

1 **Atmospheric drivers of melt on Larsen C Ice Shelf: surface energy**
2 **budget regimes and the impact of foehn**

3

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9 Submitted to *Journal of Geophysical Research: Atmospheres* on 17/01/2020

10 Revised submission 28 April 2020

11 **Key points**

12

- 13 1. Spatial variability and maxima in Larsen C melt are chiefly due to foehn-driven
14 sensible heating, though most melt is due to solar radiation
- 15 2. Low static stability reverses the usual positive correlation between melt and foehn
16 strength, explaining conflicting results in past studies
- 17 3. A high resolution atmospheric model capably reproduces melt patterns across
18 Larsen C but has notable biases in the surface radiative fluxes

19

20 **Abstract**

21

22 Recent ice shelf retreat on the east coast of the Antarctic Peninsula has been principally
23 attributed to atmospherically driven melt. However, previous studies on the largest of these
24 ice shelves – Larsen C – have struggled to reconcile atmospheric forcing with observed melt.
25 This study provides the first comprehensive quantification and explanation of the
26 atmospheric drivers of melt across Larsen C, using 31-months' worth of observations from
27 Cabinet Inlet, a 6-month, high-resolution atmospheric model simulation and a novel
28 approach to ascertain the surface energy budget (SEB) regime. The dominant
29 meteorological controls on melt are shown to be the occurrence, strength and warmth of
30 mountain winds called foehn. At Cabinet Inlet, foehn occurs 15 % of the time and causes 45
31 % of melt. The primary effect of foehn on the SEB is elevated turbulent heat fluxes. Under
32 typical, warm foehn conditions, this means elevated surface heating and melting, the
33 intensity of which increases as foehn wind speed increases. Less commonly – during cooler-
34 than-normal foehn windsover radiatively-warmed ice – the relationship between wind
35 speed and net surface heat flux reverses, which explains the seemingly contradictory results
36 of previous studies. In the model, spatial variability in cumulative melt across Larsen C is
37 largely explained by foehn, with melt maxima in inlets reflecting maxima in foehn wind
38 strength. However, most accumulated melt (58 %) occurs due to solar radiation in the
39 absence of foehn. A broad north-south gradient in melt is explained by the combined
40 influence of foehn and non-foehn conditions.

41

42 **Plain Language Summary**

43

44 The recent rapid retreat and collapse of ice shelves on the east coast of the Antarctic
45 Peninsula is known to be primarily a result of enhanced surface melt due to climate
46 warming and changing atmospheric circulation patterns. However, previous studies have
47 struggled to reconcile observed melt patterns with meteorological conditions. Here we
48 provide the first quantification and explanation of the atmospheric drivers of melt across
49 Larsen C, the largest ice shelf on the Peninsula. We find that variability in melt across Larsen
50 C is primarily governed by mountain winds known as foehn, with melt maxima in ice shelf
51 inlets coinciding with the strongest foehn winds. Foehn air is usually much warmer than the
52 ice below, resulting in elevated heating and melting of the ice, the intensity of which
53 increases with increasing wind speed. However, in rare cases where the foehn air is not
54 significantly warmer than the ice, the relationship between melt and foehn wind speed
55 reverses, which explains the seemingly contradictory results of previous studies. Whilst
56 foehn causes the highest melt rates, non-foehn driven melt is more common and, via
57 summertime solar heating, is responsible for most of the accumulation of melt across the
58 ice shelf as a whole.

59

60 **Keywords**

61

- 62 • Larsen Ice Shelf
- 63 • Larsen C
- 64 • Ice Shelf Melt
- 65 • Surface Energy Balance
- 66 • Surface Energy Budget
- 67 • Foehn

68

69 **1. Introduction**

70

71 The retreat and collapse of ice shelves on the Antarctic Peninsula over recent decades has
72 been principally attributed to surface meltwater ponding associated with atmospheric
73 warming (Scambos et al., 2000; Van den Broeke, 2005; Cook and Vaughan, 2010; Holland et
74 al., 2011; Välisuo et al., 2014; Leeson et al., 2017). Changing southern hemispheric
75 circulation patterns have led to increased warm air advection into the region via a
76 strengthening of the prevailing circumpolar westerly winds, and also to an increase in the
77 frequency and strength of low-level warming events to the east of the Peninsula caused by
78 mountain-generated local winds known as foehn (Marshall et al., 2006; Van Lipzig et al.,
79 2008; Orr et al., 2008; Cape et al., 2015). This foehn warming effect has led to asymmetrical
80 warming across the Peninsula in summer; the warming rate to the east being considerably
81 greater than that to the west (three times as great at the northern tip; Marshall et al., 2006).
82 The Larsen Ice Shelf, first mapped in 1893 (Larsen, 1894), is comprised of four distinctly-
83 evolving components (Vaughan and Doake, 1996). The northernmost two components –
84 Larsen A and B – disintegrated in 1995 and 2002, respectively. The disintegration of Larsen B
85 was immediately preceded by extensive meltwater ponding and high levels of ice
86 densification (from the re-freezing of meltwater in the firn layer), a known precursor of ice
87 shelf collapse (Holland et al., 2011; Kuipers Munneke et al., 2014). Immediately to the
88 south, Larsen C is the largest ice shelf on the Peninsula and is presently intersected by the
89 mean annual (near-surface level) -9 °C isotherm; loosely approximating the upper limit for
90 ice shelf viability (Morris and Vaughan 2003). Densification in the northwest embayments,
91 or inlets, of Larsen C are approaching those levels observed in Larsen B immediately prior to
92 its collapse (Holland et al., 2011; Hubbard et al., 2016).

93

94 Foehn is a downslope wind in the lee of a mountain that is accelerated, warmed, and dried
95 as a result of the orographic disturbance on the prevailing flow (Elvidge and Renfrew, 2016).
96 It is an intrinsic feature of mountain gravity waves, generated due to large-scale stably
97 stratified cross-mountain flow (Smith, 1979). It can also be generated or strengthened by
98 cross-mountain pressure gradients driving “gap flows” through elevated mountain passes
99 (Zängl, 2003; Mayr et al., 2007; Elvidge et al., 2015). The warmth of foehn, combined with

100 the accompanying dry, cloud-free conditions (the foehn cloud-clearance effect), makes it a
101 potent agent for ice and snow melt (Hayashi et al., 2005; Cape et al., 2015; Elvidge et al.,
102 2016). Over Larsen C, a series of case study investigations using observations supported by
103 relatively high resolution simulations have demonstrated the capacity for foehn to
104 penetrate down to surface level in the immediate lee of the mountains and in certain cases
105 (when the mountain flow regime is relatively linear) to extend across the entire ice shelf
106 (e.g. King et al., 2008; Grosvenor et al., 2014; Elvidge et al., 2015; 2016; Turton et al., 2018).
107 Foehn is typically channelled into the inlets, forming foehn jets, between which sheltered
108 regions experiencing weaker foehn winds (“wake” regions) are found (Elvidge et al., 2015).
109 Several studies have demonstrated that foehn enhances melt rates over Larsen C, via
110 increased downward surface fluxes of shortwave radiation and sensible heat (Kuipers
111 Munneke et al., 2012, 2018; Elvidge et al., 2016; King et al., 2017; Datta et al., 2019). Using
112 data from satellite observations and a regional climate model, Datta et al. (2019) have
113 attributed enhanced late summer-season meltwater percolation depths and snow
114 densification during recent years to foehn. It has also been shown that the collapse of
115 Larsen B was coincident with a summer of anomalously strong foehn warming (Cape et al.,
116 2015).

117

118 Luckman et al. (2014) presented satellite observations of climatological melt distributions
119 over Larsen C, the key features of which are corroborated by other studies (e.g. Tedesco,
120 2009; Holland et al., 2011; Barrand et al., 2013; Ashmore et al., 2017; Bevan et al., 2018).
121 They revealed that the distribution in observed melt broadly matches patterns in near-
122 surface wind speed and air temperature in case study simulations of foehn; patterns which
123 have also been seen in composite foehn conditions from a multidecadal model simulation
124 (Wiesenekker et al., 2018). More specifically, elevated melt rates in a narrow band running
125 along the Peninsula’s east coast at the foot of the mountains mirrors the diminishing impact
126 of foehn on leeside temperatures with distance downwind of the Peninsula (Elvidge et al.,
127 2016), whilst melt rate maxima in inlets are co-located with maxima in foehn wind speed
128 (Elvidge et al., 2015). A broad north to south gradient in melt, in addition to coinciding with
129 the annual mean gradient in solar irradiance at the top of the atmosphere, reflects the
130 north-south gradient in the strength of the background circumpolar westerly winds which
131 drive foehn in this region (Marshall et al., 2006). It also corresponds with the prevailing

132 foehn wind direction across Larsen C being broadly northwesterly (Turton et al., 2018; Datta
133 et al., 2019).

134

135 Given these correlations, a reasonable hypothesis is that foehn plays a governing role in
136 climatological melt patterns over Larsen C. However, the supporting evidence for this
137 hypothesis is conflicted:

- 138 • In model data spanning one melt season, King et al. (2017) found that the impact of
139 foehn on Larsen C's surface energy budget (SEB) was generally small and that, besides
140 enhanced melt towards the far north of the ice shelf, the spatial pattern of foehn-driven
141 melt bore little resemblance to satellite observations. However, noting the absence of
142 foehn jets in their meteorological analysis data, they call into question the validity of
143 these results on account of model shortcomings, including a limited resolution.
- 144 • Beyond the cloud-clearance effect, the impact of foehn is governed by a balance
145 between downward fluxes of sensible heat (SH) due to the relative warmth of the foehn
146 air and upward fluxes of latent heat (LH) due to sublimation. The available evidence
147 demonstrates significant seasonal, diurnal and spatial variability in this balance, meaning
148 the net effect is not necessarily surface warming. During wintertime and nighttime foehn,
149 SH has dominated across much of the ice shelf (Elvidge, 2013; Kuipers Munneke et al.,
150 2018). During daytime summer foehn, the two terms have either roughly cancelled, in
151 inlets (Grosvenor et al., 2014) and towards the eastern edge of Larsen C (Kuipers
152 Munneke et al., 2012; King et al, 2017), or LH has dominated (Elvidge, 2013). Relating this
153 balance of SH and LH to meteorological conditions needs clarification.
- 154 • The fact that the highest melt rates are observed within the inlets has been hypothesised
155 to be due to the incidence of the strongest foehn winds – foehn jets – in these inlets.
156 However, the validity of this hypothesis depends on the net balance of the turbulent
157 surface heat fluxes during foehn which, as established above, is as yet unclear.
158 Furthermore, this hypothesis conflicts with the observed spatial variability in foehn air
159 temperatures, which are typically lower in the jets than in wake regions due to a
160 dampened foehn effect in the jets (Elvidge et al., 2015; Elvidge and Renfrew, 2016). In
161 fact, of the two studies addressing the SEB impact of foehn jets, Elvidge (2013) found less
162 melt in the inlets, whilst Grosvenor et al. (2014) found no clear influence of jets on melt

163 rates. However, these papers only consider a small number of case studies, which are not
164 necessarily representative.

165

166 The goal of this study is to quantify and explain the atmospheric drivers of melt across
167 Larsen C, and consequently to reconcile the above contradictions, using new, ideally located
168 observations together with a long-duration, high-resolution, state-of-the-art model
169 simulation. Section 2 provides summaries of the data and details a novel method we have
170 devised to investigate the problem. In Section 3 we characterise the meteorological
171 conditions, SEB and melt at a representative inlet across three melt seasons. In Section 4 we
172 identify distinct SEB regimes and explore their characteristics and influence during both
173 foehn and non-foehn conditions. In Section 5 we investigate the local meteorological
174 controls on melt during foehn. Following a brief evaluation of model performance in
175 Sections 3 and 5, in Section 6 we focus on the model data to explore the drivers of melt
176 across the ice shelf as a whole. Section 7 summarises and concludes the study.

177

178 **2. Data and methods**

179

180 The observations in this study are from an automatic weather station (AWS) located in
181 Cabinet Inlet (Figure 1). These observations cover three austral summer seasons over 31
182 continuous months from the AWS's installation date of 25 November 2014 to 17 June 2017,
183 at half-hourly resolution. The model output is from a limited area simulation of the Met
184 Office Unified model (MetUM), covering the domain shown in Figure 1 from 25 November
185 2015 to 31 May 2016. These dates were chosen to encompass the majority of one summer
186 melt season; 96 % of annual (July 2015 to June 2016) melt in the AWS observations occurred
187 during this period. In both observational and model data, foehn conditions have been
188 diagnosed according to a location-dependent criterion based on wind direction and relative
189 humidity (see Appendix 1 for details and justification).

190

191 **2.1 Automatic Weather Station Data**

192

193 The AWS is jointly operated by the Institute for Marine and Atmospheric Research of
 194 Utrecht University (UU/IMAU) and the British Antarctic Survey (BAS) and is known as IMAU
 195 AWS 18. It is located at 66°24' S, 63°22' W at a height of ~70 m above mean sea level. It has
 196 sensors for air and surface temperature, air pressure and humidity, as well as an acoustic
 197 snow height sensor, a propeller-vane anemometer measuring wind direction and speed, and
 198 a radiometer for measuring downward and upward shortwave and longwave radiative
 199 fluxes. A bulk-algorithm-based SEB model (described in Kuipers Munneke et al., 2009) has
 200 been used to derive surface sensible and latent heat fluxes and the ground heat flux. The
 201 energy available for melt is also derived from this model, given as the SEB residual when the
 202 surface temperature, T_{sfc} , is above freezing point:

203

$$204 \text{melt}_{SEB} = \begin{cases} 0, & T_{sfc} < 0 \text{ } ^\circ\text{C} \\ \max(0, SW + LW + SH + LH + GH), & T_{sfc} = 0 \text{ } ^\circ\text{C} \end{cases} ,$$

205

206 where SW, LW, SH, LH and GH are the net surface fluxes of shortwave radiative heat,
 207 longwave radiative heat, sensible heat, latent heat and ground heat, here given as positive
 208 when directed towards the surface; and T_{sfc} is the surface temperature. Reported quantities
 209 are at nominal levels of 2 m for temperature and humidity and 10 m for wind speed,
 210 adjusted from the raw measurements typically made between 1.7 and 2.4 m.

211

212 Several quality checks and corrections have been applied to the AWS data. Solar radiation
 213 observations were tilt-corrected (Wang et al., 2016) and further constrained by calculating a
 214 24-hour running mean albedo following Van den Broeke et al. (2004). By inspecting data
 215 from the upward-facing longwave radiation sensor, we found that no rime accreted on the
 216 radiation sensors at this location. Finally, air temperature observations, performed inside
 217 naturally-ventilated radiation shields, were corrected downward during periods of sunny
 218 weather with little or no wind, following the method of Smeets et al. (2018). Compared to
 219 direct eddy correlation observations of turbulent fluxes (e.g., by using a 3-D ultrasonic
 220 anemometer), the bulk method that we apply to the AWS observations yields similar results
 221 with a root-mean-square difference of typically 3-4 W m^{-2} at Antarctic sites experiencing
 222 frequent air flow (e.g. Van den Broeke et al., 2005). With the wind sensor being at a height
 223 of 2-3 m, the bulk method captures most of the turbulent eddies while at the same time not

224 severely violating the assumption of constant flux in the layer between the surface and the
 225 instrument height.

226

227 2.2 Model Data

228

229 The MetUM is a state-of-the-art, non-hydrostatic atmospheric model used by the Met Office
 230 for operational weather forecasting and as a component in all their climate models (Walters
 231 et al., 2017). Here, we have used version 10.6 of the MetUM and a standard
 232 parameterization configuration (generally following Tang et al., 2013). This configuration has
 233 proven reasonably accurate at simulating cases of orographic flows over Antarctica (e.g. Orr
 234 et al., 2014; Elvidge et al., 2015; 2016; Elvidge and Renfrew 2016). Instead of the model
 235 defaults, a newer Land Sea Mask, developed by the British Antarctic Survey and based on
 236 the SCAR Antarctic Digital Database coastline, version 7.0 (released January 2016 and
 237 available at <https://www.add.scar.org/>), and the high-resolution Radarsat Antarctic
 238 Mapping Project (RAMP; Liu et al., 2015) digital elevation model were used to derive the
 239 model orography.

240

241 The limited area model simulation has a horizontal grid spacing of 1.5 km and 70 vertical
 242 levels (the lowest of which is at a height of 2.5 m over the ocean and there are 16 levels in
 243 the lowest km). This resolution is the same as or higher than those used for previous model
 244 studies of individual foehn events over Larsen C (e.g. Grosvenor et al., 2014; Elvidge et al.,
 245 2015; 2016; Turton et al., 2017), and is significantly higher than that used for previous
 246 model climatology studies (e.g. King et al., 2017; Datta et al., 2019). Note this model does
 247 not incorporate a multi-layer snow scheme. Consequently, a best estimate of melt in the
 248 model is provided by $\text{melt}_{\text{skin}}$; the residual energy available for surface melt when the ice
 249 surface temperature is at the melting point and, following King et al. (2008) and Kuipers
 250 Munneke et al. (2012), ground heat flux is assumed to be negligible:

251

$$252 \text{melt}_{\text{skin}} = \begin{cases} 0, & T_{\text{sfc}} < 0 \text{ } ^\circ\text{C} \\ \max(0, SW + LW + SH + LH), & T_{\text{sfc}} = 0 \text{ } ^\circ\text{C} \end{cases} .$$

253

254 In our analysis of the model data, four sites of focus are chosen (see Figure 1 for locations):

- 255 • The Cabinet Inlet IMAU AWS18 site, 66°24' S, 63°22' W
- 256 • Whirlwind Inlet, 67°27' S, 65°18' W – situated in another foehn-prone Larsen C inlet.
- 257 • Mamelon Point, 67°14' S, 64°42' W – situated between Whirlwind Inlet to the south
- 258 and Mill Inlet to the north in a region known to typically experience wake conditions
- 259 during foehn (Elvidge et al., 2015).
- 260 • Larsen East, 67°01' S, 61°29' W – situated towards the eastern edge of Larsen C,
- 261 approximately 150 km east of the Antarctic Peninsula, and the site of IMAU AWS14,
- 262 data from which has been used in several previous studies (e.g. Van den Broeke,
- 263 2005; Elvidge, 2013; Kuipers Munneke et al., 2012; King et al., 2015; Turton et al,
- 264 2018).

265

266 2.3 SEB regimes

267

268 Determining the atmospheric drivers of melt over climatological timescales is complicated
 269 by nonlinear interactions and feedbacks between SEB components and meteorological
 270 conditions. To overcome this challenge, we have categorised the SEB into distinct regimes
 271 determined by which SEB component is *dominating* and in which direction. An SEB
 272 component is said *to dominate* when it is contributing a heat flux which is greater in
 273 magnitude than all of:

- 274 a. Each of the individual contributions of the other components
- 275 b. The combined contribution of all other components
- 276 c. 50 W m^{-2}

277 For example, the logical expression below determines whether or not the downward SH-
 278 dominated regime ($\text{SEB}_{\downarrow\text{SH}}$) is occurring:

279

$$280 \text{SEB}_{\downarrow\text{SH}} = \begin{cases} \text{occurring, } \{ \text{SH} > 50 \text{ W m}^2 \} \text{ and } \{ \text{SH} > |\text{LH}| \} \text{ and } \{ \text{SH} > |\text{SW}| \} \text{ and } \{ \text{SH} > |\text{LW}| \} \text{ and } \{ \text{SH} > |\text{LH} + \text{SW} + \text{LW}| \}, \\ \text{not occurring, otherwise} \end{cases},$$

281

282 Equivalent expressions are used for all other possible regimes, 8 in total, i.e. SEB domination
 283 by each of the four components, in each direction. Of these regimes, only four occur in our
 284 data: $\text{SEB}_{\downarrow\text{SH}}$, $\text{SEB}_{\uparrow\text{LH}}$, $\text{SEB}_{\downarrow\text{SW}}$, $\text{SEB}_{\uparrow\text{LW}}$, where \downarrow and \uparrow denote downward and upward flux
 285 directions, respectively. Note that the SEB is often not dominated by any single component,

286 but during such conditions the net flux is typically small (92 % of the time smaller than ± 25
287 W m^{-2}) and so very little melt occurs (only 6 % of total melt in the Cabinet Inlet observations
288 and only 2 % of total melt at the four sites of focus in the model). Note our results are not
289 qualitatively sensitive to the value of the fixed heat flux threshold (c. in the list above),
290 though we find the chosen value of 50 W m^{-2} to be optimal in yielding useful results for the
291 attribution of melt to atmospheric drivers as it strikes a balance between being sufficiently
292 large to ensure significant differences in SEB composition between regimes, and sufficiently
293 small to ensure that only a small amount of melt occurs when no SEB component is
294 dominating.

295

296 **3. Meteorological conditions and surface energy exchange in**

297 **Cabinet Inlet**

298

299 Here we investigate the seasonal variability in atmospheric conditions and the broad
300 meteorological drivers of melt at Cabinet Inlet.

301

302 Figure 2 shows that the two most frequent wind directions in the Cabinet Inlet observations
303 are northwesterly and southerly. During melt, winds are most commonly westerly to
304 northwesterly. Both the highest wind speeds and the highest melt rates occur in westerly to
305 northwesterly flow, consistent with foehn (and sometimes katabatic winds; see Appendix 1)
306 drawn down the eastern slopes of the Peninsula. A second peak in wind speeds is found in
307 southerly wind directions, consistent with cold, southerly barrier flows along the east coast
308 of the Peninsula (see Schwerdtfeger, 1975; Parish, 1983). Modelled wind and melt
309 distributions are qualitatively similar to the observations, although the model
310 underestimates winds and melt in the westerly sector.

311

312 Statistics and monthly variability in foehn and melt occurrence and melt rates from all AWS
313 observations are shown in Figure 3 (a,b) and Table 1a. At Cabinet Inlet, foehn occurs 15 % of
314 the time and is responsible for 45 % of the melt (Table 1a). The potency of foehn in causing
315 melt reflects both elevated melt occurrence (three times more common) and elevated rates
316 of melt when melt is occurring (1.4 times greater) during foehn than non-foehn conditions

317 (note these differences are statistically significant at the 99 % level). Whilst foehn occurs all
 318 year round at Cabinet Inlet (Figure 3), our observations corroborate previous studies (e.g.
 319 King et al., 2017; Turton et al., 2018; Wiesenekker et al., 2018; Datta et al., 2019) in showing
 320 it to be least common during the summer (4 % of the time in December) and most common
 321 in mid-spring (peaking at 32 % in October) and autumn (20 % in May). Foehn explains 88 %
 322 of total melt occurring outside of the summer months (DJF), of which 98 % occurs during the
 323 spring (SON) and autumn (MAM). It is worth noting that the strong influence of foehn
 324 during the spring is also likely to play an important role in preconditioning ice shelf for
 325 summertime melt via a reduction in its albedo due to the warming, coarsening and melting
 326 of the top layers of snow (e.g. Kuipers Munneke et al., 2014). During foehn, the SEB typically
 327 comprises a balance between heat gain via the net turbulent heat flux (TurbH), and heat
 328 loss via the net radiative heat flux (RadH) (Figure 3c); with the mean turbulent term greater
 329 in magnitude than the mean radiative term during all months except December. The foehn
 330 SEB is most strongly dominated by TurbH during March, coinciding with the highest mean
 331 melt rates during foehn. Interestingly, there is no evidence for the foehn cloud-clearance
 332 effect in the Cabinet Inlet observations; the average proportion of solar irradiance at the top
 333 of the atmosphere reaching the surface (SW_{sfc} / SW_{TOA}) – a proxy for cloud cover – is similar
 334 under foehn conditions to that under non-foehn conditions (see Table 1b).

335

336 Roughly half of annual melt at Cabinet Inlet occurs during the summer months (DJF), 88 % of
 337 which is during non-foehn conditions. The non-foehn monthly mean SEB comprises a
 338 balance between downward RadH and upward TurbH (Figure 3d).

339

340 For the single melt season covered by the simulation, the observed monthly variability in
 341 foehn occurrence, melt, and SEB components (Figure 4a) are generally consistent with those
 342 described above for the three-season mean. During this single season, the differences
 343 between $melt_{SEB}$ and $melt_{skin}$ in the observations (Figure 4a) are generally negligible relative
 344 to the differences in observed $melt_{skin}$ and simulated $melt_{skin}$ (Figure 4a,d). This suggests that
 345 the omission of ground heat flux in the model is a relatively minor source of model error.
 346 Recall the penetration and absorption of SW below the surface of the snowpack is
 347 accounted for in $melt_{SEB}$ but not in $melt_{skin}$ (Kuipers Munneke et al., 2012).

348

349 The model generally performs well. Figure 4(a,d) shows that the monthly occurrence of
350 foehn is accurately reproduced; the bias never greater than $\pm 7\%$ and the difference during
351 the entire melt season being only 1% (Table 1a). Monthly melt occurrences during all
352 (foehn and non-foehn) conditions are also generally handled well (though with notable
353 biases in December and May), with a melt-season difference also of only 1%. Monthly-
354 mean variability in the SEB contributions from TurbH and RadH are qualitatively well
355 represented; the seasonal timings of peaks and troughs are generally accurate, as are the
356 key differences in these fluxes between foehn and non-foehn conditions (Figure 4b-c, e-f).
357 Despite a consistent positive bias during foehn, TurbH is also generally quantitatively
358 accurate. During foehn conditions, the monthly bias in TurbH is less than 20 W m^{-2} for all
359 months except January, whilst during non-foehn conditions the monthly bias is always $< 5 \text{ W}$
360 m^{-2} .

361

362 In RadH however, the model exhibits significant biases. During the summer months (DJF)
363 there is typically a positive model bias in mean downward SW and consequently RadH,
364 leading to exaggerated monthly melt rates during both foehn and non-foehn conditions
365 (Figure 4b-c,e-f). This overestimation is most significant for non-foehn conditions, with the
366 total accumulation of melt during the 2015-16 melt season being 150% of that observed. The
367 overestimation is smaller in the accumulation of foehn-driven melt (the simulated value
368 being 126% of the observed value), reflecting less dependence on RadH during foehn. Note
369 that biases in RadH have been highlighted in previous studies as a notable model deficiency
370 (e.g. Grosvenor et al., 2014; King et al., 2015; Kirchgassner et al., 2019; Gilbert et al., 2020).
371 Unlike in the observations, there is evidence for the cloud-clearance effect in the model,
372 with $SW_{\text{Sfc}} / SW_{\text{TOA}}$ being significantly greater during foehn than during non-foehn conditions
373 (Table 1b). This will account for a portion of the model bias in RadH during foehn conditions,
374 the size of which cannot easily be ascertained.

375

376 **4. SEB regimes in Cabinet Inlet**

377

378 We categorise the ice shelf SEB observed at Cabinet Inlet into regimes according to *which*
379 *component is dominating*, as described in Section 2.3. We explore the sensitivity of SEB

380 regime occurrence to meteorological conditions, and the sensitivity of surface temperature
381 and melt in Cabinet Inlet to the SEB regime. Figure 5 shows the prevalence of each SEB
382 regime and their contributions to mean and cumulative (i.e. time-integrated) surface energy
383 exchange and melt, for all available Cabinet Inlet observations.

384

385 During foehn conditions (Figure 5a,b), the SEB is typically positive (surface heating) and is
386 commonly (62 % of the time) dominated by a single component, with typically greater flux
387 contributions by individual SEB components than during non-foehn conditions. The $SEB_{\downarrow SH}$
388 regime is most common and is responsible for most cumulative surface warming and melt
389 (76 %). Nonetheless, significant contributions to melt during foehn are driven by solar
390 radiation in the $SEB_{\downarrow SW}$ regime (19 % of the cumulative total), despite this regime only
391 occurring 6 % of the time during foehn. The strong surface heating and melting seen in this
392 regime is largely due to the SW fluxes being commonly supported by smaller but significant
393 downward SH fluxes. During both the $SEB_{\downarrow SH}$ and $SEB_{\downarrow SW}$ regimes, smaller upward fluxes in
394 LW and LH tend to partially offset the downward fluxes. The second most common SEB
395 regime during foehn is $SEB_{\uparrow LW}$, in which upward LW fluxes – partially offset by downward
396 SW fluxes – lead to net surface cooling. Very rarely (<1 % of the time) the $SEB_{\uparrow LH}$ regime
397 occurs. This is when sublimation is the dominant energy exchange process and is
398 characterised by significant flux contributions from all the SEB components, leading on
399 average to weak surface cooling.

400

401 During non-foehn conditions (Figure 5c,d), for the majority (83 %) of time, no single
402 component dominates the SEB. During these conditions, the net SEB is typically close to zero
403 and, overall, imparts a weak net cooling effect which amounts to a significant cumulative
404 surface cooling over the course of the full observational record. For the remainder of the
405 time, the radiative flux components tend to dominate; with the $SEB_{\downarrow SW}$ and $SEB_{\uparrow LW}$ regimes
406 occurring 11 and 6 % of the time, respectively. During $SEB_{\downarrow SW}$, downward SW fluxes –
407 typically partially offset by weaker upward LW fluxes – contribute a significant net surface
408 warming effect and lead to the vast majority (>90 %) of melt occurring during non-foehn
409 conditions. Conversely, during $SEB_{\uparrow LW}$, upward LW fluxes – typically partially offset by
410 weaker downward SW fluxes – contribute a net surface cooling effect and no melt.

411

412 It is notable that during non-foehn conditions nearly all melt occurs in a radiative dominated
 413 regime ($SEB_{\downarrow SW}$); while during foehn conditions significant melt occurs during both radiative
 414 ($SEB_{\downarrow SW}$) and turbulent ($SEB_{\downarrow SH}$) dominated regimes. As a consequence, the relationship
 415 between meteorological conditions and melt is more complex during foehn conditions. As
 416 outlined in Section 1, this complexity is evident in the diversity of results from previous
 417 studies on foehn melt signatures, especially those of foehn-jet-prone inlets as distinct from
 418 those of neighbouring wake regions. In the next section we investigate this further, aiming
 419 to clarify uncertainty in the sensitivity of foehn-driven surface warming and melt to
 420 meteorological conditions.

421

422 **5. Meteorological controls on melt during foehn in Larsen C Inlets**

423

424 It has been shown in Sections 3 and 4 that the foehn SEB at Cabinet Inlet is typically
 425 dominated by SH, which in turn is governed by wind speed and the air-surface temperature
 426 gradient. On this basis, we now test the following hypothesis:

427

428 *During foehn over Larsen C, variability in the SEB and melt depends principally on foehn wind*
 429 *speed and the temperature of the incoming foehn air relative to that of the ice surface.*

430

431 Figure 6 shows the sensitivity of the SEB components and melt to wind speed for both the
 432 observational and model data. The analysis is split into two subsets using static stability
 433 (expressed as the square of the Brunt-Väisälä frequency, N) between the surface and 2 m
 434 for the observations and the surface and 1.5 m for the model. These subsets represent (i)
 435 typical *stably-stratified foehn* conditions and (ii) rare *weakly-stratified foehn* conditions. The
 436 static stability threshold used to divide the data into these subsets is chosen to be the
 437 approximate value of N^2 at which the largest contributor to surface heating transitions
 438 between SW and SH (this value is determined by averaging the fluxes across N^2 bins of
 439 interval 0.01 s^{-1}). This is, for the observations and model respectively, 0.05 (the 5th
 440 percentile in N^2 , i.e. only 5 % of foehn occurring is *weakly stratified*) and 0.07 s^{-1} (the 16th
 441 percentile in N^2).

442

443 In the *stably-stratified foehn* subset of the Cabinet Inlet observations, TurbH generally
444 dominates over RadH, with SH-driven surface heating characterising conditions in all but the
445 weakest winds ($<3 \text{ m s}^{-1}$), in which LW-driven surface cooling generally prevails (Figure 6a;
446 though, note that for simplicity the radiative heat fluxes are combined in Figure 6). As winds
447 strengthen, SH increasingly dominates the SEB, leading to increasing surface heating and
448 melting. Conversely, in the *weakly-stratified foehn* subset, generally downward SH is
449 cancelled by upward LH, and RadH dominates over TurbH, with SW-driven surface heating
450 typifying the SEB when wind speeds are $<12 \text{ m s}^{-1}$ (Figure 6b). As winds strengthen, the
451 influence of LH increases, leading to a decrease in net heating and melting culminating in an
452 approximate balance in SEB components above 12 m s^{-1} . The SEB sensitivities to wind speed
453 and static stability observed at Cabinet Inlet are generally well represented by the model
454 (Figure 6c,d). Furthermore, these sensitivities are very similar at Whirlwind Inlet (Figure 6e,f)
455 – which implies they are likely to apply to all Larsen C inlets during foehn. Note that *weakly-*
456 *stratified foehn* at Cabinet Inlet is three times more likely in the model than the
457 observations. This reflects the positive model bias in SW leading to weaker summertime
458 static stabilities (see Section 3).

459

460 Physical explanations for the relationships between SEB and foehn conditions are now
461 discussed with the aid of the schematics shown in Figure 7. In typical foehn conditions over
462 Larsen C, warm air passes over cold ice (the maximum temperature of which is limited by
463 the melting point). In moderate to strong winds this results in SH-driven net surface
464 warming and melt (Figure 7a). In weak winds the surface becomes largely decoupled from
465 the warm foehn and LW-driven net cooling prevails (Figure 7b). In cases where the foehn air
466 is cooler than usual and/or is flowing over radiatively-warmed ice, the temperature gradient
467 will be too small for SH to dominate, no matter what the wind speed. Instead, the role of SH
468 becomes reactive, varying such as to minimise changes in surface temperature relative to air
469 temperature. And it becomes more effective in this role as the wind speed and wind-
470 induced turbulence increases, until the net SEB is reduced to near-zero (Figure 6b,d,f); often
471 with large flux contributions from all SEB components (Figure 7c). During foehn
472 characterised by weak winds and weak-stratification, SW-driven net surface warming and
473 melt prevails and helps to maintain the low static stabilities (Figure 7d).

474

475 The hypothesis proposed at the start of this section has been proven. The non-linear
476 relationship between net SEB and foehn conditions can be explained by differences in wind
477 speed, the influence of which is modulated by the warmth of incoming foehn relative to the
478 ice surface, via TurbH. These wind speed sensitivities largely explain the SEB differences
479 between foehn jet-prone inlets and adjacent wake regions. Other notable meteorological
480 factors contributing to these SEB differences include the likelihood of more frequent and
481 persistent foehn in inlets than in wake regions due to the funnelling effect of local
482 orography, and jet-wake differences in temperature and humidity (jet air typically being
483 cooler and moister; Elvidge et al., 2015). The likely climatological effect of the former is
484 enhanced foehn-driven melt in inlets relative to wake regions; while that of the latter is a
485 greater proportion of foehn being of the *weakly-stratified* type in inlets than in wakes.

486

487 If we consider the high-resolution model simulation of summertime foehn (“Case A”)
488 presented in Elvidge (2013) and also studied in Elvidge et al. (2015, 2016), surface
489 temperatures in the inlets were, relative to the rest of the foehn-affected ice shelf, high
490 during the night and low during the day. Melt only occurred during the daytime, and melt
491 minima were found in the inlets. This particular event was characterised by relatively low
492 near-surface foehn air temperatures (typically 1-2 °C in inlets; corresponding to the 2nd-5th
493 percentiles of foehn air temperatures during melt in our observations). Consequently,
494 during the daytime *weakly-stratified foehn* prevailed (c.f. Fig. 7d), characterised by SW-
495 driven surface warming and melt that was lower beneath the jets than elsewhere. During
496 the nighttime, *stably-stratified foehn* prevailed, with more surface warming beneath the jets
497 than elsewhere, but with foehn air temperatures insufficiently high to cause melting. In
498 addition to the diurnal effect on surface static stabilities, foehn jet air temperatures were
499 lower (by 3-4 K) than the air temperatures in adjacent wakes. Consequently, all else being
500 equal, the jet SEB was more likely than the wake SEB to fall into the *weakly-stratified foehn*
501 state. In contrast, the foehn case studied by Kuipers Munneke et al. (2018) was
502 characterised by near-surface air temperatures in excess of 10 °C (the 95th percentile in our
503 observations) and significant melt in the Larsen C inlets. Clearly this was a case of *stably-*
504 *stratified foehn* (c.f. Fig. 7a) and would have remained so even in the presence of strong
505 solar forcing.

506

507 The high sensitivity of the net SEB during foehn to wind speed and static stability may also
508 help to explain why the model climatology of King et al. (2017) was unable to reproduce
509 observed Larsen C melt distributions. Little evidence of foehn jets was found in their model
510 wind speed data, and the model they used (the Antarctic Mesoscale Prediction System) is
511 known to struggle in representing the relationship between wind speed and static stability
512 over an ice shelf (Wille et al., 2016). Further discussion on the challenges of model
513 representation of the Larsen C SEB is presented in Section 7.

514

515 **6. Drivers of melt across Larsen C**

516

517 In this section, our investigation of the drivers of melt is extended to the entire ice shelf,
518 using model data, for the 2015/16 melt season. Sections 3 and 5 provide evidence that the
519 model is sufficiently accurate for this: it is quantitatively representative in terms of
520 meteorology (Figure 2) and qualitatively representative for the SEB and melt (Figures 2 and
521 4) and how these relate to the meteorological conditions (Figure 6). This model has also
522 performed realistically in several previous studies (e.g. Orr et al., 2014; Elvidge et al., 2015;
523 2016). However, a significant and consistent overestimate in summertime radiatively-driven
524 surface warming and melt should be taken into consideration.

525

526 Figures 8-10 show model composite plots of key fields during *widespread foehn* and
527 *widespread non-foehn* conditions across Larsen C. Here, "*widespread foehn*" is diagnosed
528 when foehn is detected in the model (according to the criterion described in Appendix 1) at
529 both the Cabinet Inlet and Whirlwind Inlet sites. Likewise, "*widespread non-foehn*"
530 conditions are diagnosed when foehn is occurring in the model at neither of these sites,
531 whilst "*limited foehn*" conditions are diagnosed when foehn is detected at one inlet site but
532 not the other. *Widespread foehn* is found to occur 12 % of the time and is coincident with
533 20 % of total Larsen C melt, whilst *widespread non-foehn* occurs 70 % of the time and is
534 coincident with 58 % of the melt. This leaves *limited foehn* occurring 18% of the time and
535 accounting for 22% of the melt. For simplicity, the *limited foehn* state is largely disregarded
536 in this analysis and not shown in the figures. Note that whilst spatial plots of composite
537 mean meteorological and surface conditions are provided for foehn conditions in Figure 8,

538 equivalent plots are not shown for non-foehn conditions. This is due to the considerably
539 greater variability in meteorology during non-foehn conditions limiting the usefulness of
540 mean meteorological fields and to the typically much smaller spatial gradients in most fields
541 across Larsen C.

542

543 *Widespread foehn* conditions are characterised in the composite-mean by large-scale
544 geostrophically-forced westerly to northwesterly flow approaching and crossing the
545 Antarctic Peninsula (Figure 8a,b). There is a clear foehn signature in the composite mean
546 leeside response to these winds. In the immediate lee of the Peninsula, a plunging flow
547 signature is apparent in a cross section of composite-mean wind vectors, associated with
548 large cross-Peninsula gradients in pressure, temperature and humidity. Further downwind
549 across the ice shelf, rising isentropes and specific humidity contours reflect the average
550 diminishing influence of foehn with distance downwind of the mountains (Figure 9a,b).
551 Elvidge et al. (2016) demonstrated using case studies that the gradient of this diminishing
552 influence depends on the linearity of the mountain flow regime in which the foehn is
553 embedded. In very “non-linear” cases, the impact of foehn on the leeside atmospheric
554 boundary layer and ice shelf is confined to the foot of the mountains, whilst in the paths of
555 jets in more “linear” cases the impact of foehn extends undiminished across the full width of
556 the ice shelf (once the foehn is fully established in the boundary layer). Note that, with the
557 foehn classification employed here, the distinction between these regimes is lost.

558

559 During *widespread foehn*, climatological foehn jets are apparent to the east of the
560 Peninsula, emerging from the mouths of major inlets (Figure 8b), as first observed and
561 explained via case studies in Elvidge et al. (2015). The largest and strongest jet signatures
562 are seen within and downwind of Cabinet Inlet and Whirlwind Inlet, whilst weaker jet
563 signatures are seen within and downwind of Mill Inlet and the former Larsen B embayment.
564 Everywhere across Larsen C, mean TurbH is downward and dominates over mean upward
565 RadH (Figure 8c,d). The jet signatures correspond with the greatest TurbH fluxes and,
566 consequently, the highest mean surface temperatures (Figure 8e). The standard deviation of
567 surface temperature is smallest beneath the jets (Figure 8f), reflecting dampened
568 (radiatively-driven) diurnal and seasonal variability in surface temperature, due to a greater
569 regulating influence of TurbH on surface temperature in these jet regions.

570

571 During *widespread foehn*, mean melt rates are relatively high and spatially variable across
 572 Larsen C (Figure 10a). The total ice-shelf-wide melt contributions by $SEB_{\downarrow SH}$ ($melt_{\downarrow SH}$) and
 573 $SEB_{\downarrow SW}$ ($melt_{\downarrow SW}$) are similar (50 % each), though the spatial variability is almost entirely
 574 due to variability in $melt_{\downarrow SH}$ (see Figures 10a and 10b). Mean rates of $melt_{\downarrow SH}$ and
 575 consequently total melt broadly decline in a southeasterly direction, reflecting the mean
 576 northwesterly direction of foehn. This pattern also reflects the Cabinet Inlet jet being
 577 associated with the greatest and most widespread mean warming (consistent with the
 578 north-south gradient in the strength of the background circumpolar westerly winds;
 579 Marshall et al., 2006). The highest mean melt rates are found in the vicinity of the
 580 climatological foehn jets emerging from Cabinet Inlet, Whirlwind Inlet and Mill Inlet, peaking
 581 at 66 W m^{-2} in the upper reaches of Cabinet Inlet. The majority of melt in these regions is
 582 due to $SEB_{\downarrow SH}$. The lowest melt rates are found at the eastern edge of the ice shelf, at the
 583 far south of the model domain (where an ice-shelf-wide minimum of 2 W m^{-2} is found), and
 584 within a strip of ice extending from Mamelon Point eastwards. The majority of melt in these
 585 regions is due to $SEB_{\downarrow SW}$. Radiative contributions to melt during *widespread foehn* are
 586 enhanced via the cloud-clearance effect, which is evident across the entire ice shelf in terms
 587 of SW_{sfc} / SW_{TOA} (compare Figures 10c and 10f). Note that cloud cover is greatest in the
 588 upper reaches of Cabinet Inlet, consistent with leeside conditions being moistest in jets
 589 during foehn due to a dampened foehn drying effect here (see Elvidge et al., 2015). The lack
 590 of any foehn cloud-clearance seen in the Cabinet Inlet observations together with the model
 591 overestimate in SW here suggests the model underestimates the moisture in jets. It is
 592 interesting that, in contrast to SH (and $melt_{\downarrow SH}$; see Figure 10a,b), SW_{sfc} / SW_{TOA} (and
 593 $melt_{\downarrow SW}$; not shown) does not diminish with distance downwind of the Peninsula during
 594 foehn. This demonstrates that in the model the impact of foehn on the ice shelf typically
 595 extends beyond the reach of low-level foehn winds, due to cloud-clearance aloft.

596

597 During *widespread non-foehn* conditions, cross-Peninsula gradients in mean MSLP (not
 598 shown), temperature (Figure 9c) and relative humidity (Figure 9d) are the reverse of that
 599 during *widespread foehn*, and the mean MSLP gradients and wind speeds are considerably
 600 weaker across the region. Over Larsen C, composite-mean temperatures and specific
 601 humidities are considerably lower (by 7-12 °C and $\sim 0.6 \text{ g kg}^{-1}$, respectively) than during

602 *widespread foehn*, whilst relative humidities are considerably higher (by 20-50 %). This
 603 reflects the cool, southerly, continentally-sourced airmasses typical of non-foehn conditions,
 604 versus the warm, maritime character of the airmasses which arrive from the west side of the
 605 Peninsula to force foehn.

606

607 Melt during *widespread non-foehn* conditions occurs at much lower mean rates, is much
 608 less spatially variable than during *widespread foehn* (compare Figures 10d and 10a) and is
 609 almost entirely (96 %) due to $\text{melt}_{\downarrow\text{SW}}$ (Figure 10e). There is a weak northeast-southwest
 610 gradient in melt, with a maximum value of 11 W m^{-2} in the far northeast and a minimum
 611 value of 4 W m^{-2} in the far southwest (see inset transect in Figure 10d). This gradient reflects
 612 that of $\text{melt}_{\downarrow\text{SW}}$ (Figure S1a), which itself results from variability in cloud cover (indicated by
 613 $\text{SW}_{\text{sfc}} / \text{SW}_{\text{TOA}}$; Figure 10f) and latitudinal variability in incoming solar radiation (SW_{TOA} ;
 614 Figure S1b). Figure S1 shows that the contributions of cloud cover and SW_{TOA} to variability in
 615 SW_{sfc} are roughly equal. Although non-foehn winds most commonly have a southerly
 616 component, mean melt rates generally vary little with wind direction (not shown).

617

618 In total, much of the spatial variability in melt across Larsen C simulated during the 2015/16
 619 melt season is due to $\text{melt}_{\downarrow\text{SH}}$, governed by foehn. This is evident in the resemblance of the
 620 distribution of accumulated melt shown in Figure 10g with that in Figure 10a. Even so, the
 621 northeast-southwest gradient in melt seen during *widespread non-foehn* does – despite its
 622 weak signal in the mean – significantly impact the distribution of accumulated melt. $\text{SEB}_{\downarrow\text{SW}}$
 623 contributes more melt than $\text{SEB}_{\downarrow\text{SH}}$ over the vast majority of the ice shelf, and in total 79 %
 624 of melt across Larsen C. This is due firstly to the predominance of non-foehn conditions,
 625 during which nearly all melt is driven by $\text{SEB}_{\downarrow\text{SW}}$; and secondly to the fact that, away from
 626 the inlets, $\text{SEB}_{\downarrow\text{SW}}$ also contributes significantly to melt during foehn conditions. In fact, as
 627 seen in the observations (see Figure 5b), the highest mean melt rates of any SEB regime are
 628 seen in $\text{SEB}_{\downarrow\text{SW}}$ during foehn; owing to secondary contributions by SH and, in the model,
 629 also due to cloud-clearance.

630

631 In Figure 11, a more detailed analysis of SEB and melt characteristics is shown for Cabinet
 632 Inlet and the three additional sites (c.f. Figure 1; Table 1). At these locations, foehn is
 633 diagnosed in a site-specific manner, as described in Appendix 1. Across all four sites melt

634 during foehn is more likely than melt during non-foehn conditions and occurs at greater
635 rates. This is especially so at the two inlet sites, where the prevalence and relative impacts
636 of the SEB regimes are qualitatively similar (Figure 11a-d). At Whirlwind Inlet, $SEB_{\downarrow SH}$
637 contributes slightly more melt, reflecting stronger mean foehn winds here than at Cabinet
638 Inlet (Figure 8b).

639

640 At Larsen East and Mamelon Point foehn occurs less frequently, owing to their locations,
641 respectively, ~ 150 km downwind of the Peninsula and in a region known to typically
642 experience wake conditions during foehn. When foehn does occur at these locations, it is
643 associated with much weaker surface warming and less melt (Figure 11e-h). The prevalence
644 and impact of $SEB_{\downarrow SH}$ is much lower, reflecting weaker foehn winds and, at Larsen East,
645 lower foehn air temperatures. Of all four sites during foehn, $SEB_{\downarrow SH}$ is least common and
646 $SEB_{\downarrow SW}$ most common at Mamelon Point. This is explained by its sheltered location, where
647 foehn flows are typically very weak (Figure 8b) and dry (not shown), as explained in Elvidge
648 et al. (2015). These particularly dry foehn conditions are associated with significantly higher
649 SW_{Sfc} / SW_{TOA} than during non-foehn conditions, consistent with the cloud-clearance effect,
650 which, of all four sites, is strongest here (Table 1b). With distance downwind of the
651 Peninsula, spatial variability in mean foehn wind speed generally decreases as foehn jets
652 broaden and weaken and wake regions disappear. This is reflected in $SEB_{\downarrow SH}$ being more
653 common at Larsen East, which experiences on average stronger foehn winds than Mamelon
654 Point. During non-foehn conditions, there is comparatively little variation between the four
655 sites in terms of the prevalence and impact of SEB regimes, with slight variability in the
656 degree of warming and melt reflecting the northeast-southwest gradient in $SEB_{\downarrow SW}$
657 described above.

658

659 The simulated spatial melt patterns described in this section closely resemble those seen in
660 the satellite observations of Bevan et al. (2018) for an annual period encompassing the
661 same melt season of 2015/16, which in turn are typical of melt distributions observed
662 during other melt seasons (e.g. Bevan et al., 2018, Luckman et al., 2014). The north-south
663 gradient in satellite-observed melt is reproduced and shown to be due to a combination of a
664 northeast-southwest gradient in mean melt $_{\downarrow SW}$ during non-foehn conditions and a broadly
665 northwest to southeast mean gradient in melt $_{\downarrow SH}$ during foehn (in nonlinear mountain flow

666 regimes and boundary layers in which the foehn has yet to fully establish). Also reproduced
667 is the observed band of generally high melt rates along the Peninsula's east coast, in
668 particular in the inlets (e.g. Figure 10g). This is demonstrated to be due to the foehn winds
669 here being generally stronger, resulting in greater SH-driven melt. In the inlets, more
670 frequent foehn occurrence also contributes to more cumulative melt. Beyond these
671 generally well-captured broad-scale features, there are regional discrepancies. Most
672 notably, the simulated melt deficit around Mamelon Point relative to neighbouring inlets
673 appears to be exaggerated compared to observations (c.f. Bevan et al. 2018). However,
674 another wake region and melt minimum in the model – between Mill Inlet and Cabinet Inlet
675 – is consistent with these observations. Figure 12 summarises in schematic form the key
676 patterns in Larsen C melt discussed here and the mechanisms which we have found to be
677 responsible for them.

678

679 **7. Discussion and conclusions**

680

681 This study has employed the first set of observations from a Larsen C inlet, in conjunction
682 with a season-long, high-resolution simulation in a state-of-the-art model (the Met Office
683 Unified Model) to provide the first comprehensive explanation of patterns in SEB and melt
684 across Larsen C. A novel approach to classifying the SEB regime according to the *dominant*
685 SEB component has afforded a useful means of attributing variability in net SEB and melt to
686 atmospheric drivers.

687

688 The climatological impact of foehn on the Larsen C SEB is distinct and significant, with
689 elevated occurrences and rates of melt, especially in inlets. During 31 months of
690 observations at Cabinet Inlet, foehn contributes 45 % of total melt despite only occurring 15
691 % of the time. During foehn, melt occurs three times more often and, when it does occur, it
692 does so at a rate greater by a factor of 1.4. Foehn melt accounts for nearly 90 % of melt
693 observed outside the summer months (DJF), virtually all of which takes place during spring
694 (SON; during which foehn is also likely to play an important role in the preconditioning of
695 the ice shelf for summertime melt) and autumn (MAM). In the model, comparable statistics
696 are simulated for inlets, and even in regions where the net impact of foehn is weakest (in

697 the southeast and in wake regions). Owing to sharp gradients in mean melt, foehn governs
698 the spatial distribution in cumulative melt simulated across Larsen C for the 2015/16 melt
699 season.

700

701 While foehn is the more potent agent for melt, non-foehn conditions occur much more
702 commonly and contribute more melt than foehn everywhere across Larsen C outside of the
703 inlets. Nearly all non-foehn-driven melt is due to SW during the summer months (90 %
704 occurring during DJF in the Cabinet Inlet observations). Non-foehn-driven melt varies
705 comparatively little in the mean across Larsen C. However, a subtle northeast to southwest
706 gradient reflects a corresponding gradient in surface solar forcing, resulting from spatial
707 variability in both top of atmosphere solar irradiance and cloud cover; this is significant to
708 the distribution of total cumulative melt.

709

710 Many previous studies, both over Larsen C (e.g. Kuipers Munneke et al., 2012; Grosvenor et
711 al., 2014; King et al, 2017) and elsewhere in the world (over John Evans Glacier, Canada;
712 Boon et al., 2003; on Hokkaido Island, Japan, Hayashi et al., 2005; over the Baltic Sea,
713 Granskog et al., 2006; and in Southern Alberta, Canada, MacDonald et al., 2018), have found
714 the impact of foehn on snow and ice melt to be largely limited to elevated contributions by
715 downward SW (due to a cancellation of SH by LH). In contrast, our results show that the
716 primary impact of foehn over Larsen C is elevated contributions to melt by downward SH.
717 This finding is consistent with the case study results of Elvidge et al. (2016) and Kuipers
718 Munneke et al. (2018). The majority (76 % in our observations) of foehn-driven melt occurs
719 when SH dominates the SEB as a result of strong, warm foehn winds passing over a much
720 cooler ice surface. The majority of such melt (and roughly half of total foehn-driven melt)
721 occurs in the absence of solar forcing, during the night or outside the summer season.
722 However, SW does significantly contribute to foehn-driven melt, with most of the remaining
723 melt (19 %) occurring when SW dominates the SEB regime. During such conditions, SH
724 typically also contributes, leading to the highest melt rates observed at Cabinet Inlet. In the
725 model, foehn enhancement of SW is evident across the entire ice shelf, reflecting
726 widespread cloud-clearance. However, this enhancement is not apparent in the Cabinet
727 Inlet observations. The foehn cloud-clearance effect has previously been inferred from both
728 observations and model output at Larsen East during the 2010/11 summer season (Kuipers

729 Munneke et al., 2012; King et al., 2017), but the effect was small and not statistically
730 significant. Further work is required to establish the significance of this effect over Larsen C
731 more generally.

732

733 Satellite observations across Larsen C have demonstrated that the foehn-jet-prone inlets
734 experience the most cumulative melt (e.g. Luckman et al., 2014; Bevan et al. 2018).

735 However, previous case study simulations have been unable to reproduce this melt pattern
736 (e.g. Elvidge, 2013; Grosvenor et al., 2014). We now know why: the impact of foehn is
737 critically sensitive to wind strength, the influence of which is modulated by the warmth of
738 incoming foehn relative to the ice surface, via the balance in the turbulent heat fluxes.

739 Typical foehn is much warmer than the ice and results in the highest melt rates occurring
740 beneath the strongest foehn winds (i.e. in the inlets) where downward SH is greatest. Less
741 commonly, cooler foehn winds result in the highest melt rates occurring beneath the
742 weakest foehn winds (i.e. in wakes) where upward LH is smallest. This more unusual *weakly-*
743 *stratified foehn* state occurs 5 % of the time in the Cabinet Inlet observations and is
744 associated with small air-ice temperature gradients and typically sunny conditions, and
745 accounts for the incidence of melt minima beneath jets in such cases as that examined by
746 Elvidge (2013).

747

748 Another notable finding of this study is the signature of a foehn jet in simulated mean wind
749 speed passing over the embayment formerly occupied by the Larsen B Ice Shelf (until its
750 collapse in 2002). This jet is associated with elevated SH-driven surface warming and is also
751 seen in the multidecadal simulation data presented in Wiesenekker et al. (2018). Whether
752 this jet exists in reality and whether it was common prior to the collapse of Larsen B is
753 unknown and could be a focus of future work.

754

755 The MetUM has been shown to provide a quantitatively accurate representation of the
756 occurrence of foehn and annual melt, and to provide a qualitatively accurate representation
757 of SEB and melt variability during the 2015/16 melt season at Cabinet Inlet. Furthermore,
758 the modelled spatial distribution of cumulative melt across Larsen C corresponds
759 remarkably well with satellite observations of melt during the same melt season (see Bevan
760 et al., 2018); which is typical of melt distributions observed during other melt seasons. This

761 provides confidence that our model results are realistic and useful. The broad, roughly
762 north-south gradient in melt seen in observations is reproduced and shown to be due to a
763 combination of the aforementioned northeast to southwest gradient in SW-driven melt
764 during non-foehn conditions, and a northwest to southeast gradient in SH-driven melt in
765 foehn conditions (due to “non-linear” cross-Peninsula flow; Elvidge et al., 2016). Also
766 reproduced is the observed band of generally high melt rates along the Peninsula’s east
767 coast, in particular in the inlets. Previous speculation that this is due to the impact of foehn
768 (and consequently SH-driven melt) being greater here is confirmed. Despite the model’s
769 successes, there is a consistent and significant positive bias in SW, which is consistent with
770 the findings of previous studies with the same and different models (e.g. Grosvenor et al.,
771 2014; King et al., 2015; Kirchgassner et al., 2019; Gilbert et al., 2020). This bias results in
772 significant overestimates in melt during the summer months, particularly during non-foehn
773 conditions, and implies deficiencies in the model’s representation of clouds and/or surface
774 albedo (largely clouds in the MetUM; Gilbert et al., 2020).

775

776 Our study demonstrates that the accuracy of model simulations of Larsen C melt depends
777 critically on the accurate reproduction of (a) summertime incoming SW at the surface (and
778 consequently clouds and albedo); (b) the occurrence, strength and warmth of foehn winds
779 at the surface; and (c) air-ice boundary-layer coupling and consequently the balance
780 between sensible and latent heat fluxes during foehn. These are all known to be challenging
781 processes for models, though in recent years there has been some notable progress. For
782 example, it has recently been shown that significant improvements in the representation of
783 the supercooled liquid phase in Antarctic clouds are possible with the adoption of a realistic
784 double-moment ice cloud microphysics scheme (Listowski and Lachlan-Cope, 2017). Recent
785 developments in the dynamical cores around which atmospheric models are built have also
786 significantly improved the capacity of models to resolve the gravity waves and flow
787 perturbations (of which foehn is an example) induced by mountains (Elvidge et al., 2017).

788

789 The degree to which Larsen C is in equilibrium with present-day atmospheric forcing is
790 unclear. Furthermore, future changes in this forcing are expected. For example, the index of
791 the Southern Annular Mode (SAM), which governs the strength of the prevailing westerly
792 winds across the Peninsula, is expected to vary in accordance with future greenhouse gas

793 emissions (Abram et al., 2014). Any future positive trend in the SAM index, as predicted in
794 high emission scenarios of the CMIP5 projections (Zheng et al., 2013), would likely yield a
795 greater-still influence of foehn on Larsen C. Changes in the atmospheric forcing may also be
796 instigated by changes in the cryosphere itself – for example calving events and sea ice
797 decline. Our ability to predict such changes and consequently the ice shelf’s future stability
798 relies on underpinning mechanistic understanding of the complex interactions at the
799 atmosphere-cryosphere interface (such as provided by the present study), the coverage of
800 strategically-located observational platforms in the region (such as the Cabinet Inlet AWS),
801 and on the capability of atmosphere-cryosphere coupled climate models.

802

803 **Appendix 1: Foehn Detection**

804

805 The algorithmic classification of foehn is a non-trivial matter, for which there is no
806 established best practice (Mayr et al., 2018). In this study, a comparatively simple approach
807 has been adopted, based on the assumption that foehn has a sufficiently distinct and
808 temporally invariant signature at a given location to be identified in-situ using simple fixed
809 thresholds of key meteorological fields in absolute terms (i.e. not relative to pre- or post-
810 foehn conditions). This assumption is supported by climatological analysis of the AWS data
811 (not shown) and by the findings of Turton et al. (2018), Kuipers Munneke et al. (2018) and
812 King et al (2017). Accordingly, we have used only leeside near-surface data and employ
813 thresholds in wind direction and relative humidity, which vary on a site-by-site basis,
814 according to (a) location with respect to the upwind orography, and (b) analysis of selected
815 cases studies. For the Cabinet Inlet site (observations and model) and the Whirlwind Inlet
816 site (model only), foehn conditions have been defined by wind directions being between
817 southwesterly and northerly and the relative humidity with respect to ice (hereafter simply
818 “relative humidity”) being below 75 %. This threshold has been chosen based on case-study
819 analysis of AWS and model data to afford detection of the great majority of foehn cases
820 whilst excluding other westerly flows at Cabinet Inlet, e.g. barrier winds and katabatic winds
821 (e.g. Grazioli et al., 2017). Despite the cross-mountain foehn drying effect, the maritime
822 influence on circumpolar westerlies means that foehn air over Larsen C is not necessarily
823 comparatively dry in terms of absolute humidity. However, the warmth of foehn air means it

824 can typically hold much more water vapour than the typically cool air sourced from east of
825 the Peninsula (including barrier winds) or the mountain slopes (including katabatic winds).
826

827 For the Mamelon Point (model only) site, foehn is diagnosed when relative humidity is
828 below 75 % and foehn is diagnosed at one or both of the two inlet sites. The rationale for
829 this is that the foehn wake conditions known to occur at the Mamelon Point site are
830 typically characterised by near-stagnant flow and recirculated foehn air (Elvidge et al.,
831 2015), rendering a wind direction criterion inappropriate. However, given the close
832 proximity to the Peninsula, the same relative humidity criterion as used for the Inlets is
833 appropriate. The fact that foehn occurrence in a wake region is unlikely without foehn
834 occurrence in nearby inlets (into which foehn is preferentially funnelled; Elvidge et al., 2015)
835 justifies the additional condition that foehn must be occurring in at least one of the two
836 inlet sites.

837

838 For the Larsen East (model only) site, the detection criterion has been designed to account
839 for its distance from the mountains of the Peninsula. Here, foehn is diagnosed when relative
840 humidity is below 80 % and either of the following two conditions are met:

- 841 1. Wind direction at Larsen East is between westerly and north-northwesterly, and
842 foehn is diagnosed at Cabinet Inlet; or
- 843 2. Wind direction at Larsen East is between west-southwesterly and westerly, and
844 foehn is diagnosed at Whirlwind Inlet.

845 The relative humidity threshold of 80 % has been inferred from the model data, being the
846 average relative humidity of air arriving at Larsen C from either of the inlets which had a
847 relative humidity of ~75 % at the inlet.

848

849 **Acknowledgements**

850

851 This paper was made possible by funding provided by NERC under the project grant
852 NE/N009754/1. P.K.M. acknowledges funding from the Netherlands Earth System Science
853 Centre. The British Antarctic Survey is acknowledged for the servicing of the automatic
854 weather station in Cabinet Inlet, the data from which is available via the following

855 repository: <https://data.bas.ac.uk/full-record.php?id=GB/NERC/BAS/PDC/01015>. The model
856 data was derived from a Met Office Unified Model simulation carried out on the Joint
857 Weather and Climate Research Programme (Met Office and NERC) MONSooN computing
858 system. These data require a large tape storage facility and have been archived through the
859 Met Office mass storage system, accessible through the STFC-CEDA platform JASMIN
860 (Lawrence et al., 2013). We thank Tony Phillips for his assistance in preparing the land sea
861 mask and orography data used for the model simulation and in Figure 1.
862

863 **References**

864

865 Abram, N.J., Mulvaney, R., Vimeux, F., Phipps, S.J., Turner, J. and England, M.H., 2014.

866 Evolution of the Southern Annular Mode during the past millennium. *Nature Climate*867 *Change*, 4(7), pp.564-569.

868

869 Ashmore, D.W., Hubbard, B., Luckman, A., Kulesa, B., Bevan, S., Booth, A., Munneke, P.K.,

870 O'leary, M., Sevestre, H. and Holland, P.R., 2017. Ice and firn heterogeneity within Larsen C

871 Ice Shelf from borehole optical televiewing. *Journal of Geophysical Research: Earth*872 *Surface*, 122(5), 1139-1153.

873

874 Barrand, N.E., Vaughan, D.G., Steiner, N., Tedesco, M., Kuipers Munneke, P., Van den

875 Broeke, M.R. and Hosking, J.S., 2013. Trends in Antarctic Peninsula surface melting

876 conditions from observations and regional climate modeling. *Journal of Geophysical*877 *Research: Earth Surface*, 118(1), pp.315-330.

878

879 Bevan, S.L., Luckman, A.J., Kuipers Munneke, P., Hubbard, B., Kulesa, B. and Ashmore,

880 D.W., 2018. Decline in surface melt duration on Larsen C ice shelf revealed by the Advanced

881 Scatterometer (ASCAT). *Earth and Space Science*, 5(10), 578-591.

882

883 Boon, S., Sharp, M., & Nienow, P., 2003. Impact of an extreme melt event on the runoff and

884 hydrology of a high Arctic glacier. *Hydrological Processes*, 17(6), 1051-1072.

885

886 Cape, M.R., Vernet, M., Skvarca, P., Marinsek, S., Scambos, T. and Domack, E., 2015. Foehn

887 winds link climate-driven warming to ice shelf evolution in Antarctica. *Journal of Geophysical*888 *Research: Atmospheres*, 120(21), 11-037.

889

890 Cook, A.J. and Vaughan, D.G., 2010. Overview of areal changes of the ice shelves on the

891 Antarctic Peninsula over the past 50 years. *The Cryosphere*, 4(1), 77-98.

892

- 893 Datta, R.T., Tedesco, M., Fettweis, X., Agosta, C., Lhermitte, S., Lenaerts, J. and Wever, N.,
 894 2019. The Effect of Foehn-Induced Surface Melt on Firn Evolution Over the Northeast
 895 Antarctic Peninsula. *Geophysical Research Letters*, 46, doi:
 896 <https://doi.org/10.1029/2018GL080845>.
 897
- 898 Elvidge, A., 2013. *Polar föhn winds and warming over the Larsen C Ice Shelf*,
 899 *Antarctica* (Doctoral dissertation, University of East Anglia).
 900
- 901 Elvidge, A.D. and Renfrew, I.A., 2016. The causes of foehn warming in the lee of
 902 mountains. *Bulletin of the American Meteorological Society*, 97(3), 455-466.
 903
- 904 Elvidge, A.D., Renfrew, I.A., King, J.C., Orr, A., Lachlan-Cope, T.A., Weeks, M. and Gray, S.L.,
 905 2015. Foehn jets over the Larsen C ice shelf, Antarctica. *Quarterly Journal of the Royal*
 906 *Meteorological Society*, 141(688), 698-713.
 907
- 908 Elvidge, A.D., Renfrew, I.A., King, J.C., Orr, A. and Lachlan-Cope, T.A., 2016. Foehn warming
 909 distributions in nonlinear and linear flow regimes: A focus on the Antarctic
 910 Peninsula. *Quarterly Journal of the Royal Meteorological Society*, 142(695), 618-631.
 911
- 912 Elvidge, A.D., Vosper, S.B., Wells, H., Cheung, J.C., Derbyshire, S.H. and Turp, D., 2017.
 913 Moving towards a wave-resolved approach to forecasting mountain wave induced clear air
 914 turbulence. *Meteorological Applications*, 24(3), 540-550.
 915
- 916 Gilbert, E., Orr, A., King, J.C., Renfrew, I.A., Lachlan-Cope, T., Field, P.F. and Boutle, I.A.,
 917 2020. Summertime cloud phase strongly influences surface melting on the Larsen C ice shelf,
 918 Antarctica. *Quarterly Journal of the Royal Meteorological Society*, doi:10.1002/qj.3753
 919
- 920 Granskog, M.A., Vihma, T., Pirazzini, R. and Cheng, B., 2006. Superimposed ice formation
 921 and surface energy fluxes on sea ice during the spring melt–freeze period in the Baltic Sea.
 922 *Journal of Glaciology*, 52(176), pp.119-127.
 923

- 924 Grazioli, J., Madeleine, J.B., Gallée, H., Forbes, R.M., Genthon, C., Krinner, G. and Berne, A.,
925 2017. Katabatic winds diminish precipitation contribution to the Antarctic ice mass
926 balance. *Proceedings of the National Academy of Sciences*, 114(41), 10858-10863.
927
- 928 Grosvenor, D.P., King, J.C., Choularton, T.W. and Lachlan-Cope, T., 2014. Downslope föhn
929 winds over the Antarctic Peninsula and their effect on the Larsen ice shelves. *Atmospheric*
930 *Chemistry and Physics*, 14(18), 9481-9509.
931
- 932 Hayashi, M., Hirota, T., Iwata, Y. and Takayabu, I., 2005. Snowmelt energy balance and its
933 relation to foehn events in Tokachi, Japan. *Journal of the Meteorological Society of Japan*.
934 *Ser. II*, 83(5), 783-798.
935
- 936 Hogg, A.E. and Gudmundsson, G.H., 2017. Impacts of the Larsen-C Ice Shelf calving event.
937 *Nature Climate Change*, 7(8), p.540.
938
- 939 Holland, P.R., Corr, H.F., Pritchard, H.D., Vaughan, D.G., Arthern, R.J., Jenkins, A. and
940 Tedesco, M., 2011. The air content of Larsen ice shelf. *Geophysical Research Letters*, 38(10).
941
- 942 Hubbard, B., Luckman, A., Ashmore, D.W., Bevan, S., Kulesa, B., Munneke, P.K., Philippe,
943 M., Jansen, D., Booth, A., Sevestre, H. and Tison, J.L., 2016. Massive subsurface ice formed
944 by refreezing of ice-shelf melt ponds. *Nature communications*, 7, p.11897.
945
- 946 King, J.C., Lachlan-Cope, T.A., Ladkin, R.S. and Weiss, A., 2008. Airborne measurements in
947 the stable boundary layer over the Larsen Ice Shelf, Antarctica. *Boundary-layer*
948 *meteorology*, 127(3), p.413.
949
- 950 King, J.C., Gadian, A., Kirchgaessner, A., Kuipers Munneke, P., Lachlan-Cope, T.A., Orr, A.,
951 Reijmer, C., Van den Broeke, M.R., Van Wessem, J.M. and Weeks, M., 2015. Validation of
952 the summertime surface energy budget of Larsen C Ice Shelf (Antarctica) as represented in
953 three high-resolution atmospheric models. *Journal of Geophysical Research: Atmospheres*,
954 120(4), 1335-1347.
955

- 956 King, J.C., Kirchgaessner, A., Bevan, S., Elvidge, A.D., Kuipers Munneke, P., Luckman, A., Orr,
957 A., Renfrew, I.A. and Van den Broeke, M.R., 2017. The impact of föhn winds on surface
958 energy balance during the 2010–2011 melt season over Larsen C Ice Shelf,
959 Antarctica. *Journal of Geophysical Research: Atmospheres*, **122**(22), 12-062.
960
- 961 Kirchgaessner, A., King, J. and Gadian, A., 2019. The representation of Föhn events to the
962 east of the Antarctic Peninsula in simulations by the Antarctic Mesoscale Prediction System
963 (AMPS). *Journal of Geophysical Research: Atmospheres* **124**, 13,663–13,679 doi:
964 10.1029/2019JD030637
965
- 966 Kuipers Munneke, P., Van den Broeke, M.R., Reijmer, C.H., Helsen, M.M., Boot, W.,
967 Schneebeli, M. and Steffen, K., 2009. The role of radiation penetration in the energy budget
968 of the snowpack at Summit, Greenland. *The Cryosphere*, **3**, 155-165.
969
- 970 Kuipers Munneke, P., Van den Broeke, M.R., King, J.C., Gray, T. and Reijmer, C.H., 2012.
971 Near-surface climate and surface energy budget of Larsen C ice shelf, Antarctic
972 Peninsula. *The Cryosphere*, **6**(2), 353-363.
973
- 974 Kuipers Munneke, P., Ligtenberg, S.R., Van den Broeke, M.R. and Vaughan, D.G., 2014. Firn
975 air depletion as a precursor of Antarctic ice-shelf collapse. *Journal of Glaciology*, **60**(220),
976 205-214.
977
- 978 Kuipers Munneke, P., Luckman, A.J., Bevan, S.L., Smeets, C.J.P.P., Gilbert, E., Van Den
979 Broeke, M.R., Wang, W., Zender, C., Hubbard, B., Ashmore, D. and Orr, A., 2018. Intense
980 winter surface melt on an Antarctic ice shelf. *Geophysical Research Letters*, **45**(15), 7615-
981 7623.
982
- 983 Larsen, C. A., 1894. The Voyage of the “Jason” to the Antarctic Regions. *The Geographical*
984 *Journal*, **4**(4), pp.333-344.
985

- 986 Lawrence, B.N., Bennett, V.L., Churchill, J., Jukes, M., Kershaw, P., Pascoe, S., Pepler, S.,
987 Pritchard, M. and Stephens, A., 2013, October. Storing and manipulating environmental big
988 data with JASMIN. In 2013 IEEE international conference on big data (pp. 68-75). IEEE.
989
- 990 Leeson, A.A., Van Wessem, J.M., Ligtenberg, S.R.M., Shepherd, A., Van den Broeke, M.R.,
991 Killick, R., Skvarca, P., Marinsek, S. and Colwell, S., 2017. Regional climate of the Larsen B
992 embayment 1980–2014. *Journal of Glaciology*, 63(240), 683-690.
993
- 994 Listowski, C. and Lachlan-Cope, T., 2017. The microphysics of clouds over the Antarctic
995 Peninsula–Part 2: modelling aspects within Polar WRF. *Atmospheric Chemistry and Physics*,
996 17(17), 10195-10221.
997
- 998 Liu, H., K. C. Jezek, B. Li, and Z. Zhao., 2015. Radarsat Antarctic Mapping Project Digital
999 Elevation Model, Version 2. Boulder, Colorado USA. NASA National Snow and Ice Data
1000 Center Distributed Active Archive Center. doi: <https://doi.org/10.5067/8JKNEW6BFRVD>.
1001 [Accessed March 2017].
1002
- 1003 Luckman, A., Elvidge, A., Jansen, D., Kulesa, B., Munneke, P.K., King, J. and Barrand, N.E.,
1004 2014. Surface melt and ponding on Larsen C Ice Shelf and the impact of föhn
1005 winds. *Antarctic Science*, 26(6), 625-635.
1006
- 1007 MacDonald, M. K., Pomeroy, J. W., & Essery, R. L., 2018. Water and energy fluxes over
1008 northern prairies as affected by chinook winds and winter precipitation. *Agricultural and*
1009 *Forest Meteorology*, 248, 372-385.
1010
- 1011 Marshall, G.J., Orr, A., Van Lipzig, N.P. and King, J.C., 2006. The impact of a changing
1012 Southern Hemisphere Annular Mode on Antarctic Peninsula summer temperatures. *Journal*
1013 *of Climate*, 19(20), 5388-5404.
1014
- 1015 Mayr, G.J., Armi, L., Gohm, A., Zängl, G., Durran, D.R., Flamant, C., Gaberšek, S., Mobbs, S.,
1016 Ross, A. and Weissmann, M., 2007. Gap flows: results from the Mesoscale Alpine
1017 Programme. *Quarterly Journal of the Royal Meteorological Society*, 133(625), 881-896.

- 1018
1019 Mayr, G.J., Plavcan, D., Armi, L., Elvidge, A., Grisogono, B., Horvath, K., Jackson, P., Neururer,
1020 A., Seibert, P., Steenburgh, J.W. and Stiperski, I., 2018. The Community Foehn Classification
1021 Experiment. *Bulletin of the American Meteorological Society*, 99(11), pp.2229-2235.
1022
- 1023 Morris, E.M. and Vaughan, D.G., 2003. Spatial and temporal variation of surface
1024 temperature on the Antarctic Peninsula and the limit of viability of ice shelves. *Antarctic*
1025 *Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives*, 79, 61-68.
1026
- 1027 Orr, A., Marshall, G.J., Hunt, J.C., Sommeria, J., Wang, C.G., Van Lipzig, N.P., Cresswell, D.
1028 and King, J.C., 2008. Characteristics of summer airflow over the Antarctic Peninsula in
1029 response to recent strengthening of westerly circumpolar winds. *Journal of the Atmospheric*
1030 *Sciences*, 65(4), 1396-1413.
1031
- 1032 Orr, A., Phillips, T., Webster, S., Elvidge, A., Weeks, M., Hosking, S. and Turner, J., 2014. Met
1033 Office Unified Model high-resolution simulations of a strong wind event in
1034 Antarctica. *Quarterly Journal of the Royal Meteorological Society*, 140(684), 2287-2297.
1035
- 1036 Parish, T.R., 1983. The influence of the Antarctic Peninsula on the wind field over the
1037 western Weddell Sea. *Journal of Geophysical Research: Oceans*, 88(C4), 2684-2692.
1038
- 1039 Radić, V., Menounos, B., Shea, J., Fitzpatrick, N., Tessema, M.A. and Déry, S.J., 2017.
1040 Evaluation of different methods to model near-surface turbulent fluxes for a mountain
1041 glacier in the Cariboo Mountains, BC, Canada. *The Cryosphere*, 11(6), p.2897.
1042
- 1043 Scambos, T.A., Hulbe, C., Fahnestock, M. and Bohlander, J., 2000. The link between climate
1044 warming and break-up of ice shelves in the Antarctic Peninsula. *Journal of*
1045 *Glaciology*, 46(154), 516-530.
1046
- 1047 Schwerdtfeger, W., 1975. The effect of the Antarctic Peninsula on the temperature regime
1048 of the Weddell Sea. *Monthly Weather Review*, 103(1), 45-51.
1049

- 1050 Smeets, P.C., Kuipers Munneke, P., Van As, D., van den Broeke, M.R., Boot, W., Oerlemans,
1051 H., Snellen, H., Reijmer, C.H. and van de Wal, R.S., 2018. The K-transect in west Greenland:
1052 Automatic weather station data (1993–2016). *Arctic, Antarctic, and Alpine Research*, 50(1),
1053 p.S100002.
- 1054
- 1055 Smith, R.B., 1979. The influence of mountains on the atmosphere. In *Advances in*
1056 *geophysics* (Vol. 21, 87-230). Elsevier.
- 1057
- 1058 Speirs, J.C., Steinhoff, D.F., McGowan, H.A., Bromwich, D.H. and Monaghan, A.J., 2010.
1059 Foehn winds in the McMurdo Dry Valleys, Antarctica: The origin of extreme warming
1060 events. *Journal of Climate*, 23(13), 3577-3598.
- 1061
- 1062 Tang, Y., Lean, H.W. and Bornemann, J., 2013. The benefits of the Met Office variable
1063 resolution NWP model for forecasting convection. *Meteorological Applications*, 20(4), 417-
1064 426.
- 1065
- 1066 Tedesco, M., 2009. Assessment and development of snowmelt retrieval algorithms over
1067 Antarctica from K-band spaceborne brightness temperature (1979–2008). *Remote Sensing*
1068 *of Environment*, 113(5), 979-997.
- 1069
- 1070 Turton, J.V., Kirchgaessner, A., Ross, A.N. and King, J.C., 2017. Does high-resolution
1071 modelling improve the spatial analysis of föhn flow over the Larsen C Ice Shelf?. *Weather*,
1072 72(7), 192-196.
- 1073
- 1074 Turton, J.V., Kirchgaessner, A., Ross, A.N. and King, J.C., 2018. The spatial distribution and
1075 temporal variability of föhn winds over the Larsen C Ice Shelf, Antarctica. *Quarterly Journal*
1076 *of the Royal Meteorological Society*, 144(713), 1169-1178.
- 1077
- 1078 Valisuo, I., Vihma, T. and King, J.C., 2014. Surface energy budget on Larsen and Wilkins ice
1079 shelves in the Antarctic Peninsula: results based on reanalyses in 1989-2010. *Cryosphere*, 8,
1080 pp.1519-1538.
- 1081

- 1082 Van den Broeke, M., van As, D., Reijmer, C. and van de Wal, R., 2004. Assessing and
1083 improving the quality of unattended radiation observations in Antarctica. *Journal of*
1084 *Atmospheric and Oceanic Technology*, 21(9), pp.1417-1431.
- 1085
- 1086 Van den Broeke, M., 2005. Strong surface melting preceded collapse of Antarctic Peninsula
1087 ice shelf. *Geophysical Research Letters*, 32(12).
- 1088
- 1089 Van den Broeke, M., Van As, D., Reijmer, C. and Van de Wal, R., 2005. Sensible heat
1090 exchange at the Antarctic snow surface: a study with automatic weather stations.
1091 *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 25(8),
1092 pp.1081-1101.
- 1093
- 1094 Van Lipzig, N.P., Marshall, G.J., Orr, A. and King, J.C., 2008. The relationship between the
1095 Southern Hemisphere Annular Mode and Antarctic Peninsula summer temperatures:
1096 Analysis of a high-resolution model climatology. *Journal of Climate*, 21(8), 1649-1668.
- 1097
- 1098 Vaughan, D.G. and Doake, C.S.M., 1996. Recent atmospheric warming and retreat of ice
1099 shelves on the Antarctic Peninsula. *Nature*, 379(6563), pp.328-331.
- 1100
- 1101 Walters, D., Baran, A.J., Boutle, I., Brooks, M., Earnshaw, P., Edwards, J., Furtado, K., Hill, P.,
1102 Lock, A., Manners, J. and Morcrette, C., 2019. The Met Office Unified Model Global
1103 Atmosphere 7.0/7.1 and JULES Global Land 7.0 configurations. *Geoscientific Model*
1104 *Development*, 12(5), 1909-1963.
- 1105
- 1106 Wang, W., Zender, C.S., Van As, D., Smeets, P.C.J.P. and van den Broeke, M.R., 2015. A
1107 Retrospective, Iterative, Geometry-Based (RIGB) tilt correction method for radiation
1108 observed by Automatic Weather Stations on snow-covered surfaces: application to
1109 Greenland. *Cryosphere Discussions*, 9(6).
- 1110
- 1111 Wiesenekker, J., Kuipers Munneke, P., van den Broeke, M. and Smeets, C.J.P.P., 2018. A
1112 multidecadal analysis of Föhn winds over Larsen C ice shelf from a combination of
1113 observations and modeling. *Atmosphere*, 9(5), p.172.

1114

1115 Zängl, G., 2003. Deep and shallow south foehn in the region of Innsbruck: Typical features
1116 and semi-idealized numerical simulations. *Meteorology and Atmospheric Physics*, 83(3-4),
1117 237-261.

1118

1119 Zheng, F., Li, J., Clark, R.T. and Nnamchi, H.C., 2013. Simulation and projection of the
1120 Southern Hemisphere annular mode in CMIP5 models. *Journal of Climate*, 26(24), pp.9860-
1121 9879.

	25 Nov 2014 - 17 Jun 2017	25 Nov 2015 - 01 Jun 2016				
	Obs, CI	Obs, CI	Model, CI	Model, WI	Model, MP	Model, LC
Foehn occurrence (% of time)	15	18	17	26	9	9
Melt occurrence (% of time)	8	13	14	15	10	14
Melt occurrence during foehn (% of time)	20	35	29	23	16	20
Melt occurrence during non-foehn (% of time)	6	8	11	12	10	13
(a) Mean melt rate during foehn melt ($W m^{-2}$)	61	62	102	99	77	73
Mean melt rate during non-foehn melt ($W m^{-2}$)	43	45	62	54	59	63
Accumulation of foehn-driven melt (mm w.e.)	446	195	245	290	54	63
Accumulation of non-foehn-driven melt (mm w.e.)	539	150	287	231	257	368
(b) SW_{sfc} / SW_{TOA} during foehn	0.50	0.54	0.64	0.67	0.74	0.67
SW_{sfc} / SW_{TOA} during non-foehn	0.52	0.52	0.58	0.56	0.58	0.63

1122

1123 Table 1. (a) Foehn and melt statistics at Cabinet Inlet (CI) from observations (“Obs”) and the
1124 model, plus from the model at Whirlwind Inlet (WI), Mamelon Point (MP) and Larsen East
1125 (LC). Note that “melt” here is given as melt_{SEB} in the column for 25 Nov 2014 - 17 Jun 2017,
1126 and melt_{skin} in the column for 25 Nov 2015 - 01 Jun 2016. (b) Median proportion of top of
1127 atmosphere solar irradiance (from model) reaching the surface (i.e. SW_{sfc} / SW_{TOA}) during
1128 foehn and non-foehn conditions in the observations and model data. Note that the
1129 differences in SW_{sfc} / SW_{TOA} between foehn and non-foehn conditions are significant at the
1130 99 % level according to the Mann–Whitney U test (in all cases but the Cabinet Inlet
1131 observations, where the difference is small, and the Larsen East model data, which are
1132 limited by the foehn sample size).

1133 Figure 1. Map of the model domain showing the orography of the Antarctic Peninsula (grey
 1134 scale is terrain height), the majority of Larsen C and the remaining section of Larsen B (in
 1135 white), and the locations of focal sites (see legend). Note that all observations used in this
 1136 study come from the Cabinet Inlet AWS site, whilst all four sites are used for model data
 1137 analysis. The sea is shown in light blue. The land-sea mask and orography data used here is
 1138 the same as that used in the model; see Section 2.2.

1139

1140 Figure 2. Rose charts summarising the distributions of wind speed, wind direction and melt
 1141 at Cabinet Inlet. (a, c, e) Wind roses, with colours denoting the distribution of wind speeds
 1142 (m s^{-1}) and bold numbers giving the mean wind speed for each segment. (b, d, f) “Melt
 1143 roses” showing melt for each wind direction segment as a percentage of total melt, the
 1144 distribution of melt rates (colour) and mean melt rates (numbers in bold; W m^{-2}). The data
 1145 used are (a, b) all available AWS observations, (c, d) the AWS observations between 25
 1146 November 2015 and 31 May 2016 (the period of the model simulation) and (e, f) the model
 1147 simulation. Note that melt_{SEB} is used for panel (b) and $\text{melt}_{\text{skin}}$ is used for panels (d, f), and
 1148 only values of melt_{SEB} and $\text{melt}_{\text{skin}}$ greater than 1 W m^{-2} are included.

1149

1150 Figure 3. Monthly-mean time series of all available AWS observations at the Cabinet Inlet
 1151 site (November 2014 to June 2017), showing (a) monthly foehn and melt_{SEB} occurrence (as a
 1152 percentage of time), (b) monthly accumulation of melt during both foehn and non-foehn
 1153 conditions; and (c, d) monthly mean melt_{SEB} and net downward radiative and turbulent
 1154 surface heat fluxes during (c) foehn and (d) non-foehn conditions, with standard deviations
 1155 in these fluxes indicated by shading.

1156

1157 Figure 4. Monthly-mean time series between December 2015 and May 2016 for the Cabinet
 1158 Inlet site (CI) of (a-c) observed and (d-f) modelled (a, d) monthly foehn and melt_{SEB}
 1159 occurrence (as a percentage of time; left axis) and monthly accumulation of melt during
 1160 both foehn and non-foehn conditions (right axis); and (b-c, e-f) monthly mean melt and net
 1161 downward radiative and turbulent surface heat fluxes during foehn and non-foehn
 1162 conditions, with standard deviations in these fluxes indicated by shading. Melt is given as
 1163 melt_{SEB} for solid bar borders in (a, d), and as $\text{melt}_{\text{skin}}$ for dotted bar borders in (a, d) and
 1164 dotted black lines in (b-c, e-f).

1165

1166 Figure 5. Prevalence and contributions to the SEB and melt for each SEB regime during
 1167 foehn and non-foehn conditions, from all available Cabinet Inlet AWS observations
 1168 (November 2014 to June 2017). In (a, c), black bars give the percentage of time during which
 1169 each regime occurs (left axis), whilst brown and orange bars give cumulative (i.e. time-
 1170 integrated) contributions to net downward heat transfer and melt_{SEB} , respectively (right
 1171 axis). In (b, d), black, solid horizontal lines denote the mean net heat flux, black dotted lines
 1172 denote the mean energy available for melt, and box and whiskers show the median,
 1173 interquartile range and 9th and 91st percentiles of each SEB component. The SEB regime
 1174 “None” denotes where no single SEB component dominates (see Section 2.3). Note that
 1175 $\text{SEB}_{\uparrow\text{LH}}$ never occurs during non-foehn conditions.

1176

1177 Figure 6. Surface energy components as a function of wind speed for *stably-stratified foehn*
 1178 conditions (top) and *weakly-stratified foehn* conditions (bottom) during (a, c, e) *stably-*
 1179 *stratified foehn* and (b, d, f) *weakly-stratified foehn*, from (a, b) all Cabinet Inlet
 1180 observations, (c, d) all Cabinet Inlet model data, and (e, f) all Whirlwind Inlet model data.
 1181 Data are binned according to wind speed. The number of data points in each wind speed bin
 1182 is denoted by the size of the plot markers and also given towards the top of each panel as a
 1183 percentage of the total number of data points in each panel, which is stated at the bottom
 1184 of each panel. Melt is given as Melt_{SEB} in (a, b) and as $\text{Melt}_{\text{skin}}$ in (c-f).

1185

1186 Figure 7. Schematics representing foehn SEB sensitivity to wind speed during (a, b) typical,
 1187 *stably-stratified foehn* conditions and (c, d) *weakly-stratified foehn* conditions. The black
 1188 arrows denote the foehn winds in the lower atmosphere (white to red shades; darker reds
 1189 denoting warmer air) descending the eastern slopes of the Peninsula and then advancing
 1190 across the ice shelf (light blue), with thicker arrows denoting stronger winds. The coloured
 1191 arrows denote heat fluxes, with their widths and label font sizes proportional to the
 1192 absolute, mean observed values at Cabinet Inlet. These values range in magnitude from 0.5
 1193 W m^{-2} (for negative LH in *weak-wind stably-stratified foehn* conditions) and 113 W m^{-2} (for
 1194 positive SH in *strong-wind stably-stratified foehn* conditions). The SEB net effect(s) of each
 1195 foehn classification on the ice shelf are described below each panel, and the occurrence of
 1196 significant melt is also denoted by dark blue shading at the top of the ice shelf in panels (a)

1197 and (d). Mean melt rates are 22, 4, 2 and 16 $W m^{-2}$ respectively for (a), (b), (c) and (d). Foehn
 1198 classifications are defined using the same Brunt-Väisälä frequency threshold as used for
 1199 Figure 6 (the 5th percentile) to distinguish between *stably-stratified foehn* and *weakly-*
 1200 *stratified foehn*, and the 25th and 75th wind speed percentiles (4.5 and 11.6 $m s^{-1}$,
 1201 respectively) to distinguish between *strong-wind foehn* and *weak-wind foehn*.

1202

1203 Figure 8. Model composite spatial plots during *widespread foehn* conditions (which occur 12
 1204 % of the time) across the Antarctic Peninsula for the 2015/16 melt season. In each panel,
 1205 the field plotted is given by the title; note here that “MSLP” stands for “mean sea level
 1206 pressure”, “sfc” stands for “surface” and “stdev” stands for “standard deviation”. Orography
 1207 contours are also plotted in greyscale (c.f. Figure 1). In (a), four inlets are labelled (CI:
 1208 Cabinet Inlet; WI: Whirlwind Inlet; MI: Mill Inlet; fLB: former Larsen B embayment), whilst
 1209 the locations of the four data sites are shown in the other panels (open black circles; see
 1210 Figure 1 for site names). The dashed line linking solid black circles marks the transect used
 1211 for the Figure 9 cross sections. Note that in panels (c-f) a smaller domain at larger scale is
 1212 presented, and data is only shown to the east of the Peninsula. In all panels, data is masked
 1213 out where terrain height exceeds 100 m in all panels and also west of the Peninsula in
 1214 panels (c-f).

1215

1216 Figure 9. Model composite-mean cross sections of (a, c) potential temperature (contours
 1217 and shading) and winds vectors (arrows); and (b, d) specific humidity (q ; shading) and
 1218 relative humidity (RH; black contours) for (a, b) *widespread foehn* conditions (which occur
 1219 12 % of the time) and (c, d) *widespread non-foehn* conditions (which occur 70 % of the time)
 1220 across the Antarctic Peninsula along the transect shown in Figure 8, for the 2015/16 melt
 1221 season. In these plots the vertical scale is exaggerated by a factor of 100 relative to the
 1222 horizontal scale. The wind vectors are true to the aspect ratio used, and the reference
 1223 vectors (above plots) indicate 10 $m s^{-1}$ horizontal winds and 0.1 $m s^{-1}$ vertical winds. The red
 1224 circle is the location of the Cabinet Inlet site.

1225

1226 Figure 10. Model composite spatial plots during (a-c) *widespread foehn* (which occurs 12 %
 1227 of the time), (d-f) *widespread non-foehn* (which occurs 70 % of the time) and (g-i) all
 1228 conditions, for the 2015/16 melt season. The fields shown are (a, d) mean melt_{skin}; (g)

1229 accumulation of melt_{skin}; (b, e, h) the ratio of the accumulation of melt_{skin} in the SEB_{↓SH}
 1230 regime (melt_{↓SH}) to that in the SEB_{↓SW} regime (melt_{↓SW}); and (c, f, i) the proportion of top
 1231 of atmosphere solar irradiance reaching the surface (SW_{sfc} / SW_{TOA}). Also shown, subset in
 1232 (d), are mean melt rates during *widespread non-foehn* along the transect marked by the
 1233 dashed line. Note that (a, d) use the colour scale shown to the left of the plots. In each panel
 1234 the locations of the four data sites are shown (open black circles; see Figure 1 for site
 1235 names).

1236

1237 Figure 11. Prevalence and contributions to the SEB and melt of all SEB regimes, during (a-d)
 1238 foehn and (e-h) non-foehn conditions from the model simulation at (a, e) the Cabinet Inlet
 1239 site, (b, f) the Whirlwind Inlet site, (c, g) the Mamelon Point site, and (d, h) the Larsen East
 1240 site. The black bars give the percentage of time during which each regime occurs and uses
 1241 the left axis, whilst the brown and orange bars give cumulative contributions to net
 1242 downward heat transfer and melt_{skin} energy, respectively, and use the right axis. For each
 1243 site the percentage of time spent and the percentage of melt_{skin} generated in both foehn
 1244 and non-foehn conditions are stated. The SEB regime “None” denotes where no single SEB
 1245 component dominates (see text).

1246

1247 Figure 12. Schematic illustrating the key features of melt variability across Larsen C, and the
 1248 meteorological conditions responsible for them. Note that “non-linear” foehn refers to
 1249 foehn embedded in a non-linear mountain flow regime (see Elvidge et al., 2016), and that
 1250 whilst the cloud-clearance effect is evident in the model results across the entire ice shelf, is
 1251 it not evident in the observations at Cabinet Inlet. The inlets are labelled CI, MI and WI;
 1252 Cabinet Inlet, Mill Inlet and Whirlwind Inlet, respectively.

1253

1254 Figure S1. (a) The accumulation of melt in the SEB_{↓SW} regime (melt_{↓SW}) and contributions to
 1255 the downward component of SW at the surface (SW_{sfc}) by (b) top of atmosphere solar
 1256 irradiance (SW_{TOA}) and (c) blocking of SW by clouds (expressed here as $SW_{sfc} - SW_{TOA}$;
 1257 smaller negative values indicating clearer conditions), all during non-foehn conditions. Note
 1258 that the colour scales used for panels (b) and (c) cover an identical range of values,
 1259 facilitating direct comparisons of the gradients in these fields.