List of relevant changes: “Surface energy fluxes on Chilean glaciers”

- data was reanalyzed (the measured longwave radiation was bias-corrected and stability corrections for turbulent fluxes in the reference database were added) and as a consequence of that Figures 4-8, Figure 10 and Table A1 were updated.
- Important parts of the abstract were reformulated
- a table was added which indicate the influence of the roughness length on the transfer coefficient
- Figure 3b was corrected
- a large paragraph was added/reformulated in the section 4.1
- an important part of section 5.2 were reformulated
- Figure 10 was separated into four subfigures to improve the readability.

Surface energy fluxes on Chilean glaciers: measurements and models

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Abstract. The surface energy fluxes of glaciers determine surface melt and their adequate parametrization is one of the keys for a successful prediction of future glacier mass balance and freshwater discharge. Chile hosts glaciers in a large range of latitudes under contrasting climatic settings: from 18°S in the Atacama Desert to 55°S on Tierra del Fuego Island, Southern Patagonia. Using three different methods, we computed surface energy fluxes for five glaciers which represent the main glaciological zones of Chile. We found that the main energy sources for surface melt change from the Central Andes, where the net shortwave radiation is driving the melt, to Patagonia, where the turbulent fluxes are an important source of energy. We inferred higher surface melt rates for Patagonian glaciers as compared to the glaciers of the Central Andes due to a higher contribution of the turbulent sensible heat flux, less negative longwave radiation balance and a positive contribution of the turbulent latent heat flux. The variability of the atmospheric emissivity was high and not able to be explained exclusively by the variability of the inferred cloud cover. The influence of the stability correction and the roughness length on the magnitude of the turbulent fluxes in the different climate settings was examined. We conclude that, when working towards physical melt models, it is not sufficient to use the observed melt as a measure of model performance: the model parametrizations of individual components of the energy balance have to be validated individually against measurements.

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1 Introduction

Glaciers are retreating and thinning in nearly all parts of the planet and it is expected that these processes are going to continue under the projections of global warming (Stocker et al., 2013). For mountain glaciers melt is mostly determined by the energy exchange with the atmosphere at its surface. The processes leading to this exchange of energy are complex and depend on the detailed (micro-) climate on the glacier. Classical empirical melt models (like for example degree day models (Braithwaite, 1995a) are getting more and more replaced by more complex models which try to quantify the detailed physical processes that govern the energy exchange at the glacier surface. These kind of models are sometimes called "physical melt models" or “physically based models” (Pellicciotti et al., 2008).

In Chile, the only glacier with a climatologically relevant long-term record of surface mass balance is Echaurren Norte Glacier near to Santiago de Chile, which is monitored since 1975 (WGMS, 2017; Masiokas et al., 2016; Farías-Barahona et al., 2019). Echaurren Norte Glacier (33.5°S) has a general negative trend in its cumulative surface mass balance (-0.48 m w.eq./year in 1976-2017) but also shows stable phases in the 1980s and the first decade of the 21st century, (Masiokas et al., 2016; WGMS, 2017; Farías-Barahona et al., 2019). The variations of the surface mass balance of this glacier can be mostly explained by variations of precipitation in the region (Masiokas et al., 2016; Farías-Barahona et al., 2019). In the semi arid Pascua Lama Region (29°S) several small glaciers have been monitored since 2003 (Rabatel et al., 2011). These glaciers also show mostly negative surface mass balance and are losing area (Rabatel et al., 2011). During the monitoring period, the limited accumulation of snow is not able to make up with the ablation processes which are dominated by sublimation (MacDonell et al., 2013). In the Chilean Lake District, Mocho Glacier is monitored since 2003 (Rivera et al., 2005). Here, a very high inter-annual variability of the surface mass balance was observed (Schaefer et al., 2017). But, on average, the annual surface mass balance was negative which coincides with the observed areal losses (Rivera et al., 2005).

Energy balance studies have been realized in Chile on different glaciers: in the semi-arid Andes MacDonell et al. (2013) quantified in detail the drivers of ablation processes on Guanaco Glacier (29°S). They found that the net shortwave radiation is the main source and that the net longwave radiation and turbulent flux of latent heat are the main sinks of energy at the surface of Guanaco Glacier (MacDonell et al., 2013). Due to the low temperatures on this high elevation site (5324 m a.s.l), they found that sublimation dominated the surface ablation and surface melt contributed only during summer month. Pellicciotti et al. (2008) studied the surface energy balance during summer at Juncal Norte Glacier in the Central Andes (33°S, near Santiago de Chile. Similar to MacDonell et al. (2013) they found that the net shortwave radiation is the main source and that the net longwave radiation and turbulent flux of latent heat are the main sinks of energy. Similar results concerning the influence of the different components of the surface energy balance where obtained by Ayala et al. (2017), who analyzed meteorological data collected on six glaciers in the semiarid Andes of North-Central Chile at elevations spanning from 3127 m.a.s.l. to 5324 m.a.s.l..

Brock et al. (2007) studied the surface energy balance of bare snow and tephra-covered ice on Pichillancahue-Turbio Glacier (39.5°S) on Villarrica Volcano in the Chilean Lake District during two summers. They found a strong reduction of surface melt on the tephra-covered part of the glacier and a change in sign of the turbulent flux of latent energy to a source due to the higher vapor pressure caused by a more humid atmosphere as compared to the northern and central part of Chile. In southernmost Chile, Schneider et al. (2007) studied the energy balance in the ablation area of Lengua Glacier, which is an outlet Glacier of Gran Campo Nevado Ice Cap (53°S). They found that during February to April 2000, due to the high air temperatures and the high wind speeds turbulent flux of sensible heat was the main source of melt energy for the glacier surface.

In a comparative study of the surface energy balance of glaciers at different latitudes, Sicart et al. (2008) found that the net shortwave radiation is driving the glacier melt at the tropical Zongo Glacier, but that at Storglaciären in Northern Sweden the turbulent fluxes of sensibel heat and latent heat dominated the melt patterns.

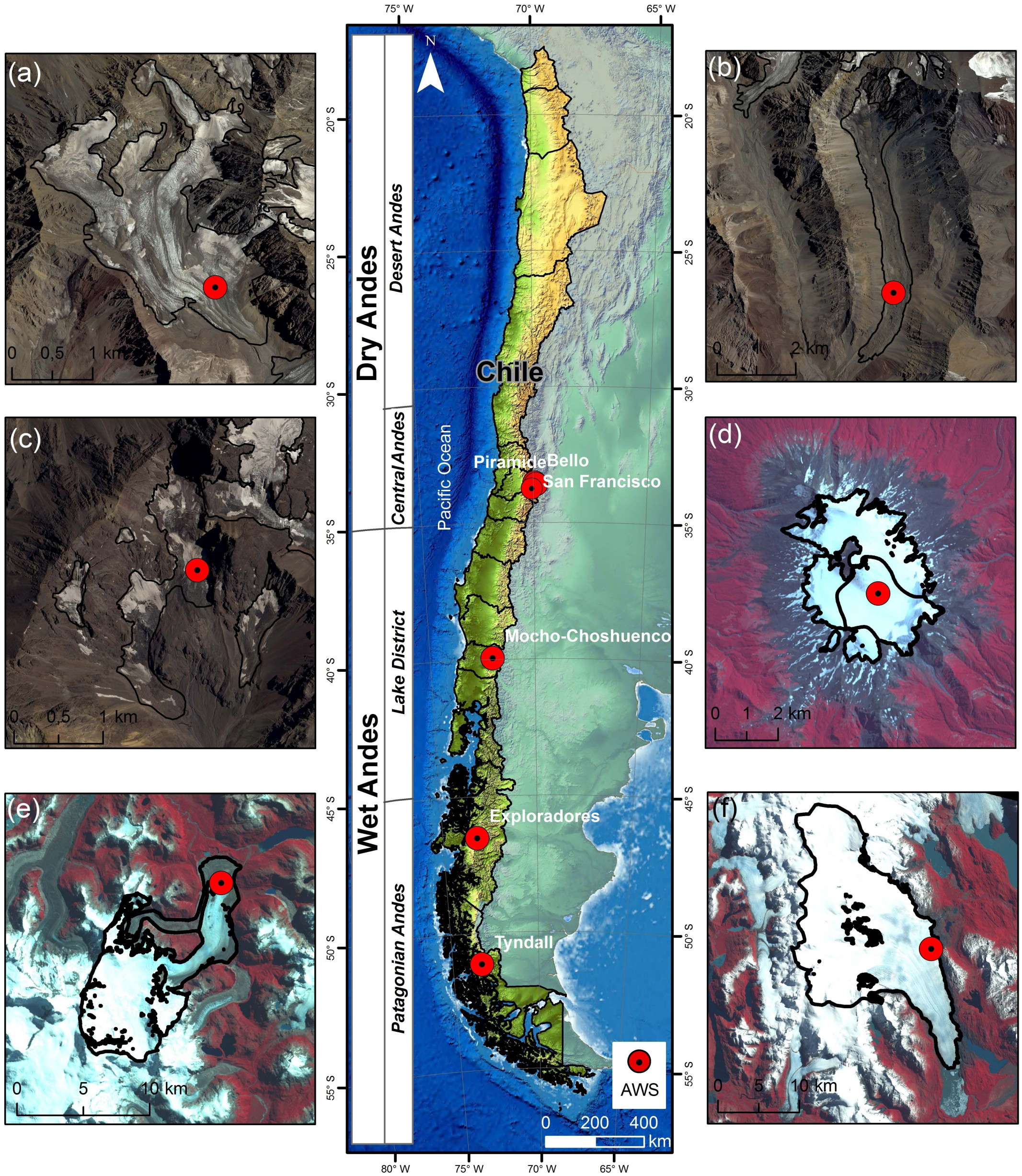

Figure 1. Middle: glaciological zones in Chile according to Lliboutry (1998) and locations of the studied glaciers: (a) Bello Glacier, (b) Pirámide Glacier, (c) San Francisco Glacier, (d) Mocho Glacier, (e) Exploradores Glacier, (f) Tyndall Glacier.

In this study we analyze data from automatic weather stations (AWSs) installed on six glaciers distributed in the different glaciological zones of Chile (Figure 1), five of them being equipped and maintained by the Unit of Glaciology and Snows of the Chilean Water Directory (UGN-DGA) (UChile, 2012; Geoestudios, 2013; CEAZA, 2015). Using the meteorological observations as input, we compare different ways to compute the glacier surface energy balance: we use direct measurements of the radiative fluxes at the glacier surface and two models that are freely available: the spreadsheet-based point surface energy balance model (EB-model) developed by Brock and Arnold (2000) and the Coupled Snowpack and Ice surface energy Mass balance model (COSIMA) (Huintjes et al., 2015b, a).

Instead of validating the ability of the energy balance calculations to adequately predict melt rates, in this study we want to test their ability to reproduce the individual energy fluxes: we want to emphasize the differences between the model parametrizations and their ability to reproduce the directly measured radiative fluxes at the glacier surfaces. We also compare different parameterizations for the turbulent fluxes of sensible and latent heat and discuss the influence of stability corrections and roughness lengths.

2 Sites

Chile's climate is strongly determined by the Pacific Anticyclone and the Andes Range which acts as a natural barrier (Fuenzalida-Ponce, 1971; Garreaud, 2009). A high climatic variety is observed due to the large north-south extension of the territory (4000 km, 17°30 – 55°S). Despite the different classifications of sub-glaciological zones (Lliboutry, 1998; Masiokas et al., 2009; Barcaza et al., 2017; Braun et al., 2019; Dussaillant et al., 2019) most authors agree that there is a transition from Dry Andes to Wet Andes at around 35°S (Figure 1.). The Central Andes of Chile (31°-35°S) are characterized by a Mediterranean climate, with dry conditions during summer. For the period 1979–2006 Falvey and Garreaud (2009) observed a cooling in the coast and a considerable temperature increase of +0.25°C/decade inland in the Maipo River catchment in the Central Andes. Precipitation in this area is highly variable, and predominantly occurs during winter (Falvey and Garreaud, 2007) controlled by El Niño Southern oscillation (ENSO) and the Southeast Pacific Anticyclone (Montecinos and Aceituno, 2003). Between 2010 and 2015 a mega-drought was observed in the Central Andes (Boisier et al., 2016; Garreaud et al., 2017).

In the northern part of the Wet Andes (35°-45°S), known in Chile as the Lake District, the elevation range steadily decreases, and wetter climatic conditions are predominant. A general decrease of precipitation in the region was observed during the 20th century (Bown et al., 2007; González-Reyes and Muñoz, 2013). The Southern part of the Wet Andes, Patagonia, is characterized by a hyper-humid climate (Garreaud, 2018), where the largest glacierized areas in the Southern Hemisphere outside Antarctica can be found. This hyper-humid condition has been recently interrupted by a severe drought during 2016 with a precipitation decrease of more than 50% (Garreaud, 2018). Under these different climatic settings, Chile hosts the majority of glaciers in South America (more than 80% of the area), which are mostly thinning and retreating in the last decades (e.g. Braun et al. (2019); Dussaillant et al. (2019)). The projections of future changes in climate depend on the different climatological/glaciological zones. This is why a detailed analysis of the processes that determine the energy exchange at the surface of the glaciers in the different climatological zones is necessary, to be able to make reliable predictions of future surface mass balance and melt water discharge of Chilean glaciers.

In the Central Andes, San Francisco (1.5 km^2) and Bello (4.2 km^2) Glaciers are mountain glaciers which are partially debris-covered at their termini and Pirámide Glacier (4.4 km^2) is an almost completely debris-covered glacier (Figure 1). On San Francisco and Bello Glacier the AWSs were installed over bare ice and at Pirámide Glacier they were installed over debris-cover. Mocho Glacier is part of the ice cap (14 km^2) which is covering the Mocho-Choshuenco volcanic complex, located in the Lake District (Schaefer et al., 2017). Exploradores Glacier (83.8 km^2) is located on the northern margin of the Northern Patagonia Icefield with a prominent portion of debris-cover at its tongue. Recently, at the glacier's front, several lateral lakes have developed and some calving activity was observed. Finally, Tyndall Glacier (309.8 km^2) is one of the large glaciers in the Southeastern part of the Southern Patagonia Icefield. Tyndall Glacier is terminating in Geike Lake, where it experiences additional mass losses through calving. All glacier areas are from Barcaza et al. (2017).

Due to the installation of AWSs on several glaciers in the country by the UGN-DGA, detailed meteorological observations from glaciers in the different glaciological zones are available now (UChile, 2012; Geoestudios, 2013; CEAZA, 2015). In Table1 we present the detailed locations of the AWSs used for this study and some relevant glacier parameters.

Table 1. Study period and geographical information of the glaciers and automatic weather stations.

Glacier	**Period**	**Latitude**	**Longitude**	**Elevation**	ELA	Exposure
Name		°	°	m a.s.l.	m a.s.l.	
Bello	01/01/2015-31/03/2015	-33.53	-69.94	4134	4600 (Ayala et al., 2016)	SE
Pirámide	01/01/2016-31/03/2016	-33.59	-69.89	3459	3970 (Ayala et al., 2016)	S
San Francisco	01/01/2016-31/03/2016	-33.75	-70.07	3466	3970 (Carrasco et al., 2008)	SE
Mocho	31/01/2006-21/03/2006	-39.94	-72.02	2003	1990 (Schaefer et al., 2017)	SE
Exploradores	01/01/2015-31/03/2015	-46.51	-73.18	191	1420 (Schaefer et al., 2013)	N
Tyndall	01/01/2015-31/03/2015	-51.13	-73.31	608	1020 (Schaefer et al., 2015)	SE
	01/01/2016-31/03/2016					

Because of its higher relevance for melt modeling, we focused our analysis to summer periods: AWSs of the UGN-DGA have a data record of several years, but during several summers some of the sensors were not working well. In Table 1 we show the selected summer period for every station. For Tyndall Glacier two summers were analyzed. On Mocho Glacier an AWS was installed only during a 50 day period during summer 2006. Figure 2 shows photos from the AWSs installed on the glaciers Bello, Exploradores and Tyndall.

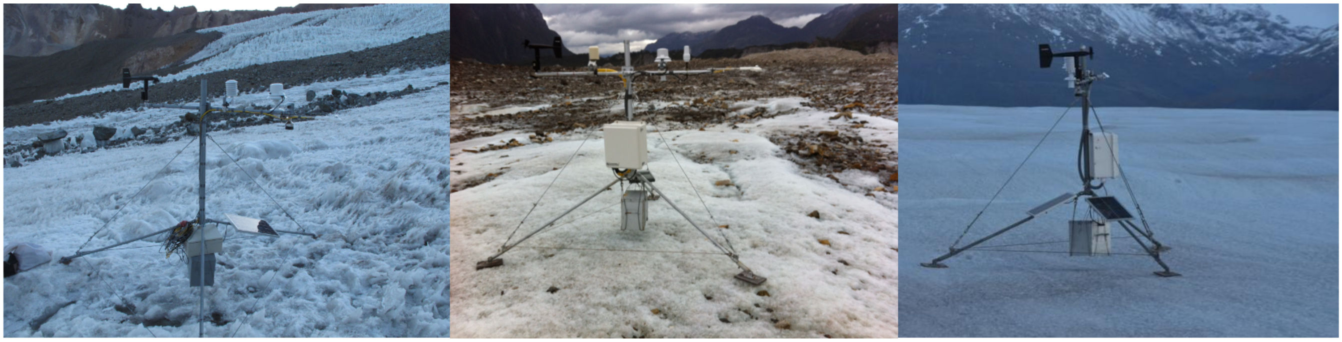

Figure 2. AWS on Bello Glacier (left), Exploradores Glacier (middle) and Tyndall Glacier (right)

3 Methods

In this contribution we want to focus on the six most important energy fluxes which normally determine the melt energy available at the glacier surface: the incoming solar radiation (SW_{in}), the reflected solar radiation (SW_{out}), the incoming atmospheric longwave radiation (LW_{in}), the longwave radiation emitted by the glacier surface (LW_{out}) and turbulent fluxes of sensible (SH) and latent heat (LH). We will compare three methods to compute these surface energy fluxes for the selected sites. Before presenting the three methods in detail, we describe the input data for our energy balance calculation in the following section.

3.1 Input data

In Table 2 we present the sensors used at the Mocho-AWS in 2006 and the instruments used at the DGA stations on the other glaciers. The main difference in the installation is the CNR4 sensor, which is installed on the DGA stations and provides detailed measurements of all radiative fluxes, while on Mocho Glacier SW_{in}, SW_{out} and the net allwave radiation is measured. At Mocho-AWS mean values of the data were recorded every 15 minutes, which were resampled to hourly data for the energy balance calculations. At the DGA stations hourly means are recorded and transmitted by a satellite connection. Data at missing hours were interpolated by taking the mean value of the hour before and after the missing one. For Bello Glacier the time resolution of the acquired data changed from hourly to three hourly on 20th of March 2015. Hourly data were generated using a matlab interpolation scheme.

3.2 Reference Database

We call this first method the Reference Database, since in this approach direct measurements of the first four fluxes (the radiative fluxes) are used (with the exception of the Mocho-AWS where the net longwave radiative flux is inferred from the incoming solar radiation, the reflected solar radiation and the overall net radiative flux). However, on several glaciers the measured mean outgoing longwave radiative fluxes were higher then the ones expected for a blackbody at zero degrees Celsius. Therefore we decided to bias-correct the measured longwave radiative fluxes in a way that the measured outgoing longwave radiative fluxes in the afternoon correspond to a melting surface at zero degrees Celsius. From this calibration of the signal we obtained

Table 2. Sensors employed at the different AWSs

Variable	AWS-DGA	nominal accuracy	AWS Mocho	nominal accuracy
Incoming solar SW_{in}	Kipp & Zonen CNR 4	7-8% on daily total	Kipp & Zonen SP-Lite	7-8% on daily total
Reflected solar SW_{out}	Kipp & Zonen CNR 4	7-8% on daily total	Kipp & Zonen SP-Lite	7-8% on daily total
Incoming longwave LW_{in}	Kipp & Zonen CNR 4	7-8% on daily total	-	-
Outgoing longwave LW_{out}	Kipp & Zonen CNR 4	7-8% on daily total	-	-
Net all waveAW_{net}	-	-	NR- lite	± 3%
Air Temperature T	HMP60	$\pm 0.6°C$	HMP45c	±0.3°C
Relative Humidity RH	HMP60	max 7%	HMP45c	max 3%
Wind Speed U	Young 05103	0.3 m/s o ± 1%	Young 05103	± 0.3 m/s o ± 1%

different correction factors for the longwave radiative fluxes which were applied to both incoming and outgoing longwave radiative fluxes (Table 3).

The turbulent fluxes of sensible and latent heat were calculated according to formulas derived in Cuffey and Paterson (2010). The bulk aerodynamic approach is employed and the following important assumptions are made.

1. The eddy diffusivity for heat has the same value as the eddy diffusivity for water vapor and the eddy viscosity (this assumption is usually associated to a neutral atmosphere).

2. The shear stress in the first few meters of the atmosphere above the glacier surface is constant.

3. The wind velocity, temperature and water vapor pressure have logarithmic profiles with the same scaling length z_0.

Using these assumptions, the following expression for the turbulent flux of sensible heat can be derived:

$$SH = c_a \rho_a C^*(z) U(z) [T(z) - T(s)], \tag{1}$$

where c_a is the specific heat of air at constant pressure which was assumed to be constant at 1.01 kJ/(kg K) , ρ_a is the air density, $U(z)$ is the wind speed measured at the height z above the surface, $T(z)$ is the air temperature at the height z of the sensor and $T(s)$ is the temperature of the glacier-atmosphere interface.

The dimensionless number $C^*(z)$ is a proportionality constant called the transfer coefficient. If the above assumptions are fullfilled, it should depend on the measurement height of the sensors of wind velocity and temperature z (two meters in our case) and the roughness length z_0 according to:

$$C^*(z) = \frac{\kappa^2}{ln^2(z/z_0)}, \tag{2}$$

where κ is the von Karman constant, which has an approximate value of 0.4. In practice however the roughness/scaling length z_0 is variable in space and time (Brock et al., 2006). There exist several recommendations in the literature of values for $C^*(z)$ that have produced satisfying results (Cuffey and Paterson, 2010), which gives $C^*(z)$ rather the interpretation of a tuning

Table 3. Variation of the transfer coefficient $C^*(2\,\mathrm{m})$ for typical values of the roughness length z_0

Roughness length in mm	$C^*(2\,\mathrm{m})$
0.01	0.001
0.5	0.0023
1	0.0028
5	0.0045
10	0.0057
30	0.009

parameter than a physical constant. In the results section we present the results obtained by using an intermediate roughness length of z_0=0.5 mm for all the glaciers. According to table 5.4 in Cuffey and Paterson (2010) this corresponds to a value between smooth ice and ice in the ablation zone and is also inside the range recommended for new and polar snow. When looking at the glacier surfaces in Figure 2, we can note that the roughness length is probably varying from glacier to glacier and in Table 3 we present how $C^*(2\,\mathrm{m})$ should vary for typical values of z_0.

Assumption 1. is normally fullfilled for a neutral atmosphere, but, over a glacier surface, the temperature gradient is often inverted (especially during summer). This stable layering of air masses reduces the vertical exchange specially for low wind speeds and we apply a stability correction to equation (1) which depends on the bulk Richardson number $Ri = \frac{gT(2m)2m}{(T(2m)+273.15)U^2}$, where g is gravitational acceleration and $T(2m)$ has to be taken in degrees Celsius. The correction factor is smaller than one for $Ri > 0.01$ (small wind speeds) and approaches zero for $Ri = 0.2$ in the same way as it is implemented in the COSIMA model (Huintjes et al., 2015a).

Using the same arguments from above and assuming the turbulent flux of latent heat to be proportional to the difference of the concentration of water vapor at the glacier surface and the air layer above it,Cuffey and Paterson (2010) derive the following expression :

$$LH = 0.622\rho_a L_v C^* U(z)\left[P_{\text{vap}}(z) - P_{\text{vap}}(s)\right]/P_a. \qquad (3)$$

Here, $P_{\text{vap}}(z)$ and $P_{\text{vap}}(s)$ are the water vapor pressure at the elevation z=2 m above the glacier and at its surface respectively, P_a is the air pressure and L_v is the latent heat of vaporization. The water vapor pressure at z=2 m depends on the (measured) relative humidity and the saturation water vapor pressure $P_{\text{vap,sat}}$ which depends on the air temperature. In Figure 3.(a) we show measurements of the saturation water vapor pressure at different temperatures (Lide, 2004) and the graphs of several parametrizations as a function of the air temperature, found in the literature (Bolton, 1980; Cuffey and Paterson, 2010; Huintjes et al., 2015a). We decided to use the parameterization proposed in Bolton (1980), since it agrees best with the measurements:

$$P_{\text{vap,sat}}(T) = 6.112\exp\left(\frac{17.67\,T}{T+243.5}\right), \qquad (4)$$

where $P_{\text{vap,sat}}$ is in hectopascal and the air temperature T is in degrees Celsius. It is assumed that at the glacier surface the water vapor pressure is equal to the saturation vapor pressure at the surface temperature $T(s)$. The turbulent flux of latent heat is corrected in the same way for stability conditions found over glacier surfaces as the turbulent flux of sensible heat (see above).

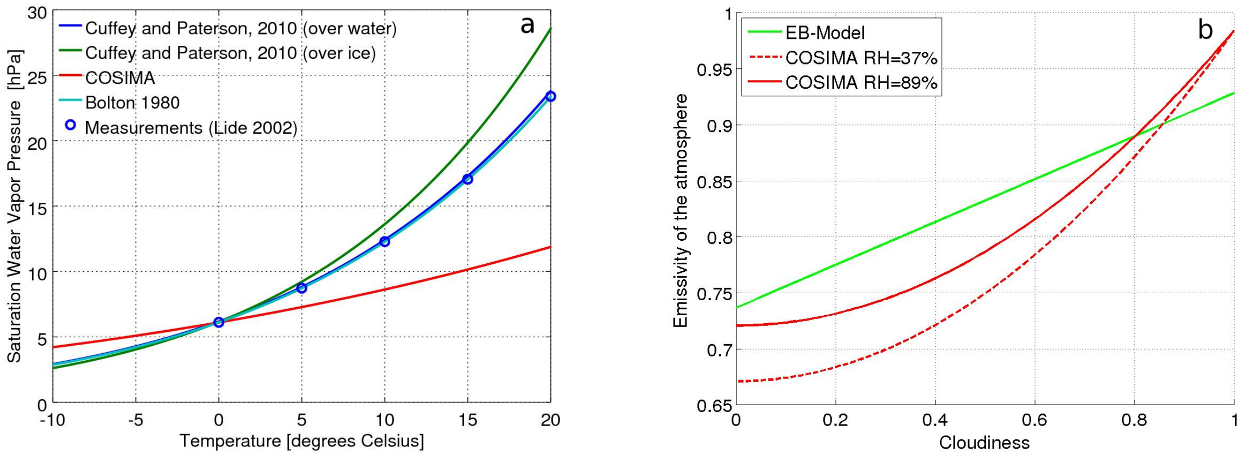

Figure 3. Different parametrizations of the models: (a) saturation vapor pressure as a function of the air temperature, (b) emissivity of the atmosphere as a function of the cloud cover.

3.3 EB-Model

In the spreadsheet-based energy balance model developed by Brock and Arnold (2000) the incoming solar radiation, two meter air temperature, the wind speed and the water vapor pressure are the meteorological input variables. The fixed input parameters are latitude, longitude and elevation of the station, the aspect and slope, the albedo α and the roughness of the surface z_0. The net shortwave radiation is calculated by multiplying the sum of the direct and diffuse incoming solar radiation by 1-α. The incoming direct and diffuse incoming solar radiation depend on the measured incoming solar radiation SW_{in} and the glacier's surface slope and aspect at the AWS. However, in our study, these parametrizations produced erroneous values for the net shortwave radiation SW_{net} in the late afternoon for several glaciers. This is why we computed SW_{net} from the measured incoming solar radiation SW_{in} by multiplying it with 1-α:

$$SW_{\text{net}} = (1-\alpha)SW_{\text{in}}, \tag{5}$$

where the albedo α is assumed to be a constant, which depends on the characteristics of the glacier surface. This parametrization should exactly agree to the parametrizations proposed in Brock and Arnold (2000) for flat surfaces (zero slope), which should be a very good approximation, since the AWSs are normally placed on flat terrain.

The net longwave radiation is computed by assuming that the snow/ice surface irradiates thermal radiation of a black body at 273.15 Kelvin (0 degrees Celsius) which is 315.6 W/m^2 according to the Stephan-Boltzmann law of thermal radiation. This value is subtracted from the incoming longwave radiation from the atmosphere which is computed with the Stefan-Boltzmann law as well, using the $T(2m)$ and an atmospheric emissivity which is a function of the cloud cover. Brock and Arnold (2000) use a parametrization of the atmospheric emissivity ε which increases linearly as a function of the cloudiness n:

$$\varepsilon_{(\text{EB})}(n,T) = (1+0.26n)\varepsilon_{\text{cs}}(T), \tag{6}$$

where $\varepsilon_{\text{cs}}(T)$ is the clear sky emissivity which depends on the air temperature T: $\varepsilon_{\text{cs}}(T) = 0.00877T^{0.788}$ (T in Kelvin). The green line in Figure 3 (b) shows the graph of $\varepsilon_{\text{(EB)}}(n,T)$ at five degree Celsius. The cloudiness is inferred by comparing the theoretically site-specific clear sky incoming solar radiation with the measured incoming solar radiation.

Similar to the Reference Database, in the EB-Model the turbulent fluxes of latent and sensible heat are calculated by expressions derived from the bulk aerodynamic method (Brock and Arnold, 2000) according to the equations (1) and (3). However, in this model the transport coefficient for the sensible heat flux C^*_{EB1} and latent heat flux C^*_{EB2} have a more complex form and do not only depend on the roughness length z_0 but also on the Monin-Obukhov length scale L and the scaling lengths of temperature z_T and humidity respectively z_H(Brock and Arnold, 2000):

$$C^*_{EB1} = \frac{\kappa^2}{(ln(z/z_0) + 5z/L)(ln(z/z_T) + 5z/L)} \tag{7}$$

$$C^*_{EB2} = \frac{\kappa^2}{(ln(z/z_0) + 5z/L)(ln(z/z_H) + 5z/L)} \tag{8}$$

z_H and z_T are calculated as a function of z_0 and the roughness Reynolds number (Brock and Arnold, 2000; Andreas, 1987). Since normally $z_H < z_T < z_0$ (Brock, 2018) and $L > 0$, C^*_{EB1} and C^*_{EB2} are smaller than C^* and $C^*_{EB2} < C^*_{EB1}$.

3.4 COSIMA

The COupled Snow and Ice Melt MAss balance model (COSIMA) was developed at RWTH Aachen (Huintjes et al., 2015b, a) and combines a surface energy balance model with a multi-layer subsurface snow and ice model to compute glacier mass balance (Huintjes et al., 2015a). In this work we want to focus on how COSIMA models the six dominant energy fluxes at the glacier surface. The input parameters for the COSIMA model are the incoming solar radiation (SW_{in}), the two meter air temperature (T), the relative humidity (RH), the wind speed (U), the solid precipitation(P_s), the initial snow height, the air pressure (P) and the cloud cover (n) (Huintjes et al., 2015a). The daily mean cloud cover over the glacier was estimated by comparing the measured SW_{in} with the theoretical, site specific clearsky radiation computed by a code developed by Corripio (2003). The cloud cover was determined from this cloud transmissivity τ_{cl} by solving the equation proposed in Greuell et al. (1997):

$$\tau_{\text{cl}} = 1 - 0.233n - 0.415n^2. \tag{9}$$

The net solar radiation is calculated using equation 5. In contrast to the EB-Model the albedo is variable and depends on the time since the last snowfall t_{snow} and the thickness h of the snow or firn layer on top of the glacier ice:

$$\alpha = \alpha_{\text{snow}} + (\alpha_{\text{ice}} - \alpha_{\text{snow}})\exp(-h/d^*), \tag{10}$$

where α_{ice} and d^* are constants and

$$\alpha_{\text{snow}} = \alpha_{\text{firn}} + (\alpha_{\text{frsnow}} - \alpha_{\text{firn}})\exp(t_{\text{snow}}/t^*), \tag{11}$$

with α_{firn}, α_{frsnow} and t^* being constants as well. This parametrization of snow albedo in COSIMA was tested at Mocho Glacier, where the glacier surface was covered by snow or firn during the observation period and precipitation data from a near-by automatic weather station were available. On the other glaciers an ice surface and a constant albedo of 0.3 was assumed.

The longwave radiative fluxes are computed using the Stefan-Boltzmann law of thermal radiation as well. The snow/ice surface is considered as a blackbody. However, in contrast to the EB-Model in COSIMA the snow/ice surface temperature is variable depending on the heat fluxes at the glacier-atmosphere interface. Similar to the EB-Model the emissivity of the atmosphere is modeled as a function of the cloudiness(n) using the following expression:

$$\varepsilon_{(\text{COS})}(n,T,P_{vap}) = \varepsilon_{cs}(T,P_{vap})(1-n^2)+0.984n^2, \tag{12}$$

where the emissivity of the clear sky depends on the air temperature and the water vapor pressure according to the following expression $\varepsilon_{\text{cs}}(T,P_{vap}) = 0.23+0.433(P_{vap}/T)^{1/8}$, where T is in kelvin and P_{vap} in pascal. The red graph in Figure 3 (b) shows the variation of $\varepsilon_{(\text{COS})}$ as a function of the cloud cover at five degrees Celsius and assuming different relative humidities.

The turbulent flux of sensible heat in COSIMA $SH_{(\text{COS})}$ is calculated using formula (1) using the modeled surface temperature on the glacier surface. The same stability correction based on the bulk Richardson number Ri describe in section 3.2 is applied here to account for the reduced vertical exchange of air masses in stable conditions (Braithwaite, 1995b).

The turbulent flux of latent heat is calculated by the following expression:

$$LH_{(\text{COS})} = 0.622\rho_a L_v C^* U(z)\left[\frac{P_{\text{vap}}(z)}{P_a - P_{\text{vap,sat}}(z)} - \frac{P_{\text{vap}}(s)}{P_a - P_{\text{vap,sat}}(s)}\right]. \tag{13}$$

Since the air pressure P_a is normally much higher than $P_{\text{vap,sat}}$, this formula should give very similar results as formula (3). This expression is multiplied by the same correction factor as SH (see section 3.2). Concerning the parametrization of $P_{\text{vap,sat}}$ as a function of temperature, we decided to replace the original parametrization in COSIMA (red line in Figure 3(a)) by the parametrization proposed by Bolton (1980), equation (4), since it agrees best with the measurements. The original parametrization of COSIMA underestimates the water vapor pressure at positive temperatures and therefore underestimates LH for positive air temperatures, which are measured during summer at the AWSs (see below). COSIMA is modeling additional energy fluxes like heat fluxes inside the snow or ice, but for a better comparison of the computed melt rates by the different methods, these fluxes were not considered in this contribution. The modelled heat flux inside the snow/ice with COSIMA depended on the initial temperature distribution inside the snow/ice and was maximum at San Francisco Glacier where it was 3% of the sum of the modelled fluxes, which are considered in this study.

4 Results

4.1 Microclimatic conditions on the glacier surface

In Table 4 we show averages of relevant climatic and glacier surface properties during summer for the six studied glaciers which are ordered according to their latitude from North to South. Variability of conditions is observed between the different glaciological regions but also inside each region. In the Central Andes the AWSs installed on Bello and Pirámide Glacier

Table 4. Mean values of relevant meteorological and glacier surface data during the study periods. For the longwave radiative fluxes bias-corrected value is indicated as well as the original measured one in parenthesis.

Glacier	SW_{in}	$\alpha_{S\bar{W}_{\mathrm{out}}/S\bar{W}_{\mathrm{in}}}$	$\bar{\alpha}_{\mathrm{daily}}$	LW_{in}	LW_{out}	T	U	RH
	$\left[\frac{W}{m^2}\right]$			$\left[\frac{W}{m^2}\right]$	$\left[\frac{W}{m^2}\right]$	$[C]$	$\left[\frac{m}{s}\right]$	[%]
Bello	297	0.26	0.28	231 (236)	300 (306)	2.3	2.9	37
Pirámide	282	0.07	0.07	267	362	7.0	4.0	40
San Francisco	211	0.36	0.37	261 (274)	303 (318)	7.1	2.0	43
Mocho	273	0.57	0.58			5.9	6.3	66
Exploradores	183	0.23	0.24	308 (349)	310 (352)	7.4	3.1	87
Tyndall 2015	188	0.51	0.52	300 (314)	314 (328)	4.8	5.6	74
Tyndall 2016	192	0.43	0.45	301 (315)	314 (330)	5.3	5.7	72

receive considerably more incoming solar radiation SW_{in} than the AWS on San Francisco Glacier which is receiving shade from Mirador del Morado peak in the morning hours (see Figures 1c and A1 in the supplementary material) The mean albedo of the surface was calculated by two methods: firstly by calculating for every day the quotient of the daily sum of outgoing divided by the sum daily incoming solar radiation and taking the average of these values ($\bar{\alpha}_{\mathrm{daily}}$) and secondly by simply dividing the mean outgoing solar radiation by the mean incoming solar radiation over the study period ($\alpha_{S\bar{W}_{\mathrm{out}}/S\bar{W}_{\mathrm{in}}}$). Both methods give similar results. The heavily debris-covered Pirámide Glacier is showing very low albedo. Bello Glacier is showing an albedo expected for debris-rich ice and San Francisco Glacier is showing an albedo which can be associated to clean ice (Cuffey and Paterson, 2010). The incoming longwave radiation LW_{in} is lower on Bello Glacier which can be explained by the lower atmospheric temperature due to its higher elevation (see Table 1.). The outgoing longwave radiation LW_{out} is highest for Pirámide glacier, whose surface is heating considerably in the afternoons (see Figure 4 f and below). No bias correction could be applied to this data since we do not know the real surface temperature of the debris which covers the glacier surface. Bello and San Francisco show bias-corrected mean values of LW_{out} of about 300 W/m^2. In the Central Andes wind speed is highest for Pirámide Glacier and the relative humidity is very similar for the three glaciers (around 40%).

At Mocho Glacier in the Lakes District, SW_{in} is slightly lower than for Bello and Pirámide Glacier and the albedo is much higher, which is explained by the fact that on Mocho Glacier the AWS was installed near the ELA and snow or firn were covering the glacier surface during the observation period (see Figure 9 and section 5.2). Both wind speed and relative humidity were clearly higher on Mocho Glacier in comparison with the glaciers of the Central Andes.

At the glaciers of the Patagonian Andes SW_{in} is clearly lower than for the glaciers of the other regions. This can be explained by its latitudinal dependency, due to the higher absorption of the solar radiation in the more humid and cloudy atmosphere in the Wet Andes and due to the fact that the glaciers in Patagonia are located at lower elevations. The albedo is higher for the clean Tyndall Glacier as compared to the partly debris covered Exploradores Glacier (Figure 2). LW_{in} is highest for Exploradores Glacier where also the highest relative humidity RH is observed. At Tyndall Glacier (the bias corrected) LW_{out} is very near to the expected value for a melting ice surface (315.6 W/m^2) in both years. For Exploradores Glacier it is slightly lower. Mean air temperature on Exploradores Glacier was similar to the one observed at Pirámide and San Francisco Glacier in the Central Andes and a bit lower at Tyndall Glacier. Measured wind speed was higher on Tyndall Glacier.

In order to study the daily cycle of the climatic variables on the glacier we calculated the average value which was measured at every hour of the day during the measurement period which are presented in Figure Cs4. As expected, the air temperature

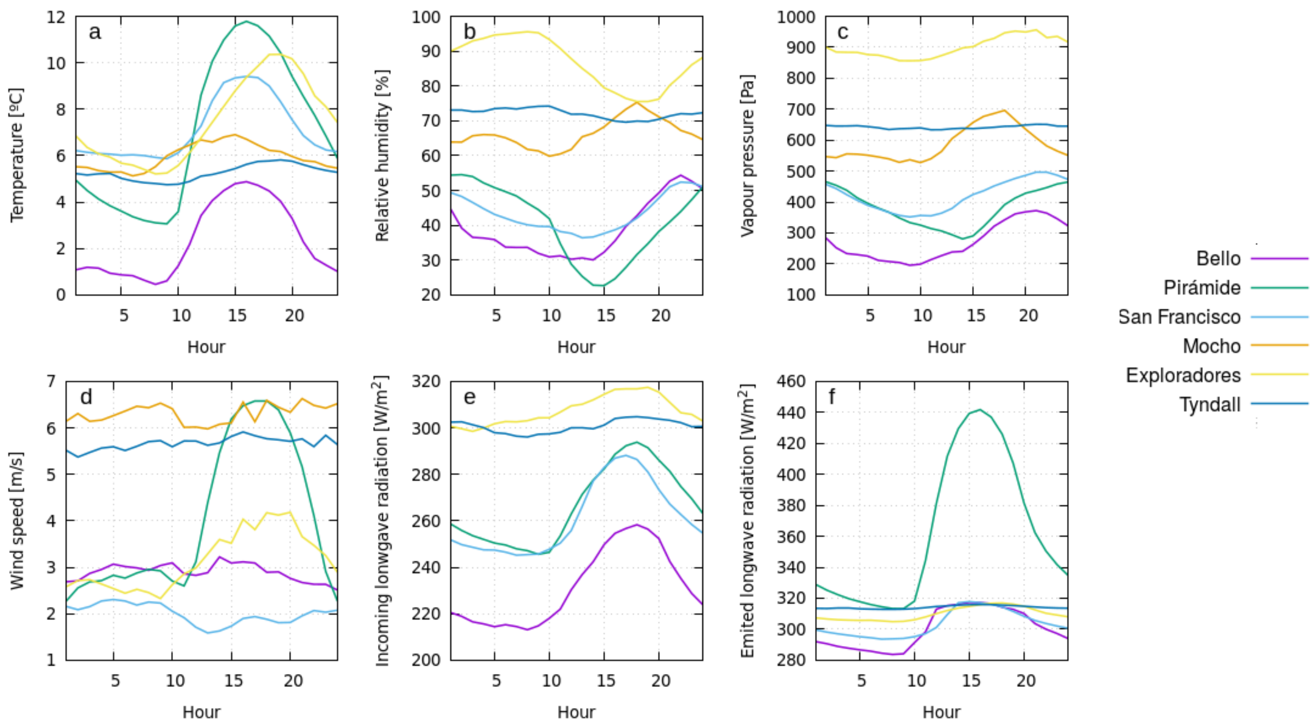

Figure 4. Averages of meteorological variables at the different hours of the day during the study periods on the six studied glaciers: a) temperature T, b) relative humidity RH, c) water vapor pressure P_{vap}, d) wind velocity U, e) incoming longwave radiation LW_{in}, f) outgoing longwave radiation LW_{out}.

shows a daily cycle for most of the glaciers, with maximum temperatures in the afternoon and minima in the early morning hours. However this daily cycle is much less pronounced for Tyndall and Mocho Glaciers. The relative humidity decreases during the daytime for most of the glaciers. The water vapor pressure shows a maximum during the late afternoon, when the air temperature is still elevated and the humidity is increasing. The wind speed shows a very pronounced increase during the daytime at Pirámide Glacier, when its debris covered surface is heating (Figure 4f). At Exploradores Glaciers an increase in wind speed during the afternoon is observed as well. The incoming longwave radiation show a maximum during the daytime, when the atmospheric temperature is highest. The outgoing longwave radiation, which is emitted by the glacier surface has a very distinct maximum during the afternoon for Pirámide Glacier (increase of more than 100 W/m^2), which means that the glacier surface is warming during the daytime. Bello, San Francisco and Exploradores Glacier also experience a maximum emission of longwave radiation in the afternoon, whereas Tyndall Glacier shows a constant rate of emission of longwave radiation, which indicates a constant surface temperature during summer.

4.2 Average energy balance and melt

Since both EB-Model and COSIMA are models designed to compute the surface energy balance over snow and ice surfaces, we exclude the heavily debris covered Pirámide Glacier from the analysis of the surface energy fluxes. In Figure 5 and Table A1 we present the mean energy fluxes and inferred melt rates for the other five glaciers using the three different methods.

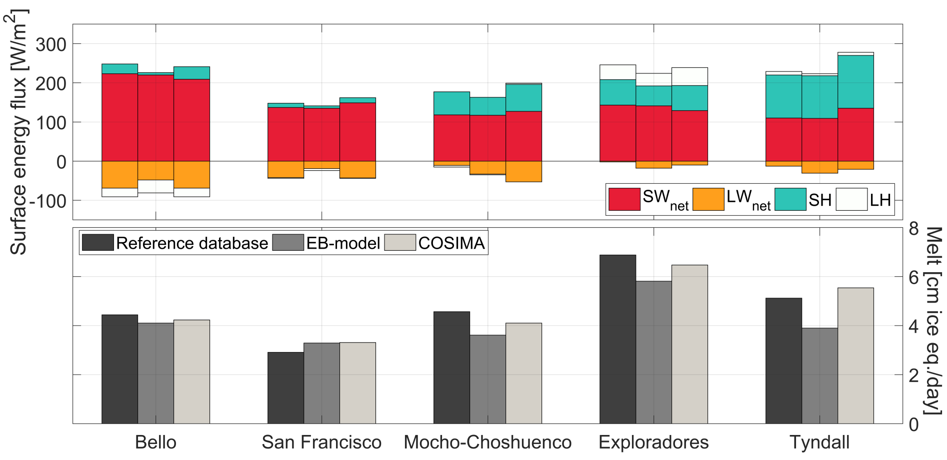

Figure 5. Mean modeled and measured energy fluxes and melt during summer for five glaciers: left bar Reference Database, middle bar EB-Model, right bar COSIMA.

In Figure 5 the three columns per glacier correspond to Reference Database, EB-Model and COSIMA from left to right. The net energy flux towards the glacier was converted into daily melt rates in ice equivalent using an ice density of 917 kg/m^3. For Tyndall Glacier only the results for the summer season 2016 are shown. The mean pattern of the energy fluxes changes from the Central Andes to Patagonia. The net shortwave radiation decreases from North to South. The net longwave radiation is negative in the Central Andes and near to zero in Patagonia. The sensible heat flux is a more important source of energy in Patagonia. The latent energy flux changes sign form sink of energy in the Central Andes to source of energy in Patagonia. This means that in Patagonia water vapor condensates at the surface of the Glaciers, which generates heat for additional melt. There are differences in the prediction of the energy fluxes on the Glacier surfaces between the different methods which will be discussed in detail in the next section. The predicted melt rates for the specific study points (locations of the AWS) in the ablation area of the glaciers are higher for the Patagonian Glaciers as compared to the glaciers of the Central Andes.

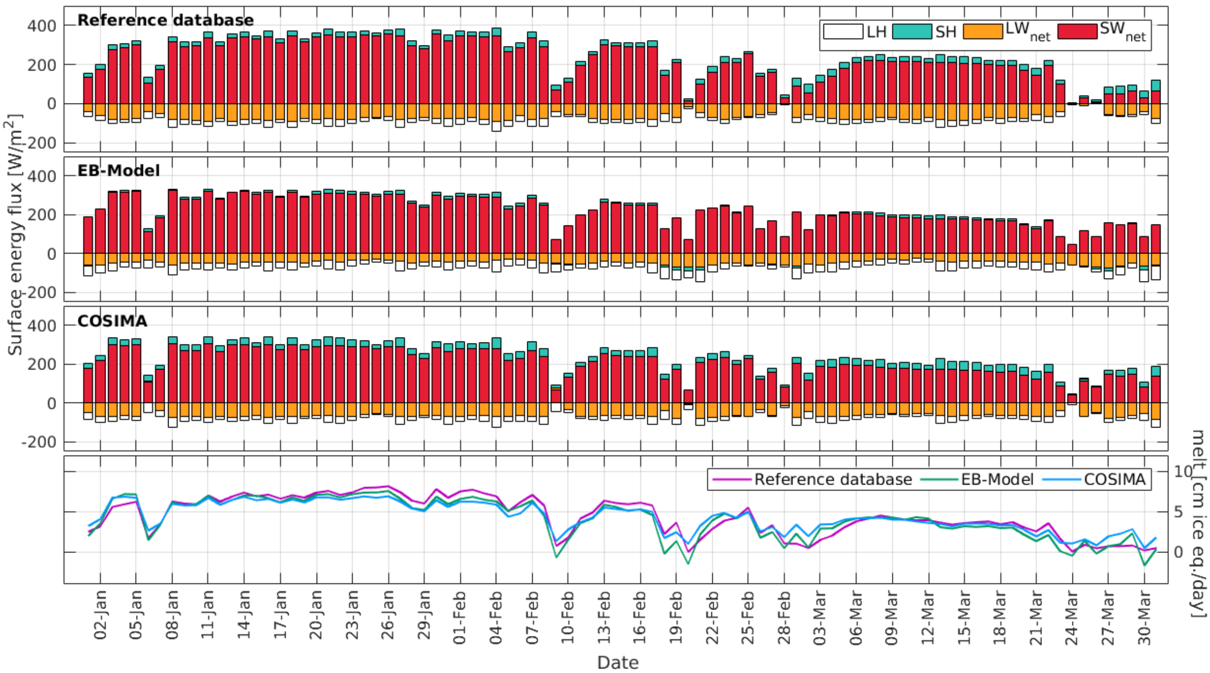

Figure 6. Daily modeled and measured energy fluxes and inferred daily melt rates during summer 2015 for Bello Glacier using the three methods.

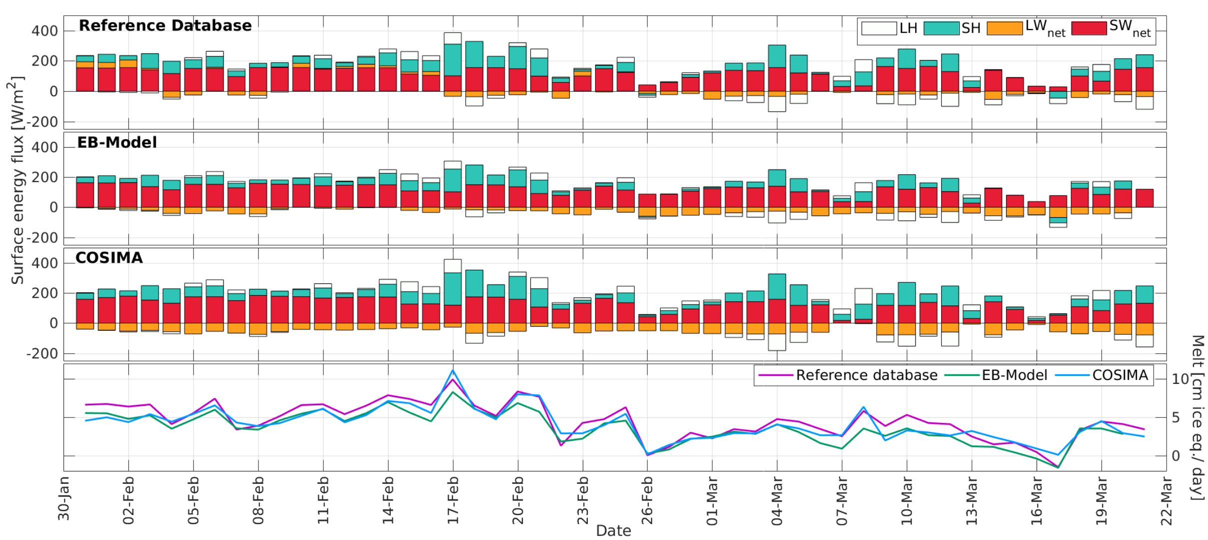

Figure 7. Daily modeled and measured energy fluxes and melt during summer 2006 for Mocho Glacier using the three methods.

4.3 Daily energy balance and melt

In the Figures 6,7,8, we present the computed daily energy fluxes and melt rates for Bello Glacier, Mocho Glacier and Tyndall Glacier (2016) respectively. On Bello Glacier the melt rates are clearly modulated by the net shortwave radiation: on days with

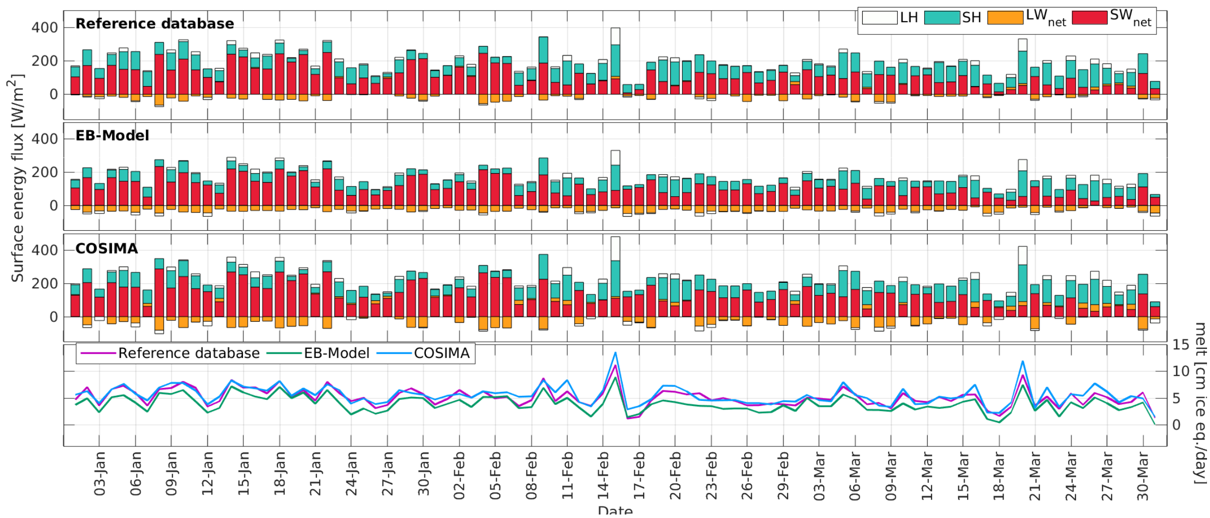

Figure 8. Daily modeled and measured energy fluxes and melt during summer 2016 for Tyndall Glacier using the three methods.

reduced net shortwave radiation (due to the presence of clouds) , melt rates show minima (Figure 6). On Mocho Glacier this picture changes: high melt rates are rather associated with low net solar radiation, high contributions of the sensible heat flux and positive values of the latent heat flux (see for example 17th of February or 8th of March in Figure 7).

Similar results can be observed for Tyndall Glacier: peaks in melt rates are associated to low contribution of the net shortwave radiation and high contributions of the turbulent heat fluxes (15th of February or 20th of March in Figure 8).

5 Discussion

5.1 Microclimatic conditions on the glacier surface

The systematic variation of several meteorological variables between the different parts of the Chilean Andes crucially determine the importance of the different energy exchange process at the glacier surfaces (Table 3). SW_{in} differs around 100 W/m^2 form the Central Andes (considering Bello and Pirámide Glaciers) to the Patagonian Andes. The difference in SW_{in} between the two glaciers in the Patagonian Andes is only 9 W/m^2, although they have opposite exposition. The difference between two summers on Tyndall Glacier is only 4 W/m^2. Another clear trend form north to south is found for the relative humidity. The values measured in the Patagonian Andes double the values obtained for the central Andes. This influences the latent fluxes: in the Central Andes moisture is transported away from the glacier surfaces whilst in Patagonia moisture is transported towards the glacier surfaces. Although the mean air temperature measured over Pirámide, San Francisco and Exploradores Glaciers were very similar, the incoming longwave radiation was much higher (>75 W/m^2) at Exploradores Glacier. This can be explained by a higher emissivity of the atmosphere due to a higher relative humidity of the air and due to more presence of clouds in the humid conditions of Patagonia.

Considering the variability of the data from the two summers measured on Tyndall Glacier, we can state that the glacier climate was similar in both summers. Especially mean LW_{in},LW_{out}, RH and U were nearly identical. SW_{in} and T were slightly lower in 2015 as compared to 2016 and the surface albedo was higher in 2015. The mean values of T,RH and U measured on Tyndall Glacier during the summers 2015 and 2016 were also very similar to the mean values measured by Takeuchi et al. during December 1993 (Takeuchi et al., 1999).

5.2 Parametrizations of the surface energy fluxes

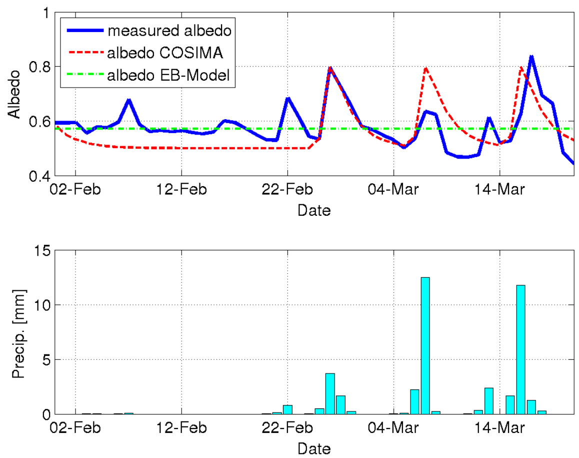

Figure 9. Measured and modeled daily albedo on Mocho Glacier and precipitation registered in Puerto Fuy during summer 2006. The albedo value used in EB-Model corresponds to the mean value of the measured albedo. In COSIMA the following parameters have been chosen: α_{frsnow}=0.8, α_{firn}=0.5, time constant t^*=2 days, snow depth constant d^*=8 cm (see equations (10) and (11)

The net shortwave radiation is an important source of energy for all the glaciers. According to equation (5) it is determined by the incoming shortwave radiation and the albedo of the surface. Albedo of snow and ice surfaces are very variable and depend on grain size and form, liquid water content, impurities and other factors (Wiscombe and Warren, 1980; Warren and Wiscombe, 1980; Cuffey and Paterson, 2010). Generally fresh snow has the highest albedo which is decreasing in time when snow grains are growing and the snow is eventually getting dirty. COSIMA tries to reproduce this albedo aging effect introducing a snow albedo which exponentially decreases in time (equation 11). In Figure 9 we show the comparison between the measured daily albedo on Mocho Glacier during February and March 2006 and the predictions of the COSIMA model.

It is clearly visible that increases in the albedo are associated with precipitation events registered at the nearby automatic weather station in Puerto Fuy. COSIMA is mostly able to capture these increases. However, the measured increases in the surface albedo are much more variable than the ones obtained from the model. A drawback of this comparison is certainly that we do not know the exact amount of snow falling on the glacier, but deduce it from the liquid precipitation measured at a automatic weather station in the valley.

The longwave radiative fluxes make important contributions to the energy exchange at the glacier surface. Since snow and ice emit like blackbodies ($\varepsilon = 1$) in this part of the electromagnetic spectrum and the atmosphere mostly shows emissivity smaller than one, the longwave radiation balance is often negative (even at positive ambient temperatures). However in the humid Patagonia the measured net longwave radiation is often balanced (Figure 5 upper panel left bar glaciers Mocho, Exploradores and Tyndall). In Figure 10 we show the "measured" daily emissivity calculated by inverting the Stefan-Boltzmann law

$$\varepsilon_{\text{measured}} = \frac{LW_{\text{in}}}{\sigma T^4}, \tag{14}$$

where σ denotes the Stefan–Boltzmann constant, as a function of the daily cloudiness for the glaciers Bello, San Francisco Exploradores and Tyndall. For a direct comparison, we show the parametrizations of the models in the plots of every glacier. Generally we can note that the data of the "measured" emissivity shows considerable scatter around their trend line. This

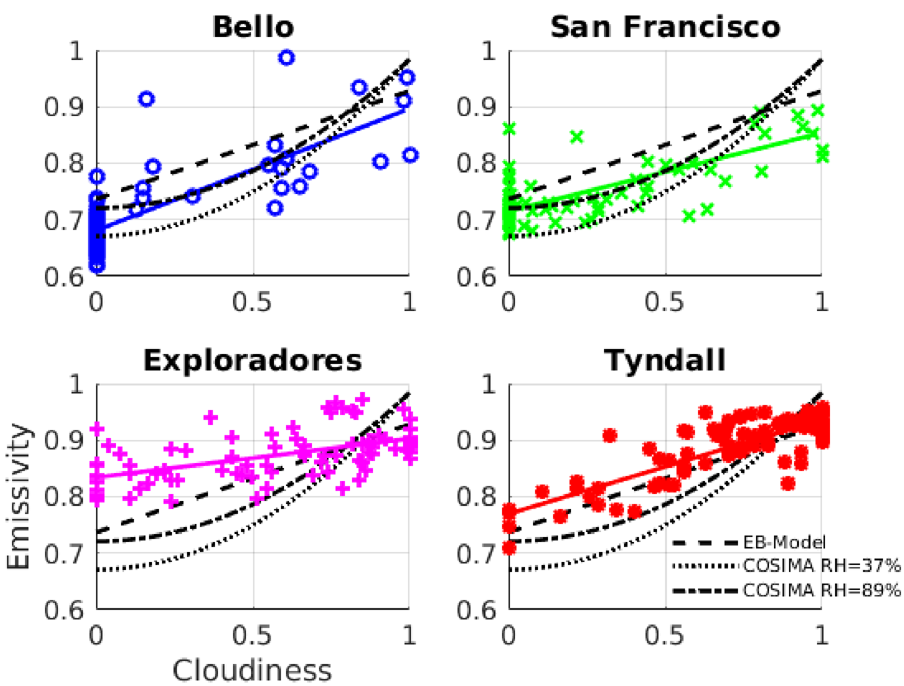

Figure 10. "Measured" emissivity of the atmosphere as a function of the cloudiness. The data points correspond to the daily emissivity obtained from equation (14) by using daily means of LW_{in} and T plotted against the inferred daily cloudiness values. The continuous colored straight lines correspond to linear fits to the data of every glacier and the black discontinuous lines correspond to the model parametrizations (same as Figure 3 b).

may indicate that the variability of the measured emissivity can not only be explained by the variability of the cloudiness.

Probably the relative humidity and other factors will influence the emissivity of the atmosphere. However the big scatter of the measured data might also be associated with the uncertainties of the determination of the cloud cover and the emissivity of the atmosphere. The cloud cover data were obtained from specific paramtrizations of the transmissivity of the atmosphere as a function of the cloudiness. However these parametrizations are not unique (see for example Oerlemans (2001)). Also the "measured" emissivity is associated to some uncertainty: it is not clear if the temperature measured at two meters over the glacier surface is representative for the temperature of the atmosphere which is emitting longwave radiation towards the glacier surface.

We can recognize that the model parametrizations underestimate the emissivity of the atmosphere at Exploradores Glacier for low cloudiness conditions. This underestimation of the emissivity of the atmosphere leads to an underestimation of the net longwave radiative balance on clear days. At San Francisco Glacier the model parametrizations overestimate the emissivity of the atmosphere for cloudy conditions.

The variability of the modeled turbulent fluxes is very similar in all three methods. This is expected since the formula to compute these fluxes have very similar aspect: in all approaches the sensible heat flux is mainly driven by the temperature difference of the glacier surface and the atmosphere at two meters elevations and wind speed and the latent heat flux is driven by the difference of the water vapor pressure at the glacier surface and the atmosphere at two meters elevations and wind speed. The mean values of the turbulent fluxes computed in EB-Model are lower than the one obtained by the other two methods (Table A1 and Figure 5). This is because the EB-Model assumes a glacier surface at zero degrees Celsius which reduces both the temperature difference between glacier surface and the overlying air layer and the difference of water vapor content between both. This causes the melt rates modeled by EB-Model to be generally lower (Figure 5). The modeled turbulent fluxes in the Reference Database and by COSIMA are very similar expect for Mocho Glacier where a glacier surface at zero degrees had to be assumed in the Reference Database, due to the lack of data of the outgoing longwave radiation.

In Table A1, for the Reference Database, we also present in parenthesis values obtained for the turbulent fluxes without applying a stability correction and the resulting inferred melt rates. Important differences can be noted especially for the glaciers where the mean wind speed is moderate (Exploradores, San Francisco and Bello). The strongest influence of the stability correction on the melt rate is for Exploradores Glacier, because both turbulent fluxes have the same sign, The stability correction for the sensible heat flux and the latent heat flux perfectly cancel out at Bello Glacier. The influence of the surface roughness on the turbulent fluxes has a similar character: doubling z_0 for Bello Glacier will change the net energy flux by only $1\ \mathrm{W/m^2}$ and using a roughness length of 10 mm (twenty times higher) by $5\ \mathrm{W/m^2}$. At the Patagonian glaciers, however, a higher surface roughness would have a much higher impact since both turbulent fluxes have the same sign.

5.3 Melt rates

Melt rates ranging from 2.9 to 4.4 cm/day of ice equivalent (cm i.e./day) for the Dry Andes and from 3.3 to 6.9 cm i.e./day for the Wet Andes were predicted by the different approaches of quantifying energy fluxes on the surface of five glaciers (Table A 1). These values lie within the range of observed melt rates during summer on these glaciers or glaciers with similar climatic conditions.

In the Wet Andes Schaefer et al. (2017) measured ablation rates of 2.6 cm i.e./day and 3.2 cm i.e./day in the summers 2010 and 2011 and measured and inferred rates of 3.6 cm i.e./day and 3.7 cm i.e./day in the summers 2012 and 2013 on Mocho Glacier at the same location where the AWS was installed in 2006. This indicates that the reference and COSIMA may overestimate the melt at this location. Here, we have to take into account that for Mocho Glacier net longwave radiation was inferred by subtracting the net shortwave fluxes from the net overall radiation, measured with the NR-lite, which is a lower precision instrument as compared to the newer sensors installed in the CR4. At Tyndall Glacier in the period November 2012 to May 2013 an average ablation rate of 3.8 cm i.e./day was observed at two stakes near to the location of the AWS. Considering that this period also includes spring and autumn months, were melt rates should be lower, this in in very good agreement to the values of 3.3 to 5.1 cm i.e./day predicted by the different approaches presented in this work. From January 2015 to March 2015 an average ablation rate of 9.1 cm i.e./day was measured at a stake network installed on Grey Glacier at an elevation range ranging from 260 m.a.s.l. to 380 m.a.s.l.. This indicates that the high melt rates modeled for Exploradores Glacier seem to have a realistic magnitude for a low elevation site on a glacier in the Patagonian Andes, although the different climate conditions at Grey Glacier make a direct comparison difficult.

In the Dry Andes ablation was measured at a stake network on Bello Glacier during summers 2013/2014 and 2014/2015 (CEAZA, 2015). A high variability of ablation rates in space and time were obtained. Several of the ablation rates inferred for stakes nearby the AWS were of similar size than the predicted ones by the methods presented in this paper. Analyzing the signal of an ultrasonic sensor installed on an ablation gate next to the AWS of San Francisco Glacier we found a surface lowering of 4.9 cm/day during December 2015. Assuming that snow melt in this period of the year with a density of 500 kg/m^3 this yields a rate of 2.7 cm i.e./day, which is in good agreement with the melt rates inferred in this contribution.

5.4 Implications for glaciological zones in Chile

Our results suggest a transition of energy sources for surface melt from the Central Andes to Patagonia. The energy sources obtained for Mocho Glacier at 40°S are more similar to the ones observed at the Patagonian glaciers than to the ones observed for the glaciers of the Central Andes, where SW_{in} is the dominating source of energy for melt (Figures 5 and 6). The greater importance of the turbulent flux of sensible heat as energy source available to produce surface melt at Mocho Glacier probably contributes to the observed strong dependency of its annual mass balance on the annual mean temperatures measured on a nunatak of the glacier(Scheiter, 2016; Schaefer et al., 2017). This picture changes strongly in the Central Andes, where a very low dependency of the annual mass balance of Echaurren Norte Glacier on the annual mean temperature observed at Embalse el Yeso was reported (Masiokas et al., 2016; Carrasco, 2018; Farías-Barahona et al., 2019). When comparing the importance of the energy sources between the two summers modeled for Tyndall Glacier (Table A 1) , we can state that in 2015 SW_{net} was slightly lower than in 2016 due to the lower SW_{in} and the higer surface albedo observed in that year (Table 3). However the overall pattern of energy sources (and sinks) is very similar for both years. All these results confirm the general division of the Chilean Andes into Dry Andes and Wet Andes, with the zonification limit being located approximately at 35°S (Lliboutry, 1998).

5.5 Implications for physical melt modeling and transferability of parametrizations

The capacity of the models to reproduce the measured radiative fluxes is still improvable. The albedo aging effect implemented in COSIMA is a big improvement regarding to constant albedo parametrizations for snow, firn and ice surfaces. However the parameters of this aging formula seem to vary strongly from one site to another and a good calibration of this formula seems to be necessary. Regarding the predictions of the net longwave radiative fluxes on the glacier surface, the parametrization of the emissivity of the atmosphere is crucial. The tested models cannot reproduce the variability of the emissivity as a function of the cloudiness for all the glaciers. Especially at Exploradores Glacier the clear-sky emissivity is underestimated by the models. This is because the used parametrizations are fits to data that were obtained in different climatic conditions. Therefore, these parametrizations are not physical and can not be simply transferred to other sites where the conditions are different.

Different parametrizations for the turbulent fluxes of sensible and latent heat were compared in this study. The transfer coefficient depends directly on the roughness length z_0 (and z_T, z_H in the case of EB-Model), which is/are therefore crucially determining the magnitude of the turbulent fluxes. However these roughness lengths are neither constant in time nor in space, which makes them very difficult to determine. A common practice is to chose the roughness length in a way that the modeled melt rates agree with the measured ones. However, this exercise does not make these formula very adequate predictors of melt rates in other situations and on other glacier surfaces. More direct measurements of turbulent fluxes over glacier surfaces (for example using the eddy-covariance technique (Cullen et al., 2007)) are necessary to find physical parametrizations of these fluxes..

Generally, there is still a strong need of measurements of the energy exchange processes over glacier surfaces and we think that coordinated efforts of governmental agencies, such as the Glaciology and Snows Unit of the Chilean Water Directory in our case, can make important contributions. If we want to work towards physical melt models, then we have to test the capacity of the models to reproduce the different physical processes that take place at glacier surface. Bringing the melt rates predicted by these highly parameterized models in agreement with the observed ones seems to be rather a curve adjustment exercise than a indicator of correct physics.

6 Conclusions

Performing an extended study of surface energy fluxes during summer on five Chilean glaciers on a north-south transect and under strongly varying climate settings we reached to the following conclusions:

- The contribution of the different surface energy fluxes over glacier surfaces change from the Central Andes towards the Patagonian Andes: the net shortwave radiation as main source of energy in the Central Andes looses importance further South, where the turbulent fluxes of sensible and latent heat are providing more energy for melt. The net longwave radiation changes from a strong sink of energy for the glaciers of the Central Andes to a net zero contribution in the Patagonian Andes.

- The inferred melt rates in the ablation area of the glaciers were higher for the Patagonian Andes than for the Central Andes.
- Mocho Glacier in the Chilean Lake District is showing similar patterns of surface energy fluxes to the glaciers in the Patagonian Andes.
- The models underestimated the emissivity of the clearsky atmosphere at Exploradores Glacier, an extremely humid place in the Wet Andes.
- From our study it is difficult to infer which parametrization of the turbulent fluxes is the most appropriate one. More detailed studies on this topic are necessary, which include direct measurements of these fluxes.
- To develop or improve physical melt models, we have to validate every single model parametrization against data and cannot judge the model's performance only by the final output. In this highly parameterized models the effect of physically wrong parametrizations might cancel out and the final result might be satisfying, without reproducing well the individual physical processes.
- Openly shared codes are the best way to improve physical models, since everyone can test the individual parametrizations against his data and adjust or improve them accordingly. This is the preferred way to obtain physical parametrizations as opposed to large chains of models which supposedly model physical processes whose individual performance, however, is not validated and the final results rather come out of a black box.

Code and data availability. TEXT

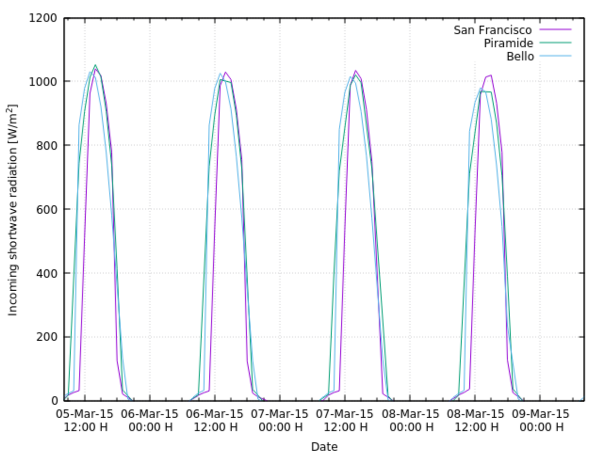

Figure A1. Incoming shortwave radiation at the AWSs installed on Bello, Pirámide and San Francisco Glacier during March 2016.

Table A1. Mean values of the computed surface energy fluxes and melt rates during the study periods on the five studied glaciers using the three different methods. For the Reference Database turbulent fluxes and melt rates calculated without using stability corrections are indicated in parenthesis.

Glacier	Method	SW_{net}	LW_{net}	SH	LH	Melt
		$\left[\frac{W}{m^2}\right]$	$\left[\frac{W}{m^2}\right]$	$\left[\frac{W}{m^2}\right]$	$\left[\frac{W}{m^2}\right]$	[cm ice eq./day]
Bello	Reference Database	223	-69	25(32)	-22(-29)	4.4 (4.4)
	EB-Model	220	-48	6	-33	4.1
	COSIMA	208	-69	32	-22	4.1
San Francisco	Reference Database	137	-42	11(41)	-2(-9)	2.9 (3.6)
	EB-Model	135	-19	6	-5	3.3
	COSIMA	149	-43	13	-1	3.3
Mocho	Reference Database	118	-11	59(74)	-4(-5)	4.6 (5.0)
	EB-Model	117	-33	46	-2	3.6
	COSIMA	127	-53	69	3	4.0
Exploradores	Reference Database	143	-2	65(94)	38(55)	6.9 (8.2)
	EB-Model	141	-18	51	32	5.8
	COSIMA	129	-10	64	46	6.4
Tyndall 2015	Reference Database	94	-14	65(80)	9(10)	4.5 (4.8)
	EB-Model	92	-30	52	5	3.3
	COSIMA	132	-22	70	9	5.3
Tyndall 2016	Reference Database	110	-13	76(87)	9(10)	5.1(5.5)
	EB-Model	109	-29	55	5	3.9
	COSIMA	135	-21	75	8	5.5

Author contributions. M.S. designed the research, ran the COSIMA model, wrote the manuscript and prepared several figures, D.Fonseca prepared the Reference Database, ran EB-Model and prepared several figures, D.Farías provided detailed information about the DGA-AWS and prepared Figure 1, G.C. measured the surface energy fluxes on Mocho Glacier. All authors discussed the results and commented on the manuscript.

Code availability. Eb-Model is freely available at: https://onlinelibrary.wiley.com/doi/abs/10.1002/1096-9837%28200006%2925%3A6%3C649%3A%3AAID-ESP97%3E3.0.CO%3B2-U and COSIMA is available at https://bitbucket.org/glaciermodel/cosima/src/master/ and the newer version implemented in python at: https://github.com/cryotools/cosipy (recomended).

Data availability. Input and output data presented in this manuscript can be obtained by solicitude to the corresponding author.

Competing interests. no competing interests are present

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Comments for the Authors:

The paper addresses relevant scientific questions within the scope of TC. It shows a good data set of meteorological measurements and estimates of the surface energy balance of Chilean glaciers of contrasting climates.

Unfortunately, in my opinion the manuscript does not represent substantial progress beyond current scientific understanding. The overall presentation is well structured and clear. However, the text can be improved; it should be more concise and accurate. I found that some scientific methods were not suitable and that some assumptions were not clearly outlined. Finally, the discussion does not reach substantial conclusions. In my opinion, the main problem is that the objectives of the study are not clearly defined. The manuscript presents various results but the overall purpose of the study remains imprecise. The analysis of this interesting dataset could be an interesting contribution to the literature if the objectives were articulated more clearly and reflected in an appropriate methodology.

The paper would certainly need major improvements to be innovative and merit publication in TC. These points are detailed in the comments below.

Major comments:

The objectives should be redefined. The main contribution of the study is the presentation of a comprehensive set of meteorological measurements on glaciers of contrasting climates along the Andes. The data certainly allow for correct estimation of the energy fluxes at the surface of the glaciers. Radiation flux measurements seem appropriate and accurate. Turbulent flows are not measured directly, but meteorological measurements probably allow correct estimates(if the appropriate methods are applied, see comments below). Thus, I would suggest focusing on a comparison of the energy fluxes partitioning in the different climates from the dry Andes to the wet Andes (the measurements above debris-covered ice are not useful here). The effects of latitude and of altitude on the energy fluxes need to be discussed in more detail.

Ok. Section 4.1 was revised completely.

One limitation of the study is that general interpretations of different climates are deduced from point-scale measurements. The partitioning of the energy fluxes depends on the position of the weather station. For instance, the albedo varies greatly over short distances near the snow line, so that the interpretation of punctual energy flux measurements can lead to an erroneous generalization of the melting characteristics to the entire ablation area. This point should be discussed.

Ok. This point is mentioned now.

Some applied methods are not suitable The NR-Lite sensor is less accurate than the CNR4. Thus, calculations of long wave radiation fluxes can be problematic on the Mocho glacier.
Ok. We agree that it is difficult to draw sound conclusions about longwave radiative fluxes using the data from NR-Lite sensor. Still, we think that the results for the longwave net fluxes obtained on Mocho fit well in the general North-South trend, which makes us more confident about them.

Comparing different models does not bring much newness here. Some assumptions are not valid (Ts=0◦C, constant albedo...) or some formulations are not adequately described (see below).

I would suggest discussing the energy fluxes derived from the most direct approach: the 'reference database' based on measurements. For example,there is no need to assume that the surface temperature is fixed to 0◦C (P7, line 14)if outgoing longwave measurements are available. This assumption (which does not seem valid on the San Francisco and on Bello glaciers) has a significant impact on the turbulent sensible heat fluxes derived from the bulk method.

Ok. For the computation of the Reference Database, we compute now the surface temperature using bias-corrected outgoing longwave radiation data. Comparing the performance of the different model parameterizations under different climatic conditions is the core part of this study.

P8, Equation 4: use the standard relationship of saturation vapor pressure as a function of temperature, no need to test different parametrizations.
It seems there exist several "standard" parameterizations in the literature. We used the one which we think interpolated best the measurements.
P8, line 13: why mentioning direct and diffuse components of solar irradiance if global radiation is directly measured?
Here we are describing the parameterizations of one of the models which we are applying. In this model the division into direct and diffuse components is used to infer the cloud cover.
Sections 3.2, 3.3 and 3.4: the comparison of the different turbulent 'transfer coefficient'(P7, line 16) should refer to stability concepts. A stability correction must be included over glacier surfaces, using the Monin-Obukhov length scale or the Richardson number. This important point should be clarified. The values of the roughness lengths for momentum, temperature and humidity should also be discussed in more detail with reference to the state of art.
Ok we added some discussion on that.

P11, lines 9-12: no need to compare the two methods (especially if they give 'similar results').
We think that it makes our results more robust, when two different ways of computing albedo give similar results.
The effects of cloud cover in the different climates should be investigated more rigorously. The applied method is inappropriate (the text does not say how the cloud cover is calculated) and appropriate references are missing. Figure 10 is unclear and its interpretation P17-18 remains vague. Robust methods have been proposed for estimating cloud cover from solar and longwave radiation fluxes measurements (e.g., Marty etal., TAC, 2002 in the Alps; Sicart et al., JOG, 2010 in the tropical Andes; McDonell etal., TAC, 2013 in the semiarid Andes of Chile; Munneke et al., IJC, 2011...). These parametrizations, once calibrated at each site, will make it possible to distinguish clear skies from cloudy conditions. This point, with an adequate methodology, could be an interesting contribution of the study.
For EB-Model and COSIMA the cloud-cover is estimated using incoming solar radiation fluxes measurements (see section 3.3 and 3.4). Figure 10 has been divided into 4 subplots now, to facilitate the visualization of our analysis.

Many results are presented without proper interpretation Figures 5, 6, 7 and 8 show many results, but most of them remain poorly analysed. The turbulent fluxes are not measured directly, so their estimates are not very accurate. The large differences in sensible heat flux in the different climates are certainly significant. However, I think no much can be said about the latent heat fluxes shown in figure 5; the fluxes remain close to zero and the uncertainties are certainly large.

We do not agree here with your statement about the latent heat fluxes: these fluxes depend on the moisture content of the atmospheric layer next to the glacier surface. If the moisture content in this layer is less than the moisture content of a saturated air layer at zero degrees Celsius just above the glacier surface, then the latent heat flux has a negative sign (moisture is transported from the glacier surface to the atmosphere, which causes more evaporation or sublimation to happen on the glacier surface, which are processes that consume energy). This is happening in the Central Andes. If on the other hand the moisture content of the lowest atmospheric layer is higher than the moisture content of a saturated air layer at zero degrees Celsius just above the glacier surface, then the latent heat flux has a positive sign (moisture is transported from the atmosphere to the glacier surface, which causes condensation to happen on the glacier surface, which is processes that provides energy). This is happening in the Patagonian Andes (especially Exploradores Glacier).

- The text must be carefully proofread. Be more specific and accurate, for instances:

- P2, lines 23-25: give numbers to quantify the trends in mass balance
ok, number was added.
- P5: the correct terms are ‘irradiance’ or ‘radiationfluxes’ (in W/m2)
The correct terms for what on page5? Not all energy fluxes on the glacier are radiative!
- P13, line 6 ‘ice equivalent’? Do you mean water equivalent?
As the glaciers surfaces to which we applied the model approach were mostly ice, we decided to present the results in ‘ice equivalent’
- P13 where are the figures 12 and 13?
Sorry, these figures existed in an earlier version of the manuscript. They were removed now!
- P16, line 16: Equation 12?
Sorry, we meant equation (11)
- Where is Table 4?
Sorry. We refer to table A 1. Changed!
Minor comments:
- P16, lines 2-4: the effects on longwave radiation of the “very humid and temperate air column between the sensor and the glacier surface” is probably small and can be estimated [e.g., Pluss and Ohmura, 1997].
Ok, now we bias-corrected the measured longwave radiation following a suggestion form reviewer2.
- P19: why not using the meteorological and ablation measurements on the Bello glacier during the summers 2013/14 and 2014/2015 to validate (in a rigorous way)the calculations of the energy fluxes?
We are using data from summer 2014/2015, since in summer 2013/2014 there was a problem with the sensor which is measuring shortwave radiation. Sadly for the summer 2014/2015 no ablation measurements are available at the location of the automatic weather station (see page 87 in CEAZA: Modelación del balance de masa y descarga de agua en glaciares del Norte Chico y Chile Central, Tech. rep., Dirección General de Aguas, S.I.T. No. 382, 2015.)

This paper focuses on calculations of the surface energy balance (SEB) of glaciers along the Andes of Chile. The analysis is covering a large latitudinal range, between18∘S and 55∘S, and tries to describe the main differences existing in the processes controlling melting under diverse climate settings. The paper compares three differentmodelling approaches applied on a dataset of 6 glaciers. The authors intend determining adequate parameterization of SEB models and conclude that the use of observed melt is not sufficient to assess model performance.The dataset and SEB analysis are important for the community in particular for model validation and deserve to be published. However, in its present state, the modelling analysis is not sufficiently robust, because
1) raw data still present biases,

2) models are too different to be compared,

3) none of the models is currently sufficiently accurate to be referred to as the reference.

In particular, the authors write that “Bringing the predicted melt rates by these highly parameterized models in agreement with the ob-served ones seems to be rather a curve adjustment exercise than a indicator of correct physics.”. However, I feel that this opinion is not supported by results.I propose authors produce a (real) reference modelling, using adapted calibration for each glacier (see point 2), and then compare this reference with other “simplified” approaches (i.e. the EB-model and the COSIMA model as presented in the present version of the paper). When radiative fluxes are modelled, I propose to perform acalibration/validation step. Finally, in the discussion, I suggest that authors cautiously consider the differences in surface states, elevation and latitude (in particular when the authors compare ablation amounts). For this task, I have a few suggestions which may improve the accuracy of results:

1) A pretreatment of field data has not been made in depth. Indeed, LW data are biased by very large artefacts, and this introduces large uncertainties in the SEB analysis. + Large biases are observed in LWin and LWout data. These are clearly visible in figure 4. They are likely due to CNR4 heating caused by solar radiation, or to an incorrect calibration. I personally worked during 20 years with these sensors (CNR1,CNR4) and I never observed continuous biases of about 20 W m-2. Obleitner and deWolde (1999) proposed bias corrections as a function of SWin values, but this does not remove potential biases during the nights. In order to remove biases, I propose that authors analyse LWout values when the surface is melting (LWout should be 315 W m-2). LWnet is possibly correct because corrections may be similar for both LWin and LWout.+ Potential other artefacts are not discussed in the text (existing shadows on sensor caused by the station mast, snow accumulation on CNR4, etc). Generally, non aspirated temperature sensors may be biased

high by solar radiation at wind speeds less than 3 m s−1 (Huwald et al., 2009; Georges and Kaser, 2002). A correction for the solar bias is complex but possible. At least, observed temperatures may be flagged when low wind speeds (i.e., <3 m s−1) are observed during the daytime. This has an impact on turbulent heat fluxes calculations. + Data gaps are also not described. =>I suggest that authors accurately correct field data.
Ok. We bias-corrected longwave radiative fluxes now, using the assumption that the glacier surfaces are melting (are at zero degrees Celsius) during afternoon (1 p.m. to 6 p.m.). Data gap treatment is described in the section 3.1.

2) The “reference model” is not accurate enough due to assumptions made on Ts and turbulent heat flux calculations. SWnet and LWnet would possibly be accurate because these values are directly measured (if biases are removed), but turbulent heat fluxes are clearly not accurate in the reference model, because 1) surface temperatureTs is assumed to be at 0∘C, and 2) calculations are done without considering stability conditions in the surface boundary layer. Conversely, the COMISA approach very likely produces more accurate LH and SH, but then the radiation terms are not accurate (see the important differences with observed fluxes in Table A1). =>I propose to run the COMISA model using the measured SWin, Albedo, LWin (after correction), T, Rh and wind speed, solid precipitation, the initial snow height and cloudiness (I am not sure that this variable will impact results since LWin and SWin will be already assimilated).I propose to force the model using specific surface roughness length values according to the surface state. Indeed, Bello Glacier (see photograph) presents small penitents at the surface when Tyndall presents a very smooth surface. Surface roughness length values have already been proposed in the literature for the different studied areas.

In the revised manuscript we do not assume Ts to be at 0∘C any more. We compute Ts now using the bias corrected values of LWout (except for Mocho, where we do not have this information). We now use the stability correction implemented in COSIMA for the turbulent fluxes for the reference database. The influence of different surface roughness values is discussed now.

3) LW/SW schemes have never been calibrated/validated in the study. When modelled(i.e., in the simplified modelling approaches), albedo and LWin/SWin schemes could be calibrated using a simple monte carlo approach (scores could be computed using field measurements of albedo and LWin/SWin). A sensitivity analysis could also offer interesting information for the discussion.
SWin are input data for the modeling approaches. SWout, that is parameterization for albedo, are calibrated and validated on Mocho Glacier (Figure9). LWin is validated in Figure10.

For turbulent heat fluxes, authors could test various surface roughness length values given in the literature. Validation of the“reference model” could also be done between modelled and observed Ts. The modelled ablation could be compared with observation on stakes or on sonic gauges (when available). =>I propose that authors calibrate the different schemes on one period and validate it on another one. This is possible at least for Bello and Tyndall glaciers.

Ok, now we discussed the influence of the roughness length on our results. Sadly no direct ablation measurements are available for the modeling periods.

4) How do authors compute melting? Do they use the mean daily energy excess, or do they compute melting at a 1h time step? This is crucial because calculations must consider that surface melting depends on heat storage in the subsurface. In particular, the existence of subsurface fluxes is never mentioned (heat conduction and transmission of solar radiation in snow and ice) even in the COSIMA model. These fluxes are crucial to explain daily melt intensities. => Does COSIMA compute these fluxes? if not, would it be more accurate to run a model that includes these fluxes?(see for instance Thomas Mölg’s model (e.g., Mölg et al., 2008, 2009b, 2012; Gürgiseret al., 2013)). If subsurface fluxes are not considered, please justify this assumption.

Daily and overall melt rates were computed by summing up hourly energy flux data (negative fluxes are considered as well).

Subsurface fluxes are modeled by COSIMA but are not considered in the other approaches. The maximum energy exchange with the subsurface modeled by COSIMA was 3% of the sum of the fluxes considered in this study. This was mentioned now in the manuscript.

5) Finally, a deep review on SEB modelling in the Andes is lacking. Many SEB modelling are available along the Andes, but currently the review of literature is limited to(MacDonnell et al., 2013 ; Brock et al. 2007; Schneider et al., 2007 ; Pellicciotti et al.,2008 ; Ayala et al., 2017; Sicart et al., 2008), which is not up-to-date (papers mainly re-fer to studies published more than 10 years ago). A more exhaustive review of studies performed along the Andes would offer interesting information for the discussion.

Ok. Since this work is about Chilean Glaciers we restricted the literature review mainly to studies on Chilean Glaciers. We are happy to receive additional recommendations for studies of relevance for our work to include them in the literature review.

As a summary, I suggest that the authors take a slightly different approach in order too present their study. I suggest to: a) compute a real reference SEB b) describe the differences in fluxes according to the altitude/latitude, c) compute simplified EB-model and COSIMA modelling. d) conclude on the differences existing between the“simplified approaches” and the

reference model e) Please reconsider the conclusion of the paper if you don't clearly demonstrate that SEB modelling is harder to apply than an empirical model, and that it does not offer better results. f) I suggest that authors make a thorough editing of the text to improve the language style.
Thank you for your constructive comments. We think that our re-submission is quite in the line of what you proposed.

Minor Comments,
Line 5: Please write "Turbulent sensible heat flux", "Turbulent latent heat flux" and"turbulent heat fluxes" **ok**
Line 9 : transport coefficient => do you mean bulk exchange coefficient? Or bulktransfer coefficient? **Bulk transfer coefficient (changed)**
Line 20: "These kind of models are sometimes called "physical melt models" => please include references, at least in the Andes. **Ok added.**

Section 1 : Introduction => the introduction is confusing and is not focusing on the main objective of the paper. This introduction should present the interest of SEB modelling on glaciers, and a review of knowledge on the SEB in the Andes and under similar climates. I propose that authors reorganize the introduction and remove several sentences: For instance, the paragraph "Chile is well-known [...] future surface mass balance and melt water discharge of Chilean glaciers" could be included in a subsection of the section "sites" which could be titled "climate settings". **Ok.**

Page 2 Line 1 : "Chile is well-known for the climatic variety due to its north-southextension of the territory" => why do the authors focus on Chile only, and not onChile/Argentina? please rewrite. **We only analyze data from Chilean Glaciers in this manuscript, therefore we think that it is consistent to talk about the climate setting in Chile.**

Page 2 Line 2 : "Pacific anticyclone plays a key role" => on what?
On the climate in general (formulation changed) .
Page 2 Line 3: "sub-glaciological zones " => please cite (Braun et al., 2019) and (Dus-saillant et al., 2019) **ok**
Page 2 line 14 : Are you sure that the mega-drought reached Patagonia?
We are not sure if this drought in Patagonia in 2016 can be associated to the Central Chile mega-drought. We not associate the two phenomena in our manuscript..
Page 2 line 16 : "Chile hosts the majority of glaciers in South America (more than 80% of the area)," => what about Argentina?
There is much less glacier area in Argentina, again: our study focuses on Chilean glaciers.

Page 2 line 17 : Â´ n which are mostly thinning and retreating in the last decades (e.g.Braun et al. (2019)).” => please also cite (Dussaillant et al., 2019) **ok**
Page 2 line 17-20, and elsewhere: “The projections of future changes [...] climato-logical zones is necessary” => glacier wastage projections for calving glaciers are impossible if we only consider the SMB and the SEB (e.g., Collao-Barrios et al., 2018).The authors never write that Exploradores and Tyndall are calving glaciers. Please comment this point.
Ok, now we mentioned in section 2 that Exploradores and Tyndall glaciers are calving glaciers.

Page 2 line 21: “There exist few surface mass balance observation programs on Chilean glaciers:” => why considering only Chile?.
Because our study is about Chilean Glaciers!
Page 2 line 23: “Echaurren Norte Glacier“ => please introduce also the Piloto glacier and other glaciers under study in Argentina.
As mentioned above: since this study is about Chilean Glacier, we think it is more consistent to focus on Chilean glaciers in the intro. Again: suggestion of articles about Argentinean glaciers which you estimate of high relevance for our study are very welcome.

Page 2 line 29 : “the limited accumulation of snow is not able to make up with theablation processes” => If a glacier is present, this means that there was a time when the glacier had a positive SMB.
ok, we added: “During the monitoring period”
Page 4, line 17: “glacier melt at equator near Zongo Glacier” => Zongo Glacier is inBolivia, not at the equator.
Ok, we replaced “equator near” by “tropical”
Page 4, line 26-29: “in this study we want to test their ability to reproduce the individual energy fluxes” => This is relevant, but this is not really done in the paper. I suggest that authors compare each modelled and observed fluxes, with figures and statistics.
Modeled and observed fluxes are compared in Figures 5,6,7,8 and model parametrizations are compared to measurements in Figures 9 and 10. The only statistics that are computed up to now are overall mean values and daily mean values. Regarding the great similarity of the course of the melt rates observed in the Figures 6,7,8 we do not think that additional statistics (like correlations and standard deviations) would add some crucial new insights.
“we want to emphasize the differences between the model parameterizations and their ability to reproduce the directly measured radiative fluxes at the glacier surfaces” =>It is currently hard to conclude, because the authors use 3 very different models, with different assumptions on many variables (SWin, LWin, albedo, Ts, and turbulent heat fluxes). It would be easier to

force COSIMA with observations in order to produce a reference modelling, then make simplified EB-model and COSIMA approaches. An-other interesting way to reach conclusions would be to make a sensitivity analysis on COSIMA model.

We have chosen a very similar approach now: the reference database is composed of the measured radiative fluxes and turbulent fluxes based on measured surface temperature and using the stability correction which is implemented in COSIMA.

“We also compare three different parameterization for the turbulent fluxes of sensible and latent heat” => Here, the authors used different equations, in which stability calculations were simplified, but they also changed the values of Ts. It is thus really hard to conclude on comparisons.

Now the stability correction in the reference database and COSIMA are the same.

Section 2: Sites => please present different regions using a bulleted list and include here the paragraph which is currently in the introduction. Piramide, San Francisco and Bello glaciers should enter in the same region; Tyndall and Exploradores glaciers would be in the of Patagonia.

Ok!

Please remind in the text that Tyndall and Exploradores are calving glaciers.

Ok, we added that Tyndall and Exploradores glaciers experience some calving as well.

Section 3: Methods Page 5, Line 16: “to a very good approximation sum up to the melt energy available at the glacier surface” => Here and elsewhere in the text: please include values, scores, statistics.

Ok, we indicate the maximum difference between our simplified approach and the full COSIMA model now at the end of section 3.4 now.

Page 5, Line 18: Heat conduction and solar radiation transfer in the ice are neglected when they play a crucial role even in summer (See for instance Gürgiser et al., 2013).Please justify the choice of neglecting these fluxes. Are they considered in the COSIMAmodel?

Heat conduction through a solid is determined by two things: the thermal conductivity of the solid and temperature gradient. The thermal conductivity of ice is 2.1 W/(mK). The temperature gradient should be zero for the temperate glaciers of Patagonia where mean annual air temperatures are positive. This is also valid for the place on Mocho Glacier, where the energy balance is measured (Schaefer et al. 2017).

For the Glaciers in the Central Andes the temperature gradients in the ice should be small by January. Assuming an residual temperature gradient of 1 K/m the heat conduction into the ice would be 2.1 W/m², a small value in comparison to the other fluxes that were analyzed in our study.

Yes in COSIMA heat conduction is modeled, but for a more consistent comparison of the models we do not consider this fluxes in our study.

Section 3.1: could be included in sites. Please inform on potential data gaps, and data treatment. Please remove biases in the data (see point 1).

Data gaps and data treatment are commented in section 3.1. Bias was removed from the longwave radiation data.

Section 3.2 Reference database: I suggest that authors change the reference modelling as described in the introduction of my review.
Ok!

Page 7, line 7 : “The bulk aerodynamic approach is employed” => The bulk aerodynamic approach is not never fully used here. The methods used here are simplified approaches.
What do yo mean with “fully” used? To our understanding the bulk aerodynamic approach is a way of quantifying the turbulent fluxes by making three important assumption (which are stated in the manuscript). We are happy to get feedback from you in the case you are thinking that we forget to mention another important assumption of this approach.

Page 7 Line 14 : “T(s) is the temperature of the glacier-atmosphere interface, which is assumed to be 0◦C”=> Please use corrected LWout (using obleitner and deWolde(1999) approach) to compute Ts.
Ok.

Equation (2) : is only valid for neutral surface boundary layer and assuming that z0m =z0T = z0q, These points are suggested before in the text (see “the eddy diffusivity for heat has the same value as the eddy diffusivity for water vapor and the eddy viscosity”),but writing that the SBL is assumed to be neutral is more direct.
Ok we now added an indication to this assumption that it is associated to a neutral atmosphere

Page 7, line 22: “constant roughness length of z0=0.5mm” => please discuss this value because turbulent heat fluxes directly depend on it (they are twice larger if z0 is 10 times larger). z0 is expected to differ between snow and ice, and have very specific values over penitentes. There are many references proposing values assuming that z0= z0m = z0T = z0q. Another option would be to consider different z0m for snow and for ice, and then apply Andreas [1987] polynomials.
As indicated in the text, the value 0.5mm, which we chose for z_0 is an intermediate value which is in the range of recommended values for both smooth ice and snow surfaces (page 155, Cuffey&Paterson).

Figure 3a. I don’t understand why the authors don’t use (Goff, J.A., and Gratch, S.1946). Relationships.
Bolton(1980) seems to interpolate the measurements very well.
In Particular, the COSIMA relationship looks like erroneous.
You are right. This formula was implemented in the first version of COSIMA that we downloaded and was indicated in Huintjes et al. 2015a. But this seemed to be a bug which was changed now.
Moreover, I don’t understand why two curves are given above 0◦C (one for ice, and the other for snow), and only one below 0◦C, when it should be the reverse (saturation against solid or liquid phase makes sense below 0◦C).
All the curves are indicated below zero degrees as well, but the different parametrizations overlap for these temperatures, which is the reason why the three curves are not so easy to distinguish

Figure 3b. The differences are so large that the authors could calibrate a relationship between atmospheric emissivity, T and Rh, using their field data. They also could consider MacDonell et al., (2013) study. Section 3.3, EB-Model
Sorry, here we used an older version of the Graph where there was a problem with the units of P_vap to calculate the clearsky emissivity. The correct parametrization is shown now in the new graph and the different parametrizations are more similar now. The idea of this piece of work is not to derive new parametrizations but to test transferibility of parametrizations obtained at other glaciers.

Page8 Line 13: “the sum of the direct and diffuse incoming solar radiation” => Does EB-Model consider data from a DEM to compute Diffuse/direct components?
No, it considers only reflection from the surroundings in case of the installation of the AWS on a non-zero slope, where part of the slope should be visible for the sensor.
How is it computed in the case of overcast conditions?
Increased cloudiness increases the relative contribution of the diffuse radiation (see formulas (2),(5) and (6) in Brock and Arnold 2000).

Page 9 line 1: It seems strange to assume a constant albedo on a glacier, and snow patches, when solid precipitation occurred. It would be better to consider the albedo scheme from COSIMA.
The idea of this study is to test and compare the performance of different parametrizations. The COSIMA albedo scheme is validates against measurements on Mocho Glacier (Figure 9).

Page 9, Line 5: LWout= is 315.6 W/m2 => this assumption is really strong again. If you consider that melt is observed when values are maximum, then refreezing is observed at night in Figure 4 (except for Tyndall).

We agree. However this assumption is part of this model that we decided to test in this piece of work.

Page 9 line 10: "clear sky emissivity"=> again, validation of the equation may be easily done using field data.

Correct. This is what we are doing in section 5.2 (Figure 10)

Page 9 Line 12:" theoretically site-specific clear sky incoming solar radiation": how is it computed?

It is computed according to the formulas derived in Corripio, J.: Vectorial algebra algorithms for calculating terrain parameters from DEMs and solar radiation modelling in mountainous terrain,International Journal of Geographical Information Science, 17, 1–23,

Moreover, do the authors compute n with same equation in every models?Is it computed with equation 9?

Equation 9 is only used in the third method, EB-model has its own scheme and for method1 it is not necessary to calculate cloudiness, since the longwave radiation is directly measured.

Equations 7 and 8 or only for stable conditions, which are generally not verified in the morning.

During the measurements period air temperature is > 0 degrees Celsius also in the early morning, which should guaranty stability.

Why do they assume this, when computing a Richardson number is very easy when surface temperature is available? Please justify.

Again, in this study the primary goal is not to change the different assumptions made by the models employed but to show how these parametrizations vary between the model and what are consequences of this assumptions on the results.

Page 9 line 22: "the roughness Reynolds number (Brock and Arnold, 2000)." => you mean using Andreas (1987) polynomials?

Yes, reference added!

Page 9, Line 31 : "theoretical, site specific clearsky radiation computed by a code developed by Corripio (2003)"=> Do you mean SOLTRAN? Please give the exact reference.

A collection of codes are used in which the formula derived in Corripio (2003) are applied. These codes are written in IDL.

Page 10 Line 6: please cite : U.S. Army Corps of Engineers (1956).
We do not have access to this piece of work!

Page 10, Line 22: "However here SH is multiplied by a correction factor which depends on the bulk Richardson number Ri" => Please precise.
Ok. reformulated.
Why do the authors use this formulae instead of the bulk approach?
Again, here we use the parametrizations that are already implemented in the models.
In particular, the assumptions behind equation13 are not clear to me. Could they compute the turbulent heat fluxes offline using the bulk method and Ts, Tair, Rh, and U given by COSIMA and compare the results with COSIMA's turbulent heat fluxes?
Here it would be good to know what you call THE bulk method. To our understanding (and according to the authors of COSIMA), COSIMA IS using the bulk method. Perhaps it is using different stability corrections to the ones you are used to?

Section 4.1 : Glacier climate => please reformulate this title
Ok. Now we call this section: "Microclimatic conditions on the glaciers surfaces"

Table 3: I suggest that the authors make a bulleted list and first compare glaciers in the same region, and then compare glaciers at different locations. Please discuss the differences in altitude and surface state in a same region.
Ok. The formulation of this complete paragraph has been changed now following your suggestions.
Page 11, Line 15: "incoming longwave radiation increases from increased cloudiness in the Wet Andes." => elevation and temperature also play a key role here. In particular, differences in LWin between Bello, Piramide and San Francisco are largely related to temperature.
Ok, we mention this now.

Figure 4f: the surface at Tyndall glacier is constantly melting. This suggests that sensors are biased by a constant value of 15Wm-2. This bias seems to be retrieved on other glaciers (except on exploradores, where it seems to be even larger).
Ok, we removed the bias now!
Section 4.2: Page 13, Line 3: "we exclude Pirámide Glacier from" => Instead of removing this glacier, I suggest that authors compare with results on Pichillancahue-TurbioGlacier (Brock et al., 2007).
We do not have measured ablation data for Pirámide Glacier for the study period, which makes it impossible to compare with the results of Brock et al. 2007.

Page 13, Line 13: “The predicted melt rates are higher for Patagonian Glaciers as compared to the Glacier in the Central Andes” => This sentence does not make sense,melting rates depend on elevation. At 4000 m asl, melting is zero in Patagonia.
This is right, but this study is about comparing melt rates in the ablation area of the glaciers. We precised this in the text now.

Figure 6, 7 and 8: show that the big differences between the 3 models are observed inLWnet and SWnet, probably due to the very strong assumptions made on LWout and albedo variations. But if we analyse Table A1, the main differences are observed in the mean SH and LH values. I suggest that authors discuss this point.
A stability correction of the turbulent fluxes was applied now to in the reference database and the resulting fluxes are very similar to the ones predicted by COSIMA now. Differences between the fluxes obtained by the different models are discussed in section 5.2.

Page 15, Line 10: “although they have opposite exposition” => The studied surfaces are expected to be flat (no slope).
Yes, but the exposition of the glacier still can make a difference due to shading of the the high peaks which constitute the accumulation area of the glaciers.

Page 15, Line 16: “LWout detected on the glaciers are surprisingly higher than the expected 315.6 W/m2” => please correct biases in data before analysing the SEB.
Ok. We performed the bias correction now!
Caption of Figure 9: “albedo. In COSIMA the following parameters have been cho-sen: frsnow=0.8, firn=0.5, time constant t= 2 days, snow depth constant d= 8 cm (see equations (11) and (12)” => How did the authors calibrate these parameters?
By comparison with the measured (daily) albedo.

Page 17, Line 14 (and Page 18, Line 3): “At Exploradores Glacier the measured emissivity reaches values higher than one.”=> Please correct LWin before computing the emissivity.
Ok!
Page 18, Line 8 (and the end of the paragraph): “The variability of the modeled turbulent fluxes is very similar in all three methods[...] have very similar aspect: in all approaches the sensible heat flux is mainly driven by the temperature difference”=>please refer to Table A1. For instance, if we consider the Bello Glacier, SH is ranging from 6 to 30 W m-2 and LH from -23 to -53 Wm-2. Considering the sum of turbulentheat fluxes, SH+LH is ranging from -40 to +7 W m-2 . This maximum difference between the 3 models (47 W m-2) is larger than those observed in LWnet (22 W m-2)and in SWnet (15 W m-2). Perhaps I did not understand the

end of the paragraph, but the large difference in turbulent heat fluxes results from the very different assumptions done on Ts and on stability corrections.
Ok! Reformulated!

Section 5.3: melt rates: I propose that authors include a table to allow a quick validation between modelled ablation and observed ablation from stakes or sonic gauges. In thisTable, it would be interesting to include the elevation of ablation measurements, the latitude, the time period of measurements.
Thank you for this suggestion. Sadly we do not have ablation data for the modeled summers which is why we have to compare with data from different years and/or different glaciers. This is why we also are not able to judge the results of the different methods on the basis of the observed melt rate. In this sense it would be probably not correct to include a "validation table".

Page 18, line 23 :" observed melt range"=> "observed melt rates"
Ok!
Page 18, line 35: This comparison looks strange because Exploradores is located in campo de Hielo Norte, whereas Grey Glacier is located in Campo de Hielo Sur.
Again the comparison with the values measured at Grey Glacier are not meant as a "validation" of one special method. We just want to show that the high melt rate that we obtained with one of the methods for Exploradores Glacier is in the range of observed melt rates at Patagonian Glaciers at a similar elevation range. We indicate this more clearly in the manuscript now.

Page 19, Line 23: "The capacity of the models to reproduce the measured radiative fluxes is still improvable." => This conclusion looks strange when only 3 simple approaches are used. Please note that there is a large number of complex snow models and many complex experiments are done to improve these models (e.g., ESM-SnowMIP (Krinner et al., 2018).
This statement refers to the two models tested in this contribution and is detailed in the paragraph which follows the statement. Specially the difficulties to transfer model parameterizations for me is a clear indication that even if the energy balance models are trying to reproduce correctly the energy fluxes their parametrizations are based on measurements and they are therefor empirical and not physical . Model Intercomparison Studies like the one you are citing are very valuable but their conclusions are mostly similar to ours: individual model results can be far away from the reality, but, if I use a huge set of models, the average between all these models is mostly doing fine. But this is due to statistics and not due to good physics!

Page 19, Line 28 : “This is because the used parameterizations are fits to data that were obtained in different climatic conditions.” => This sentence seems trivial. I propose that authors calibrate their model with their observation, and then perform a model sensitivity analysis.
I am sure that the sentence is not trivial for all the readers of the Cryosphere. Indeed I have seen few publications of measurements of longwave radiative fluxes over glaciers. Again, the goal of this study is not to find THE best parametrization for every glacier (also we indicate them in Figure 10), but to test how transferable or “universal” are the parametrizations proposed in the tested models.

Page 19 Line 31: “Different parameterizations for the turbulent fluxes of sensible and latent heat were compared in this study,”=> because assumptions made on Ts and equations used were different in the 3 approaches, it is hard to conclude.
We agree with this statement. This is why we encourage direct measurements of turbulent fluxes over glacier surfaces to be able to better judge the different parameterizations.

Page 19 Line 33 (and page 20, Line 1): “There are many parameters involved in these parameterizations”=> I don’t agree, the bulk method only requires to define z0m.
In general there exist three different roughness lengths (z_0, z_H, z_T). Formulation was changed!

Page 20, second paragraph: “Bringing the predicted melt rates by these highly paameterized models in agreement with the observed ones seems to be rather a curve adjustment exercise than a indicator of correct physics.” => Perhaps this conclusion is real for EB-model and COSIMA, but I would not extrapolate this conclusion to all the SEB models.
The SEB models we know, all have a high quantity of non-physical parameters (because their parameterization stem from empirical fits to data).

Page 20, Line 18: “The inferred melt rates were higher for the Patagonian Andes than for the Central Andes.”=> it depends on elevation of study sites. Melt is zero in Patagonia at 4000 m asl.
Ok, we added: “in the ablation area of the glaciers”
Page 20, Line 20: “The models underestimated the measured emissivity of the clearsky atmosphere in the Wet Andes.”=> please correct LWin before concluding.
If we firstly “corrected” our model results according to the measurements, then the validation against the measurements would not make sense any more!

Page 20, line 23 : “To develop or improve physical models we have to validate every single model parameterization against data”=> this could be done in present study.

We DO it (for the radiative fluxes): for example red dashed line against blue line in Figure 9 or black lines against colored lines in Figure 10.