<u>**Summary of the Master Thesis**</u>

Paolo Colosio

Enhanced resolution mapping of melting over the Greenland and Antarctica ice sheets (1979 - 2016) using passive microwave brightness temperatures

Università degli Studi di Brescia, DICATAM, Laurea magistrale in Civil and Environmental Engineering

Tutor: Prof. Roberto Ranzi (Università degli Studi di Brescia)

Co-tutor: Prof. Marco Tedesco (Columbia University)

School Year 2018/2019

1) Introduction

Greenland and Antarctica ice sheets are the largest glaciated masses on planet Earth. They store enough ice to rise the average ocean level of 7 m and 55 m, respectively, if completely melted. From gravimetry observations sensed by GRACE satellite mission it is possible to estimate that the ice mass loss of the Greenland ice sheet contributed to rise the average sea level of about 7.9 mm per decade, between 2002 and 2016, while Antarctica contributions corresponds to 4 mm per decade. Both contributions have been increasing between 1992 and 2010 (Rignot et al., 2011). Hence, monitoring ice sheets mass balance is crucial for better understanding their contribution to sea level rise.

Surface melting is a major contributor among the processes influencing surface mass balance. Passive microwave remote sensing is an irreplaceable tool for monitoring surface melting over polar regions (Tedesco, 2009; Fettweis et al., 2011). These sensors measure the energy naturally emitted from Earth surface, the so-called brightness temperature (T_b [K], Ulaby et al., 1986) and are characterized by a high temporal resolution (at least one image every other day), a long temporal coverage (1979-now) and a large spatial coverage, in particular in polar region where these satellites pass multiple times during a day. The trade-off of passive microwave sensors is the slightly coarse spatial resolution (25 km for the 37 GHz channel). Melt detection techniques build on the strong difference in emissivity between dry snow and wet snow condition (Macelloni et al., 2005). The appearance in the snowpack of a small amount of liquid water content (LWC) due to the melting process leads to a strong increment in the T_b signal. This characteristic in the timeseries allows us to classify melting days during the year.

Here, we use a recently released dataset at the enhanced spatial resolution of 3.125 km (37 GHz) to map surface melting over the Greenland and Antarctica ice sheets and to study its spatial and temporal variability.

2) Datasets and methods

In this work we use a newly developed dataset of Tb maps at 37 GHz (horizontal polarization) at the enhanced resolution of 3.125 km, obtained from a new re-gridding technique. We selected the following sensors: SMMR-Nimbus 7, SSM/I (F08, F11 e F13) e SSMI/S-F17. The temporal coverage of the dataset used in this work ranges from 1979 to 2016 (now updated to 2019). In order to improve the consistency of the timeseries and reduce the error related to the different intrinsic characteristics of the sensors we calibrated the oldest portion of the dataset by applying a linear correction. We obtained the correction coefficients computing the linear regression between the data sensed by the two satellites during the overlap period.

In order to map surface melting we applied five threshold-based melt detection algorithms. The simplest is a fixed threshold of 245 K, considered as the value of Tb above which an increase of LWC does not lead to a further increase of T_b (Tedesco, 2009). Then, we selected three threshold (called M+DT) based on the increment ΔT due to the presence of LWC with respect to the dry snow condition (M), computed as the average of winter T_b. The selected values of ΔT are 30 K, proposed by Zwally & Fiegles (1994), 35 K and 40 K, as sensitivity analysis to this parameter. Finally, we implemented an algorithm based on the snowpack emission model MEMLS to estimate the ΔT dynamically (varying in space and time), following the methodology proposed by Tedesco (2009). This algorithm (simply called MEMLS) is designed to detect sporadic melt events, when the LWC reach the value of 0.2%, providing consistency in terms of minimum LWC detected.

In order to evaluate the performances of the proposed algorithms we used air temperature data (Tedesco, 2009) measured by the automatic weather stations of the Greenland Climate Network (GC Net) in Greenland and of the Antarctica Automatic Weather Stations Program (AAWSP) in Antarctica. We evaluated the commission error, occurring when melt is detected by passive microwave when air temperature is below melt threshold, and, vice versa, the omission error. The air temperature thresholds selected are 0°C, -1°C e -2°C (as sensitivity analysis, considering that the melting process can occur below the 0°C threshold due to radiating forcing). For this reason we additionally compared the results from satellite data analysis with the outputs of the regional climate model MAR (Fettweis et al., 2011), considering the simulated LWC in the first 5 cm and 1 m of snowpack (for Greenland only). An example of the timeseries of the datasets used for Greenland is reported in Figure 1.

We finally computed the main melting parameters from literature. We computed melt onset date (MOD) and melt end date (MED) as the first and last two consecutive days detected as melting. The melt duration (MD, an example for Antarctica is reported in Figure 2) is computed as total number of days classified as melting. We computed these parameters both pixel-by-pixel and averaged at ice sheet level to obtain synthetic parameters. Then we computed the maximum melting surface (MMS) as the surface are where melting occurred at least once in a year and the melt index (MI) defined as the area subject to melting multiplied by the number of melting days. Then, we computed the temporal trends and evaluated the statistical significance.

3) Results

By applying the five melt detection algorithms we created a dataset of daily melting maps from 1979 to 2016. From the comparison with the air temperature data and MAR simulation we obtain satisfactory results for the case of Greenland. The fixed threshold of 245 K is the most conservative, partly underestimating surface melting but still able to detect the most intense phase of the melting season. The M+30 K, M+35 K and M+40 K thresholds showed a strong overestimation problem, both in terms of duration and extent, with a high commission error. The MEMLS threshold does not show this problem, providing the best accuracy in terms of commission and omission error and still being able to detect sporadic melt events. For what concerns Antarctica, the comparison with in-situ data does not show equally satisfying results. A possible reason is related to the stronger presence of clouds and the different processes driving melting/freezing cycles in Antarctica with respect to Greenland. Using a lower frequency (e.g. 19 GHz) might lead to better results, removing the interference of strong precipitation events. According to these results, we used the melting maps obtained from 245 K and MEMLS to compute the long-term trends.

We then computed the trends of the selected melting parameters. According to the results with in situ data we consider more reliable the results obtained for Greenland, reported in Figure 3. The melt duration increased, on average, of 3.5 (4) days every decade according to 245 K (MEMLS) algorithm, the melt index increase of about 1.8% every year since 1979 and the maximum melting surface increased of 0.17% and 1.19 % every year. For what concerns the MOD and MED, we obtained statistically significant trends in the area towards the ocean only, with the melting season beginning on average 0.86 days earlier every year and ending 0.87 days later every year. For what concerns the Antarctica ice sheet we did not find statistically significant trends. However, we consider these results less reliable than the ones obtained for the Greenland ice sheet and we think that further analysis including other datasets are necessary.

4) Conclusion

The measured ice sheet mass loss in Greenland and Antarctica is accompanied by a general increment of surface melting. For the Greenland case, the computed trends show an increment of surface melting in terms of both duration and spatial extension, with peaks around the coasts where the most intense mass loss is also recorded. For the Antarctica case, further investigations are needed in order to obtain stronger results, using different satellite data and simulations of climate models.

5) Figure

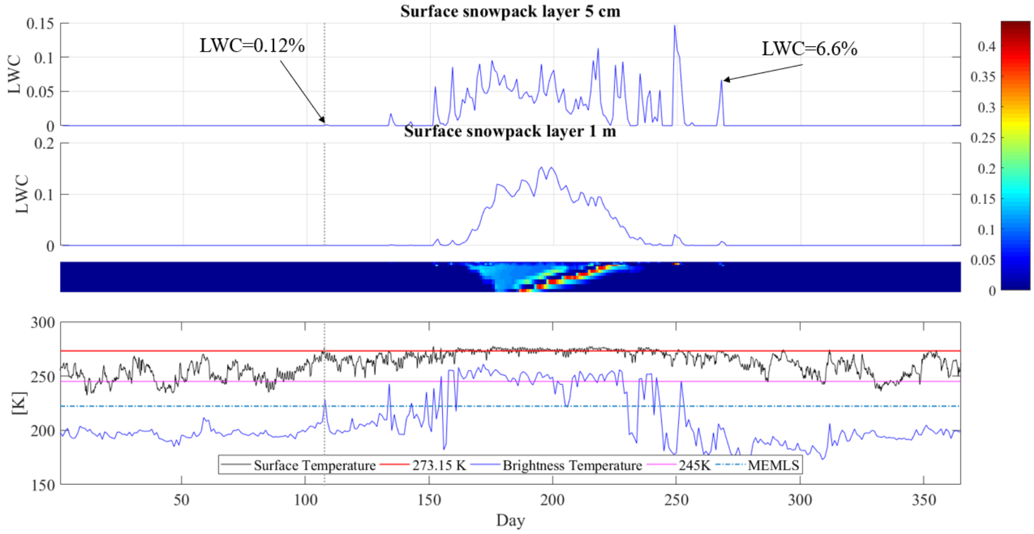

Figure 1 Timeseries of the datasets used for Greenland at Swiss Camp Site (2001). In the first two panels the LWC in the first 5 cm and 1m of snowpack from MAR is reported. In the third panel the evolution of the vertical profile of LWC simulated by MAR. In the bottom panel timeseries of brightness temperature (blue) and air temperature (black) are reported. The thresholds are represented as horizontal lines.

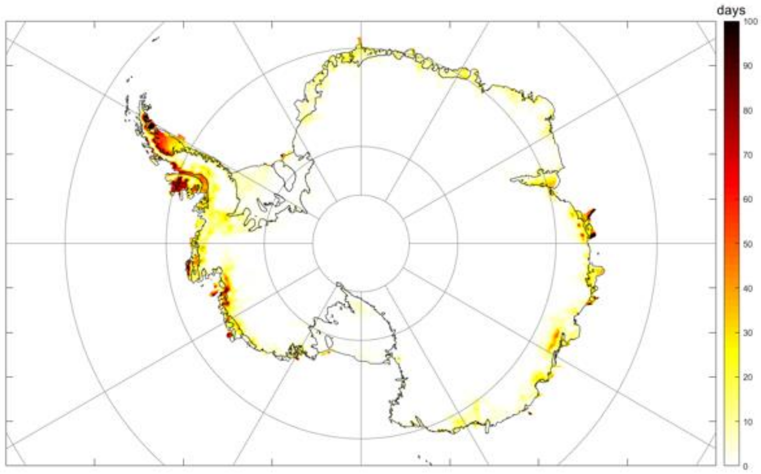

Figure 2 Melt duration map of Antarctica for the 2008-2009 summer, computed as the total number of melting days detected in one year.

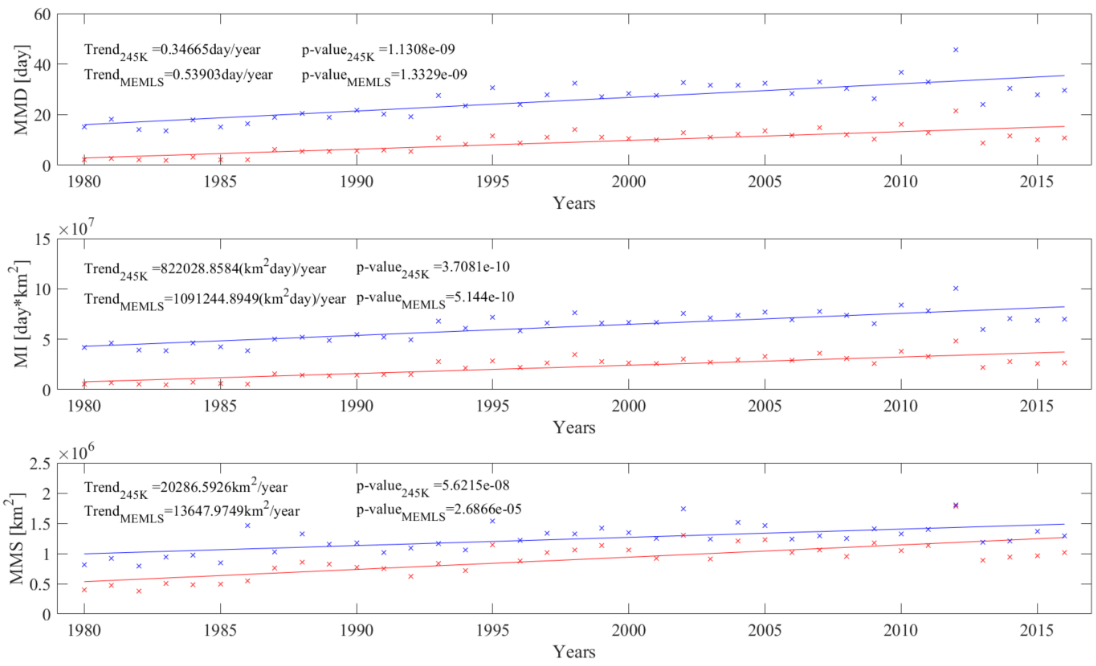

Figure 3 Trends of the synthetic melt parameters (MMD, mean melt duration; MI, melt index; MMS, maximum melting surface) computed for Greenland.

Trend dei principali parametri sintetici di fusione (MMD, durata media della fusione; MI, melt index; MMS, massima estensione della fusione).

6) Reference

Fettweis, X., Tedesco, M., van den Broeke, M., & Ettema, J. Melting trends over the Greenland ice sheet (1958–2009) from spaceborne microwave data and regional climate models, The Cryosphere, 5, 359–375, 2011.

Macelloni, G., Paloscia, S., Pampaloni, P., Brogioni, M., Ranzi, R. & Crepaz, A. Monitoring of melting refreezing cycles of snow with microwave radiometers: The Microwave Alpine Snow Melting Experiment (MASMEx 2002-2003), IEEE Transactions on Geoscience and Remote Sensing, 43(11), 2431-2442, 2005.

Portner, H.O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Nicolai, M., Okem, A., Petzold, J. & Rama, B. IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, 2019.

Rignot, E., Velicogna, I., van den Broeke, M.R., Monaghan, A. & Lenaerts, J.T.M. Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, Geophysical Research Letters, 38(5), 2011.

Tedesco, M. Assessment and development of snowmelt retrieval algorithms over Antarctica from K-band spaceborne brightness temperature (1979–2008), Remote Sensing of Environment, 113(5), 979–997, 2009.

Tedesco, M. & Fettweis, X. Unprecedented atmospheric conditions (1948-2019) drive the 2019 exceptional melting season over the Greenland ice sheet, The Cryosphere, 14(4), 1209–1223, 2020.

Ulaby, F.T., Moore, R.K., & Fung, A.K. Microwave remote sensing: Active and passive. Volume 3-From theory to applications, 1986.

Zwally, H.J. & Fiegles, S. Extent and duration of Antarctic surface melting, Journal of Glaciology, 40(136), 463–475, 1994.