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Giacomo TRAVERSA [1,2*], Marta ZAPPETTI [2] & Antonella SENESE [2]

SPRING AND SUMMER SPATIAL EVOLUTION OF BLUE ICE AREAS IN ANTARCTICA

Abstract: Traversa G., Zappetti M., Senese A., *Spring and Summer Spatial Evolution of Blue Ice Areas in Antarctica.* (IT ISSN 0391-9838, 2021).

Blue ice areas (BIAs) are relevant ablation surfaces present on the Antarctic continent, mainly located in proximity of the coast or mountainous zones, in sloping areas. Featuring negative values of surface mass balance, in a continent where this parameter is averagely positive, their study gains of importance, in particular regarding their evolution in time and space and the reasons of their variations. Therefore, taking advantage of remote sensing techniques and satellite products, we analysed the intra-annual BIA variation in 2000-2021 spring-summer periods. Basing the detection on topographic slope and albedo values from MCD43A3 product of Moderate Resolution Imaging Spectroradiometer (MODIS), trends are detected for all the analysed seasons, showing a steady and significant increase from the spring to the summer and only in half of the cases a final decrease in early autumn. Comparing these areal patterns with meteorological parameters (i.e., air temperature and wind speed) acquired by an automatic weather station located on the Amery Ice Shelf (Eastern Antarctica), a relation between positive temperatures and BIA increase was found (R = 0.60), possibly due to snow melting or sublimation processes, which expose the beneath bare blue ice. In addition, weak relations between area increase and high and steady wind speed conditions are detected. Finally, the areal decrease in early autumn observed in a certain number of seasons could be explained with intense phenomena of melting, as a result of continuing days of positive air temperatures, which lead to the formation of drainage systems, or with extreme solid precipitation events. In both the cases, water and snow cover the BIAs, making them impossible to be detected from remote techniques.

Key words: Blue ice areas, Antarctica, Amery Ice Shelf, MCD43A3 MODIS, Albedo.

Riassunto: Traversa G., Zappetti M., Senese A., *Evoluzione Spaziale delle Aree di Ghiaccio Blu in Antartide in Primavera ed Estate.* (IT ISSN 0391-9838, 2021).

Le aree di ghiaccio blu (o *Blue ice areas - BIAs*) sono importanti superfici di ablazione presenti sul continente Antartico, perlopiù situate sulle coste. Queste presentano valori negativi di bilancio di massa, in un continente dove questo parametro risulta essere mediamente positivo, e dunque il loro studio risulta essere fondamentale ed in particolare acquisiscono importanza la loro evoluzione nel tempo e le ragioni che stanno dietro queste variazioni. Utilizzando tecniche di telerilevamento e prodotti satellitari, qui si propone un'analisi intra-annuale dell'estensione delle BIAs nel periodo primavera-estate 2000-2021. Basando l'identificazione delle BIAs sulla pendenza topografica e sui valori di albedo superficiale derivata dal prodotto MCD43A3 del *Moderate Resolution Imaging Spectroradiometer* (MODIS), si sono identificati dei trend per tutte le stagioni analizzate, che mostrano aumenti significativi e stabili di area dalla primavera all'estate e solamente in metà dei casi una diminuzione finale ad inizio autunno. Confrontando queste tendenze areali con parametri meteorologici come la temperatura e la velocità del vento, acquisiti da una stazione meteorologica automatica localizzata sull'Amery Ice Shelf (Antartide Orientale), è stata trovata una relazione tra valori positivi di temperatura e l'espansione delle BIAs (R = 0,60), probabilmente dovuta a processi di fusione o sublimazione della neve, che scoprono così il sottostante ghiaccio blu. Inoltre, è stata identificata una debole correlazione tra l'aumento areale e velocità del vento elevate e continuative. Infine, il decremento areale di inizio autunno ritrovato in certe stagioni potrebbe essere spiegato con la presenza di intensi fenomeni di fusione, come risultato di più giorni consecutivi di temperature positive, che portano alla presenza di acqua sulla superficie, oppure di eventi estremi di precipitazioni solide. In entrambi i casi, acqua e neve coprono le BIAs, rendendole impossibili da identificare con il telerilevamento.

Termini chiave: Aree di ghiaccio blu, Antartide, Amery Ice Shelf, MCD43A3 MODIS, Albedo.

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INTRODUCTION

One of the most challenging and long research in the cryosphere sciences regards the reconstruction of processes and factors which control the mass balance in Antarctica, in relation with climate change. A relevant feature is represented by the blue ice, a surface type peculiar of the Antarctic continent. In fact, blue ice areas (BIAs) are known to be ablation areas, i.e., zones featuring a negative surface mass balance (SMB), where net annual ablation exceeds accumulation, in contradiction with the rest of the continent where it is mainly positive (Agosta & *alii*, 2019). Therefore, it has an important control on ice sheet mass balance (Bintanja & Van Den Broeke, 1995), contributing to the global sea level change (Van den Broeke & *alii*, 2011). Thus, an eventual increasing of these areas could bring to a relevant mass loss in future, leading to consequences to the global climatic system. BIAs are one of the few areas in Antarctica presenting an anomalous SMB, as well as the wind crust or glazed snow surfaces, which, however, show a near-zero SMB and have a significant lower extent (Scambos & *alii*, 2012; Traversa & *alii*, 2021a). Both these ablation areas are shaped by the effect of the wind scouring phenomenon (Das & *alii*, 2013), i.e., the interaction of snow (and its morphogenic stage transition), steady catabatic winds and peculiar topographic conditions, which lead to mass loss by melting, evaporation, sublimation and wind erosion. BIAs covers approximately 1-1.7% of Antarctic continent (Bintanja, 1999; Winther & *alii*, 2001; Hui & *alii*, 2014) and they are usually located in proximity of the coast or mountainous zones, in sloping areas (Winther & *alii*, 2001). Historically, the first glaciological and geomorphological surveys on BIAs were carried out in the early fifties in Dronning Maud Land (van Autenboer, 1964; Worsfold, 1967; Juckes, 1972), but then their interest increased significantly after the discovery of several meteorites trapped inside (Yoshida & *alii*, 1971), which show ages up to 2.5 Ma and are mainly located at altitudes over 2000 m a.s.l., suggesting that high-altitude BIAs are also the most stable ones (Cassidy & *alii*, 1992).

Geomorphologically, we can distinguish four types of BIAs (Bintanja, 1999): *i*) associated to nunataks or located on the edge of barriers which help the snow accumulation, with lengths that can be 50-100 times higher than barrier height (Takahashi & *alii*, 1992); *ii*) located along valley glaciers, emerging by the effect of catabatic wind erosion; *iii*) located on relatively sloping surfaces where a wind effect similar to type *ii* is encountered; *iv*) located at the bottom of mountains and due to the effect of wind acceleration which removes/sublimate snow/firn/ice from the surface. In general, most of the BIAs in Antarctica are of type *i*, even if other types show averagely wider areas. Their formation can be divided into four main phases (Bintanja, 1999): i) rock is in depth below ice and does not have any influence on the surface, ii) ice-flow is affected by topographic slope and downstream glacier surface melts becoming steeper, then katabatic winds become stronger eroding snow and exposing bare ice, iii) nunatak emerges and on its leeward flank ice thickness decreases and blue ice enlarges by effect of snow erosion and sublimation, iv) further ice lowering releases completely the nunatak, increasing turbulences, sublimation and snow transport. In addition, progressive loss of blue ice mass is owed to its lower albedo (0.50-0.70, Bintanja & Van Den Broeke, 1995; Bintanja, 1999; Reijmer & *alii*, 2001) than surrounding snow (0.80-0.85, Grenfell & Warren, 1994), increasing the available energy for sublimation/melting. An increase in wind action on leeward flanks can additionally lead to an enlargement of their surface.

After a first field approach (van Autenboer, 1964; Worsfold, 1967; Juckes, 1972), BIAs started to be studied via remote sensing (Orheim & Lucchitta, 1990) and the present study intends to analyse their distribution taking advantage of these techniques. In detail, images from satellites Terra and Aqua of the product *Moderate Resolution Imaging Spectroradiometer* (MODIS) in the spring-summer seasons (October-February) of period 2000-2021 were used, in particular data of albedo. After a first methodological validation on a sample area of Victoria Land by comparing MODIS data with higher resolution Landsat 8 OLI images (calculated using the recent model proposed by Traversa & *alii*, 2021b), a preliminary continental scale analysis of variation in space and time of the BIAs was carried out. Then, a local study on the BIAs on the Amery Ice-Shelf region (East Antarctica) is proposed, with an analysis of their extent as a function of the altitude and finally the so calculated trends were compared with meteorological measurements (i.e., temperature and wind speed) collected by an Automatic Weather Station (AWS).

DATA AND METHODS

Two significant parameters fundamental for the automatic detection of BIAs were used: topographic slope and albedo. As regards the slope, it was calculated from the Reference Elevation Model of Antarctica (REMA, Howat & *alii*, 2019), the highest spatial resolution Digital Elevation Model (DEM) available for this continent (with a resolution of 8 m). For the albedo product, since the aim of the work is an analysis of the entire Antarctica, a middle-resolution dataset was chosen (500 m), i.e., MODIS imagery from Terra (EOS AM) and Aqua (EOS PM) satellites, which acquire daily data since 2000 and 2002 respectively in 36 bands having a 0.4-14.4 μm of spectral resolution. In fact, products with higher resolution would entail more storage space and working time. In detail, we tested three products of MODIS, in order to find the best one for our objectives: MOD10A1 (Terra), MYD10A1 (Aqua) and MCD43A3 (Terra and Aqua). For MOD10A1 and MYD10A1 products, we used the broadband albedo layer, defined as the albedo integrated over the entire solar spectrum. Regarding the MCD43A3 product, we considered the Near Infrared (NIR) spectral albedo (i.e. reflectance for specific wavelengths bands) and the broadband black sky albedo (i.e., the directional hemispherical reflectance, that is inherent to specific locations and is linked with the structure and optical properties of the land cover, Schaaf & *alii*, 2011), since mostly clear-sky conditions are here considered as suggested by Tedesco & *alii* (2016) and Traversa

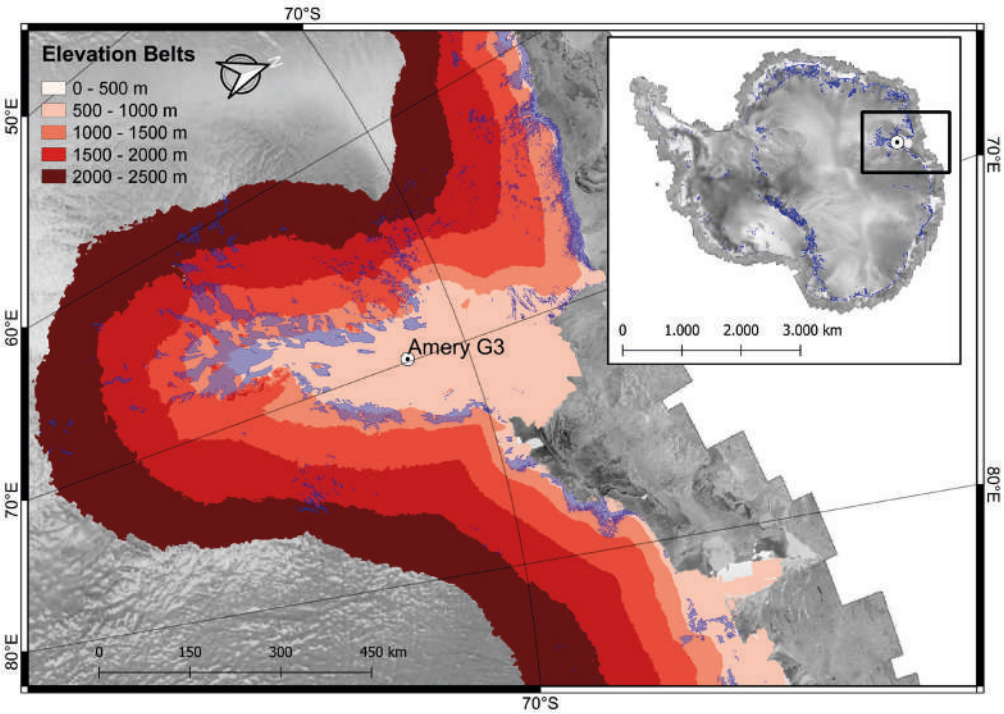

FIG. 1 - Amery Ice Shelf divided in elevation belts and the location of the Amery G3 AWS, with BIAs (Hui & *alii*, 2014) in blue and RAMP RADARSAT mosaic (Jezek, 1999) in the background. Location of the Amery Ice Shelf area in the zoom out.

& *alii* (2019). The main difference between these products is that MOD10A1 and MYD10A1 provide daily data and MCD43A3 uses 16-day (of Terra and Aqua MODIS data) temporally weighted to the ninth day. The choice fell on MCD43A3 since, mainly, it provides a more complete albedo map per each scene, with less no-data values due to cloud cover, as the values are based on 16 days instead of one. Additionally, MOD10A1 and MYD10A1 seem to present a latitudinal gradient of albedo values, which makes the albedo increase moving towards the South Pole, even on constant snow surfaces (possibly due to Solar Zenith Angle, SZA, effect, see Pirazzini, 2004). MCD43A3 allowed to analyse the BIAs from 2000 and we focused on the spring and summer (October-February) seasons, detailly on 9 scenes per season with 16 days of display (corresponding to MCD43A3 data-weight time), i.e., 14/10, 31/10, 17/11, 04/12, 21/12, 07/01, 24/01, 10/02 and 27/02 (dd/mm), thus analysing the period from 14/10/2000 to 27/02/2021. Finally, in order to validate the MCD43A3 product in BIA automatic detection, we used also albedo calculated from Landsat 8 OLI imagery (calculated through the methodology validated by Traversa & *alii*, 2021b), which present a higher spatial resolution of 30 m from the visible to shortwave infrared (SWIR) wavelengths (0.43-2.29 μm).

Then, we decided to compare the variations of the BIA with the variations of temperature and wind speed, as a preliminary way to better understand their evolution in time and the reasons of these changes. In order to do so, we focused on an AWS located at 84 m a.s.l. on the Amery Ice Shelf on the East Antarctic Ice Sheet (EAIS), area characterised by a vast cover of blue ice (Budd, 1966; Markov & *alii*, 2019). The AWS is part of the *Australian Antarctic Data Centre* (AADC) and is named Amery G3, coordinates: 70° 53' 31'' S, 69° 52' 21'' E, and distant about 50 km from the nearest BIA (fig. 1). It provides several data, including hourly data of air temperature and wind speed at 2 m from the surface. Air temperature is available from 1999 to 2011, while wind speed data are provided only until 2008. Therefore, we compared only the first eight seasons (i.e., from 2000-2001 to 2007-2008) with corresponding area evolution.

BIA automatic detection and MCD43A3 albedo product validation

In order to automatically detect and map the BIAs on the entire Antarctic continent, four remote-sensing products and two parameters were considered, i.e., albedo and topographic slope. As regards the albedo, we used both the broadband and NIR spectral albedo, taking advantage of the thresholds given by Bintanja (1999) and Hui & *alii* (2014) (i.e., 0.50-0.70 for broadband albedo and 0.30-0.70 for NIR albedo). For the topographic slope, we followed Hui & *alii* (2014) who stated that almost 97% of Antarctic BIAs are in areas with a slope ≤ 5°. Finally, in order to automatically exclude nunataks from the analyses, *Making Earth System Data Records for Use in Research Environment* (MEaSUREs) *Bedmachine* product (Morlighem, 2020; Morlighem & *alii*, 2020) was taken into account, since this raster classifies the continent based on surface types, including rock outcrops. Then, using a conditional calculation based on the previous thresholds, we could automatically detect the BIAs and vectorize the so obtained raster map. However, in our survey, NIR albedo thresholds appeared to be slightly overestimated for MCD43A3 product of MODIS, and thus we calculated a new useful range starting from ten sample polygons on certain blue ice surfaces (manually digitalized using the *Landsat Image*

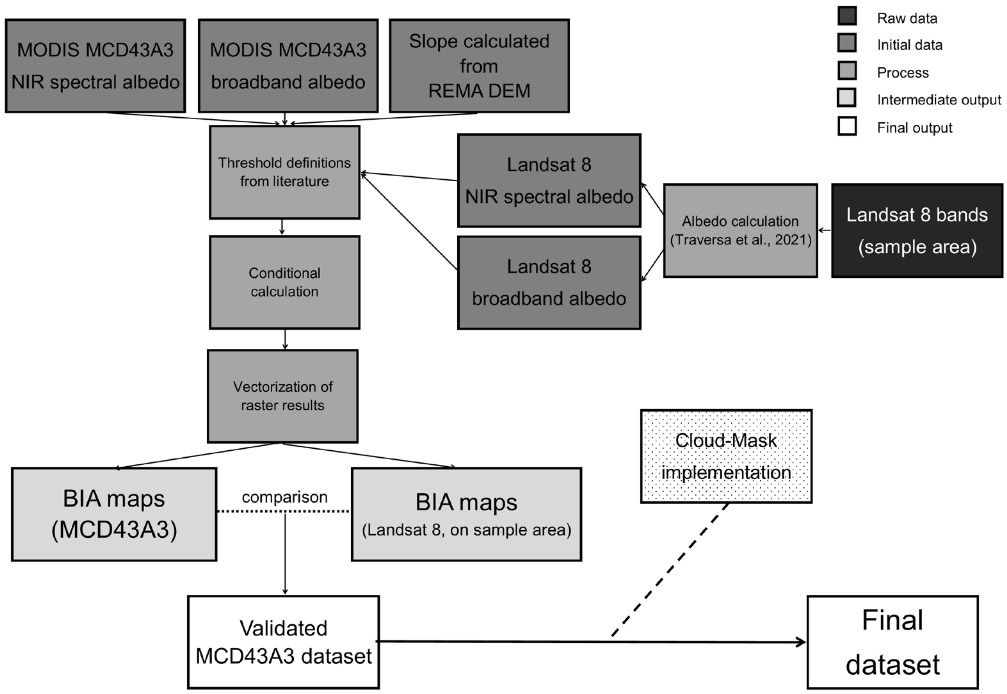

FIG. 2 - Workflow of the methodology used to calculate BIAs.

Mosaic of Antarctica, LIMA at 15 m spatial resolution as background, Bindschadler & *alii*, 2008). The new calculated NIR albedo range was 0.20-0.50.

Once the MODIS product and thresholds useful for the automatic detection were selected, we compared the use of MCD43A3 product of MODIS in BIA detection with a higher resolution satellite imagery (i.e., Landsat 8 OLI with 30 m of spatial resolution). The classification of the surface was processed using the same methodology followed for MCD43A3, i.e., conditional calculation based on slope and albedo (both NIR spectral and broadband). In order to calculate the dataset of albedo, both broadband and NIR spectral, from Landsat 8 imagery, the methodology proposed by Traversa & *alii* (2021b) was followed, which permits to derive reliable albedo values for the ice-sheets by four main process steps: zenith, atmospheric and topographic corrections and spectral to broadband albedo conversion using the Liang algorithm (Liang, 2001). For this reason, bands 2-4-5-6-7 of Landsat 8 (i.e., blue, red, NIR and SWIRs) were used. In this case, the range for BIAs of broadband albedo proposed by Hui & *alii* (2014, 0.30-0.70) was applied. With the aim of comparing the obtained results, a sample area was chosen (~100,000 km^2), located in Victoria Land (EAIS), in proximity of Mario Zucchelli Italian station, since a large presence of blue ice occurs in this zone (Folco & *alii*, 2006). Three consecutive scenes (same path) of Landsat 8 acquired on 31/12/2013 date (which presented almost no cloud cover above all the sample area) were used and compared to the corresponding date for MCD43A3.

After having validated the MCD43A3 product, an additional step was added to the dataset processing, fundamental for the intra-annual analysis: the cloud-mask application. In fact, focusing on the entire continent and calculating trends in time based on the amount of BIA surfaces, the effect of cloud cover could be relevant and removing those areas interested by this phenomenon was essential. Thus, a specific cloud-mask per each year was calculated, in order to exclude all those pixels presenting cloud-coverage in at least one analysed scene. This allowed to always compare the same cloud-free areas (pixels) during all a certain season and obtain a more significant areal trend in time. The cloud-mask was calculated using a conditional calculation which took into account the no-data pixels of each MCD43A3 scene, corresponding to cloud-covered pixels. A summarize of the image processing and the steps adopted for BIAs identification is showed in a workflow (fig. 2).

BIA distribution as a function of the altitude

Once having analysed the intra-annual trends of BIAs over the entire continent, we investigated a possible relation between BIA extension and the altitude, focusing on the area of the Amery Ice Shelf, where the AWS Amery G3 is located. In this context, starting from the REMA DEM (Howat & *alii*, 2019), we classified the area of the Amery Ice Shelf into five sub-zones of altitude (fig. 1), taking also advantage of its big extension in terms of height, as here the ice shelf and the blue ice extend from the sea level to around 2500 m a.s.l. (in accordance with REMA DEM, Howat & *alii*, 2019). The five zones are defined every 500 m as follows: between 0 and 500 m a.s.l., between 500 and 1000 m a.s.l., between 1000 and 1500 m a.s.l., between 1500 and 2000 m a.s.l. and between 2000 and 2500 m of altitude. In doing so, we assigned the corresponding zone to the BIA polygons and analysed the aerial trends in time for each zone.

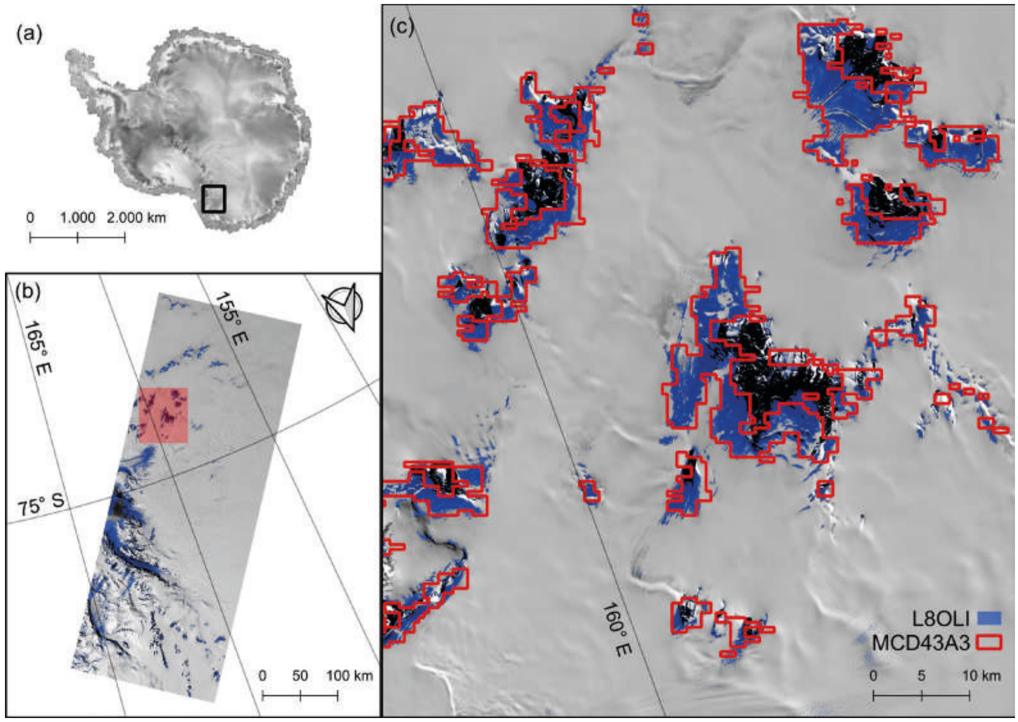

FIG. 3 - a) RAMP RADARSAT mosaic (Jezek, 1999) with b) the zoom in of the sample area on Victoria Land (Landsat scene on 31/12/2013) and in c) a focus of it, showing the comparison between BIAs calculated from Landsat 8 OLI imagery (blue polygons) and MCD43A3 of MODIS (red perimeters).

Temperature and wind measurements from the Automatic Weather Station

In order to better understand the BIA evolution, we investigated the factors driving the BIA genesis or exposition. In fact, as reported above, the BIAs of the previous year can be covered by snow and then return to be exposed once the snow has completely melted. For the BIAs genesis we considered wind conditions following Bintanja & Van Den Broeke (1995), where it stated that a wind speed higher than 8 m s^{-1} can initiate the BIAs formation provided no mass is being imported into the region other than the background mass balance. Regarding snow melt, we evaluated thermal conditions affecting the melt processes: air temperature higher than 0 °C. In particular, we counted the number per day of hours with wind speed data higher than 8 m s^{-1}. Similarly, we counted the number per day of hours with positive temperature data.

We performed the comparison between these meteorological parameters and BIA extent only over the elevation belt 0-500 m a.s.l., since the AWS is geographically located in this area (height of 84 m).

RESULTS

At first, in order to quantify the error in mapping BIAs, we compared the results obtained from MCD43A3 of MODIS and Landsat 8 OLI (on 31/12/2013, fig. 3). We found about 8% areal overestimation of automatic detection using MCD43A3 of MODIS (~5600 km^2 out of a ~100,000 km^2 of analysed surface) if compared to the results obtained using Landsat 8 OLI (~5200 km^2), probably due to the large difference in spatial resolution (500 m and 30 m, respectively). Nevertheless, considering that the aim of this study is to analyse the entire continent, such an overestimation can be considered acceptable and therefore MCD43A3 can be considered suitable for the next analyses.

Once validated the dataset, the results are here presented in three sections, corresponding to the three subsections of *Data and Methods* section: i) an initial overview of seasonal blue ice surface variability in time at continental scale, ii) the focus on Amery Ice Shelf region where the division as a function of the altitude was applied, and iii) the results of temperature and wind obtained from the Amery G3 AWS located on the ice shelf.

In general, the maximum extent per year of BIAs is, on average, approximately equal to 1.1% of Antarctica (~150,000 km^2), similar to the value obtained by Bintanja (1999, 1%), and significantly lower if compared to the one of Hui & *alii* (2014, 1.7%).

Intra-annual analysis of BIA variability at continental scale

In order to find a trend in time of areal evolution of BIAs in Antarctica, an intra-annual or seasonal analysis is here calculated for each spring-summer season from 2000-2001 to 2020-2021 period (20 seasons), moving from 14/10 to 27/02 scenes of MODIS MCD43A3 product. In every studied season, nine dates were considered with 16-day span. For all the analysed seasons, a positive areal trend in time is found from the beginning of the spring (October) to the end of the summer (February). Generally, two types of trends are found. In 9 seasons (i.e., 2005-2006, 2011-2012, 2012-2013, 2013-2014, 2014-2015, 2015-2016, 2018-2019, 2019-2020 and 2020-2021) the increasing of blue ice area in time is constant and the maximum of extent is reached at the end of February. In 12 seasons (i.e., 2000-2001,

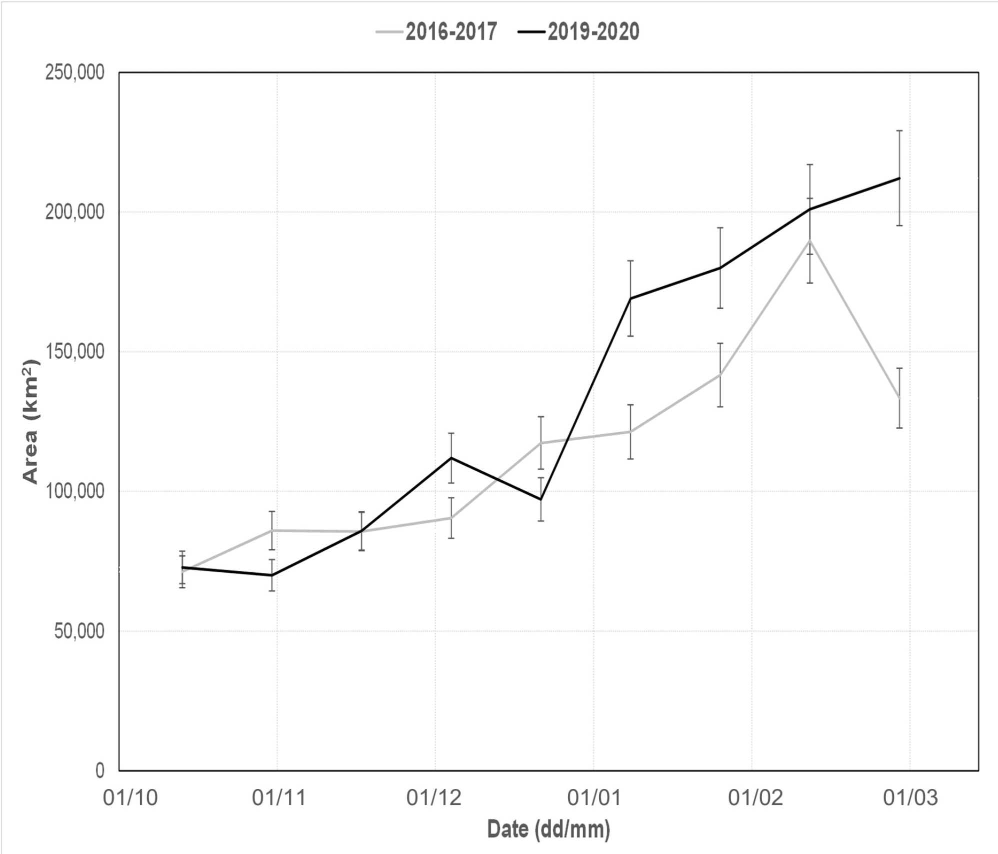

FIG. 4 - Variations of BIA extents at continental scale during 2016-2017 and 2019-2020 spring-summer seasons. Percentage-error bars of 8% are shown.

2001-2002, 2002-2003, 2003-2004, 2004-2005, 2006-2007, 2007-2008, 2008-2009, 2009-2010, 2010-2011, 2016-2017 and 2017-2018) the increasing is steady until the end of December and averagely between January and February turnarounds are detected, with the area that tends to decrease in the last considered scenes. Two examples of these two kinds of trends are in fig. 4 (2019-2020 season for the first type, and 2016-2017 season for the second one).

These trends were found both applying or without applying the cloud-mask on the original data and the evolution in time remains approximately the same in both the cases. It is interesting to note that most of the seasons of the first type (i.e., steady increase during all the period) are mostly encountered in the second decades of analysis (i.e., 2011-2021) and the second type is mostly detected in the first decade (i.e., 2000-2011), with just three exceptions in total. In general, the BIAs result to be doubled or more in terms of extension from the beginning to the end of the season (increasing of 150% on average) and therefore their percentage on the total of Antarctic surface varies significantly, from about 0.4% to 1.1% of the total area.

Intra-annual analysis of BIA as a function of the altitude in Amery Ice-Shelf region

In this section, an analysis of the BIA variation in time for the different altitudinal areas is provided, on the area of the Amery Ice Shelf, the largest ice shelf of the EAIS, SW of Prydz bay in Mac land. Here, generally, on average 20,000-30,000 km^2 of BIA are detected at their seasonal maximum extent, in accordance with previous studies (Liu & *alii*, 2006; Yu & *alii*, 2012). The altitudinal areas are five from 0 to 2500 m a.s.l., each of 500 m range (fig. 1). Spatially, the distribution of the BIAs is evidently influenced by the altitude, as a decrease is found moving from the coast to the highest zones. In fact, on average 70% of the total is located in the first 500 m of height. Then, in 500-1000 m a.s.l. and 1000-1500 m a.s.l. areas respectively 16% and 11% are observed. The remaining 3% is in the last two higher zones, subdivided in 2.6% and 0.4% in 1500-2000 and 2000-2500 m a.s.l. areas, respectively. Moving to the temporal variation in blue ice extent in each elevation belt, we found a positive trend for all the years in the first belt (0-500 m a.s.l.) with similar patterns to the ones described for the entire continent. In most of the cases, the major increase in area happened between the end of December and the beginning of January. In fact, on average an increase of +15,000 km^2 along the summer season was detected, with maximum value of +25,000 km^2 on 2004-2005 and minimum +9,000 km^2 on 2001-2002. In certain seasons, the decrease at the end of season was detected, being on average -9,500 km^2 from the peak, with maximum decrease again on 2004-2005 showing -17,000 km^2 (thus, 2004-2005 resulted to be most heterogenous analysed season), and minimum decrease on 2006-2007 (-2,000 km^2). As regards the second belt (500-1000 m a.s.l.), no well-defined trends are

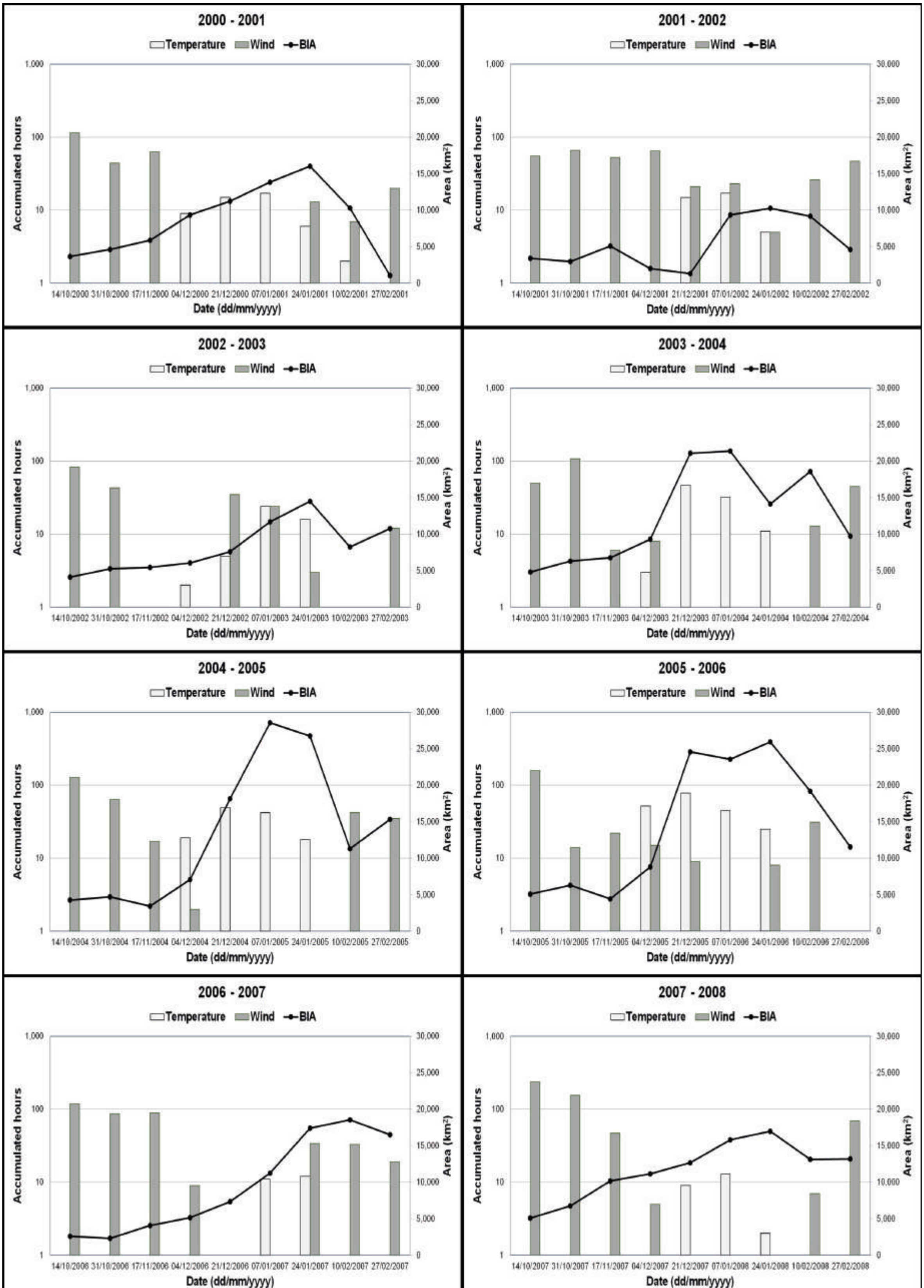

FIG. 5 - Seasonal variations of BIA extents in Amery Ice-Shelf area at the lowest altitude belt (0-500 m a.s.l.) in 2000-2008 period. Corresponding accumulated (16-day temporally weighted to the ninth day) hours above the thresholds of temperature and wind speed from Amery G3 AWS are shown (for a better representation, a logarithmic scale is applied to these two parameters).

detected and they change year by year, even if some seasons present a decrease from December after an initial increase (e.g., 2006-2007, 2011-2012, 2012-2013, 2013-2014), so an opposite behaviour in respect to the previous cases. The third belt (1000-1500 m a.s.l.) present a different general trend, with the area decreasing in the middle of the analysed period (December) and then it increases at the end of the summer, reaching values similar to the initial ones. Regarding the last two elt (1500-2000 and 2000-2500 m a.s.l.), no particular trends are detected, and the obtained values tend to be more constant with slight variations during the spring and summer.

AWS temperature and wind variability in Amery Ice-Shelf region

Temperature and wind speed present two opposite trends in time (fig. 5). In fact, on the one hand, the temperature is positive only in the middle of the summer (i.e., December and January) with the highest number of hours showing positive values between the end of December and the beginning of January, when the average maximum is about 9 hours per day ranging from 4 hours in 2007-2008 to 14 hours in 2005-2006. The only two exceptions are represented by 2006-2007 and 2007-2008 seasons, where the peaks are slightly postponed in time, mostly located only in January. At the same time, these last two seasons are also the two with the lowest values of positive-temperature hours (with 2000-2001 season), as they present peaks around 5 hours, in contradiction with the other five seasons which present values that are even more than doubled.

On the other side, the wind speed presents a different pattern, with the highest number of hours per day with values > 8 m s^{-1} located during the spring, mainly October (with three seasons, i.e., 2004-2005, 2005-2006 and 2007-2008, having entire days always over the threshold). The wind speed tends to decrease in the middle of the study period, when the temperature presents its peaks, reaching no-data with speed higher than 8 m s^{-1}, especially in between December and January (the only exception is represented by 2001-2002 season, which shows mostly positive values). The wind speed then starts to increase again showing high values at the end of the studied season, in February, even if these peaks result to be lower if compared to October ones (averagely, 21 hours in October and 15 hours in February).

DISCUSSION

In the present work, we detected a maximum extent of BIA per year of about 150,000 km^2 at continental scale with a low inter-annual variability, corresponding to 1.1% of the Antarctic surface, in agreement with previous findings (Bintanja, 1999). However, the strong difference between our results and the one by Hui & *alii* (2014, 1.7% of Antarctica) could depend on the different satellite dataset used, as in the previous effort also Landsat imagery (i.e., with higher spatial resolution) was used and thus more precise results could have been obtained, as demonstrated by the 8% of overestimation calculated in the Victoria Land using MODIS. In addition, the application of the cloud mask could have significantly underestimated the final amount of detected BIA, as well as the vectorization of the raster maps of BIA detection, in consideration of the included simplification step in polygon conversion procedure. Last but not least, the difference could be affected by an overestimation of BIA in the work by Hui & *alii* (2014), who detected as BIA also other surface features, such as glazed snow (albeit shows higher albedo values compared to blue ice, Traversa & *alii*, 2022). Nevertheless, good agreements are found for the Amery Ice-Shelf area, where on average 20,000-25,000 km^2 of BIA are detected in 2000-2008 period, extremely similar to other works at even higher spatial resolutions (Liu & *alii*, 2006; Yu & *alii*, 2012).

Seasonal variation interpretation and comparison between areal and meteorological features

Analysing the variation of spatial distribution of BIAs in Antarctic continent during the spring-summer seasons, we found a general increase of area in every intra-annual analysis, from 2000-2001 to 2020-2021. The only difference between the seasons stands the general trends, which show two main types: steady increase from October to February (the entire analysed period) or increase of the area until December/January and then a decrease in the last scenes. These two kinds of trends are approximately equally subdivided in the twenty analysed seasons, as nine are characterized by the first case (steady increase) and eleven by the second one (turnaround in December/January). Additionally, the two categories are also well divided in the two studied decades, as from 2000-2001 to 2010-2011 the second type is dominant and from 2012-2013 to 2020-2021 the first one results to be more predominant. However, in general, despite of these differences, the detected increase in terms of extent of the BIAs during all the studied seasons is relevant, as the evolution in time leads to a doubled area or more. As a first attempt to explain this relevant increase, we could consider the melting of the snow which covers the BIAs as a main reason, since in most of the years the final extent results to be almost unvaried. This could mean that the BIA tends to remain mainly the same through years and what gives the variability from a remote approach is the snow layer, which covers the blue ice in certain frames of the season. Additionally, summer melting of the covering snow could also be suggested by an increase in temperature in Antarctic coastal area during the last 50 years (Turner & *alii*, 2005), where a significant number of the BIAs are located. On the other hand, the final decrease in blue ice extent in certain seasons cloud be explained by increasing snowfall events, which are temporally anticipated before autumn-winter seasons and quantitatively more significant, according to Medley & *alii* (2018) and Medley & Thomas (2019). Nevertheless, some points remain unexplained, e.g., the presence or not of the turnaround in some analysed seasons, and thus a more deepen analysis is required. Taking advantage of the Amery G3 AWS, we can focus on the coastal portion of the Amery Ice Shelf, where these trends are detected as well as at continental scale. In order to do

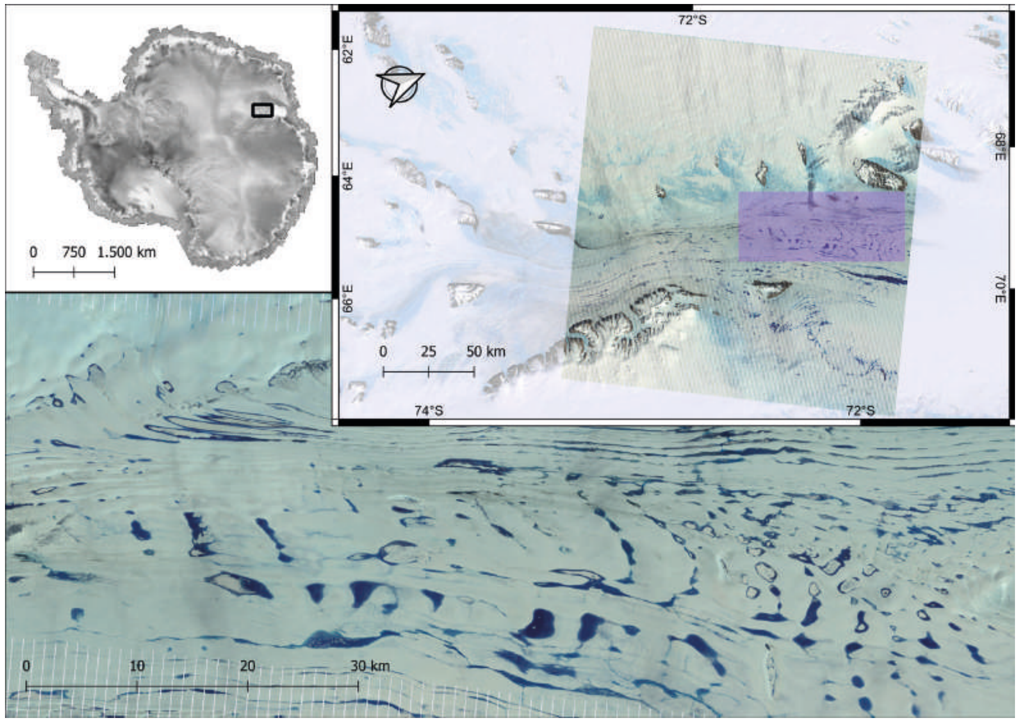

FIG. 6 - Zoom in of a drainage system of supraglacial lakes and canals on Amery Ice Shelf on 25/01/2005. Landsat 7 ETM+ image; RAMP RADARSAT mosaic (Jezek, 1999) and Landsat Image Mosaic of Antarctica (LIMA, Bindschadler & *alii*, 2008) as backgrounds.

so, we compared 8 seasons of areal distributions, from 2000-2001 to 2007-2008, corresponding to the AWS data time span with sufficient data to reproduce a significant meteorological analysis. From the trends of temperature and wind speed above a certain threshold, as described in *Results* section, we can detect the exact time when melting and sublimation respectively could take place. Looking at the comparison between blue ice extent and daily cumulative positive temperatures (fig. 5), it is evident the correlation between these two parameters, as the major increases of BIA happen in concomitance with the first dates with positive temperatures and significant increases take place when daily positive temperatures last for 3-5 hours or more. In fact, the BIAs increases or their major increases are detected during December and January, exactly when the temperatures become positive, promoting melting processes of the overlying snow.

On the other hand, wind speed values higher than 8 m s^{-1} occur mainly at the beginning (October-November) and the end (February) of the analysed period, with highest cumulative peaks at the beginning of the period (21 hours versus 15 hours per day above the threshold). In this second case, the increase in area of blue ice is evidently less related with an increase in wind speed if compared to positive temperatures. However, periods of strong and persistent wind (i.e., at least 10 hours with wind speed > 8 m s^{-1}) could suggest a relation with weak increase in BIA at the end of the spring (November) or beginning of the autumn (February), by erosion phenomena of snow which expose the beneath blue ice (Scambos & *alii*, 2007; Lenaerts & *alii*, 2017). The first increase (November) is evident in all the 8 analysed seasons, and it cannot be related with melting due to the temperature effect, as no continuative melting periods can be detected. In addition, this initial increase becomes more relevant when many strong windy days are continuously found (e.g., 2006-2007 and 2007-2008 seasons). In this view, also the final increase in blue ice extent of 2004-2005 season could be explained by the presence of many consecutive days with high wind speed. We could then conclude that both temperature and wind could have an impact on BIA extent by increasing it with higher values, but temperature presents certainly a higher control on its exposure. In this context, in order to statistically support this control, a linear regression between area variations and the two meteorological parameters was calculated, finding a multiple R of 0.61, even if the corrected R^2 resulted to be lower (0.35). However, it was statistically proved the higher role of temperature (R = 0.60) in respect to wind (R = -0.12), being also the only significative ($p < 0.05$) parameter in the correlation. It should be noted that in certain seasons, i.e., 2002-2003, 2003-2004 and 2007-2008, the corrected R^2 increases to > 0.50 values. Therefore, we could explain the variations of BIAs with the calculated trends of temperature and wind speed, especially the link with temperature variations, and possibly the not so high statistical correlation (0.35) could be due to the use of a single AWS, explaining the huge 0-500-m-belt area of the Amery Ice Shelf. Additionally, our approach did not consider another relevant aspect, i.e., the different location and the related topographic characteristics of BIA that are on the ice shelf or in sloping areas at higher altitudes. In fact, some issues could arise applying this approach. The AWS is located at lower altitudes and in a flatter area, compared to BIAs that are mostly in steep high zones. For this reason, the meteorological conditions, both temperature and wind, could not be completely representative of all the BIAs. Nevertheless, Amery G3 AWS seems to be the unique station providing available data in the area. Then, we decided to consider only this AWS, since this methodology represents a preliminary way to interpret the relation between BIA extent and the meteorological parameters.

Finally, as we detected along all the 8 studied spring-summer seasons a decrease in the last period (end of summer-beginning of autumn), taking advantage of the meteorological parameters already analysed, we could provide two possible scenarios. Firstly, the decrease sometimes corresponds to the absence of days with hourly positive temperatures, corresponding to no melting conditions. Therefore, the BIA decrease could be due to snowfalls in this time frame, since blue ice becomes covered by snow that will not melt. In fact, Amery Ice Shelf area is known to be interested by extreme solid precipitation events which are concentrated in less than 10 days, mainly in autumn (50% of annual precipitations, Turner & *alii*, 2019). In general, this sort of events concern all the Antarctic continent and are the main factor in controlling the interannual variability in snow accumulation (Turner & *alii*, 2019) and thus could also explain the detected inter-annual variability and the presence of two distinct trends at the end of the studied seasons. Nevertheless, in certain cases (i.e., 2000-2001, 2003-2004, 2004-2005 and 2007-2008) the final decrease corresponds to many consecutive days with possible melting by positive temperature effect. In accordance with previous works (Phillips, 1998; Zhou & *alii*, 2019; Spergel & *alii*, 2021), who reported the presence of supraglacial drainage systems composed by lakes and canals on the Amery Ice Shelf at the end of the summer season, we could explain the decrease of BIA with the hypothesis of a water coverage which makes the blue ice undetectable from space, by decreasing its albedo. In this context, we visually checked the presence of bodies of water at the end of 2004-2005 summer season (25/01/2005) with a higher spatial-resolution satellite image (natural colour composite from Landsat 7 ETM+) on the Amery Ice Shelf (fig. 6). There we easily detected huge drainage systems covering the blue ice, confirming then our hypothesis. Also at continental scale drainage systems are knowingly present on BIA (Kingslake & *alii*, 2017; Lenaerts & *alii*, 2017) and therefore the decrease in blue ice exposure at the end of the summer after many melting days at continental scale could be explained. Nevertheless, accordingly to Tuckett & *alii* (2021), these meltwater areas reach their maximum in January and then decrease in February for freezing over. Therefore, the very final areal decrease in February could be reasonably depending on snow cover, and not on the meltwater area formations.

CONCLUSIONS

In the present study an analysis of spatial distribution of BIAs in the Antarctic continent is carried out, focusing on their variations in time by means of remote-sensing applications. Taking advantage of an automatic detection based on albedo (broadband and NIR from MODIS product MCD43A3) and topography (topographic slope calculated from REMA DEM, Howat & *alii*, 2019), we analysed the intra-annual evolutions of BIAs of Antarctica in 2000-2021 period from October to February. With a percentage on the total Antarctic of 1.1% (150,000 km^2 on average), we detected an evident trend in areal increase along the season for all the analysed years, with change in surface of about +150% or more from the end of the autumn to the summer. However, in half of the analysed periods a turnaround in tendency was detected, with the steady increase of area reaching its maximum in December/January followed by a final decrease in February. Then, moving to the Amery Ice-Shelf region, where the Amery G3 AWS is, we first divided the area in 5 elevation belts, and we detected the same trends found at continental scale in the ones closer to the coast, especially in the first belt (0-500 m a.s.l.), where most of the BIA are located. In order to explain these trends, we evaluated thermal and windy conditions focusing on the first belt, where the Amery G3 AWS is located. An evident relation was found between the increase of BIA in the middle of the season and the dates presenting melting phenomena (i.e., air temperature higher than 0 °C; R = 0.60), especially explaining the strong increase in extension, peculiar of December and January. The other weaker increases can be explained by the effect of wind, which presents high values of accumulated hours with wind speed higher than 8 m s^{-1}, suggesting the occurrence of erosion of superficial snow cover (Scambos & *alii*, 2007; Lenaerts & *alii*, 2017). In both cases, the areal variations can be explained by a higher portion of BIA which becomes uncovered by the snow, due to melting/sublimation or erosional phenomena. As concerns the decrease of BIA mainly at the end of the seasons, it could be explained by snow or water cover above the blue ice, caused by intense events of snowfall (Turner & *alii*, 2019) or by the creation of relevant drainage systems owed to snow and blue ice melting (Phillips, 1998; Zhou & *alii*, 2019; Spergel & *alii*, 2021).

Future efforts could focus on BIA variations in different sectors or specific areas of Antarctica in order to confirm the present results or to find areal discrepancies across the continent, possibly taking advantage of other AWSs located in proximity or above BIA and in gullies of katabatic wind flow. In addition, also a differentiation of BIA based on type and topographic location could be a better approach in respect to our preliminary methodology based on the altitude. Data of snow cover (especially fresh snow) measured by an AWS could also be useful in order to detect extreme snowfall events leading to the observed BIA decrease. In addition, an inter-annual analysis of continental BIA based on the proposed methodology could be considered.

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