Summary of the Master Thesis by **Marta Zappetti**

SPATIAL AND TEMPORAL ANALYSIS OF THE DISTRIBUTION OF BLUE ICE AREAS IN THE ANTARCTIC CONTINENT

State University of Milan
Faculty of science and technology
Master degree course in Biogeosciences: ecosystem analysis and science communication
supervisor: **Antonella Senese** assistant supervisor: **Giacomo Traversa**
Academic year 2019/2020

INTRODUCTION

Antarctica is the fourth largest continent on Earth and makes up 10% of the surface of our planet (King and Turner, 1997). It is 98% covered with ice which corresponds to almost 90% of the fresh water present on Earth. The extremely cold temperatures of the Antarctic Plateau and the scarce rainfalls make this continent a real cold desert. The absolute minimum temperature reached at the South Pole was recorded by the University of Colorado between Dome Argus and Dome Fiji and corresponds to -98,6°C and, generally, mean annual temperatures are around – 50°C (King and Turner, 1997). Regardless of the low temperatures, Antarctica seems to be affected by the climate change. Several studies concerning the variations of the atmospheric circulation in the Southern Hemisphere report an evident warming of the Antarctic Peninsula with a temperature increase of 2.5 °C in the last 50 years (Turner et al., 2005) and a slight positive trend in average temperatures at continental scale since 1957 (Steing et al., 2009). Fortunately, the increase of temperatures has not brought to a loss of ice mass in the most internal parts of the continent. However, this phenomenon could lead to an increase in the surface of the ablation areas, that are those areas where glacial mass is lost by sublimation, melting and the erosive action of winds. For this reason, this thesis wants to analyze and map the trends of specific ablation areas called blue ice areas (BIAs), which affect the surface mass balance of Antarctica, leading to implications on the Earth's climate system and on the increase in mean sea level. The blue ice areas (BIAs) currently cover the 1% of the surface of the Antarctic continent and extend near the coast and mountainous areas (Bintanja, 1999; Winther et al., 2001). They originate from the erosive action of katabatic winds, the most important winds on the Antactic continent, which can reach speeds of 300 km/h. The blue ice areas (BIAs) were analyzed through Remote Sensing in particular through the use of satellite images of MODIS product of Terra (EOS AM) and Aqua (EOS PM) satellites of NASA, in the period of spring and Antarctic summer (october-february) between 14/10/2000 and 27/02/2021, through mapping based on albedo (or reflectivity), in order to study their variations in time and space. In fact, the blue ice areas assume albedo values between 0,5 and 0,7 (Hui at al., 2014), differentiating from the higher snow values (fresh snow assumes albedo values between 0,8 and 0,9 (Gardiner and Shanklin, 1989)) and by the rock's values which appear to be lower. The so calculated areas were then compared with meteorological data from automatic weather stations.

MATERIALS AND METHODS

Firstly, we focused on identifying the best MODIS product to use in the visualization of the BIAs present in the entire Antarctic continent. The choice between MOD10A1 (Earth) MYD10A1 (Water) and MCD43A3 (Terra and Aqua) fell on the MODIS product of MCD43A3 as, by reinterpreting the cloud cover values over 16 days, it allowed us to analyze a wider area of continent. Then a local scale comparison was carried out between MCD43A3 images product with a spatial resolution of 500 m, and the existing images of Landsat 8 OLI product, with a spatial resolution of 30 m with the aim validating its use. In order to monitor the large scale spatial and temporal changes of the BIAs, it was decided to use MODIS product images compared to those Landsat 8 images for the contained amount of digital memory. This analysis enabled to confirm the efficacy of the

MCD43A4 product in the discrimination of BIAs (with albedo values between 0,5-0,7) with an error of 9% compared to the areas observed through Landsat 8. We proceeded to process the necessary data to create a representative database of spatial values of BIAs to perform intra- and inter-annual trend analyses. The 9 dates analyzed for all 20 years have been 14/10, 31/10, 17/11, 04/12, 21/12, 07/01, 24/01, 10/02 and 27/02. In order to confirm the results obtained in the intra-annual trend, we proceeded with a cloud mask creation, carried out along 5 sample years, to avoid a possible dependence on cloudiness variability between the dates considered. To confirm again the intra-annual trend, we also performed an analysis of the distribution of BIAs as a function of altitude along the Amery Ice Shelf (again for 5 sample years). Finally, we compared the data obtained with temperature and wind speed data obtained via the Amery G3 automatic weather station (located at 84 m), one of the few weather stations present in proximity of blue ice areas.

RESULTS AND DISCUSSION

The inter-annual analysis identified a stability in the spatial evolution of BIAs over time. However, this stability shows a slightly positive trend in the spatial tendency of blue ice over the 20-year period analyzed, signaling an spatial increase in blue ice during time. This minimal spatial increase in BIAs with the passage of the twenty-year period could be due to an increase of temperatures recorded near the coast (Turner at al., 2005) that would lead to a reduction in snow cover for melting processes. However, after analyzing the evolution of BIAs over time based on the single date of 21/12 throughout the 20 years of data, a slightly negative trend was found. This trend was also confirmed by the analysis of the average spatial values of the days 04/12, 21/12 and 07/01 distributed along 20 years of data. This phenomenon could highlight the presence, for the years with a minimum spatial distribution of BIAs, of surface body of water located above the areas of blue ice, a phenomenon related also in this case to the increase temperatures. We then performed an intra-annual analysis of the spatial evolution of BIAs along the Antarctic spring and summer for all 20 years of analyzed data. This study identified a positive trend (Figure 1) for all 20 years considered. This positive trend was also confirmed by the analysis of BIAs using the cloud mask. For 11 out of 20 years there was also an spatial decrease near the end of the season (Figure 2). This trend reversal near February could confirm the presence of meltwater located above areas of blue ice due to melt processes.

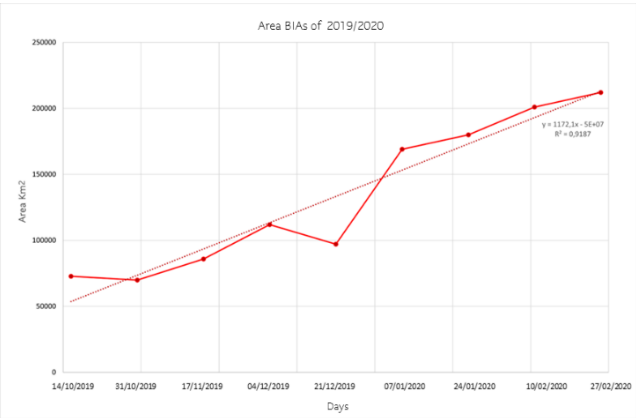
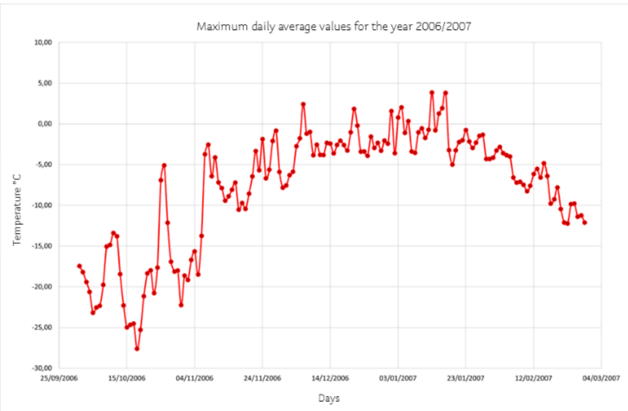
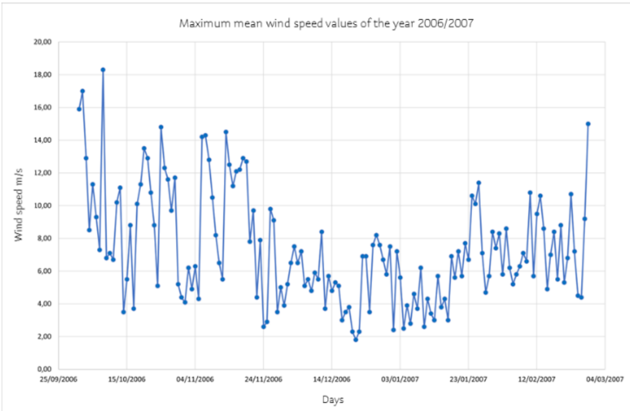


Figure 1: Graph of the year 2019/2020 showing a constant spatial increase in the area of BIAs with the trend line (dotted line) and the equation referring to the increase calculated with the trend line.

Figure 2: Graph of the 2016/2017 year showing an spatial decrease in the area of BIAs towards the end of the season. Through the trend line (dotted line) it is possible to observe the presence of a positive intra-annual trend.

This positive intra-annual trend was also confirmed by the analysis of the seasonal trend of BIAs along 5 altitudinal bands (500 m; 1000 m; 1500 m; 2000 m; 2500 m) carried out on the Amery Ice Shelf, where a positive trend was detected for more than 80% of the analyzed area. Subsequently, the seasonal trend detected along the first altitudinal band (0-500 m) was compared with the temperature and wind speed values detected through the Amery G3 automatic weather station of the year 2006/2007. This analysis identified an influence of wind speed and temperature elevation on the spatial increase in BIAs along the spring-summer season. The analysis of the maximum temperature values obtained from the daily hourly averages of the year 2006/2007 allowed to identify a constant increase in temperature with the passing of the season until January and then to observe instead a decrease (figure 3). As it can be observed from figure 4, representative of the average maximum wind values, the spatial increase of BIAs at the beginning of the season could be caused by the erosive action of katabatic winds. In fact, as it can be observed, the maximum speeds are reached mainly near the beginning of the season. On the opposite, the accentuated increase of the BIAs surface, visible from mid to late season (21/12-27/02), would combine with the presence of temperature values above 0°C. In order to confirm the influence of the increase in temperature with the increase in the surface area of the BIAs, the spatial increase of the blue ice areas of the first altitudinal band in the year 2006/2007 was compared with the "degree hour" values (sum of the daily hourly average positive temperatures) obtained in the same time interval. As it can be seen from Figure 5, the spatial increase in BIAs would occur precisely in the vicinity of "degree hour" temperature values greater than 0°C. The accentuated increase is found in proximity of the maximum "degree hour" values which correspond to 7.94°C on 13/01/2007 and 8.02°C on 17/01/2007. This analysis would therefore confirm that the intra-annual spatial increase in BIAs is due to the erosive action of katabatic winds also associated with the presence of temperatures above 0°C.





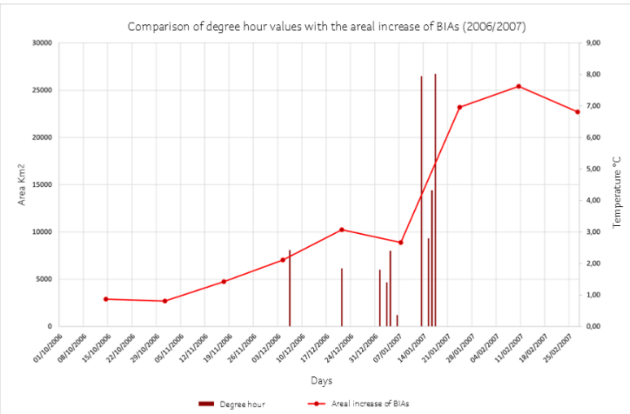


Figure 3 (at the top left): Trend of daily maximum mean values of temperature.

Figure 4 (at the top right): Trend of daily maximum mean values of wind speed

Figure 5 (down to the left): Comparison of spatial increase in BIAs (red line) with temperature degree hour values (red columns).

Another thing to be taken into account is that also on the Amery Ice Shelf spatial decreases were detected near the end of the season that can also be explained in this case by the presence of meltwater. The analysis of satellite images of the Landsat 7 ETM+ product allowed to confirm the presence of surface body of water near the end of the season along the first and second altitudinal bands confirming the hypothesis previously described.

CONCLUSIONS

This thesis work has identified and analyzed the spatial and temporal variations of blue ice areas (BIAs) present on the surface of the Antarctic continent over the last 20 years of data. The inter-annual trend of BIAs would have confirmed the presence of a slight spatial increase of blue ice with time, a phenomenon likely due to increasing temperatures. The inter-annual trend observed with the analysis of the spatial distribution of the BIAs on the date of 21/12 and the averages of the spatial values of the days 04/12, 21/12, 07/01 instead would show an spatial reduction caused by a greater presence of melt water on the surface of the BIAs, thus confirming, albeit with an inverse trend, the increase in temperature. The intra-annual analysis also confirmed the presence of a positive evolutionary trend along the Antarctic spring and summer (October-February) for all 20 years analyzed. This seasonal spatial increase of BIAs is probably due to the increase of temperatures during the summer season. Also significant are the spatial decreases detected at the end of the season for 11 out of 20 years that would again identify the presence of meltwater at the surface caused by increased temperatures. The analysis performed on the Amery Ice Shelf would also confirm the presence of a positive intra-annual trend as the season progresses. The temperature and wind speed data recorded by the Amery G3 automatic weather station would also confirm the influence of the erosive action of katabatic winds and increasing temperatures in the formation of a positive intra-annual trend, at least along the first altitudinal band (0-500 m), where however is located more than 80% of the area of the BIAs in the area. Finally, observation of satellite images obtained from the Landsat 7 ETM+ satellite would confirm the presence of meltwater near the end of the season, corroborating the previously elaborated hypotheses.

BIBLIOGRAPHY

Bintanja R (1999), On the glaciological, meteorological and climatological significance of Antarctic blue ice areas. Rev. Geophys., 37(3), 337–359 (doi: 10.1029/1999RG900007)

Gardiner B.G. and Shanklin J.D. (1989), Measurements of Solar and Terrestrial Radiation at Faraday and Halley, British Antarctic Survey, Cambridge, 45 pp.

Hui, F.; Ci, T.; Cheng, X.; Scambos, T.A.; Liu, Y.; Zhang, Y.; Chi, Z.; Huang, H.; Wang, X.; Wang, F. (2014), Mapping Blue-Ice Areas in Antarctica Using ETM+ and MODIS Data. Ann. Glaciol. 55, 129–137.

King, J. C., & Turner, J. (1997), Antarctic meteorology and climatology. Cambridge University Press.

Steig, E.J., Schneider, S.D. Rutherford, M.E Mann, J.C. Comiso, and D.T. Shindell, (2009), Warming of the Antartici ce-sheet surface since 1957 international Geophysical Years. Nature, 457, 459-462.

Turner, J., Colwell, S. R., Marshall, G. J., Lachlan-Cope, T. A., Carleton, A. M., Jones, P. D., ... & Iagovkina, S. (2005), Antarctic climate change during the last 50 years. International journal of Climatology, 25(3), 279-294.

Winther J-G, Jespersen MN and Liston GE (2001), Blue-ice areas in Antarctica derived from NOAA AVHRR satellite data. J. Glaciol., 47(157), 325–334 (doi: 10.3189/172756501781832386)