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Agenda Item 5: Airspace Safety Monitoring Activities/Requirements in the Asia/Pacific Region

STATISTICAL ANALYSIS OF ALTIMETRY SYSTEM ERROR (ASE) VARIATION BASED ON LARGE-DATA ANALYSIS OF AUSTRALIAN AHMS RESULTS – CORRECTING FOR BIAS

1 JANUARY 2022 TO 31 DECEMBER 2022

(Presented by Australian Airspace Monitoring Agency)

SUMMARY

Altimetry System Error (ASE) for aircraft can be calculated using ADS-B data; the AHMS process. This paper examines 7-years of Australian ASE data, from 2525 aircraft with stable ASE each using the WGS-84 ellipsoid height reference. Over 93,000,000 separate data points (each a summary of 1-minute) was used.

The results demonstrates a predictable bias in ASE with position (latitude, longitude), date and time of day up to ± 30 ft. There was no significant bias with flight level. For most aircraft with ASE calculated over a range of locations, times and dates, this bias will average to zero. For some aircraft with smaller data sets, correcting for the bias has helped determine geoid height reference and improve ASE estimation.

1. INTRODUCTION

1.1 This paper considers the calculation of Altimetry System Error (ASE) using ADS-B data. This is called the AHMS process (ADS-B Height Monitoring System) and was developed through SASP and implemented by several regional monitoring agencies (RMAs) around 2015.

1.2 The process uses large-scale ADS-B data from aircraft which identifies flight level (and hence pressure altitude), geometric altitude, position (latitude, longitude), and date-time.

1.3 Meteorological data from NOAA estimates the geometric versus pressure altitudes at different locations and times; in 6-hourly estimates. Computer code from the FAA uses this data, and the ADS-B data, to estimate the difference between the aircraft's pressure altitude and the meteorological pressure altitude. Australian computer code automates data being fed into the FAA code and then takes the output to enable large-data collection and analysis.

1.4 Aircraft transponders give ADS-B geometric altitude as either height above the WGS-84 ellipsoid (hae) or above an estimate of height above mean sea level (msl). DO-260B transponders all use a hae geoid reference frame. Older transponders may use either hae or msl. The ADS-B data indicates a DO-260B transponder, and analysis of the data for older transponders can statistically verify the geoid if the aircraft travels across a sufficient range of geographic location. In this analysis, only

aircraft which obviously use a hae geoid reference were used; and this was visually checked for every aircraft.

1.5 There is no truth data for the ASE of an aircraft. But with sufficient ADS-B and meteorological data, statistical variations can be eliminated, to an accuracy sufficient for monitoring RVSM risk.

2. METHOD

2.1 The method involved use of 7-years of ASE calculations from the Australian Airspace Monitoring Agency (AAMA) of 6492 separate aircraft. Each of these was individually assessed to ensure the aircraft was using the hae geometric height reference, and had a long-term stable ASE value established from a range of geographic locations. Additionally, the results for each aircraft in the data sample were visually checked to establish the date range for analysis, where the ASE value was stable.

2.2 This resulted in 2525 aircraft and 93,814,042 separate data points (each a summary of 1-minute) data being available. Most data came from Australia's two large domestic operators, since each aircraft then had a very large number of data points as the aircraft repeatedly crossed the continent. The second largest group were international operators flying repeatedly to and from Australia.

2.3 For each aircraft, the ASE was normalised to have mean zero before the data set was grouped together to form a standardised 'super set' of data.

2.4 A difficulty in the analysis is the large data size, being of order several gigabytes, which can overwhelm computer random access memory. This required care in splitting data into smaller sets, analysing them and then recombining results. However, since results may be correlated with latitude, longitude, date, season, time of day and altitude there may also be insufficient data in a particular region for statistical correlation. Hence, the analysis is complicated by both too much data and a lack of data. Thus, doing a 'simple correlation' of the whole data with the key variables (latitude, longitude, date, time flight-level) was not possible.

2.5 The initial analysis uses data discretised into 10 x 10 degree regions, to first explore variation with location, date and time of day. Reduction to a small grid may reduce sample sizes to a point where insufficient data is available for any analysis. Larger grids may hide geographic variability. Further work will be done to reduce the grid size in regions where sufficient data is available.

2.6 The grid reference is the bottom left corner. For example, grid (-30, 120) refers to data in the latitude band [-30, -20) ($-30 \leq \text{lat} < -20$) and longitude band [120, 130) ($120 \leq \text{lon} < 130$).

2.7 **Figure 1** shows the overall distribution of normalised ASE with mean 0 and standard deviation 23 ft.

2.8 **Figure 2** shows a map of the data and **Figure 3** illustrates the discretisation of the region into 10 x 10 degree grids along with the number of hours of data in each grid.

2.9 **Figure 4** shows the mean ASE each day over the time interval, with an obvious variation between -10 and + 10 ft. This figure also shows the number of data samples per day, which varies considerably since the AAMA processing of ASE was interrupted during several periods and there was the traffic reduction over due to Covid-19. Some historic ASE data was missing when data was transferred between computer systems a few years ago.

2.10 **Figure 5** shows the distribution of hours for each aircraft, with around 600 aircraft having a small number of hours, and a small number of aircraft having a very large number of hours. This plot also shows that these latter aircraft contribute most to the data.

2.11 **Figure 6** shows the histogram of flight levels.

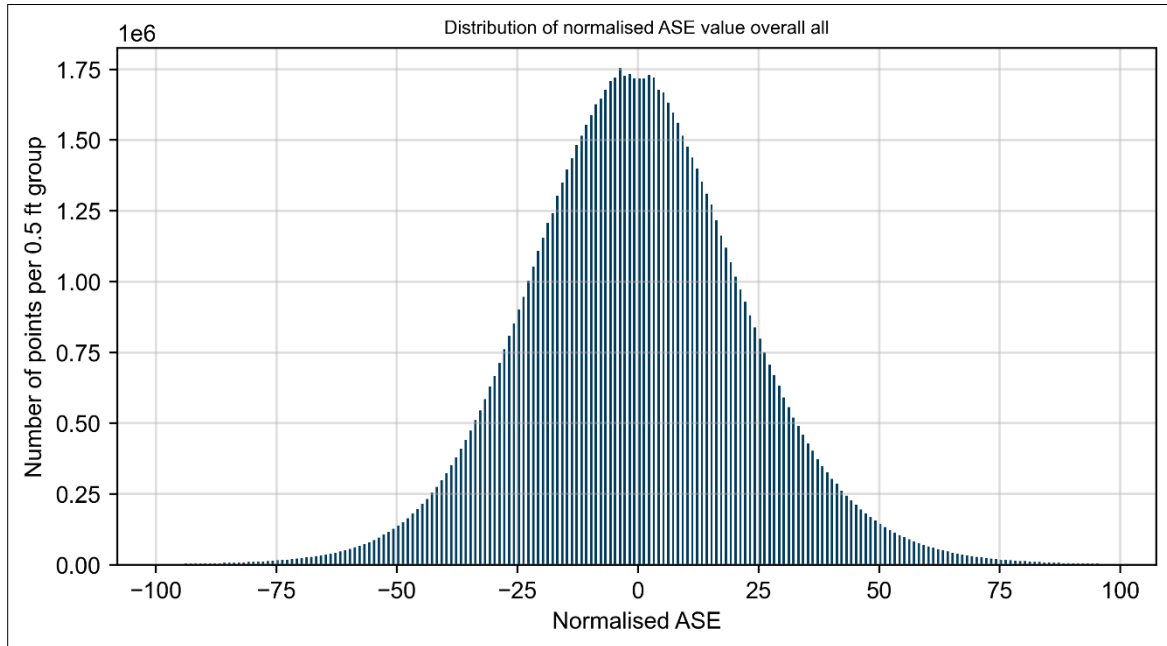


Figure 1: Overall distribution of all normalised ASE values from 2525 aircraft and 93,814,042 separate data points (each a summary of 1-minute). The mean is 0 and standard deviation is 23 ft.

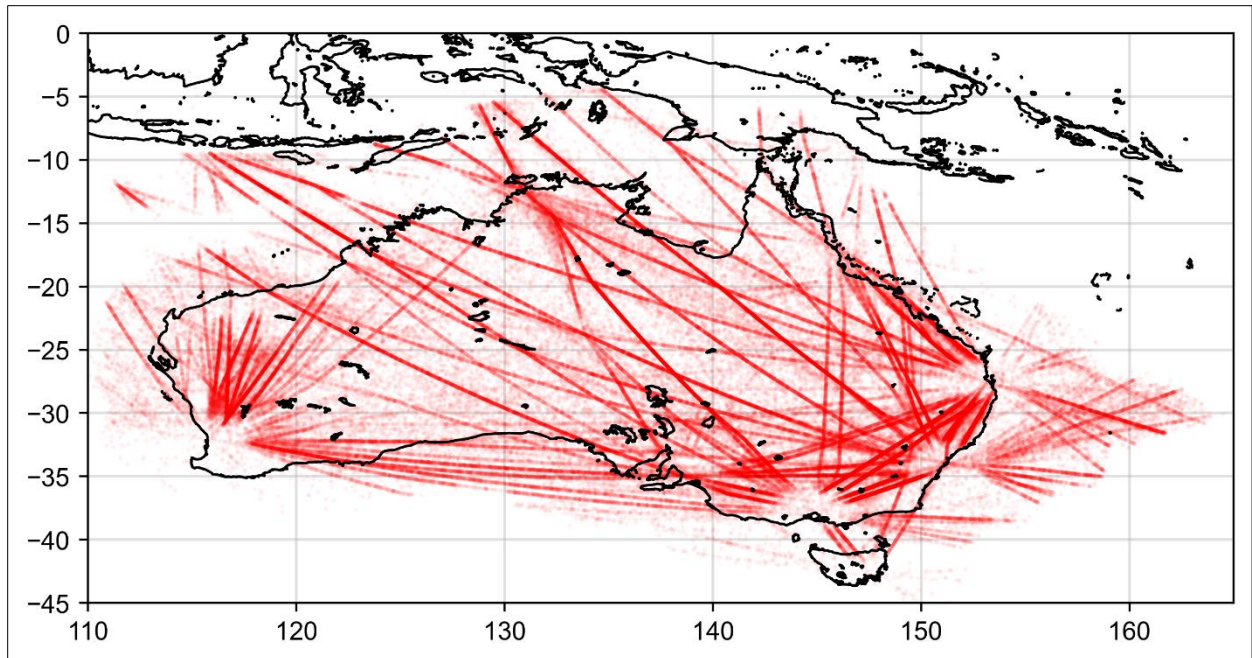


Figure 2: Map of data from from 2525 aircraft and 93,814,042 separate data point, with only 1 in every 1000 points shown due to data size limitation.

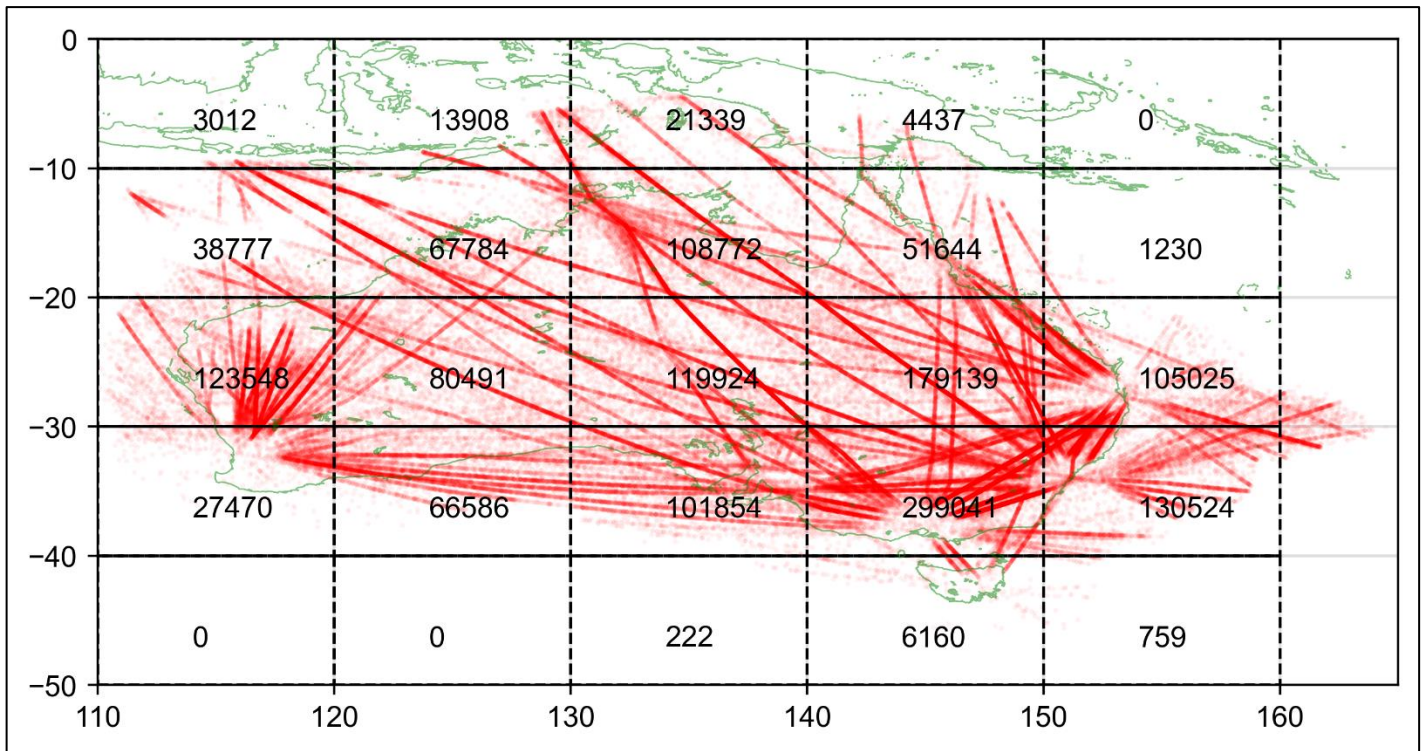


Figure 3: Illustration of the discretisation of the region into 10 x 10 degree grids, and the number of hours of data in each grid.

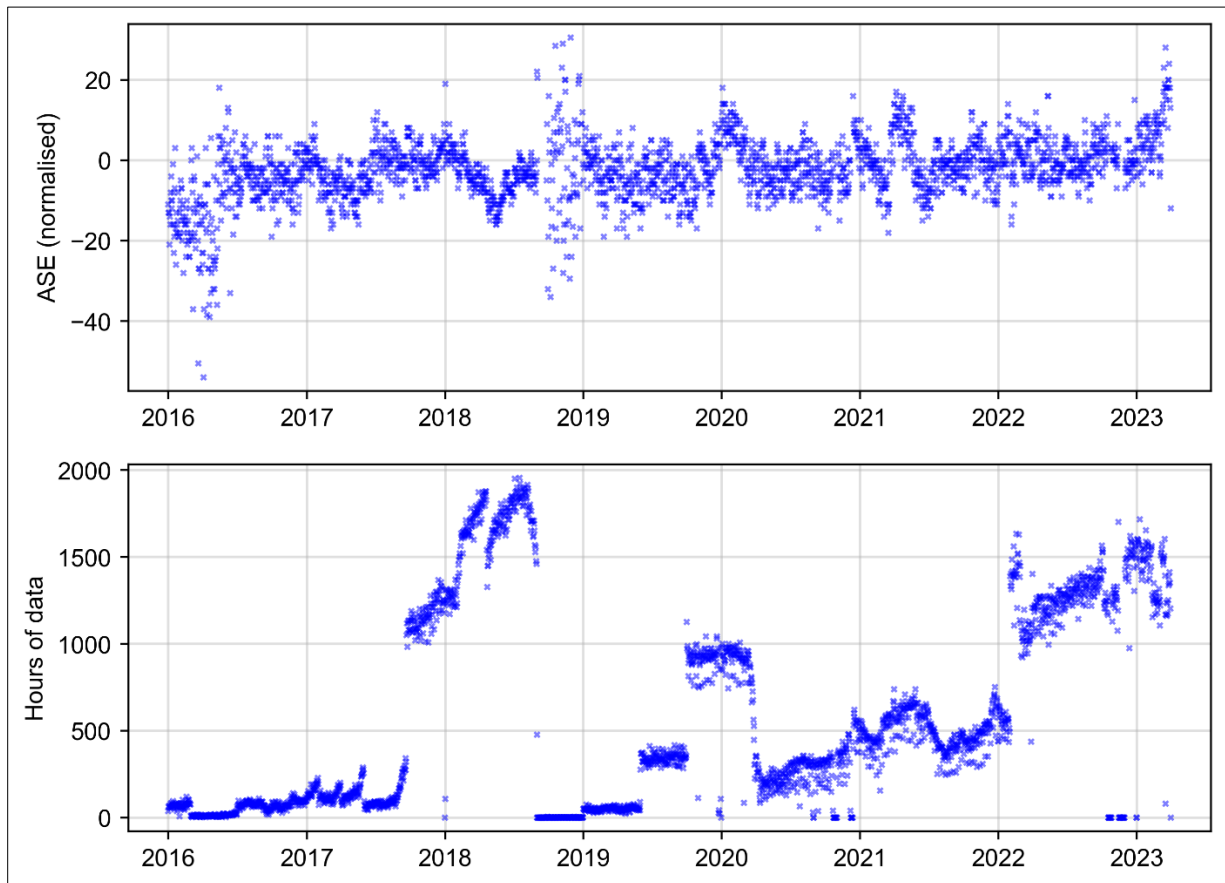


Figure 4: Time series of data with normalised ASE shown in the top plot per day, and the hours of data per day in the bottom plot over time. The variations in count data relate to

periods where the AAMA reduced calculations of ASE, where some historic data was lost, and where Covid-19 reduced flights. Hence, some the variation in the top plot is where the number of calculations in each day was small.

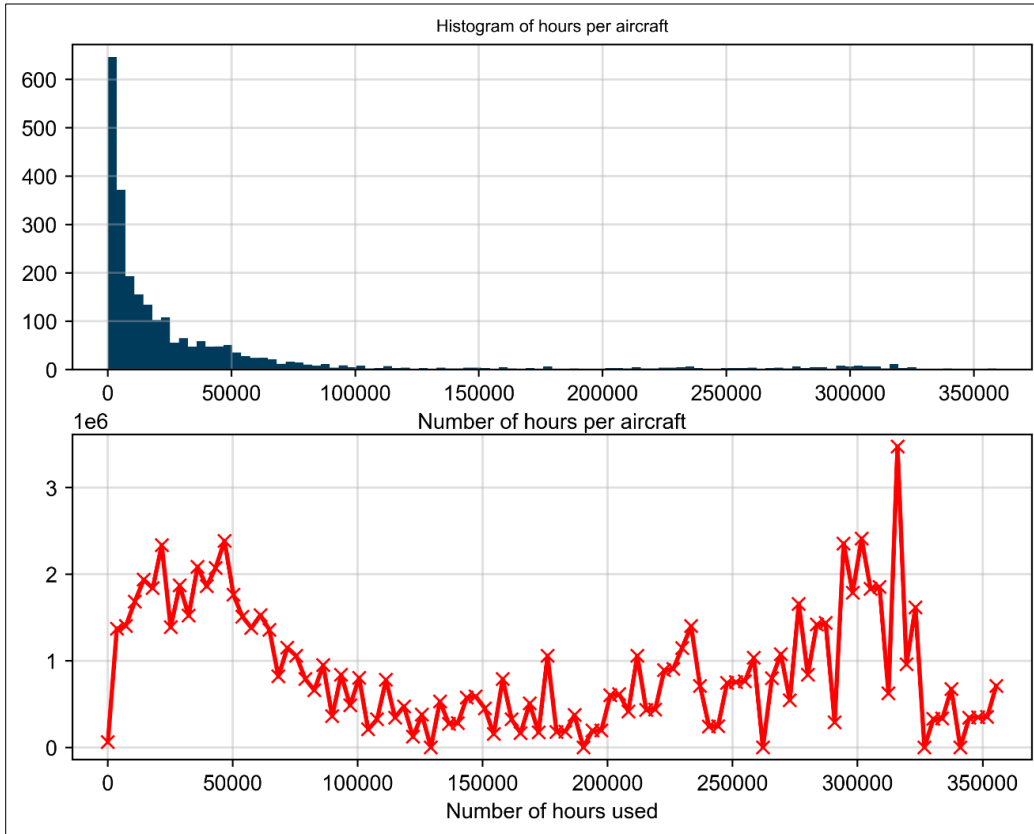


Figure 5: Each of the 2525 sampled aircraft had a different number of hours. Slightly over 600 aircraft had a small number of hours with some aircraft having over 300,000 hours of data as shown in the top plot. The bottom plot shows the contribution of data by aircraft, with the small number of aircraft with over 250,000 hours each, naturally contributing greatly to the overall data set.

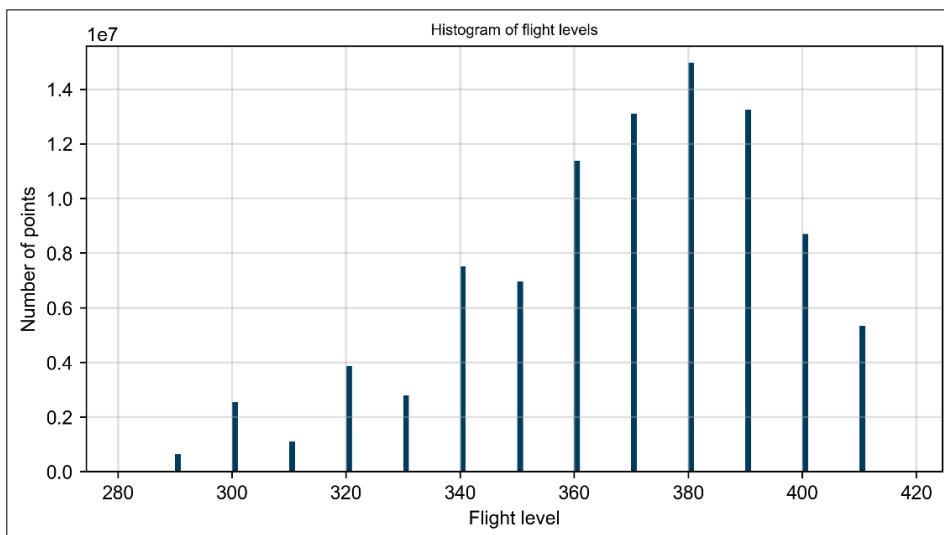


Figure 6: Histogram of flight level for the 93,814,042 separate data points (minutes).

2.12 **Figure 7 to Figure 10** show example of ASE results for four separate aircraft. In each figure the:

- top left plot is the ASE value over time with the red values the ASE using the correct hae geoid reference for each day and the blue using the incorrect height above mean sea level (msl) reference.
- top right plot is the distribution of all ASE values, showing a tight Gaussian.
- bottom left plot shows the ASE value as a function of the difference between hae and msl geoid references. This is broadly reflective of ASE variation by location. The red (hae) values should remain constant and the blue (msl) values should have slope 1.
- bottom right plot shows the aircraft paths in red on a map. The green line is where msl and hae geoid references have the same value, and the blue lines where they differ by 10 ft.

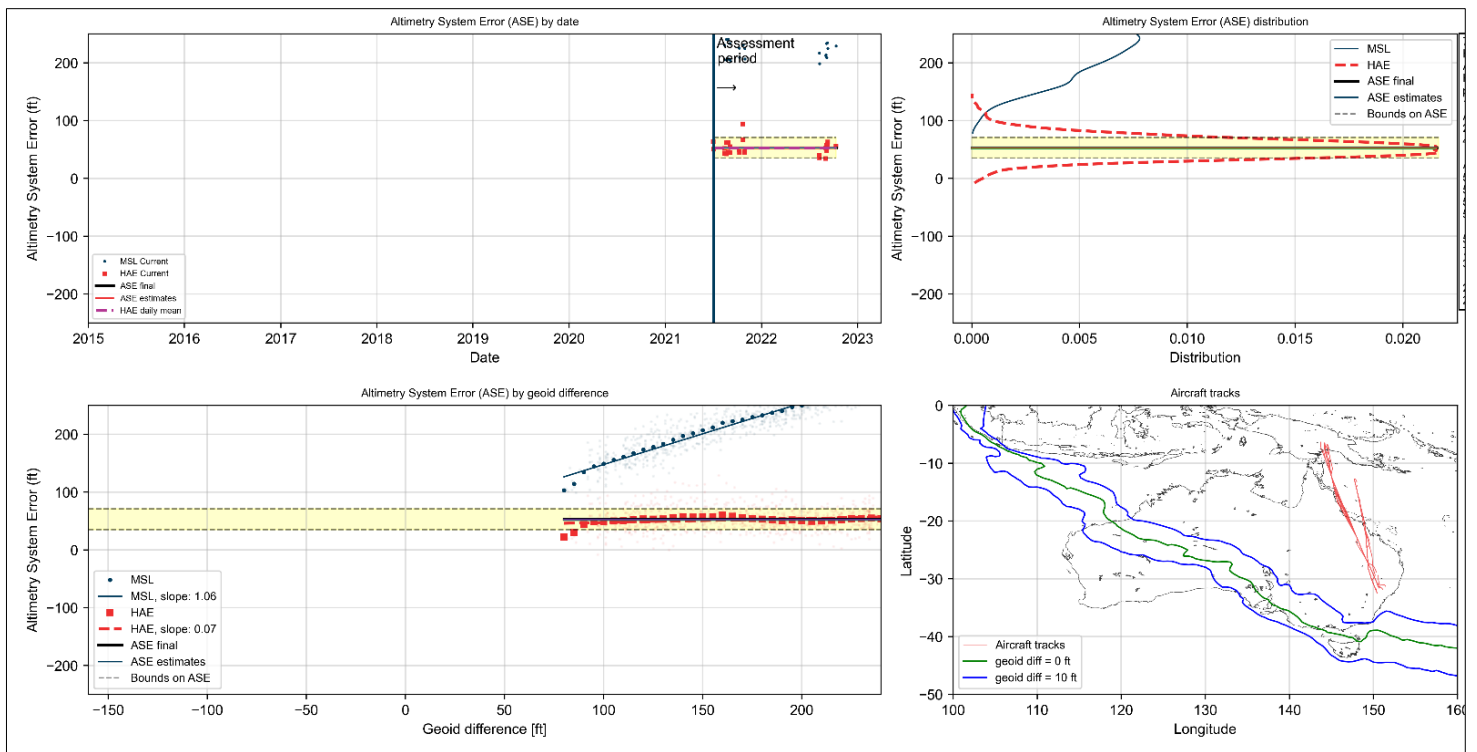


Figure 7: Example of a relatively small set of data from an A330 aircraft with 25 days and 4363 data points.

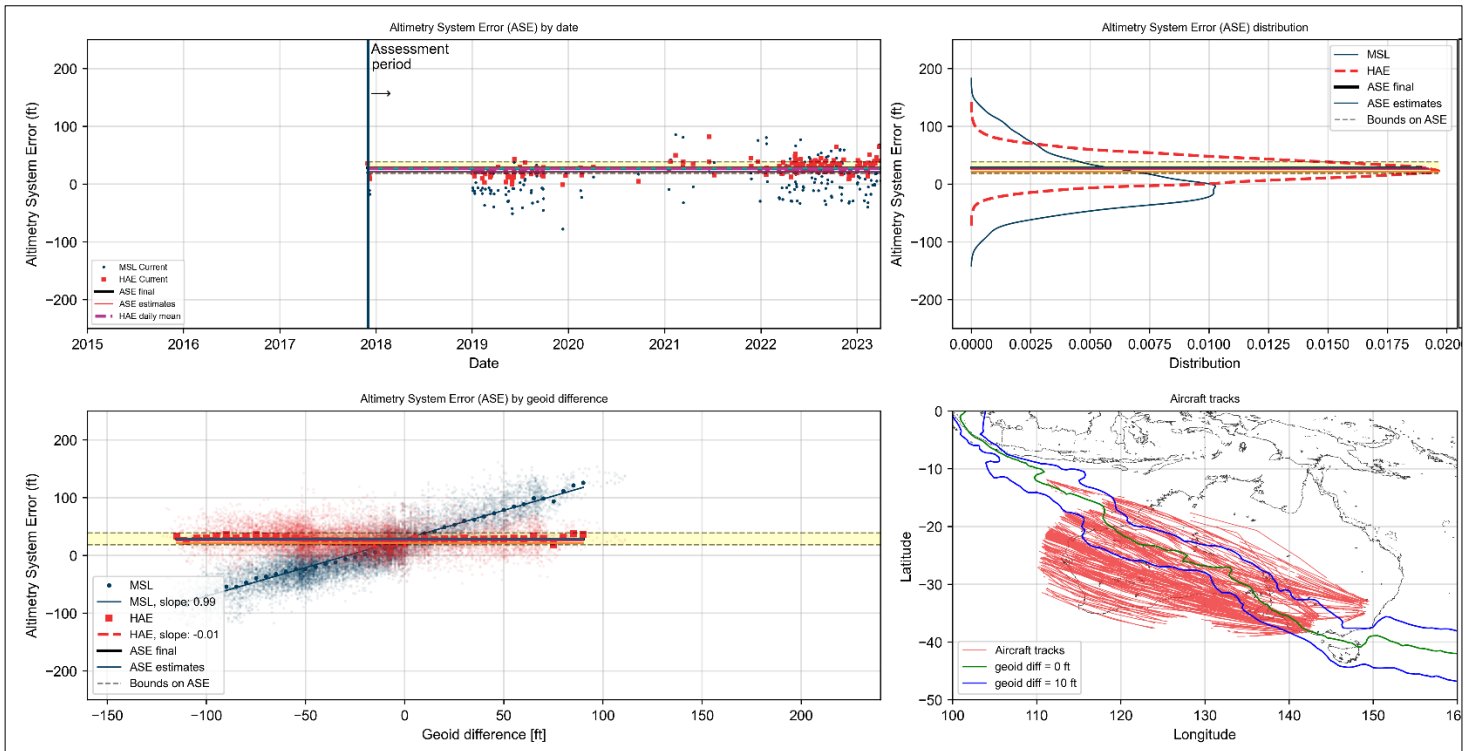


Figure 8: Example of data from an A330 aircraft from an international operator with 176 days and 63740 data points.

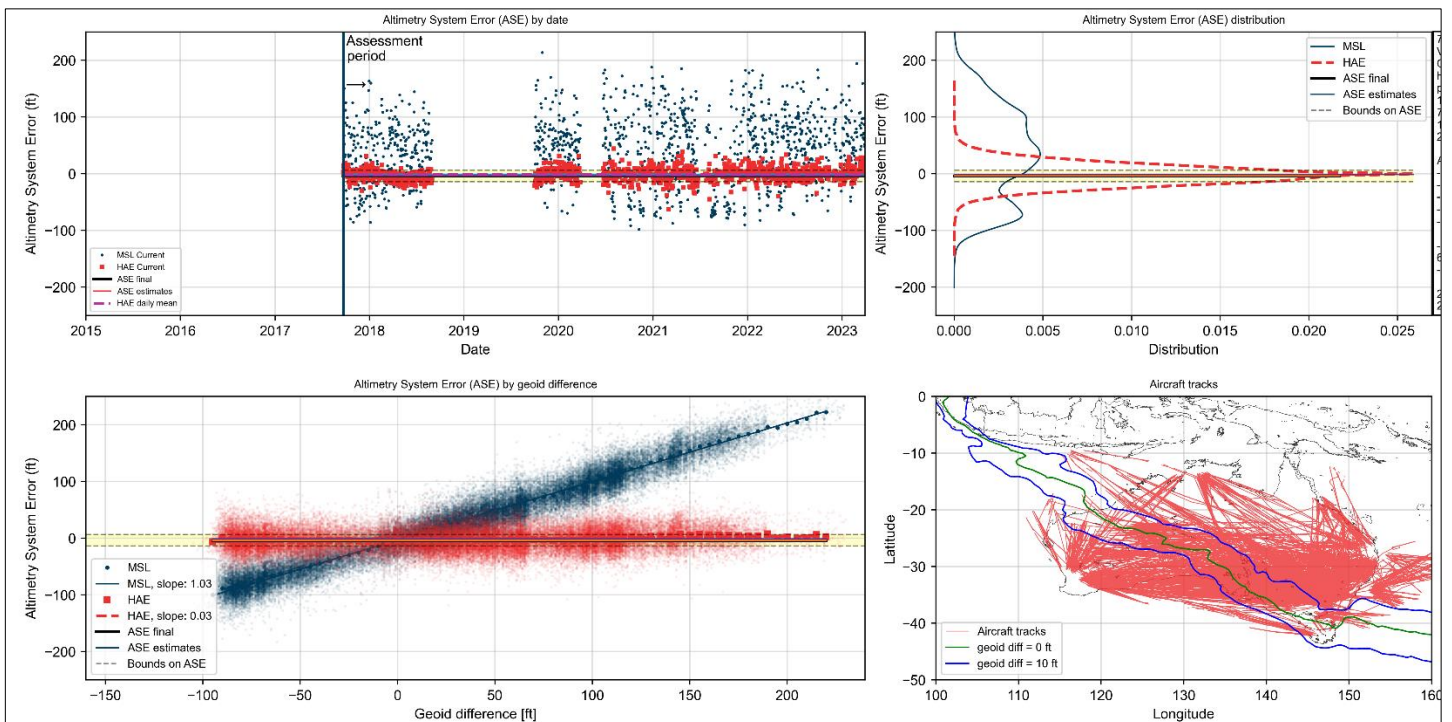


Figure 9: Example of a B738 aircraft with 1272 days and 296,976 data points.

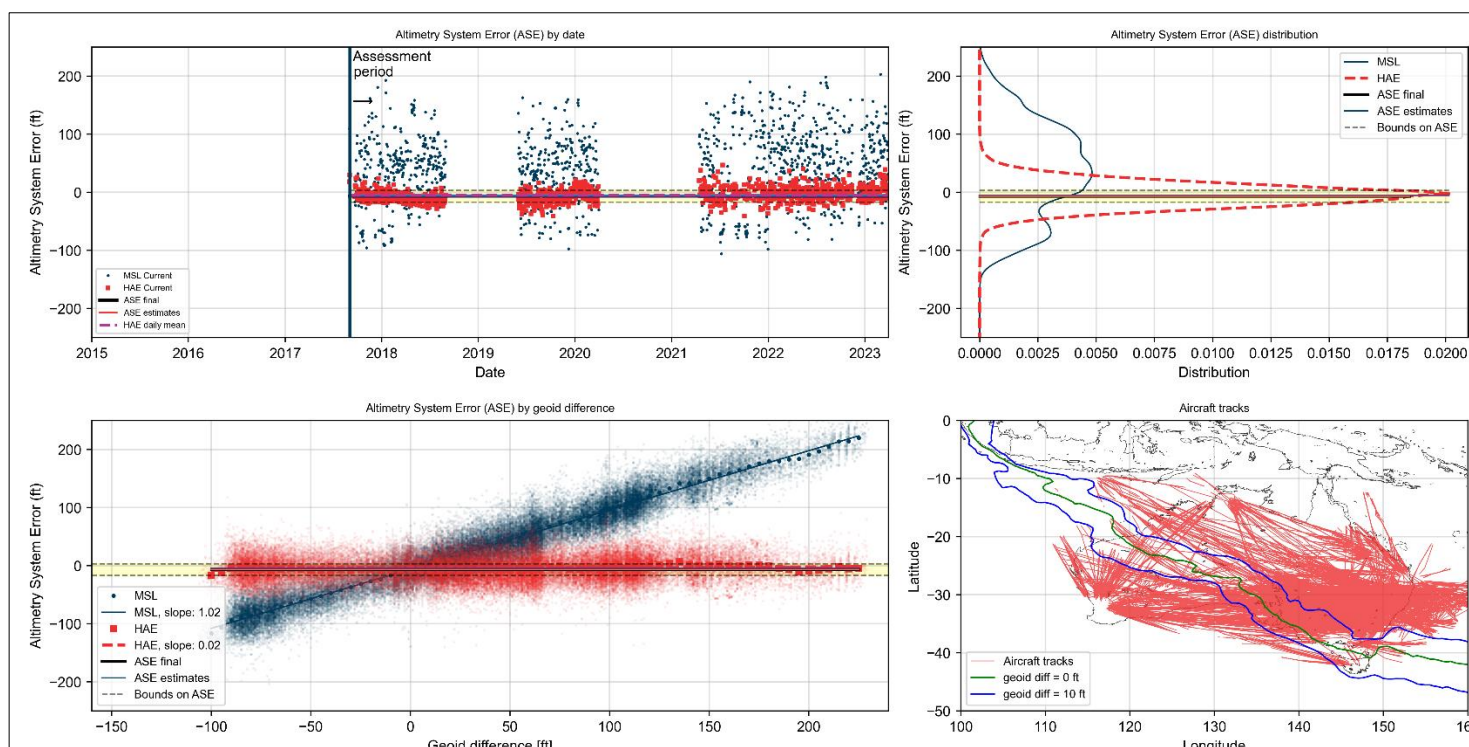


Figure 10: Example of a B738 aircraft with 1205 days and 295, 103 data points (of 1-minute each).

3. RESULTS – VARIATION OVER DATE

3.1 The variation over time for each 10 x 10 degree grid is different. This section explores the variation in normalised ASE over 7 years, with values calculated each day and then smoothed.

3.2 **Figure 11** shows the results per day for grid (-40, 140) with a bias from + 7ft to -23 ft and a mean bias of -7 ft.

3.3 **Figure 12** the results per day for grid (-30, 140) with a bias from + 12 ft to -19 ft and a mean bias of -2 ft.

3.4 **Figure 13** the results per day for grid (-20, 140) with a bias from + 17 ft to -15 ft and a mean bias of 2 ft.

3.5 **Figure 14** shows bias per day for the 7 years for all the relevant grids. This indicates similar trends and behaviour, without any obvious predictability.

3.6 **Figure 15** is similar to **Figure 14** but restricted to longitude 140 degrees showing predictable trend with latitude

3.7 **Figure 16** and **Figure 17** are similar to **Figure 14** but restricted to latitude -30 and -40 degrees respectively, showing more correlation with longitude variation, but still not predictable.

3.8 **Figure 18** and **Figure 19** show variation with date with results shown with flight level bands. This indicates no significant difference between flight levels.

3.9 **Figure 20** is a map of the region showing the how much the normalised ASE changed over time in different regions. This indicates more instability in estimated ASE for regions in the North West.

3.10 **Figure 21** is a map of the region showing the mean ASE over the 7-year period for each grid. This indicates a bias of -7 ft in the South East, progressing to + 11 ft in the North West.

3.11 These results indicate that a the AHMS process can have a measurable bias over date, with this bias being of order ± 20 ft depending on location. There is no significant bias with flight level.

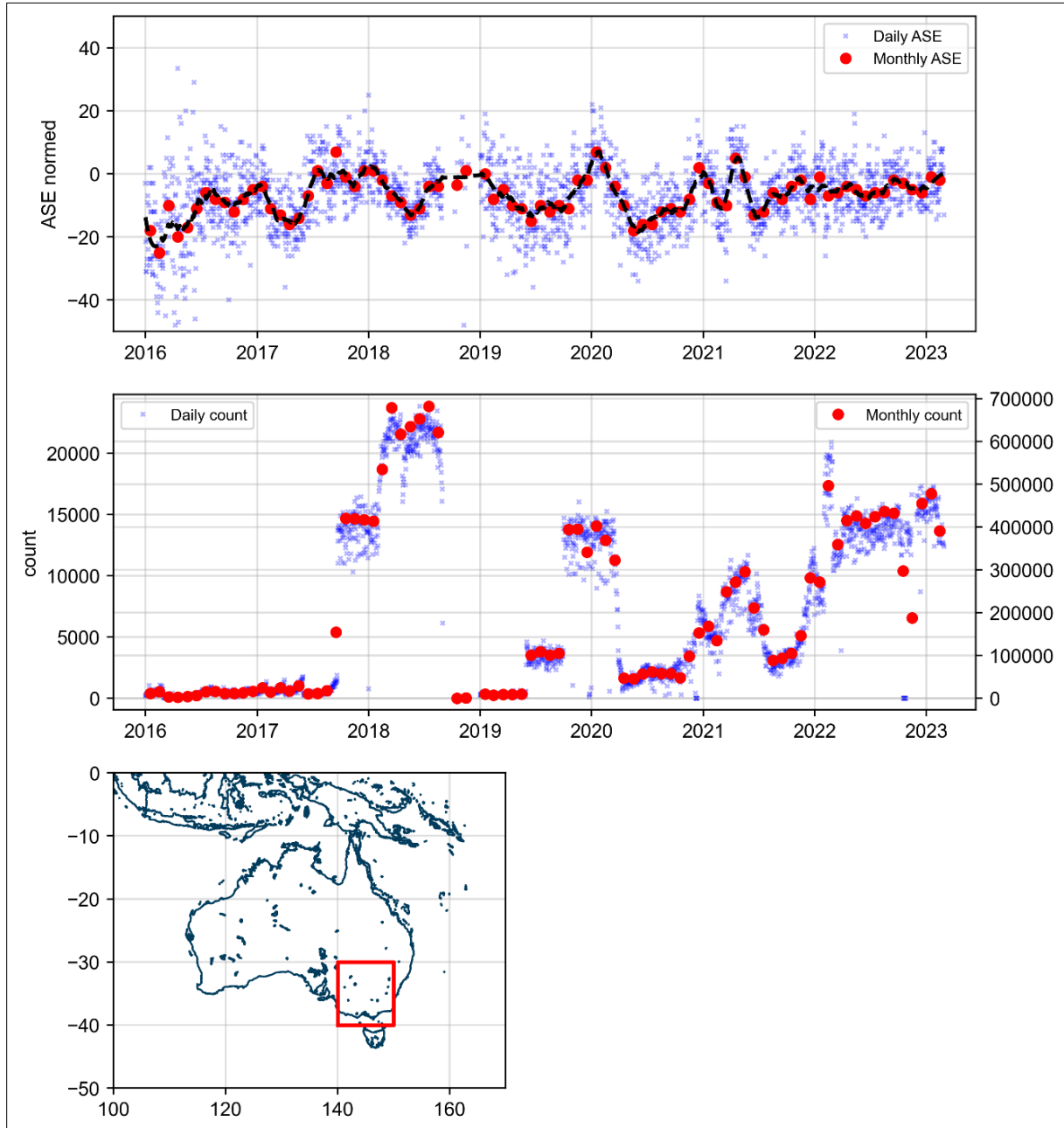


Figure 11: Results over time for grid (-40, 140). Blue dots are daily averages, red dots are monthly averages and the black solid line is the smoothed value, indicating the underlying bias in the results. Additional variation in daily results are where data samples were smaller.

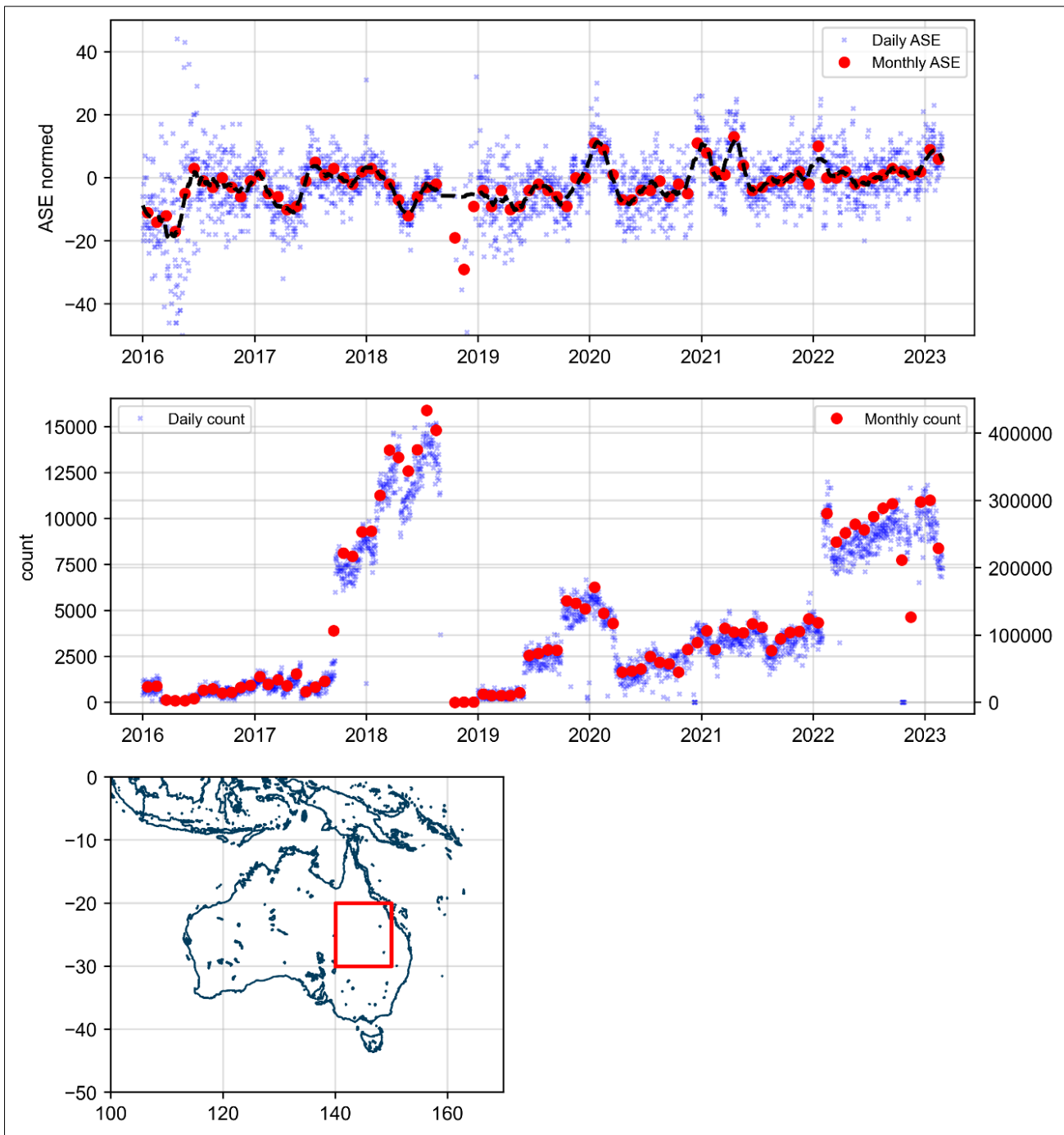


Figure 12: Results over time for grid (-30, 140). Blue dots are daily averages, red dots are monthly averages and the black solid line is the smoothed value, indicating the underlying bias in the results. Additional variation in daily results are where data samples were smaller.

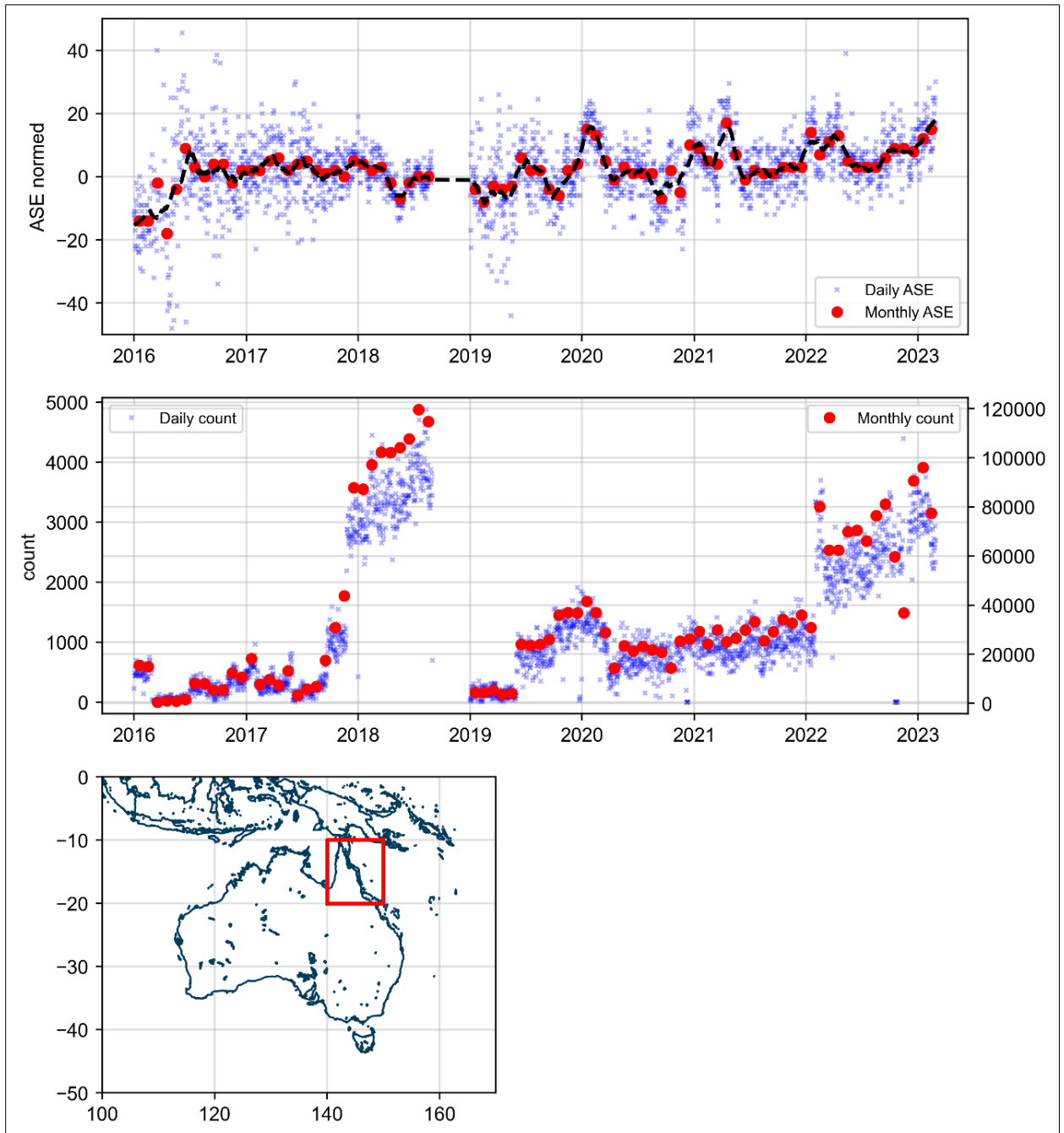


Figure 13: Results over time for grid $(-20, 140)$. Blue dots are daily averages, red dots are monthly averages and the black solid line is the smoothed value, indicating the underlying bias in the results. Additional variation in daily results are where data samples were smaller.

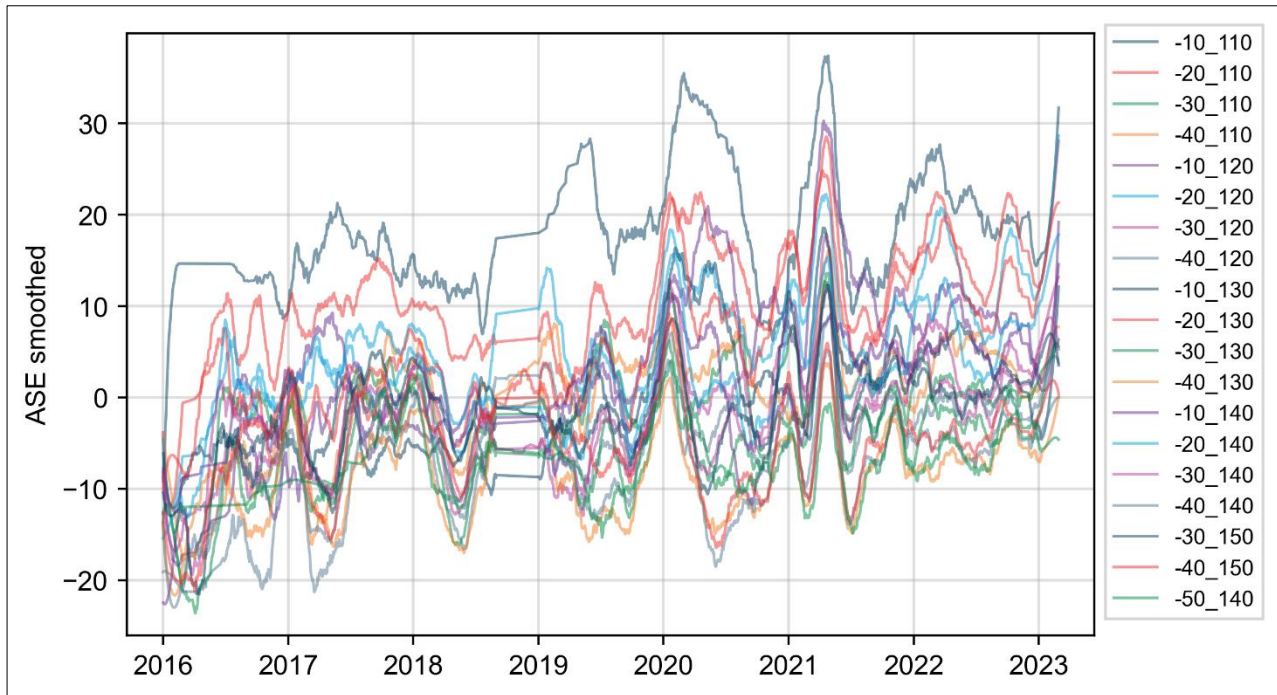


Figure 14: Variation in ASE over time for latitude-longitude grid; for example '-10_100' is for the region latitude in [-10, 0) and longitude in [110, 120). Note that there is some correlation between regions, but also no obvious trend.

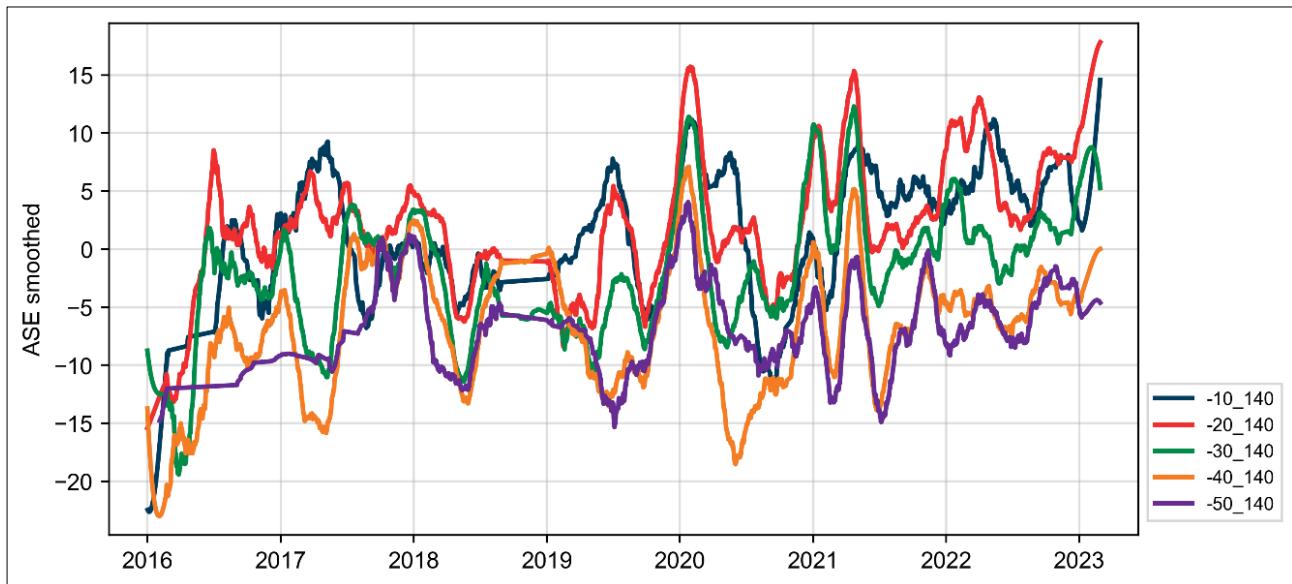


Figure 15: Variation in ASE over time for latitudes (-10,0), (-20,-10), ... (-50, -40) with longitude in (140, 150). This is a subset of the previous figure to focus on increasing latitude. Note that there is some correlation between regions, but also no obvious trend.

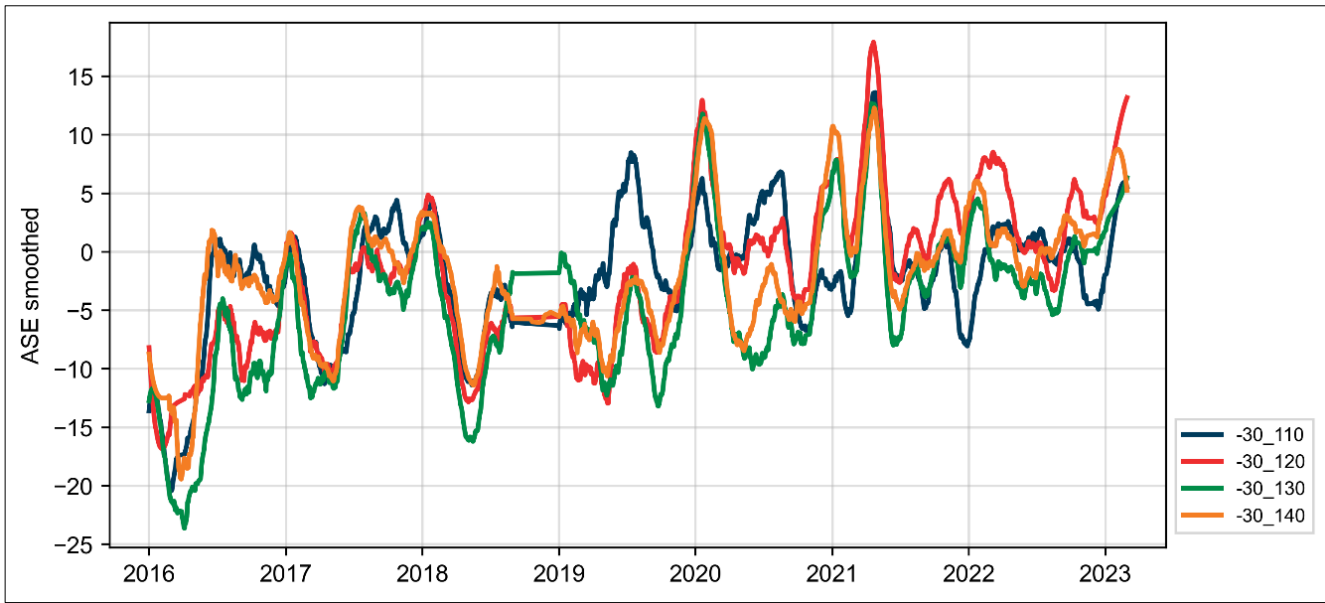


Figure 16: Variation in ASE over time for longitudes with latitude in (-30, -20). This is a subset of Figure 14 to focus on increasing longitude. Note that there is some correlation between regions and more correlation than with latitude.

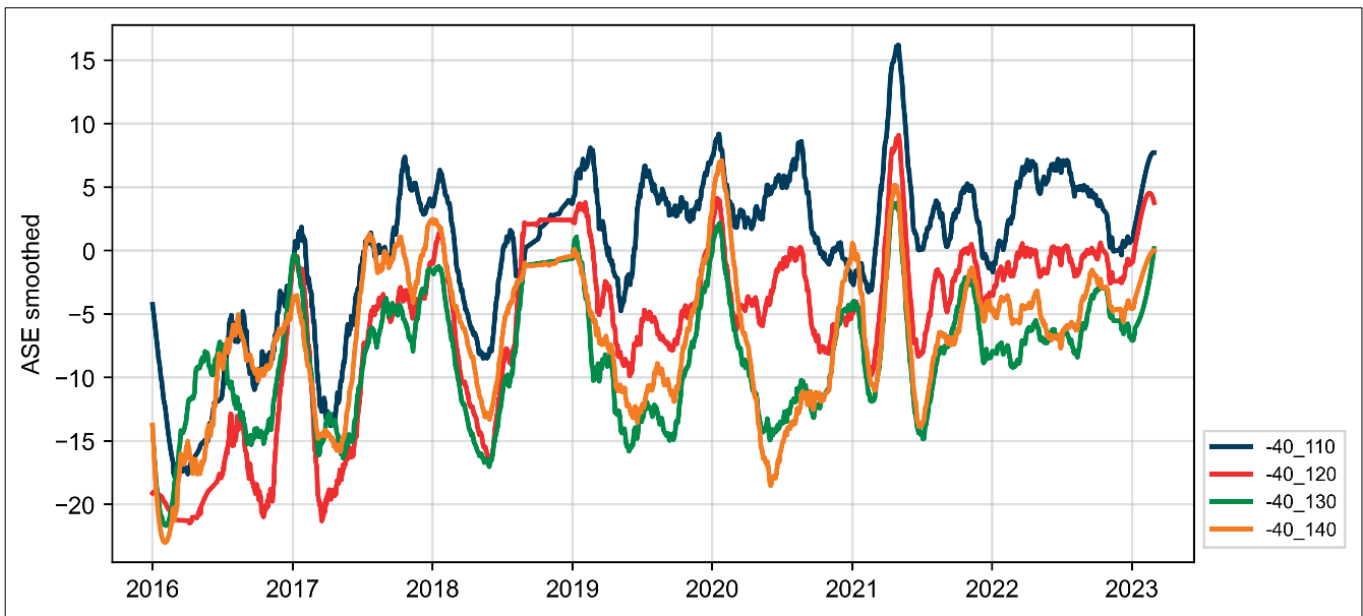


Figure 17: Variation in ASE over time for longitudes with latitude in (-40, -30). This is a subset of Figure 14 to focus on increasing longitude. Note that there is some correlation between regions and more correlation than with latitude.

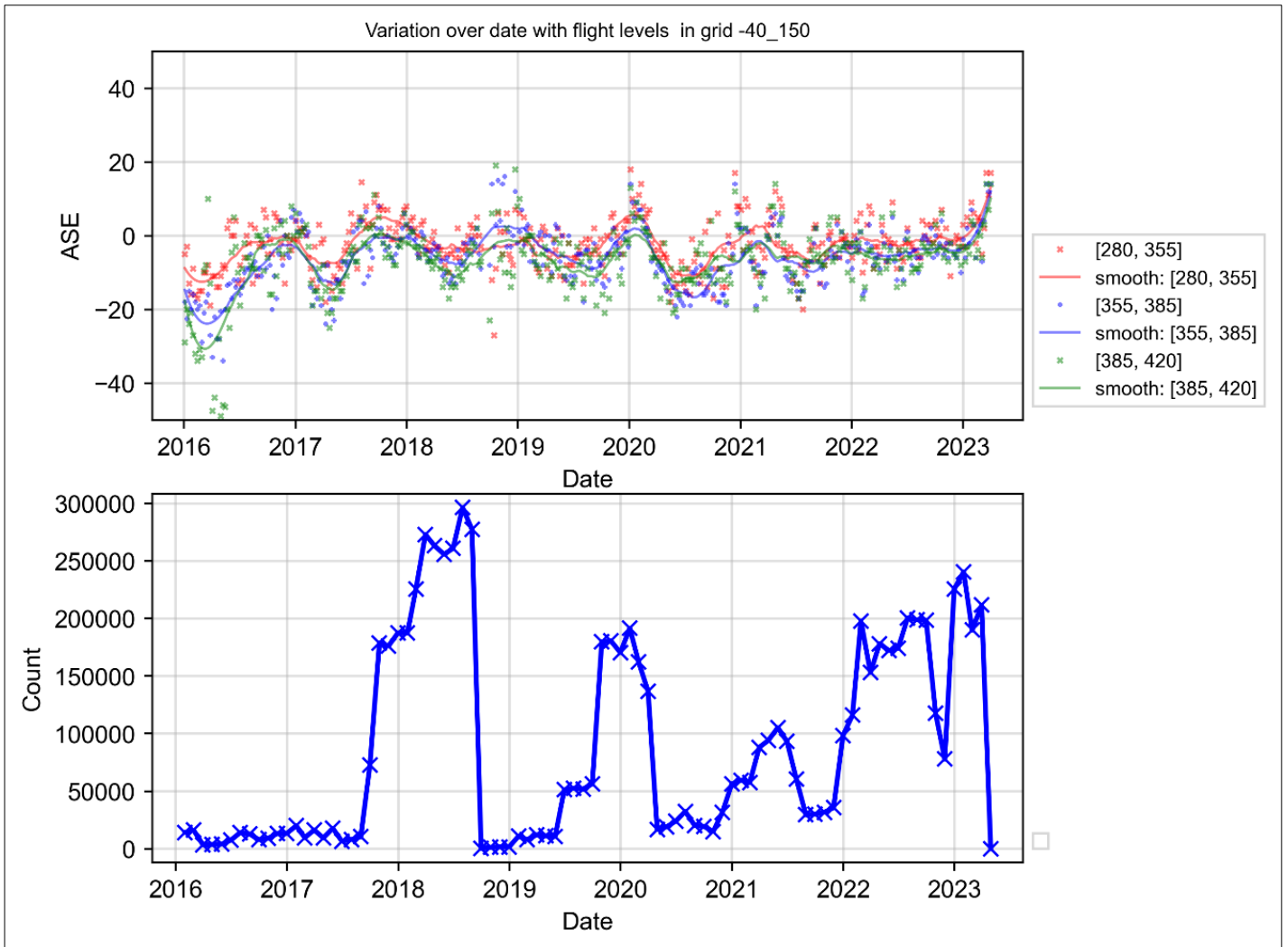


Figure 18: Variation in ASE by date, with different flight level bands shown. Here grid (-40, 150) is shown. The flight levels gives similar results with some small difference when where less data is available causing statistical variation swamping underlying trends.

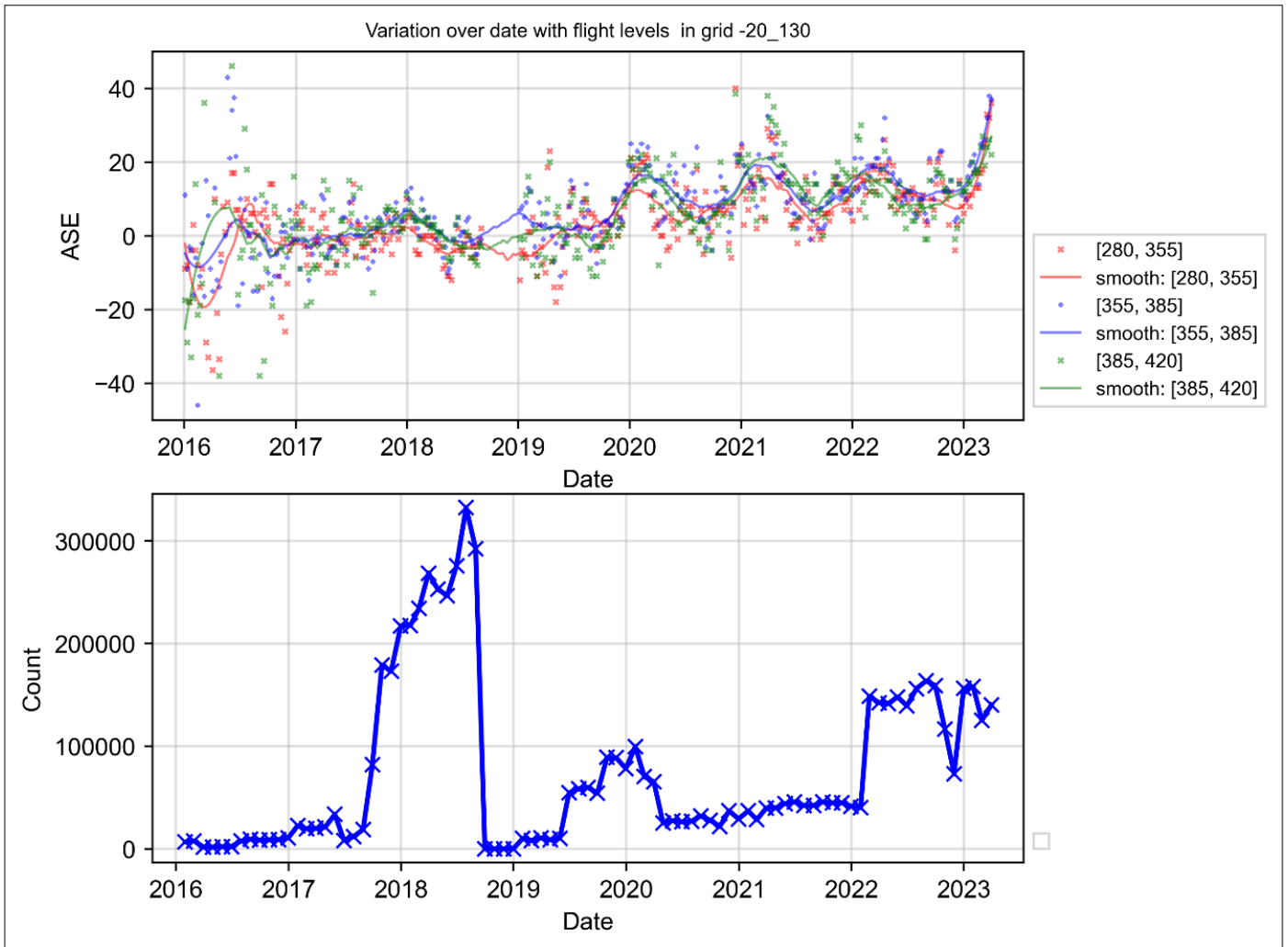


Figure 19: Variation in ASE by date, with different flight level bands shown. Here grid (-20, 130) is shown. The flight levels gives similar results with some small difference when where less data is available causing statistical variation swamping underlying trends.

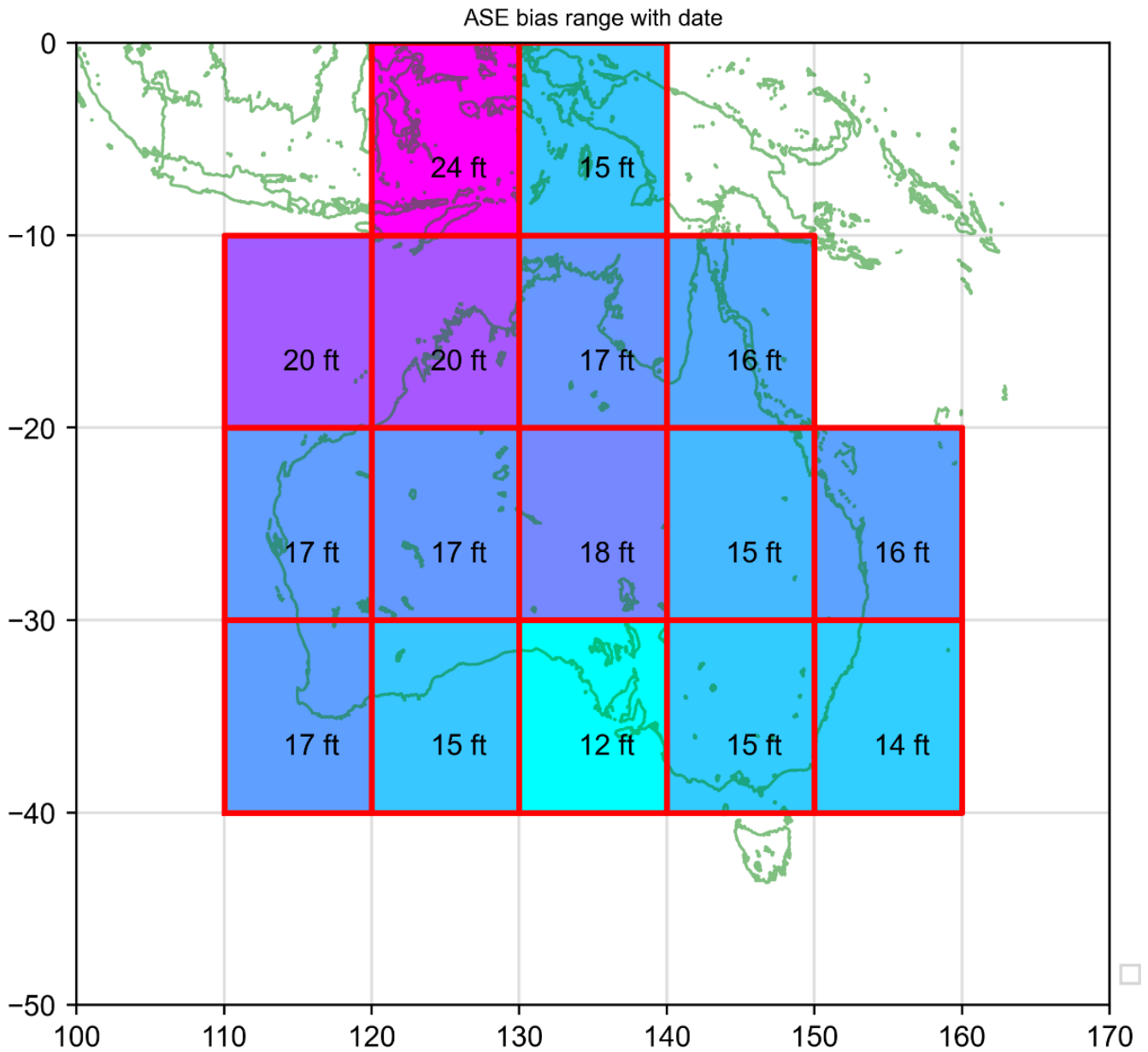


Figure 20: Variation in ASE over date for a 7-year period. This indicates the highest variation was nearer the equator with approximately a +/- 24 ft difference over time.

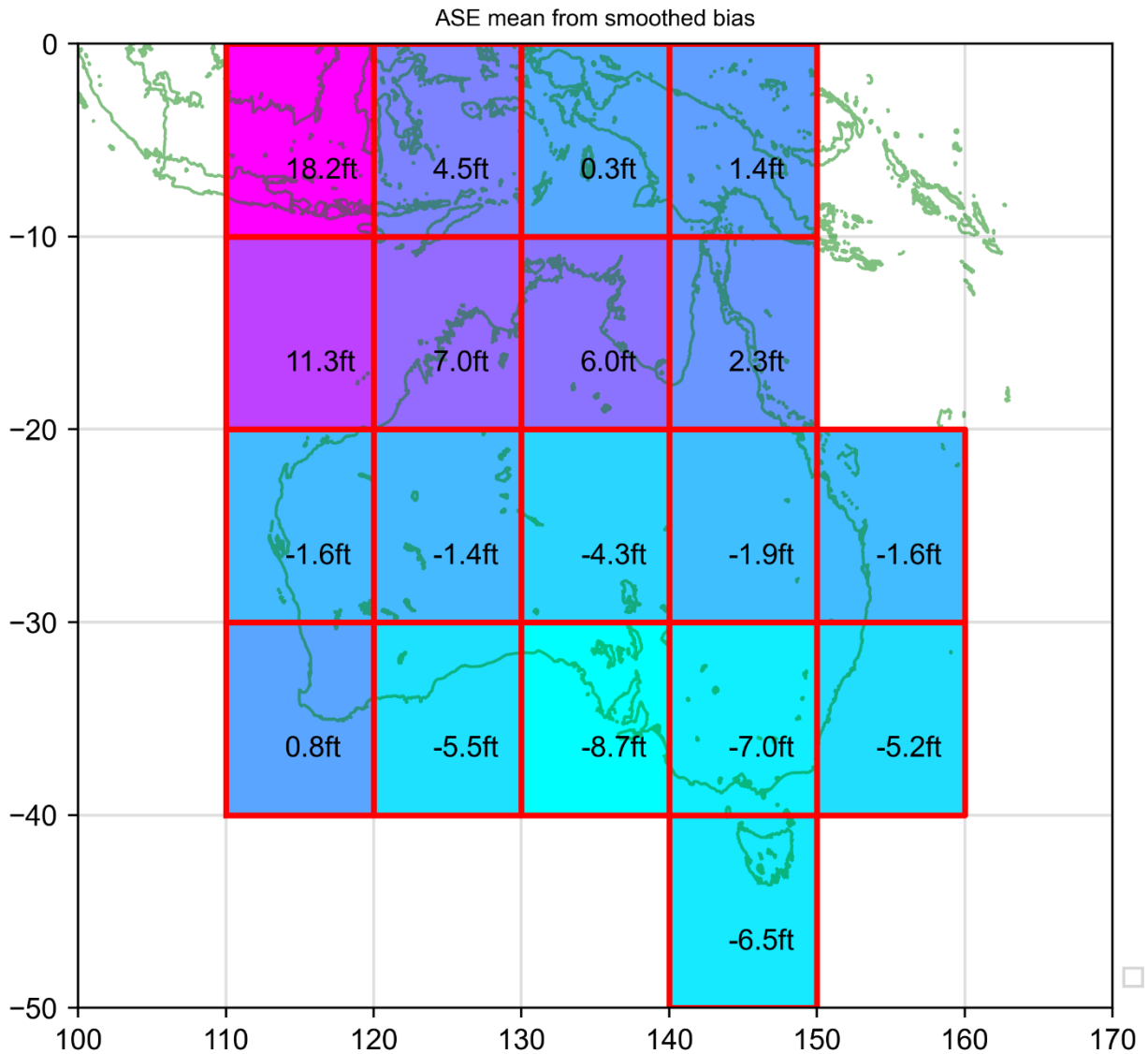


Figure 21: ASE mean bias in each grid over the 7-years. The top left grids may be impacted by insufficient data.

4. RESULTS – VARIATION OVER TIME OF DAY

4.1 This section considers the variation with time of day. For each 10 x 10 degree grid, the ASE values are corrected for date as with the previous section.

4.2 **Figure 22 to Figure 24** illustrate the variation over time of day for three different regions. Each region has an obvious diurnal variation of order ± 30 foot variation, with magnitude varying by location. Unfortunately the variation is not a simple sine or trigonometric cycle, requiring a more complex parameter fit. In this work, we did not attempt to fit any functional form, but relied on a simple bias per each distinct hour of the day.

4.3 **Figure 25** shows variation over time of day with plots for different 3-month periods. This indicates no significant bias with month.

4.4 **Figure 26** and **Figure 27** shows variation over time of day with plots for different flight level bands. This indicates no significant bias with flight level.

4.5 **Figure 28** is a map showing the range of diurnal variation for the different geographical regions, with variation of order 10 ft in the South East and of order 25 ft in the North West.

4.6 **Figure 29** shows the diurnal variation for all grids, showing less variation around hours 0, 6, 11 and 18 in line with NOAA data. While the behaviours share common features, it is not possible to find a simple formula for the diurnal variation and its relationship with latitude and longitude.

4.7 These results indicate that a time-of-day bias is consistent and hence can be corrected for via a value for each discrete hour of day.

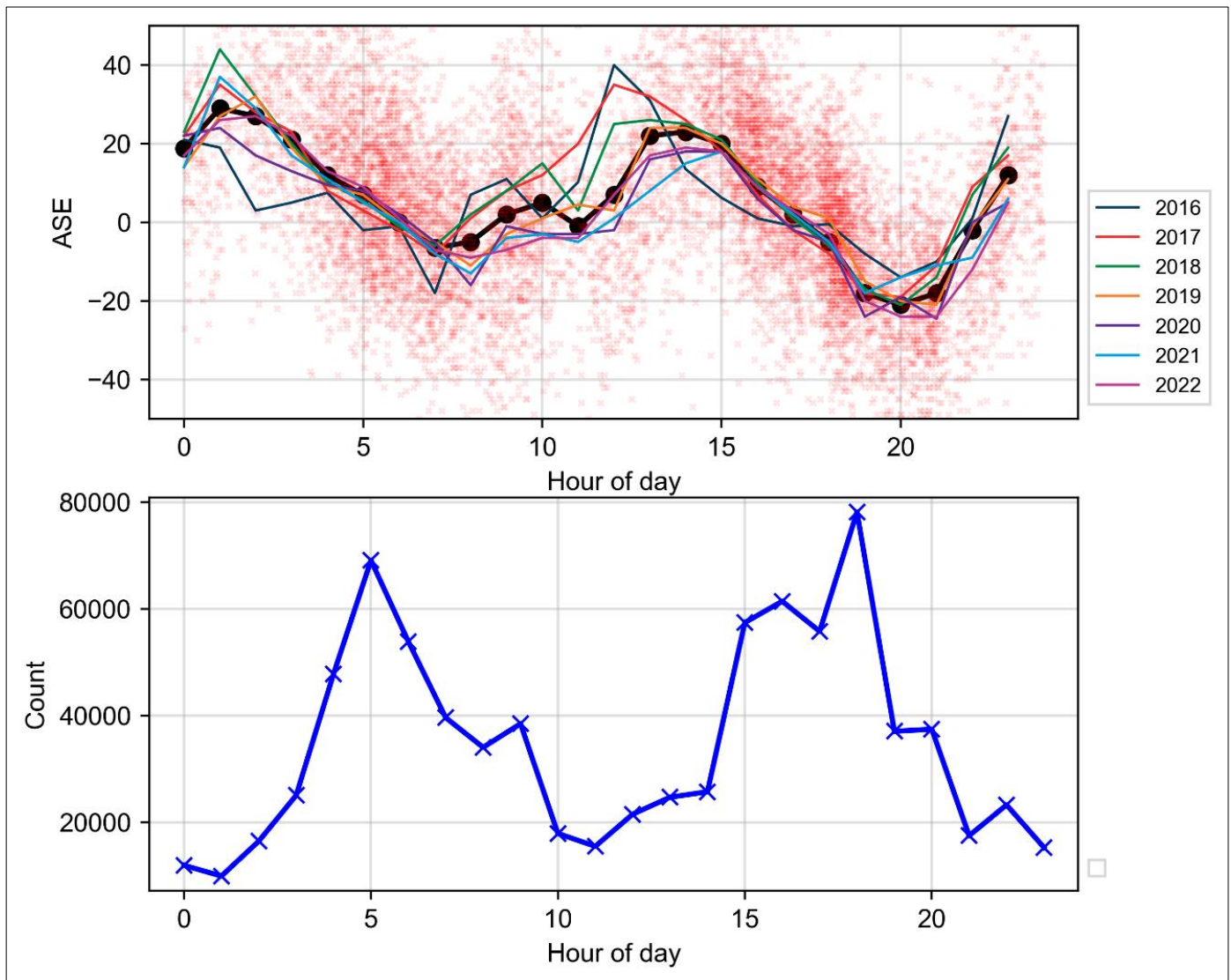


Figure 22: Hourly variation for latitude [-10, 0) degrees and longitude [120, 130) degrees. The solid blackline and circles is overall variation. Obviously, during periods of low traffic counts, the bias may be less reliable, however, here it appears that even in these periods the results are consistent.

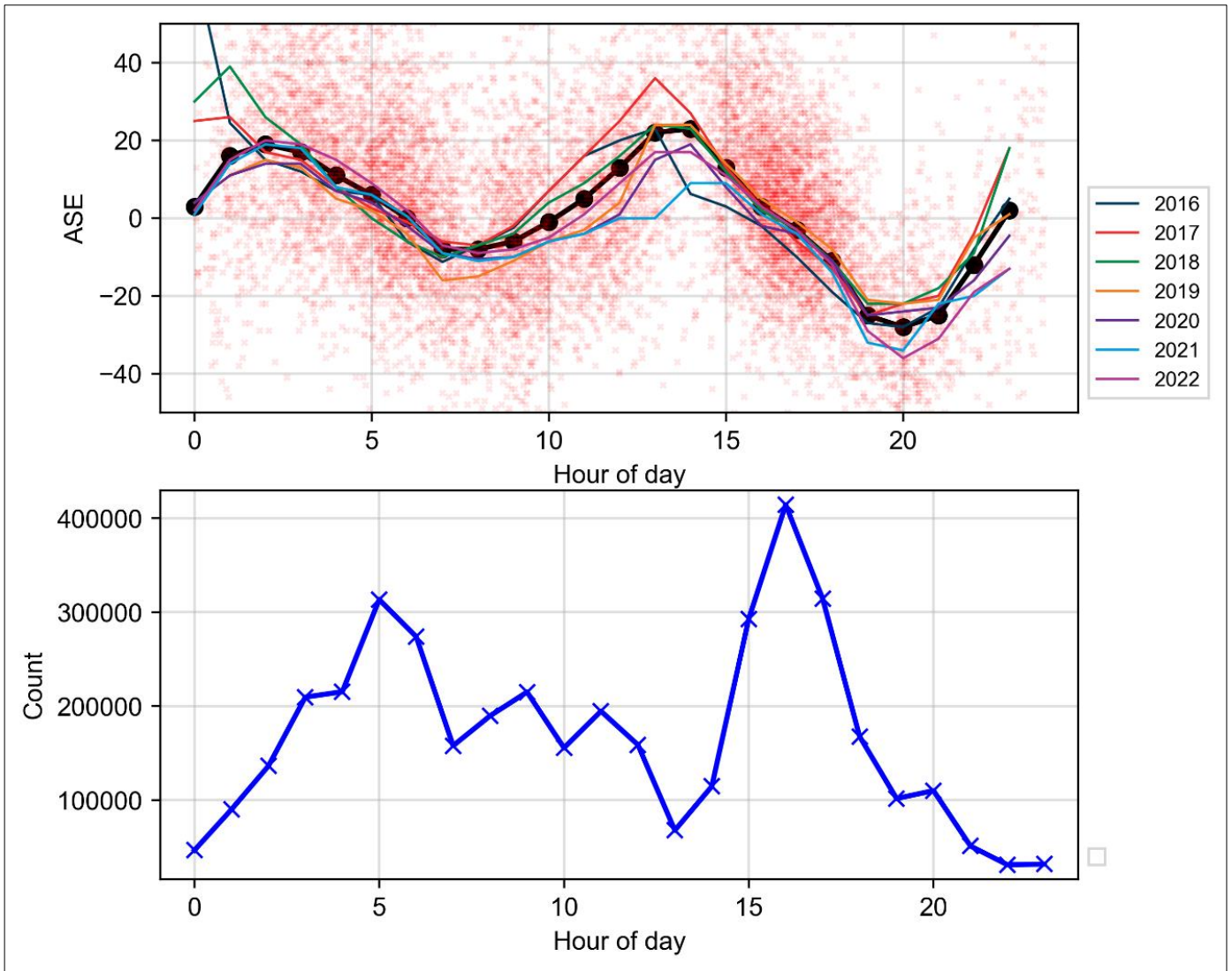


Figure 23: Hourly variation for latitude $[-20,-10)$ degrees and longitude $[120, 130)$ degrees. The solid blackline and circles is overall variation.

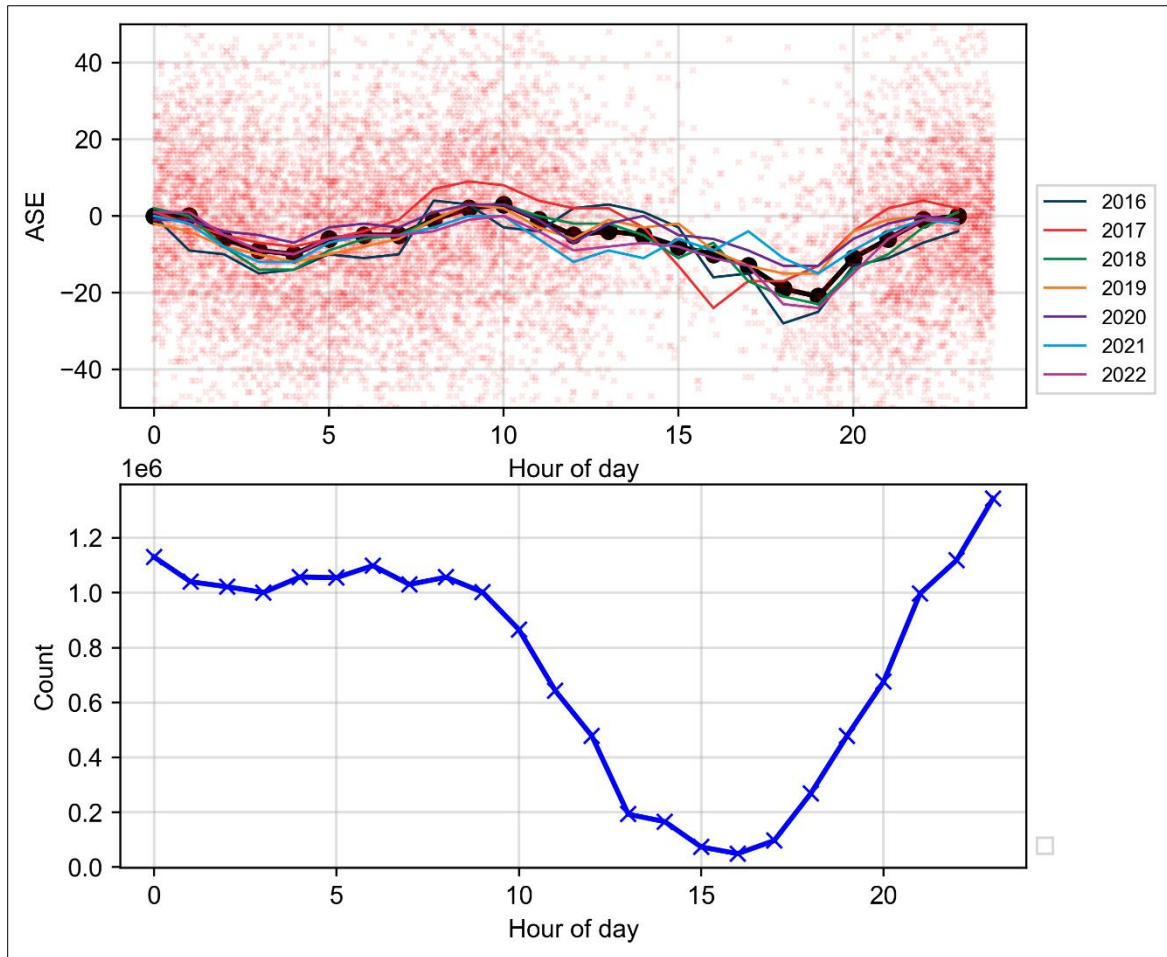


Figure 24: Hourly variation for latitude $[-40,-30)$ degrees and longitude $[140, 150)$ degrees. The solid blackline and circles is overall variation.

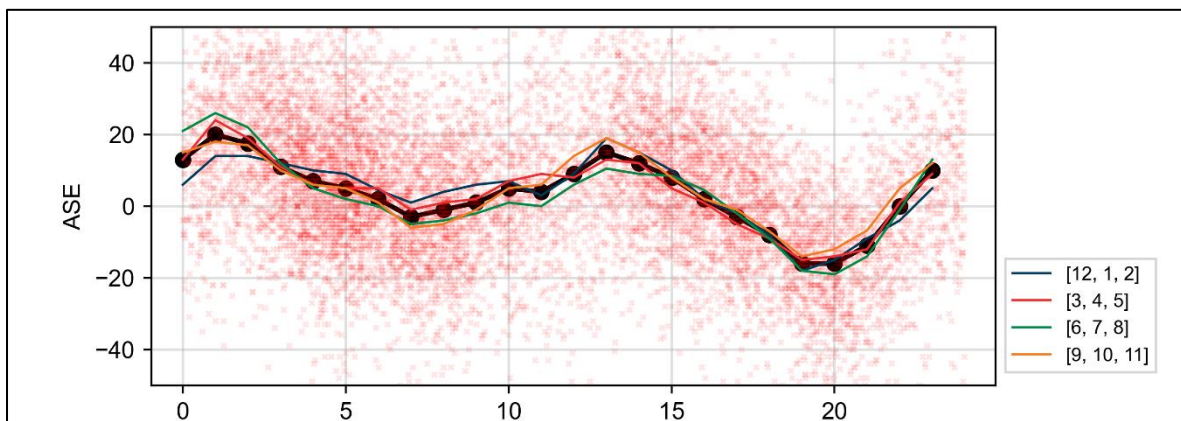


Figure 25: Variation of ASE with time of day for grid (lat=-20,lon=130). The solid black line and dots are overall results and the other lines indicate data split into 3-month periods.

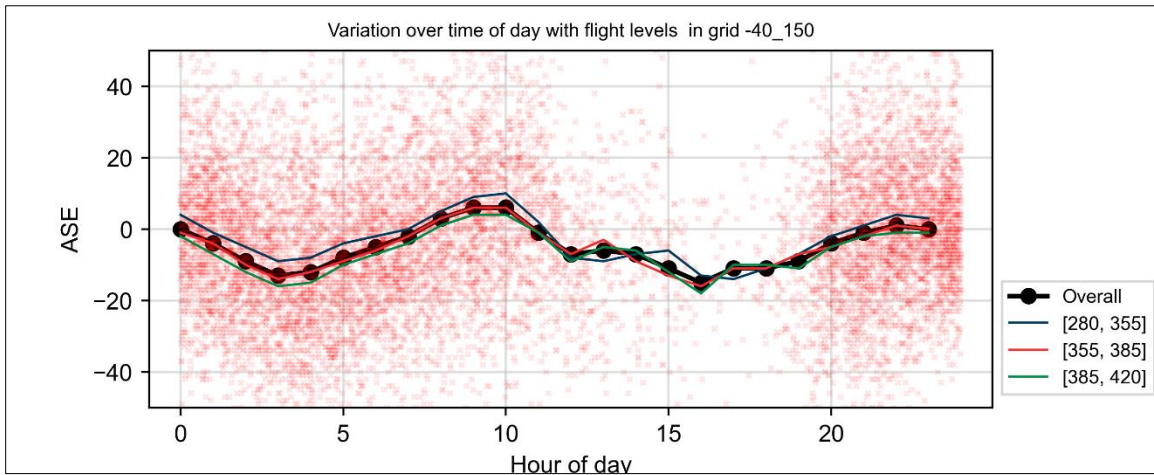


Figure 26: Variation of ASE with time of day for grid (lat=-40,lon=150). The solid black line and dots are overall results and the other lines indicate data split into three flight level bands (FL 290 to 355, FL 355 to 385, and Fl 385 to 420).

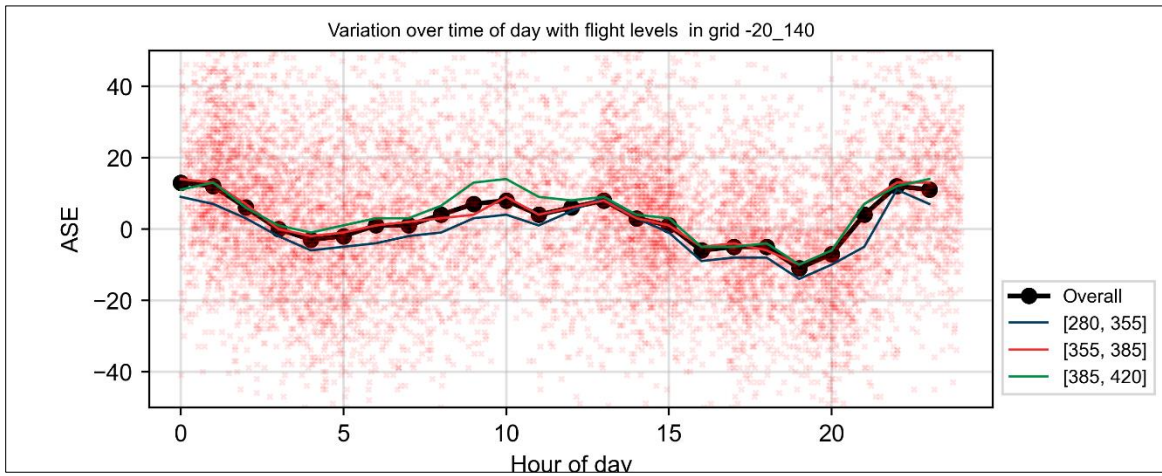


Figure 27: Variation of ASE with time of day for grid (lat=-20,lon=140). The solid black line and dots are overall results and the other lines indicate data split into three flight level bands (FL 290 to 355, FL 355 to 385, and Fl 385 to 420).

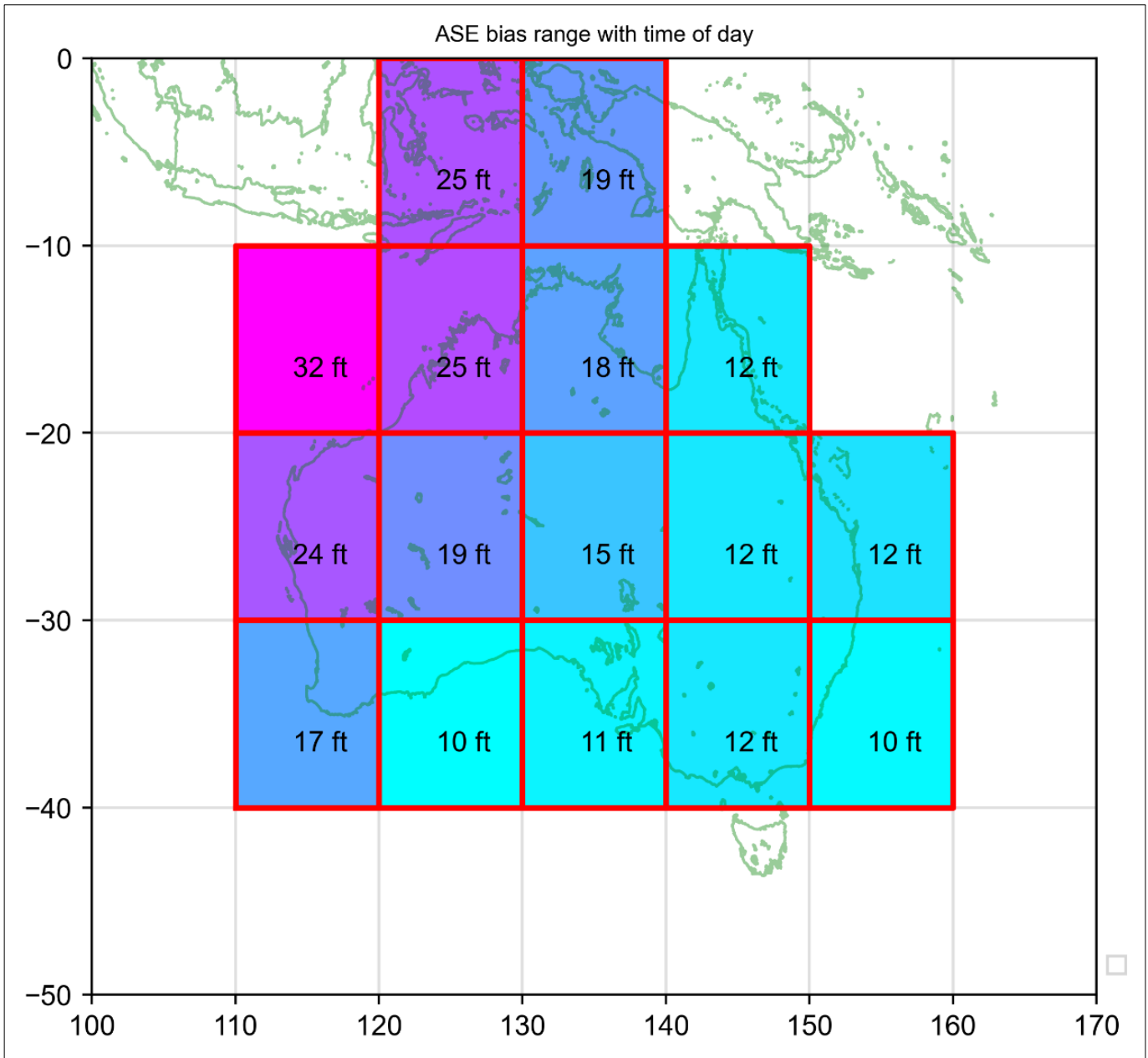


Figure 28: ASE variation by time of day indicating a +/- variation of order 32 ft over a day nearer the equator.

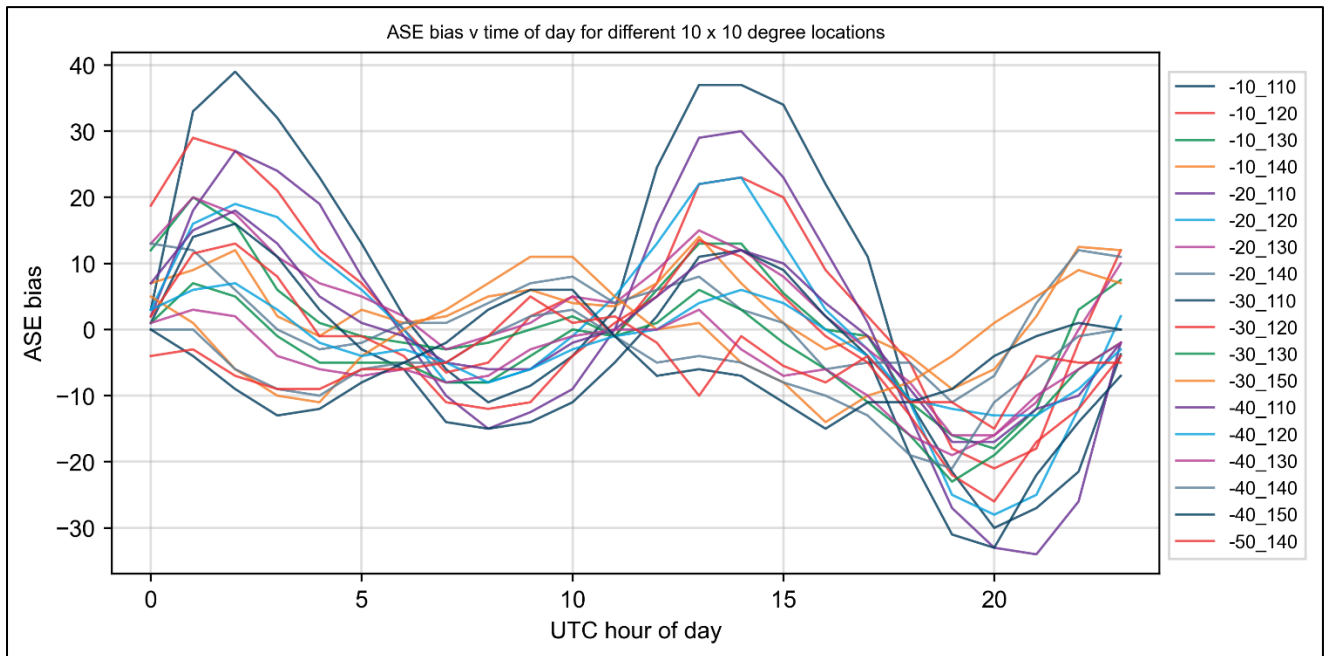


Figure 29: Variation over time of day for different geographic grids (i.e. -10_110 corresponds to the grid with latitude in [-10, 0) and longitude in [110, 0)). Results are more consistent near hours 0, 6, 11 and 18 corresponding to NOAA data predictions.

Using correction to change results

4.8 It is interesting to see how correcting the ASE data for time of day and date affects individual assessments of ASE.

4.9 The following figures illustrate ASE behaviour before and after correction. It must be emphasised that this correction is based on the average behaviour of many hundreds of aircraft over a long-period and hence we are not correcting this aircraft with itself.

4.10 In each case, the ASE values become more consistent.

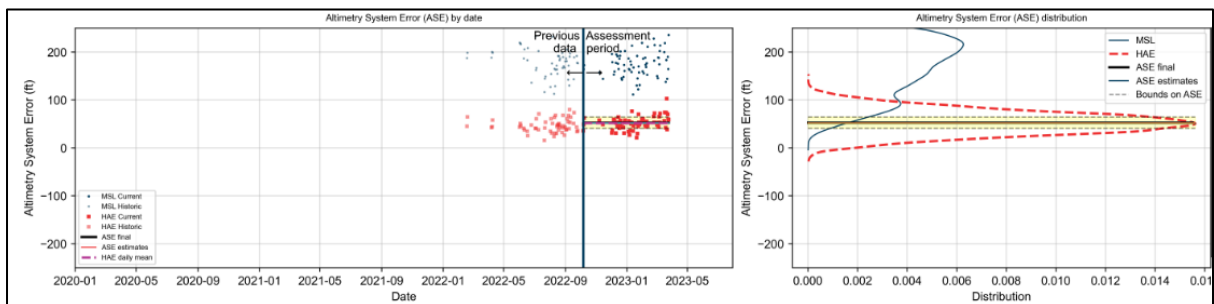


Figure 30: ASE data for an A330, prior to correction with ASE estimate of 52 ft

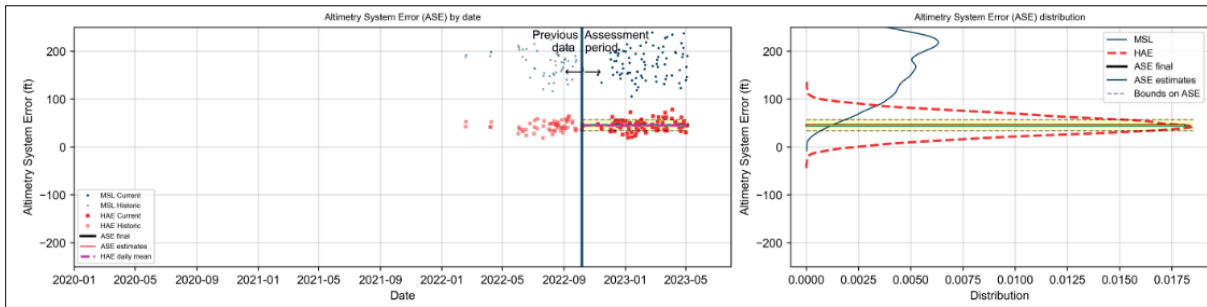


Figure 31: ASE data for the same A330 as the previous figure, after correction with slightly more data and an ASE estimate of 45 ft. The variation for each day are slightly more consistent.

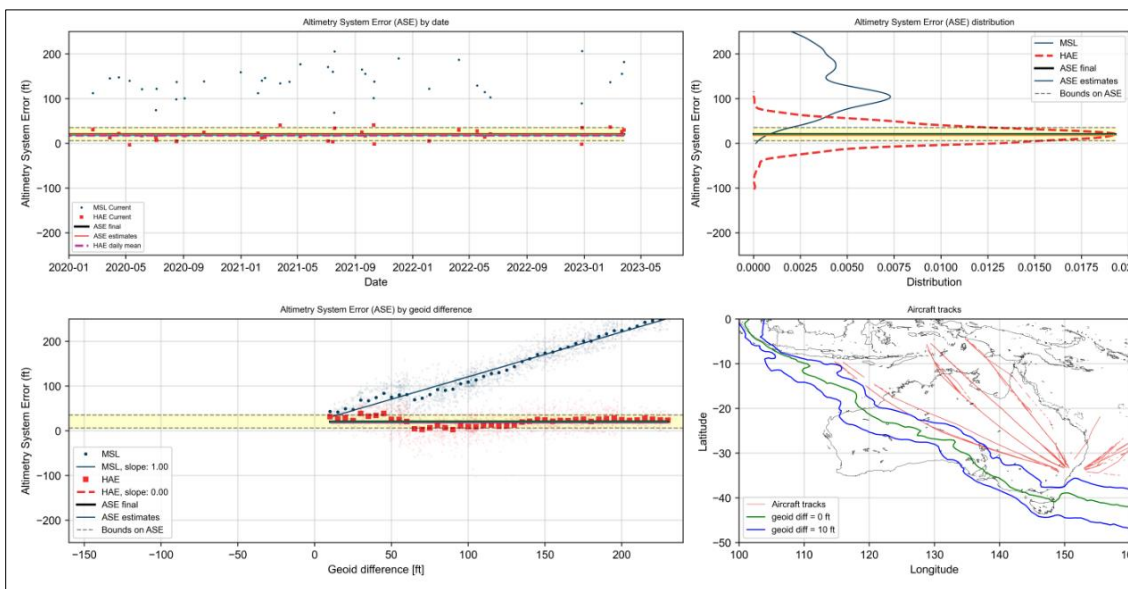


Figure 32: ASE data for a B772 prior to correction with ASE estimate of 19 ft

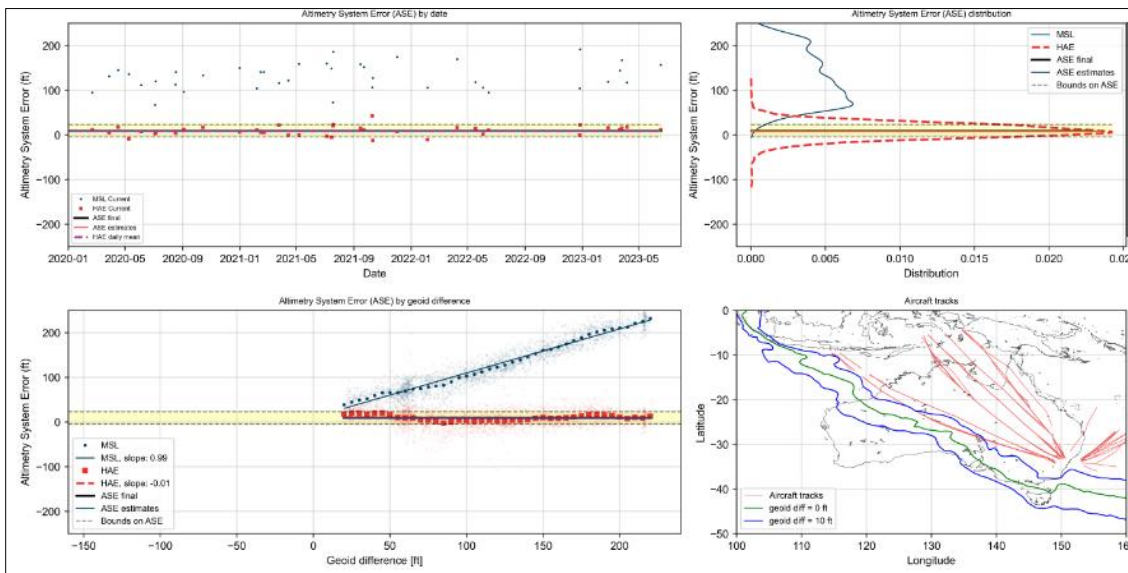


Figure 33: ASE data for the same B772 after correction with ASE estimate of 8 ft. Note

the more even and consistent values against geoid difference in the bottom left plot.

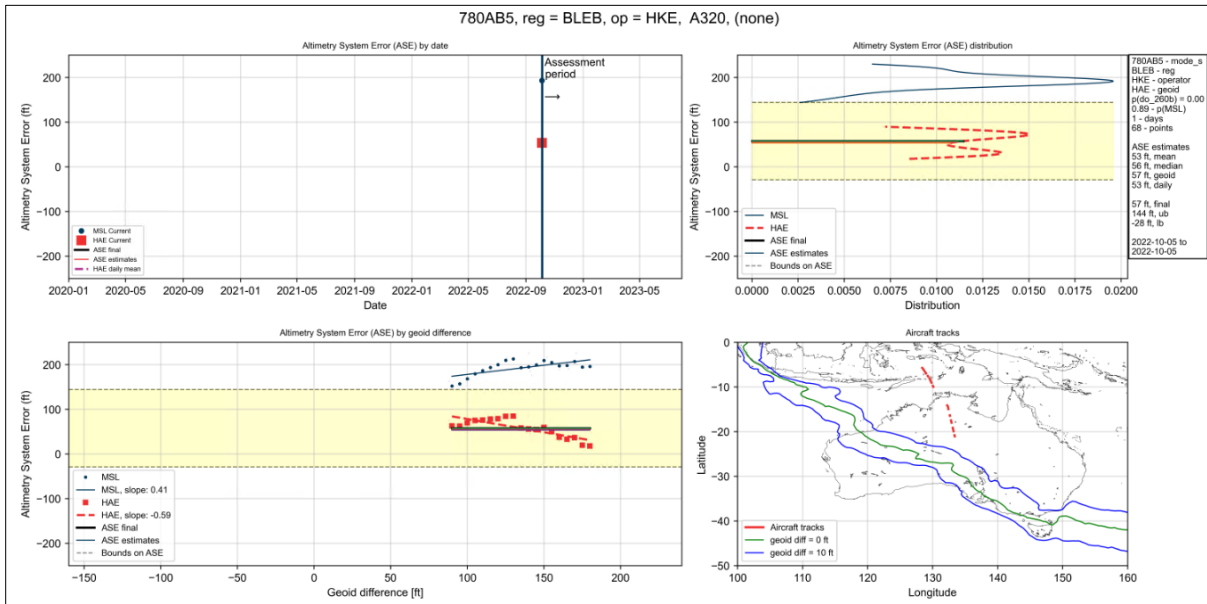


Figure 34: ASE data for an A320 with limited data (1 day, 69 minutes) prior to correction. Here the estimate is 57 ft and the evaluation of which geoid reference is unclear.

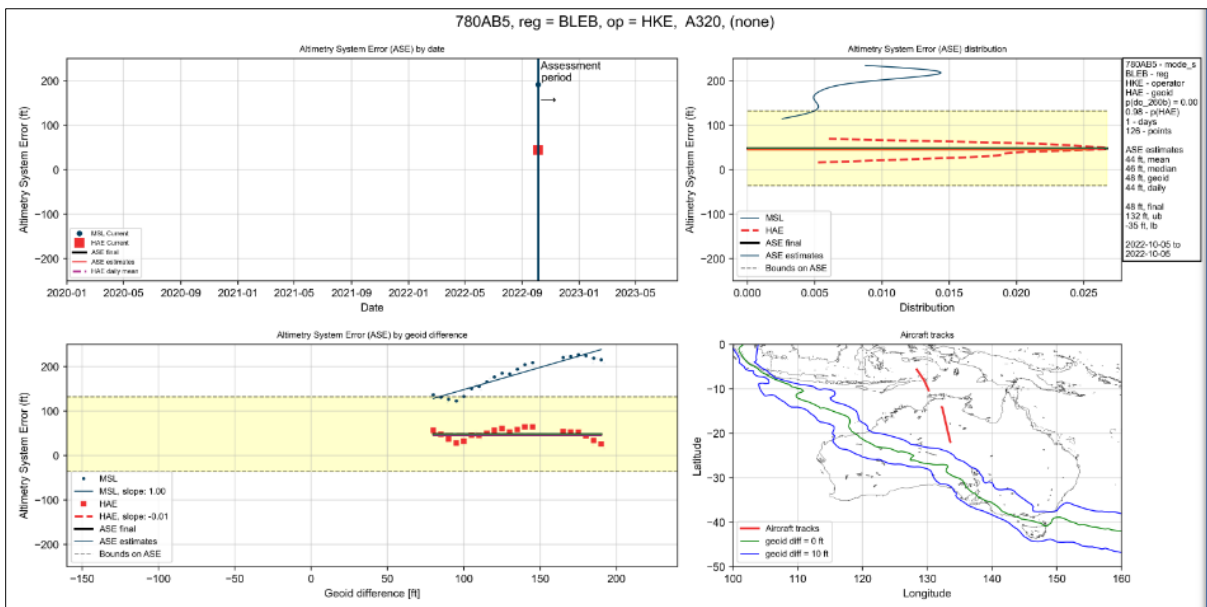


Figure 35: ASE data for the same A320 with limited data (1 day, 69 minutes) after correction. Here the estimate is 44 ft and the evaluation of which geoid reference is clear and the ASE versus geoid different is much more consistent (bottom left plot), and the ASE distribution more Gaussian (top right plot)

5. DISCUSSION

5.1 These results appear to indicate consistent variation and trends.

5.2 There is a variation over date of approximately ± 20 ft over a 7-year period ; this variation is somewhat random and depends on location with a gradual increase of ~ 15 ft over the 7 years;

5.3 The FAA have developed a new AHMS code which may correct some of these bias. Additionally, the AAMA will hopefully explore use of GRIB 2 Australian data which has a finer resolutions. These may dampen some of this bias and will be the subject of further work.

5.4 There is daily variation, over hour of day, roughly sinusoidally with a +20 ft to -30 ft variation. This variation changes with location and in some cases by month of the year, but not significantly over different years. As expected, the ASE bias is less around UTC hours 0, 6, 11 and 18. Within the Australian region, the least variation was between hours 6 and 12, with large variations around hours 2, 13-14, and 20.

5.5 There is little variation with flight level within the range FL 290 to FL 410.

5.6 In the Australian region, the ASE variation over the 7-years period and over a day were larger in the North-West direction, having roughly double the variation as in the South-East regions.

5.7 These biases in ASE by date, time and location are most likely due to the predictability of pressure altitude with geometric altitude in the meteorological models. Given the large and wide variation in aircraft used in the data, it is unlikely this variation is due to any aircraft-dependent variable.

5.8 Naturally, where an aircraft has data over several hours, days and geographic regions, any bias will be averaged out to zero.

5.9 When an aircraft appears either for only a short time, or in a small geographical region, or a consistent time of day (typical for international arrivals and departures), there may a possibility of the bias affecting an ASE calculation.

5.10 This bias may be as high as 70 ft in an extreme case of a flight at a time of day, at a location and date where the different affects coincide to reinforce the bias. This level of bias is relevant when considering uncertainty in ASE estimations for aircraft with limited data.

5.11 For aircraft with limited data, identification of bias and the level of uncertainty allows more data-driven decision making as to whether additional monitoring is required for that aircraft.

5.12 For example, an aircraft one hour of data on a single day, in a similar region, may have an ASE estimate of 30 ft. In this case, even with a bias and other uncertainties in ASE estimation, the aircraft would be considered to have an acceptable ASE.

5.13 But, in another example, an aircraft with an ASE estimate of 130 ft, from 1 hour of data in a region with high variability, may not be considered to have an acceptable ASE, given the possibility of bias. If this bias can be corrected, using the statistical relationships demonstrated here, then the ASE may become acceptable.

5.14 Given the non-uniform nature of the ASE bias over date, and the nonlinear variation over time of day and location, it is not feasible to obtain a simple statistical formula for the bias.

5.15 Instead, where sufficient data in a region is available, a simple dictionary look up table can be defined. This would give a correction for the bias.

5.16 **Figure 30 to Figure 32** give the distribution of normalised ASE before and after correction for bias, for three sample grids. In each case the resultant mean was corrected and the standard deviation reduced slightly, with the affect most noticeable for the North West grid.

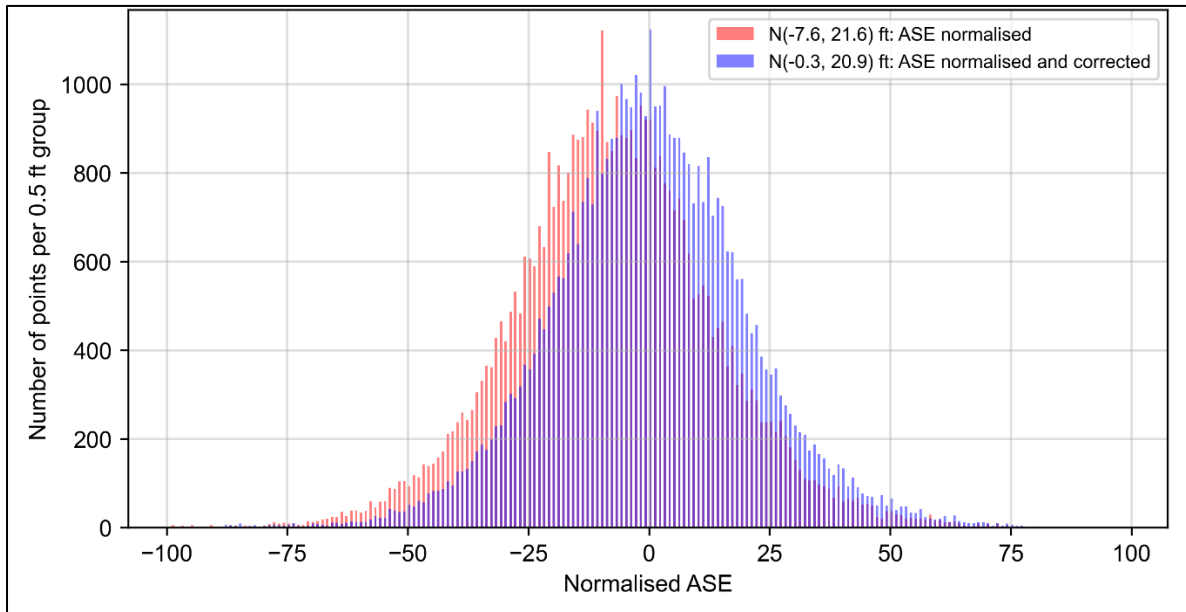


Figure 36: For grid -50, 150 – South East the distribution of normalised ASE (red with mean -7.6 ft and standard deviation 21.6 ft), and after correction for bias (blue with mean -0.3 ft and standard deviation 20.9 ft).

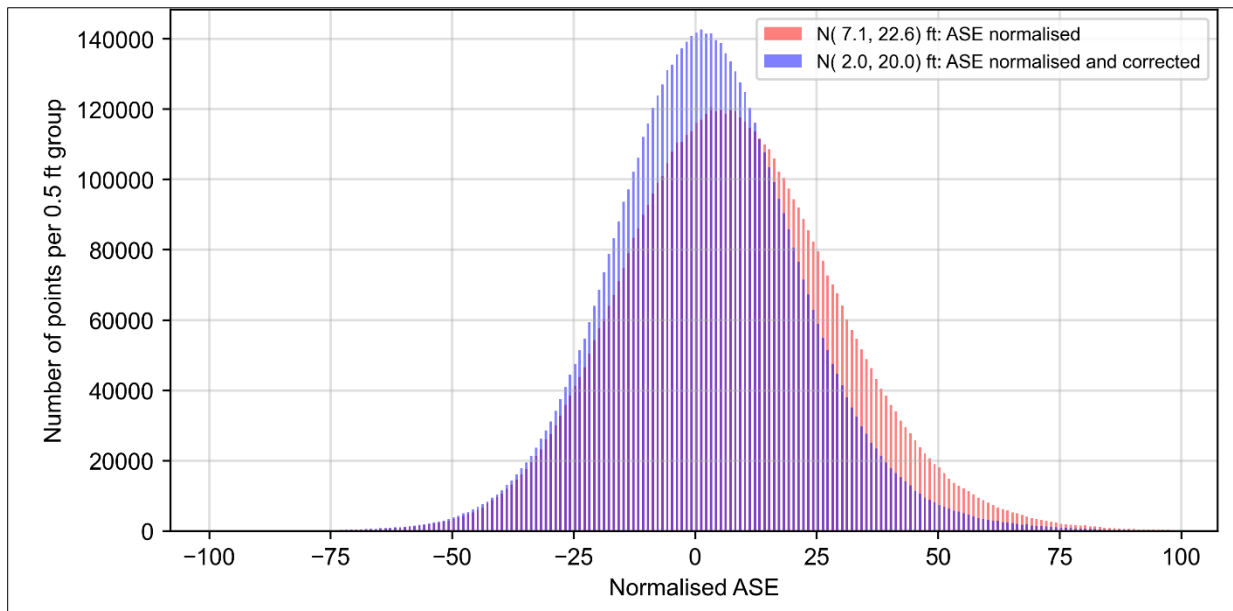


Figure 37: For grid -20, 130 the distribution of normalised ASE (red with mean +7.1 ft and standard deviation 22.6 ft), and after correction for bias (blue with mean +2 ft and standard deviation 20. ft).

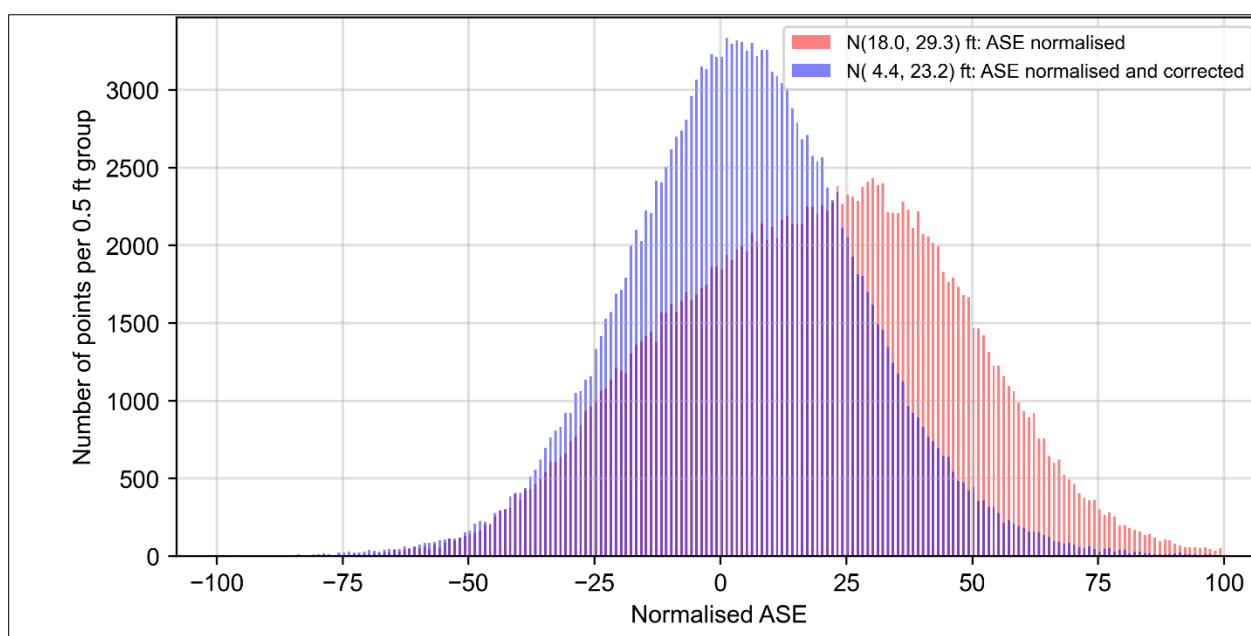


Figure 38: For grid -10, 110 North West, the distribution of normalised ASE (red with mean +18 ft and standard deviation 29.36 ft), and after correction for bias (blue with mean +4.4 ft and standard deviation 23 ft).

6. CONCLUSION

6.1 The AHMS process is an excellent way of determining and aircraft's ASE, with data able to be collected over a wide range of times, dates and geographic regions. This large data capture allows for any bias to be 'averaged out' creating an accurate estimation of ASE.

6.2 The AHMS also allows for aggregation of data for 2525 aircraft with stable ASE and over 93,000,000 separate data points (each a summary of 1-minute). This very large data set, over 7-years, allows for statistical determination of bias in ASE calculations.

6.3 Here we found:

- a) bias over date of order ± 20 ft with more variation in the North West region of Australia.
- b) bias over time of day of order +20 ft to -30 ft which was mostly consistent with date, month, year and flight level ; although with more data it might be possible to determine slight statistical bias with month or flight level.
- c) bias with location of order -7ft (South East) to 18 ft (North West)
- d) no large or significant bias with flight level.

6.4 It is important to note two points :

- a) this bias and ASE variation is due to natural limitations in the meteorological model; and is not due to aircraft ASE changes.
- b) the bias is relatively small and for most aircraft will not affect the final estimation of ASE.

6.5 Accounting for the bias reduced overall standard deviation and corrected for bias in mean values.

6.6 While these results are only applicable to the Australian airspace, the same methodology can be applied to other airspaces using the AHMS process.

6.7 The results may be of use where a given aircraft has only small data samples or data restricted by location or time of day. This may be true for smaller regional operators, or international flights arriving and leaving at the same time of day. The RMAs estimation of ASE for these aircraft may be more accurate by correcting the bias, and additionally given an indication in uncertainty in an ASE calculation. For example, an ASE calculation in the South East of Australia, around UTC hours 0, 6, 11 or 18, may give is a smaller uncertainty in our estimate of ASE and greater confidence that our estimation for that aircraft of correct. However, a small data sample in the North West of Australia, during hours with high uncertainty, may mean that more data is required for that aircraft, particularly if the ASE estimate is large.

6.8 An RMA must make decisions as to whether enough data has been collected from a given aircraft, given the data size, the ASE estimation and the uncertainty in the ASE estimate. For example, an ASE estimate of 145 ft may be ‘acceptable’ for monitoring purposes when the aircraft has a large amount of data from ‘stable’ regions, but may be unacceptable for monitoring where the data has come from a region with high variability and bias – requiring more data from the aircraft.

6.9 Further work will refine the bias estimation to smaller geographic grids (5 x 5 degrees, or 2 x 2 degrees) where sufficient data exists.

6.10 When the AAMA used the correction for observed aircraft, ASE estimates did not change markedly for individual aircraft with most aircraft seeing negligible change some aircraft seeing a 10-20 ft modification which does not affect whether they were acceptably monitored or not. For some aircraft with limited data, the correction clarified the geoid height reference used, enabling the AAMA to determine an ASE value when this could not be determined prior to correction.

7 ACTION BY THE MEETING

7.1 The meeting is invited to:

- a) note the information contained in this paper; and
- b) discuss any relevant matters as appropriate.

References

The following references were considered directly or indirectly in this work

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9. FAA, ASE data introduction seminar,
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