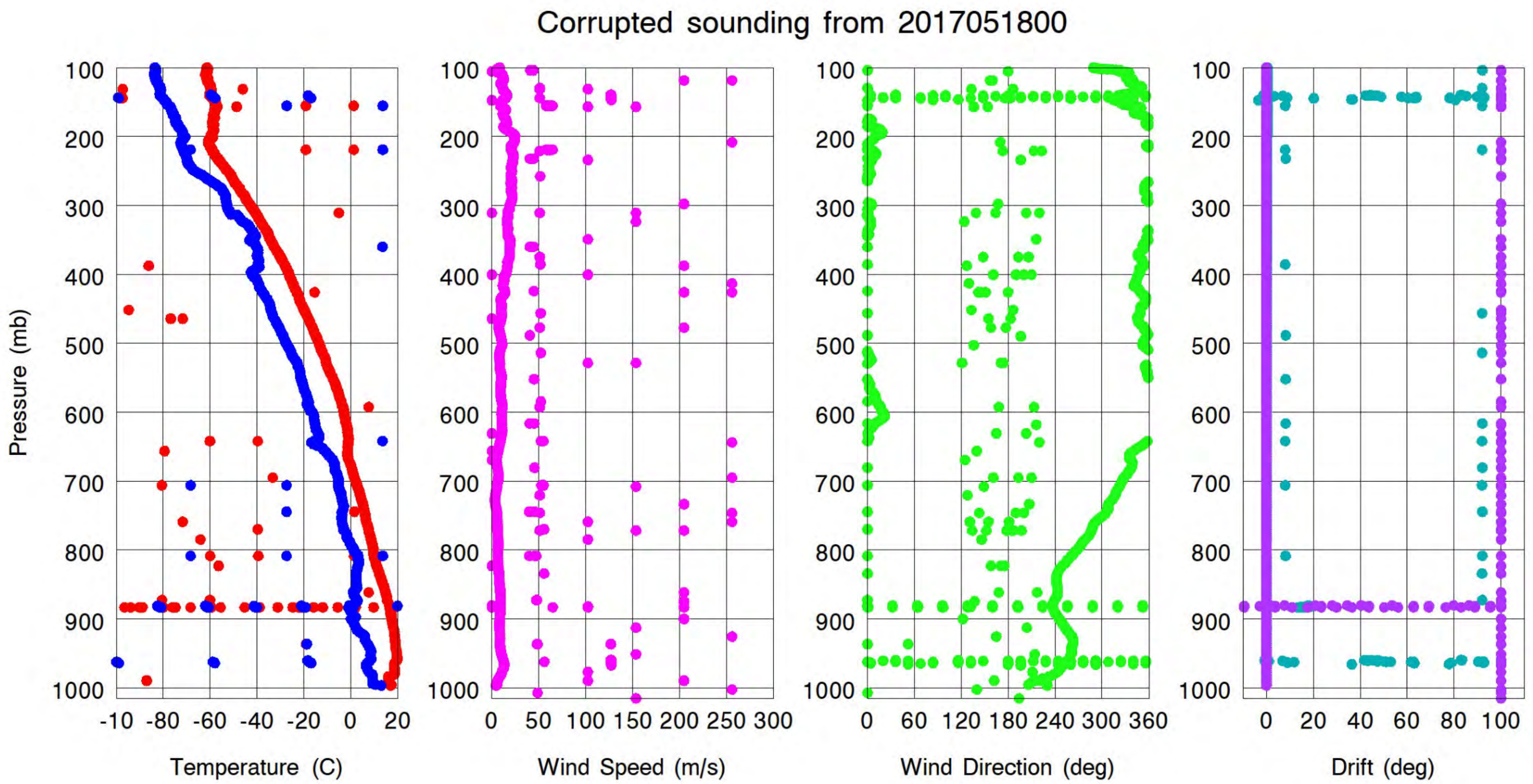
Error Example



Error in ground station software

- U.S. NWS previous ground station software allowed operators to manually delete "bad" data
- Deleted dewpoint depressions set to missing values in corrected TAC messages
- Corresponding dewpoint temperatures erroneously set to 0°C in corrected BUFR messages
- Ground station software update was required to correct the problem
- **QC solution:** Look for negative dewpoint depressions

Error Example

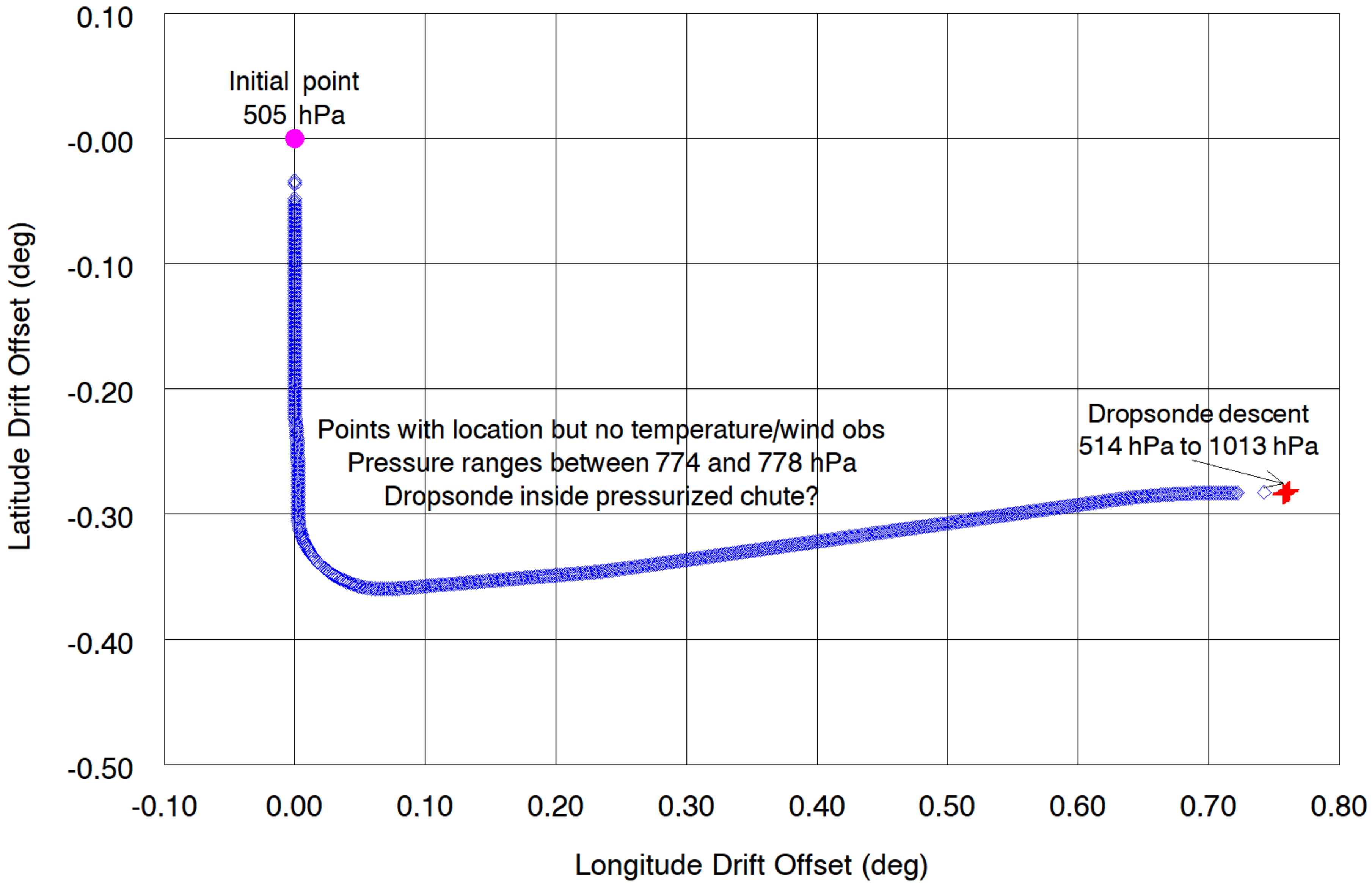


Corrupted sounding

- BUFR messages are binary => ftp as “image” not “ASCII”
- ftp looks for end of line characters when transferring files from Windows to Unix as “ASCII”
- Windows uses <CR> <LF>; Unix uses <LF>; ftp deletes <CR> during transfer
- If the file is binary, deleting the 8 bits for <CR> corrupts the file after that point

QC solution: Reject soundings with a significant percentage of rejected values

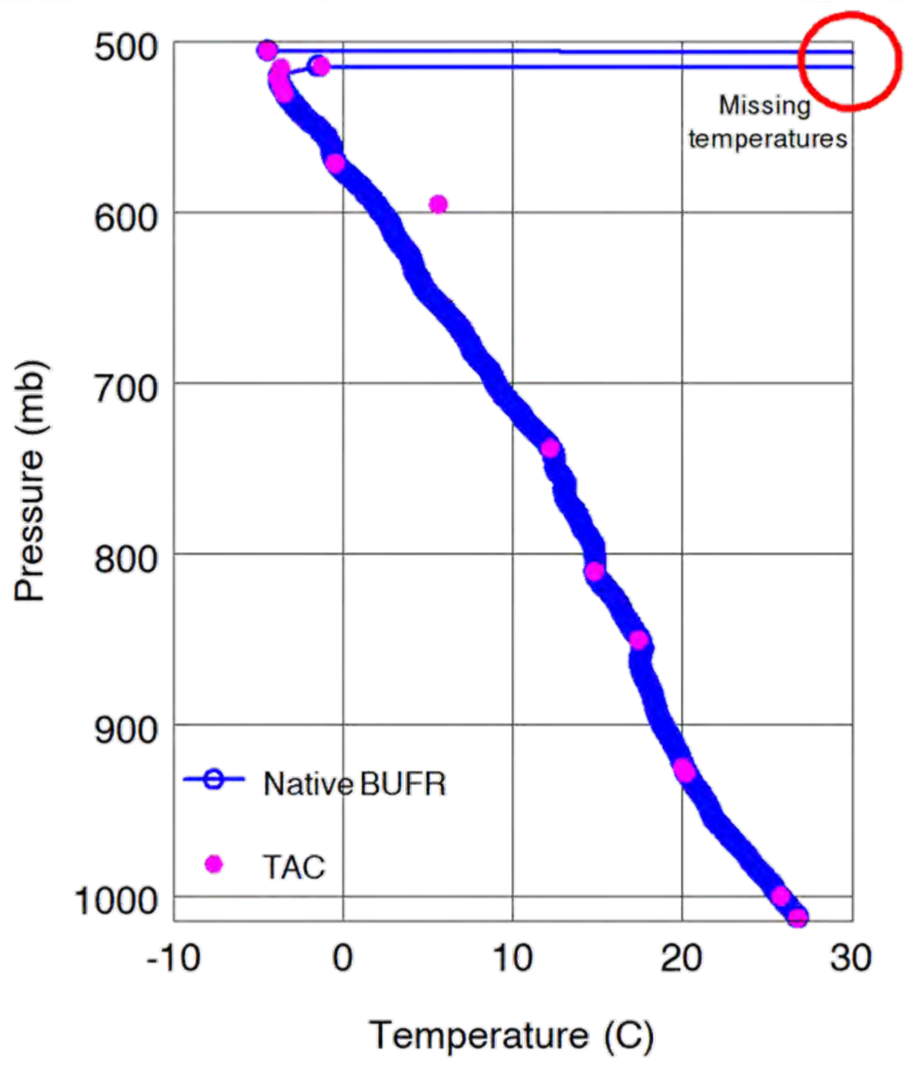
Error Example

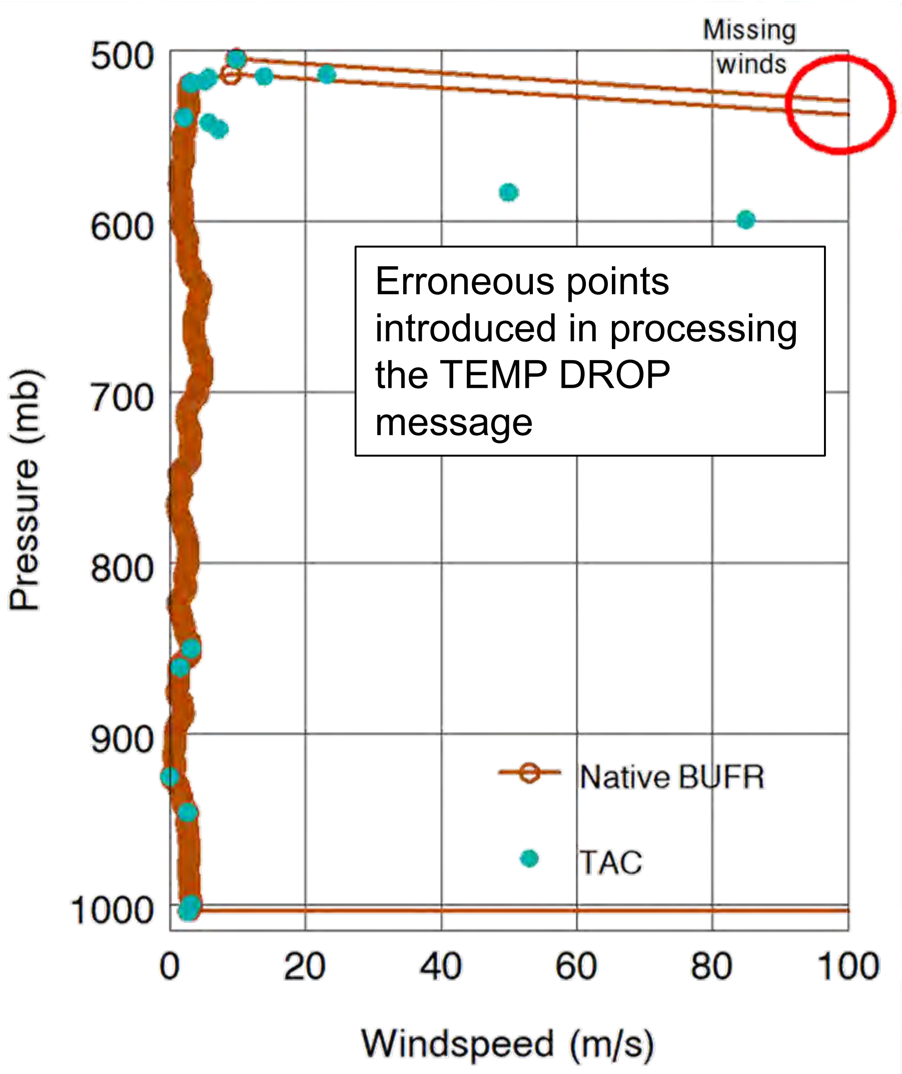


Dropsonde with "early launch detect" problem

- Dropsonde from NOAA2 flying TS Gordon (9/3/2018)
- BUFR dropsonde messages have one-sec resolution and include GPS drift data
- Dropsonde likely inside pressurized chute at locations in blue
- Launch: 2118Z 3 Sept 2018 at 25.78°N, 84.0°W
- Splash: 2137Z 3 Sept 2018 at 25.50°N, 83.24°W

Error Example

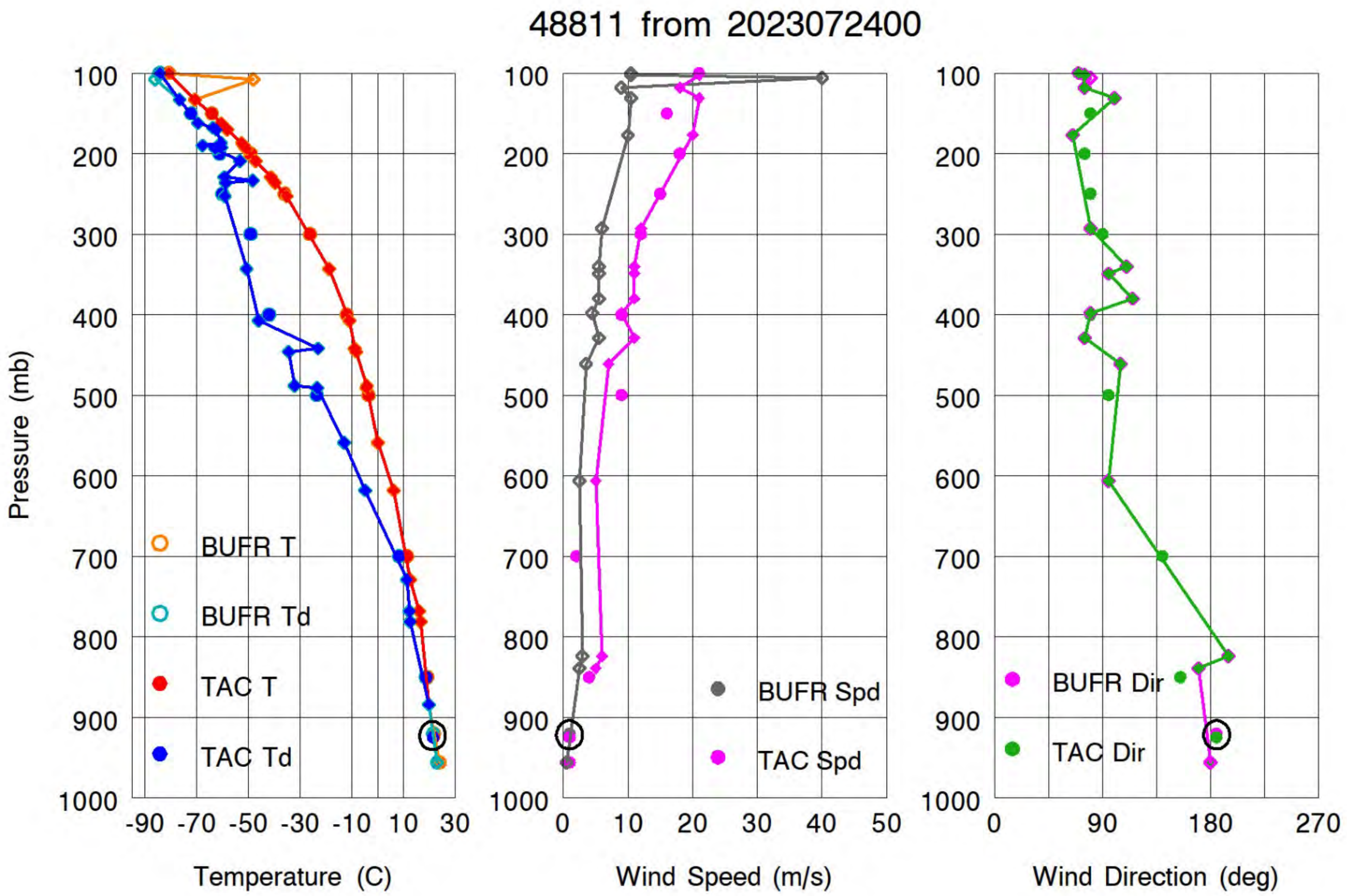




Dropsonde with "early launch detect" problem

- Dropsonde from NOAA2 flying TS Gordon (9/3/2018)
- BUFR dropsonde messages have one-sec resolution and include GPS drift data
- Dropsonde likely inside pressurized chute at locations in blue
- Launch: 2118Z 3 Sept 2018 at 25.78°N, 84.0°W
- Splash: 2137Z 3 Sept 2018 at 25.50°N, 83.24°W
- BUFR has 1112 "levels" (1s); TAC has 27 levels

Error Example

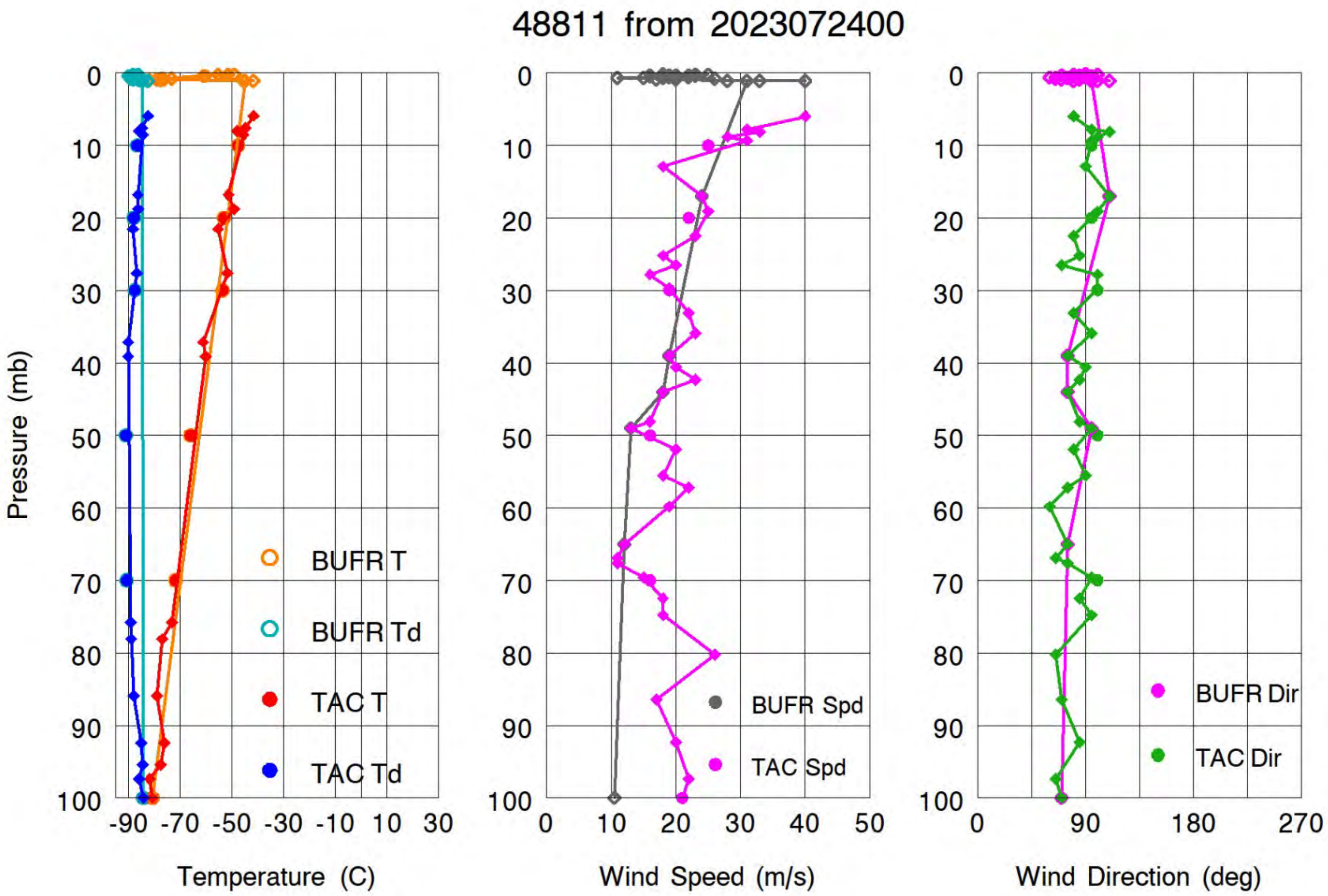


Below 100 hPa

Encode errors in reformatted BUFR

- BUFR data should be the same as TAC
- 925 hPa mandatory level has a BUFR pressure of 920 hPa
- BUFR Significant-level wind speeds appear to be in m/s while all mandatory-level and TAC significant-level wind speeds appear to be in knots

Error Example



Above 100 hPa

Encode errors in reformatted BUFR

- BUFR data should be the same as TAC
- 925 hPa mandatory level has a BUFR pressure of 920 hPa (corrected in QC)
- BUFR significant-level wind speeds below 100 hPa appear to be in m/s while all mandatory-level and TAC significant-level wind speeds appear to be in knots
- BUFR significant-level data above 100 hPa reported with incorrect pressures of 1.1 hPa or less, but with wind speeds that appear to be in knots
- QC rejects obs with pressures <= 1.0 hPa
- Significant level winds rejected in a country-specific check

Outline

- Background: traditional vs. high (vertical) resolution radiosonde data
- Radiosonde data in U.S. Navy numerical weather prediction
- Examples of errors in high resolution radiosonde data
- **Upcoming changes**
  - **WIGOS Station Identifiers**

WIGOS Station Identifiers

- **Some countries are running out of WMO block-station numbers**
  - Five-digit WMO block-station numbers are composed of a two-digit block number (referring to a country or region) followed by a three digit station number.
  - For example, Canada was recycling block station numbers since it had only one block number until recently. Some identifiers were reassigned to a location on the opposite side of the country, creating problems where local stations lists used the old location.
- **WIGOS station identifiers (WSIs) are the solution chosen by the WMO.**
  - WSIs are in four parts with a total length (without dashes) of up to 28 characters.
  - WSIs have no inherent meaning, unlike block numbers assigned by country/region.
  - WSIs can only be used in BUFR, since TAC code forms assume block-station numbers.
  - Block-station numbers are no longer being assigned, so new stations cannot use TAC.

WIGOS Station Identifiers

WIGOS Identifier Series (number)	Issuer of Identifier (number)	Issue Number (number)	Local Identifier (characters)
0 01 125	0 01 126	0 01 127	0 01 128
4 bits = 2 digits	16 bits = 5 digits	16 bits = 5 digits	128 bits = 16 chars (a-z), (A-Z), (0-9), (-), (_), (.)
Only series “0” has been defined; identifies observing stations	WMO Program or Country/National Identifier (3 digits)	Typically zero for WMO Programs & WMO Co-Sponsored Programs; can range from 0-65535 for national schemas	For WMO Programs & Co-Sponsored Programs, typically the “legacy” WMO Identifier; can be (up to) any 16 char string for national schemas
0	20001	0	72662
0	208	0	04417

WIGOS Station Identifiers

- **Decoding BUFR observations with WIGOS Station IDs is relatively trivial, however…**
  - Data users will need to update applications to handle the longer WSIs
  - Without updating, applications will not be able to take advantage of observations from new stations/networks that will only be assigned WSIs
- **Will need to work in two worlds**
  - Block-station numbers for TAC observations
  - Mix of block-station numbers and WSIs for BUFR obs
  - OSCAR/Surface allows searches by block-station number or WSI

WIGOS Station Identifiers

- **Decoding BUFR observations with WIGOS Station IDs is relatively trivial, however…**
- **Will need to work in two worlds**
- **Accounting for long WSIs poses a major challenge for NWP centers and other users**
  - FNMOC's DA systems use 16-character platform identifiers with the station identifier itself limited to 5 characters for radiosonde data
  - Accommodating WSIs poses significant difficulties!
  - One possible way forward: map WSIs to short identifiers in some way
    - e.g., NCEP plans to fit the WSI local identifier in the prepBUFR 8-character id
- **WSI implementation was delegated to the national level to develop country-specific schemas**
  - The U.S. plan is included in Federal Meteorological Handbook #13
  - https://www.icams-portal.gov/resources/icams/related_documents/2021_fmh13.pdf
- **Widespread use of WSI expected to take time, but we need to be ready!**

WIGOS Station Identifiers

What we must avoid!

(*Atmospheric Modeling, Data Assimilation and Predictability*, Kalnay, 2002)

The effect of modern quality control systems is difficult to gauge, but Kistler *et al.* (2001) showed an impressive example of the positive impact from the modern approach compared with the quality control that was operational at NCEP in the 1970s. They pointed out that in 1974 NMC (now NCEP) introduced a modern observation formatting system (known as Office Note 29, ON29), which later became the basis of the official World Meteorological Organization (WMO) Binary Universal Format Representation system for the encoding of observations. ON29 included more information about the observation than previously used encoders. This change in formatting required a complete overhaul of the NMC decoding system, and errors must have been introduced during this complex reprogramming process. The NMC operational forecast skill actually went down and it took a few years before it recovered to the pre-1974 error levels (Kalnay *et al.*, 1998). During the

WIGOS Station Identifiers

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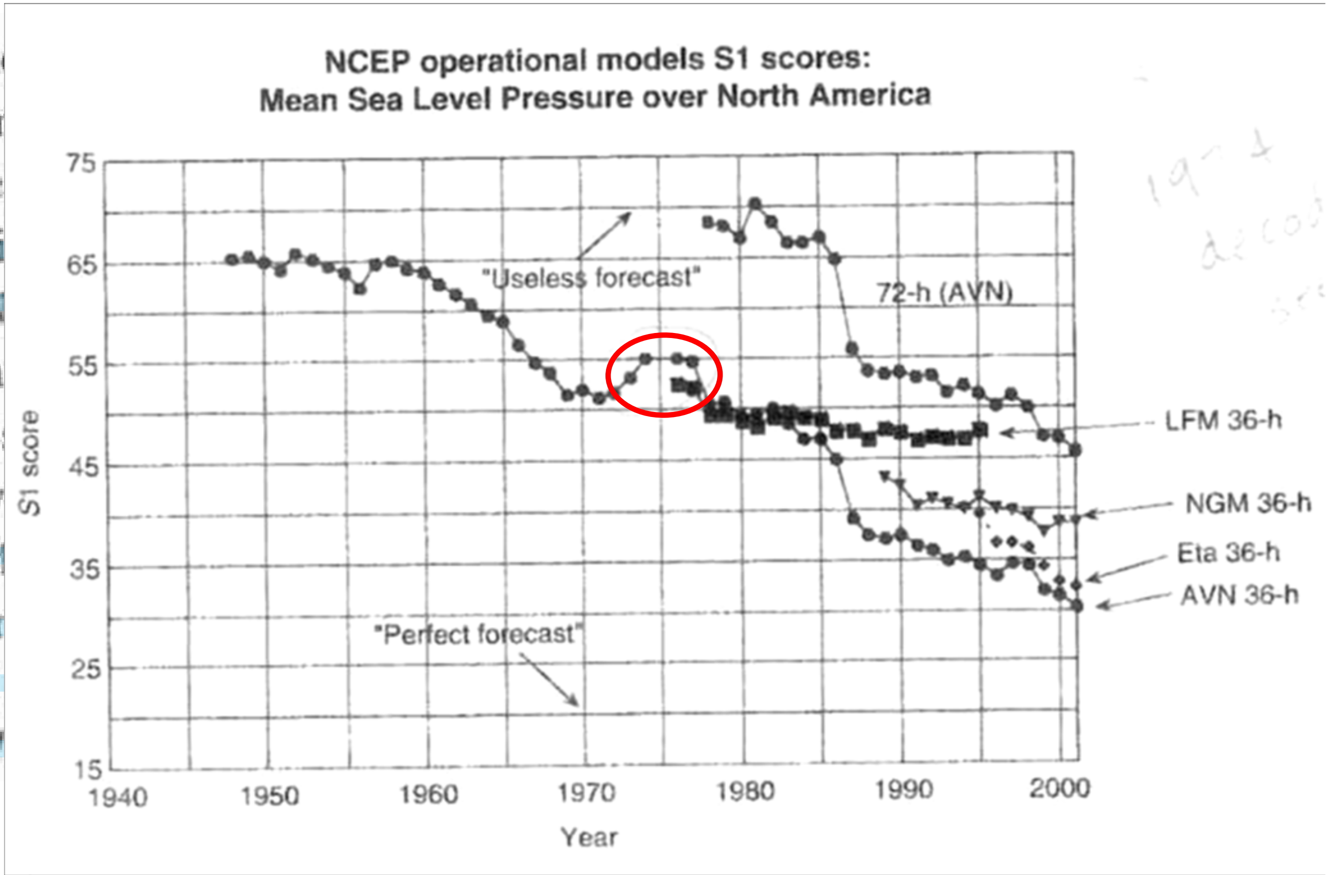


Questions?