Estimating degree-day factors of snow based on energy flux components

Editor: Harry Zekollari (Comments and Responses)

Comments to the author:

Dear Muhammad Fraz Ismail and colleagues,

Many thanks for having addressed all the comments by the four reviewers in great detail and for having updated your manuscript accordingly. Originally, I had anticipated to send out the manuscript for a second round of reviews but given your very detailed and adequate answering of all issues raised, I do not consider this to be necessary at this stage. Instead, I have re-read your manuscript entirely again, and provided a (relatively long) list of comments to be addressed in the PDF directly. Most of these are minor (including many grammar suggestions) and will require very little work, while a few comments are slightly more substantial and will require to have some extra info in the manuscript (but normally not requiring additional/new analyses to be performed).

Additionally, the figures require some work (see comments for every figure in the pdf directly), and there is room to shorten the overall length of the manuscript (as pointed out by some of the reviewers): I have indicated parts of the manuscript that are quite long (/ too long?), and/or not directly relevant for your story and that could therefore be removed or reduced (including some tables to be moved to suppl. mat.). Finally, while the topic you are addressing is timely, you refer in many cases to (only) (very old) studies: it would be good to have some more recent references in some places. The timeliness of your study is also clear from the recent debate that has (re)appeared on having constant (stationary) degree-day factors over time when modelling snow and ice melt. The debate strongly relates to whether degree-day approaches are capable of capturing non-linearities in melt, which may be important in a changing climate where the relationship between degree-days and melt is likely to change.

More specifically, I suggest you to have a look at the recent works by Bolibar et al. (2022, Nature Communications), Vincent and Thibert (2022, The Cryosphere Discussions), and Matthews et al. (preprint, https://www.researchsquare.com/article/rs-2166876/v1), and to potentially include these in your discussion and how your work fits in this existing 'debate'.

Thanks a lot for your work, and I look forward to seeing your updated manuscript.

Best regards,

Harry

Dear Editor,

Thank you very much for your constructive comments and suggestions to improve the manuscript. We are very grateful for the comprehensive manuscript summary and acknowledging our contribution. We have now updated all the figures as tables as per your comments and suggestions. We have also put all the necessary tables and figures in the supplementary materials. Some of the paragraphs are removed/reduced as per your recommendations. If we intend to retain any paragraph, then we also provide the reason for retaining it. We thank you very much for providing us with the updated recent references. We have included these updated references in the revised manuscript.

Based on your comprehensive comments and suggestion, we have made numerous changes in the revised version of our manuscript. Below, we repeat each of your comment and our reply to them one by one. All responses are in blue font for clarity of reading.

Muhammad Fraz Ismail

On behalf of all the authors

DETAILED POINTS

Title: "Of snow" (In general, need to specify this. Also, in some locations in text. Otherwise, could also be ice (+for outsiders is not given that they know this typically applies to snow and ice).

We have now changed the title of the manuscript to *Estimating degree-day factors **of snow** based on energy flux components* as per your recommendations.

Line 55: Update references!

We have now updated the references in the manuscript as per your comments and suggestions. A list of all new references has been provided at the end of this document.

Line 99: Quite a lot on this recently. Would be good to go a bit more in detail into this. See also general comment and work by Matthews et al. (under review), Bolibar et al. (2022), and Vincent and Thibert (2022).

We have now provided these references in the literature review as well as in the discussion section.

Table 1: Make sure this is on page when resubmitting

Table 1 is now on page. Kindly refer to the manuscript version without track changes.

Figure 3: Test to small SWE (mm w.e.) vs. [] I don't get this comment Axes too small Not sharp. Export/save as vector (e.g. PDF, SVG) instead of raster. Of higher res raster.

All the figures have been updated and all your comments have been addressed. We have now provided a separate PDF document with only high-resolution figures.

Line 202: Maybe remove?

"Unit area column" was mentioned according to a comment of RC4, but we appreciate using the original formulation as follows.

The energy flux available for snowmelt Q_M can be calculated from the balance of energy fluxes entering or leaving the snowpack and the change in the internal energy stored in the snowpack ΔQ.

Line 275 – 277: Then, probably best to remove entire part here (see next comment)

We would like to keep this paragraph in order to mention approaches that can be used in situations where only temperature data is available.

Line 284 – 285: Formula 14 & 15: Why two? What is difference? Specify or only give one.

In eq. (14) and (16) only the parameter *a* of eq. (11) is a function of altitude *z*, while in eq. (15) and (17) also the parameter *b* is dependent on *z*.

Line 300: Why? Would be good to give at least a hint.

We have rephrased the paragraph as follows, hoping it becomes clearer:

… It should be noted, that although *Kz* is higher for overcast than for clear sky conditions, the absolute increase of the clearness index K_T with altitude is higher under clear sky conditions because of the higher base value K_{T_0}. For example, at z = 2000 m a.s.l. model Jin (b) (eq. **Error! Reference source not found.**) has a clearness altitude factor K_z of 1.27 for overcast and 1.10 for clear sky conditions. However, when multiplying by the respective clearness factors at sea level K_{T_0} of 0.15 and 0.72, the resulting clearness indices K_T at z = 2000 m a.s.l. increase by 0.04 under overcast and 0.07 under clear sky conditions to an absolute value of 0.19 and 0.79 respectively.

Figure 4: Increase font size! Figure will be reduced in size -> will be hard to read What is the difference between Jin (a) and Jin (b)? see also comment on this earlier. Remove all unused space in graphic Replace [] with ().

All the figures have been updated as per your comments and suggestions.

Caption Figure 4: What does this mean? Applicable to what?

We have now rephrased the caption as follows.

Clearness altitude factor *Kz* for latitude 45° and different altitudes, based on different models presented in equations (14 – 17, i.e. Jin (a), Jin (b), Rensheng, and Liu).

Line 310 – 311: Twice the name. Don't have more recent reference?

These are two different papers. We have also added a more recent reference i.e., Amaral et al., (2017).

Line 312: Really? So old?

The basic exponential approach has not changed since then. There are more recent approaches to obtain albedo from satellite data, but we don't want to go into this.

Line 358: Screen Level: What is this?

The level at which the instruments take the measurements.

Line 372 – 378: Not needed here I would say. Too detailed. Focus on methodology that matters for your work!

This was an important comment of **RC1**. As we demonstrate effects of altitude (pressure), temperature and humidity on sensible and latent heat later, we think respective equations should be given.

Line 380 – 382: Does not seem to be relevant for your story here.

Example values are given to show the magnitude of density change.

Line 388 – 392: Possibly remove?

We have now removed the paragraph.

Section 3.2.5: So no need for this section. Be more compact, focus on the essence.

As suggested, we have deleted the section.

Line 391: How is this related to other half-year (which you do not show from my understanding?)

The curve for the other half of the year will be mirror image. That is why we only show half the part.

Figure 5: Make more compact, all 3 on one line, increase font size, because will be (much) smaller when typesetted + quality -> export as vector of high-res raster

All the figures have been updated as per your comments and suggestions.

Table 2: Seems redundant with fig. 6 -> suggest moving to suppl. Mat, will also help reducing the (excessive) length of manuscript.

We have now moved this table to the supplementary materials.

Figure 6: Legend not color blinding proof (e.g., Green + red) add info (also) next to respective line, Larger font size

All the figures have been updated as per your comments and suggestions.

Line 574 – 579: Suggest to remove. Aside-track from main story and not part of your results. Eventually to part of the discussion.

We have now removed the paragraph.

Table 3 Merge with **table 4**

We have now deleted Table 3, and Table 4 has been moved to the Supplementary Materials because Figure 07 has been drawn from Table 4.

Figure 7: Legend not colorblind proof. Add info in figure also Remove blank space Larger font size Replace [] with ()

All the figures have been updated as per your comments and suggestions.

Table 5: To suppl. Mat. Info in Figure 8

Table 5 has been moved to the Supplementary Materials.

Figure 8: Remove blank space larger legend and not colourblind proof See remarks for fig. 6

All the figures have been updated as per your comments and suggestions.

Figure 9: Font size larger Reduce hight by about 50%

All the figures have been updated as per your comments and suggestions.

Line 684: Linked to cloudiness? Maybe give hint here.

We have added the hint to the relevant figure (see Figure 4).

Line 695: Over which altitude range?

We have now provided the altitude ranges from respective references. The updated paragraph reads as follows:

For example, in the Nepalese Himalayan region, seasonal-average *DDF* increases from 7.7 to 11.6 mm d^{-1} $°C^{-1}$ with respect to altitude ranging 4900 to 5300 m a.s.l. (Kayastha et al., 2000) whereas Kayastha and Kayastha, (2020) found that the model-calibrated range of the *DDF* in central Himalayan basin varies between 7.0 – 9.0 mm d^{-1} $°C^{-1}$ over an approximate altitude range of 4000 – 8000 m a.s.l.

Line 705: Include albedo info in figure!

We have included albedo in the figure.

Line 734: A bit vague when formulated as such. -> can you be more specific? The reason?

We have reformulated the paragraph as follows:

Under overcast conditions, DDF_L is neutral or slightly positive while the DDF_S component decreases because degree-days are rising faster than input from solar radiation, which implies that sky conditions (i.e., overcast, and clear sky) are more decisive for an estimate of the *DDF* than the day of the year.

Line 742: breaking in (What is this?)

The English terminology was suggested by **RC1**. Meaning a sudden and fierce change of weather conditions.

Line 744 – 749: Too detailed and not crucial in your story it seems. Suggest removing

We have now removed it as per your suggestion.

Line 803: Where is this shown (SNOWPACK results)? Did you do this? Not clear + provide info (e.g. in suppl. Mat).

We have now provided the graphs/figures in the supplementary materials section S2.

Figure 11: Data source and period in caption not in figure. How are these new snow events defined? When is it new?

All the figures have been updated as per your comments and suggestions. New snow events are defined with a threshold of precipitation ≥ 5mm d^{-1}.

Line 818: Why for this region and not for your study site? Would be good to explain.

The following para has been added.

In the current example, the Upper Jhelum catchment is discussed because of elevation zone wise data availability in comparison to test site where only point data is available (for more detail see Sec. 2).

Line 823: Where does future climate come from? Why RCP´s and no SSPS? Need more info here on how this is calculated Ok given later (see last comment on this page) can you provide this here?

The following para has been added.

Figure 12 shows the overall picture that how the *DDF* for snow will change over time and under climate change (i.e., Present, RCP2.6, RCP8.5 (for *DDF* estimates under climate change, see Sec. 5.2.3)).

Line 830: You (almost) never mention snow for DDF, so confusing when you do here. Suggest removing.

As per your suggestion, we have now modified the manuscript title as well as mentioned several times in the manuscript. We hope that now it is clear.

Line 855: Here could include studies Bolibar et al (2022) Vincent and Thibert (2022) + Matthews et al for discussion

We have included the necessary references in the revised manuscript.

Figure 12: Remove blank space, Legend and font larger, Quality : vector

We have retained the x-axis from February to August in all facets because we want to show how the DDFs vary over time and under climate change. In our opinion it would be nice to show the same time frame for all the facets. We have also incorporated your comments about legend size and picture quality.

Line 869: Most of which I suggest moving to suppl. Mat. Given limited added value compared to figures.

As per your suggestions, we have moved the necessary tables in the supplementary materials.

Line 886: Conclusion: Not sure I understand. How can DDF be moderate?

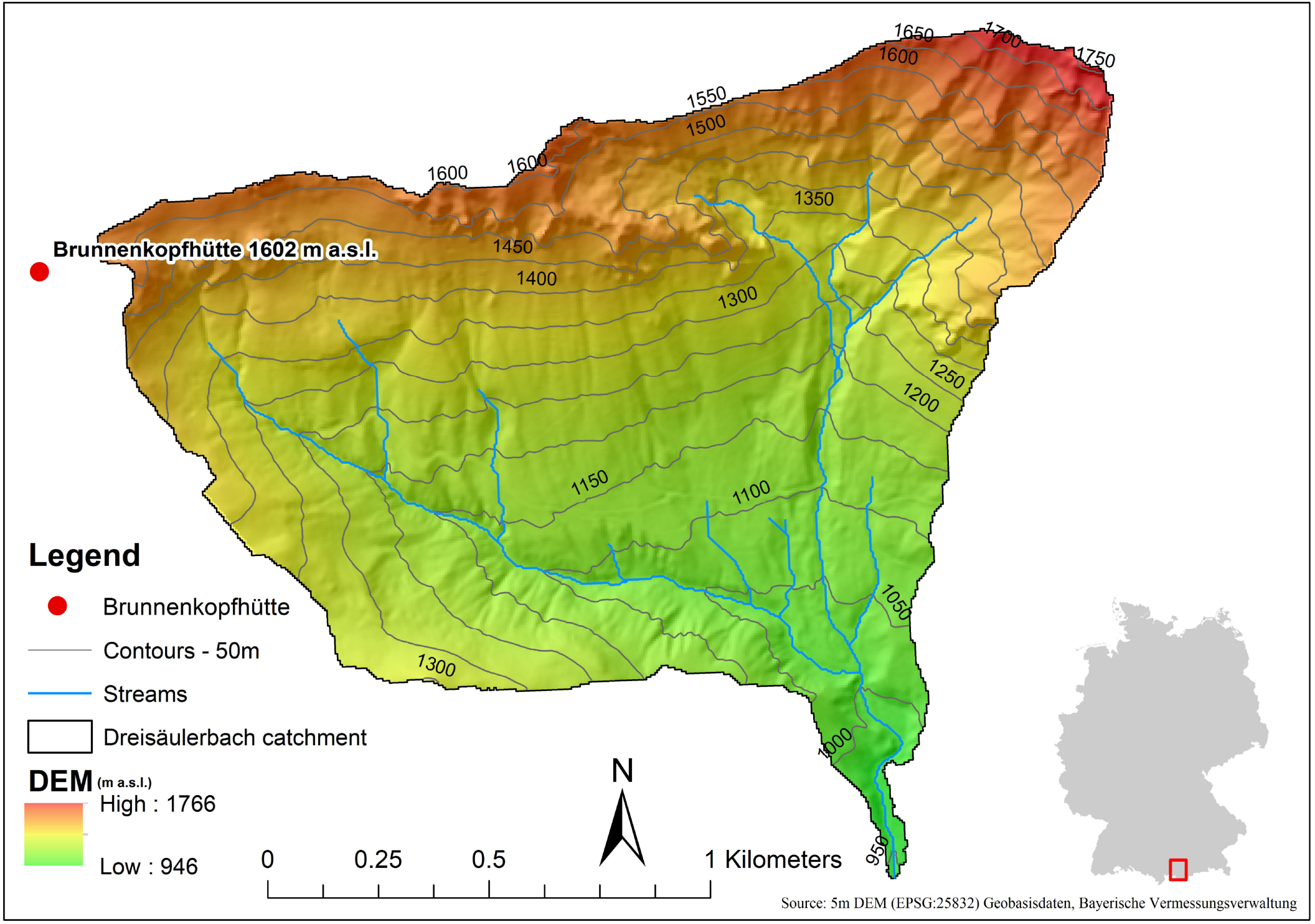
We have reformulated the sentence as follows:

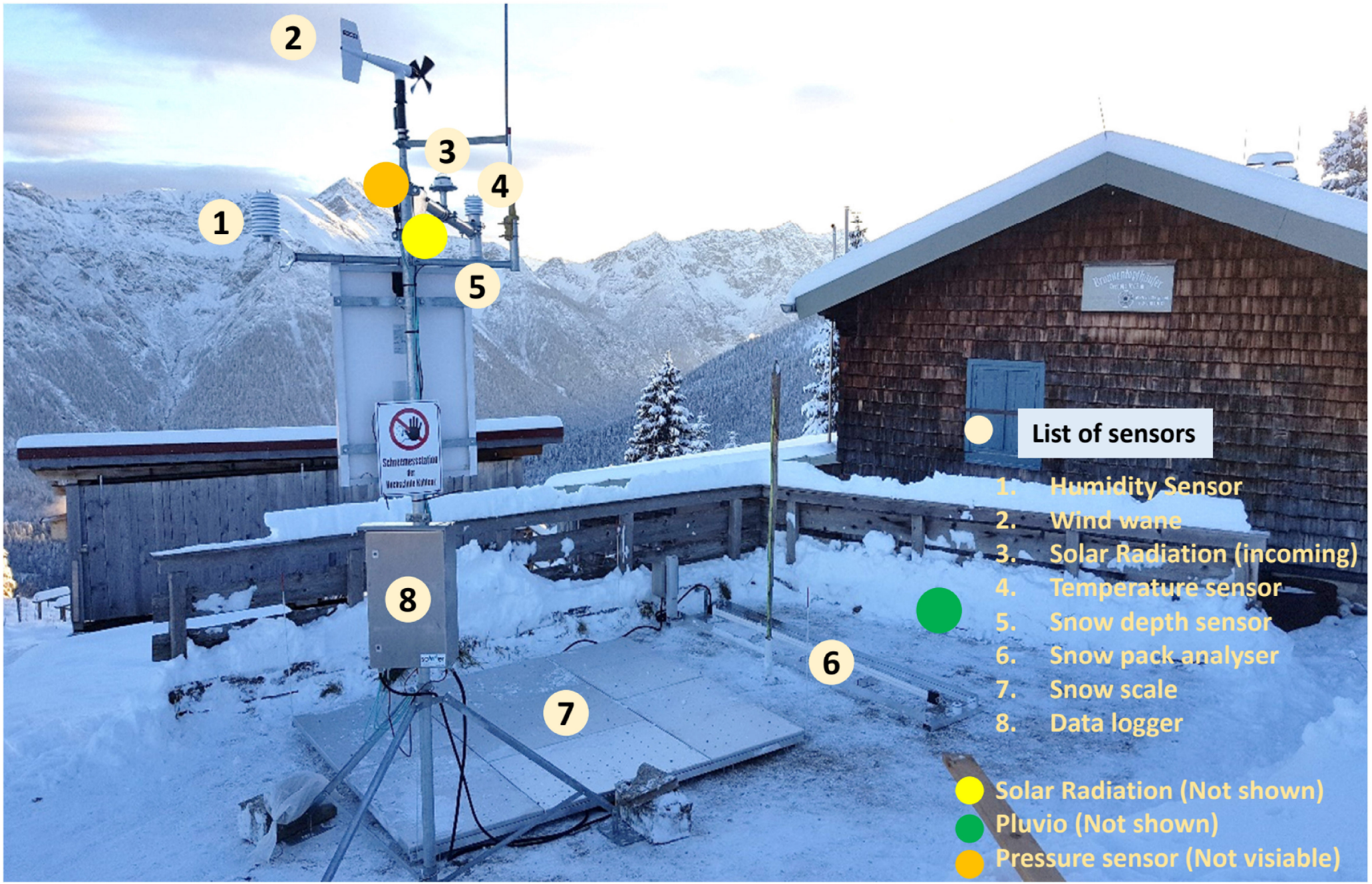
Therefore, total *DDF* value is not very high and variations due to other factors are usually limited, apart from exceptional rainstorm events, for which energy balance models are the more suitable approach.

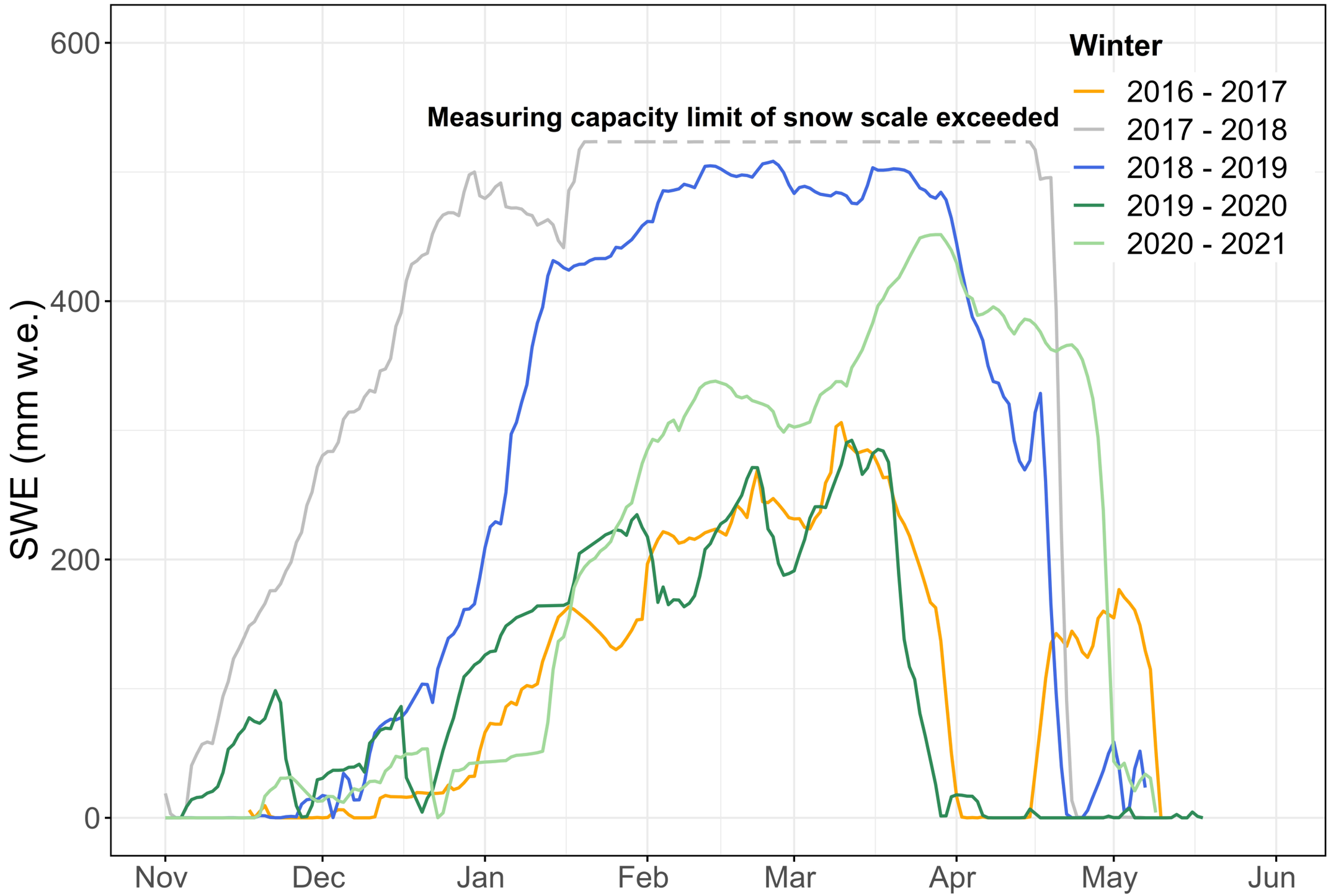
List of new References:

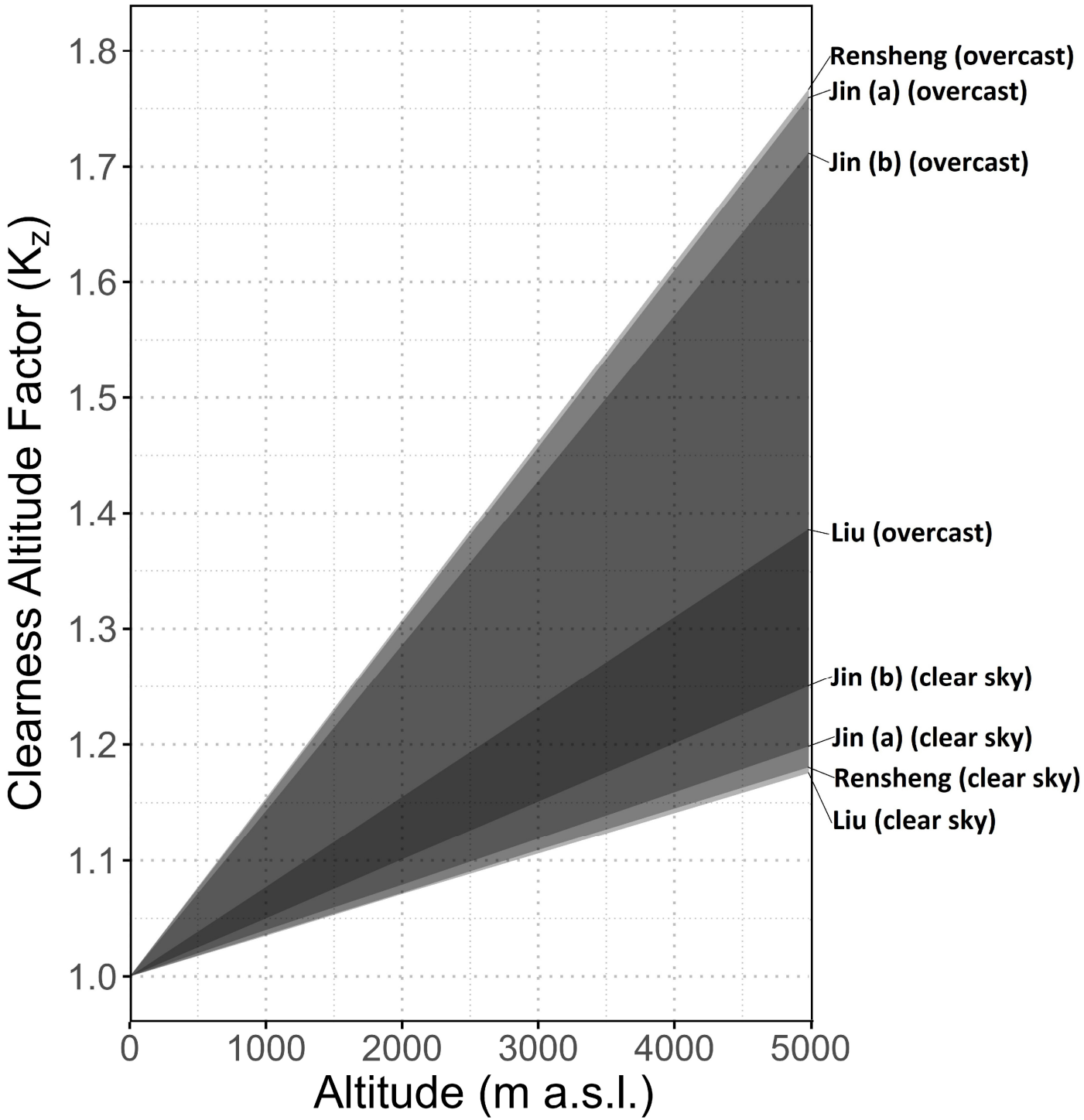
- Amaral, T., Wake, C. P., Dibb, J. E., Burakowski, E. A., and Stampone, M.: A simple model of snow albedo decay using observations from the Community Collaborative Rain, Hail, and Snow-Albedo (CoCoRaHS-Albedo) Network, J. Glaciol., 63, 877–887, https://doi.org/10.1017/jog.2017.54, 2017.
- Badescu, V. (Ed.): Modeling solar radiation at the earth's surface: recent advances, Springer, Berlin, 517 pp., 2008.
- Bolibar, J., Rabatel, A., Gouttevin, I., Zekollari, H., and Galiez, C.: Nonlinear sensitivity of glacier mass balance to future climate change unveiled by deep learning, Nat Commun, 13, 409, https://doi.org/10.1038/s41467-022-28033-0, 2022.
- Huss, M. and Hock, R.: Global-scale hydrological response to future glacier mass loss, Nature Clim Change, 8, 135–140, https://doi.org/10.1038/s41558-017-0049-x, 2018.
- Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A. B., Viviroli, D., Wada, Y., Xiao, C., Yao, T., and Baillie, J. E. M.: Importance and vulnerability of the world's water towers, Nature, 577, 364–369, https://doi.org/10.1038/s41586-019-1822-y, 2020.
- Muhammad, S., Tian, L., Ali, S., Latif, Y., Wazir, M. A., Goheer, M. A., Saifullah, M., Hussain, I., and Shiyin, L.: Thin debris layers do not enhance melting of the Karakoram glaciers, Science of The Total Environment, 746, 141119, https://doi.org/10.1016/j.scitotenv.2020.141119, 2020.
- Oerlemans, J.: Glaciers and climate change, A.A. Balkema Publishers, Lisse ; Exton, (PA), 148 pp., 2001.
- Swinbank, W. C.: Long-wave radiation from clear skies, Q.J Royal Met. Soc., 89, 339–348, https://doi.org/10.1002/qj.49708938105, 1963.

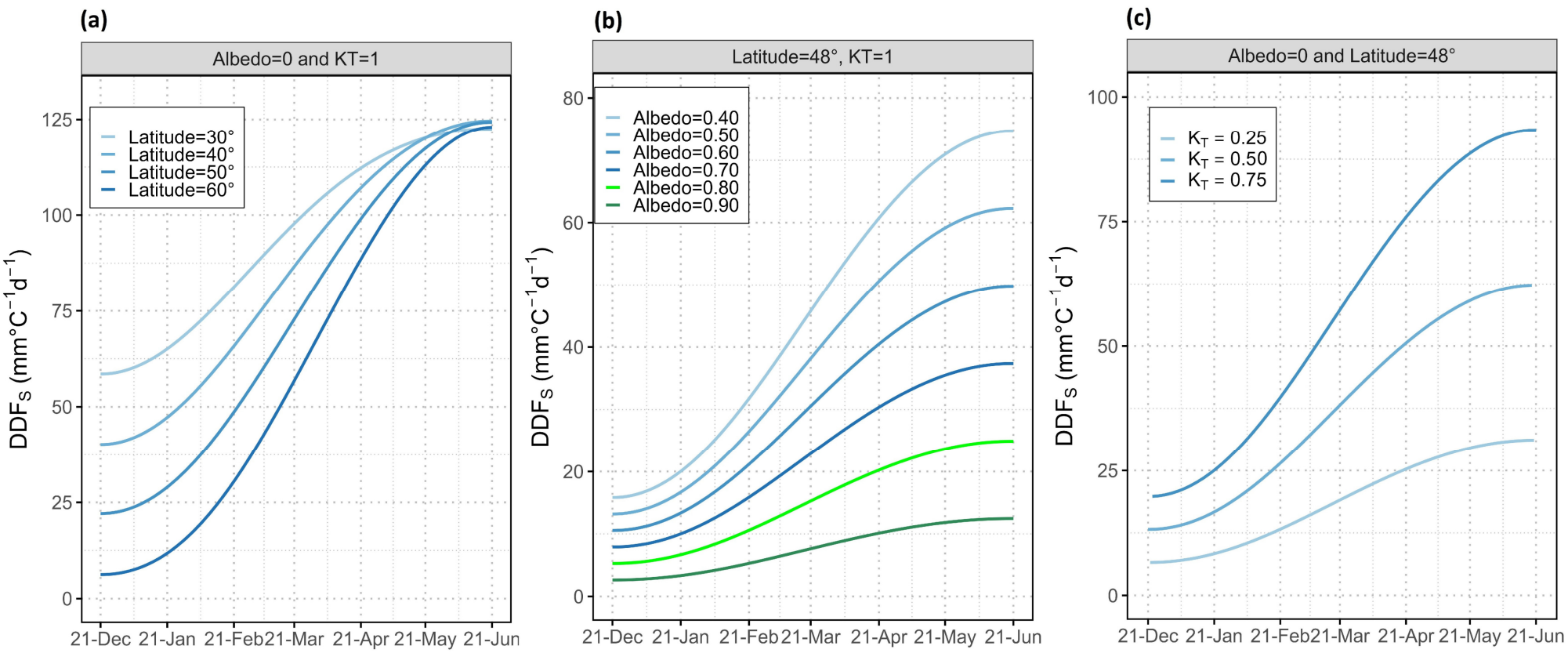
- Vincent, C. and Thibert, E.: Brief communication: Nonlinear sensitivity of glacier-mass balance attested by temperature-index models, Glaciers/Alpine Glaciers, https://doi.org/10.5194/tc-2022-210, 2022.
- Yang, K. and Koike, T.: A general model to estimate hourly and daily solar radiation for hydrological studies: GENERAL SOLAR RADIATION, Water Resour. Res., 41, https://doi.org/10.1029/2005WR003976, 2005.

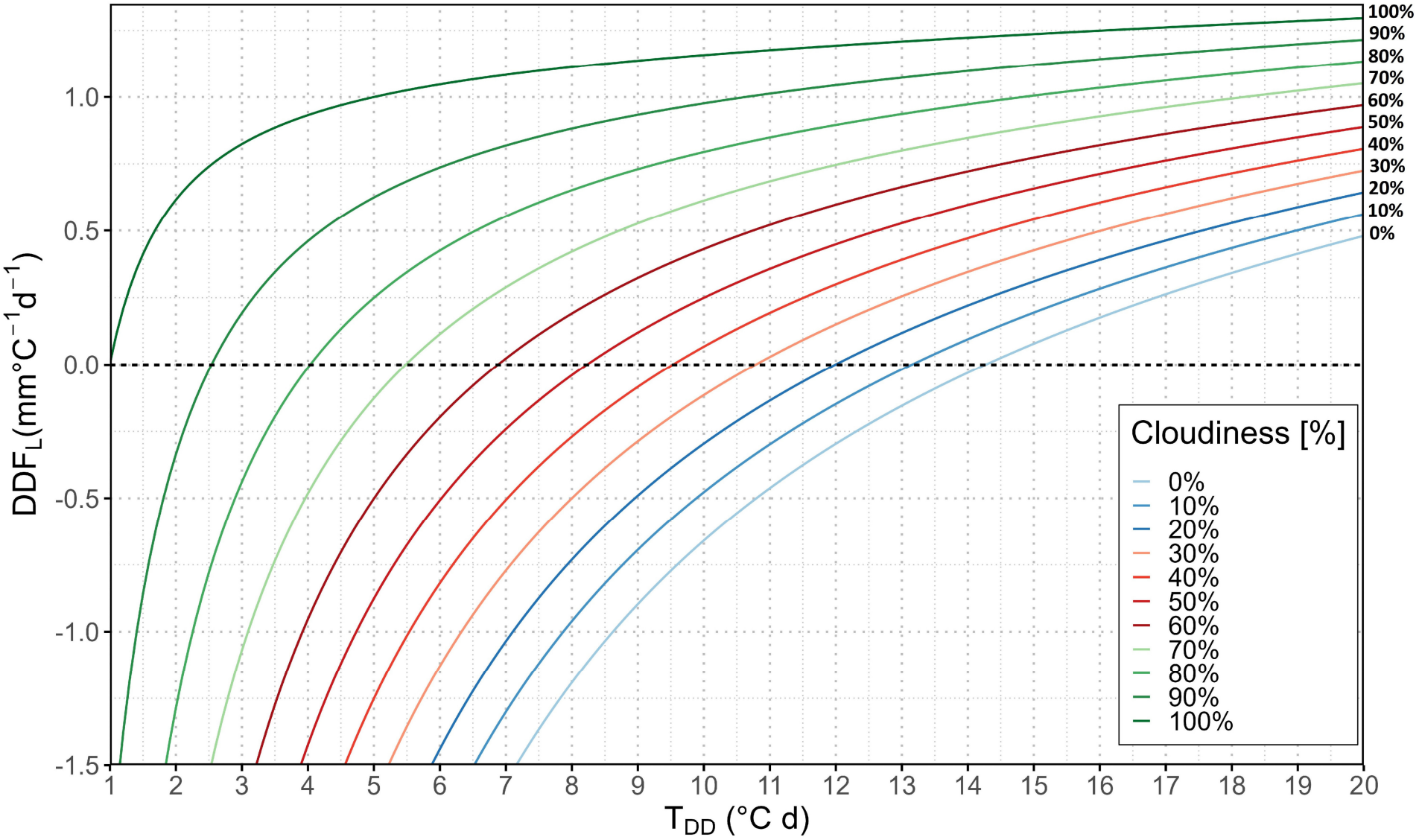

Brunnenkopfhütte 1602 m a.s.l.
1650
1700
1750
1600
1550
1500
1600
1600
1350
1450
1400
1300
1250
1200
1150
1100
1050
1300
1000
950
Legend
Brunnenkopfhütte
Contours - 50m
Streams
Dreisäulerbach catchment
DEM (m a.s.l.)
High : 1766
Low : 946
0
0.25
0.5
1 Kilometers
N
Source: 5m DEM (EPSG:25832) Geobasisdaten, Bayerische Vermessungsverwaltung

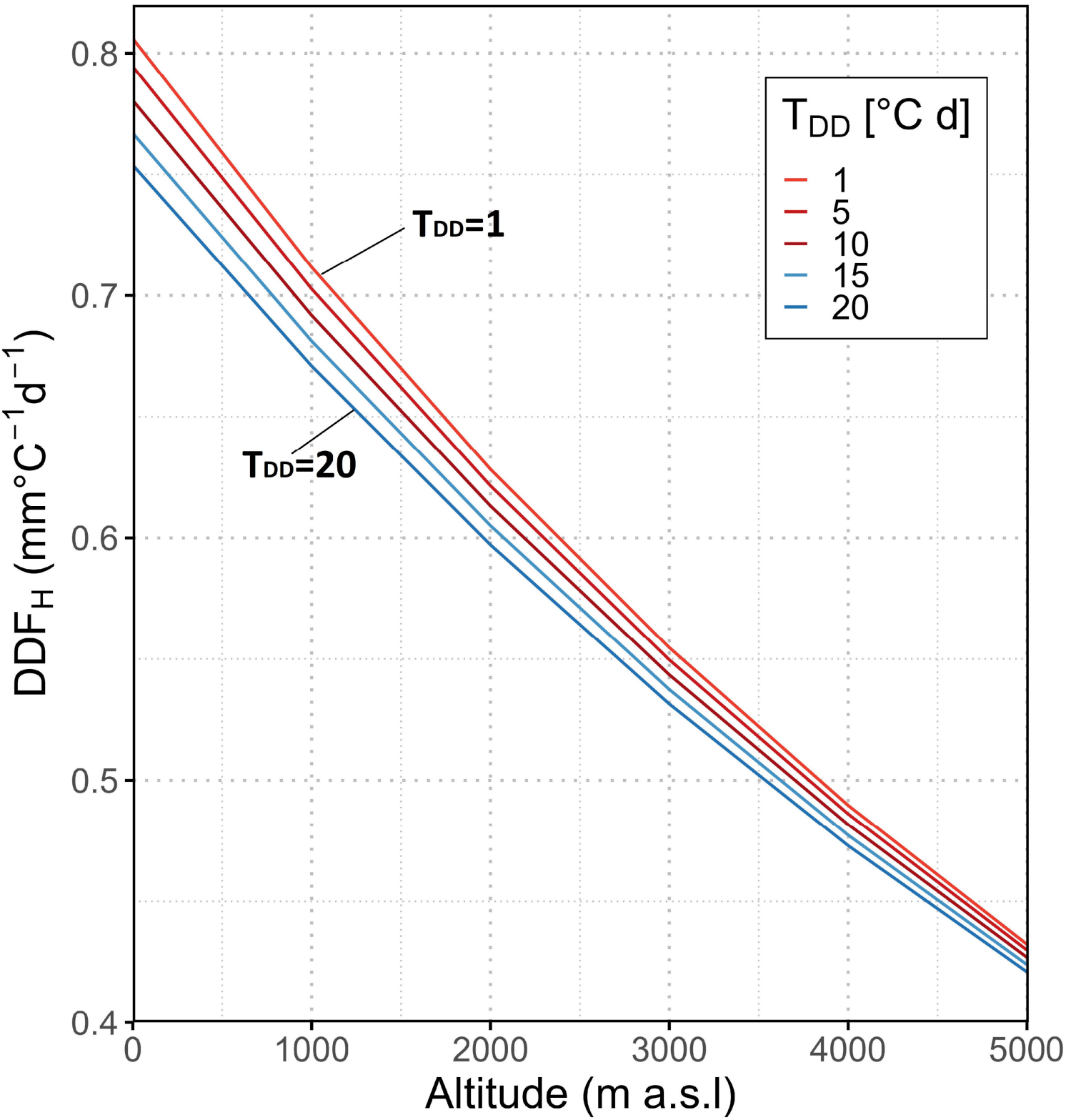

2
3
4
1
5
8
6
7
List of sensors
1. Humidity Sensor
2. Wind wane
3. Solar Radiation (incoming)
4. Temperature sensor
5. Snow depth sensor
6. Snow pack analyser
7. Snow scale
8. Data logger
Solar Radiation (Not shown)
Pluvio (Not shown)
Pressure sensor (Not visiable)

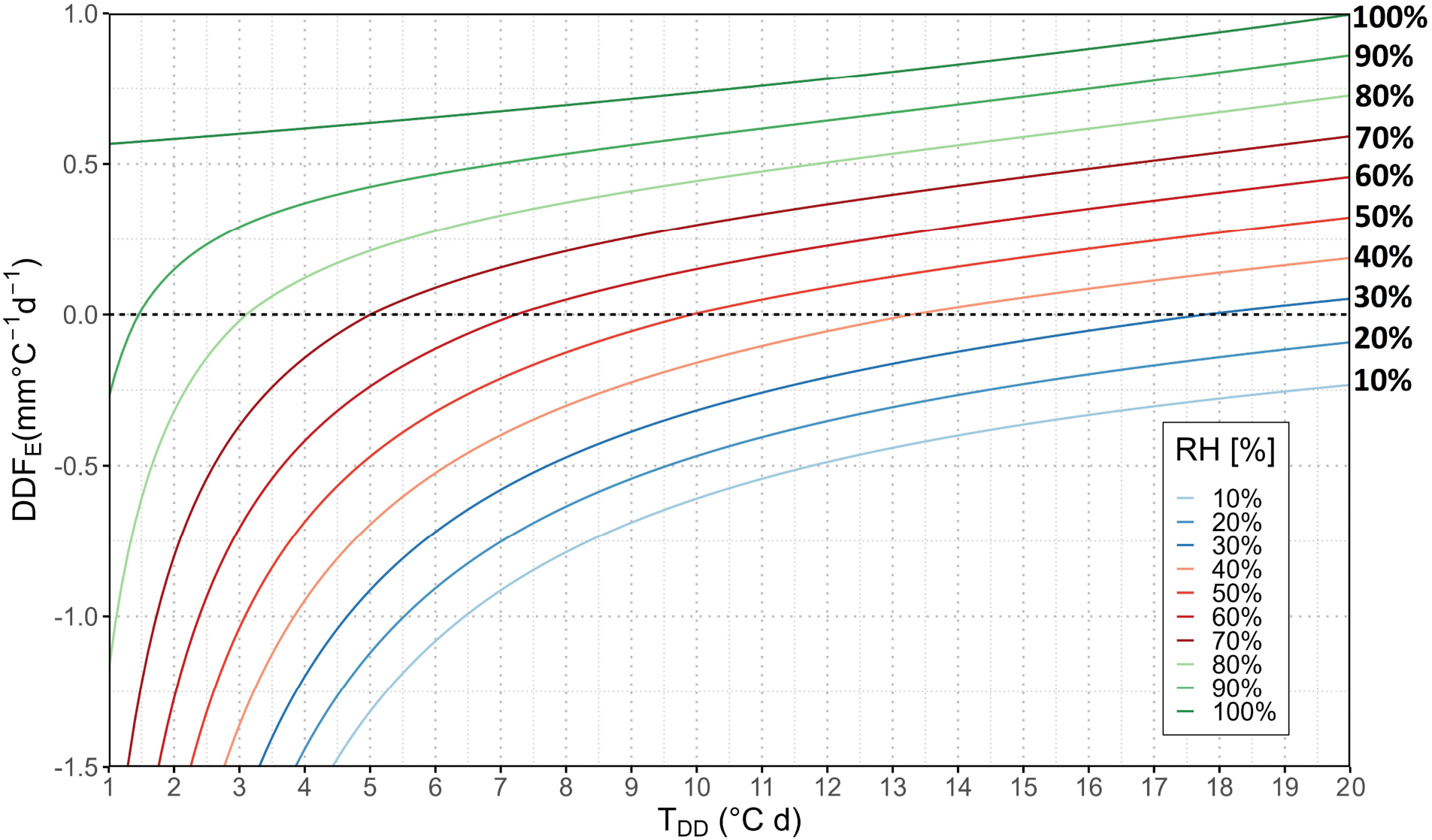

Measuring capacity limit of snow scale exceeded
Winter
2016 - 2017
2017 - 2018
2018 - 2019
2019 - 2020
2020 - 2021
SWE (mm w.e.)
600
400
200
0
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun


Clearness Altitude Factor (K_z)
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0
1000
2000
3000
4000
5000
Altitude (m a.s.l.)
Rensheng (overcast)
Jin (a) (overcast)
Jin (b) (overcast)
Liu (overcast)
Jin (b) (clear sky)
Jin (a) (clear sky)
Rensheng (clear sky)
Liu (clear sky)


(a)
Albedo=0 and KT=1
Latitude=30°
Latitude=40°
Latitude=50°
Latitude=60°
DDFS (mm°C−1d−1)
0
25
50
75
100
125
21-Dec
21-Jan
21-Feb
21-Mar
21-Apr
21-May
21-Jun
(b)
Latitude=48°, KT=1
Albedo=0.40
Albedo=0.50
Albedo=0.60
Albedo=0.70
Albedo=0.80
Albedo=0.90
DDFS (mm°C−1d−1)
0
20
40
60
80
21-Dec
21-Jan
21-Feb
21-Mar
21-Apr
21-May
21-Jun
(c)
Albedo=0 and Latitude=48°
KT = 0.25
KT = 0.50
KT = 0.75
DDFS (mm°C−1d−1)
0
25
50
75
100
21-Dec
21-Jan
21-Feb
21-Mar
21-Apr
21-May
21-Jun


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
1.0
0.5
0.0
-0.5
-1.0
-1.5
DDF_L(mm°C^-1d^-1)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
T_DD (°C d)
Cloudiness [%]
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


0.8
0.7
0.6
0.5
0.4
0
1000
2000
3000
4000
5000
Altitude (m a.s.l)
DDF_H (mm°C^-1d^-1)
T_DD [°C d]
1
5
10
15
20
T_DD=1
T_DD=20


1.0
0.5
0.0
-0.5
-1.0
-1.5
DDF_E(mm°C^-1d^-1)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
T_DD (°C d)
100%
90%
80%
70%
60%
50%
40%
30%
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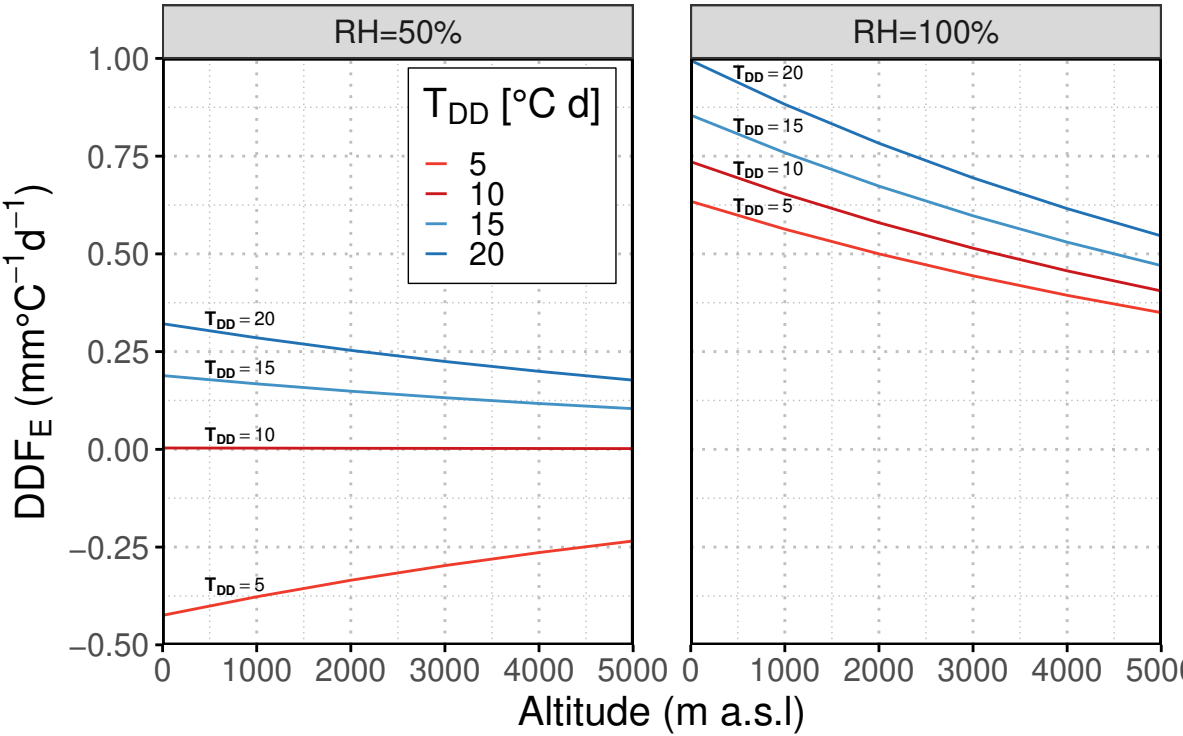
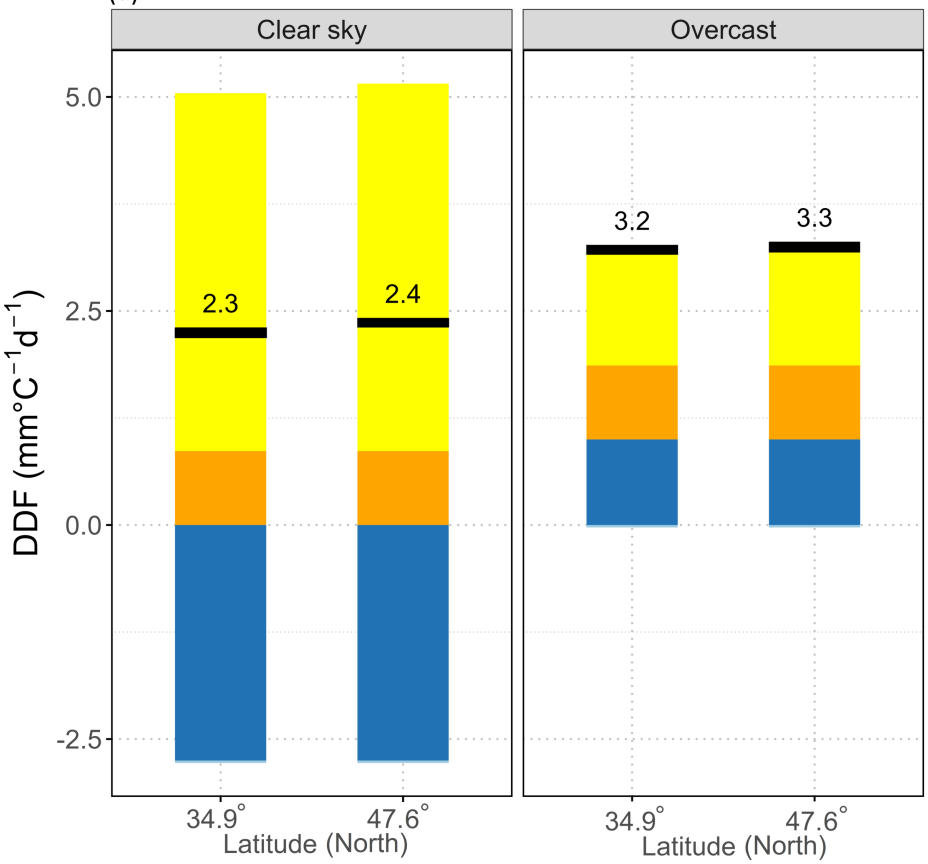
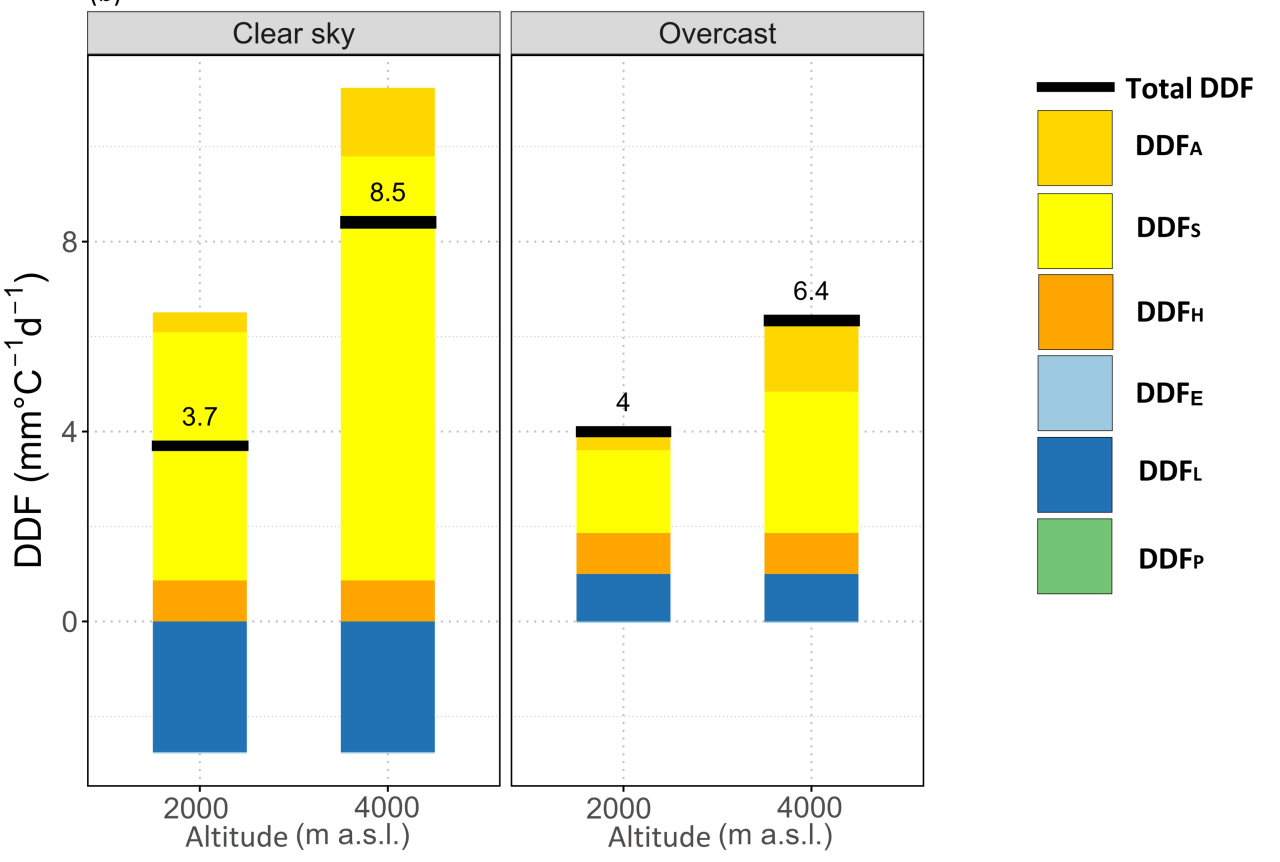
RH [%]
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%


RH=50%
RH=100%
T_{DD} [°C d]
5
10
15
20
T_{DD} = 20
T_{DD} = 15
T_{DD} = 10
T_{DD} = 5
DDF_E (mm°C^{-1}d^{-1})
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
0
1000
2000
3000
4000
5000
Altitude (m a.s.l)

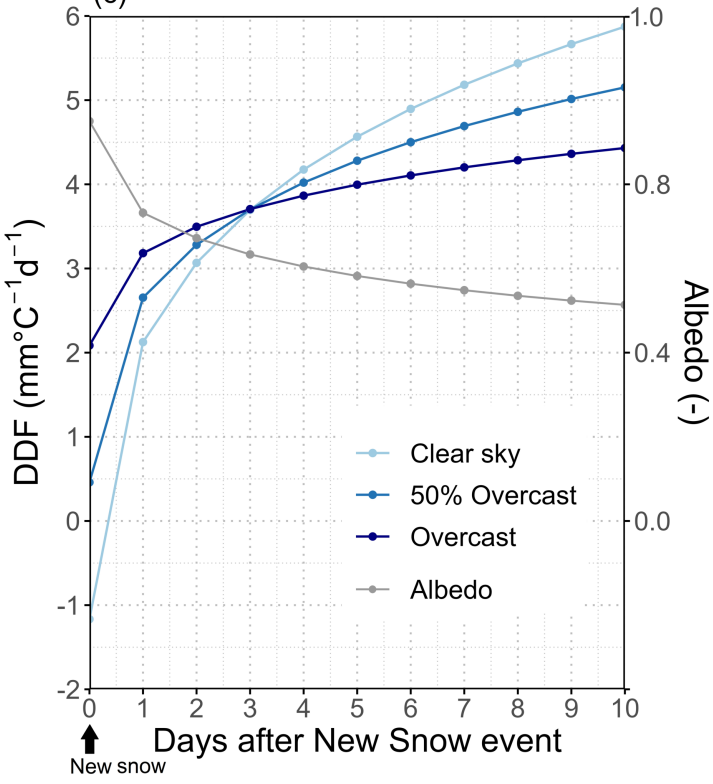
(a)


Clear sky
Overcast
DDF (mm°C⁻¹d⁻¹)
5.0
2.5
0.0
-2.5
2.3
2.4
3.2
3.3
34.9°
47.6°
Latitude (North)

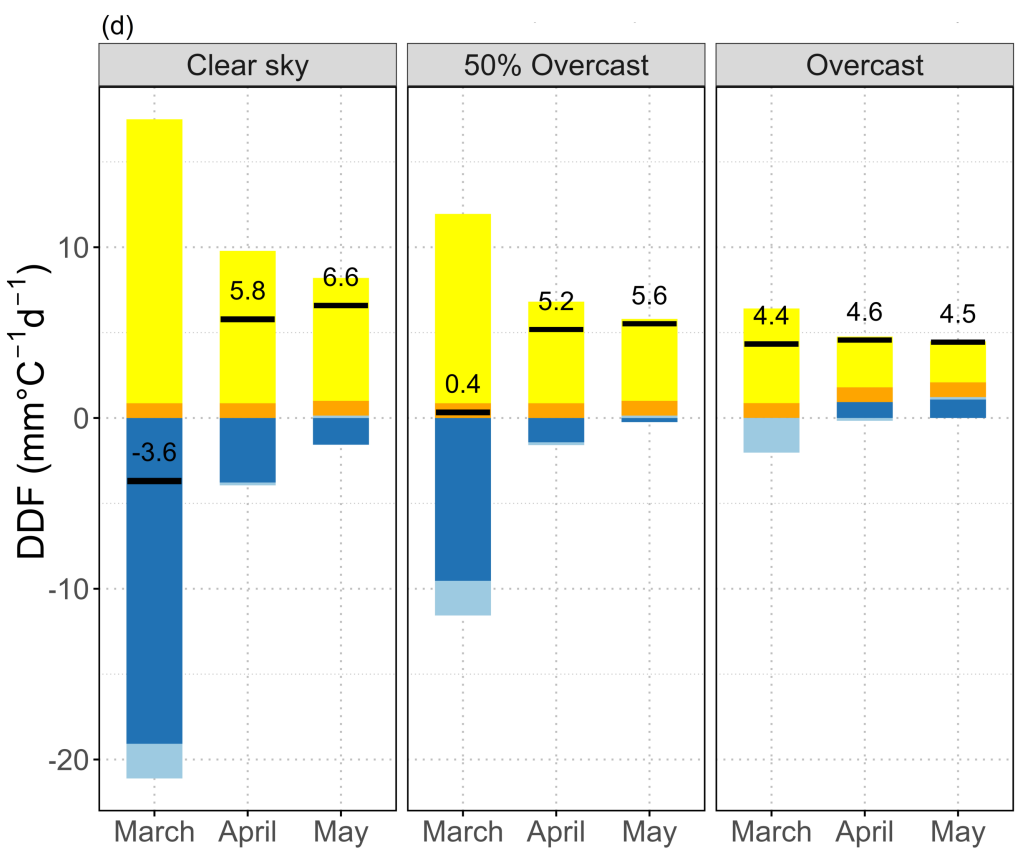
(b)


Clear sky
Overcast
DDF (mm°C⁻¹d⁻¹)
8
4
0
3.7
8.5
4
6.4
2000
4000
Altitude (m a.s.l.)
Total DDF
DDFA
DDFS
DDFH
DDFE
DDFL
DDFP

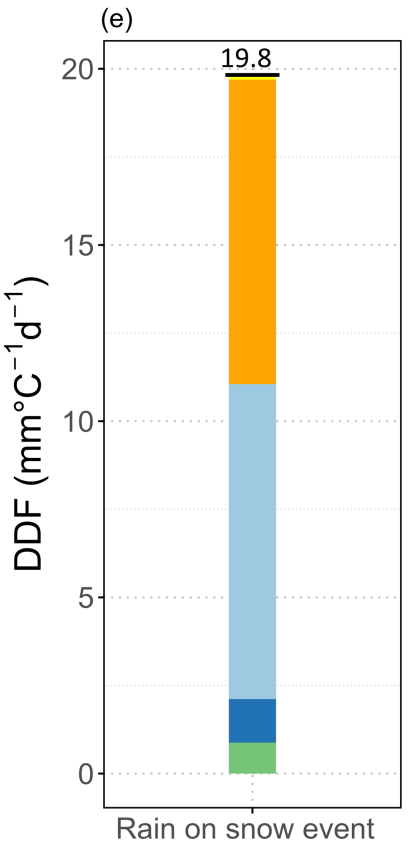
(c)

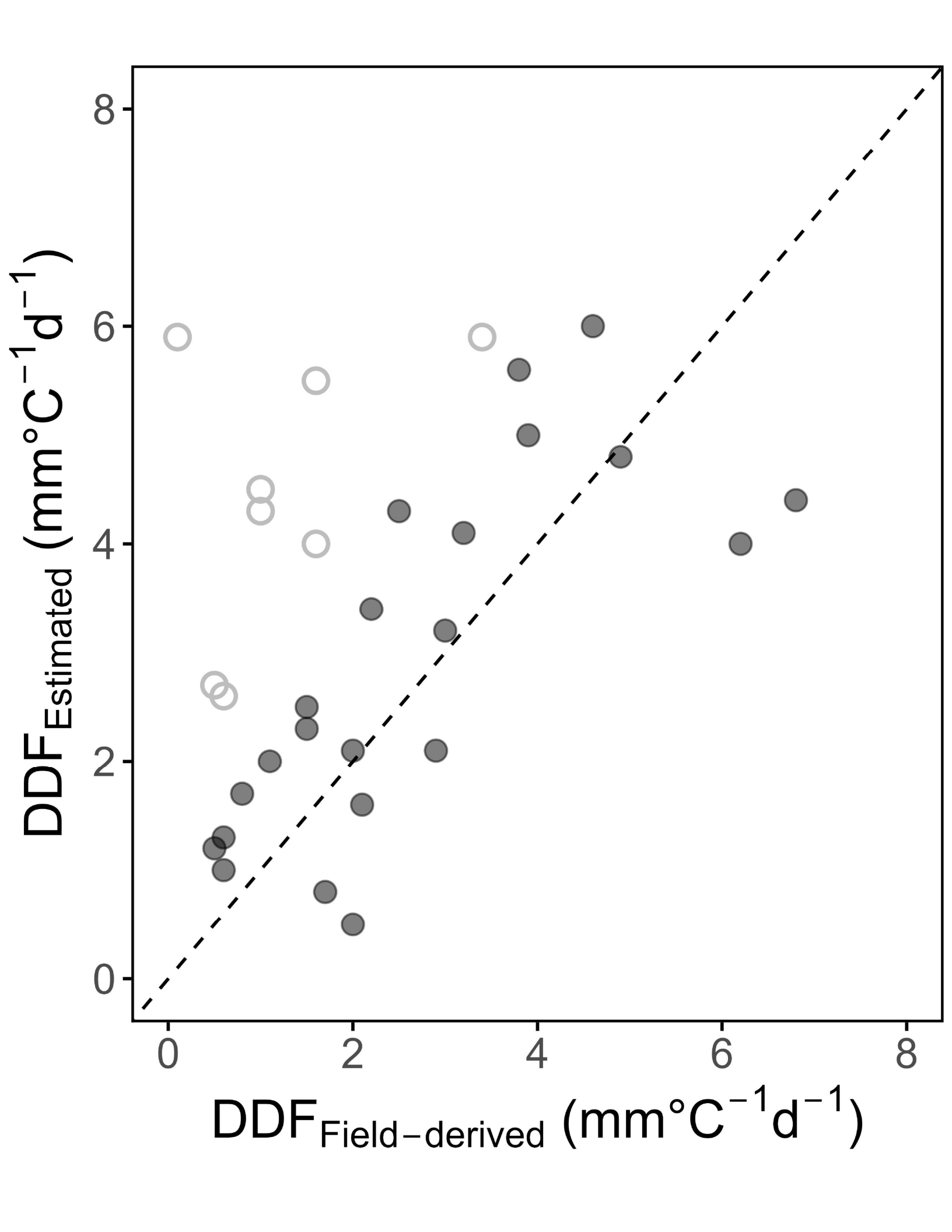

DDF (mm°C⁻¹d⁻¹)
Albedo (-)
Clear sky
50% Overcast
Overcast
Albedo
Days after New Snow event
New snow

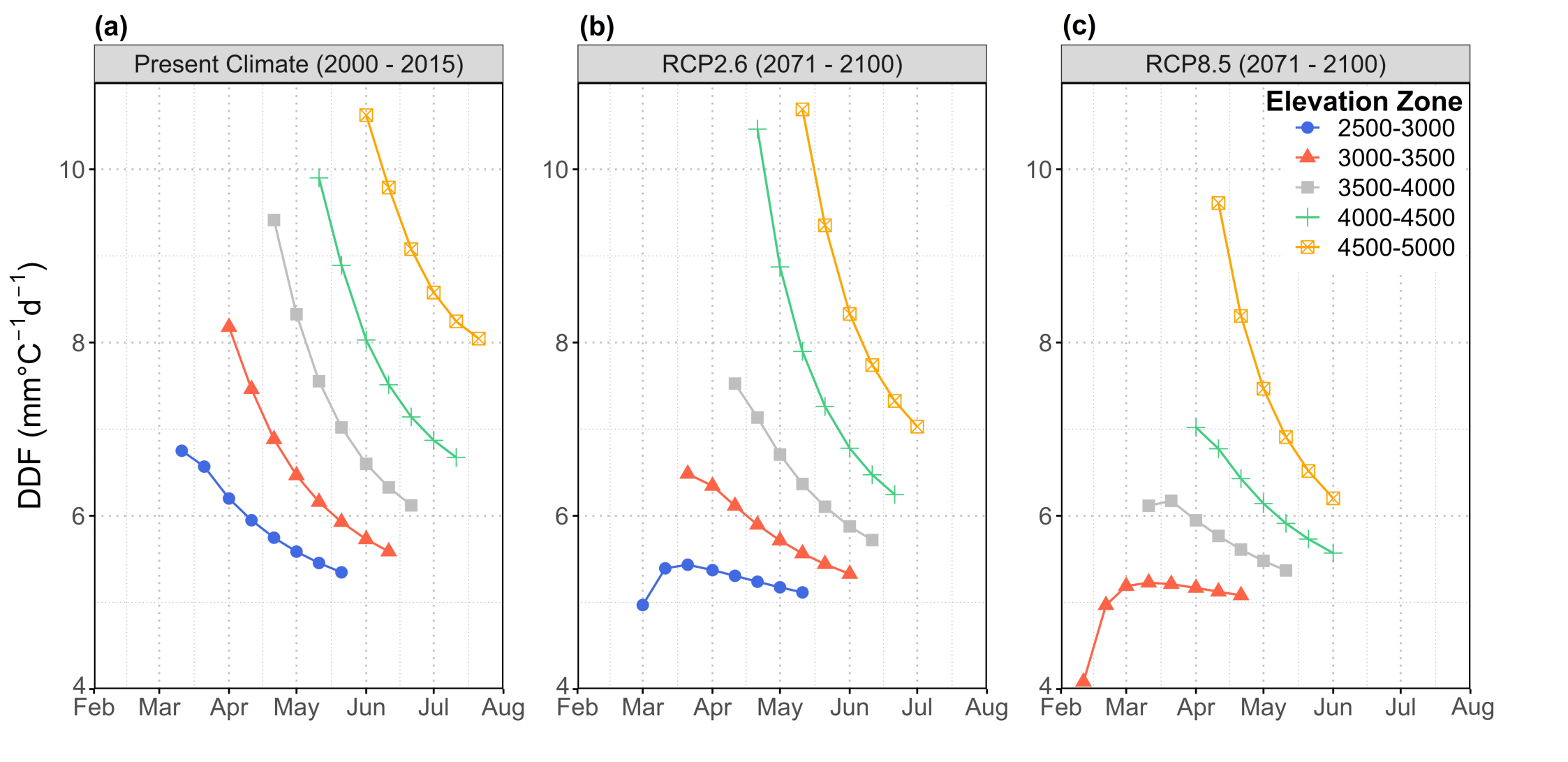
(d)


Clear sky
50% Overcast
Overcast
DDF (mm°C⁻¹d⁻¹)
-3.6
5.8
6.6
0.4
5.2
5.6
4.4
4.6
4.5
March
April
May

(e)


DDF (mm°C⁻¹d⁻¹)
19.8
Rain on snow event


8
6
4
2
0
0
2
4
6
8
$DDF_{Estimated}$ ($mm°C^{-1}d^{-1}$)
$DDF_{Field-derived}$ ($mm°C^{-1}d^{-1}$)


(a)
Present Climate (2000 - 2015)
(b)
RCP2.6 (2071 - 2100)
(c)
RCP8.5 (2071 - 2100)
Elevation Zone
2500-3000
3000-3500
3500-4000
4000-4500
4500-5000
DDF (mm°C⁻¹d⁻¹)
10
8
6
4
Feb
Mar
Apr
May
Jun
Jul
Aug