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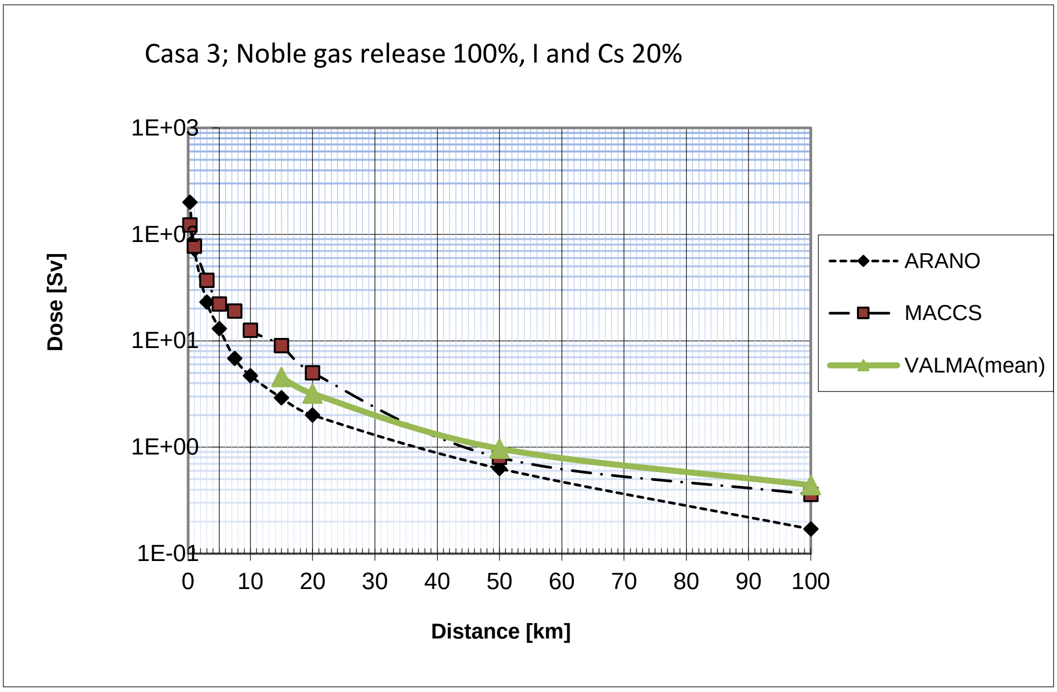
RESEARCH REPORT

VTT-R-00136-19



Comparison of MACCS, ARANO and VALMA

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Confidentiality: Public

RESEARCH REPORT VTT-R-00136-19

Report's title	
Comparison of MACCS, ARANO and VALMA	
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Summary

The purpose was to learn and understand the functionality of WinMACCS. Besides available documentation, it is necessary to exercise in practice the usage of the code. Comparison calculations were carried out by ARANO and VALMA. Calculations deal with offsite dose calculations without countermeasures in a single weather condition as well as with the probabilistic approach employing annual weather data.

The principal phenomena included in both codes are atmospheric transport and deposition under prevailing meteorology, short- and long-term mitigation actions and exposure pathways, deterministic and stochastic health effects, and economic costs. MACCS was developed as a general-purpose tool applicable to diverse reactor and nonreactor facilities licensed by the US Nuclear Regulatory Commission.

Calculation results indicate significant differences in some single atmospheric dispersion cases but differences are reduced if annual weather is used and fractile values are presented. Then ARANO typically predicts smaller dose values than MACCS. Implementation of MACCS demonstrates that the code is available and capable to calculate offsite radiation doses. In addition, long-range model VALMA was included in comparisons. Comparable dose estimates of VALMA predict smaller dose values than MACCS.

To study the differences possibly caused by different weather data sources (NPP weather mast, or SILAM dispersion model), some parameter distributions are included in the Appendix.

Confidentiality	Public

Espoo 14.2.2019

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Preface

This report is a result of the CASA project, which in turn is a part of the SAFIR2018 research programme.

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Author

Contents

1. Introduction

Comparison of WinMACCS code version 3.10 (in brief MACCS) [Randall J., et al. 1997] with ARANO started by doing two sets of comparison calculations. These consist of offsite dose calculations without countermeasures:

- in a single weather condition and
- in probabilistic approach with the annual weather data.

The target was to learn and understand the functionality of WinMACCS. Besides available documentation, it is necessary to exercise in practice the usage of the code. Comparison calculations were carried out primarily by ARANO. In addition, some comparisons were made with the available results of the long-range model VALMA. In the case of VALMA weather data for the meteorological mast is picked from the particle trajectories of a numerical weather prediction model. In principle, the input was defined to be simple so that the same approach would be maintained in all codes. Default values were applied as much as possible.

ARANO assumes straight-line trajectories and time-invariant meteorology. MACCS code assumes straight-line trajectories and time-variant meteorology and models for the release with multiple Gaussian plumes. The extensive and comprehensive intercomparison study of the level 3 PSA codes was organised by OECD/NEA in 1993-1994. ARANO and MACCS2 were among participants [OECD/NEA 1994].

2. Single weather trial runs

Non-ingestion doses

Exposure pathways here are: cloudshine, groundshine and inhalation. Moreover, resuspension is included in MACCS. Dose is the sum of these components.

In the source term there were the first case consisting of a release of one nuclide. The parametric input is: Cs-137 (t_{half} = 30 a) 100 TBq, duration of the release 0,5 hour without delay from the shutdown, release altitude 100 m. Table 2.1 shows different weather conditions used in these comparison calculations.

Table 2.1. Different weather situations used in single weather cases.

Pasquill stability	Wind speed (m/s)	Rain (mm/h)
D	5	no rain
C	5	5
F	1	no rain
D	5	0.7

Figure 1.1 illustrates the effective dose as a function of distance in both code cases. Exposure time is one week. Weather condition was stability D, wind speed 5 m/s, no rain.

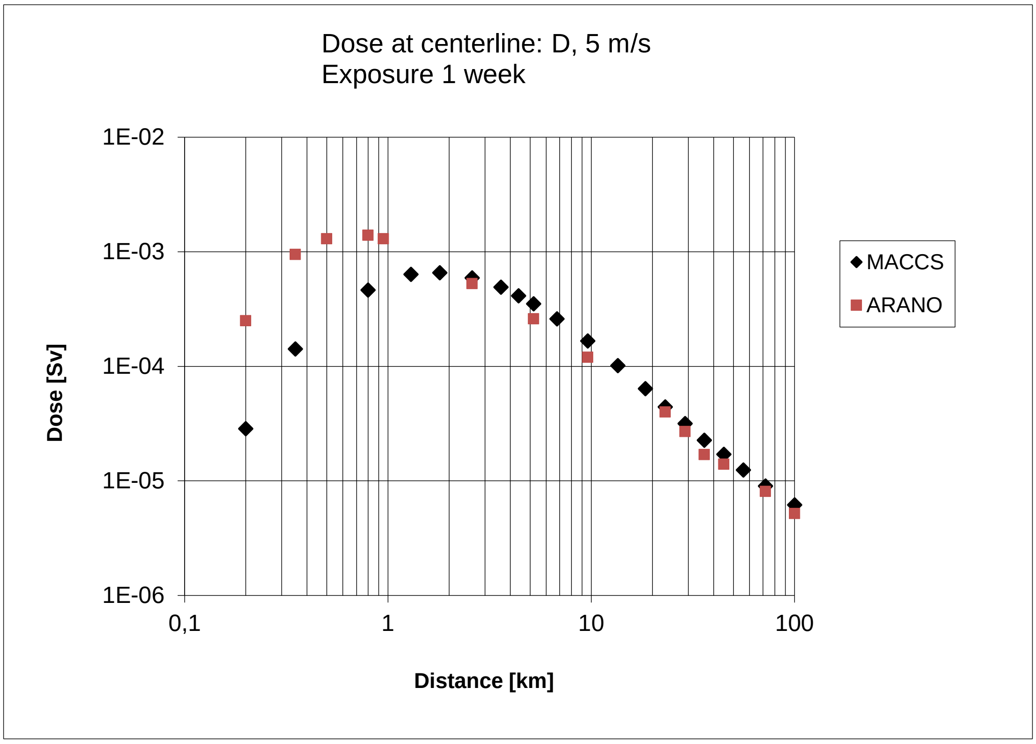


Fig. 1.1. Dose (cloudshine+groundshine+inhalation) as a function of distance calculated by ARANO and MACCS.

Figure 1.1 shows that up to the distance of 1 km there is a remarkable difference of an order of magnitude at the most. However, at longer distances the doses are rather similar. Figure 1.2 illustrates the doses as figure 1.1 but exposure time is one year.

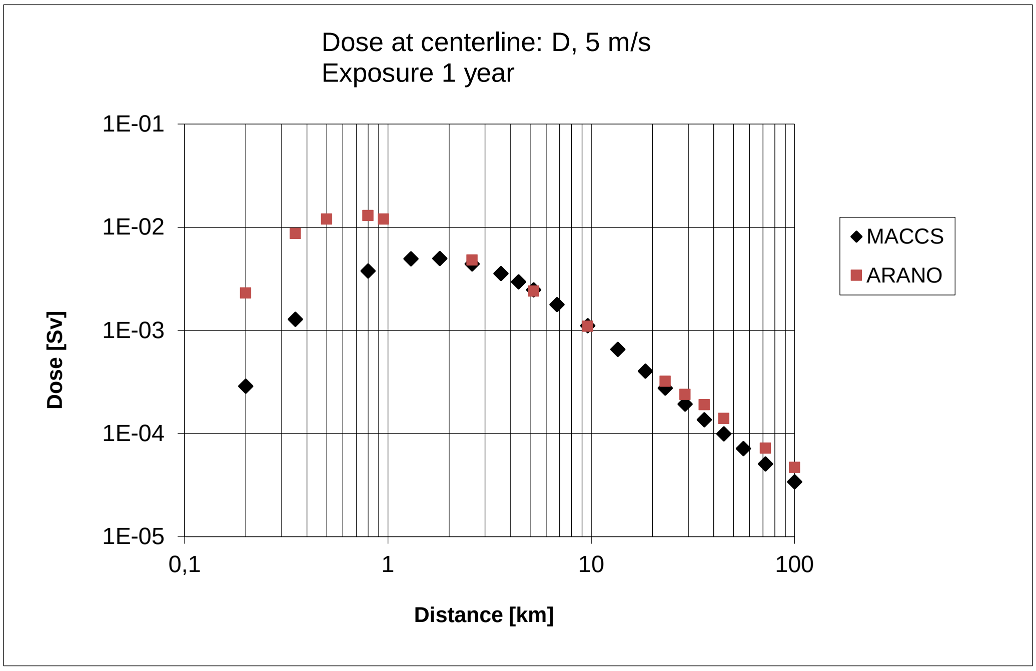


Fig. 1.2. Dose (cloudshine+groundshine+inhalation) as a function of distance calculated by ARANO and MACCS.

Figure 1.2 shows that up to the distance of 1 km there is a remarkable difference of an order of magnitude at the most. However, at longer distances the doses are rather equal. Now, the external dose from the deposited activity dominates the dose due to one year exposure.

Next the short-lived isotope I-133 (t_{half} = 21 h). All the other parameters remain the same as in the case of Cs-137. Figure 1.3 illustrates the dose as function distance in both code cases. Exposure time is one week. Due to short half-life of I-133, the dose is only 1…2% higher if exposure time would be one year.

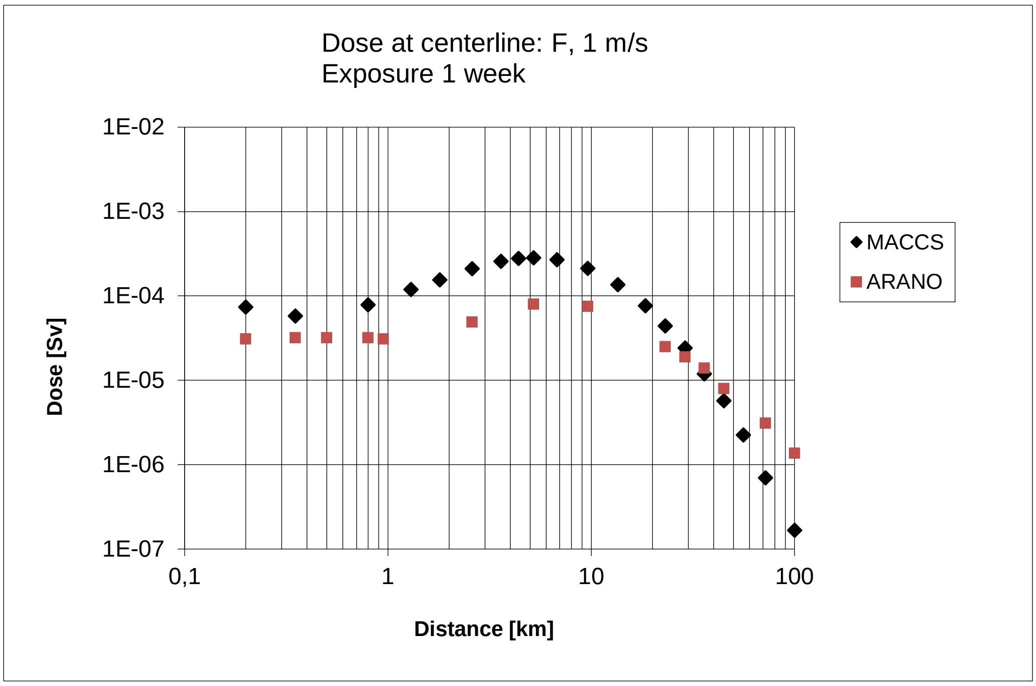


Fig. 1.3. Dose (cloudshine+groundshine+inhalation) as a function of distance calculated by ARANO and MACCS.

Figure 1.3 depicts that in the case of stable dispersion condition (F, 1m/s) ARANO predicts little lower dose up to the distance of 30 km, but then higher dose at the longer distances.

Figure 1.4 shows the effect of rain 5 mm/h. Release is Cs-137.

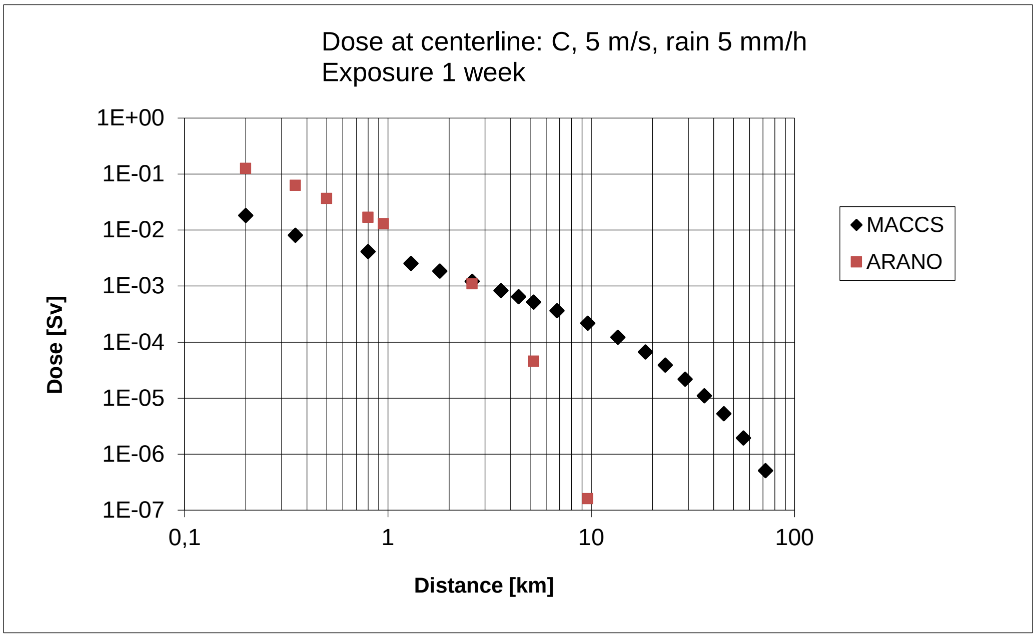


Fig. 1.4. Dose (cloudshine+groundshine+inhalation) as a function of distance calculated by ARANO and MACCS.

Figure 1.4 shows that rather heavy rain affects in ARANO more strongly than in MACCS. Washout coefficient is $5 \cdot 10^{-3} s^{-1}$. This means that ARANO removes effectively radioactive material from the plume onto the ground due to rain. In MACCS the effect of rain on the deposition remains moderate.

Figure 1.5 shows the effect of weaker rain of 0.7 mm/h (washout coefficient $7 \cdot 10^{-5} s^{-1}$). Release is 100 TBq of Cs-137.

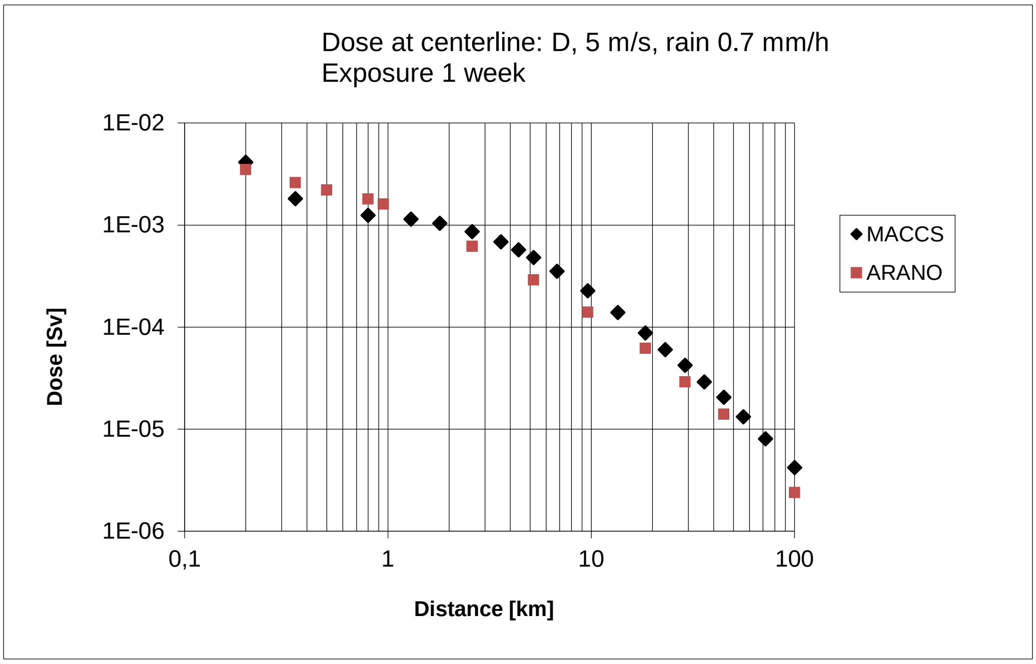


Fig. 1.5. Dose (cloudshine+groundshine+inhalation) as function of distance calculated by ARANO and MACCS.

Figure 1.5 illustrates that the doses are very close to each other. This indicates that models predict weak rain in a similar way.

Ingestion doses

In MACCS it is possible to include a premodule, COMIDA2, to include local parametric values for MACCS. This was done and AGRID specific parameters were created and adopted to MACCS. A little similar procedure was carried out when AGRID parameters were adopted to VALMA (Ilvonen, Rossi 2017). AGRID is ingestion dose model, including seasonal effects, integrated in ARANO. AGRID includes ingestion pathways of cow milk and meat, grain, green vegetables and roots.

COMIDA2 serves as an interface program between COMIDA and MACCS. The COMIDA code estimates nuclide concentrations in agricultural food products (grains, leafy vegetables, roots, fruits, legumes, milk, beef, poultry, and “other animal”), following an acute fallout event. COMIDA2 exercises COMIDA a number of times to generate the information needed for the MACCS run. It automatically loops on multiple fallout dates, translates the COMIDA-calculated foodstuff concentrations into units of dose broken down by crop category, and writes a binary file of dose-to-source ratios for use by MACCS. COMIDA2 functions include: (1) calculation of data for multiple release dates, (2) calculation of the resulting individual and societal doses per unit deposit, (3) reconciling differences between COMIDA's discrete harvesting and continuous harvesting models, and (4) accounting for decay and ingrowth that occurs between harvest and consumption.

Individual doses from Cs-137 were compared in two atmospheric conditions. Figure 1.6 shows weather condition stability D, wind speed 5 m/s, no rain (deposition in summer) and Figure 1.7 (deposition in winter). Cow milk and meat dominate the total dose.

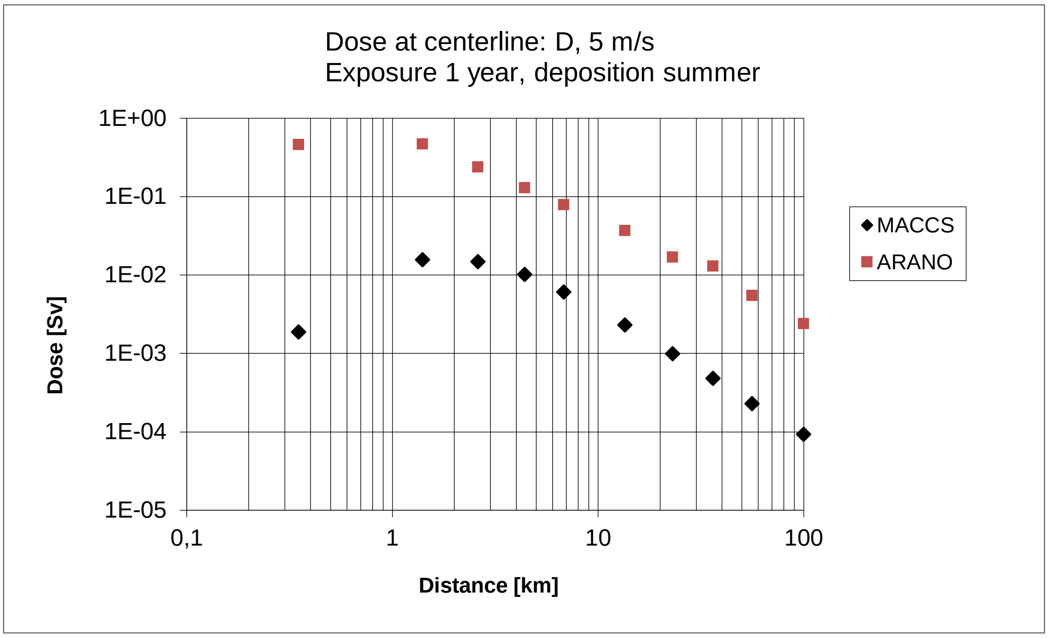


Fig. 1.6. Ingestion dose as function of distance calculated by ARANO and MACCS. Accident occurs in summer.

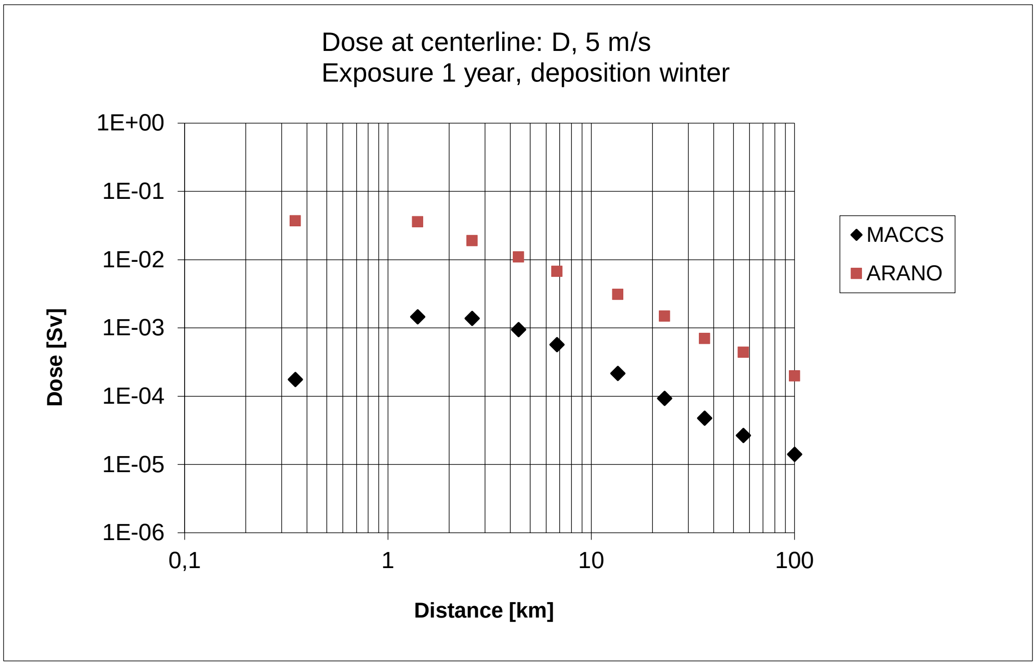


Fig. 1.7. Ingestion dose as function of distance calculated by ARANO and MACCS. Accident occurs in winter.

These two figures indicate that ingestion doses calculated by ARANO are about an order of magnitude larger than ingestion doses obtained by MACCS.

Next two figures illustrate ingestion dose from I-131((t_{half} = 8 d). Cow milk and meat dominate the total dose.

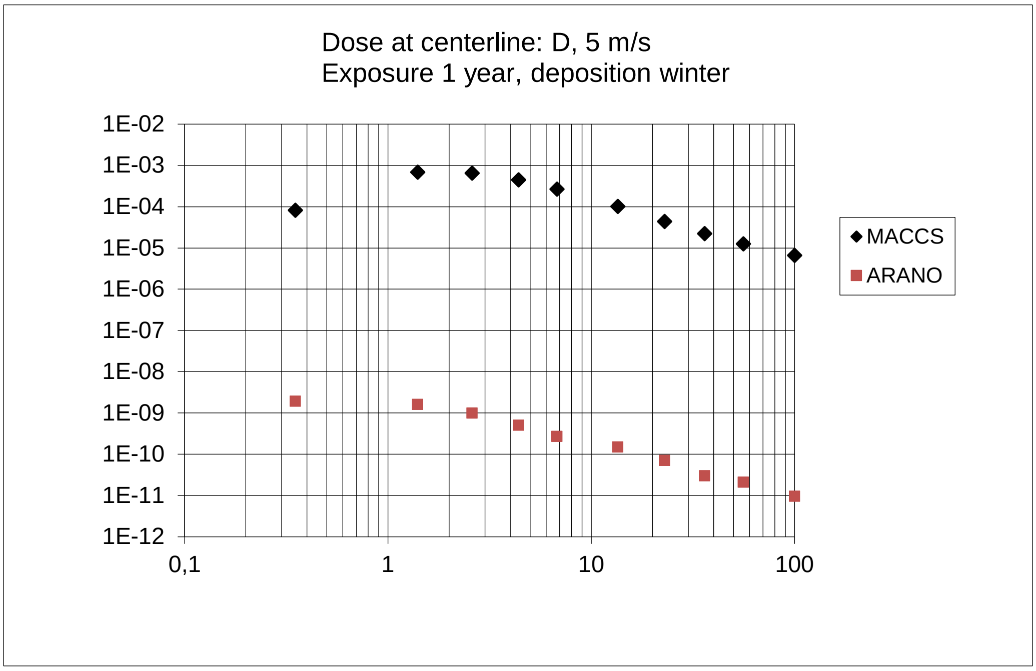


Fig. 1.8. Ingestion dose as function of distance calculated by ARANO and MACCS. Accident occurs in winter.

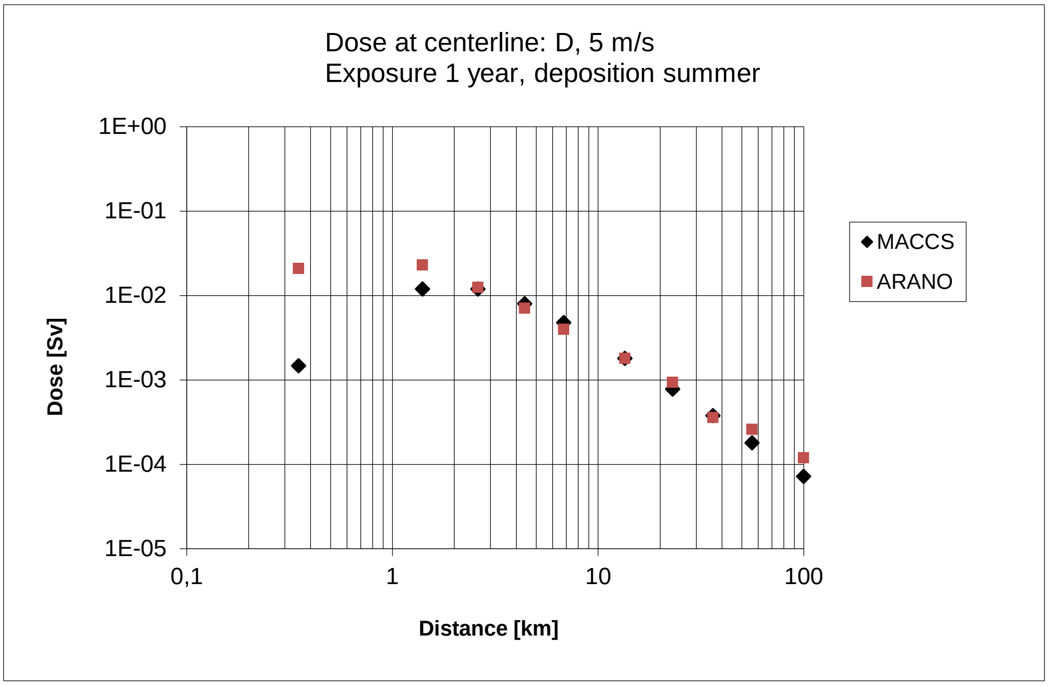


Fig. 1.9. Ingestion dose as function of distance calculated by ARANO and MACCS. Accident occurs in summer.

In figure 1.8 the ARANO curve indicates that if deposition occurs during winter, the dose from short-lived isotope I-133 is very small. In MACCS, the dose seems to remain at higher level.

Figures 1.1 - 1.9 show that doses may differ significantly from each other especially at short distances up to one kilometer in a single dispersion condition. In addition, similar behavior can be found.

3. CCDF results

Here doses are calculated based on the annual weather data of Olkiluoto 2009. Weather data has to be formulated for the two codes separately. In MACCS this means that hourly data consists of dispersion direction, wind speed, stability and rain occurrence for 8760 time points. In ARANO the annual weather data consists of probabilities of dispersion sectors, stability occurrence in dispersion sectors, wind speed occurrence in predefined speed categories in stability classes and rain occurence. As a result of this categorization there are 1008 different dispersion cases. The VALMA tarjectories are based on the 2012 data (Ilvonen, Rossi 2017).

Casa source terms [Rossi, Ilvonen 2015] were used:

- Case 1: ‘CASA1’, noble gases 1%, I-131 1000 TBq, Cs-137 100 TBq (Severe accident release)
- Case 2: ‘CASA2’, noble gases 20%, iodine + caesium 2%
- Case 3: ‘CASA3’, noble gases 100%, iodine + caesium 20% (No containment)

Nuclide specific source term was calculated from a large LWR core inventory.

Effective doses were calculated as a function of distance in figures 3.1, 3.2 and 3.3 for non-ingestion pathways. The values corresponding 95% fractiles of the CCDF (complementary cumulative density function) curve are illustrated. This means that there are about 50 higher dose values. The result is the sum of the external dose from the plume, inhalation and external dose from the fallout. Exposure time was one year in this case.

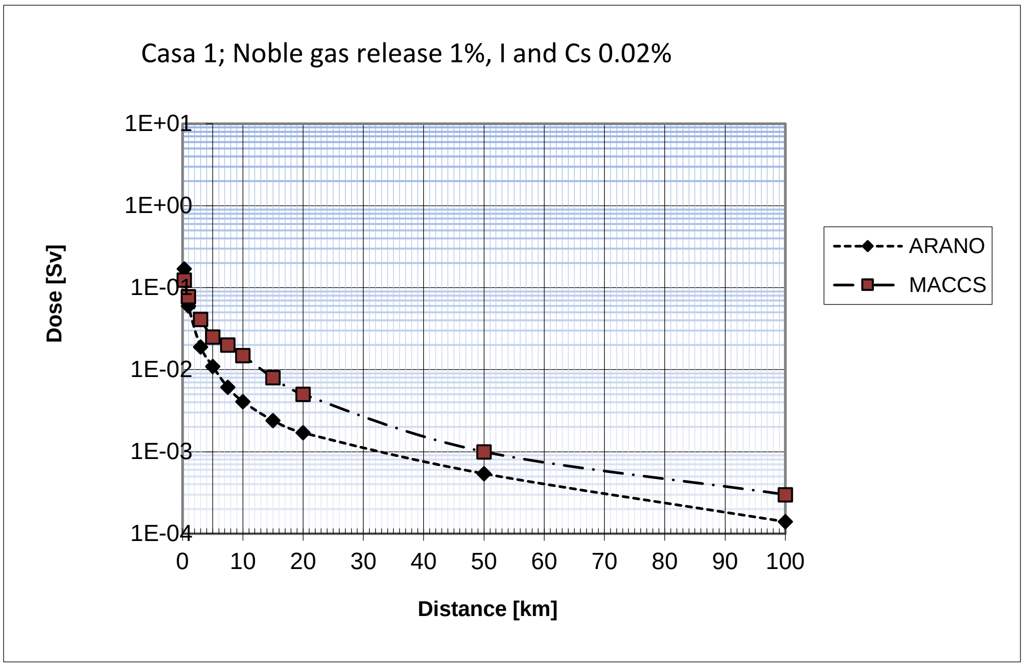


Fig. 3.1. The dose of 95% fractile as a function of distance from the power plant. Release case 1, integration time is one year for external radiation from the ground.

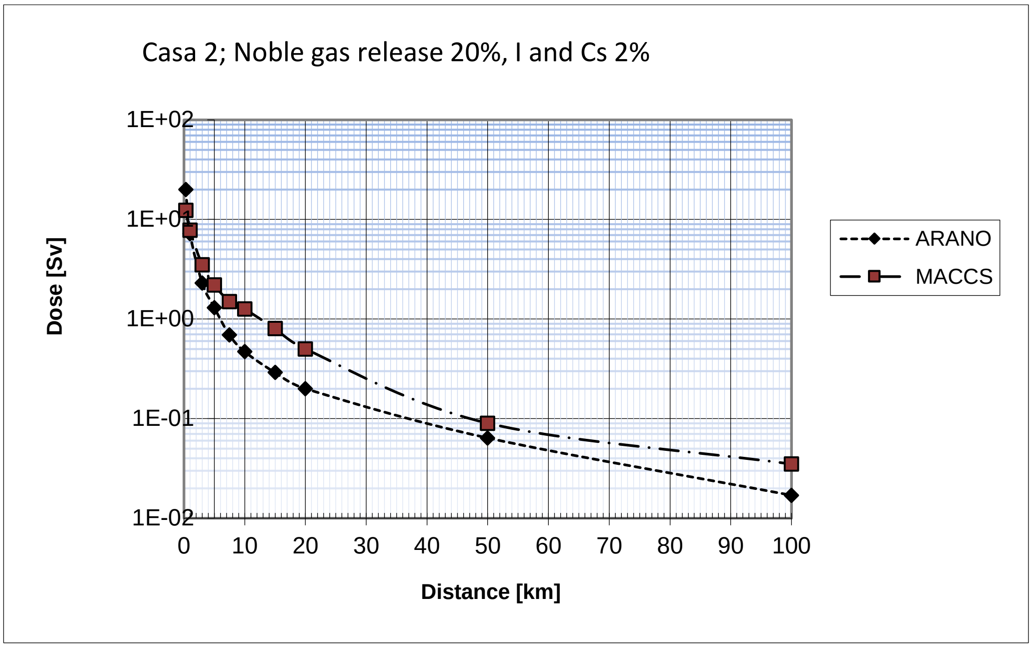


Fig. 3.2. The dose of 95% fractile as a function of distance from the power plant. Release case 2, integration time is one year for external radiation from the ground.

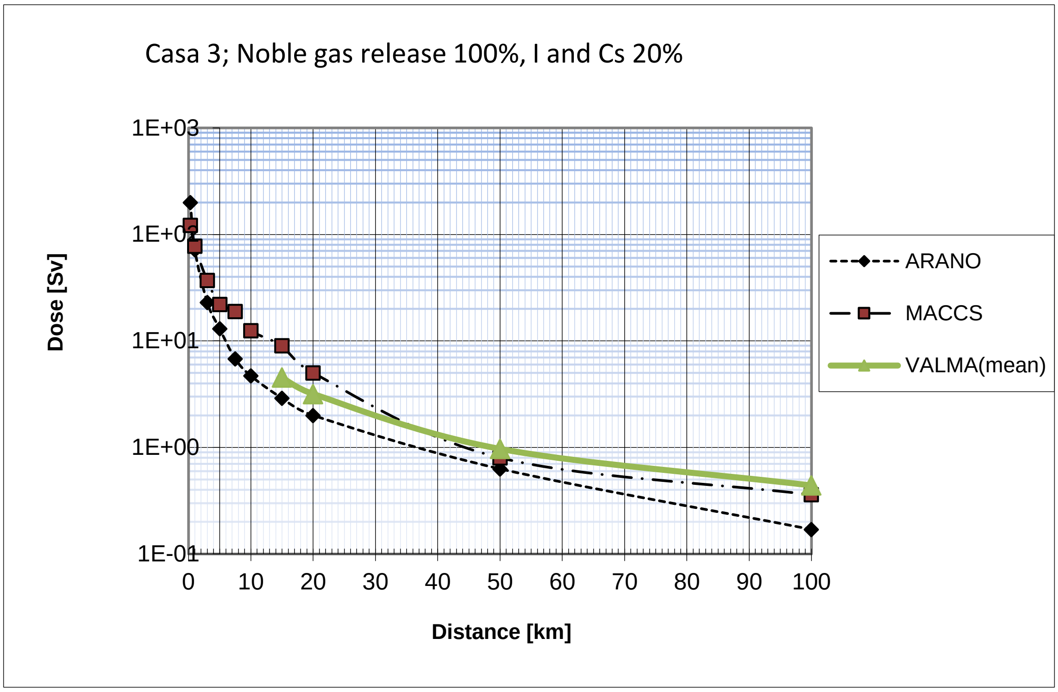


Fig. 3.3. The dose of 95% fractile as a function of distance from the power plant. Release case 3, integration time is one year for external radiation from the ground. VALMA result is added beyond 15 km from (Ilvonen, Rossi 2017).

Figures 3.1, 3.2 and 3.3 indicate that the dose curves from MACCS and ARANO behave similarly. MACCS predicts at the most three times as high a dose as ARANO. The parameter values in the codes were set to default or best estimate values, but not in-depth evaluation between the values was done. The VALMA curve predicts slightly higher dose values than ARANO and MACCS, beyond 40 km.

Figure 3.4 depicts the 95% fractiles **of ingestion pathways**. In ARANO and VALMA food consists of local food production of cow milk and meat, grain, green vegetables and roots. MACCS includes the following foodstuffs: grains, leafy vegetables, roots, fruits, legumes, milk, beef, poultry. Milk consumption rates (kg/a) were as follows 365, 200, 100 in VALMA, ARANO, MACCS, respectively. There are some differences also in other exposure pathways, which may affect the results.

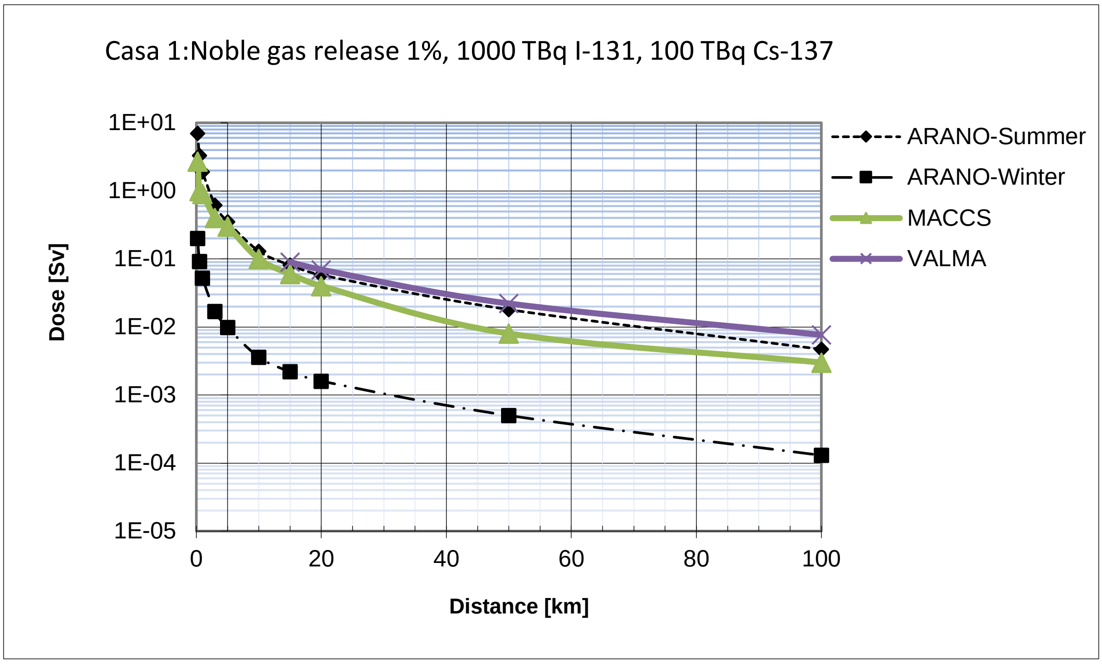


Figure 3.4. Comparison of ingestion pathways. Consumption period is one year.

ARANO results consist of doses when deposition occurs in summer or in winter but in the case of MACCS there is only one curve representing dose from the whole year weather. It seems that the dose values by MACCS are slightly lower than the dose values obtained with ARANO in summer conditions. The VALMA curve may be affected by highest consumption rate.

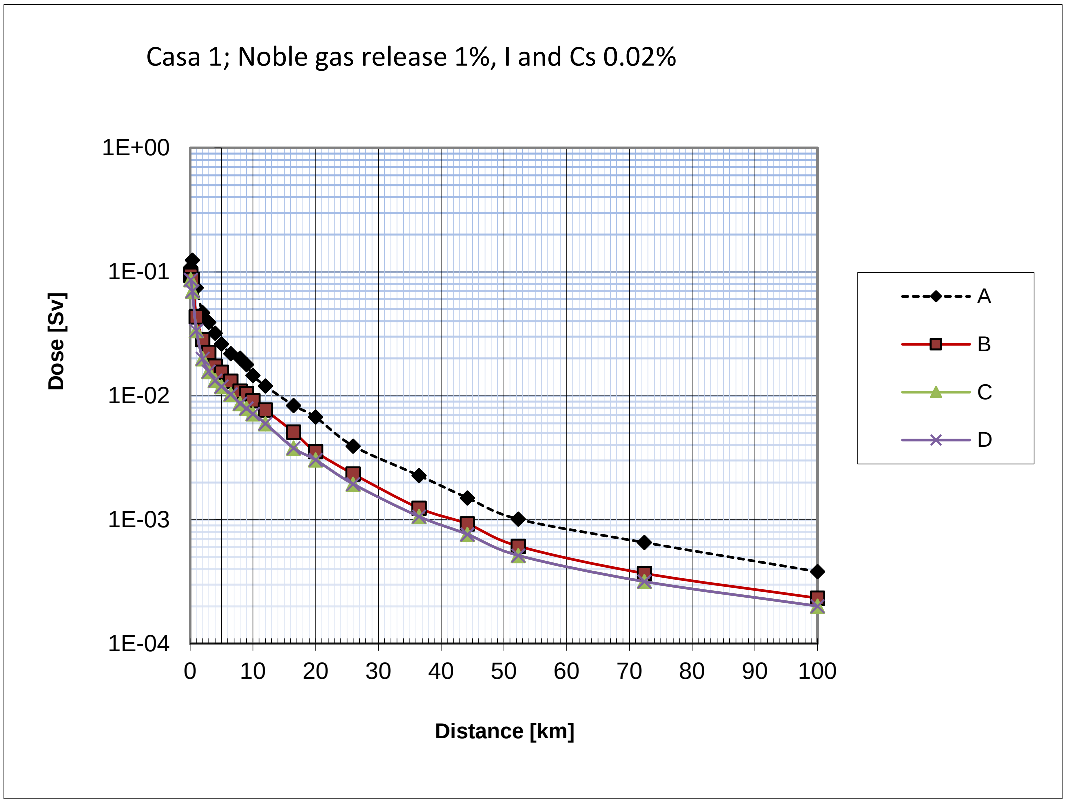
Figure 3.5 illustrates dose dependency on the release segmentation. In MACCS there is a possibility to split the release of three hours into one hour's segments, each having own weather parameters. Moreover there are three alternatives how the prevailing hourly weather can be considered in MACCS. ARANO accepts only one segment and the whole plume is dispersed in the initial direction.

In MACCS there are two terms describing plume dispersion in probabilistic approach: wind shift and rotation.

Choosing ***No Wind Shift with Rotation*** means:
- All subsequent plume segments move in the same direction as the initial plume segment.
- All plume segments are rotated around the compass, creating an expanded set of results for each weather trial when weather bin sampling is selected. The total number of results generated by this process is the number of compass sectors times the number of weather trials. The results for each weather trial are weighted using the wind rose for the weather bin or the user-defined values for the wind rose.

Choosing ***Wind Shift with Rotation*** means:
- Plume segments move in the direction that the wind is blowing at the time of their initial release. Thus, each plume segment is allowed to travel in its own direction.
- All plume segments are rotated around the compass, creating a result for each sector and for each weather trial when weather bin sampling is selected. The results are weighted using the wind rose for the weather bin or the user defined values for the wind rose.

Choosing ***Wind Shift without Rotation*** means:
- Plume segments move in the direction that the wind is blowing at the time of their initial release.
- Only the wind direction indicated in the meteorological file or input is used for the plume segments. Thus, only a single result is generated per weather trial.



A: 1 segment; No Wind Shift with Rotation
B: 3 segments;No Wind Shift with Rotation
C: 3 segments; Wind Shift with Rotation
D: 3 segments; Wind Shift without Rotation

Figure 3.5. Effective non-ingestion dose at 95% fractile. Dependency on the release segmentation in MACCS.

Figure 3.5 shows that the curves with different plume handling behave rather similarly and there is no remarkable difference in dose values. Alternatives C and D produce equal curves. There is a difference with a factor of less than two in the curve values.

It should be noticed that wind rose has no effect on the individual peak dose. However wind rose affects population dose and further e.g. the number of health effects.

<u>Comparison of different weather data</u>

The following two figures 3.6 and 3.7 illustrate effects of weather data for the release Casa 3. There are four different approaches, how weather data is obtained:

Weather 1: mast measurement 2009, stability 60 m, dispersion direction and wind speed 20 m, wind speed conversion to 10 m by STUK's method (Valmari et. al 2003)

Weather 2: mast measurement 2012, stability 100 m, dispersion direction and wind speed 100 m, wind speed conversion to 10 m by MACCS's method (Jow et al. 1990).
Weather 3: converted from FMI's SILAM data for 2012.
Weather 4: mast measurement 20012, stability and dispersion direction 100 m, wind speed 20 m, wind speed conversion to 10 m by STUK's method.

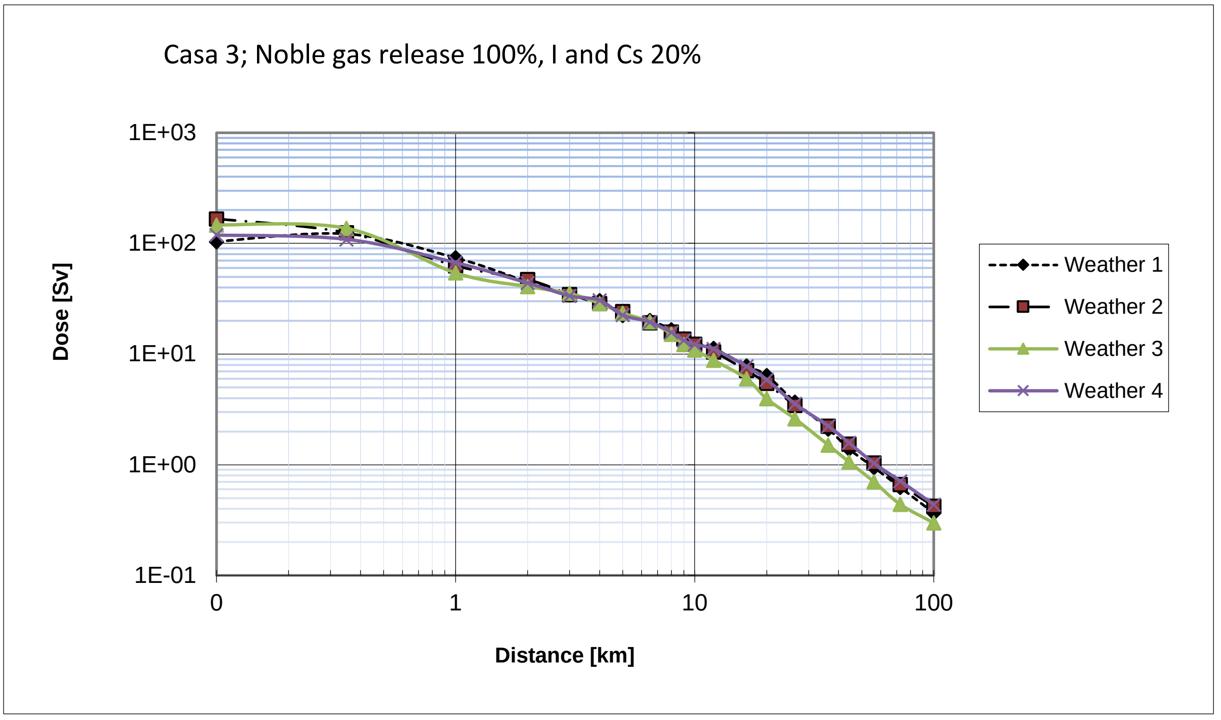


Figure 3.6. Effective dose from the cloudshine, inhalation and ground shine at 95% fractile. Exposure time one year. Dependency on different weather data in MACCS.

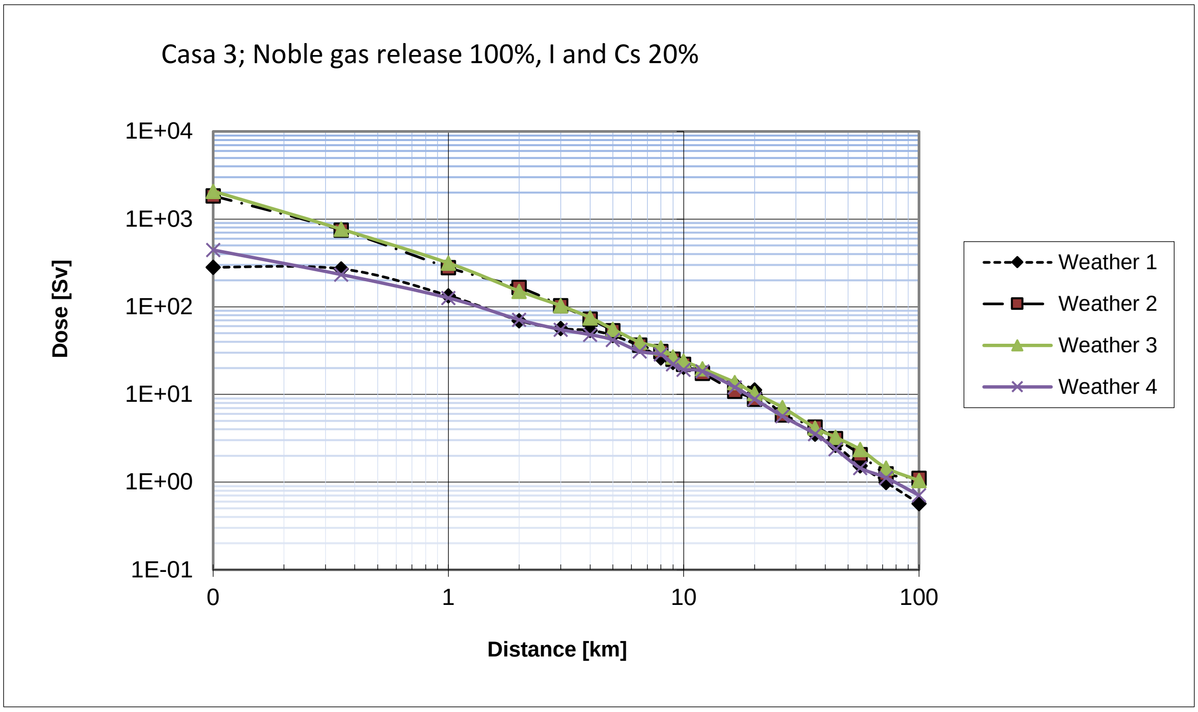


Figure 3.7. Effective dose from the cloud shine, inhalation and ground shine at 99.5% fractile. Exposure time one year. Dependency on different weather data in MACCS.

Figure 3.6 shows that the results representing 95% fractile values are quite similar in different weather cases. In Figure 3.7, there differences are larger especially at short distances.

Table 3.1 represent comparison of dose values obtained by MACCS and VALMA. Here the source term is based on the SMR type reactor accident source term as presented in (Ilvonen M. 2018). It is assumed that only 4 hours of decay cooling took place before the release into the atmosphere starts, and the release duration is only 3 h. Released fractions (of NuScale core radioactive inventory) used in the MACCS and VALMA source term:

```
1    0.0114   'fr_noble_gases'
2    0.0      'fr_organic_iodine'
3    2.4e-4   'fr_iodine'
4    1.8e-4   'fr_alkali_metals'
5    2e-4     'fr_metalloids'
6    2e-4     'fr_alkaline_earth'
7    2e-4     'fr_transition_metals_1'
8    2e-4     'fr_transition_metals_2'
9    2e-4     'fr_lanthanides_1'
10   2e-4     'fr_actinides'
11   2e-4     'fr_transition_metals_3'
12   2e-4     'fr_lanthanides_2'
13   2e-4     'fr_misc_1'
14   2e-4     'fr_transition_metals_4'
15   2e-4     'fr_misc_2'
```

Table 3.1. MACCS vs VALMA: sum cloud+fallout+inhalation (Sv), maximumn of values appearing at the distance, 95 % fractile of year 2012 cases.

	1 km	2 km	3 km	5 km	8 km	12 km
1-week exposure						
MACCS	0.2630	0.1940	0.1730	0.1380	0.0756	0.0497
VALMA	0.1220	0.0597	0.0374	0.0206	0.0112	0.0063
1-year exposure						
MACCS	0.3310	0.2430	0.2210	0.1490	0.0898	0.0523
VALMA	0.1370	0.0668	0.0418	0.0231	0.0125	0.0070

Table 3.1 shows that differences in dose values are small at short distances. There is a maximum difference with a factor of eight in dose, VALMA calculates smaller values.

In VALMA different distributions, complementary cumulative density functions (ccdfs) are prepared. Because at a certain time point several measurement points at a target ring may be affected, it is necessary to select in some way the quantity for the ccdf. Here three different choices were used: mean, median and maximum. The values are determined from the non-zero values on the ring.

MACCS also produces ccdfs of the results. Each source term results in one ccdf when annual weather data is used for dose calculations (mean dose and centerline dose, median not available). From the ccdfs it is then possible to pick different fractile values. Figure 3.8 shows as an example the ccdf of the centerline dose at distance of 5 km.

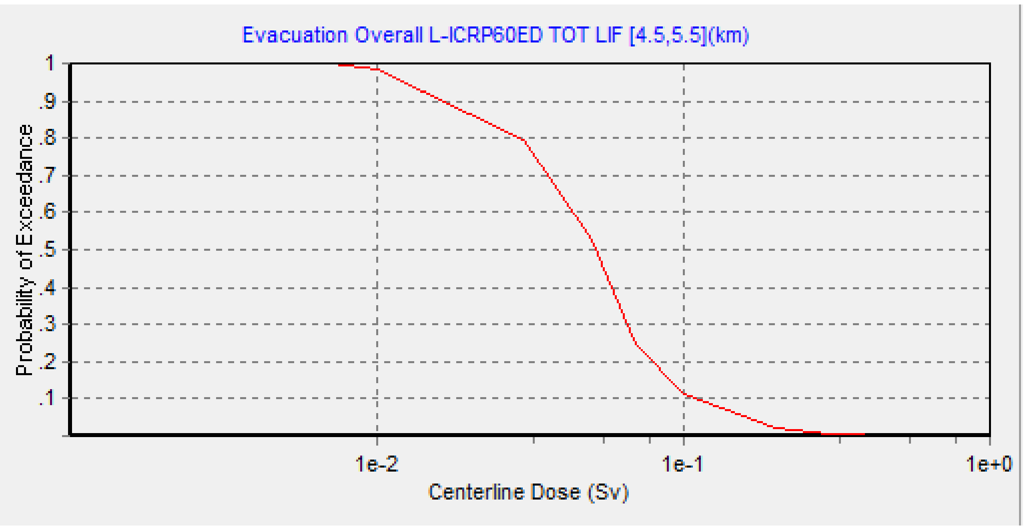


Figure 3.8. The ccdf of the centerline dose at the distance of 5 km from MACCS output.

In figure 3.8 it is possible to adjust axis bounds to some degree.

4. Conclusions

Offsite dose prediction codes MACCS and ARANO are purposed for level 3 PSA studies. Implementation of MACCS was started with studying its features and making some basic dose calculations. There are of course differences in modeling between MACCS and ARANO. Vertical dispersion model of ARANO is based on K_z -model, but MACCS uses traditional Gaussian model. ARANO removes activity on to the ground surface from the lowest part of the plume, but in Gaussian model removal occurs from all the plume altitudes.

These codes were compared with each other by calculating offsite doses in single dispersion conditions as well as applying one year’s weather data measured at the meteorological mast of the nuclear power plant site.

Calculation results demonstrate that there may be a rather significant difference in dose in single dispersion situation but when probabilistic approach is adopted and the dose at 95% fractile is considered, the difference is at the most less than a factor of three. In addition, long-range model VALMA was included in comparisons. Comparable dose estimates of VALMA predict smaller dose values than MACCS at distances up to 15 km. This comparison indicates that MACCS in many cases calculates conservative dose estimates.

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Appendix: Mixing height and stability class distributions

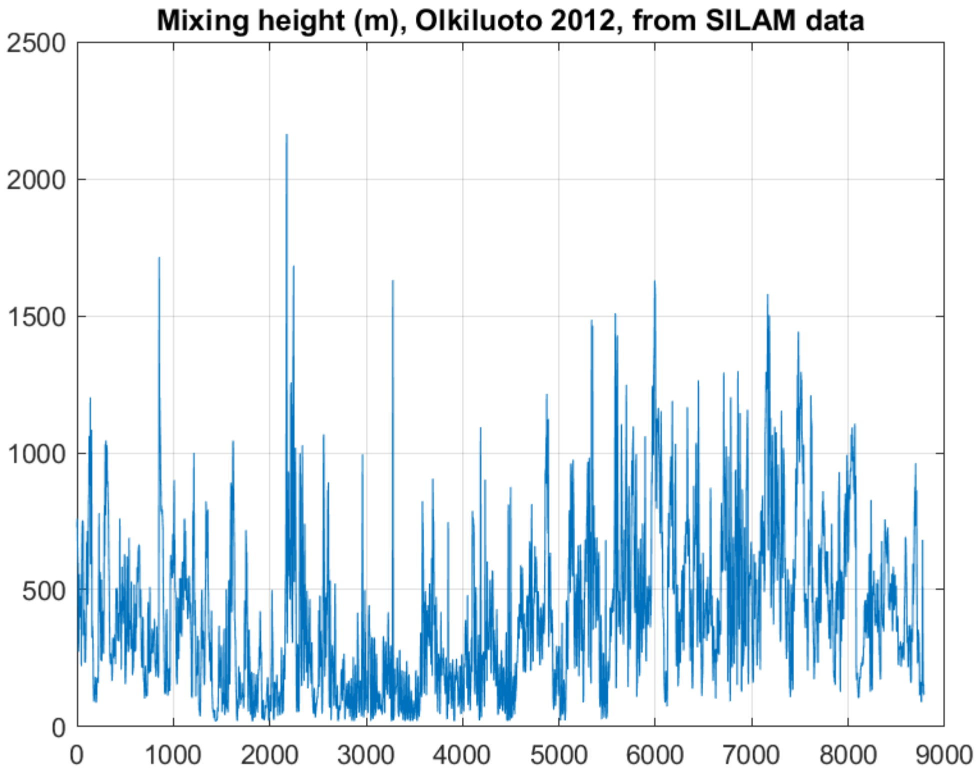
In the code comparisons, VALMA used SILAM-based meteorological data for Olkiluoto (year 2012), whereas ARANO and MACCS were used with mast-based meteorology (parameters measured at the Olkiluoto NPP weather mast). VALMA can also be used with just single-points measurements, but that is not the recommended use, if SILAM data is available. Even for ARANO and MACCS, there are differences in how they use the measured parameters. In ARANO, the mixing height follows from the vertical profiles of the Kz model, and it is basically a function of atmospheric stability. MACCS on the other hand uses only seasonal average mixing heights. ARANO uses basically wind speeds measured for the release height, whereas MACCS wants wind speeds for its fixed reference height, and then calculates the needed speed for the actual release height from a logarithm formula. Considering the differences, it is evident that the meteorological parameters alone could be responsible for significant differences in results, let alone what may be caused by actual modelling differences of the codes.

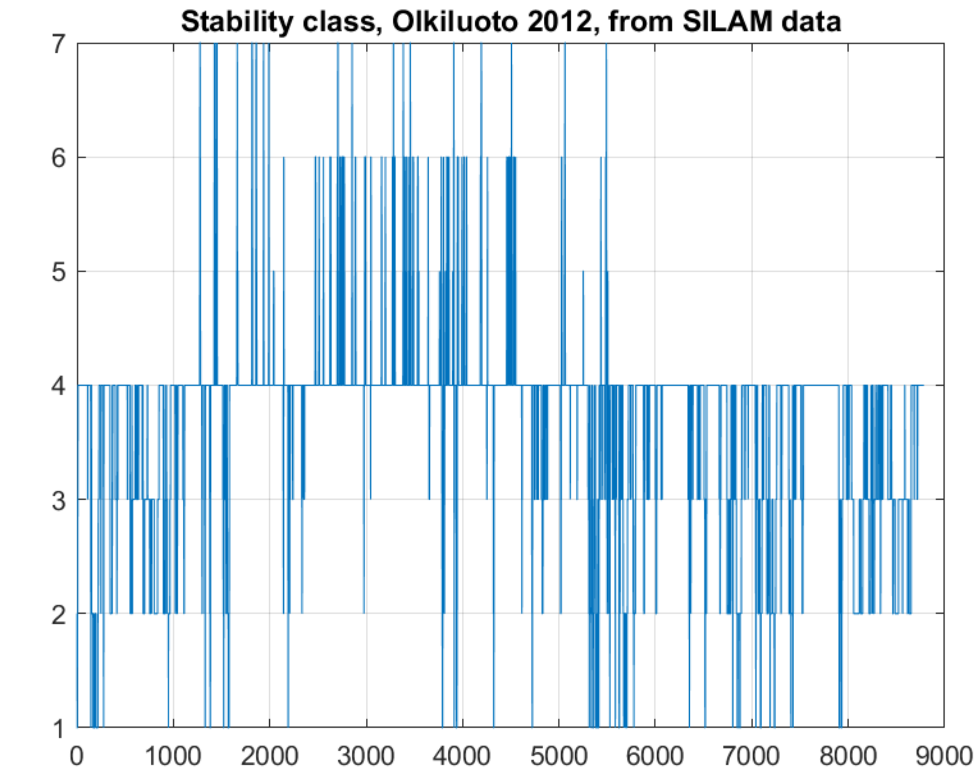
To clarify the situation with different parameters, some temporal plots and distribution histograms of mixing heights and stability classes are included in this Appendix. They show that differences exist, but to dig into the causes and effects would be a huge work, as for example the stability class may be derived from measurements by several methods.

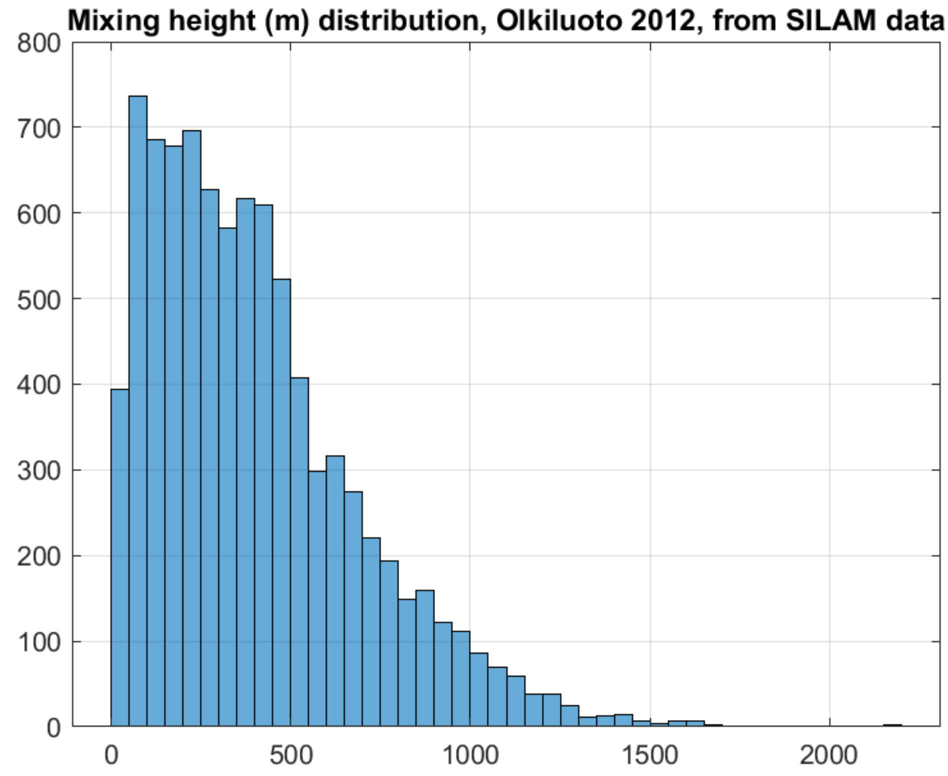
The figures in this Appendix are the following, in order:

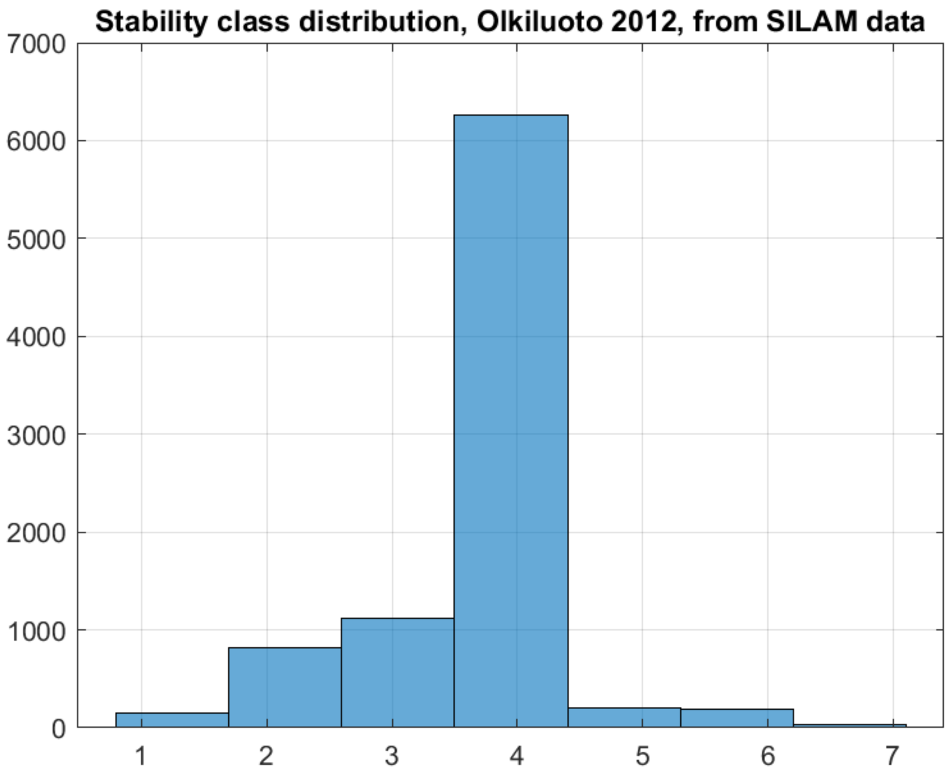
- Mixing height and stability (from 1 = A to 7 = G) from SILAM, for the starting point of trajectories (Olkiluoto NPP), for each hour (366 x 24 = 8784) of the leap year 2012 (2 figures). In these two plots, seasonal differences seem evident. Stable conditions are concentrated in spring and summer (1 March = hour 1440).
- Distributions of mixing height and stability class from SILAM, for the whole year 2012 (2 figures).
- Distributions of SILAM mixing heights for the 4 seasons separately (4 figures).
- Distributions of SILAM stability classes for the 4 seasons separately (4 figures).
- Distributions of mast-derived stability classes for the 4 seasons separately (4 figures). The method based on temperature differences was used. However, newer methods include wind direction variations and also Monin-Obukhov length.

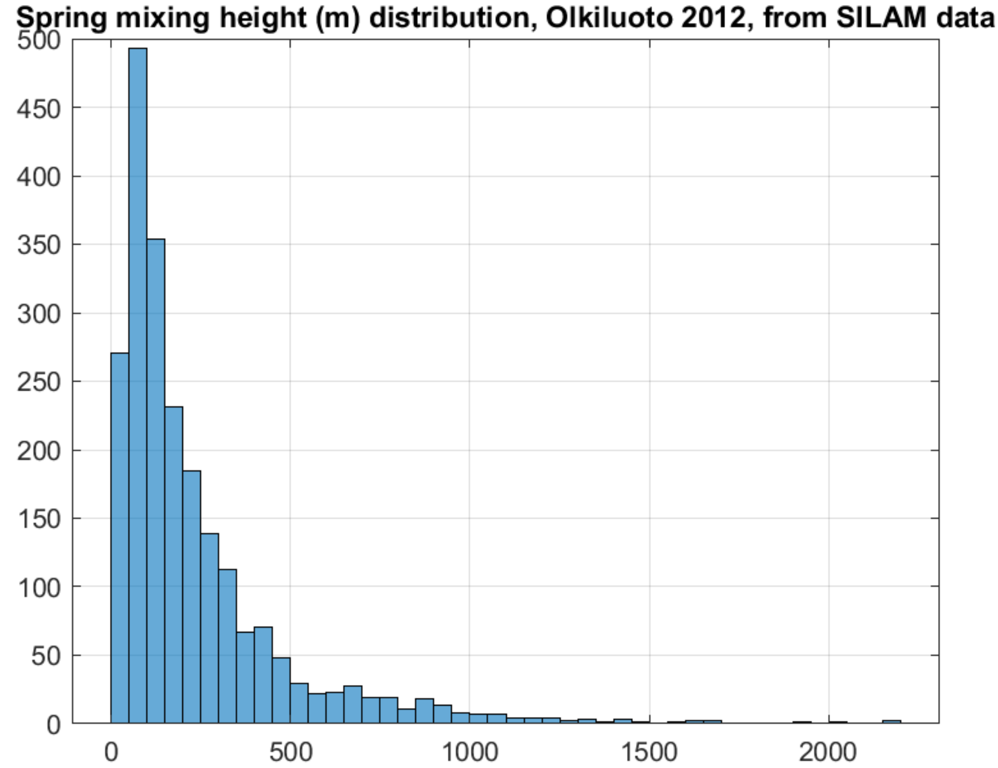
Comparing the stability class distributions, it seems that SILAM has emphasized neutral (4 = D), whereas the mast-derived stabilities have relatively more of the stable and unstable values. However, from both sources, D is the dominating class.

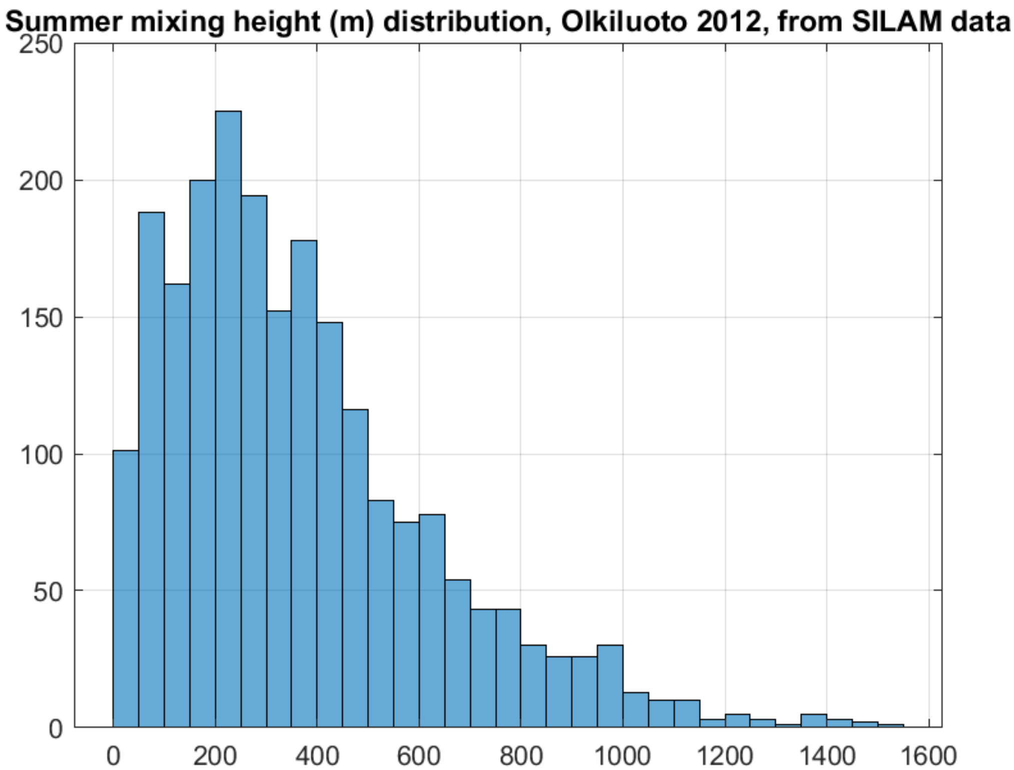

Mixing height (m), Olkiluoto 2012, from SILAM data
0
500
1000
1500
2000
2500
0 1000 2000 3000 4000 5000 6000 7000 8000 9000


Stability class, Olkiluoto 2012, from SILAM data
1
2
3
4
5
6
7
0 1000 2000 3000 4000 5000 6000 7000 8000 9000

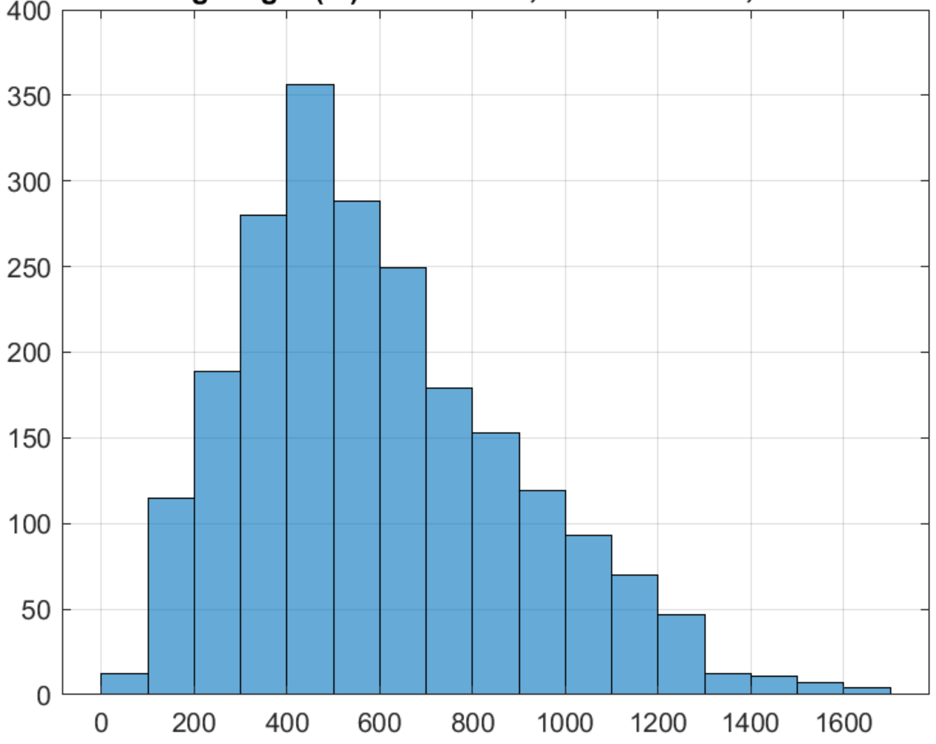

Mixing height (m) distribution, Olkiluoto 2012, from SILAM data
800
700
600
500
400
300
200
100
0
0
500
1000
1500
2000


Stability class distribution, Olkiluoto 2012, from SILAM data
7000
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7

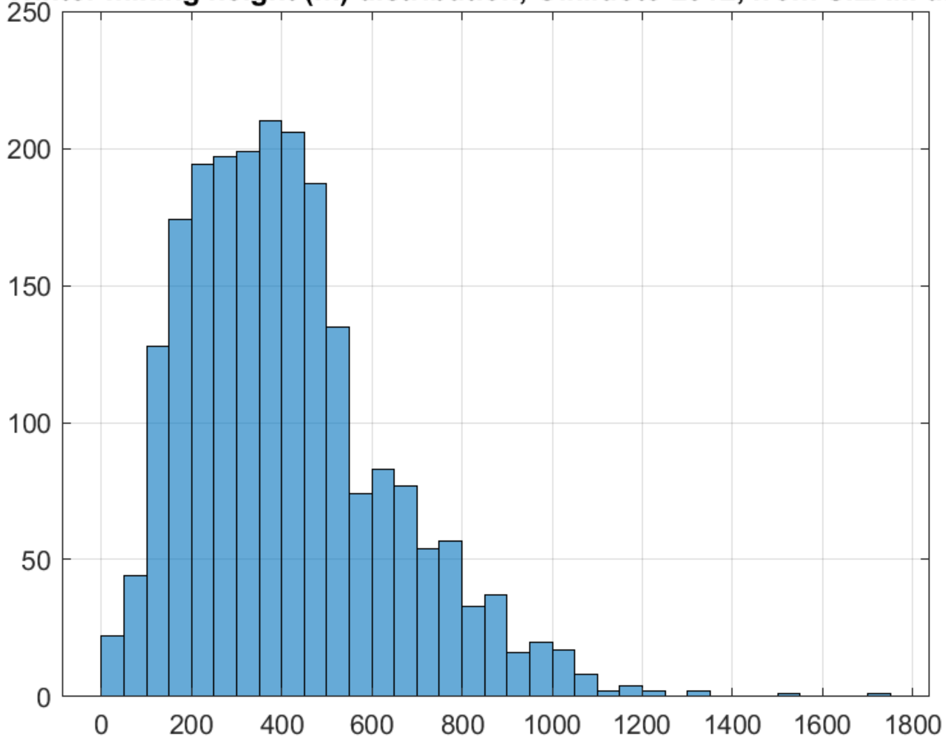

Spring mixing height (m) distribution, Olkiluoto 2012, from SILAM data
500
450
400
350
300
250
200
150
100
50
0
0
500
1000
1500
2000

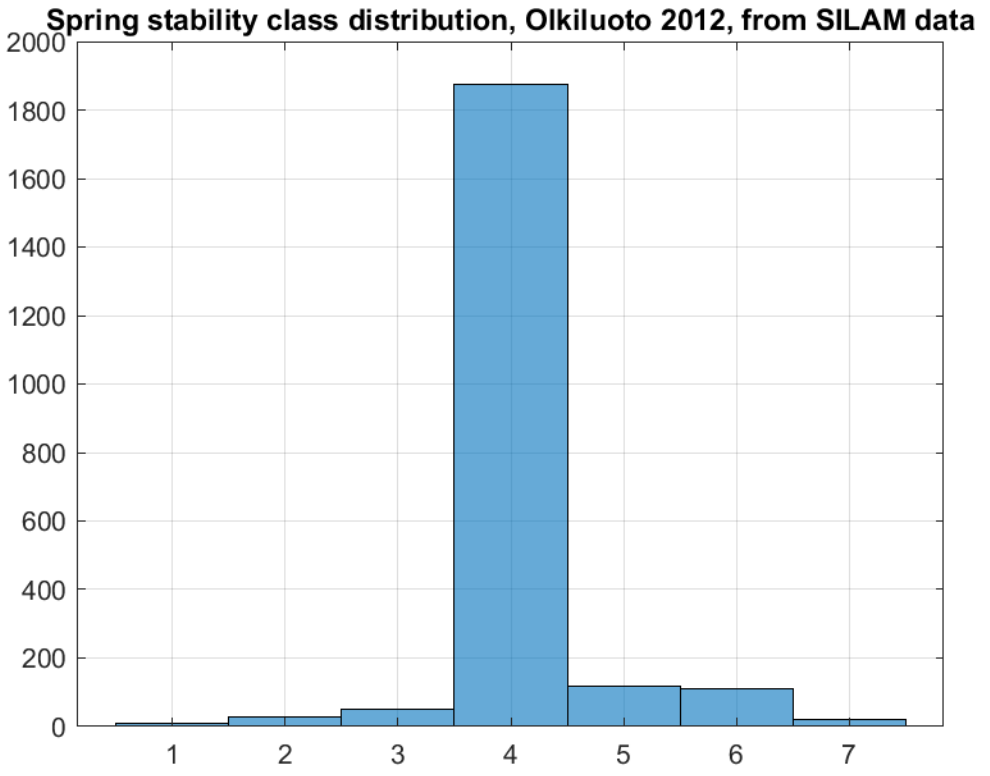

Summer mixing height (m) distribution, Olkiluoto 2012, from SILAM data
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600

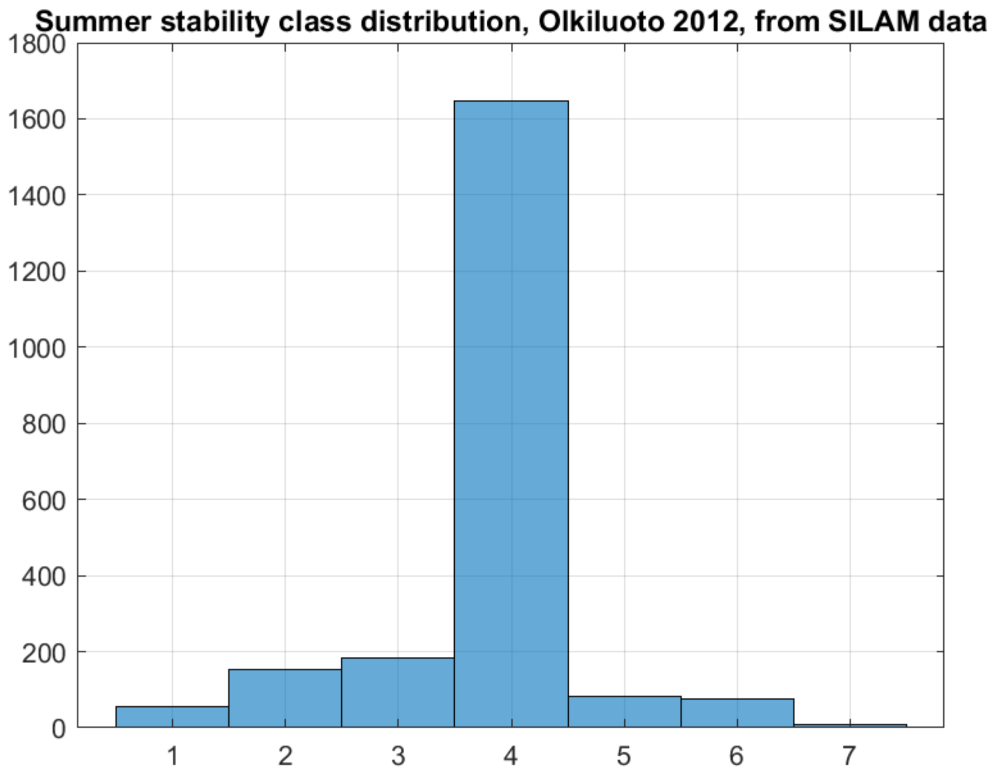
Autumn mixing height (m) distribution, Olkiluoto 2012, from SILAM data

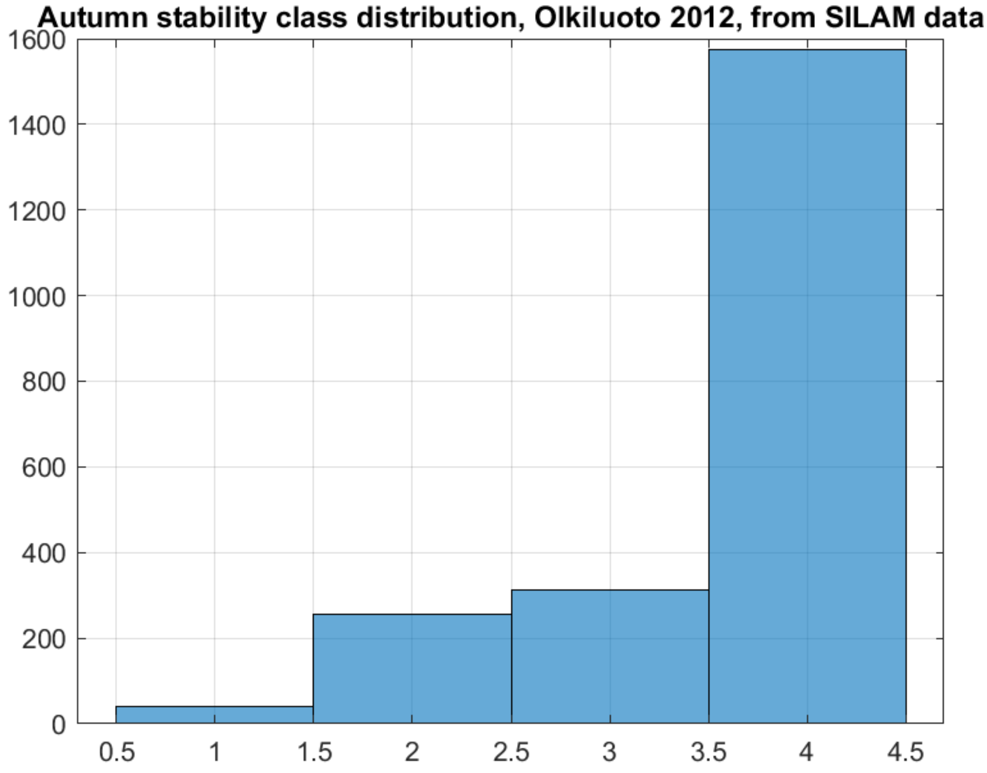


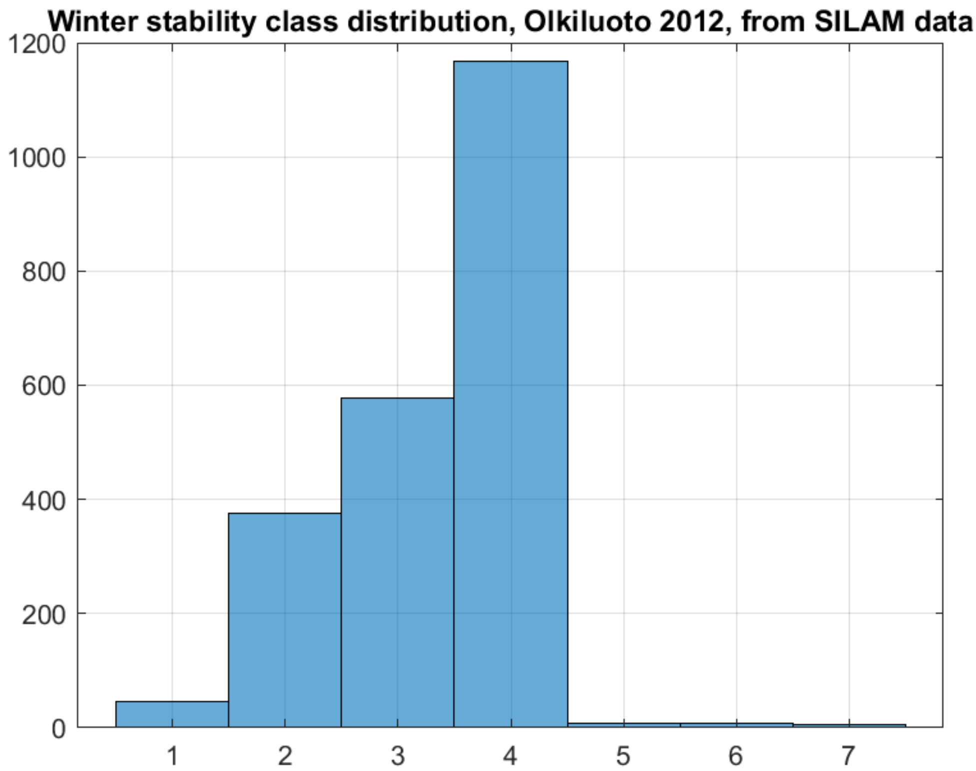
Winter mixing height (m) distribution, Olkiluoto 2012, from SILAM data

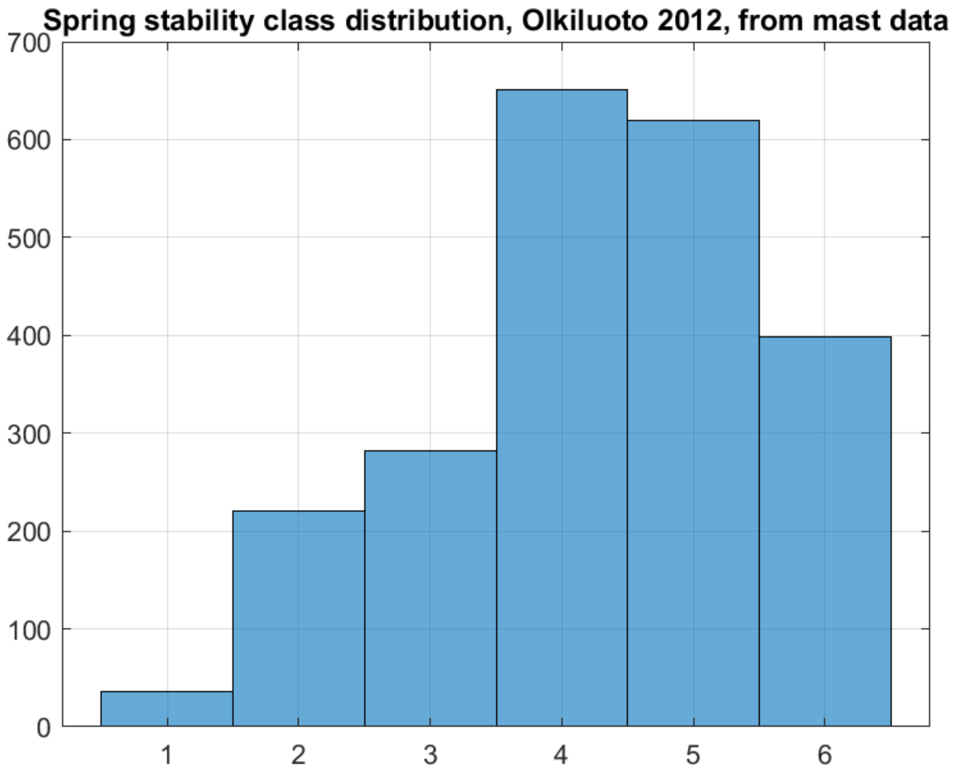


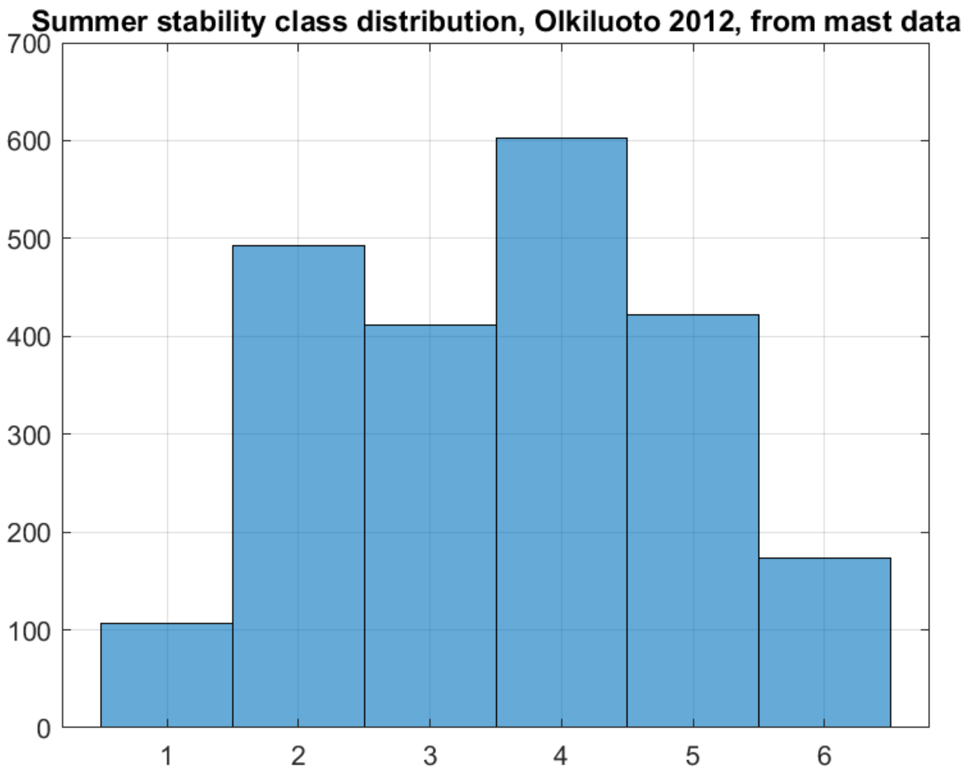

Spring stability class distribution, Olkiluoto 2012, from SILAM data
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1
2
3
4
5
6
7

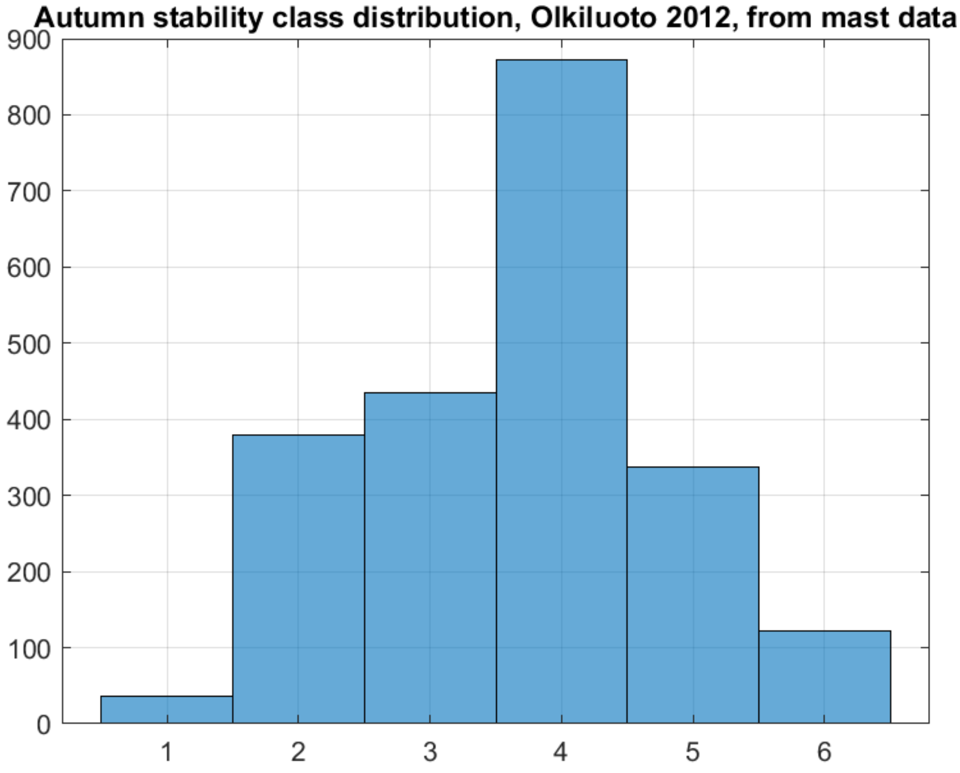

Summer stability class distribution, Olkiluoto 2012, from SILAM data
1800
1600
1400
1200
1000
800
600
400
200
0
1
2
3
4
5
6
7

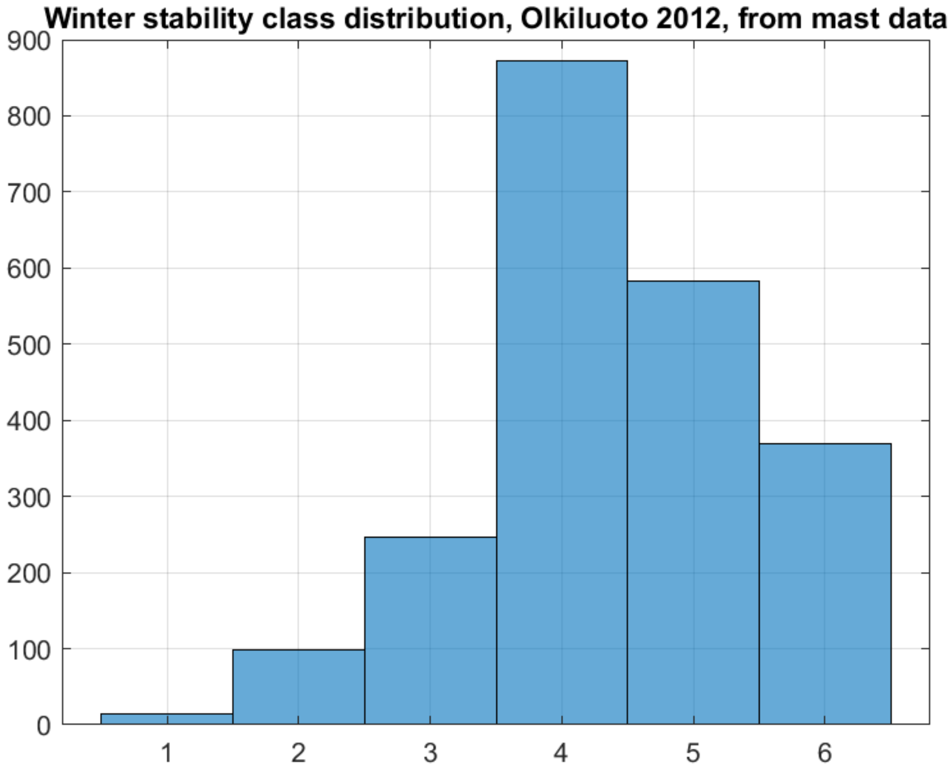

Autumn stability class distribution, Olkiluoto 2012, from SILAM data
1600
1400
1200
1000
800
600
400
200
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5


Winter stability class distribution, Olkiluoto 2012, from SILAM data
1200
1000
800
600
400
200
0
1
2
3
4
5
6
7


Spring stability class distribution, Olkiluoto 2012, from mast data
0
100
200
300
400
500
600
700
1
2
3
4
5
6


Summer stability class distribution, Olkiluoto 2012, from mast data
0
100
200
300
400
500
600
700
1
2
3
4
5
6


Autumn stability class distribution, Olkiluoto 2012, from mast data
900
800
700
600
500
400
300
200
100
0
1
2
3
4
5
6


Winter stability class distribution, Olkiluoto 2012, from mast data
900
800
700
600
500
400
300
200
100
0
1
2
3
4
5
6