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1 **Downscaling MODIS-derived maps using GIS and boosted regression trees:**
2 **the case of frost occurrence over the arid Andean highlands of Bolivia**

3

4 **Pouteau R., Rambal S., Ratte J.P., Gogé F., Joffre R., Winkel T.**

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23

24 **Abstract**

25 Frost risk assessment is of critical importance in tropical highlands like the Andes where human
26 activities thrive at altitudes up to 4200 m, and night frost may occur all the year round. In these semi-
27 arid and cold regions with sparse meteorological networks, remote sensing and topographic modeling
28 are of potential interest for understanding how physiography influences the local climate regime. After
29 integrating night land surface temperature from the MODIS satellite, and physiographic descriptors
30 derived from a digital elevation model, we explored how regional and landscape-scale features
31 influence frost occurrence in the southern altiplano of Bolivia. Based on the high correlation between
32 night land surface temperature and minimum air temperature, frost occurrence in early-, middle- and
33 late-summer periods were calculated from satellite observations and mapped at a 1-km resolution over
34 a 45000 km² area. Physiographic modeling of frost occurrence was then conducted comparing multiple
35 regression (MR) and boosted regression trees (BRT). Physiographic predictors were latitude, elevation,
36 distance from salt lakes, slope steepness, potential insolation, and topographic convergence. Insolation
37 influence on night frost was tested assuming that ground surface warming in the daytime reduces frost
38 occurrence in the next night. Depending on the time period and the calibration domain, BRT models
39 explained 74% to 90% of frost occurrence variation, outperforming the MR method. Inverted BRT
40 models allowed the downscaling of frost occurrence maps at 100-m resolution, illustrating local
41 processes like cold air drainage. Minimum temperature lapse rates showed seasonal variation and
42 mean values higher than those reported for temperate mountains. When applied at regional and
43 subregional scales successively, BRT models revealed prominent effects of elevation, latitude and
44 distance to salt lakes at large scales, whereas slope, topographic convergence and insolation gained
45 influence at local scales. Our results highlight the role of daytime insolation on night frost occurrence at
46 local scale, particularly in the early- and mid-summer periods when solar astronomic forcing is
47 maximum. Seasonal variations and interactions in physiographic effects are also shown. Nested effects
48 of physiographic factors across scales are discussed, as well as potential applications of physiographic
49 modeling to downscale ecological processes in complex terrains.

50

51 **Key words**

52 altiplano; Andes; Bolivia; boosted regression trees; DEM; downscaling; frost risk mapping; MODIS;
53 physiography; temperature lapse rate; topoclimate model; satellite land surface temperature; seasonal
54 variation; spatial variation

55

56

57 1. Introduction

58 Low air temperature is one of the most important factors controlling vegetation zonation and key
59 processes such as evapotranspiration, carbon fixation and decomposition, plant productivity and
60 mortality in natural and cultivated mountain ecosystems (Chen et al., 1999; Nagy et al., 2003).
61 Depending on vegetation structure, landscape position or soil properties, frost can damage plant tissues
62 thus affecting forest, pasture and crop productivity (Blennow & Lindkvist, 2000). These damages have
63 consequences for human populations, particularly in the tropics where highlands often remain densely
64 populated (Grötzbach & Stadel, 1997). In the Andes of Argentina, Bolivia, Chile, Ecuador and Peru
65 agriculture thrives at altitudes up to 4200 m (Del Castillo et al., 2008) and treeline reaches its world's
66 highest elevation up to 5100 m (Hoch & Körner, 2005) in spite of night frost occurring on more than 300
67 days practically spread all over the year (Garcia et al., 2007; Gonzalez et al., 2007; Rada et al., 2009;
68 Troll, 1968). In the southern Andes, sparsely vegetated areas juxtaposing extended flat plains around
69 salt lakes and steep slopes on the cordilleras and volcanos, display semi-arid and desert landscapes
70 largely dominated by terrain structure. Subjected to the night/day and sunlit/shaded slope contrasts
71 characteristic of the mountain climate, this environment is well suited for examining the influence of
72 regional and landscape-scale physiography on the local climate regime, and particularly frost
73 occurrence.

74 Several studies on topoclimate in highlands showed that elevation and slope are the main
75 explanatory variables in modeling local climate spatial variability (Chuanyan et al., 2005). By means of
76 digital elevation models and astronomical equations, the potential insolation (incoming solar radiation)
77 has been included as an additional independent variable in some of these models, substantially
78 improving their capacity to predict free-air as well as soil-surface temperature distributions (Benavides
79 et al., 2007; Blennow & Lindkvist, 2000; Fridley 2009; Fu & Rich, 2002). Among the physiographic
80 variables, elevation and slope steepness are known to influence cold air drainage at night and, hence,
81 the distribution of frost risks at landscape scale (Lundquist et al., 2008; Pypker et al., 2007a). In the
82 daytime, slope aspect and physiographic shading effects control the effective radiation load per unit of
83 soil areas, resulting in very contrasted values of daily maximum soil temperature (Fu & Rich, 2002).
84 Minimum night temperature might be sensitive to insolation during the previous day, since soil surface
85 warming during that day could dampen soil radiative cooling in the next night. Though challenged by
86 studies on minimum air temperature variations in moderately high mountains under temperate climate
87 (Blennow 1998; Dobrowski et al., 2009), this hypothesis should be tested in the central part of the
88 Andes, where low latitude, high elevation (typically ranging between 3600 and 4200 m) and sparse
89 vegetation result in much greater radiation load and thermal contrasts across shaded and sunlit areas.
90 Besides, using a downscaling approach, Fridley (2009) noticed that the lack of relationship between
91 daytime radiation and nighttime temperature is true at local scale lower than 1000 m but not at regional
92 scale (Great Smoky Mountains, USA), where variations in radiation balance across locations do
93 influence nighttime temperature distribution particularly in cooler situations. Considering the Andes,
94 recent work by Bader & Ruijten (2008) and Bader et al. (2008) used topographic modeling and remote
95 sensing data to examine the response of vegetation distribution to climate warming, but we should go
96 back to Santibañez et al. (1997) and François et al. (1999) to find studies on the links between frost

97 climatology and physiography over this region. These early works were not continued, and the case of
98 the Andean highlands remained poorly documented in spite of the potential interest of that region,
99 densely populated and representative of the tropical mountains vulnerable to global warming (Vuille et
100 al., 2008).

101 Analyzing topographic effects on free-air or land surface temperature also led to reevaluate the
102 simplifying assumption of a generic environmental lapse rate (the decrease in free-air temperature as
103 elevation rises, typically assumed to be $-0.6\text{ }^{\circ}\text{C}$ per 100 m), commonly applied in hydrological and
104 ecological studies to extrapolate air temperature in mountain areas. In fact, several studies show
105 temperature lapse rate variations due to seasonality, height above the ground, or ground surface
106 characteristics (Blandford et al., 2008; Dobrowski et al., 2009; Fridley 2009; Lookingbill & Urban, 2003;
107 Marshall et al., 2007), though no detailed reports were published for the Central Andes.

108 Most of the above mentioned studies used multiple linear regression for modeling the influence of
109 physiography on free-air or soil-surface temperatures. The present study resorts to an advanced form of
110 regression, the boosted regression trees (BRT). BRT use the boosting technique to combine large
111 numbers of relatively simple tree models to optimize predictive performance. BRT have been used
112 successfully in human biology (Friedman and Meulman 2003), land cover mapping (Lawrence et al.,
113 2004), biogeography (Parisien & Moritz, 2009), species distribution (Elith et al., 2008), and soil science
114 (Martin et al., 2009). They offer substantial advantages over classical regression models since they
115 handle both qualitative and quantitative variables, can accommodate missing data and correlated
116 predictive variables, are relatively insensitive to outliers and to the inclusion of irrelevant predictor
117 variables, and are able to model complex interactions between predictors (Elith et al., 2008; Martin et
118 al., 2009). Though direct graphic representation of the complete tree model is impossible with BRT, the
119 model interpretation is made easy by identifying the variables most relevant for prediction, and then
120 visualizing the partial effect of each predictor variable after accounting for the average effect of the
121 other variables (Friedman & Meulman, 2003).

122 The aims of the present work were: i) to explore how regional and landscape-scale physiography
123 influence frost occurrence in Andean highlands through integration of field and remote sensing data,
124 digital terrain analysis, and GIS, ii) to downscale regional frost occurrence maps at a level relevant for
125 farming and land management decisions using BRT models. This study was focused on the austral
126 summer period, from November to April, when frost holds the greatest potential impact for local farming
127 activities.

128 **2. Material and methods**

129 *2.1. Study area and regional climate*

130 The study area was located at the southwest of the Bolivian highlands, near the borders of
131 Argentina and Chile, between $19^{\circ}15'$ and $22^{\circ}00'$ South and between $66^{\circ}26'$ and $68^{\circ}15'$ West. This
132 region, boarded by the western Andes cordillera, is characterized by the presence in its centre of a
133 ca.100 x 100 km dry salt expanse, the Salar of Uyuni, while another salt lake, the Salar of Coipasa, lies
134 at the north of the study area. The landscapes show a mosaic of three types of land units: more or less
135 extended flat shores surrounding the salt lakes (elevation ca. 3650 m) and an alternation of valleys and

136 volcanic relieves (culminating at 6051 m) in the hinterland. The native vegetation of this tropical Andean
137 ecosystem, also known as *puna*, consists of a mountain steppe of herbaceous and shrub species (e.g.
138 *Baccharis incarum*, *Parastrephia lepidophylla*, and *Stipa spp.*) (Navarro & Ferreira, 2007) traditionally
139 used as pastures but progressively encroached by the recent and rapid expansion of quinoa crop
140 (*Chenopodium quinoa* Willd.) (Vassas et al., 2008).

141 Due to its low latitude and high elevation, the study area is characterized by a cold and arid tropical
142 climate. Average precipitations vary between 100 and 350 mm year⁻¹ from the South to the North of the
143 region (Geerts et al., 2006), presenting an unimodal distribution with a dry season from April to October.
144 The annual average temperature (close to 9 °C) hides daily thermal amplitudes higher than seasonal
145 amplitudes, of up to 25 °C (Frère et al., 1978). These particular thermal conditions lead to high frost
146 risks throughout the year. Advections of air masses from the South Pole represent only 20% of the
147 observed frosty nights (Frère et al., 1978) and are four times less frequent in the summer than during
148 the winter, when the intertropical convergence zone goes northward (Ronchail, 1989). Therefore, the
149 main climatic threat lies in radiative frost, occurring during clear and calm nights. As reported by local
150 peasants, frost occurrence shows a strong topographical and orographical dependence, as well as a
151 marked seasonality. This seasonality lead us to split the active vegetation period into three time periods
152 characterizing the mean regional climate dynamics in the summer rainy season: November-December
153 when precipitation and minimum temperature rise progressively, January-February when precipitation
154 and temperature are at their maximum, and March-April when both begin to decrease.

155 2.2. Data

156 2.2.1. Meteorological ground data

157 In the study area, daily air temperature records were available in three meteorological stations: one
158 at Salinas de Garci Mendoza (19°38'S, 67°40'W) managed by the SENAMHI (Meteorology and
159 Hydrology National Service, Bolivia) where daily minimum air temperature (T_n) was recorded in 1989
160 and from 1998 to 2006, and two others at Irpani (19°45'S, 67°41'W) and Jirira (19°51'S, 67°34'W)
161 where meteorological stations set up by the IRD (Research Institute for Development, France) recorded
162 semi-hourly air temperature from 23 November 2005 to 18 February 2006 in Irpani, and from 6
163 November 2006 to 31 December 2007 in Jirira. This dataset was temporally and spatially insufficient to
164 interpolate frost risks at a regional scale, but it allowed to establish the relationship between air
165 temperature and remotely sensed land surface temperature.

166 2.2.2. Remotely sensed data

167 The two sensors, Terra and Aqua, of the satellite system MODIS give daily images of the Earth
168 radiative land surface temperature. Images from the fifth version of the MYD11A1 MODIS product were
169 concatenated and projected in the UTM-19S (Universal Transverse Mercator 19 South) coordinate
170 system using the MODIS projection tool. In this way, daily 1-km resolution images of the radiative land
171 surface temperature (T_s) over the study area were obtained. T_s images recorded by the Aqua sensor
172 around 2 a.m. were used as they were closer to the T_n data recorded at ground level and closer to the
173 true physiological conditions experienced by the vegetation (François et al., 1999). Time series of
174 nominal 1-km spatial resolution MODIS data were downloaded from NASA's EOS data gateway

175 (<https://wist.echo.nasa.gov/>) from 20 July 2001 to 25 April 2006 and from 01 January 2007 to 31
176 December 2007. Due to the particular surface properties of the salt lakes of Coipasa and Uyuni in terms
177 of surface moisture and radiative emissivity, parameter estimations were considered dubious there and
178 Ts data for the salt lakes were discarded from the analysis. This database was managed and analyzed
179 using the ENVI 4.2. software (ITT Visual Information Solutions, www.itvis.com). The statistical
180 correspondence between Tn data recorded in the meteorological stations of Salinas, Irpani and Jirira
181 and Ts data of the pixels including these three localities was examined by linear regression and
182 Pearson correlation.

183 Apart from Ts measurements during clear nights, MODIS images also bring information about the
184 possible presence of clouds between the Earth surface and the satellite at the time of the record. The
185 information of these “flagged” images is valuable for our purpose since radiative frost would not occur
186 during cloudy nights. The frequency of cloudy pixels in the daily MODIS images was thus calculated
187 and used in the frost occurrence calculation (see below).

188 *2.2.3. Digital elevation model and physiographic predictors*

189 The SRTM digital elevation model (Farr et al., 2007) with a 90 m horizontal resolution and a
190 vertical accuracy better than 9 m was used after resampling to 100 m to make easier the
191 correspondence between the digital elevation model and the MODIS images at 1-km scale. In a GIS
192 environment using Idrisi Kilimanjaro, Envi 4.2. and ArcMap 9.2. softwares, eight physiographic variables
193 were calculated at a 100-m resolution for each location to examine their potential role in the spatial
194 determinism of frost and to downscale frost maps to levels closer to those of frost impacts on anthropic
195 activities (Table 1). The compound topographic index (CTI) was used as an index of cold air drainage
196 (Gessler et al., 2000), with low CTI values representing convex positions like mountain crests and with
197 high CTI values representing concave positions like coves or hillslope bases. Three insolation variables
198 (DPI, MPI and API) were calculated by the ArcMap 9.2. solar analysis tool. They express the amount of
199 radiative energy received across all wavelengths over the course of a typical seasonal day (DPI), or
200 from sunrise to 12:00 (MPI), or from 12:00 to sunset (API) of such a day.

201 These insolation variables account for site latitude and elevation, slope steepness and aspect,
202 daily and seasonal sun angle, and shadows cast by surrounding heights. API was calculated to
203 examine the specific influence of insolation in the afternoon just before the considered night, with the
204 hypothesis that high soil surface insolation and warming would affect the soil energy balance, and thus
205 reduce the risk of radiative frost in the following night (without regards to other potential factors such as
206 soil albedo, soil water content, air humidity, etc. see Garcia et al. (2004)). Similarly, MPI was calculated
207 as a surrogate to the early morning insolation, with the hypothesis that areas in the shade of
208 surrounding heights in the early morning would experience cooler conditions for a longer time, thus
209 being more vulnerable to frost than sunlit areas. In the calibration procedure, these 100-m resolution
210 variables were upscaled at 1-km resolution by averaging 10 x 10 pixel clusters in the DEM 100-m
211 images, thus fitting the 1-km resolution of the remotely sensed frost occurrence maps.

212

213

214 **Table 1.** Ranges of physiographic variables observed over the study area.

Variable	Minimum	Maximum	Unit
LAT latitude in UTM 19 South	-22.00	-19.24	decimal degree
ELE elevation	3540	6051	m
SLO slope steepness	0	35	degree
DPI daily potential insolation			
Nov-Dec	6900	9075	W m ⁻²
Jan-Feb	7040	8935	W m ⁻²
Mar-Apr	4604	7897	W m ⁻²
MPI morning potential insolation			
Nov-Dec	510	1861	W m ⁻²
Jan-Feb	466	1772	W m ⁻²
Mar-Apr	264	1240	W m ⁻²
API afternoon potential insolation			
Nov-Dec	2819	5075	W m ⁻²
Jan-Feb	2816	5000	W m ⁻²
Mar-Apr	2079	4308	W m ⁻²
LDS distance from salt lakes	0	5.04	Ln (km + 1)
CTI compound topographic index	5.7	14.1	-

215

216 *2.3. Physiographic modeling of frost occurrence over regional and subregional domains*

217 *2.3.1. MODIS-derived frost occurrence*

218 Frost is detected by remote sensing when surface temperature appears negative on cloudfree
 219 images. Based on the standard meteorological threshold of 0 °C, frost occurrence (R) for a specific time
 220 period was therefore defined as follows:

221

222 $R = Prob(T_s < 0\text{ }^{\circ}\text{C}) * F$ (1)

223

224 where: R = frost occurrence at the 0 °C threshold (relative probability ranging from 0 to 1), *Prob* ($T_s < 0$
 225 °C) = probability of the surface radiative temperature being lower than 0°C, F = frequency of cloudless
 226 days in the considered period. Note that “frost occurrence” is used here instead of frost risk to
 227 differentiate our estimates based on 6-year daily T_s values from climatological estimates based on
 228 longer data series.

229 In order to calculate the probability *Prob* ($T_s < 0\text{ }^{\circ}\text{C}$), the distribution of the random variable T_s
 230 during successive time periods (namely: November-December, January-February, March-April) was
 231 studied, checking its normality through the Kolmogorov-Smirnov test. For each 1-km pixel and each
 232 time period, T_s mean and standard deviation, cloudless day frequency (F) and, finally, frost occurrence

233 (R) were calculated from the available nighttime remotely sensed data series (n = 366 , 355, and 361 in
234 the ND, JF and MA periods respectively). Maps of observed (remotely sensed) frost occurrence at 1-km
235 resolution were then generated by applying Eq. (1) for each time period.

236 2.3.2. Frost occurrence models over regional and subregional domains

237 A subsample of 1-km pixels (n = 7500) was randomly selected for the calibration of the
238 physiography-frost occurrence relationships over the entire study area (hereafter called "regional
239 models"). Regional BRT were built for each seasonal period (November-December, January-February,
240 March-April) using the *gbm* package version 1.6-3 developed under R software (R Development Core
241 Team 2006). A bag fraction of 0.5 was used which means that, at each step of the boosting procedure,
242 50% of the data in the training set were drawn at random without replacement. The loss function (LF),
243 defining the lack-of-fit, used a squared-error criterion. The learning rate or shrinkage parameter (LR),
244 the tree size or tree complexity (TS), the number of trees (NT) and the minimal number of observations
245 per terminal node (MO) were the main parameters for these fittings, and were set through a tuning
246 procedure (Martin et al., 2009). LR, determining the contribution of each tree to the model, was thus
247 taken equal to 0.05. NT, the maximal number of trees for optimal prediction was set to 2000. For
248 optimal prediction, TS, the maximal number of nodes in the individual trees, was set to a value of 9, and
249 MO was set to 10 observations per terminal node. For sake of comparison, multiple linear regression
250 models were calculated at the regional scale using the same predictors and the same calibration
251 datasets as for the regional BRT. These " regional MR" were built using the Statistica package (StatSoft
252 France 2005).

253 The regional BRT and MR models were validated comparing observed (remotely sensed) and
254 predicted frost occurrence over the entire study area in the three time periods. This was made
255 excluding the pixels used for calibration, which resulted in a 49353 pixels validation set. The predictive
256 capacity of the models was analysed examining the observed versus predicted values plots, the bias
257 (B), the root mean square error of prediction (RMSE), and the coefficient of determination of the
258 regression between estimated and observed values (R^2). Once validated, the BRT were interpreted,
259 looking first at the relative contribution of the physiographic variables to the predictive models, and then
260 considering the partial dependence of the predictions on each variable after accounting for the average
261 effect of the other variables.

262 In order to test the scale-dependence of the predictors, a similar BRT procedure was applied over a
263 smaller spatial domain defined by a selected range of regionally varying factors, namely: latitude
264 between 19°5 and 20° South and elevation lower than 4200 meters (total area = 7775 km²). This spatial
265 domain corresponds to the *Intersalar*, the area of major agricultural activities in the region, where local
266 populations cultivate quinoa and rear camelids up to an altitude of ca. 4200 meters. A new set of 7500
267 training pixels was randomly selected from this smaller domain to calibrate these "subregional BRT",
268 using the same values of fitting parameters and a similar validation procedure as in the previous
269 analysis. Excluding the training pixels, this validation was conducted on the remaining 275 pixels of this
270 smaller domain. The relative contribution of the physiographic predictors to the subregional models was

271 also examined. The interactions between predictive variables were considered by joint plots of their
272 partial dependence in the subregional models.

273 2.3.3. Downscaling frost occurrence prediction at 100-m resolution

274 Once validated, the regional BRT were applied on each pixel of the DEM 100-m image in order to
275 downscale frost occurrence from 1-km to 100-m resolution in the three considered time periods. An
276 indirect validation of these 100-m frost occurrence maps was then conducted by aggregating 10 x 10
277 pixel clusters of 100-m frost predictions and comparing the resulting 1-km predictions to the observed
278 (remotely sensed) frost occurrence at 1-km resolution. A qualitative validation was also conducted by
279 examining the capacity of these 100-m maps to display well-known local patterns of frost and cold air
280 distribution over complex terrains.

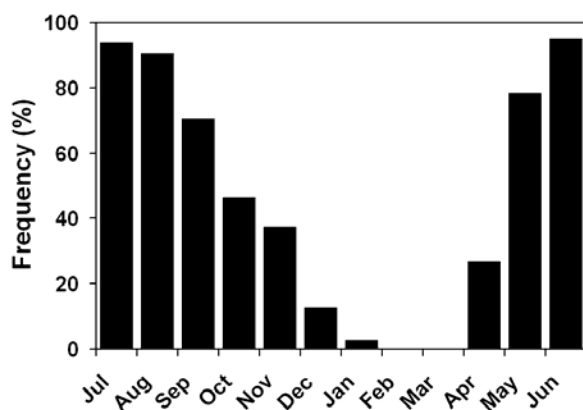
281 2.3.4. Estimation of the land surface temperature lapse rate

282 The regression of T_s recorded over sloping areas *versus* elevation of the corresponding pixels
283 allowed to calculate average values of the land surface temperature lapse rate at night for successive
284 dates in each considered time periods. Sloping areas were defined as terrains with slope steepness
285 greater than 3° and elevation lower than 5000 meters. This elevation limit was chosen to discard high-
286 altitude sites possibly covered with snow or ice which superficial thermal properties modify lapse rate
287 estimations (Marshall et al., 2007). The resulting sampling area represented 22529 km², covering an
288 elevation range of 1341 m (from 3659 to 5000 m).

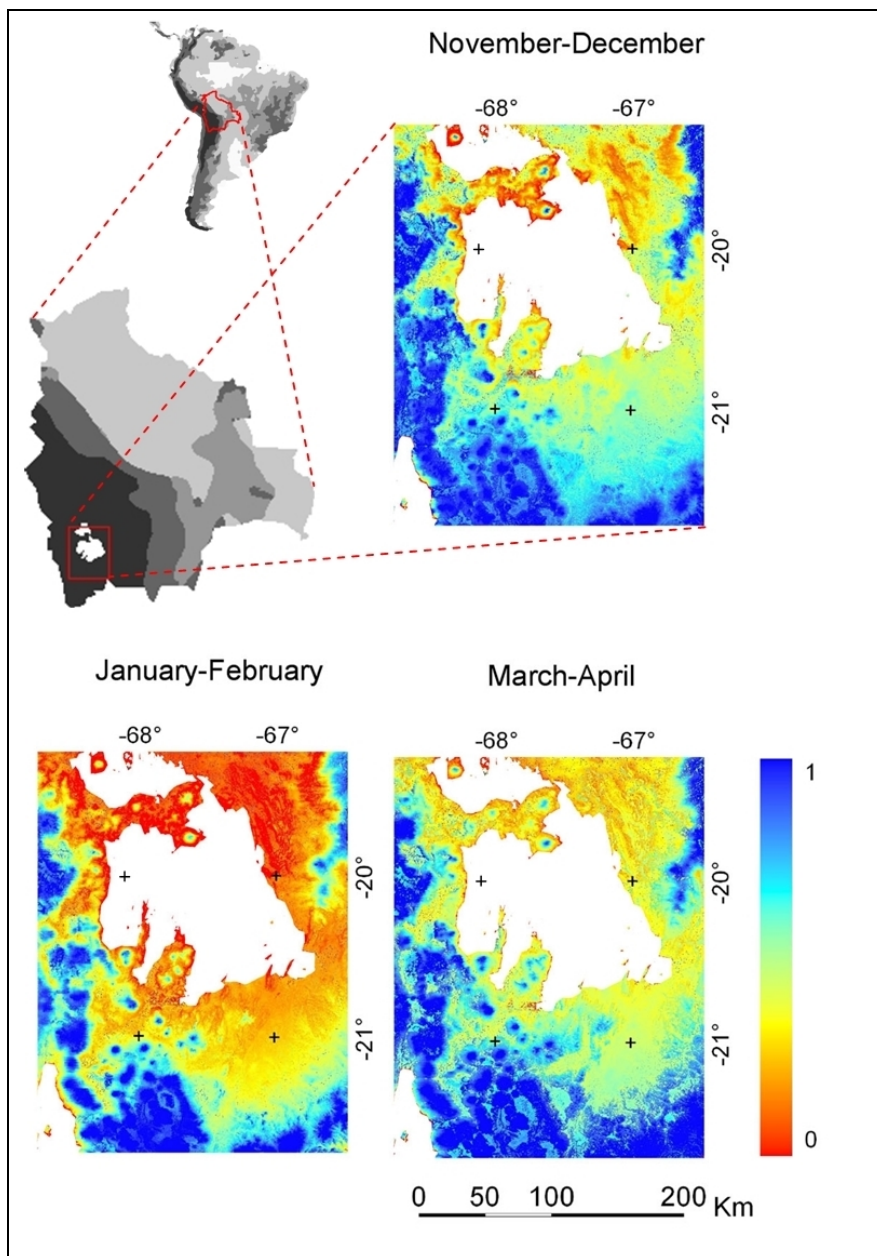
289 3. Results

290 3.1. Climate information and remotely sensed frost occurrence evaluation

291 The frequency analysis of daily minimum air temperature (T_n) recorded at Salinas over 10
292 discontinuous years (1989, and the 1998-2006 period) was made using the standard climatological
293 threshold of 0°C (Fig. 1).



294
295 **Fig. 1.** Frequency analysis of daily minimum air temperatures lower than 0°C registered at Salinas in
296 1989 and from 1998 to 2006.



297

298 **Fig. 2.** One-kilometer resolution maps of MODIS-derived frost occurrence in southern Bolivia in three
 299 successive time periods (the color scale at the right shows the frost probability)

300 During the austral summer (November-April), two periods of frequent below zero temperatures
 301 surround a ca. 80-day time interval of low frost occurrence, from the beginning of January to the end of
 302 March.

303 Daily T_n values recorded at screen height by the meteorological stations of Salinas, Irpani and Jirira
 304 were highly correlated to T_s data remotely sensed over these three localities at night by the MODIS
 305 satellite ($T_n = 0.97 \cdot T_s + 0.93$, $R^2 = 0.81$, $n = 750$). The percentage of cloudy pixels on the MODIS
 306 images gives a general information about the seasonal pattern of cloud cover in the study area: the
 307 January-February period was the most overcast with on average $46 \pm 8.2\%$ of the study area masked
 308 by clouds in each daily satellite image, while this percentage fell to $30 \pm 7.4\%$ and $29 \pm 6.6\%$ in the
 309 November-December and March-April periods respectively. The test of Kolmogorov-Smirnov applied to

310 the Ts data series was statistically significant in all the cases ($P < 0.05$). This allowed to apply a normal
311 probability density function in equation (1) in order to generate the 1-km resolution maps in Fig. 2
312 showing the regional patterns of frost occurrence variations in three successive time periods as derived
313 from satellite observations.

314 3.2. *Physiographic modeling of frost occurrence*

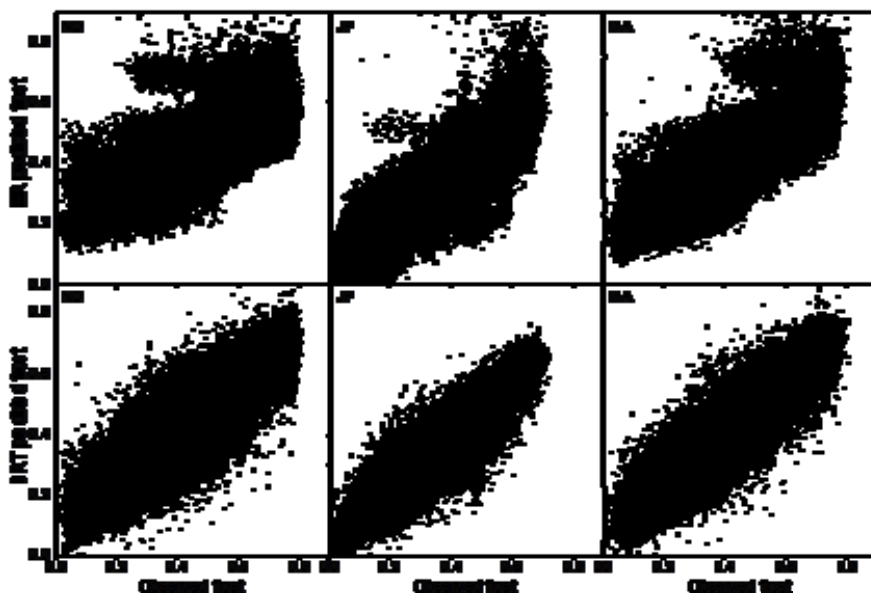
315 3.2.1. *Model validation of regional and subregional BRT models*

316 The results of the statistical comparison between observed and predicted frost occurrence at 1-km
317 resolution in three time periods are presented in Fig. 3 and Table 2. The regional BRT clearly
318 outperformed the MR models, the latter being affected by strong non linearities in the high frost
319 occurrence range, showing its poor predictive capacities in the early and late summer periods. On the
320 other hand, the regional BRT negligibly overestimated the satellite observations with practically no bias
321 whatever the time period. The RMSE and R^2 values showed that BRT predictions were fairly good in
322 January-February (RMSE = 0.057, $R^2 = 0.90$), and only slightly more dispersed by the beginning or the
323 end of the summer season (RMSE between 0.07 and 0.08, R^2 between 0.78 and 0.83). With an error
324 generally less than 8% on predicted frost occurrence values, the regional BRT thus appear suitable for
325 predicting frost occurrence from physiographic variables alone. Table 2 shows similar performances of
326 the regional and subregional BRT, with only higher bias for the subregional model.

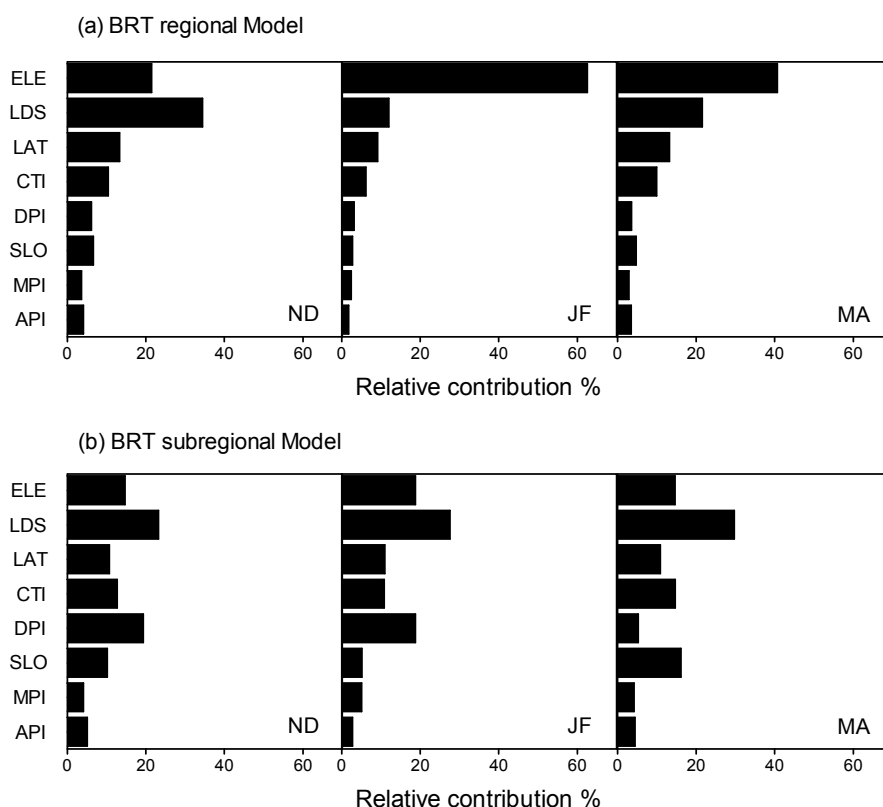
327 3.2.2. *Hierarchy of physiographic variables in regional and subregional BRT*

328 Regional BRT showed large effects of elevation, distance from the salt lakes, latitude and CTI on
329 frost occurrence, while slope and insolation variables had only marginal influence (Fig. 4a). Comparing
330 the three time periods, the relative contributions of the predictive variables showed some variations,
331 with the distance from the salt lakes dominating in the initial period (November-December), while
332 elevation became more important from January to April, and particularly in the mid-summer period. In
333 contrast, latitude, CTI and insolation variables kept a fairly constant effect with similar contributions at
334 the beginning and at the end of the season. Calibrating BRT models over a limited spatial domain
335 reveals slightly different patterns in the contributions of the predictors (Fig. 4b): distance from the salt
336 lakes gained importance on elevation in the three time periods, and daily potential insolation showed
337 noticeable contribution until mid-summer (though the influence of its morning and afternoon
338 components remained marginal). The weights of CTI and latitude were intermediate whatever the time
339 period, while the contribution of slope became important by the end of the season.

340



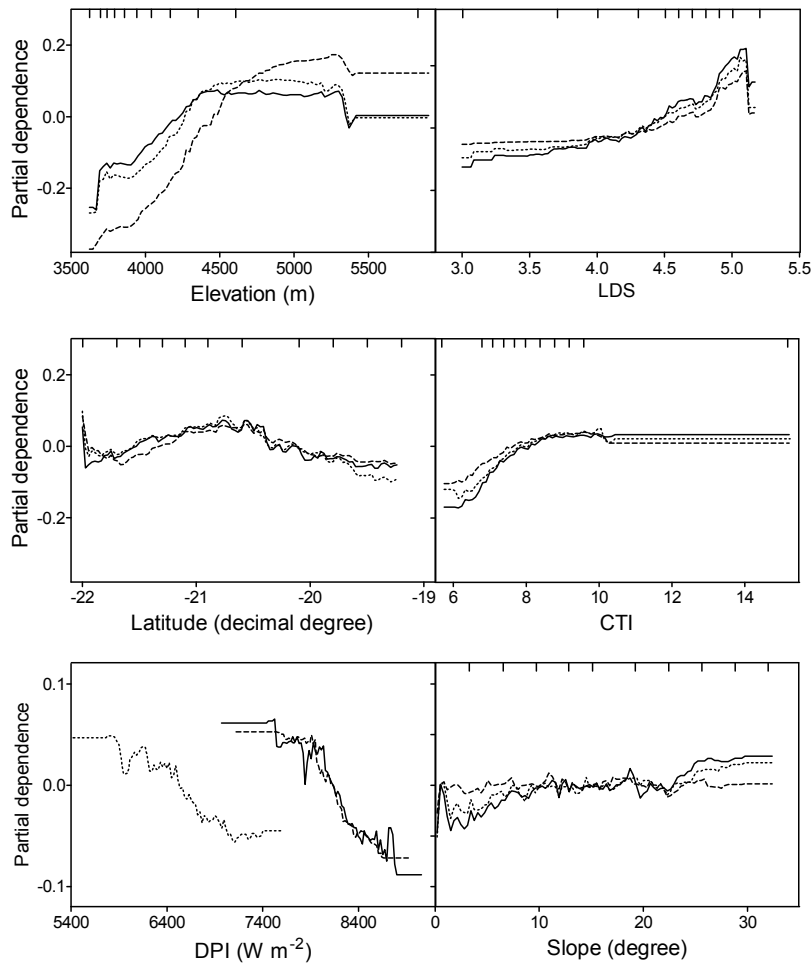
341
 342 **Fig. 3.** Comparison of frost occurrence values observed in three time periods with frost occurrence
 343 predicted by the MR (multiple regression) and BRT regional models (ND = November-December; JF =
 344 January-February; MA = March-April, n = 49353 in each time period)



345
 346 **Fig. 4.** Relative contributions of the physiographic variables in the regional (a) and subregional (b) BRT
 347 in three time periods. (ND = November-December; JF = January-February; MA = March-April; see
 348 Table 1 for variables abbreviations)

349 3.2.3. Partial dependence in regional and subregional BRT

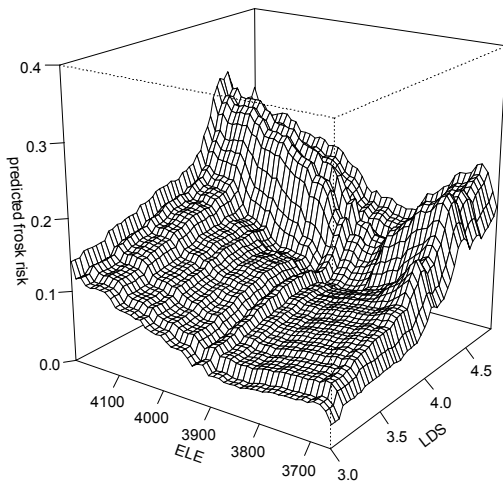
350 The plots of partial dependence for frost occurrence in the regional BRT (Fig. 5) indicate that frost
351 events in the study area occur mostly at high and medium latitude, increase continuously up to 4500 m
352 elevation, and are more frequent far away from the salt lakes. Concave positions (high CTI values) are
353 more prone to frost, and low daily potential insolation in those shaded areas also increases frost
354 occurrence at night, though separating the morning and afternoon components of the daily insolation
355 gives opposite results (data not shown). The dependence of frost occurrence on slope steepness
356 remained fairly constant. These partial responses of frost occurrence to the most active physiographic
357 variables show only limited seasonal changes.



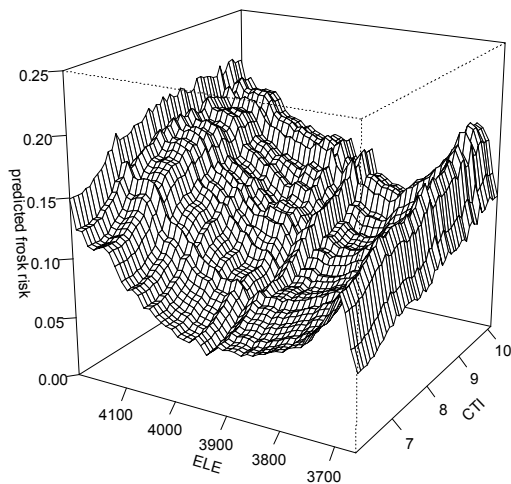
358
359 **Fig. 5.** Partial dependence plots of the six most influential physiographic variables in the regional BRT
360 in three time periods (continuous line: November-December, dashed line: January-February, dotted
361 line: March-April; ticks at the inside top of the plots show deciles of site distribution across the variable;
362 see Table 1 for variables abbreviations).

363 More details emerge from the partial dependence plots of interactions in subregional BRT (Fig. 6
364 illustrating the January-February period, with similar results in the other two periods). For instance, up
365 to a distance of 10 km from the salt lakes (LDS \approx 4.0) the effect of elevation on frost occurrence is low
366 and nearly constant below 3900 m, and then rises gradually above that level. But farther than 10 km

367 away from the salt lake borders, frost occurrence first decreases as elevation rises up to 3900 m and
368 then increases sharply above. This suggests that thermal inversions at night are more frequent at
369 distance from the salt lakes. Considering the interaction of elevation with CTI, while frost occurrence at
370 low elevation increases gradually up to CTI values of 9 and more sharply thereafter (concave
371 situations), at high elevation the effect of CTI is already important at values below 8 and then rose only
372 marginally. The effect of landscape concavity thus appears prominent at low elevation, where cold air
373 can accumulate in local depressions, while it becomes negligible at high elevation where crests and
374 peaks dominate.



375



376

377 **Fig. 6.** Joint partial dependence plots of some interactions between topographic variables in the
378 subregional BRT of the January-February period (see Table 1 for variables abbreviations).

379

380 **Table 2.** Validation statistics of frost occurrence multiple regression (MR) and boosted regression trees
 381 (BRT) models calibrated over the entire study area (regional models) or the Intersalar area (subregional
 382 models). B: bias; RMSE: root mean square error of prediction; R²: determination coefficient of the
 383 regression line between observed and predicted values. ND = November-December; JF = January-
 384 February; MA = March-April.

385

Calibration procedure	Period	B	RMSE	R ²
Regional MR (n = 49353)	ND	2.7 10 ⁻⁵	0.129	0.45
	JF	2.1 10 ⁻⁴	0.093	0.72
	MA	8.5 10 ⁻⁴	0.110	0.59
Regional BRT (n = 49353)	ND	1.7 10 ⁻⁵	0.082	0.78
	JF	0.5 10 ⁻⁵	0.057	0.90
	MA	0.6 10 ⁻⁵	0.071	0.83
Subregional BRT (n = 275)	ND	2.9 10 ⁻⁵	0.062	0.80
	JF	1.4 10 ⁻³	0.031	0.82
	MA	2.9 10 ⁻³	0.049	0.82

386

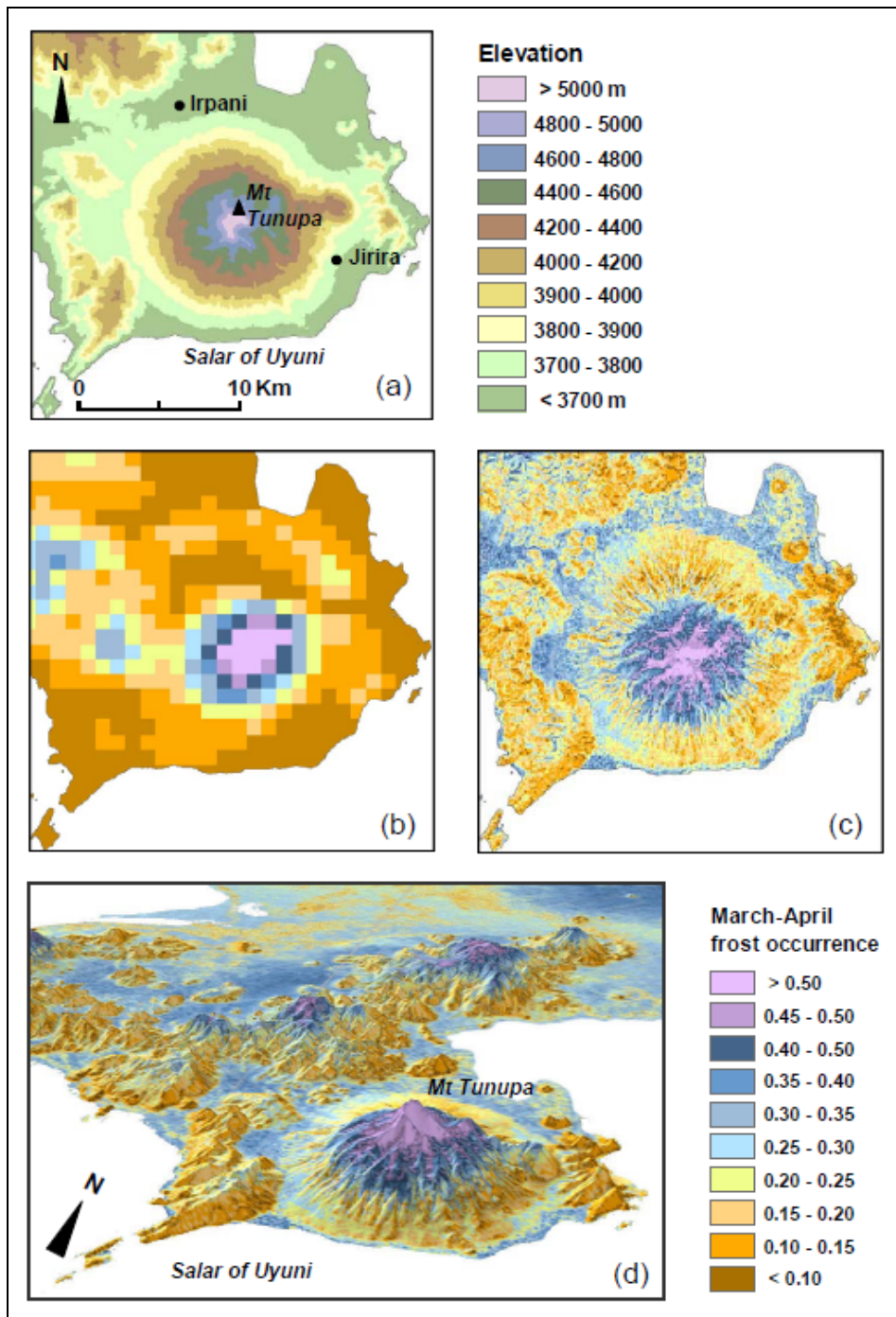
387 3.3. Fine resolution frost occurrence maps

388 Regional BRT were used in prediction to downscale frost occurrence maps from the 1-km to the
 389 100-m scale. The statistical validation conducted on reaggregated 1-km pixel clusters shows good fit
 390 between predicted and observed (remotely sensed) frost occurrence values (Table 3), with RMSE of
 391 predicted values of the same order than in the BRT regional model directly applied at the 1-km
 392 resolution (Table 2). The 100-m scale maps display topoclimatic variations resulting in a detailed
 393 zonation of frost occurrence. As an example, Fig. 7c-d shows that flat areas surrounding Mount Tunupa
 394 are more prone to frost occurrence than the slopes of the volcano up to an elevation of approximately
 395 4000 m, while sites located at higher altitudes are naturally colder. All over this area, east-facing slopes
 396 appear less exposed to frost than west-facing slopes. In some particular places at the west, cold air
 397 stagnation is also identifiable in the lower parts of local depressions. Such details were not visible on
 398 the 1-km resolution map (Fig. 7b).

399 **Table 3.** Statistical comparison of 100-m frost occurrence predictions reaggregated at 1-km with
 400 observed 1-km frost occurrence values (n = 49353). B: bias; RMSE: root mean square error of
 401 prediction; R²: determination coefficient of the regression line between observed and predicted values.
 402 ND = November-December; JF = January-February; MA = March-April.

Period	B	RMSE	R ²
ND	0.0252	0.0925	0.74
JF	0.0008	0.0644	0.87
MA	0.0543	0.0945	0.80

403



404
 405 **Fig. 7.** Elevation map of the Mount Tunupa area (a), and frost occurrence in the March-April period
 406 mapped at 1-km resolution from MODIS observations (b), at 100-m resolution (c) and in 3-D view using
 407 regional BRT (d). Frost occurrence is scaled between 0 and 1 as the probability of daily occurrence of
 408 negative T_s values in the March-April period.

409

410 3.4. Lapse rate estimation

411 Table 4 shows significant seasonal variations in the average lapse rate in land surface night
 412 temperature calculated over the study area, with statistically stronger values in the mid-summer period
 413 (-0.64 °C/100 m) in comparison with the beginning or the end of the season (ca. -0.60 °C/100 m). The

414 linear relationship between elevation and temperature was also greater in mid-summer compared to the
415 other two periods. The spatio-temporal variability in lapse rates was high since the coefficients of
416 variation were between 24 and 35% in the successive time periods, with lower variation in the mid-
417 summer.

418 **Table 4.** Descriptive statistics of lapse rates of land surface temperature at night in three successive
419 time periods.

Period	Mean (°C/100 m)	Coefficient of variation (%)	Coefficient of determination	Sample size
November - December	-0.609	35.5	0.50	366
January - February	-0.642	24.3	0.68	355
March - April	-0.598	29.8	0.56	361

420

421 **4. Discussion**

422 The present study provides the first application of MODIS products to characterize frost occurrence
423 over a 45000 km² area in the Andean highlands. Frost occurrence over the summer period was either
424 calculated directly from land surface temperature remotely sensed at a 1-km scale, or estimated and
425 downscaled at 100-m by means of physiographic modeling. To our knowledge this is also the first
426 application of BRT in physiographic modeling. Both techniques are complementary in characterizing
427 frost occurrence: remote sensing brings spatialized and repetitive information on land surface
428 temperature and physiographic features, while BRT allow to explore the relative contribution of
429 physiographic factors at various scales and, hence, to downscale satellite information to a level
430 appropriate to farming and land management applications.

431 *4.1. Application of remote sensing data for frost occurrence characterization*

432 As pointed by François et al. (1999) at least three factors may potentially affect the relation between
433 Ts and Tn records: a difference in time (ca. 6 a.m. for minimum night air temperature versus 2 a.m. for
434 satellite radiative temperature), a difference in height (1.5 m above the soil surface for meteorological
435 data versus land surface temperature for satellite data), and a difference in spatial resolution (ca. 100
436 m² footprint for local meteorological data versus 1 km² for satellite data). In spite of this, these authors
437 observed only a stable shift of some degrees between Tn records in the Bolivian altiplano and Ts
438 registered at 2 a.m. with a 1-km spatial resolution by the NOAA/AVHRR satellite. A similar result was
439 found in the present study showing a linear and highly significant correlation of MODIS land surface
440 temperature at night with minimum air temperature recorded in meteorological stations ($R^2 = 0.81$).
441 However, this validation may be biased since, as in most mountain areas in the world, the available
442 meteorological records are likely not representative of the most elevated and isolated parts of the study
443 area. Regarding the MODIS satellite, recent studies have improved and validated its calibration
444 algorithm for land surface temperature in various situations encompassing Bolivian highlands, semiarid
445 and arid regions, or nighttime/daytime overpasses (Wan, 2008; Wang et al., 2008). This ensures the
446 reliability of MODIS temperature data in the study area in spite of its specific location in cold and arid
447 tropical highlands. After verifying for the normality of the distribution of Ts data, the probability of frost

448 occurrence can be easily calculated from the available satellite data series (eq. (1)). It should be noted
449 that the available series of 6-year daily records was long enough to statistically characterize frost
450 occurrence at the standard meteorological threshold of 0 °C, but not at lower temperature levels due
451 the scarcity of observations of severe frost events over the considered period. Frosts at -4 or -7 °C
452 would, however, be more relevant for agroclimatic purposes since they correspond to the frost tolerance
453 levels of major Andean crops such as potato and quinoa (Bois et al., 2006; Garcia et al., 2007; Geerts
454 et al., 2006; Jacobsen et al., 2005). This limitation should progressively disappear as the MODIS
455 archives grow and allow for the statistical evaluation of less frequent (and more severe) frost events.

456 *4.2. Spatial and temporal patterns of frost occurrence*

457 *4.2.1. Frost occurrence as affected by regional physiography and climate seasonality*

458 The frost occurrence maps derived from MODIS data at 1-km resolution (Fig. 2) clearly show the
459 influence of regional-scale physiography like the mountain distribution or the proximity of the salt lakes,
460 as well as the seasonal variation of frost occurrence over a 6-month period. In their attempt to map
461 agroclimatic suitability in the Bolivian altiplano, Geerts et al. (2006) notice that frost risk is difficult to
462 interpolate spatially. Nevertheless, based on data from 41 ground climatic stations of the altiplano, they
463 achieve a description of regional frost risk patterns that are globally confirmed by our satellite maps,
464 with lower frost probabilities in the Intersalar region and higher probabilities at the south-west of the salt
465 lake of Uyuni. Geerts et al. (2006) also mention that their kriging interpolation was improved by
466 incorporating a WNW anisotropy due to the combined north-south influence of the Lake Titicaca and the
467 west-east effect of zonal winds. These zonal winds affect the entire altiplano and largely control the
468 synoptic weather types (Garreaud et al., 2003). As demonstrated in other cold regions or mountain
469 areas in the world (Blandford et al., 2008; Dobrowski et al., 2009; Marshall et al., 2007), the occurrence
470 and spatial patterns of the zonal winds could be important drivers of the seasonal variation in land
471 surface temperature and temperature lapse rate found in the study area.

472 Another driver of frost seasonality is cloud cover which, in a typical tropical unimodal rainy season,
473 results in progressive overcasting at the beginning of the rainy season, maximum cloud cover in the
474 mid-season, and then progressive decrease by the end of the season. This cloud cover pattern is
475 recorded daily at the 1-km scale by the MODIS satellite and was integrated in the calculation and
476 mapping of frost occurrence (equation 1, Fig. 2).

477 The seasonal change in sky cloudiness also influences temperature lapse rates. Blandford et al.
478 (2008) thoroughly discuss the effect of seasonal and synoptic conditions on lapse rate calculated for
479 average or daily extreme values of near-ground temperature in temperate mountains. They outlined that
480 minimum temperature lapse rate are shallower when air masses are dry and cold, which is explained by
481 increased frequency of cold air drainage and temperature inversions under clear-sky and dry air
482 conditions at night. Minimum temperature lapse rate values are also more variable during seasonal
483 transition between summer and winter, due to fluctuating weather regime at that time and higher
484 frequency of temperature inversions. Our estimates of minimum temperature lapse rate in successive
485 time periods (Table 4) are consistent with both assertions, showing steeper and less variable values in
486 mid-summer (January-February) when the sky is more cloudy and air conditions are relatively humid,

487 temperate, and stable. These estimates approximating $-0.6\text{ }^{\circ}\text{C}/100\text{ m}$ appear fairly high compared to
488 minimum temperature lapse rate values, typically ranging from -0.15 to $-0.35\text{ }^{\circ}\text{C}/100\text{ m}$, in mountains
489 of mid-latitude regions (Blandford et al., 2008; Dobrowski et al., 2009; Harlow et al., 2004). In
490 subtropical mountains however, De Scally (1997) states that, due to their high thermal regime, the
491 temperature lapse rate is generally higher than in mid-latitude mountains. The high lapse rate values
492 thus quoted for the Himalaya (De Scally, 1997) or the Andes (Frère et al., 1978; Snow, 1975 cited by
493 Pielke & Mehring, 1977; Trombotto et al., 1997) refer unfortunately to mean daily or mean annual
494 temperatures which cannot be compared directly to our estimates of minimum temperature lapse rates
495 in specific time periods.

496 Astronomic forcing is another cause of seasonality in the topography-frost relationship, explaining
497 why topographic controls, usually treated as stationary, show actually pronounced seasonal variations,
498 as pointed by Deng et al. (2007) in the case of topography-vegetation relationships. In our study,
499 seasonal changes in the effects of slope steepness and aspect on frost occurrence are illustrated by
500 varying SLO and DPI contributions (Fig. 4b). They are explained by astronomical forcing resulting in
501 insolation values in the early and mid-summer higher by 25% in average than in the late-summer period
502 (see Table 1), thus giving higher influence of DPI over SLO in the former two periods.

503 Fig. 2 shows that the shores of the salt lakes are less prone to frost, while highlands at the west
504 and south of the region are continuously exposed, even in mid-summer (January-February) when frost
505 occurrence is generally low. This latter situation is obviously due to extreme elevation, while the
506 "milding" effect of the salt lakes could be due to the specific thermal properties of these vast salted
507 extenses. François et al. (1999) observed warmer night temperatures over the Coipasa and Uyuni salt
508 lakes and suggest that water covering these lakes part of the summer, as well as the higher thermal
509 conductivity and thermal capacity of the salted substratum, could explain that their borders remain
510 warmer than the surrounding areas.

511 *4.2.2. From regional to subregional physiographic influences on frost occurrence*

512 Multiple regression methods were used in previous studies to evaluate the relative contribution of
513 topographic factors to near-ground temperature and frost occurrence. These studies were generally
514 conducted in mid- or high-latitude mountains (Bennie et al., 2009; Chuanyan et al., 2005; Dobrowski et
515 al., 2009), and often in densely forested areas at mid-altitude (Blennow, 1998; Lindkvist et al., 2000;
516 Pypker et al., 2007b). Our study explored an extended agricultural region at its extreme elevation limit in
517 cold and arid tropical highlands. In this context, BRT models clearly outperformed multiple regression
518 models, probably due to their capacity to include nonlinear effects and interactions between predictors
519 (Martin et al., 2009). At the regional scale, BRT analyses show that elevation, distance to the salt lakes
520 and latitude were the physiographic features most contributing to frost occurrence variations, while
521 features directly or indirectly related to slope or topographic convergence (SLO, CTI, DPI, API, and
522 MPI) were less important. These regional BRT models based on physiographic features alone explain
523 between 78% and 90% of the variation in frost occurrence observed in different time periods (Table 2).
524 In their study of the influence of physiography on the distribution of climate variables across the United
525 States, Daly et al. (2008) outline that the effects of elevation and proximity to large water bodies exceed

526 those of other topographic factors at large scales, whereas the effects of slope and landcover features
527 become prominent at relatively smaller scales. In complex terrains, local variations in slope aspect and
528 steepness create a mosaic of hillslopes experiencing contrasting climatic regimes (Daly et al., 2008),
529 while topographic depressions are another landscape feature commonly associated with cold air
530 drainage and frost occurrence (Lundquist et al., 2008; Pypker et al., 2007b). These local landform
531 features emerge as forcing factors of frost occurrence at the local scale, where the range of variation in
532 elevation and latitude became limited while that in local landscape features remained large. When
533 applied to the reduced spatial domain of the *Intersalar*, our BRT analyses indeed showed that elevation
534 lost some importance at the benefit of daily potential insolation (DPI), slope steepness (SLO), or
535 topographic convergence (CTI) (Fig. 4b). As a major characteristic of the physiography of south-
536 western Bolivia, the vast salt lakes of Coipasa and Uyuni remained influential at that local scale, as
537 shown by the high contribution of the distance to the salt lakes (LDS) in these BRT subregional models.
538 The good fit of frost occurrence values predicted by BRT models applied either at the 100-m or the 1-
539 km resolution (Tables 2 and 3) validates the use of BRT regional models for local frost occurrence
540 estimations since these models were able to seize both the influences of large-scale factors like latitude
541 and elevation, and of local factors like slope steepness, insolation, and landscape position. The
542 resulting local mosaic of cold depressions and warmer slopes at particular elevations and exposures is
543 illustrated by the map in Fig. 7c. We hypothesized that small-scale variations in soil warming due to
544 differential insolation in the day before (or the morning after) a given night could influence soil cooling
545 and thus radiative frost at night in particular places. In fact, the contribution of DPI appeared significant
546 in the BRT subregional model, at least from November to February when potential insolation is at its
547 seasonal maximum (Table 1), thus leading to highest contrasts in soil energy balance between sunlit
548 and shaded locations. However, the small contributions of the afternoon or morning components of
549 insolation (API and MPI) (Fig. 4b) seem to belie the idea that potential insolation is directly involved in
550 frost vulnerability at particular places. Actually, Blennow (1998) states that the larger amount of heat
551 stored into the ground in sunlit places cannot compensate for soil cooling at night since this cooling
552 occurs within a few hours after sunset. Nocturnal soil cooling should be still faster under clear-sky
553 conditions at high altitude. This is, however, in contradiction with the common perception of lower frost
554 occurrence in sunlit slopes, particularly in stony terrains and shallow soils supposed to benefit from the
555 thermal stability provided by the rocks. Microclimate stability associated to rock outcrops has been
556 documented by Rada et al. (2009) in the *paramo* ecosystem of Venezuelan Andes at lower elevation
557 (3800 m) and under wetter conditions (969 mm of annual precipitation). It is likely that the much drier
558 conditions of the *puna* ecosystem in southern Bolivia reduce the thermal inertia of the soils, thus leading
559 to a very fast soil cooling at night. Apart from astronomical forcing discussed previously, the varying
560 importance of CTI, DPI and SLO in the BRT models, as well as the interactions between them (Fig. 6)
561 reflect complex spatio-temporal relations between insolation and landform factors producing
562 multiplicative or mitigating effects on near-ground temperature. At the microscale level, unobserved soil
563 and vegetation properties might also interfere with landform features. Soil moisture and vegetation
564 cover, for example, are known to influence the radiative balance at the soil surface, and might
565 contribute to buffer the near-ground temperature from cold extremes in particular places (Fridley, 2009;
566 Geiger, 1971).

567 *4.3. Ecological implications*

568 The relationships between ecological patterns and processes change across spatial and temporal
569 scales, with singular complexity in mountain areas (e.g., Deng et al., 2007; Saunders et al., 1998).
570 Regarding air or soil surface temperature in mountains, nested factors are interacting, from regional
571 synoptic weather forcing to local topoclimatic situations and microscale variations in vegetation cover
572 and soil moisture. All these factors in turn may dominate the distribution of temperatures, depending not
573 only on the dynamics of the situation (turbulent or stable, nighttime or daytime conditions...) but also on
574 the spatial and temporal scale of interest (from macroscale to microscale, from seasonal to
575 instantaneous). In this way, macroscale conditions of clear sky and calm nights are required for
576 radiative frost to occur, but the frequency and severity of these frost events are further increased by low
577 site position (or conversely, extremely high location) and, at still smaller scales, by vegetation
578 sparseness and soil surface dryness or roughness (De Chantal et al., 2007; Fridley 2009; Langvall &
579 Ottonson Löfvenius, 2002; Oke, 1970). In the Andean highlands, instantaneous near-ground minimum
580 temperature may be 4°C lower in a sparsely vegetated area compared to a neighboring forest
581 understory (Rada et al., 2009). Similar fine scale variations in minimum air temperature occur within
582 cultivated canopies despite the low plant cover of most Andean crop species (see Winkel et al., 2009,
583 for the quinoa crop). These local variations in minimum near-ground temperatures may be sufficient for
584 some part of the vegetation to escape lethal freezing. Potential frost impacts on vegetation operating at
585 regional and subregional scales may thus be over-shadowed by microscale variability in minimum
586 temperature. Yet, contrary to what occurs in dense forests where plant interactions within canopies are
587 significant (Bader et al., 2008; Turnipseed et al., 2003), the sparse and low vegetation typical of the
588 Andean highlands is likely to exert an influence limited to small spatial scales, with topography and
589 coarse scale factors controlling most of the variation in minimum air temperature. In fact, Blennow
590 (1998) outlines that topographic influences on minimum air temperature increase in parallel with
591 decreasing vegetation cover.

592 *4.4. Practical implications*

593 The latter consideration implies that agroclimatic applications, such as crop zonation or suitability
594 assessments, require a multi-scale approach, ideally complementing frost risk characterization at the
595 topoclimatic scale by an evaluation of the local effects of crop practices on canopy structure and soil
596 surface moisture and roughness. Though limited to topography-frost relationships, our attempt of
597 downscaling frost occurrence at a 100-m scale usefully expands previous works on regional
598 agroclimatic zoning in the Bolivian altiplano (François et al., 1999; Geerts et al., 2006). To our
599 knowledge, this is the first time that such a detailed zonation of topoclimate is reported for this region,
600 providing fine-scale information helpful for land management and rural planning (Theobald et al., 2005).
601 Considering the scarcely available meteorological records in the study area, these 100-m scale maps
602 bring new information about the spatio-temporal variation of frost occurrence, allowing now to localize
603 exactly the seasonal pattern of frost typical of the Andean summer period (Frère et al., 1978; Troll,
604 1968). For instance, the virtual zero value of frost frequency in January and February derived from
605 meteorological records at Salinas (Fig. 1), covers in reality a wide range of situations with still significant
606 frost occurrence in mid-summer, as on the nearby border of the salar of Coipasa or the western and

607 southern part of the study area (Fig. 2). In fact, the recent expansion of quinoa crop in the region was
608 firstly and mostly located in flat areas near the Coipasa and Uyuni salt lakes (Vassas et al., 2008),
609 which exemplifies the complex trade-offs between agroclimatic risks and economic expectancies
610 operating in farmers' decision making (Luers 2005; Sadras et al., 2003).

611 4.5. Perspectives

612 Through remote sensing of land surface temperature and modeling of topographic features
613 implemented within a boosted regression procedure, we were able to explicitly downscale frost
614 occurrence at the landscape scale. The method developed here may be adapted to climatic or
615 ecological processes other than frost. Rainfall distribution could be a candidate since its spatio-temporal
616 patterns clearly depends on landscape characteristics over complex terrains. Current literature outlines
617 the importance of landform as a factor of rainfall variability in the Andes (Giovannettone & Barros,
618 2009), though most studies were conducted at the coarse spatial resolution appropriate to continental
619 scale climatology (Garreaud & Aceituno, 2001; Misra et al., 2003; Vuille et al., 2003). Canopy energy
620 budget, soil water balance, or ecosystem productivity are other ecological processes tractable for
621 topographic modeling (Bradford et al., 2005; Rana et al., 2007; Urban et al., 2000). Such applications
622 depend firstly on the availability of remotely sensed proxies for the considered process. For example,
623 the remotely sensed daily amplitude in surface temperature and vegetation indices can be used to
624 derive daily evapotranspiration (Wang et al., 2006). Similarly, satellite estimates of absorbed
625 photosynthetically active radiation may serve to evaluate net primary productivity (Bradford et al., 2005;
626 Turner et al., 2009). An additional requisite for the calibration of these applications consists in local
627 ground measurements for the variable of interest. This is a major issue in the case of the tropical
628 highlands where, similarly to what occurs for meteorological data, reliable datasets on matter and
629 energy fluxes at ground level are and will remain scarce (Vergara et al., 2007). The methods and
630 results presented here can contribute to a better understanding of the potential risks associated with
631 climate and land use changes in complex terrains, so that decision-makers can develop efficient
632 strategies to improve the ecological sustainability of natural and agricultural ecosystems in vulnerable
633 mountain areas.

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