Investigating Arctic Melt Season Onset Trends: Observations vs. Earth System Models

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1. Abstract

Over the years, the Arctic has been warming at a rate above the global average (more than 3 times faster), leading to ecosystem disruptions. A key aspect of these changes is the onset and length of the melt season (or summer), which signals the shift from winter to summer conditions in the Arctic. This spring transition is mostly determined by the dominance of newly formed particles, a process known as new particle formation (NPF), over the larger particles that are present during winter. Inspired by the studies of *Freud et al. (2017)* and *Engvall et al. (2008)*, we investigate if this transition is influenced by the geographic location of Arctic stations (Zeppelin, Nord, Alert, Utqiagvik, Tiksi), and specifically when it approximately occurs. At first some results of the *Freud et al. (2017)* study were replicated to ensure the reproducibility of the data sets that were used. Then, the analysis was focused on the comparison of particles in Aitken and accumulation mode, as done in *Engvall et al. (2008)*, by computing the ratio and the ATIs (Aerosol Transfer Indices) of the particles. The results revealed that, in general, the onset of summer occurs earlier in the southernmost stations, while there is a delay of around 20 days for the northernmost ones. However some deviations from the expected results were revealed for the Tiksi and Utqiagvik stations that were discussed in the end.

2. Introduction

As climate warming progresses, the onset of ice melt occurs earlier each year, affecting multiple processes like the ecosystem's dynamics and the interactions between aerosols and clouds. The Arctic region is warming at an alarming rate, almost 4 times above the global average, highlighting how sensitive this area is to climate perturbations.

The Arctic winter is characterized by a 'haze', a phenomenon dominated by long range transported particles in the accumulation mode of about few hundreds of nm in diameter. Historical reports of dirty snow and hazy skies date back in the 19th century, which later on were attributed to anthropogenic activity. This phenomenon exhibits a strong annual cycle with a maximum in spring and a minimum in summer and is characterised by increased atmospheric turbidity due to high concentrations of accumulation mode aerosols.

In summer instead, new particles in the aitken mode start forming via gas to particle conversion processes the onset of which is highly dependent on precursor gases and the solar radiation availability. Such chemical reactions happen both in spring and summer though, typically initiated by HIO_3 and sulfuric acid respectively.

In addition, large scale oceanic phenomena might affect the variability of Arctic haze and NPF over the years. However, on shorter (daily or weekly) timescales the aerosol properties are mainly governed by the meteorological conditions which may induce deviations from the mean annual patern. To address these challenges continuous, long-term and high-resolution measurements at multiple locations are essential in order to characterise the aerosols in Arctic throughout the year. Yet, there is a lack of studies that examine the aerosol number size distribution across multiple Arctic sites. On top of that, the inability of many models to reproduce the spring transition, highlights the necessity of observational data in order to get more accurate parameters for the models. Hence, this study aims to fill this gap by using hourly mean observations of the aerosol number size distribution from five stations and for different time periods (Zeppelin 2010-2015, Nord 2010-2013, Alert 2011-2013, Utqiagvik 2007-2009 and 2013-2015, Tiksi 2013-2015) in order to approximate the transition day averaged over the years.

3. Method

In the following cells we can see the packages and the data sets (https://doi.pangaea.de/10.1594/PANGAEA.877333) used for this analysis:

In [1]:
```
''' Packages '''

import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import cartopy.crs as ccrs
import csv
import seaborn as sns
import re
import matplotlib.ticker as ticker
from matplotlib.lines import Line2D
from matplotlib.patches import Patch
from matplotlib.font_manager import FontProperties
from mpl_toolkits.axisartist import SubplotHost
import matplotlib.gridspec as gridspec

import functions as fun
import importlib
importlib.reload(fun)
```

Out[1]:
```
<module 'functions' from '/home/fc-3auid-3a73d7ab48-2d5074-2d4709-2d822e-2dc1ed73a
c8034/escience2025-projects/group7/Dimitris/functions.py'>
```

In [2]:
```
''' Paths to datasets '''

paths = {
    "Zeppelin": "/mnt/craas2-ns9988k-ns9252k/escience2025/data/group7/Freud-etal_20
    "Nord": "/mnt/craas2-ns9988k-ns9252k/escience2025/data/group7/Freud-etal_2017/d
    "Alert": "/mnt/craas2-ns9988k-ns9252k/escience2025/data/group7/Freud-etal_2017/
    "Utqiagvik": "/mnt/craas2-ns9988k-ns9252k/escience2025/data/group7/Freud-etal_2
    "Tiksi": "/mnt/craas2-ns9988k-ns9252k/escience2025/data/group7/Freud-etal_2017/
```

At first, some of the results of *Freud et al. (2017)* study were reproduced in order to ensure the replicability of its outcomes as well as to understand the general structure of the data that will be analysed. The plots that were replicated were the data availability, the aerosol total and accumulation-mode number concentrations along with the total surface and volume area and finally the monthly aerosol number size distributions. Then the focus shifted on *Engvall et al. (2008)* approach where daily ratios of the Aitken over accumulation mode particles were calculated.

$$R_{\text{mean}} = \frac{N_{\text{Aitken}}}{N_{\text{Accumulation}}} \quad (1)$$

Having calculated the daily ratios, we proceeded to compute the daily Aerosol Transfer Index (ATI), averaged over the years, that is defined as the ratio of the frequency of days where $R_{\text{mean}} > 1$ to the frequency of days where $R_{\text{mean}} < 1$ for a period of a week:

$$\text{ATI} = \frac{f(R_{\text{mean}}>1)}{f(R_{\text{mean}}<1)} \quad (2)$$

Finally a threshold of 0.4 was selected for the ATI. Exceeding this value for 10 consecutive days is considered to mark the onset of the summer season. Plots indicating the transition period and day will be presented based both on the mean ratios and ATIs.

4. Results

In [3]:
```
importlib.reload(fun)
fun.availabilities_plots(paths)
```

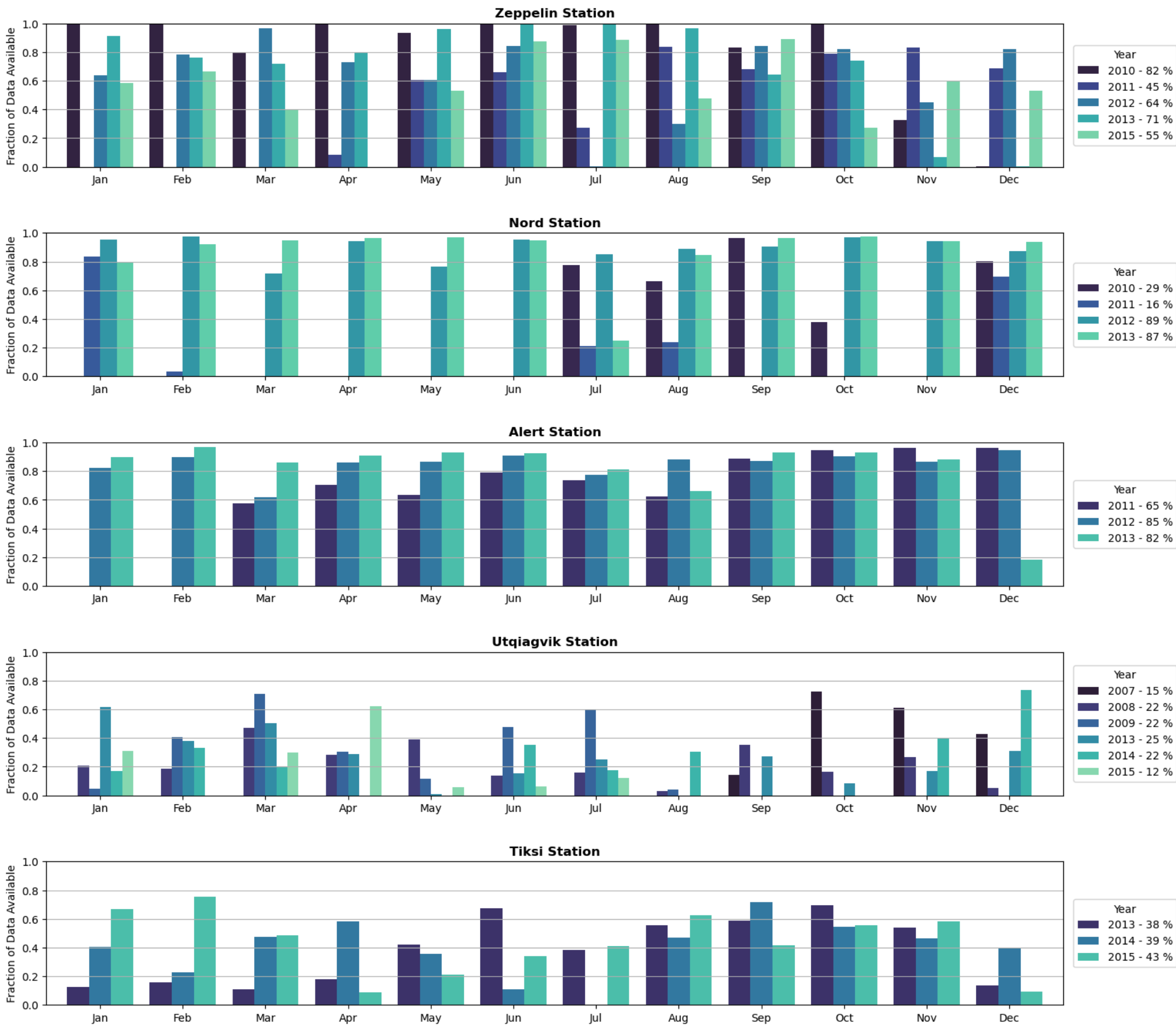

Figure 1: Data availability. The fraction of the time within each month with available aerosol data. The percentages indicate the yearly total data coverage. For this figure only the data with the total number concentration of particles between 20 to 500 nm was used. To get these fractions, the available hours on each year were compared with the non-NaN entries that were available. Then the percentages shown in the legends were computed by taking the mean of these fractions.

In [4]:
```
importlib.reload(fun)
diameters, monthly_data = fun.preprocess_monthly_distributions(paths)
fun.plot_monthly_distributions(diameters, monthly_data)
```

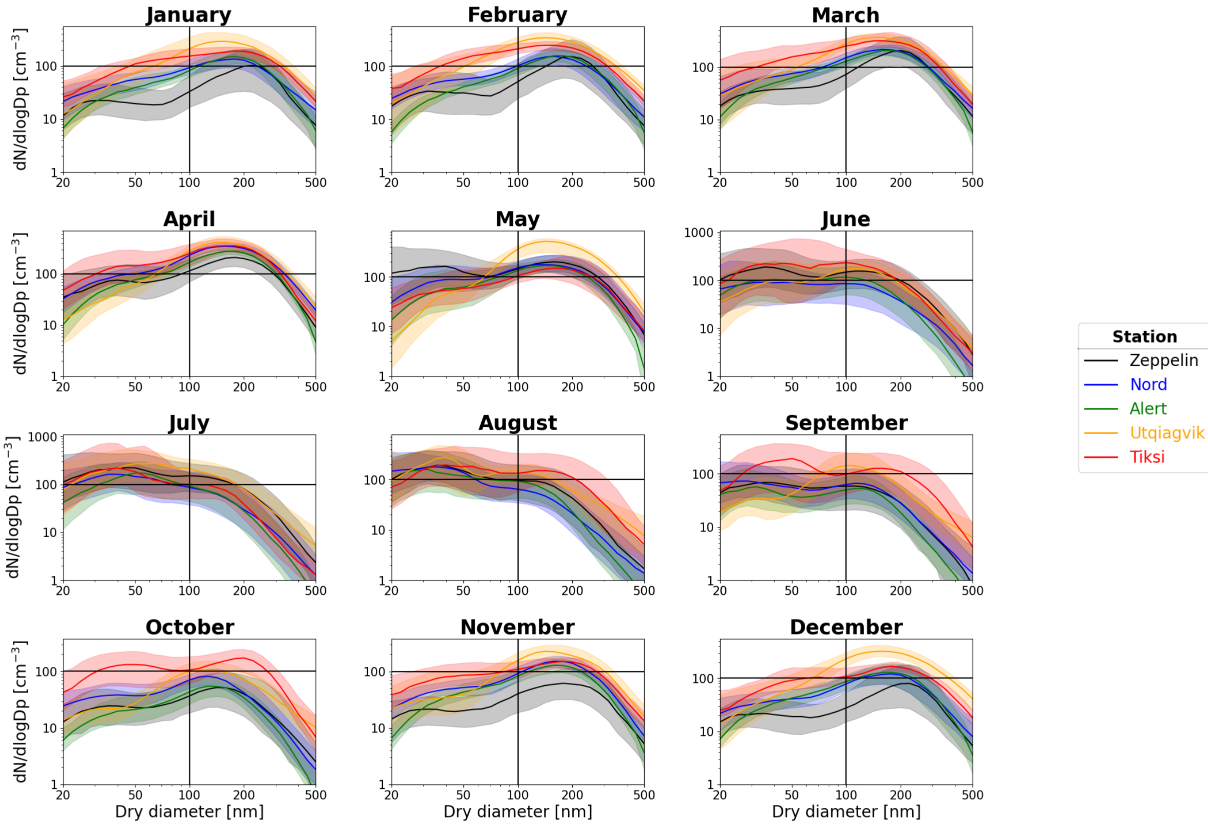

Figure 2: The monthly aerosol number size distributions. The solid curves represent the median distributions of each site's dataset for the particular month, with the colors matching the colors of the stations in the legend. The shaded areas represent the spread of the distribution and was computed by taking the 25% and 75% quantiles of the datasets. The horizontal and vertical lines are used for comparing the distributions between the months.

In [5]:
```
importlib.reload(fun)
fun.total_NSV_plot(paths)
```

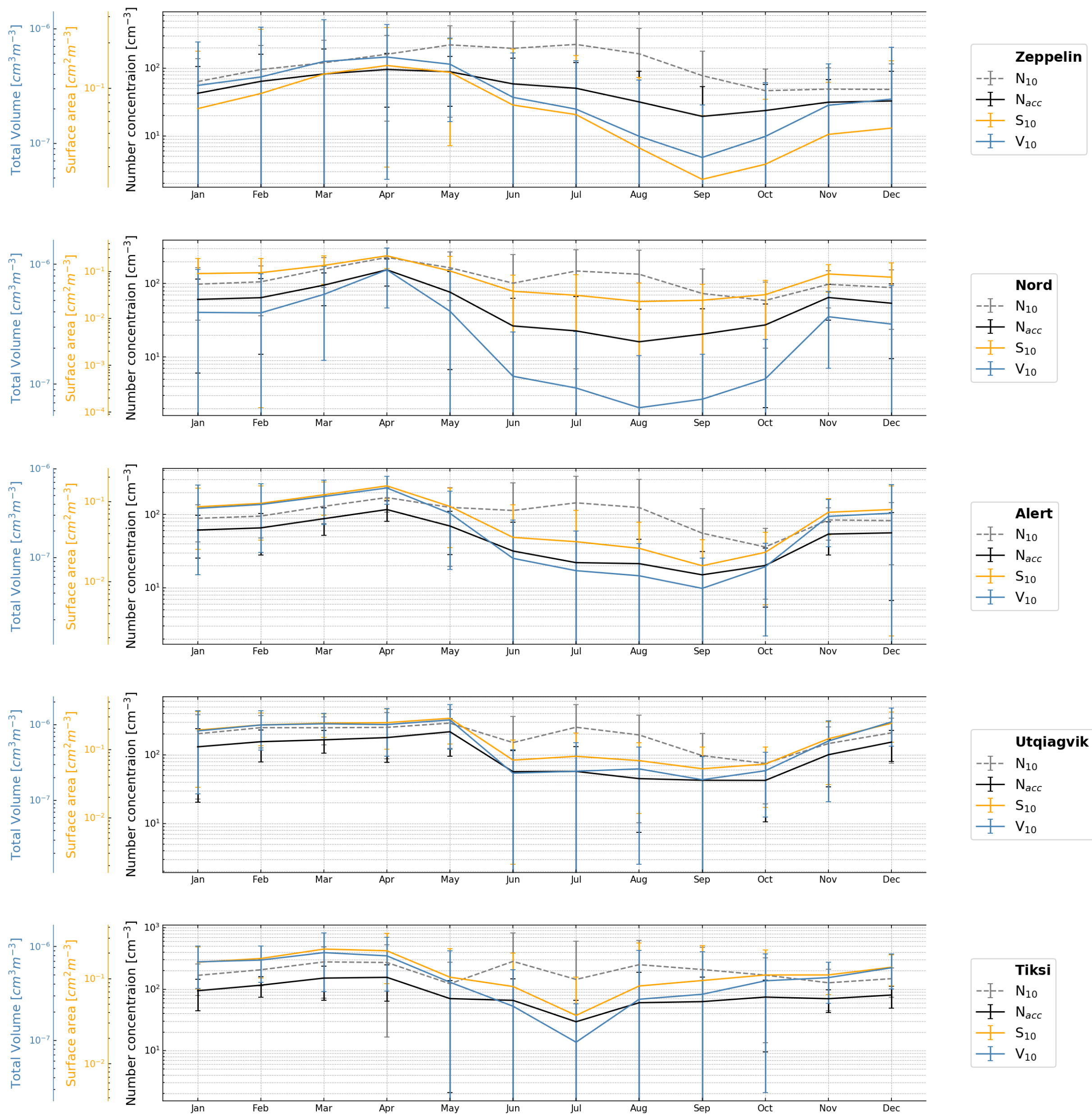

Figure 3: The monthly median and interquartile ranges of the aerosol total and accumulation-mode number concentrations, aerosol total surface and the total volume. The total (N_{10}) and the accumulation mode (N_{acc}) concentration numbers are indicated in grey dashed and black solid lines respectively while the total volume (V_{10}) and surface (S_{10}) are plotted in blue and orange. For the total values, aerosols between 20-500 nm in diameter were taken into account while the accumulation mode size is defined by particles between 100-500 nm. Since the data used are log-normal size distributions, we had to integrate (using the trapezoidal rule) over the log of the particles' diameters to get the concentration numbers. In addition, for the total surface and volume, we assumed spherical symmetry for the aerosol particles.

In [6]:
```
importlib.reload(fun)
fun.plot_aitken_VS_acc(paths , scale='log', tran_period=False , save=True)
```

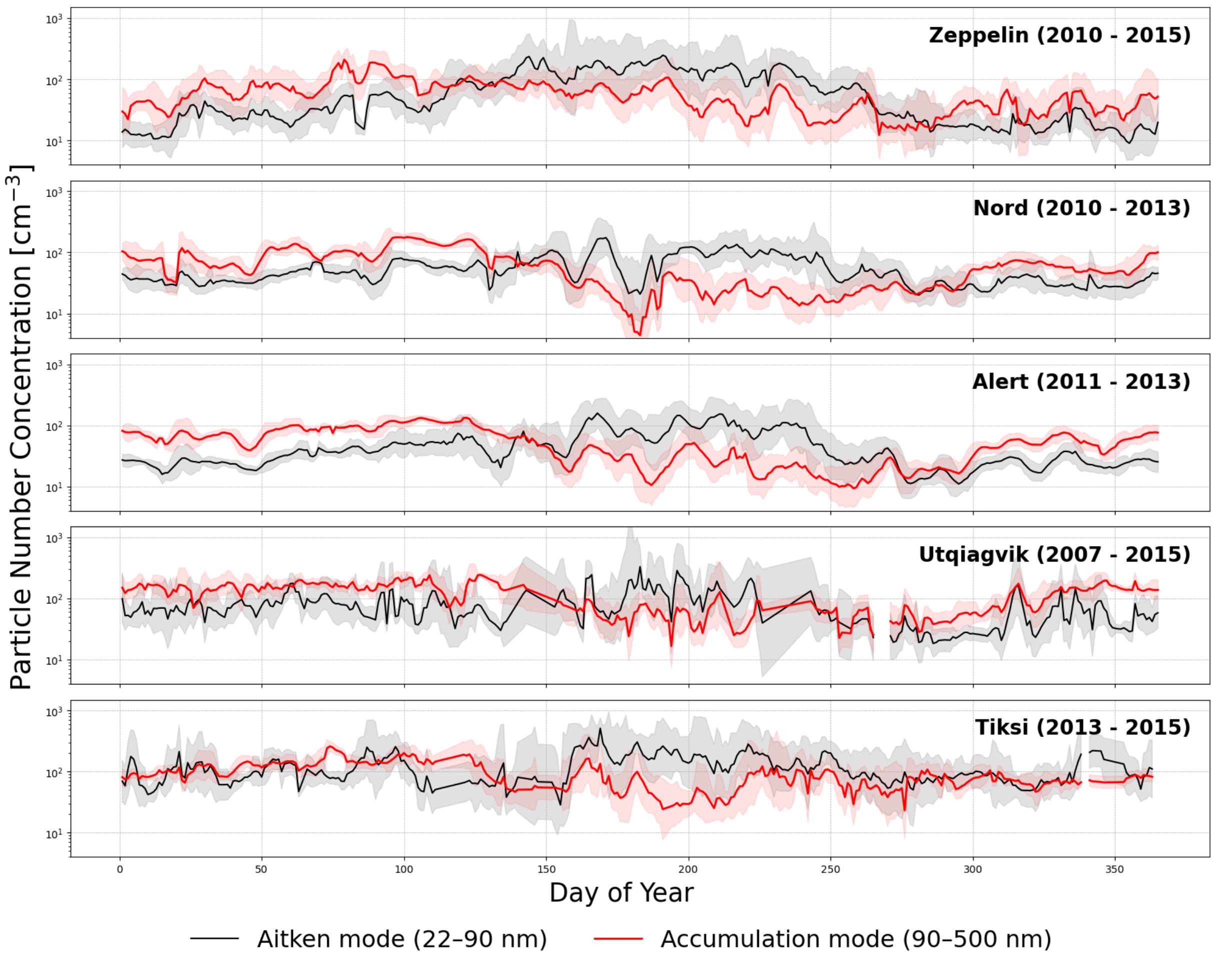

Figure 4: Annual weekly moving average of the Aitken (22–90nm) and the accumulation mode particles (90–500nm). The black and red solid lines represent the geometric mean over a weekly window for the Aitken and accumulation mode aerosols respectively. The shaded areas are the standard deviation of the rolling weekly window.

In [7]:
```
importlib.reload(fun)
fun.plot_aitken_VS_acc(paths , scale='log', tran_period=True , save=True)
```

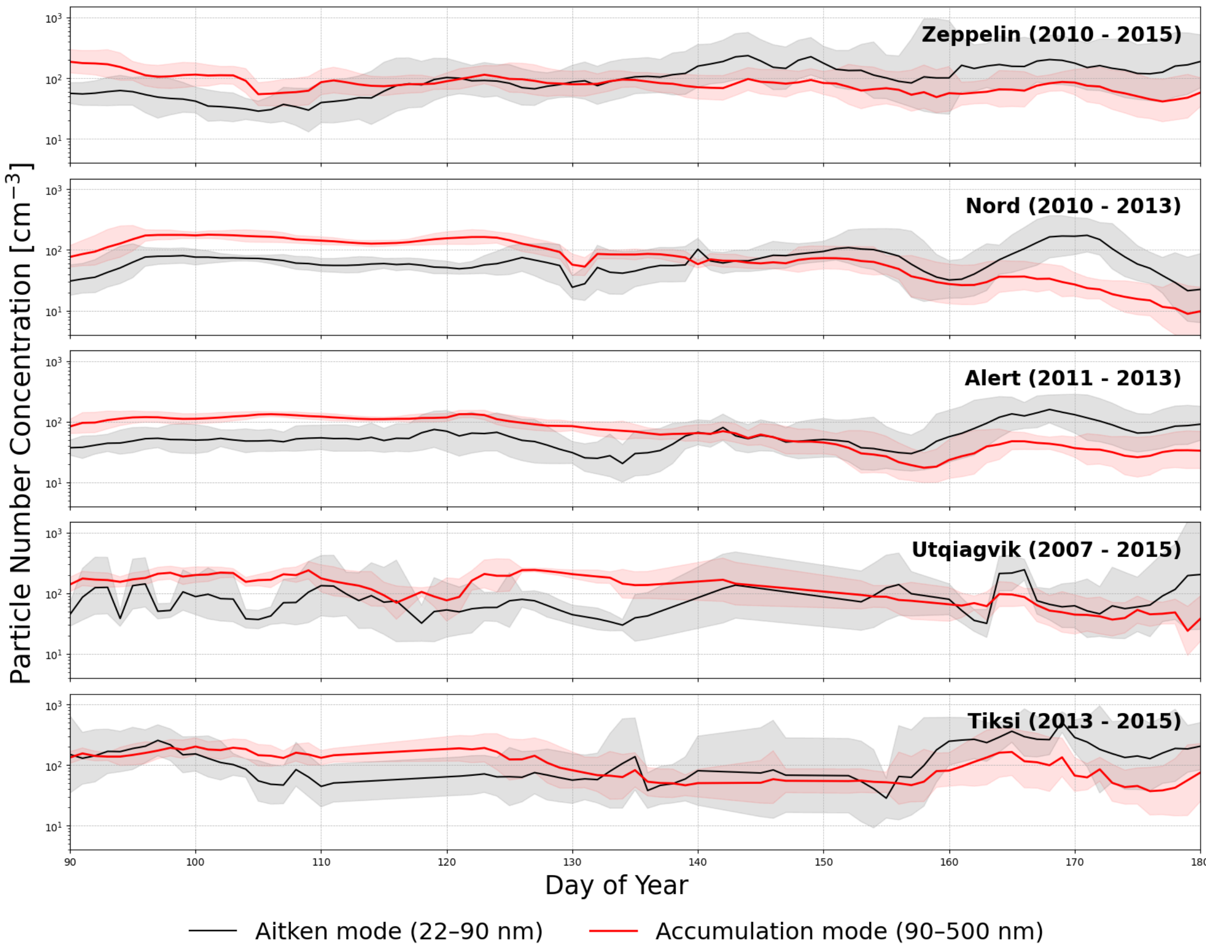

Figure 5: Weekly moving average of the Aitken (22–90nm) and the accumulation mode particles (90–500nm) for the transition period (April-June).

In [8]:
```
importlib.reload(fun)
fun.plot_ratio(paths)
```

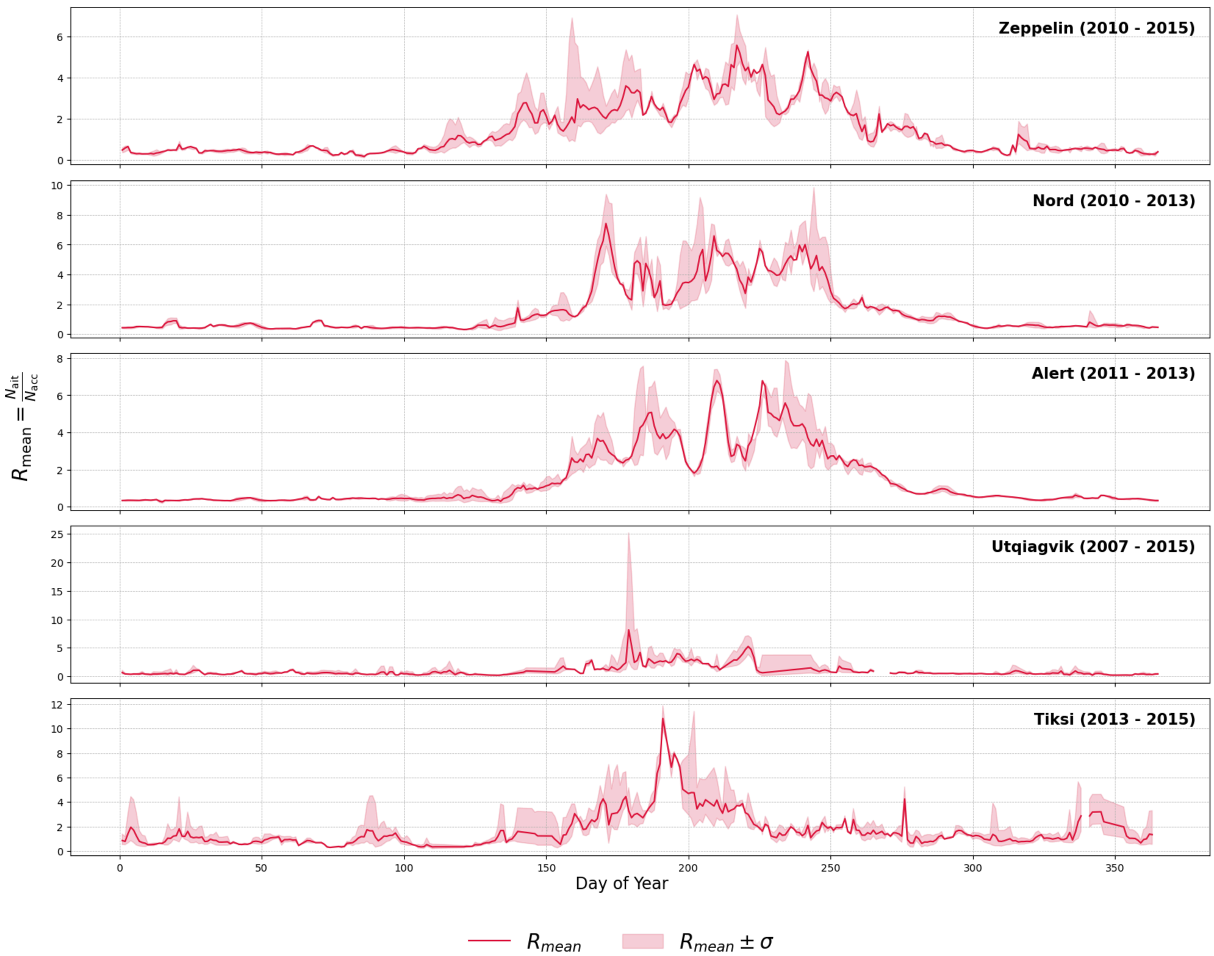

Figure 6: Annual weekly running mean of the ratio of particle number concentration between Aitken and accumulation mode based on geometric mean and standard deviation.

In [9]:
```
importlib.reload(fun)
fun.plot_ati(paths, label_fontsize=17, legend_fontsize=15, title_fontsize=14)
```

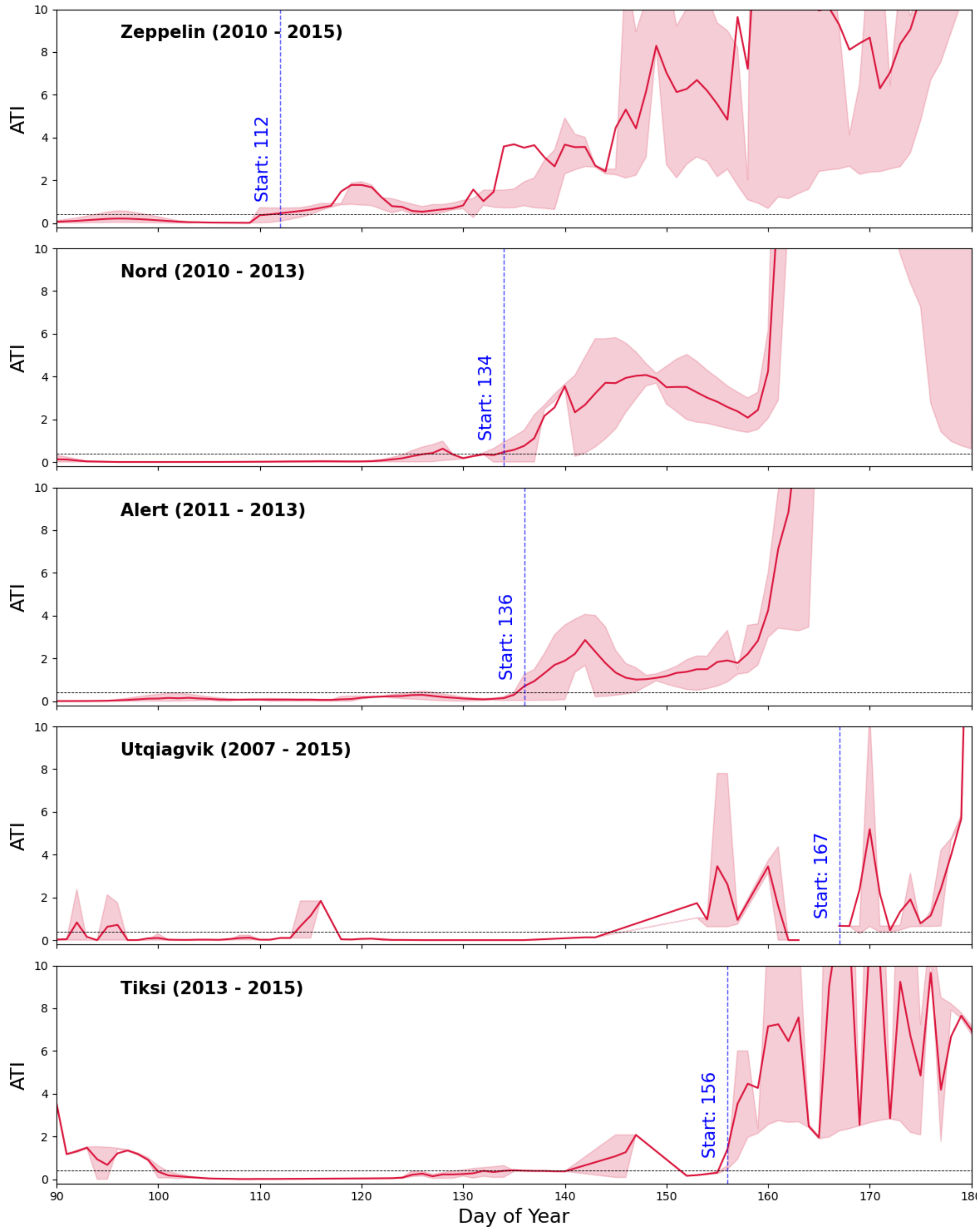

Figure 7: Weekly running mean and standard deviation of the ATI for the transition period. The red solid lines along with their spreads, represent the weekly running mean of the ATI and their respective quantiles. The blue vertical dashed lines indicate the onset of the the summer period as described earlier. For this analysis, low concentration numbers (<1) both in Aitken and accumulation mode were not included, in order to avoid sudden spikes and infinities in our graph.

5. Discussion

The first three figures reproduced the results of *Freud et al. (2017)* quite accurately, showing the replicability of their study. In detail, Fig. 1 presents the available data among the stations. Zeppelin, Nord and Alert stations seem to have detected enough aerosols during the years while we can not say the same for Utqiagvik and Tiksi. Their data lack a bit of consistency making their future analysis questionable. Fig. 2 illustrates the annual cycle we talked about in the introduction. The accumulation mode peaks around in March while Aitken mode has a maximum in July. In between those months is the transition period where we aim to find the transition day as accurately as possible. Fig. 3 demonstrates the same cycle but in a different way, by showing the evolution of the concentration numbers over the year. Moreover, it is worth mentioning that during the summer period, there is a gap between N_{10} and N_{acc} which is due to new particle formation. On top of that, since N_{acc} consists only of bigger particles, the total surface and volume follow the same trend as these aerosols.

Moving on to Fig. 4 and 5 and focusing on the transition period (90-180th day), we observe a more sudden increase of the Aitken mode in Zeppelin while the opposite happens in Nord and Alert stations where the number concentration of larger aerosols decrease on a higher rate than the production of new ones. This phenomenon can be explained by the location of these stations where the southernmost ones like Zeppelin will detect first the newly formed particles. A similar behavior with Zeppelin would be expected for Utqiagvik and Tiksi. However they seem to deviate from normal patterns since there are sudden shifts and irregular variations in both modes. Specifically, there are periods with minimal change in the number concentration as well as gaps indicating discontinueties in the data.

Finally, for Fig. 6 and 7, the ratio of the modes peaks during summer as expected with a maximum at around 10 for all stations. Once more the results are more consistent for Zeppelin, Nord and Alert where the ratios fluctuate between 2-8 in summer months and are below 2 for the rest of the year with few spikes during winter. On the contrary, Utqiagvik and Tiksi follow a different pattern where the distribution deviates from normal. In particular, Utqiagvik has its maximums in the beginning and end of summer while the in between ratios fluctuate at lower values. Tiksi also behaves abnormally, where its ratio peaks at the end of June and then constantly decreases for the rest of the year. Having done the previous analysis we conclude with the following transition days from Fig. 7:

Station	Transition day
Zeppelin	112
Nord	134
Alert	136
Utqiagvik	167

Tiksi	156

Table 1: Transition day for each station

In Zeppelin, summer conditions are reached on day 112 for the years 2010-2015. This result is 28 days earlier than what was found in *Engvall et al. (2008)* study for the years 2000-2005. Although the difference is quite significant, a shift towards earlier transition was expected due to the ongoing global warming. Nord and Alert, even though they are not much further north than Zeppelin, show a delay of around 20 days. For Utqiagvik and Tiksi the delay is even more significant while we would expect the transition to occur around the same time with Zeppelin. This behavior can be justified by the lack of enough continuous data on these sites. Another parameter that might have an influence in our results and that has not been taken into account is the atmospheric conditions around the stations. Being close to land, sea, or ice can affect the aerosol size distribution, thus delaying or accelerating the onset of summer conditions.

6. Conclusions

Concluding, we can say that the overall analysis yielded satisfactory results. Specifically, compared with former studies, the melt season started earlier in Zeppelin as it was expected while the northern stations (Nord, Alert) exhibit quite a delay. However, deviations from the expected outcomes occured and can be attributed to the inconsistent data and to additional parameters that have not been considered. In addition since we did not have access to the exact analyses that were used in the aforementioned studies, the final results are expected to deviate on some extent.

7. References

Freud, E., Krejci, R., Tunved, P., Leaitch, R., Nguyen, Q. T., Massling, A., Skov, H., & Barrie, L. (2017). *Pan-Arctic aerosol number size distributions: Seasonality and transport patterns*. *Atmospheric Chemistry and Physics, 17*, 8101–8128. https://doi.org/10.5194/acp-17-8101-2017

Engvall, A.-C., Krejci, R., Ström, J., Treffeisen, R., Scheele, R., Hermansen, O., & Paatero, J. (2008). *Changes in aerosol properties during spring-summer period in the Arctic troposphere*. *Atmospheric Chemistry and Physics, 8*, 445–462. https://www.atmos-chem-phys.net/8/445/2008/

8. Acknowledgments

First of all I would like to thank the rest of my group members, Jenny and Tom and of course our great assistant Julia. It was a great experience working with you all and really enjoyed our discussions and the funny moments in between. A well deserved applause goes to Paul, Michael and Matias too for their informative lectures, the insightfull experience they provided us and generally for making this course run smoothly. Last but not least, a huge thanks to all of the students that attended this course. It was a pleasure meeting you all and hopefully our paths cross again someday.

9. Declaration on the usage of AI

As for AI, ChatGPT was used. Not being familiar with the field we are studying, ChatGPT helped me clarify some terms and processes involved in the analysis. In addition, it was used to assist in the customization of the plots presented earlier. Its contribution was valuable for the final report but was always validated before used by me.