The Cyclonic Mode of Arctic Ocean Surface Circulation

CLIVAR Observing, Modeling, and Understanding the Circulation of the Arctic Ocean and Sub-Arctic Seas Workshop

June 27-30, 2022

Jamie Morison

Polar Science Center

University of Washington

jhm2@uw.edu

Acknowledgements

Ron Kwok, Suzanne Dickinson, Ignatius Rigor, Roger Anderson, Cecilia Peralta-Ferriz, John Guthrie, Sarah Dewey

In Situ Observing Concentrated in the Beaufort Sea

- Over the last 30 years *in situ* observations largely concentrated in the Beaufort Sea and Transpolar Drift have revealed a freshening and increased strength of the anticyclonic Beaufort Gyre leading to the impression that the whole Arctic Ocean circulation has become more anticyclonic [e.g., *Hofmann et al.* 2015; *McPhee et al.* 2009; *Proshutinsky et al.* 2015; *Proshutinsky et al.* 2009]

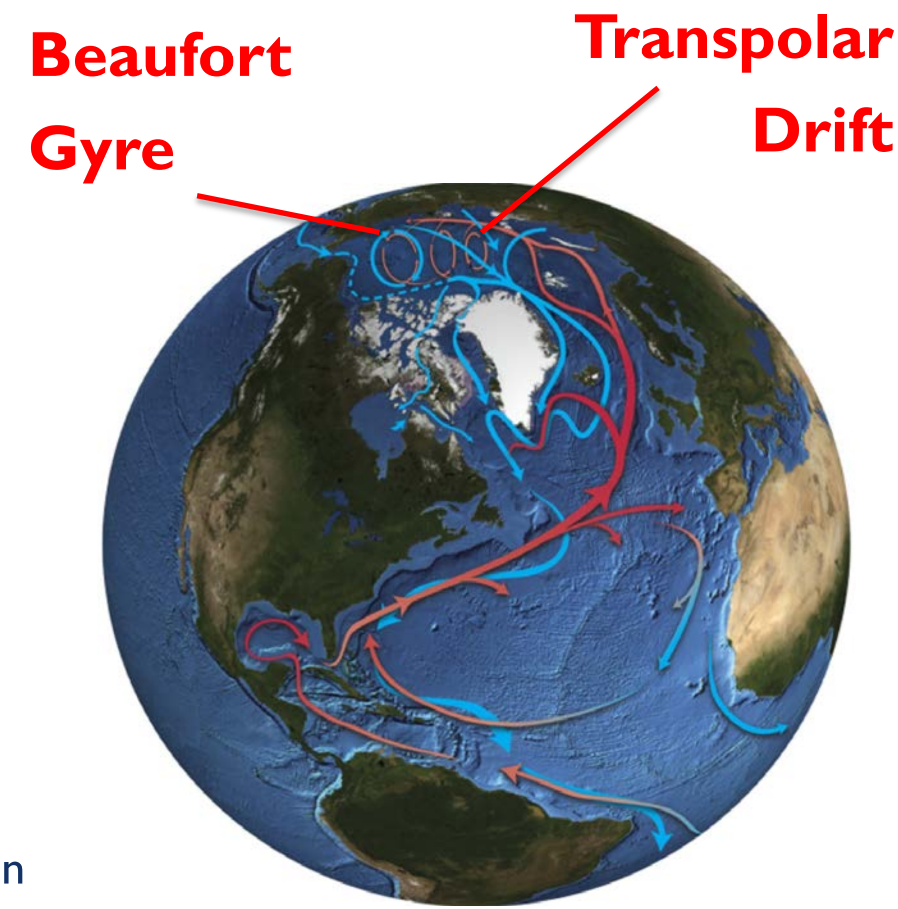


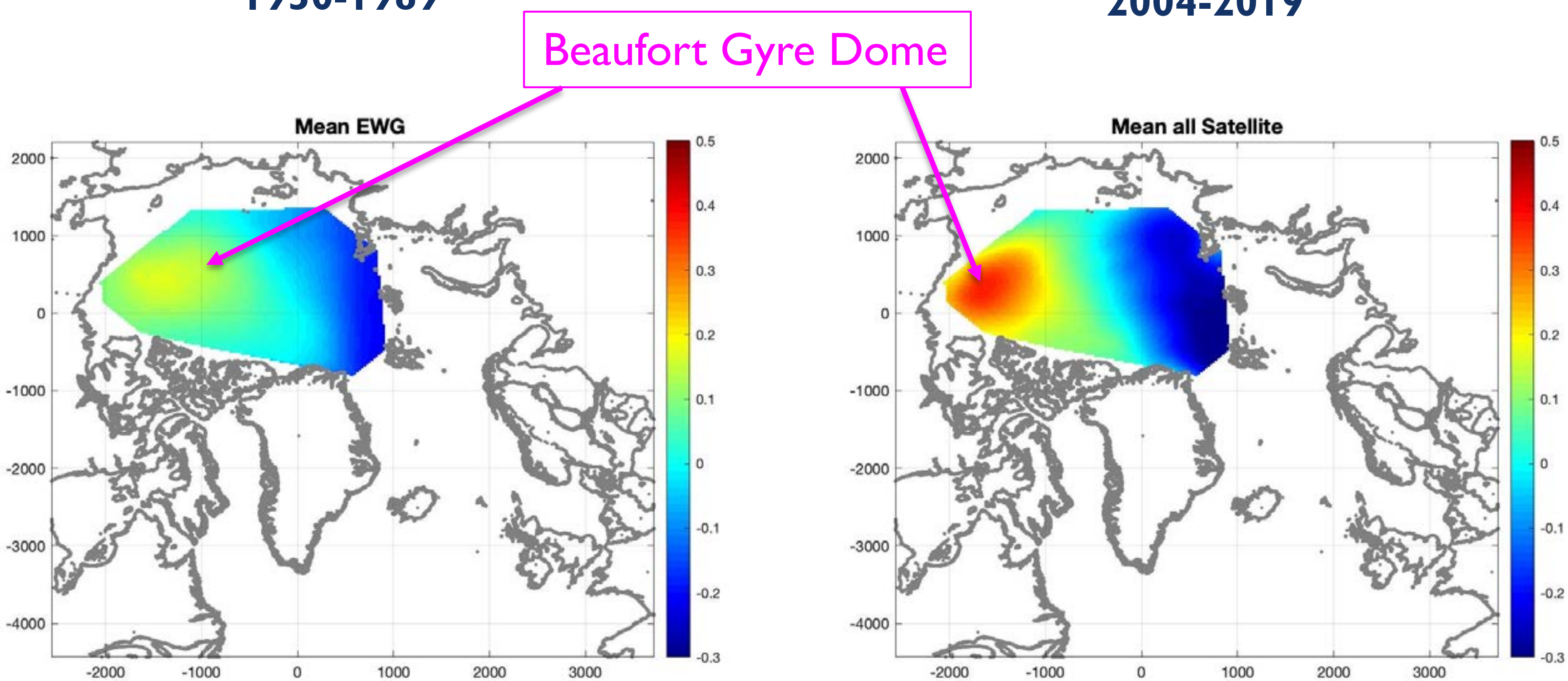
Figure 1 from Hoffman et al. (2015)

Hoffman et al. [2015]:“ An anticyclonic circulation regime has dominated in this region (Arctic Ocean) for the past ~16 years, intensifying the buildup of fresh water in the gyre”.

The Beaufort Gyre is a key feature of the mean Arctic Ocean circulation but does its strength dominate variability? Let's look at the annual anomalies of DH_{500} and DOT about their means and see.

Mean Winter DH_{500}, 1950-1989

Mean Winter ICESat/CryoSat2 DOT, 2004-2019



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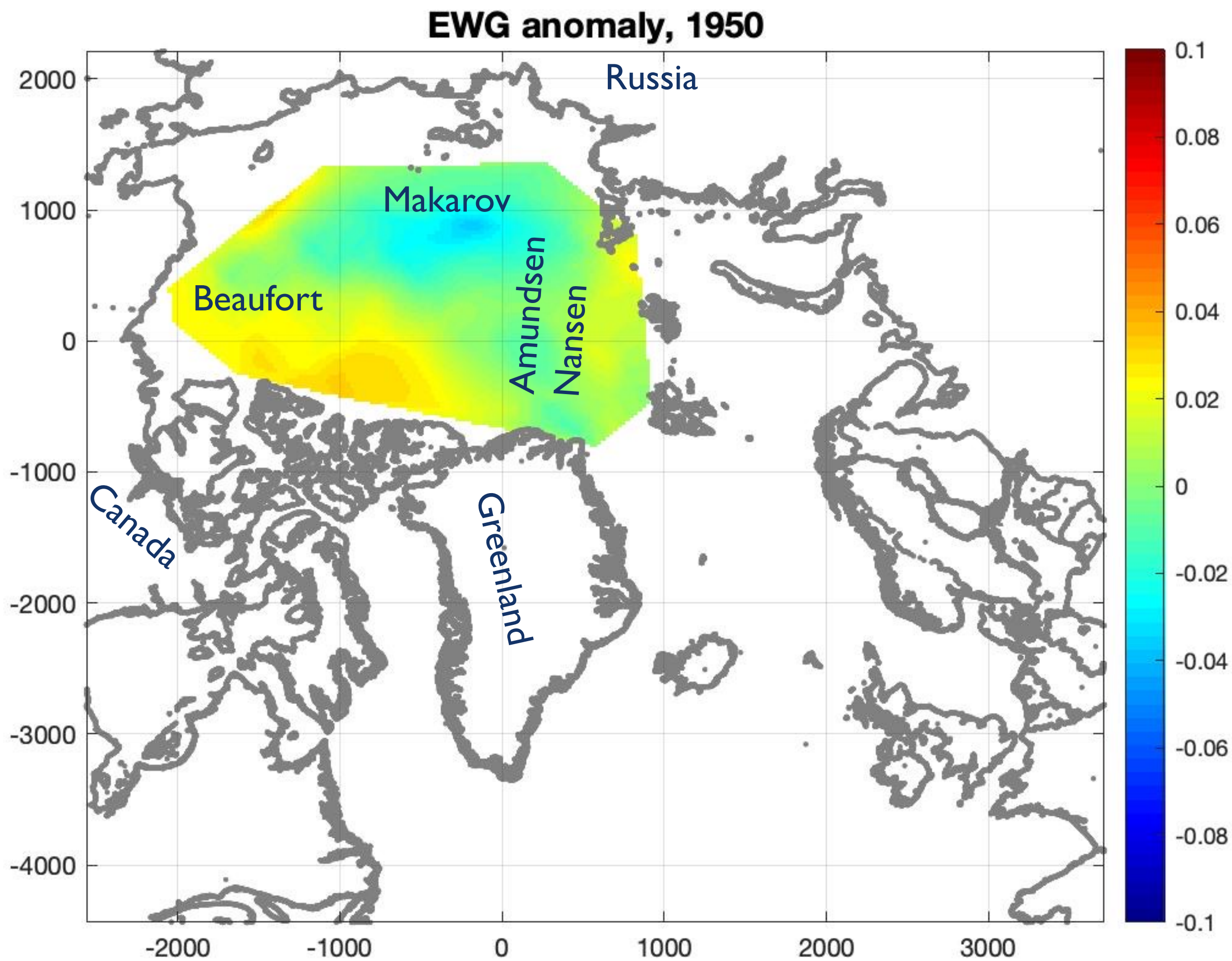

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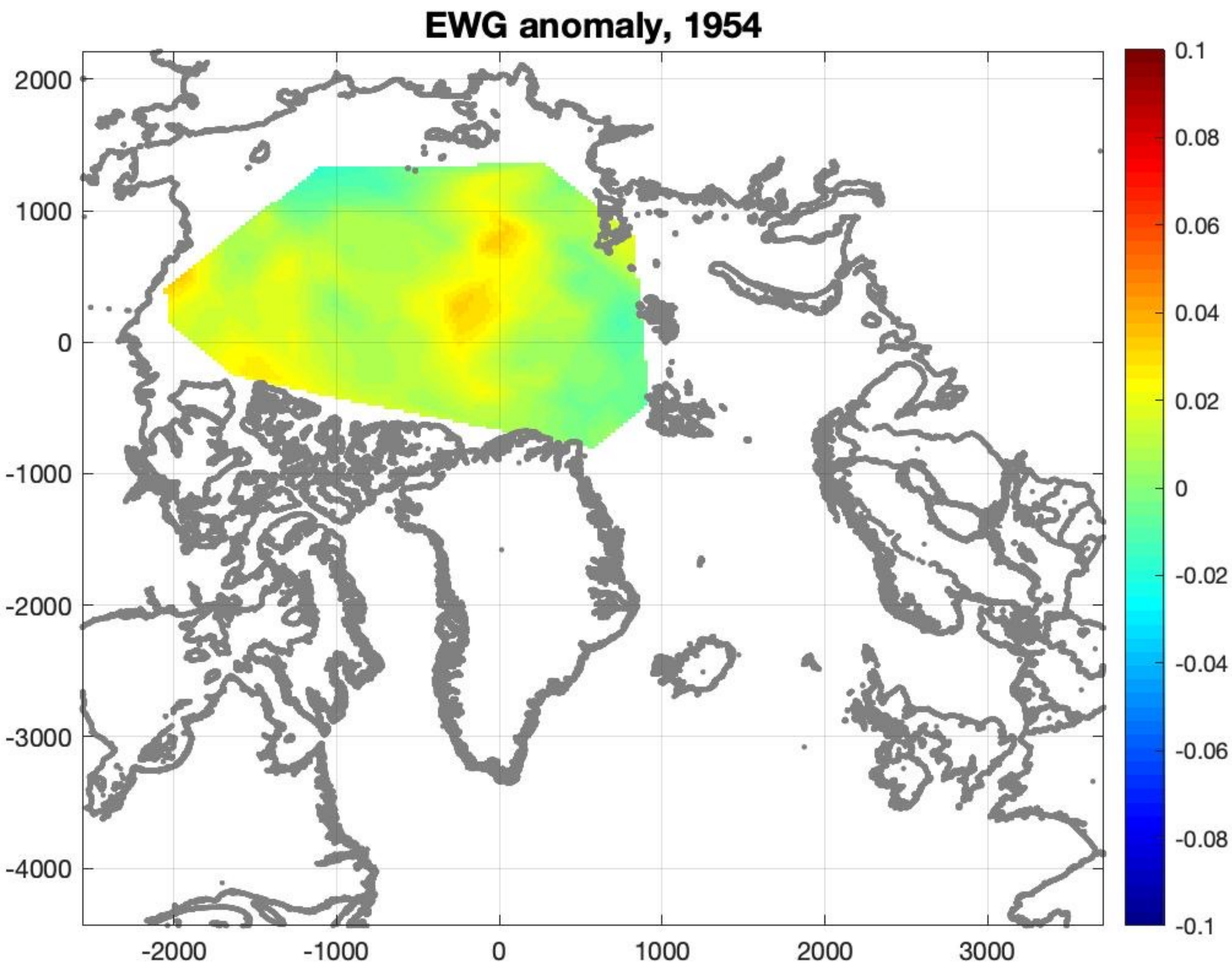

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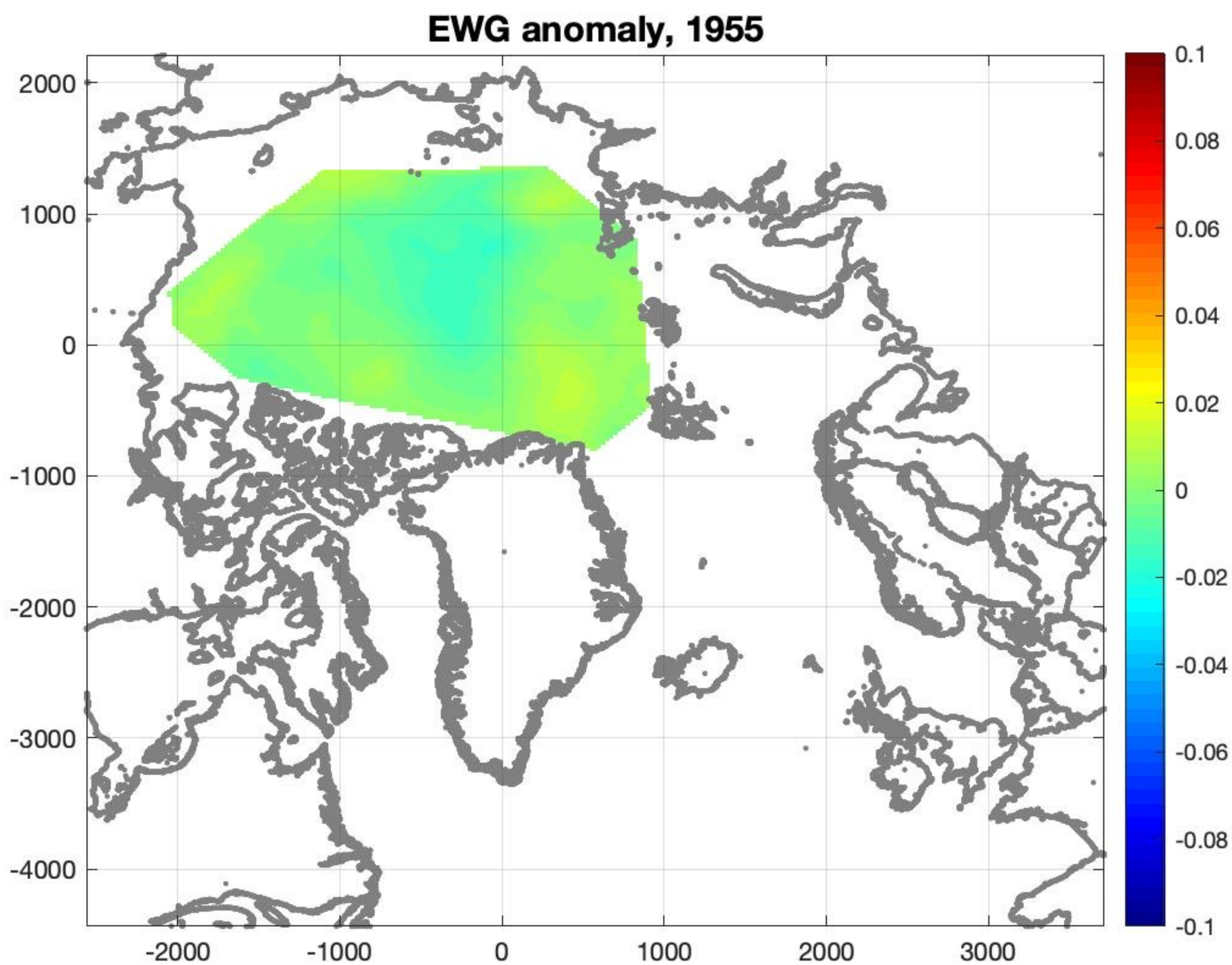

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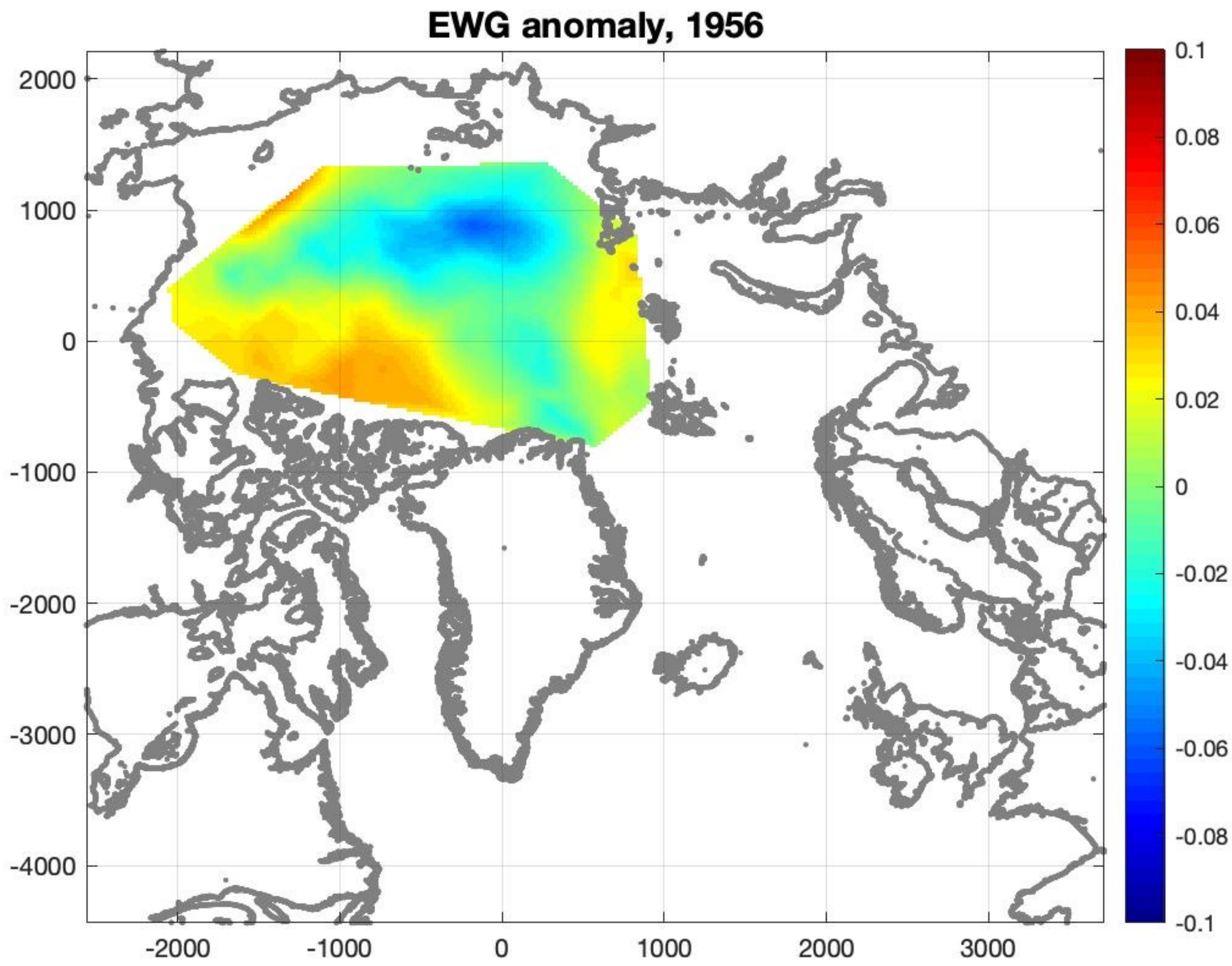

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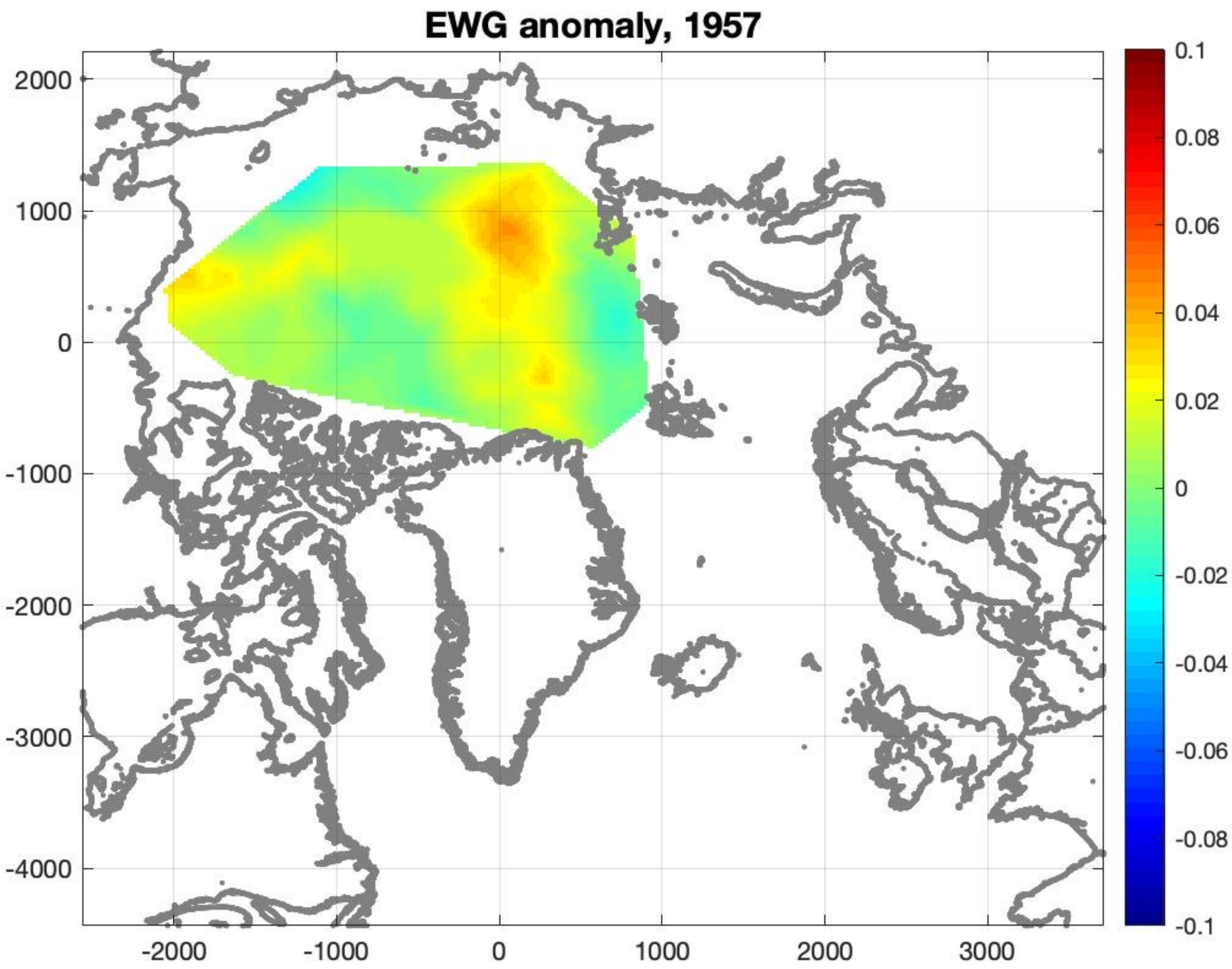

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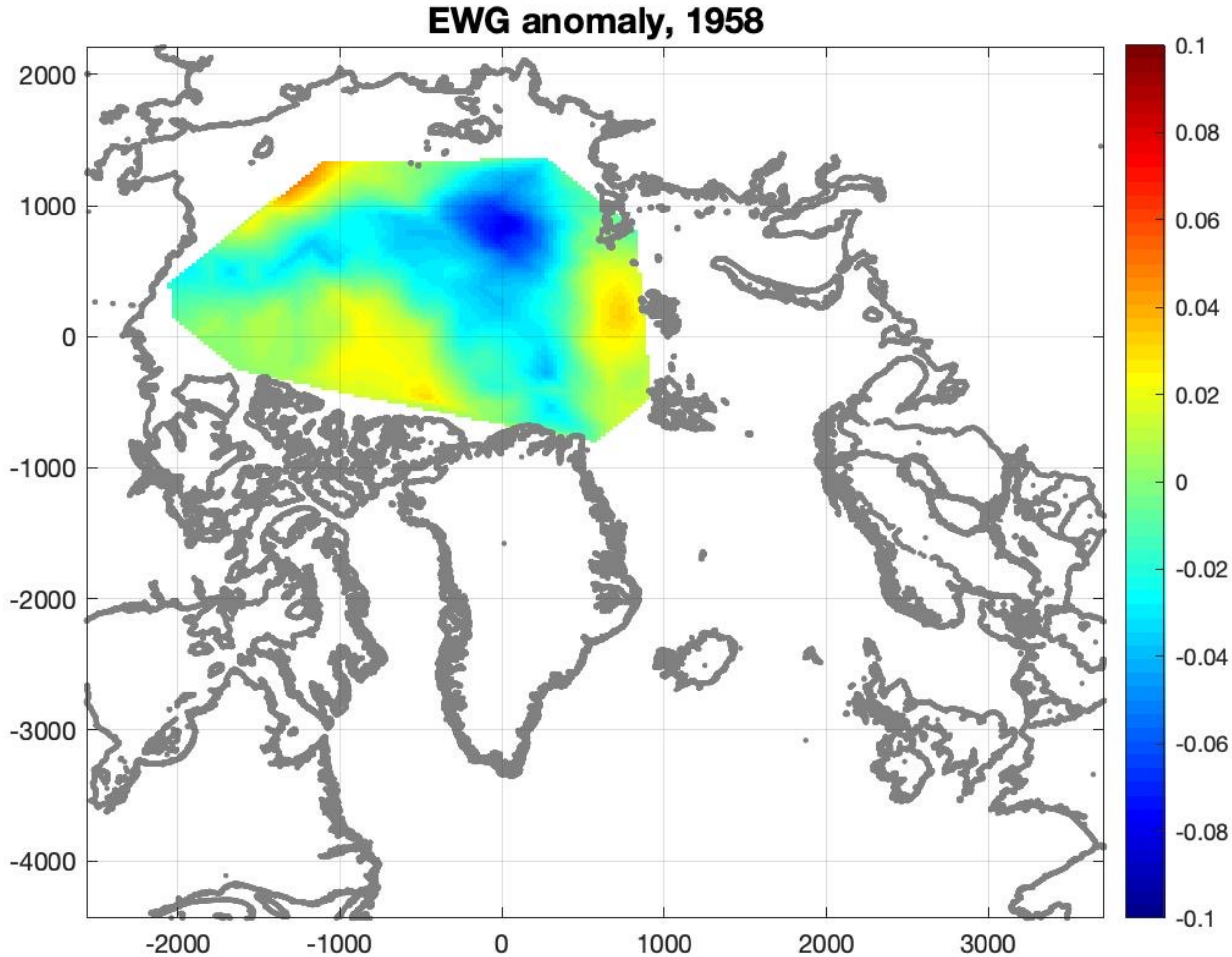

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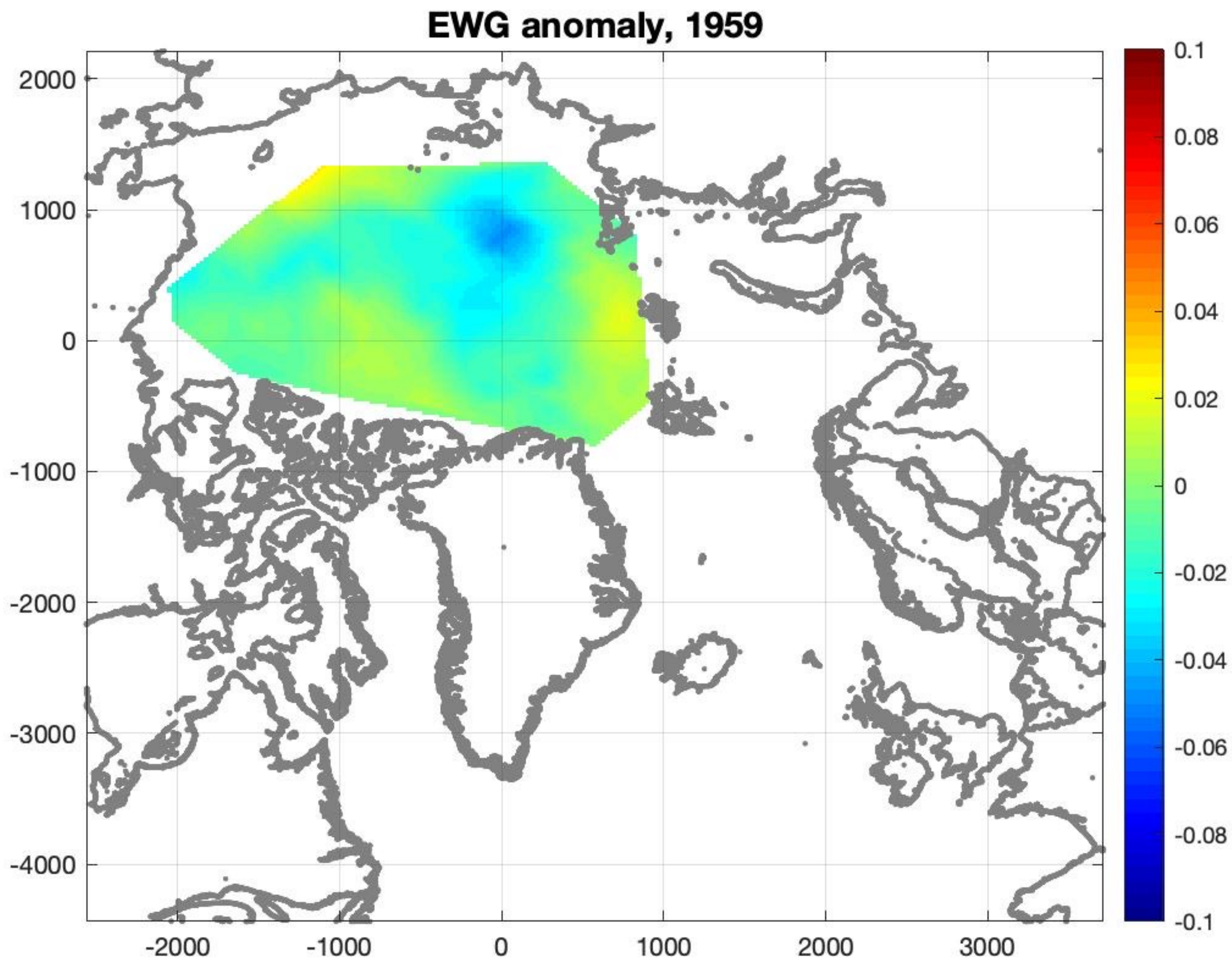

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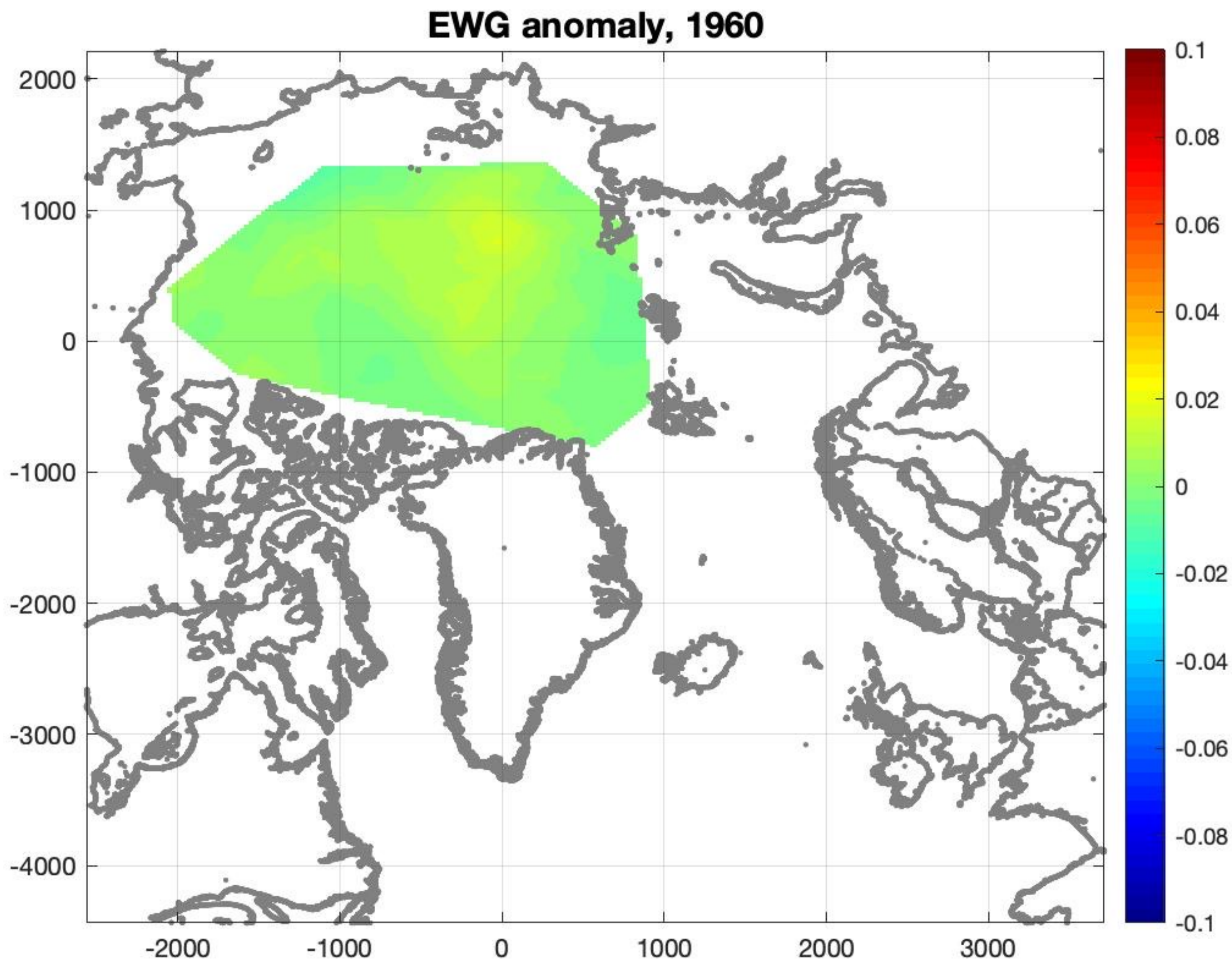

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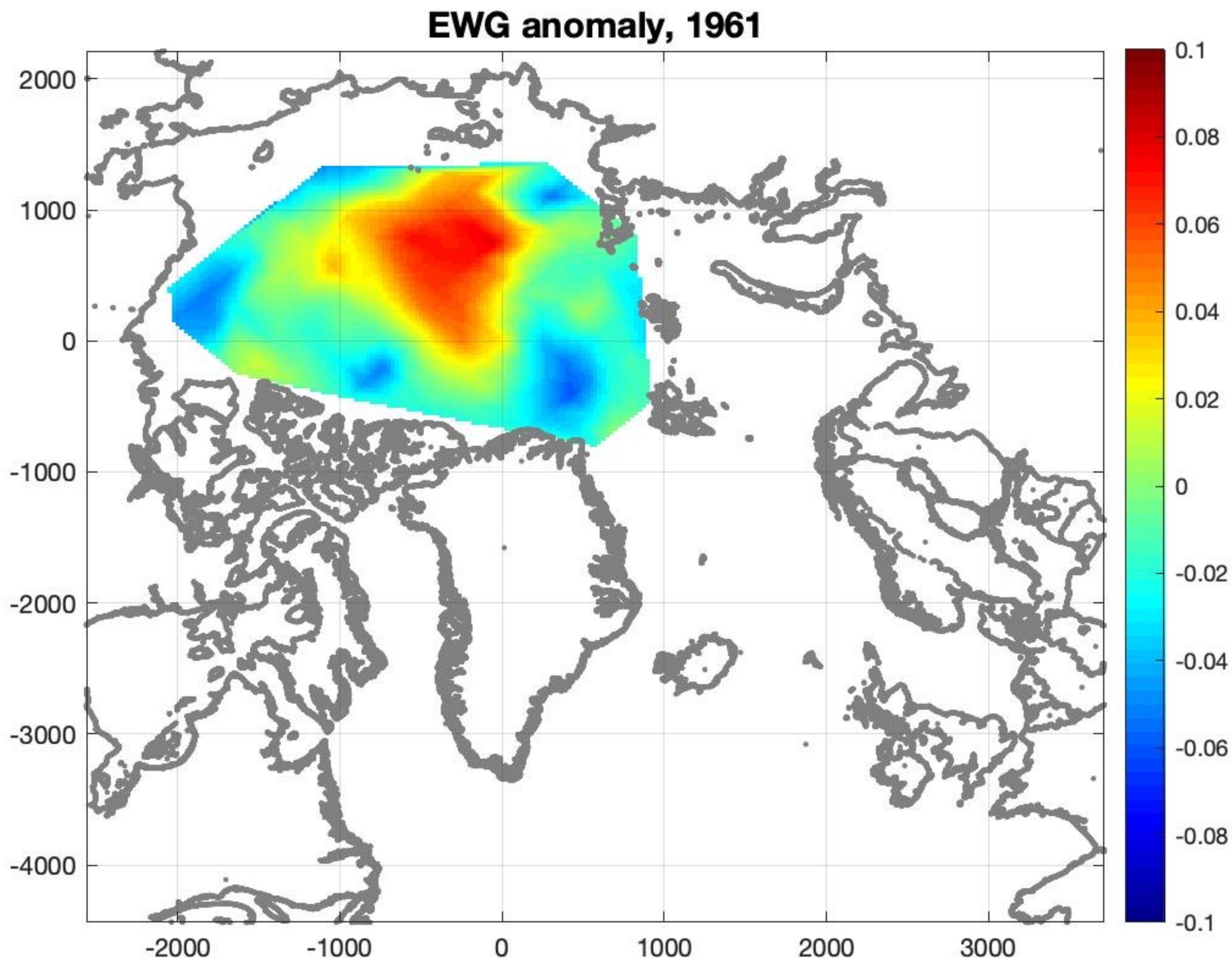

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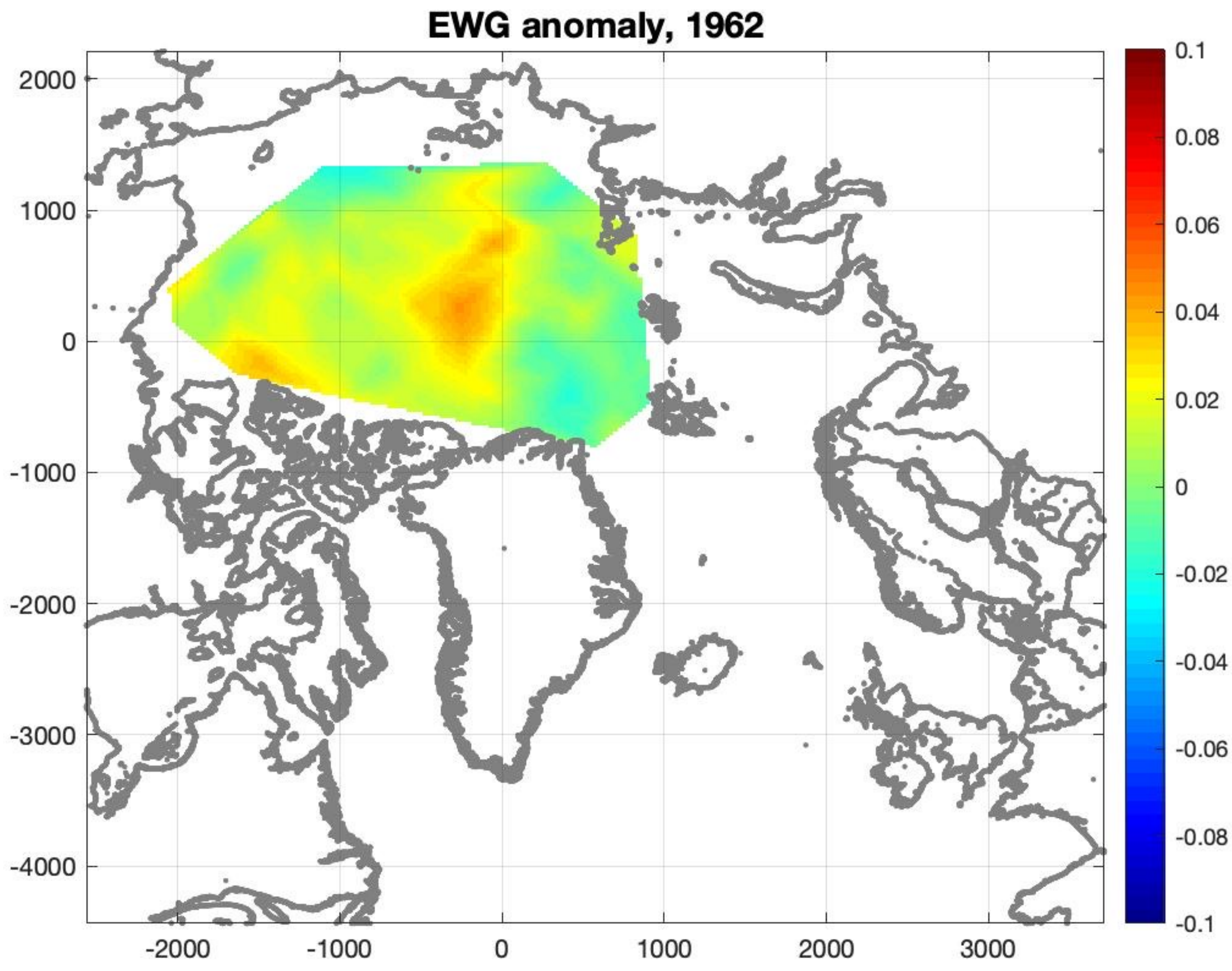

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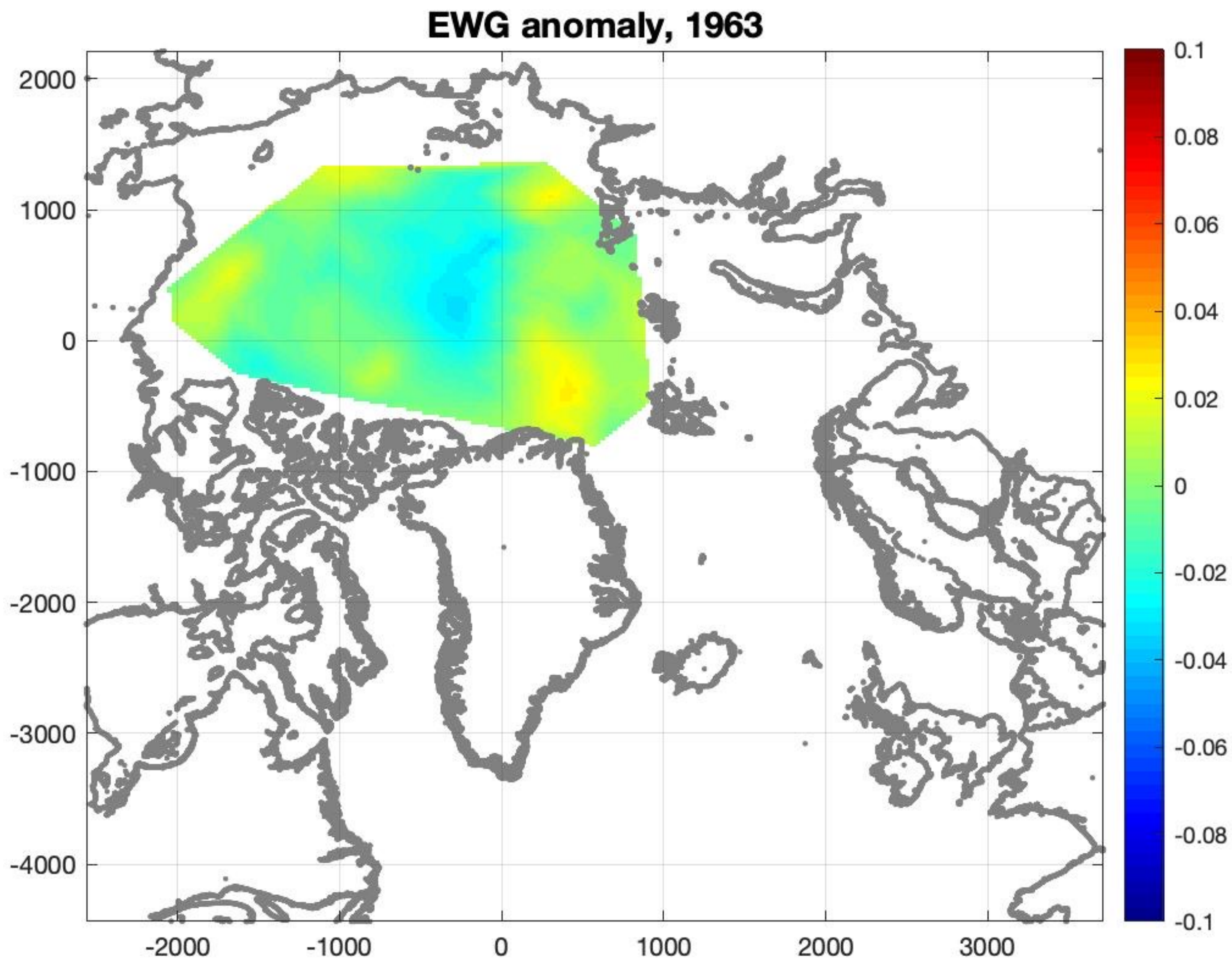

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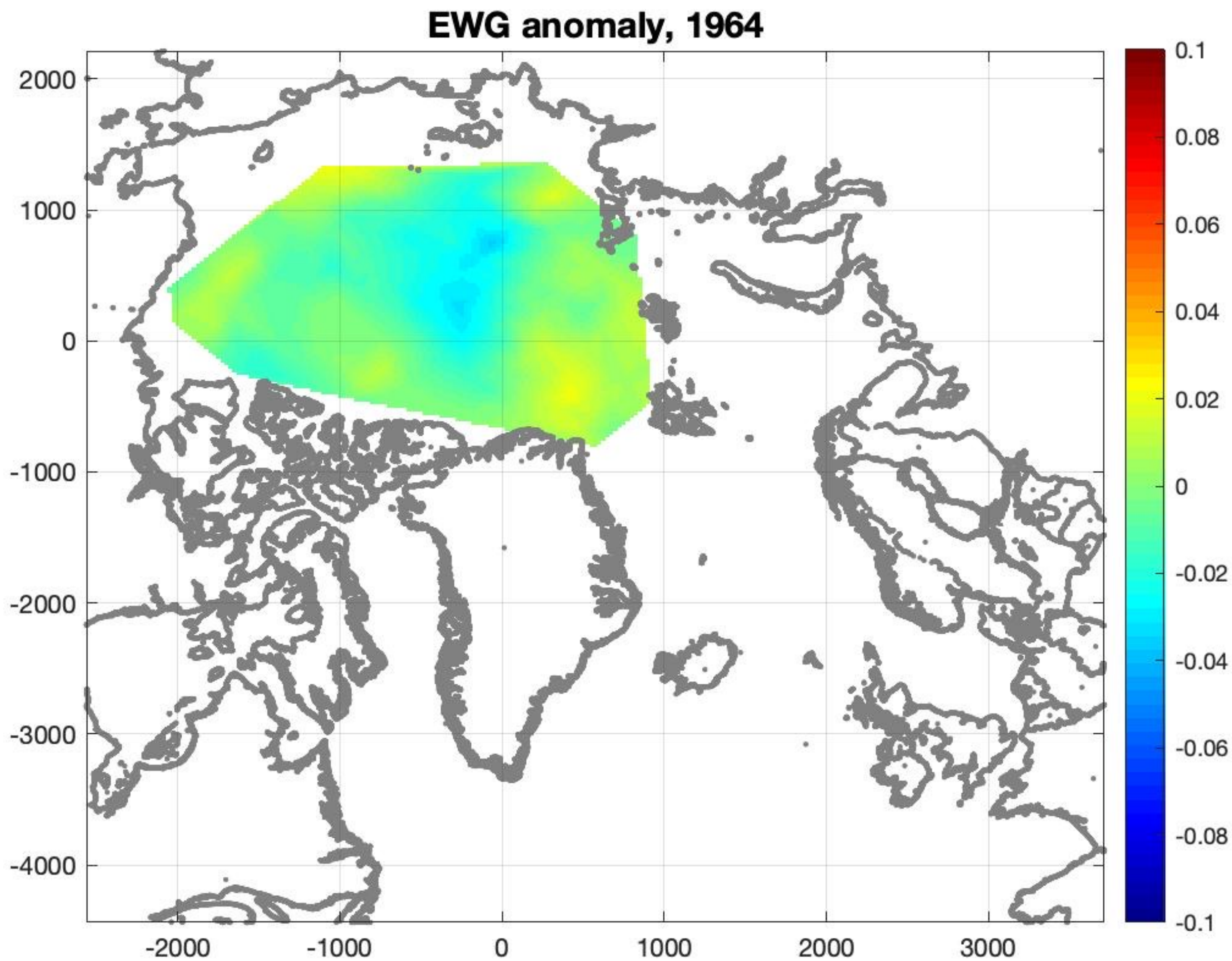

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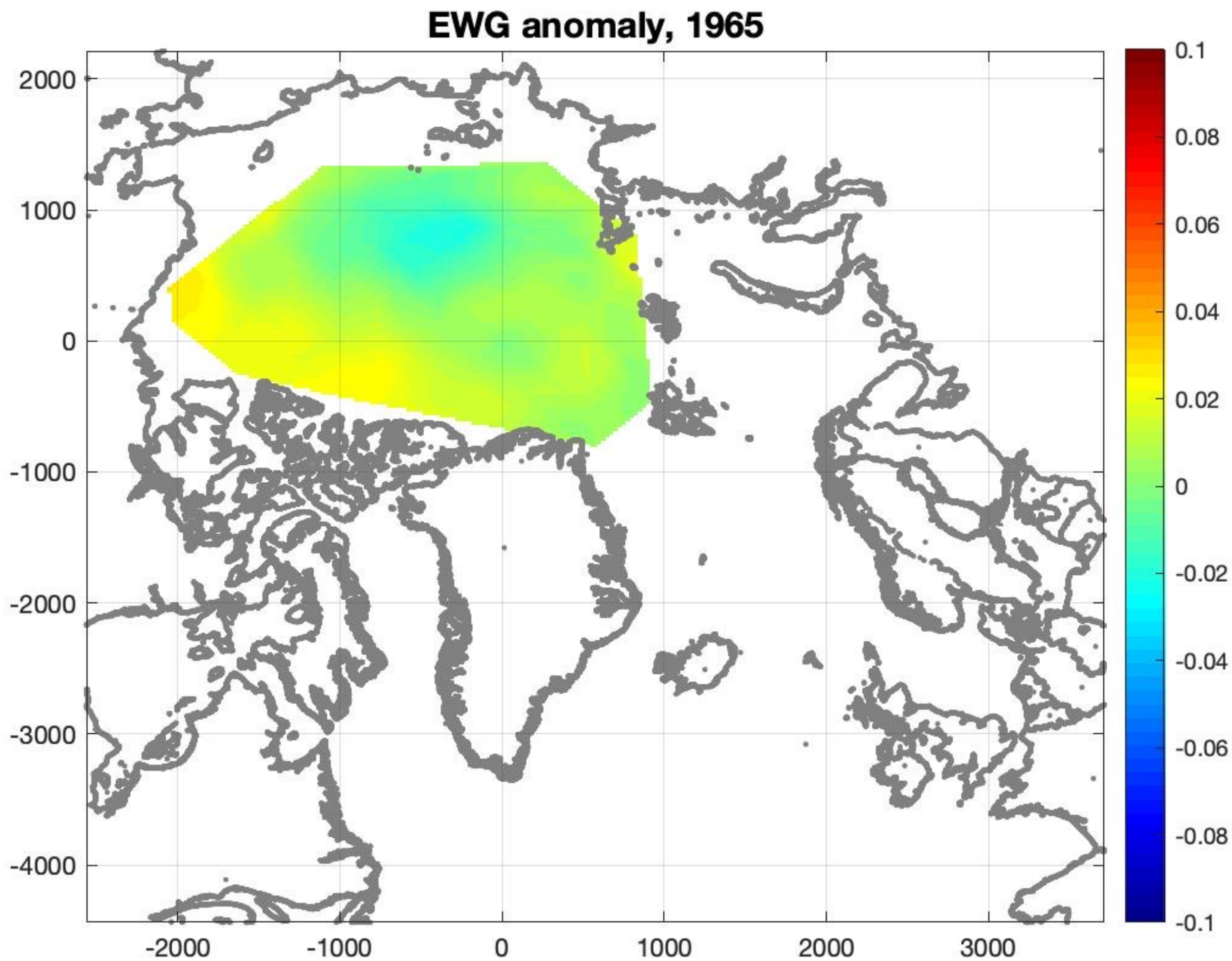

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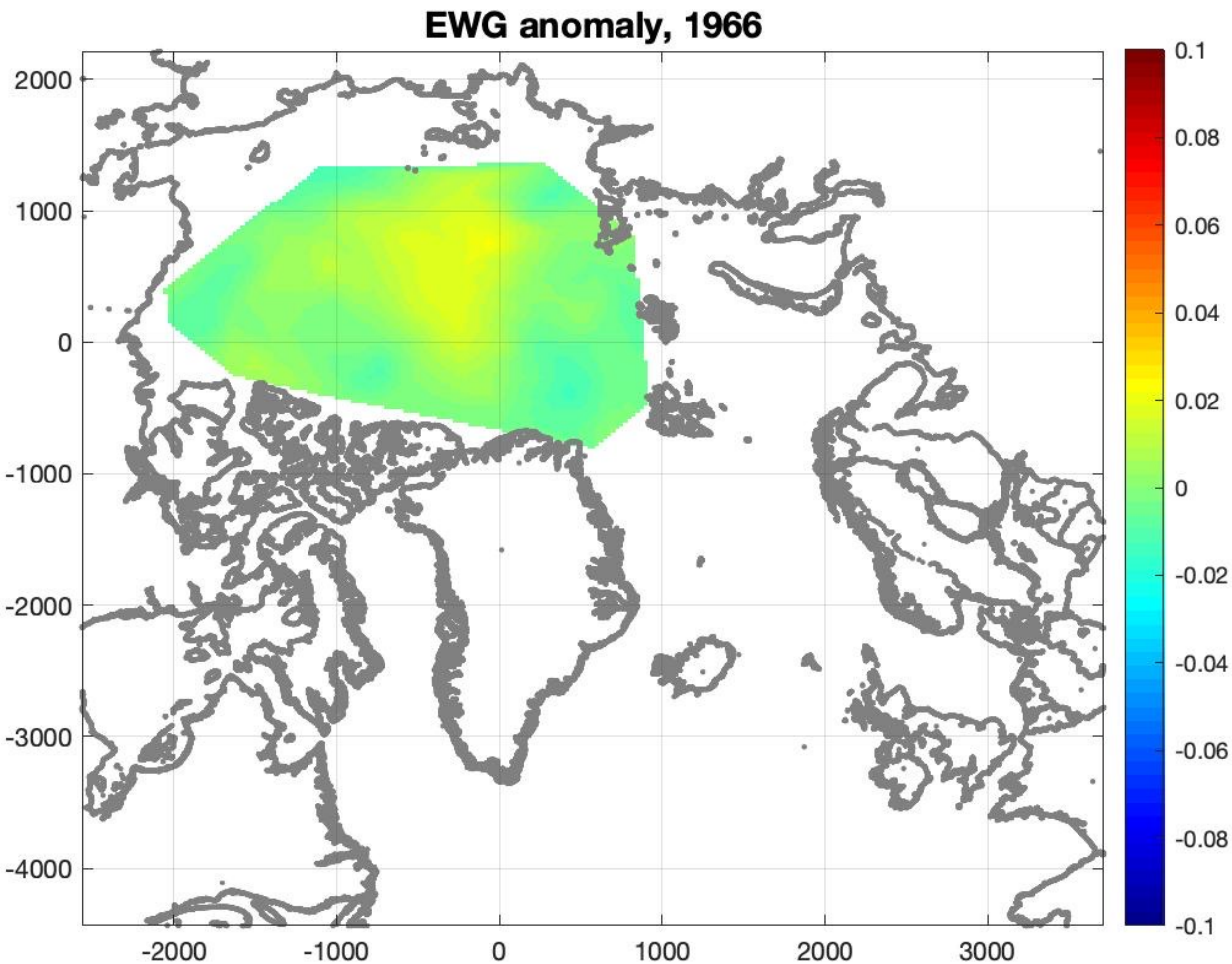

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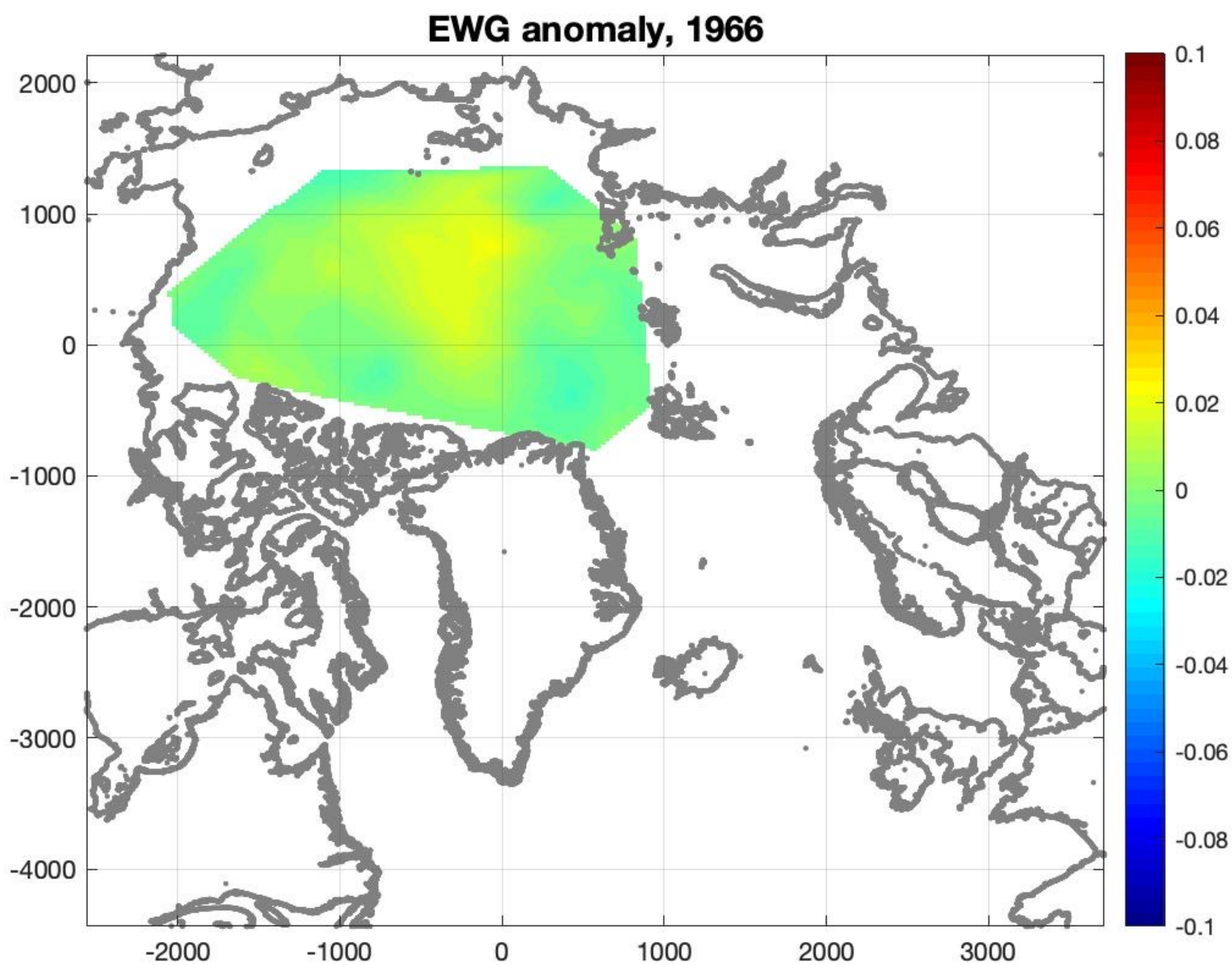

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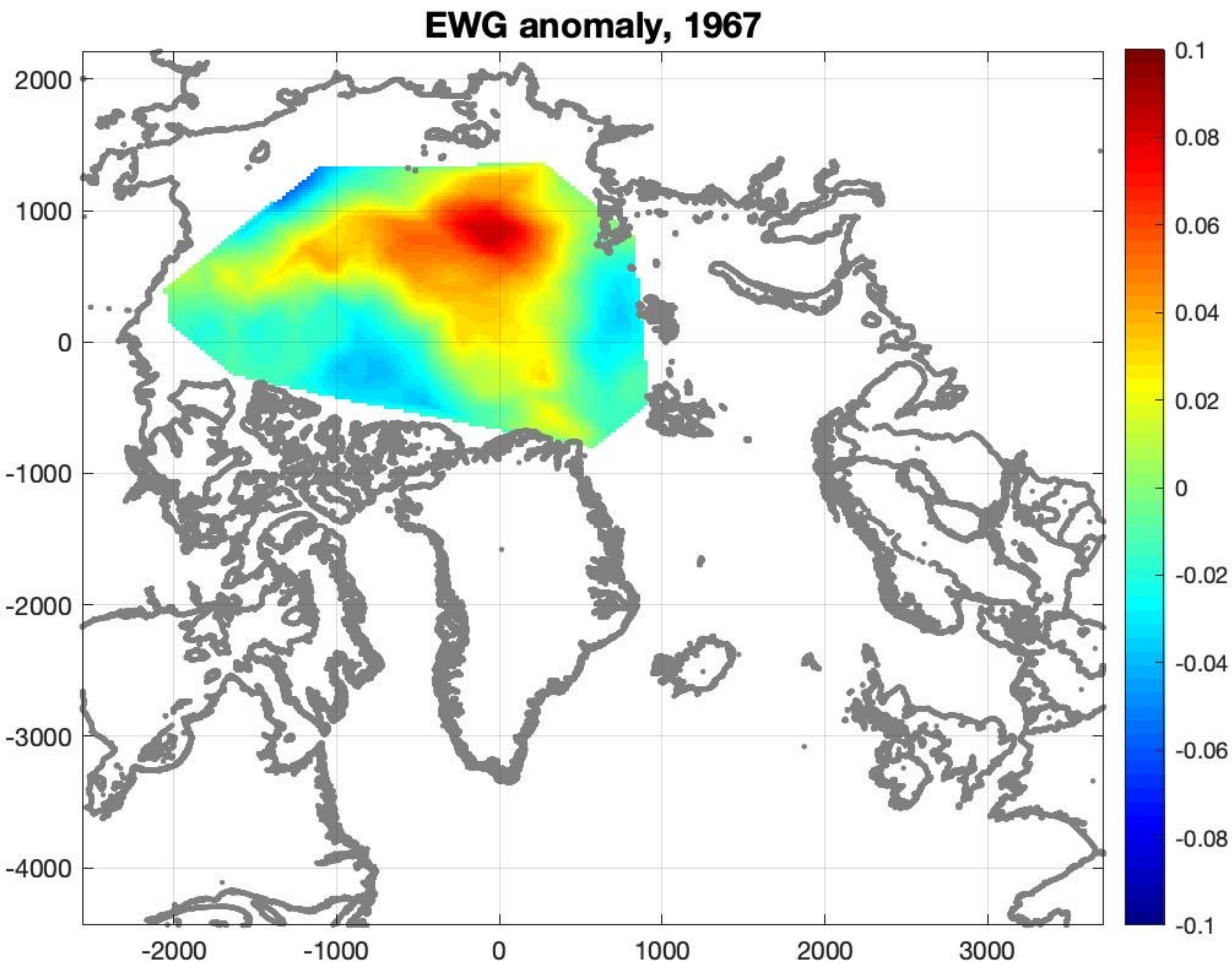

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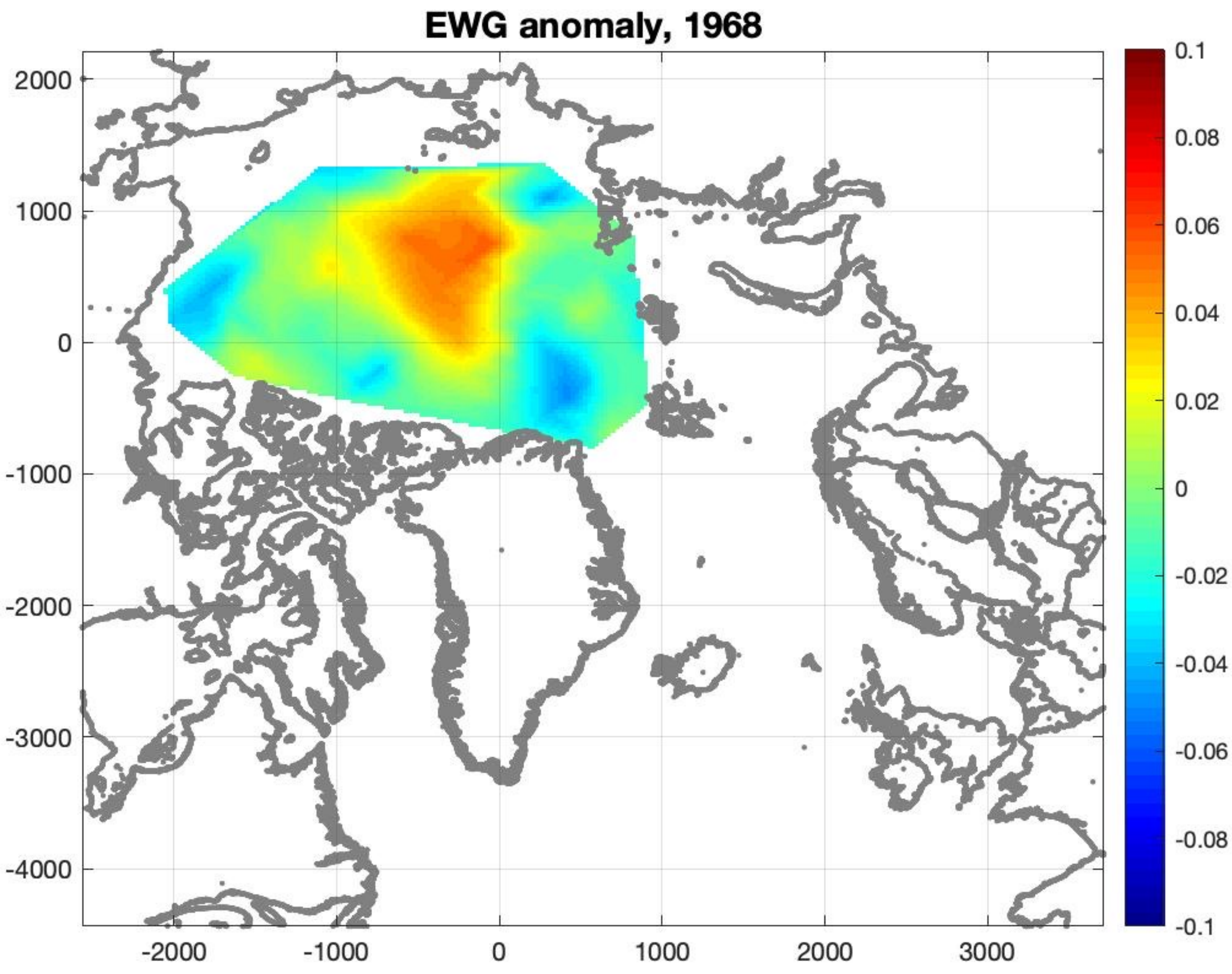

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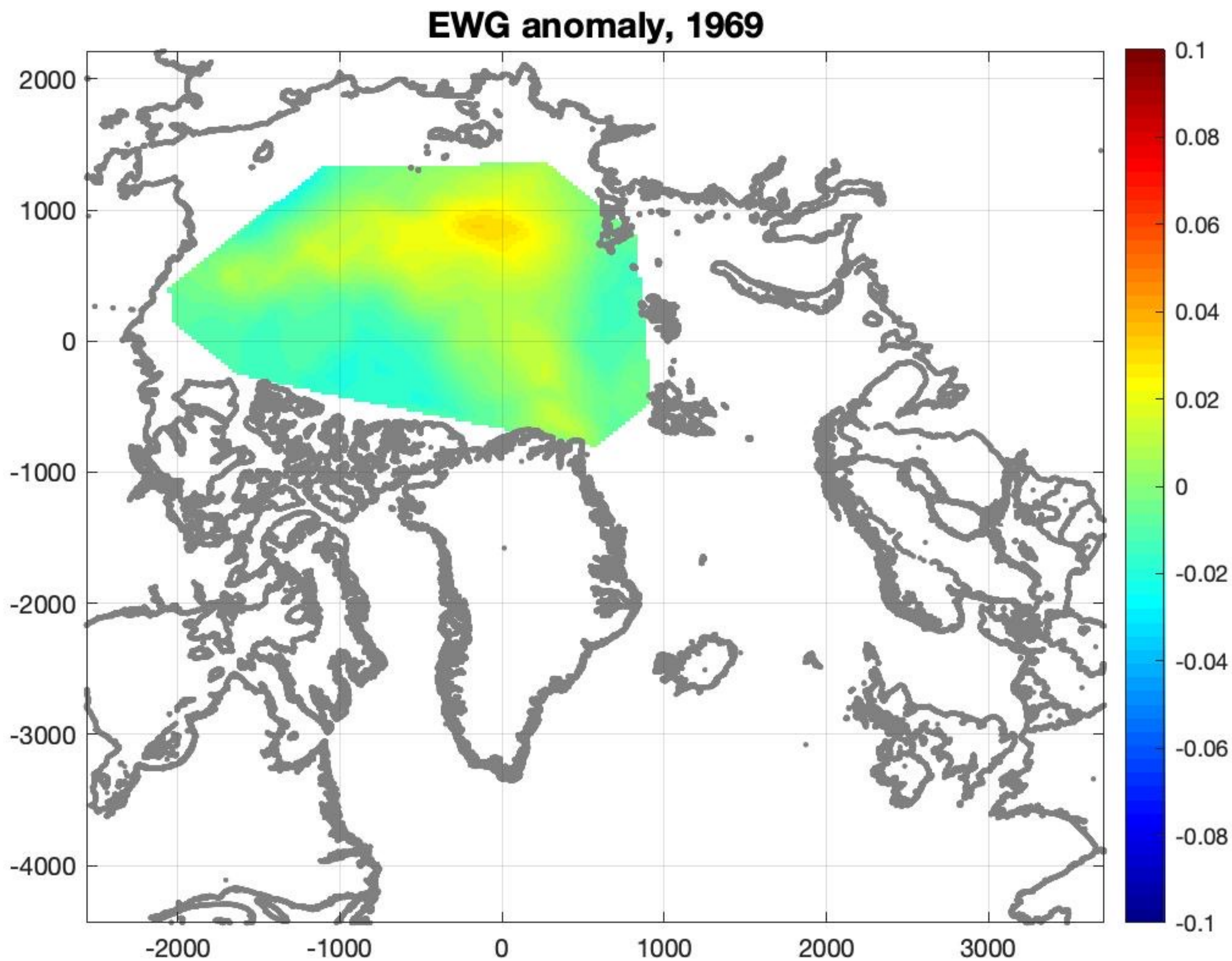

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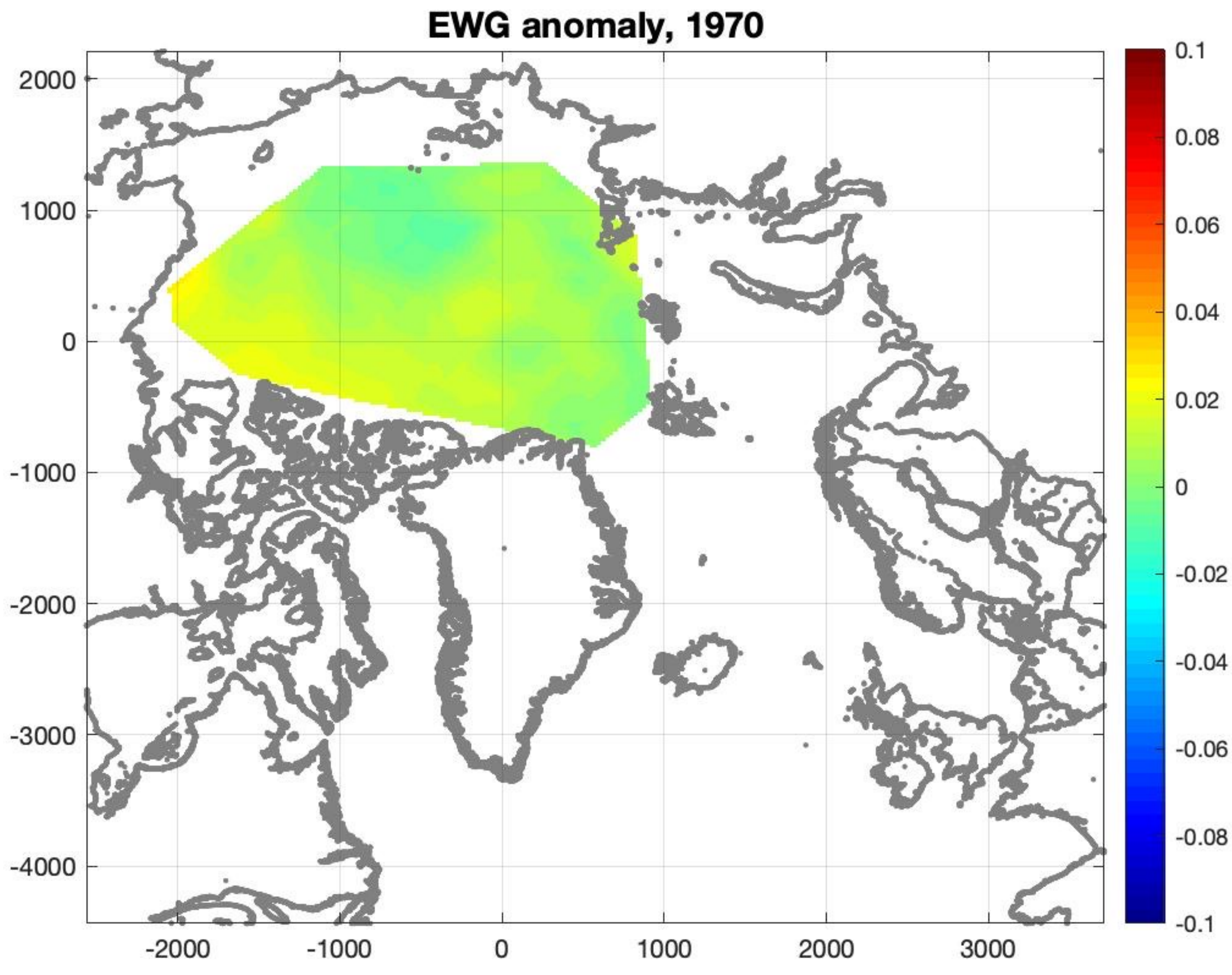

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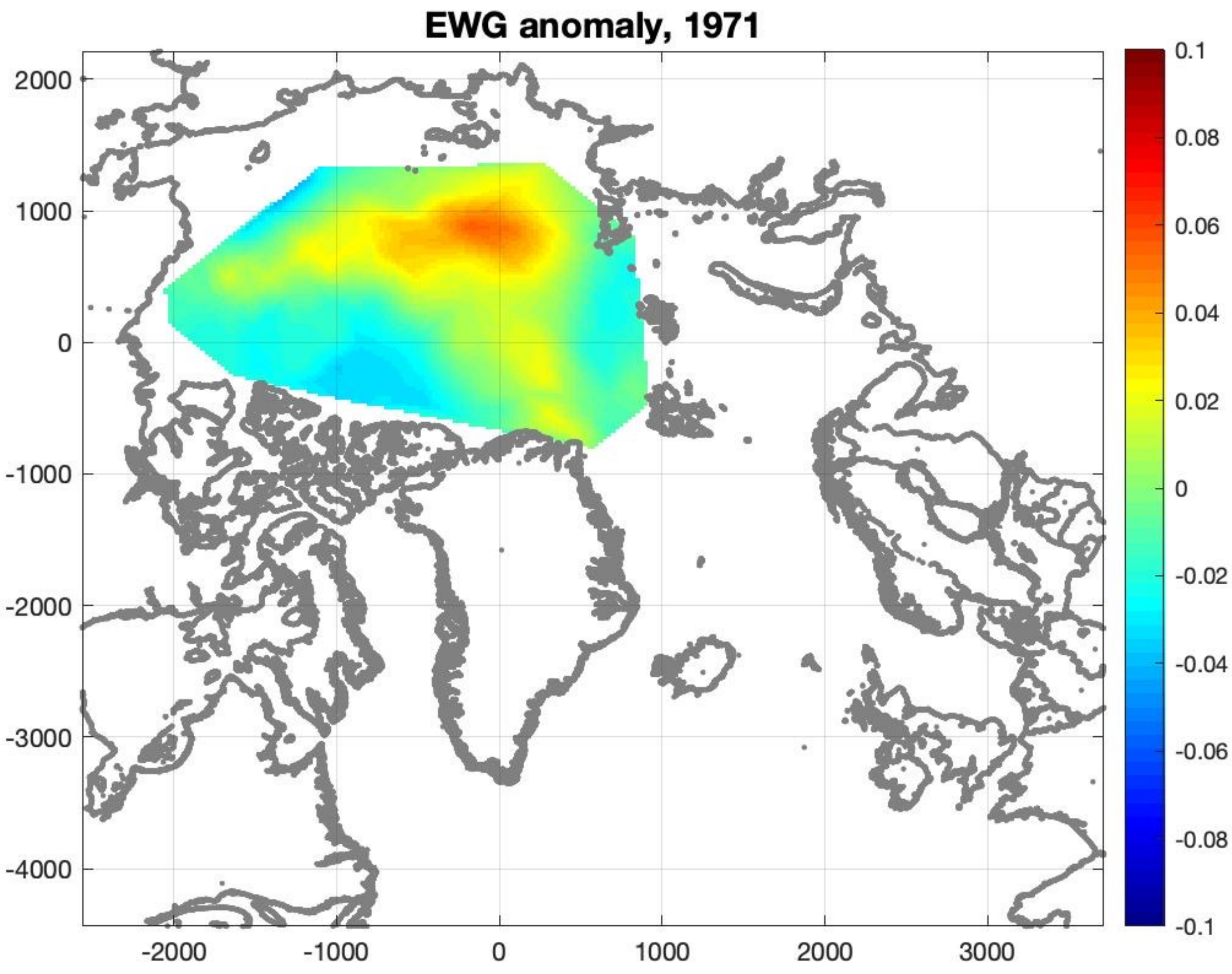

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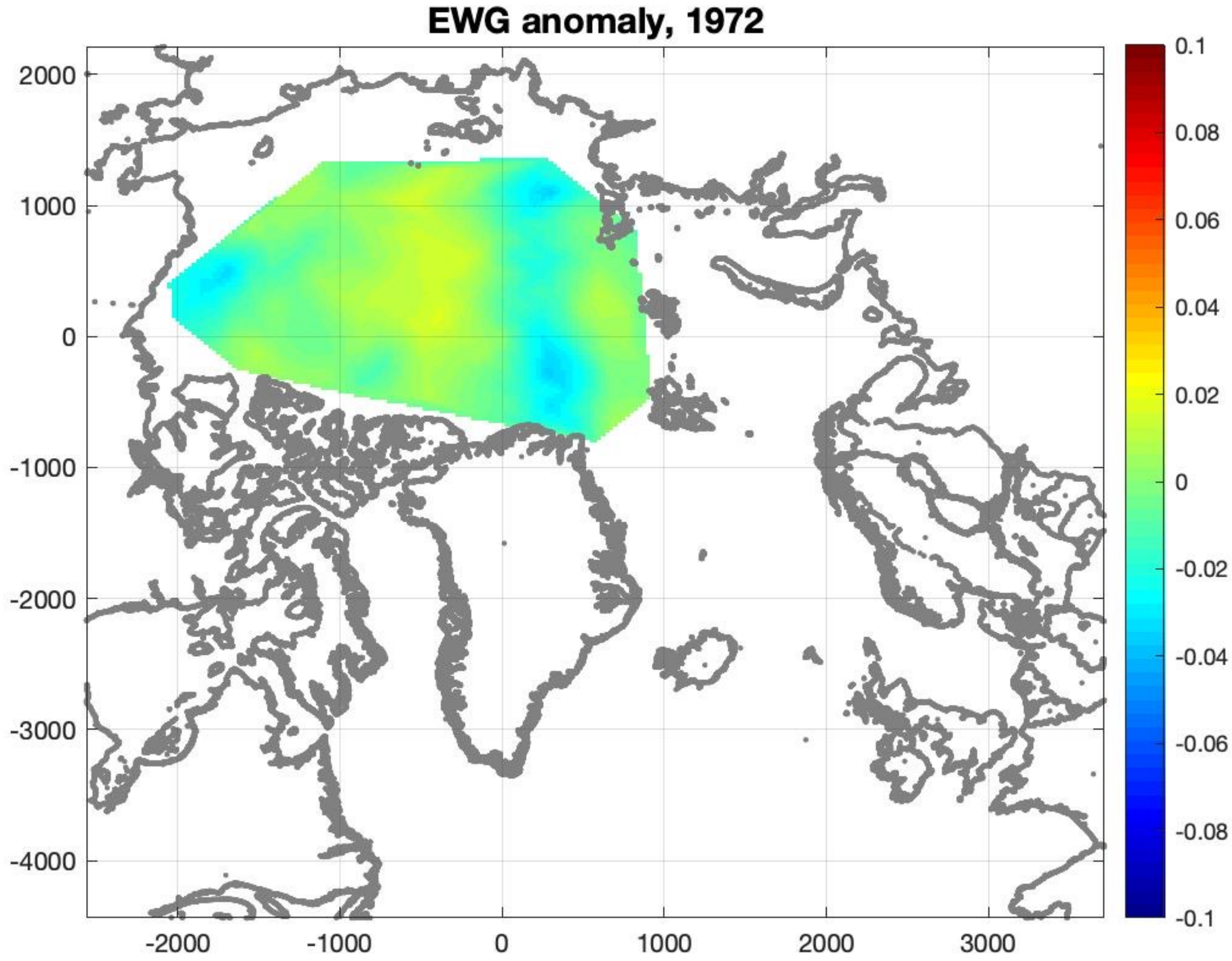

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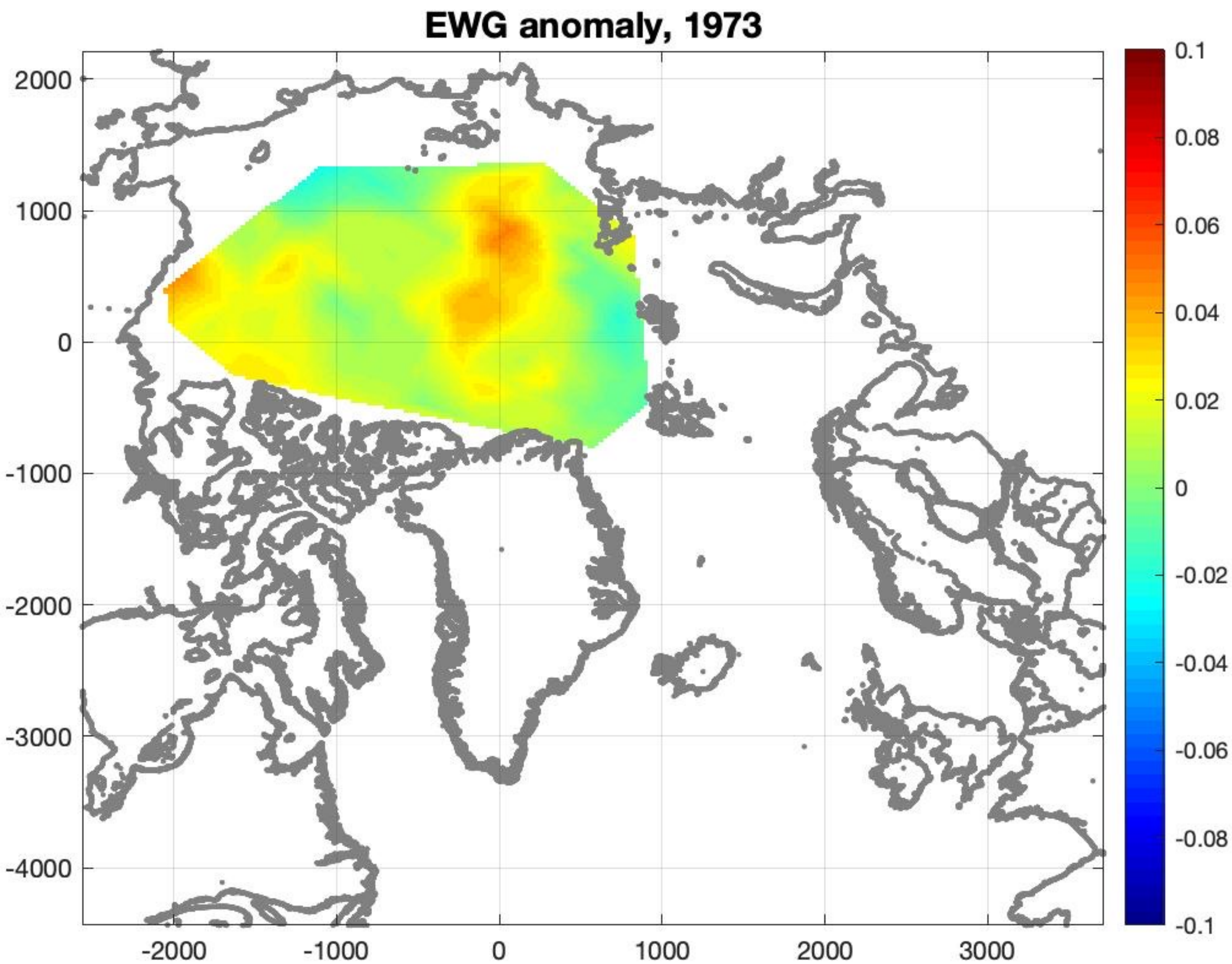

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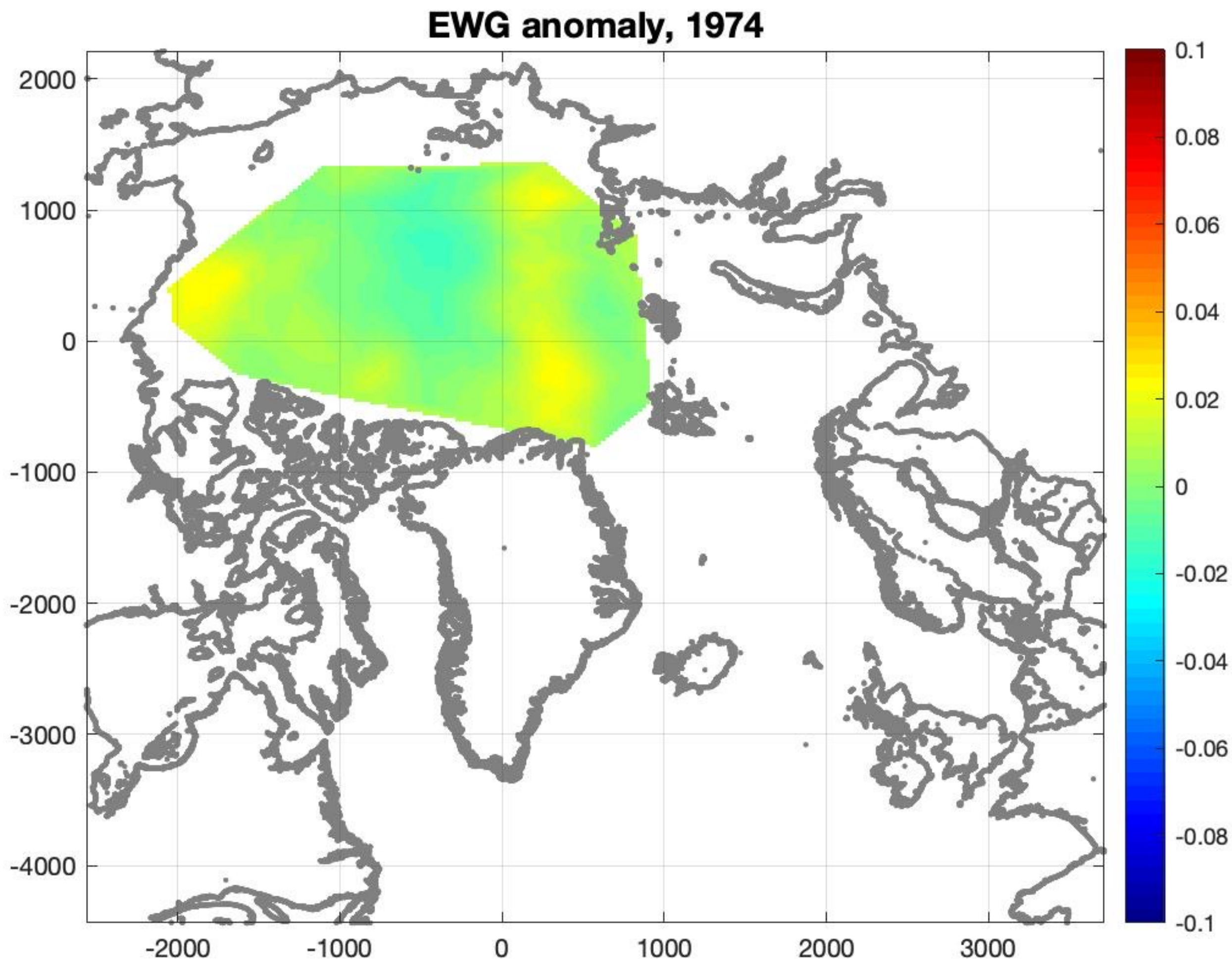

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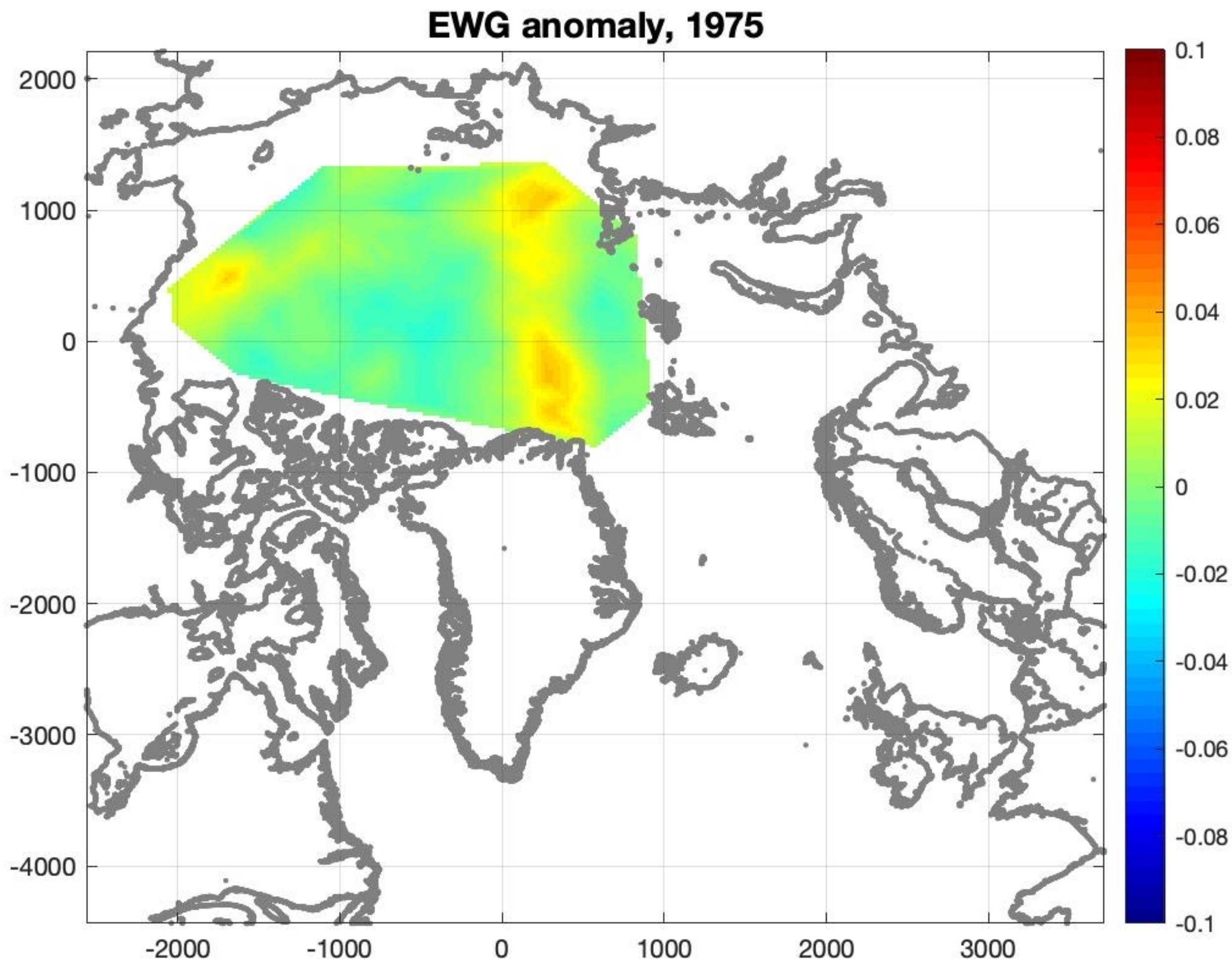

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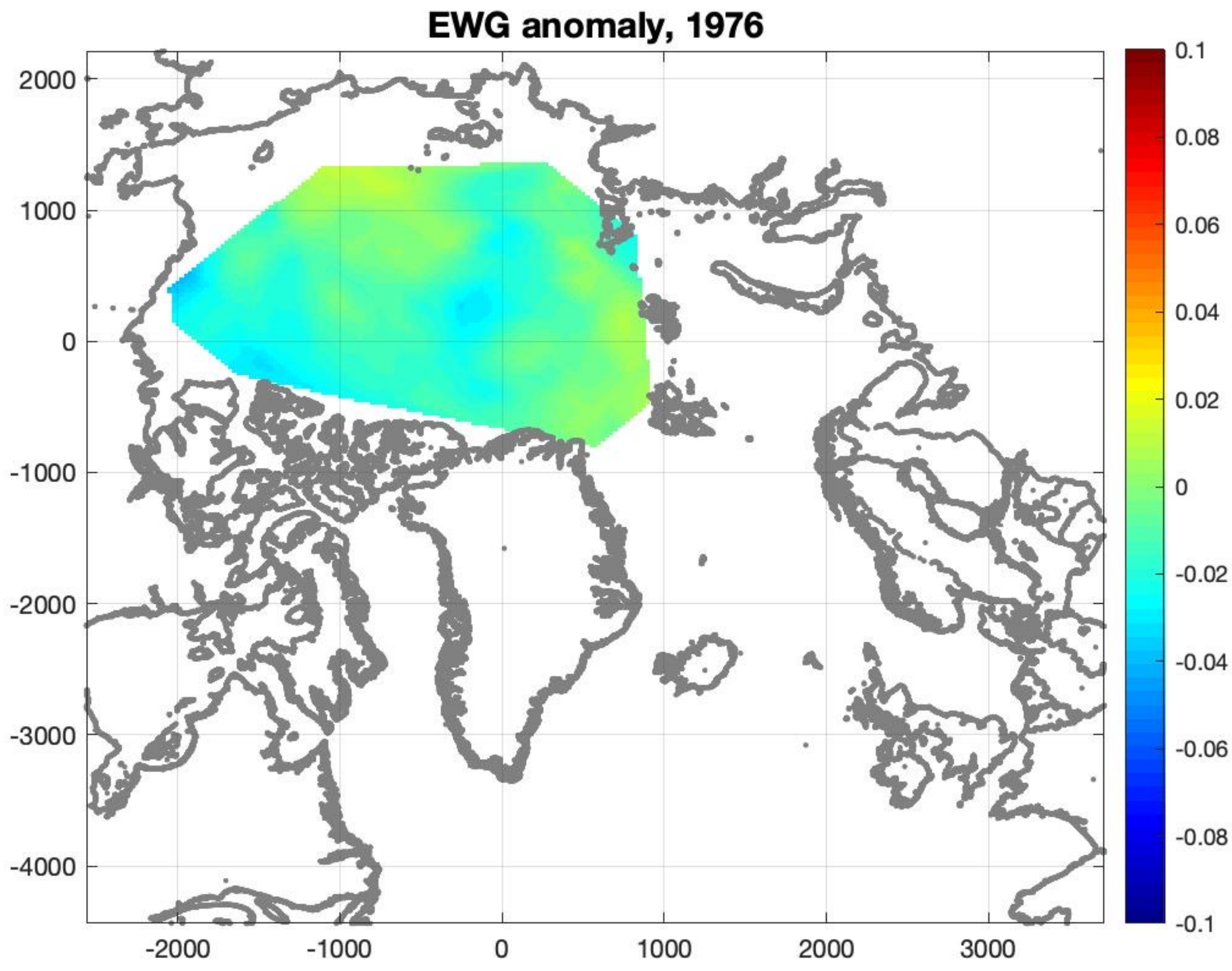

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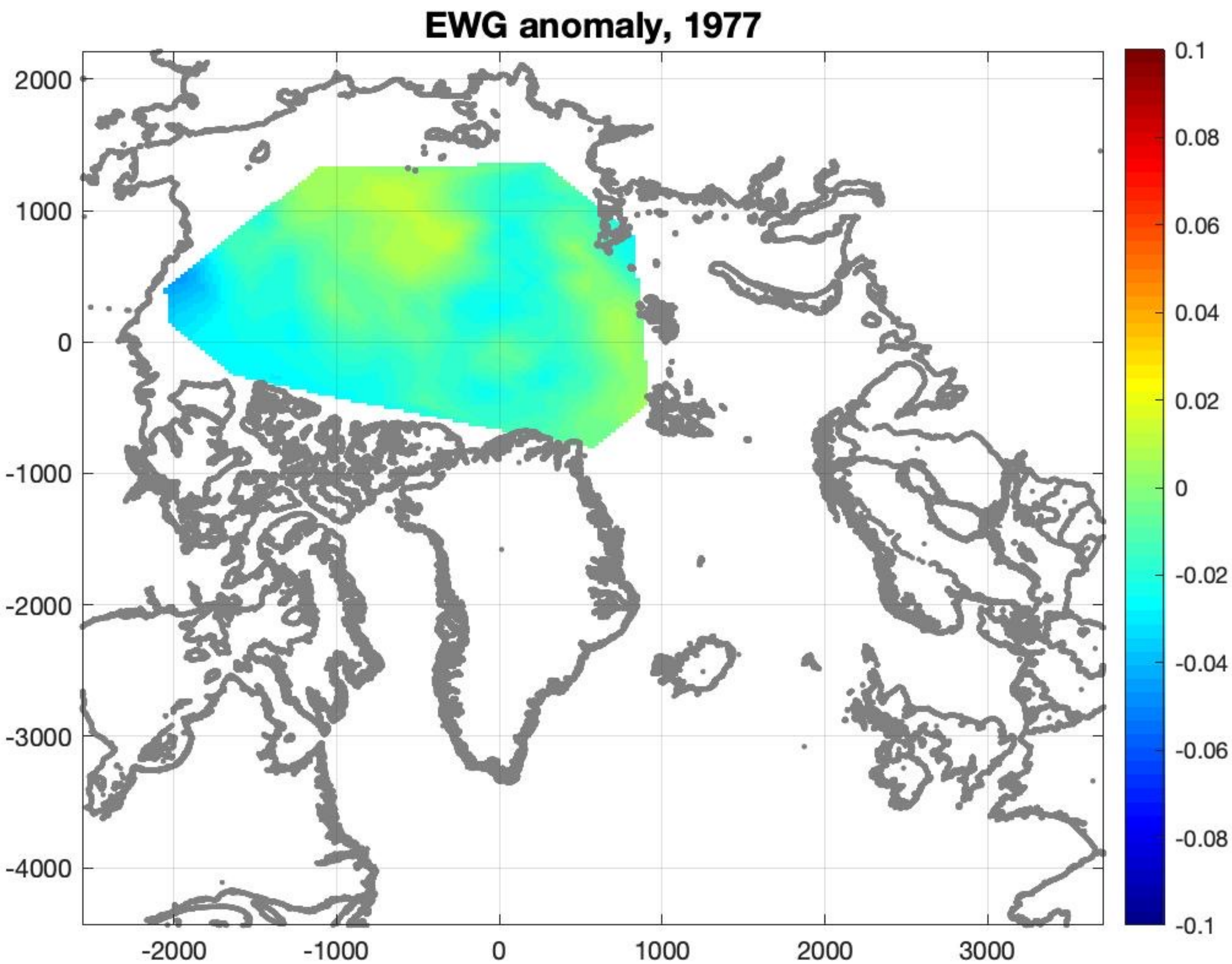

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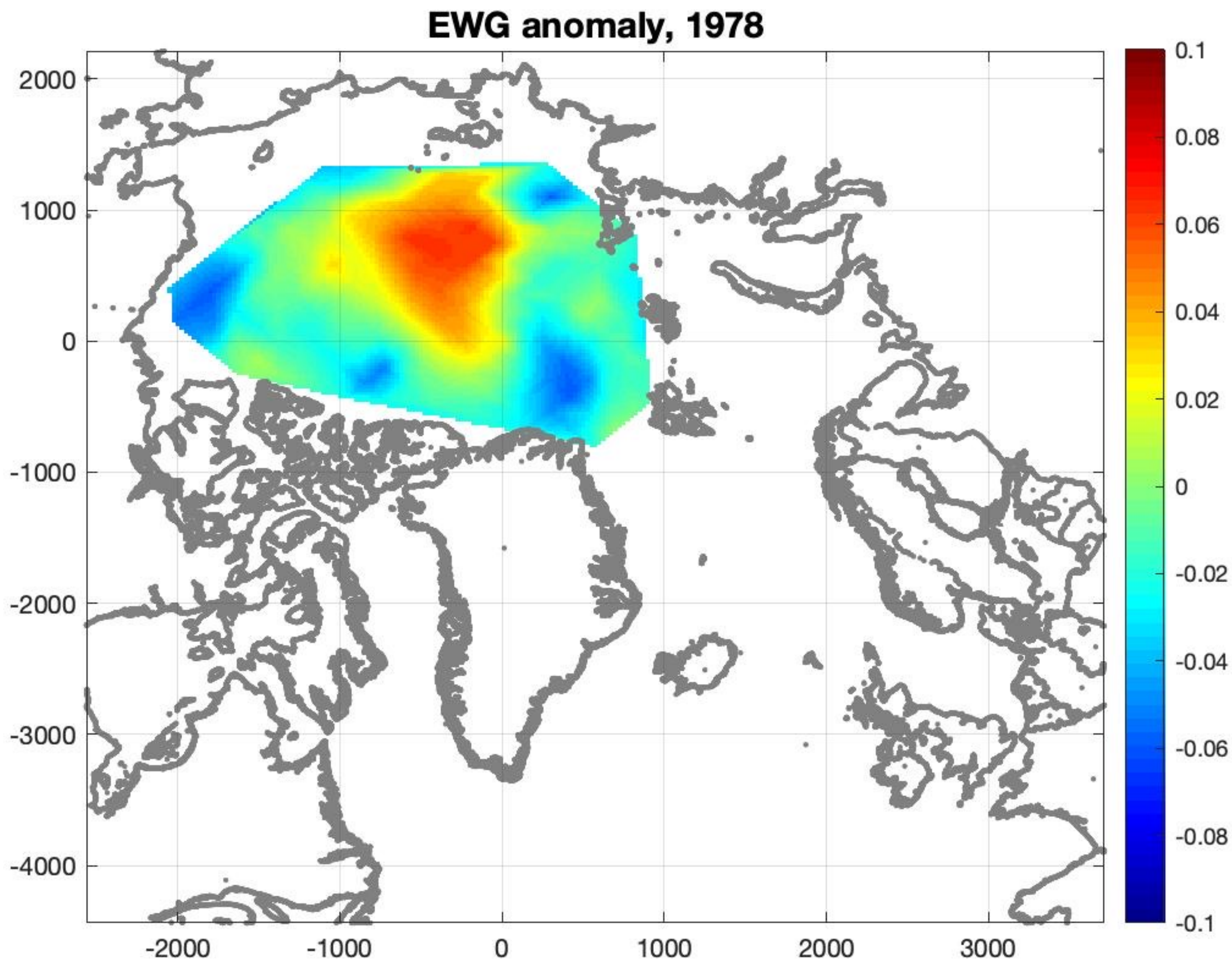

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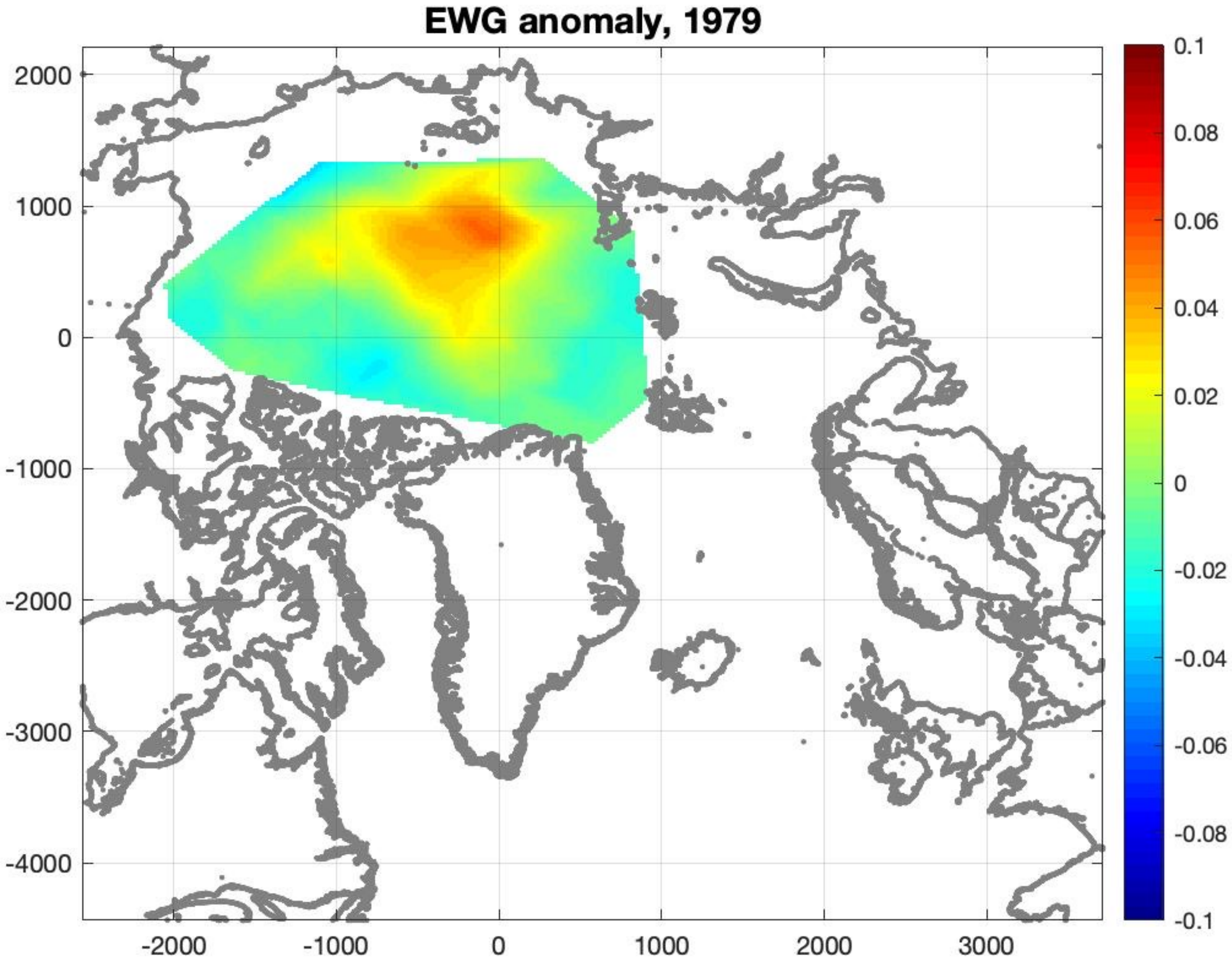

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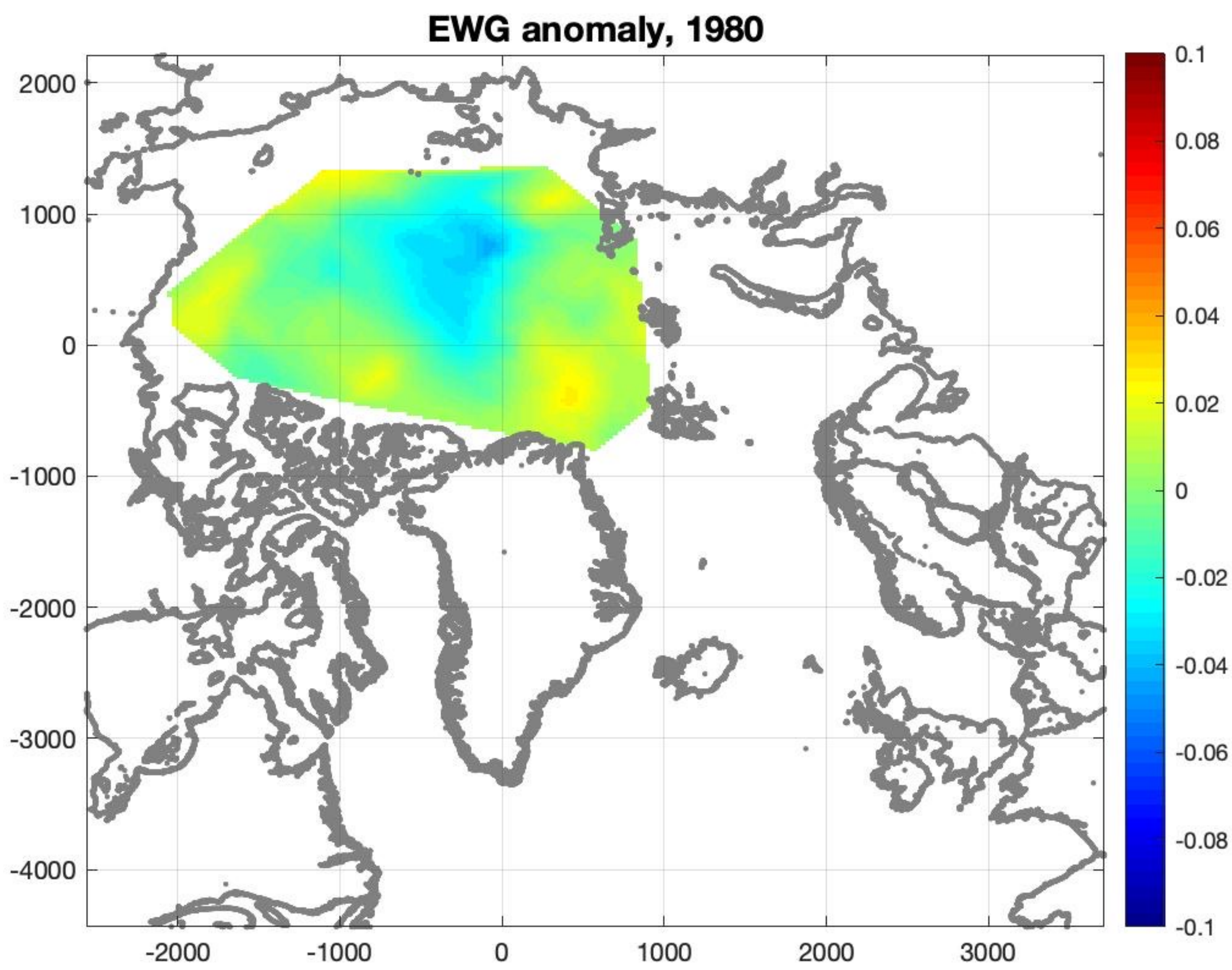

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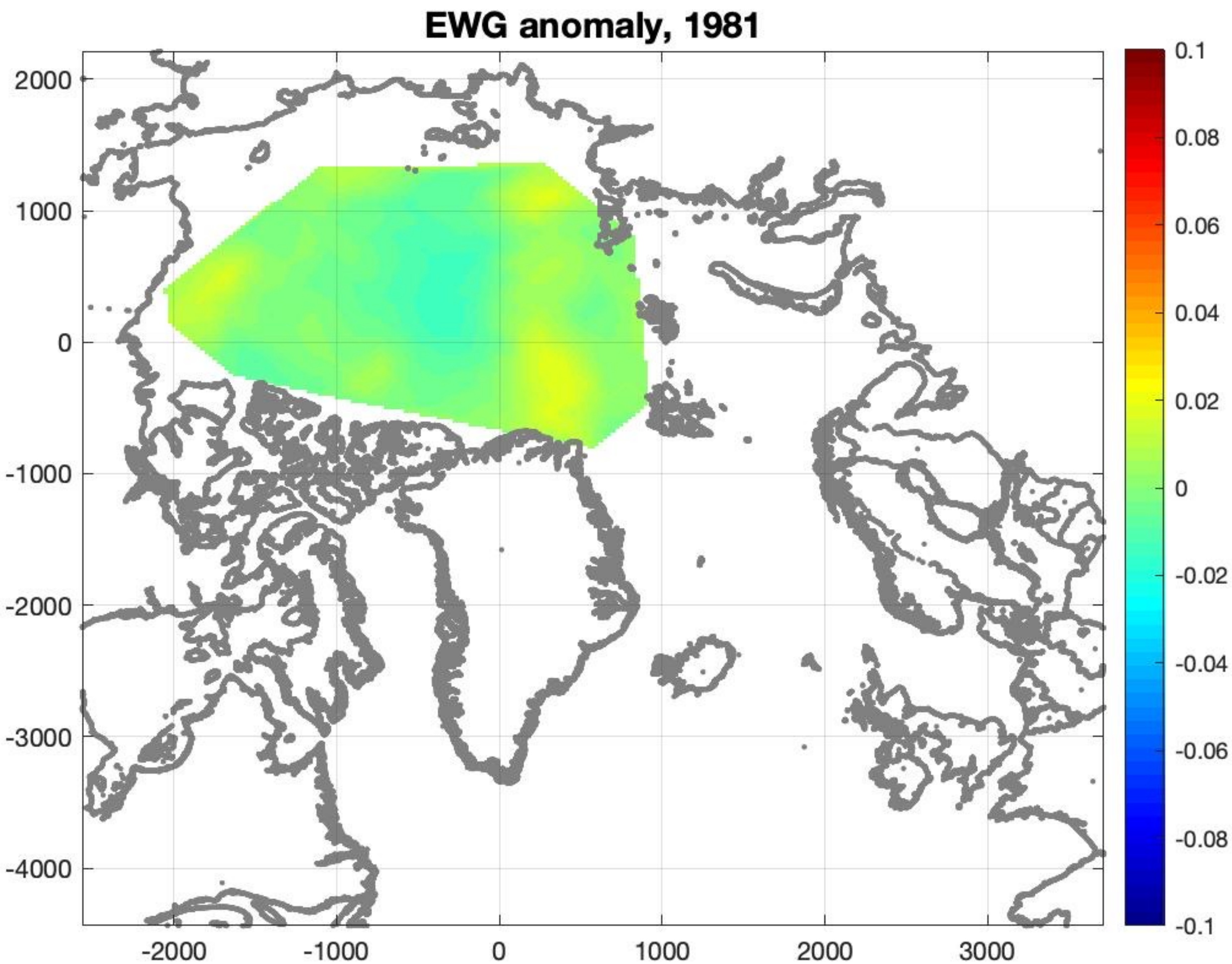

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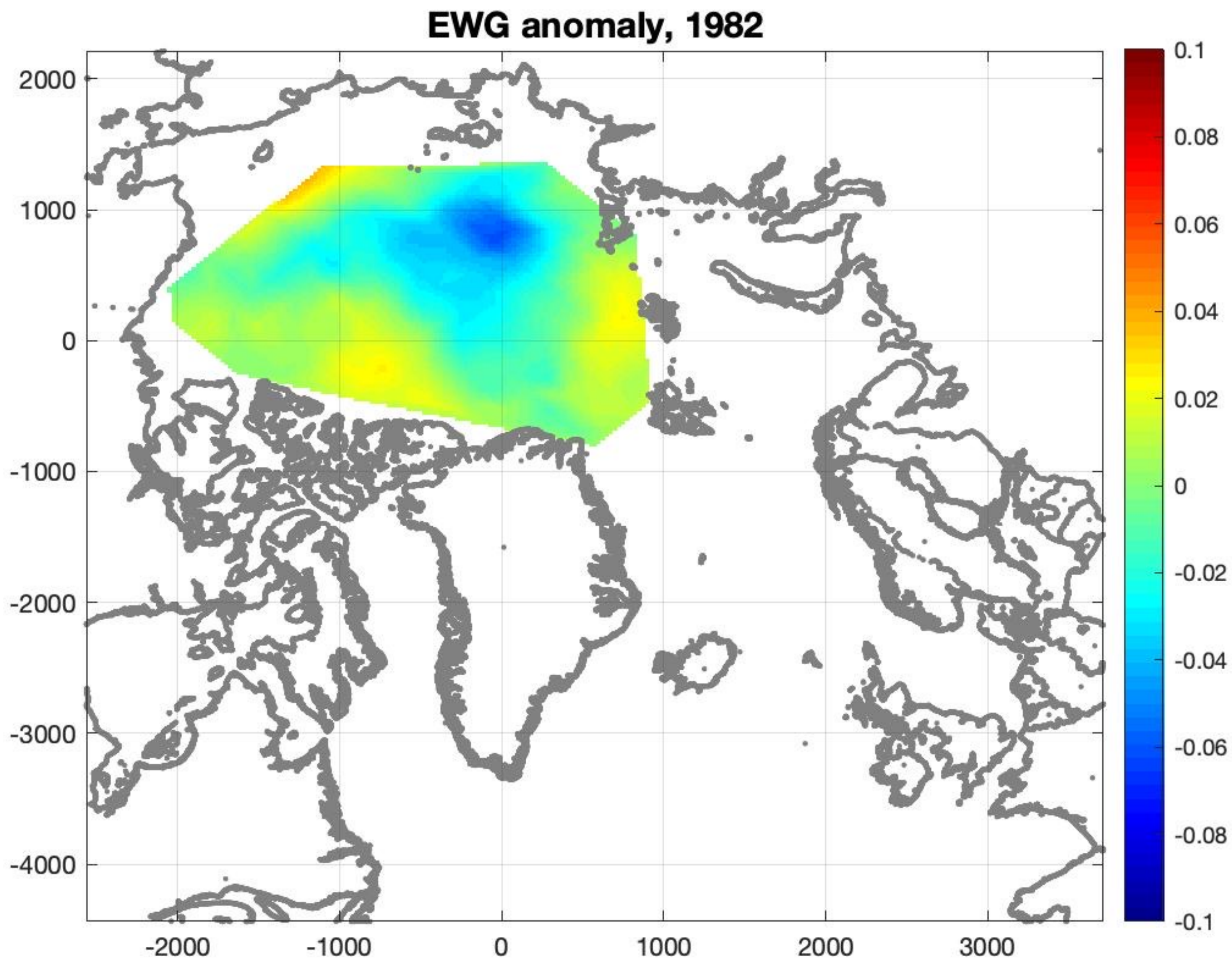

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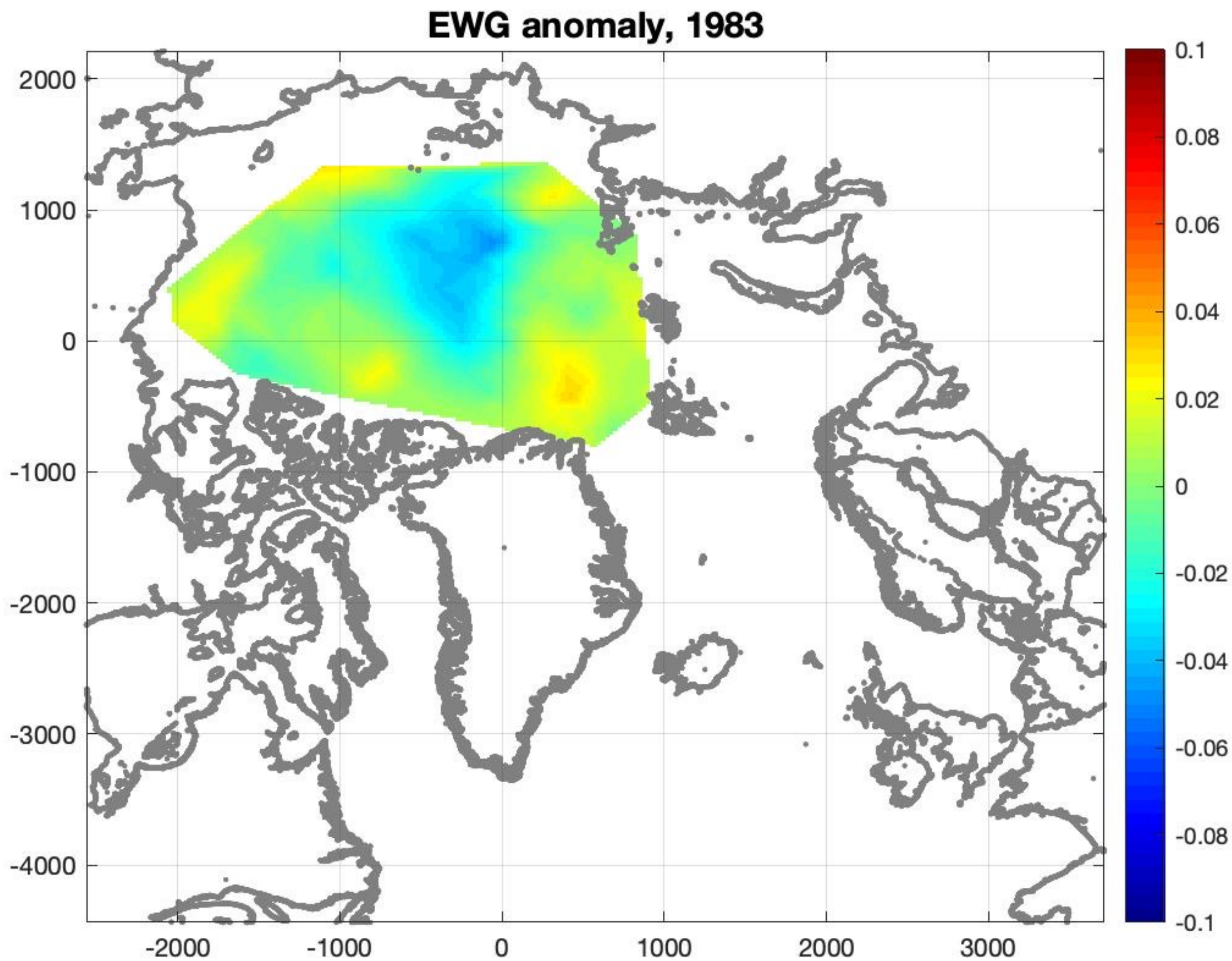

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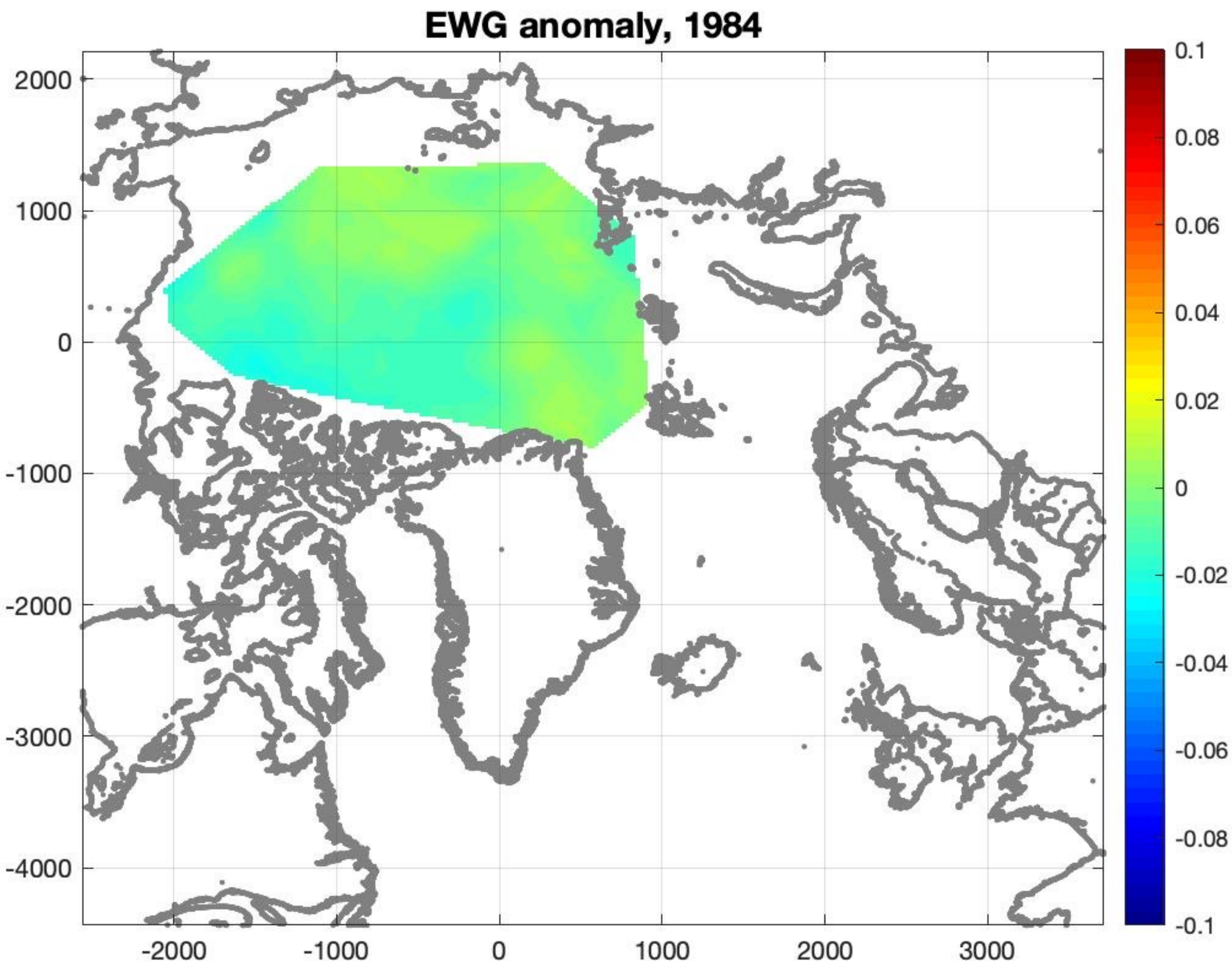

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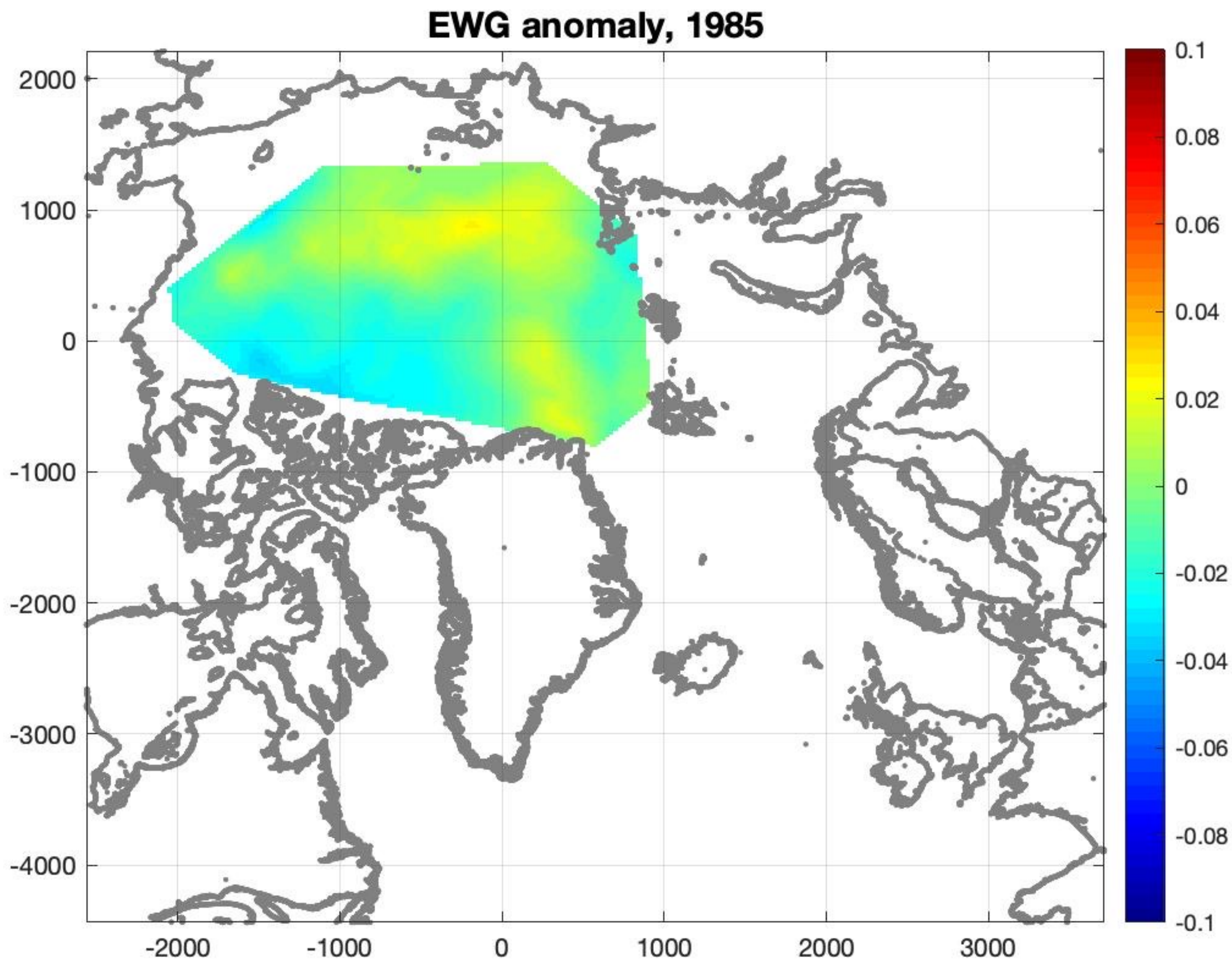

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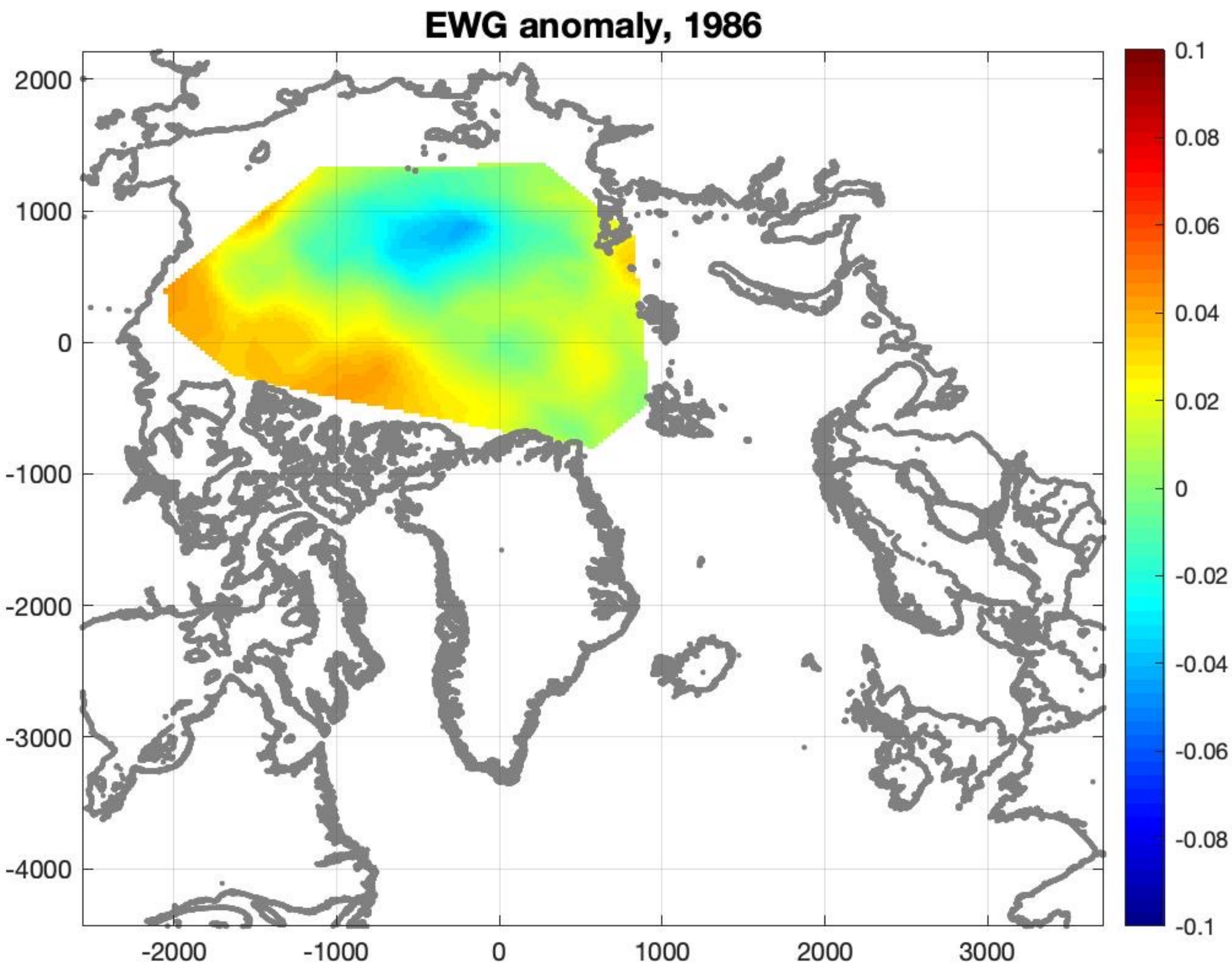

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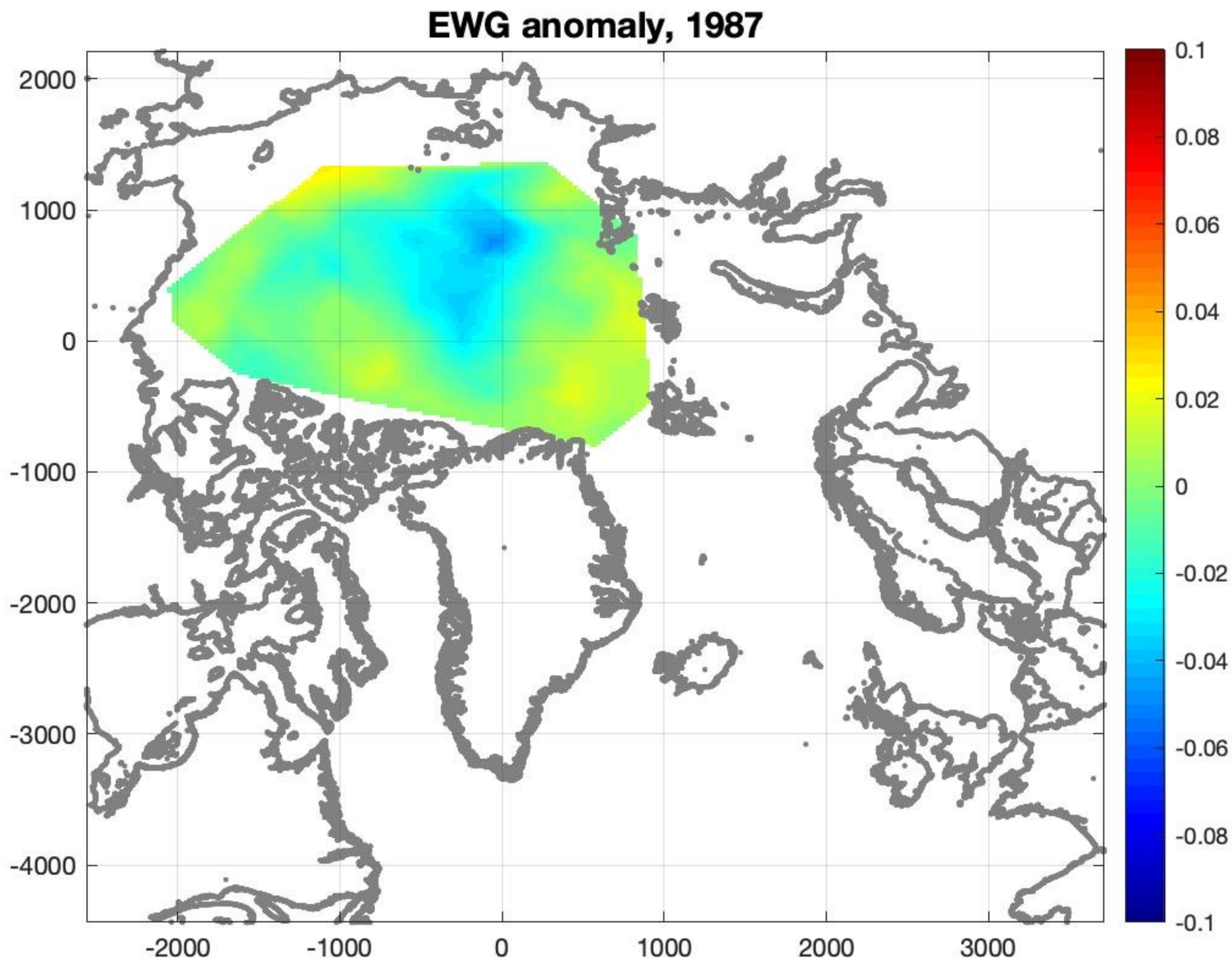

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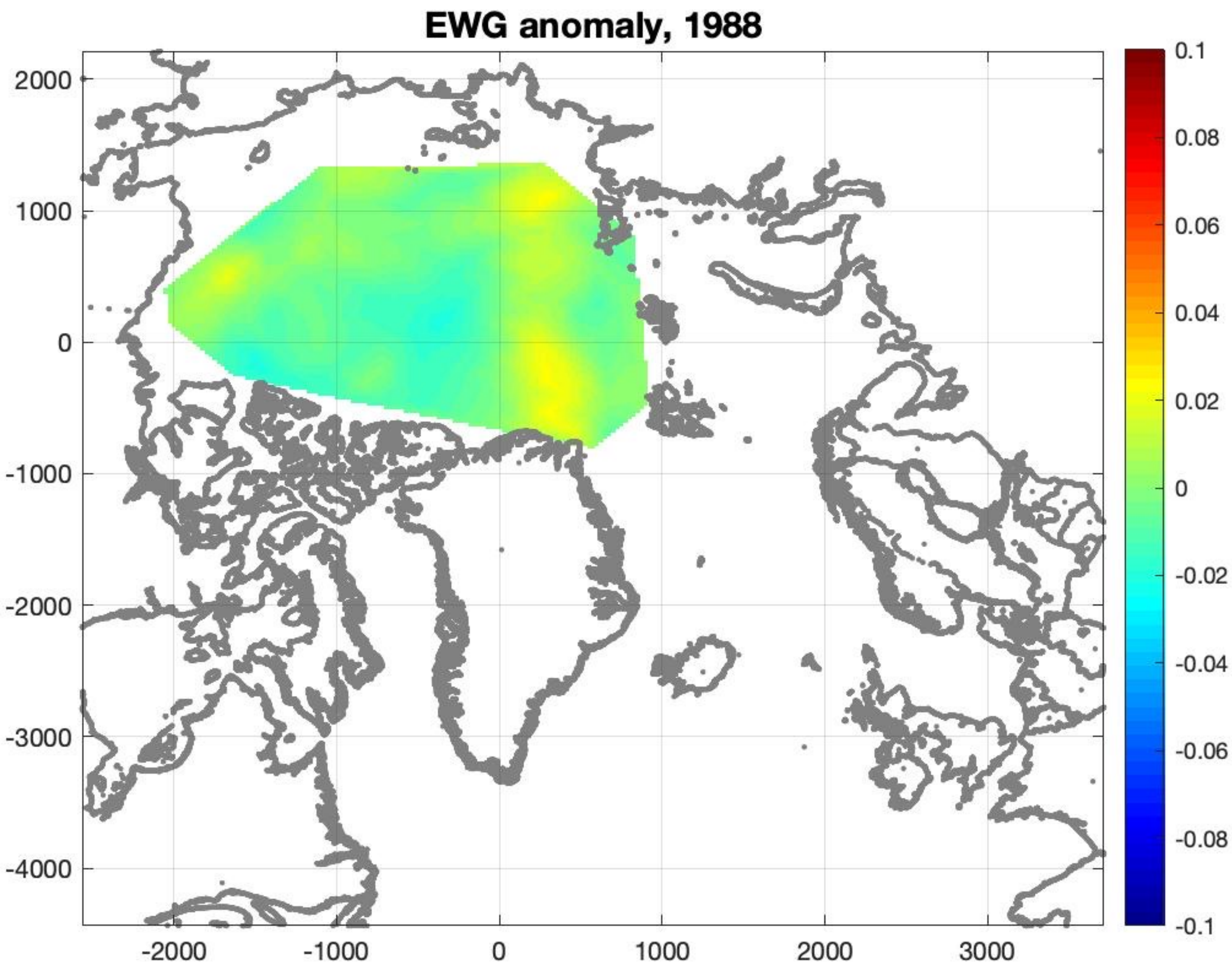

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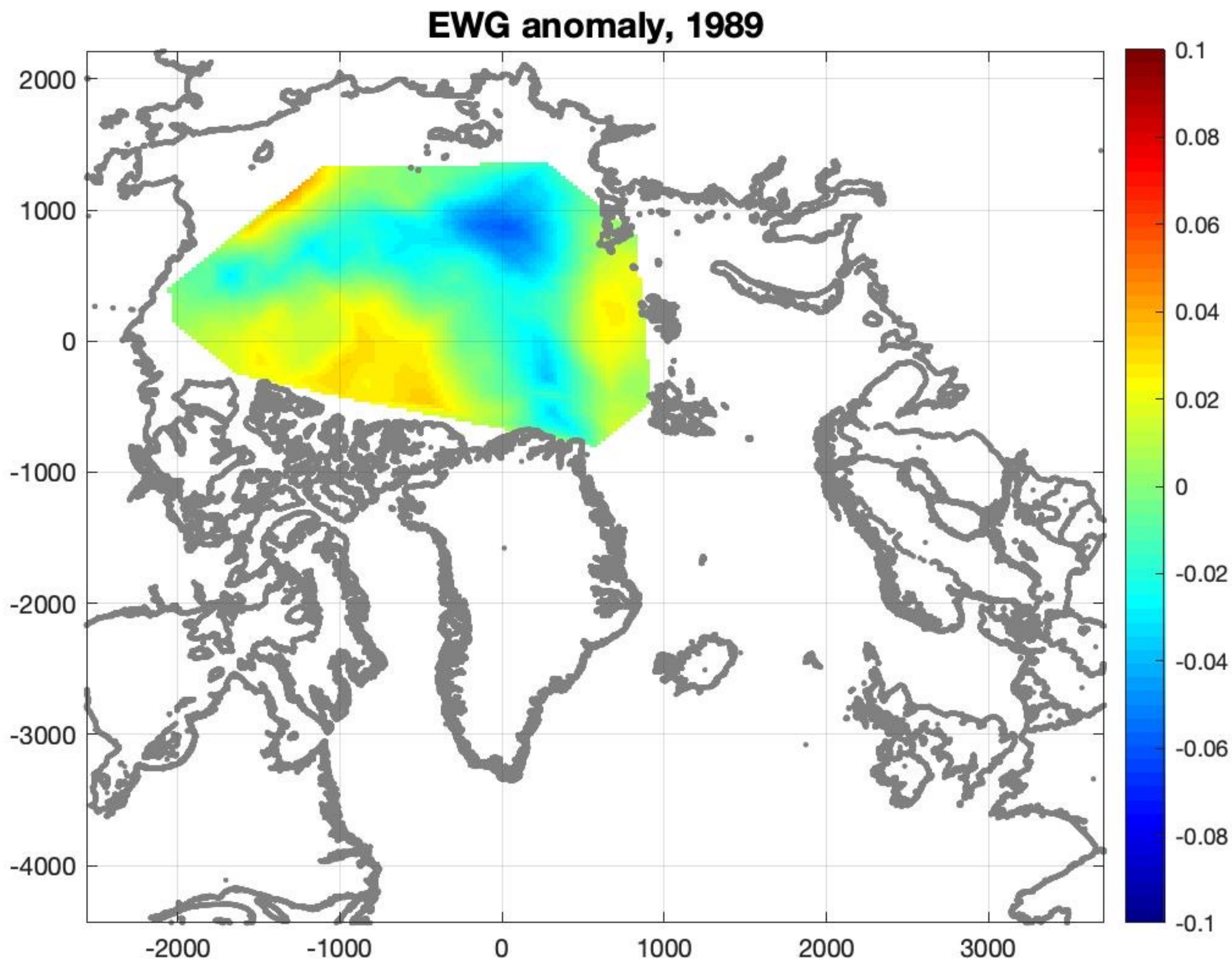
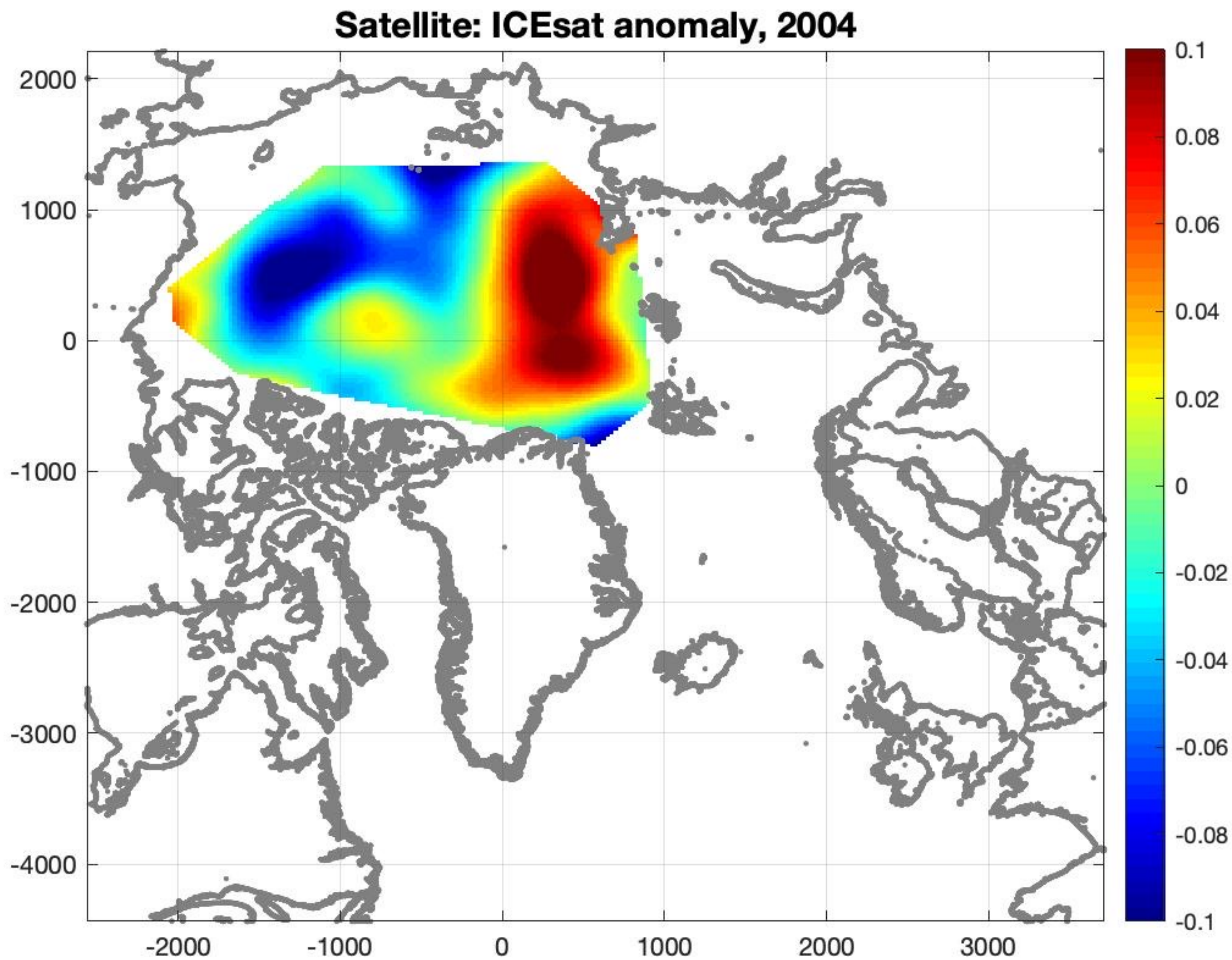


Anomalies, ICESat &CryoSat2 DOT - Mean DOT



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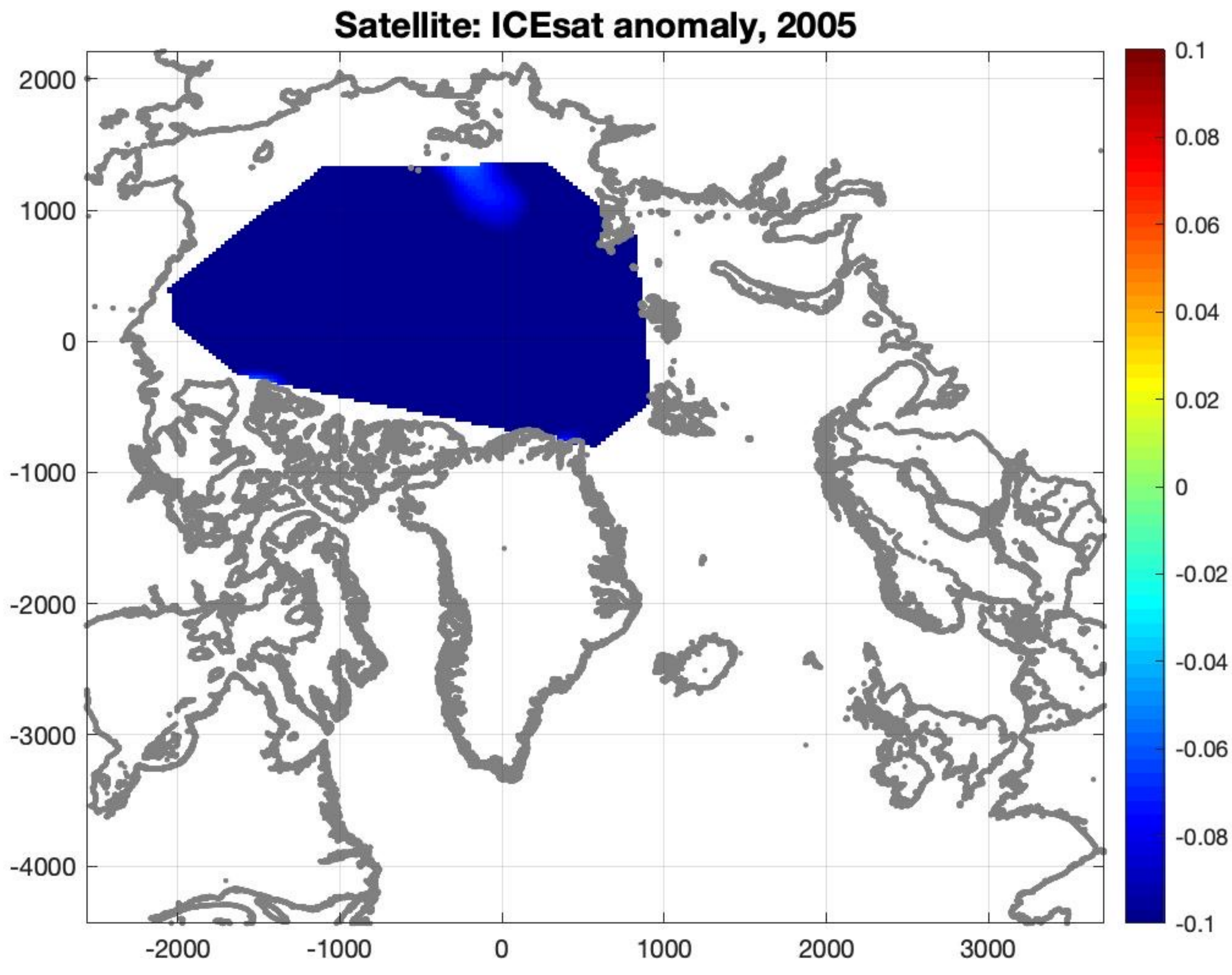

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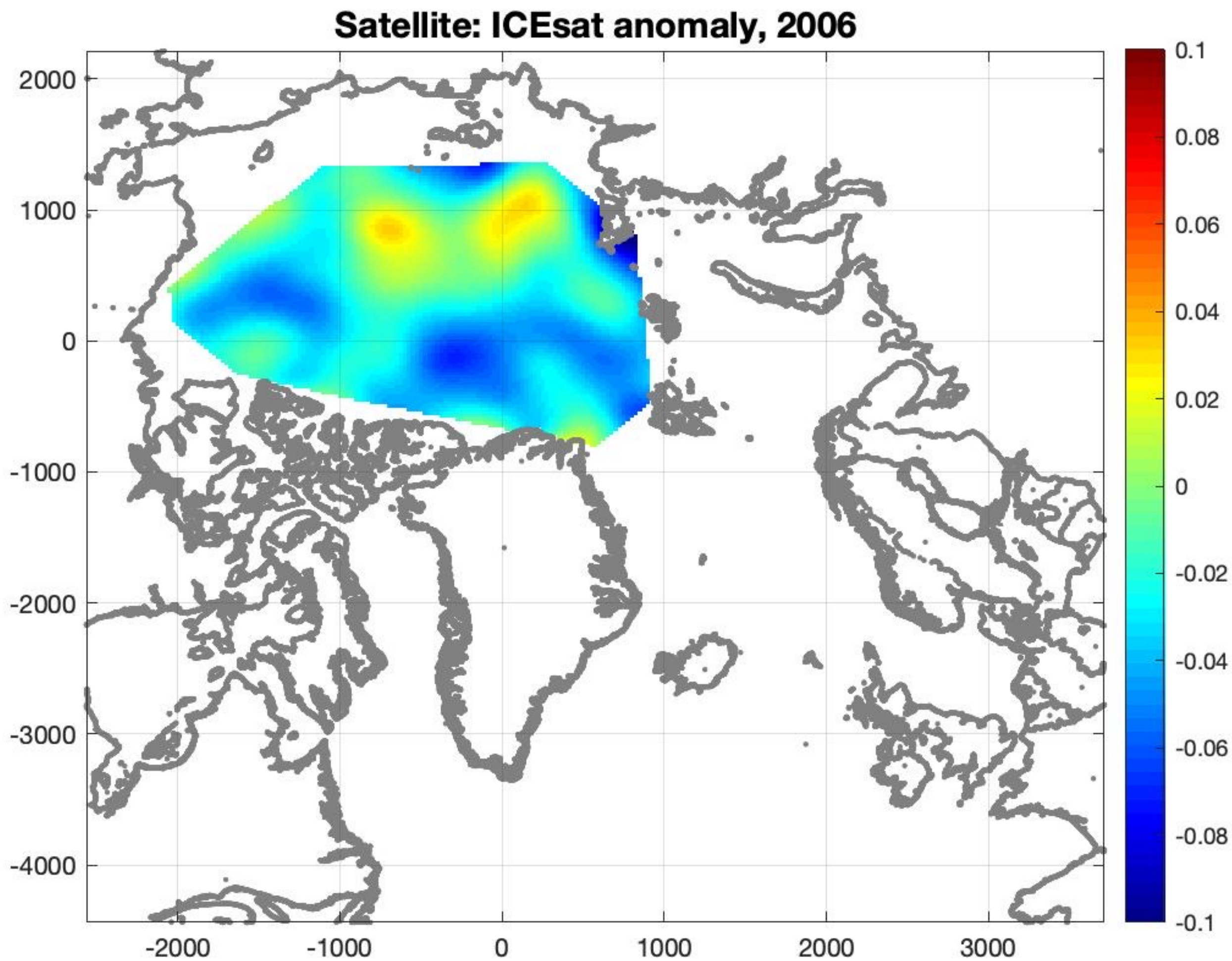

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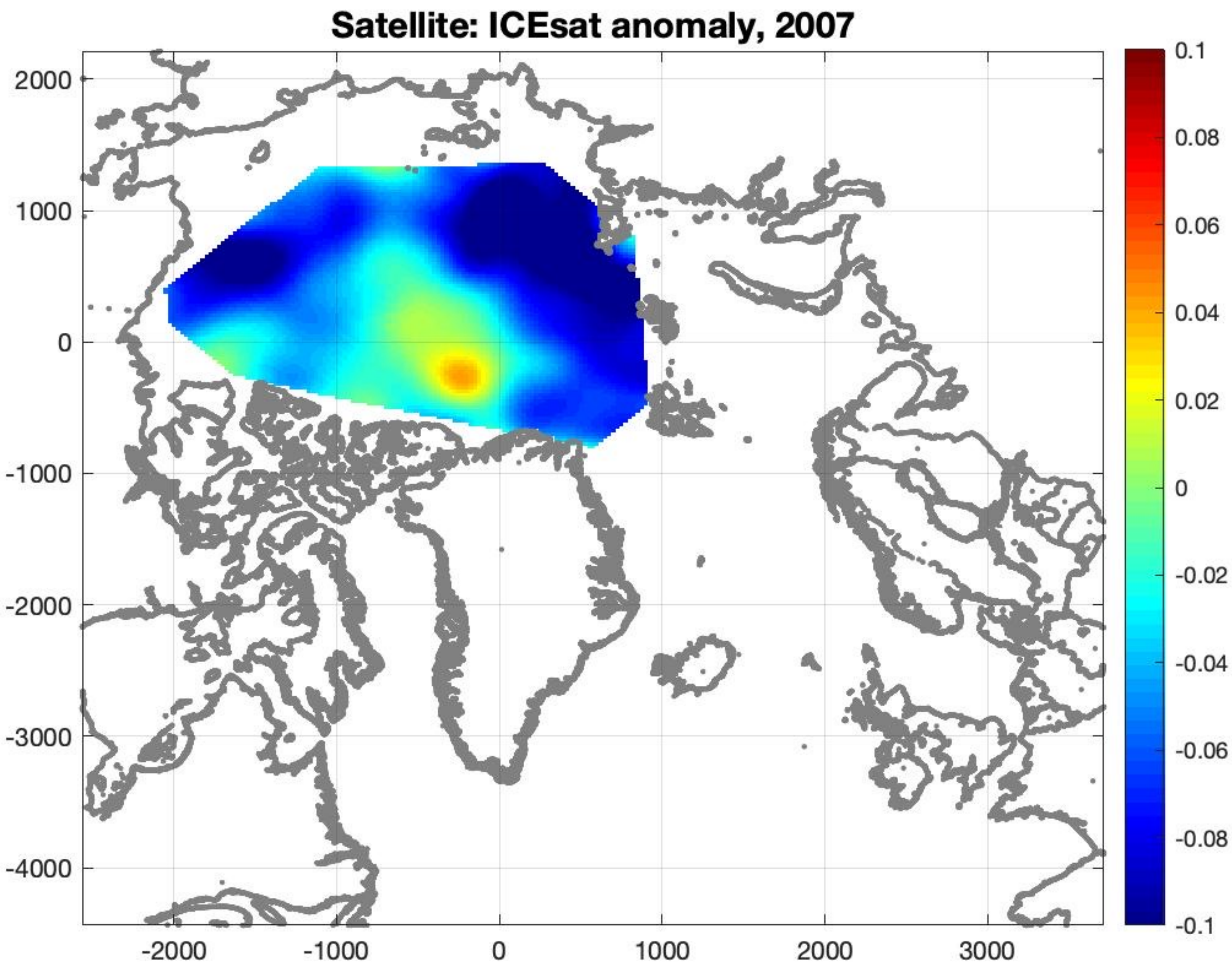

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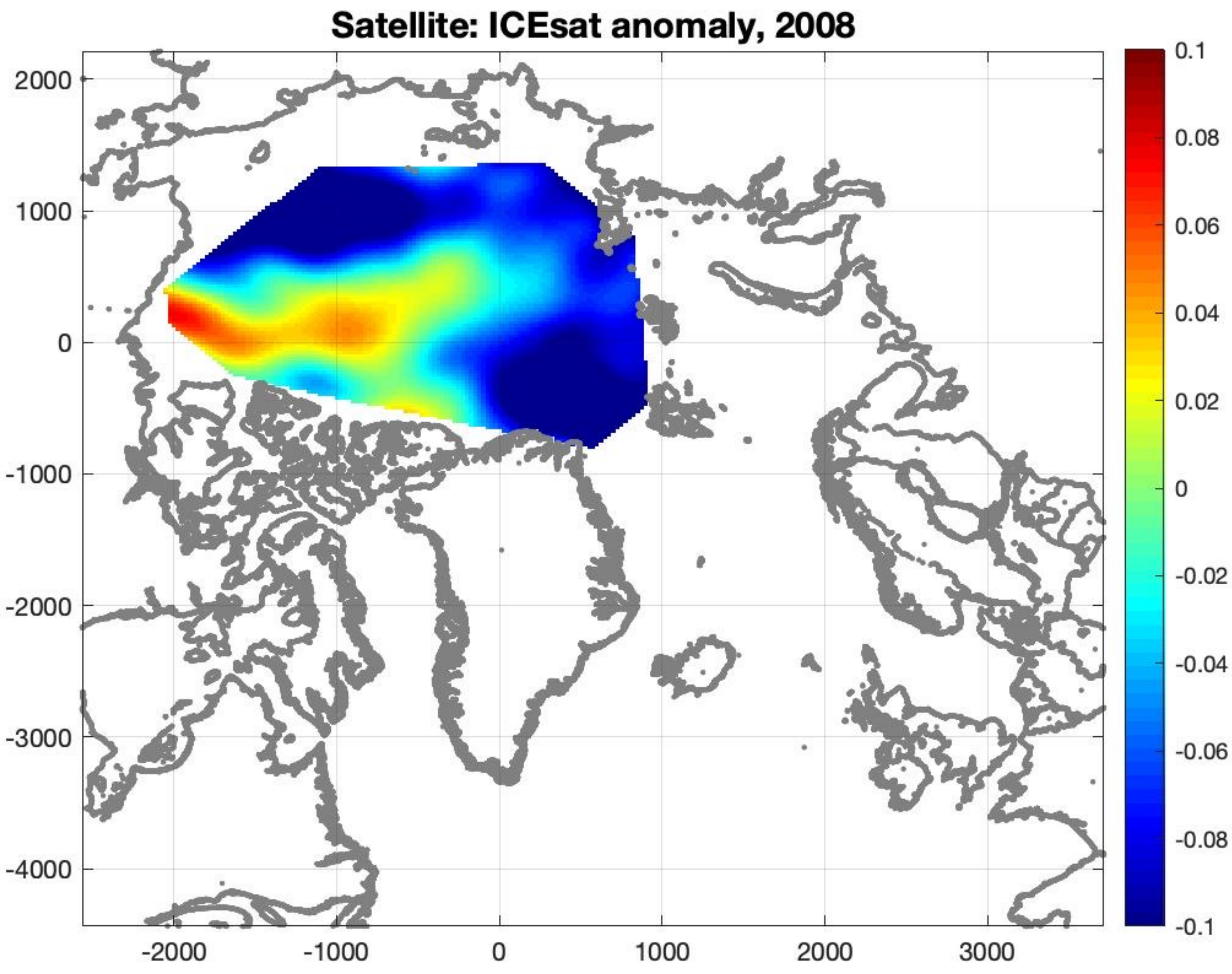

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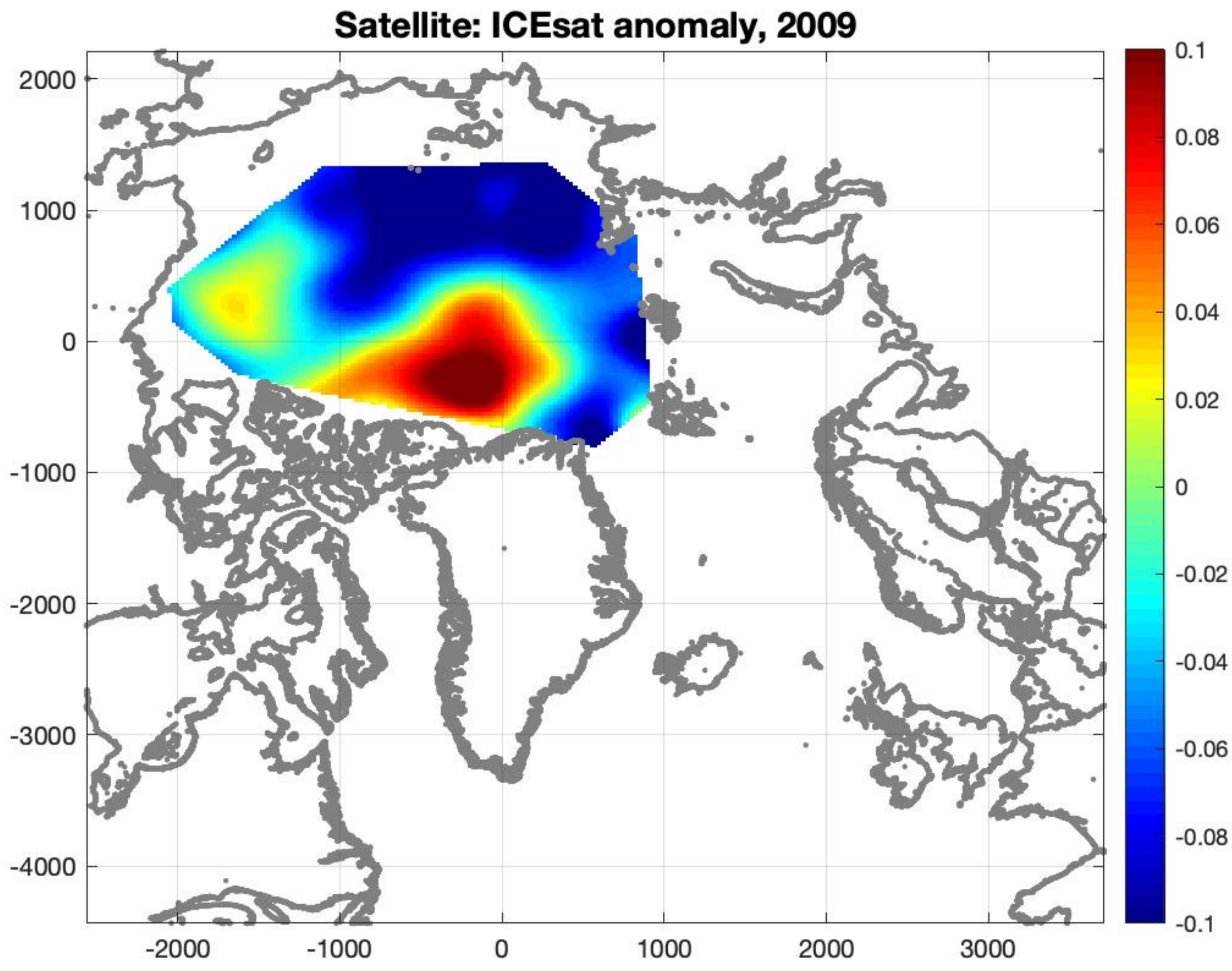

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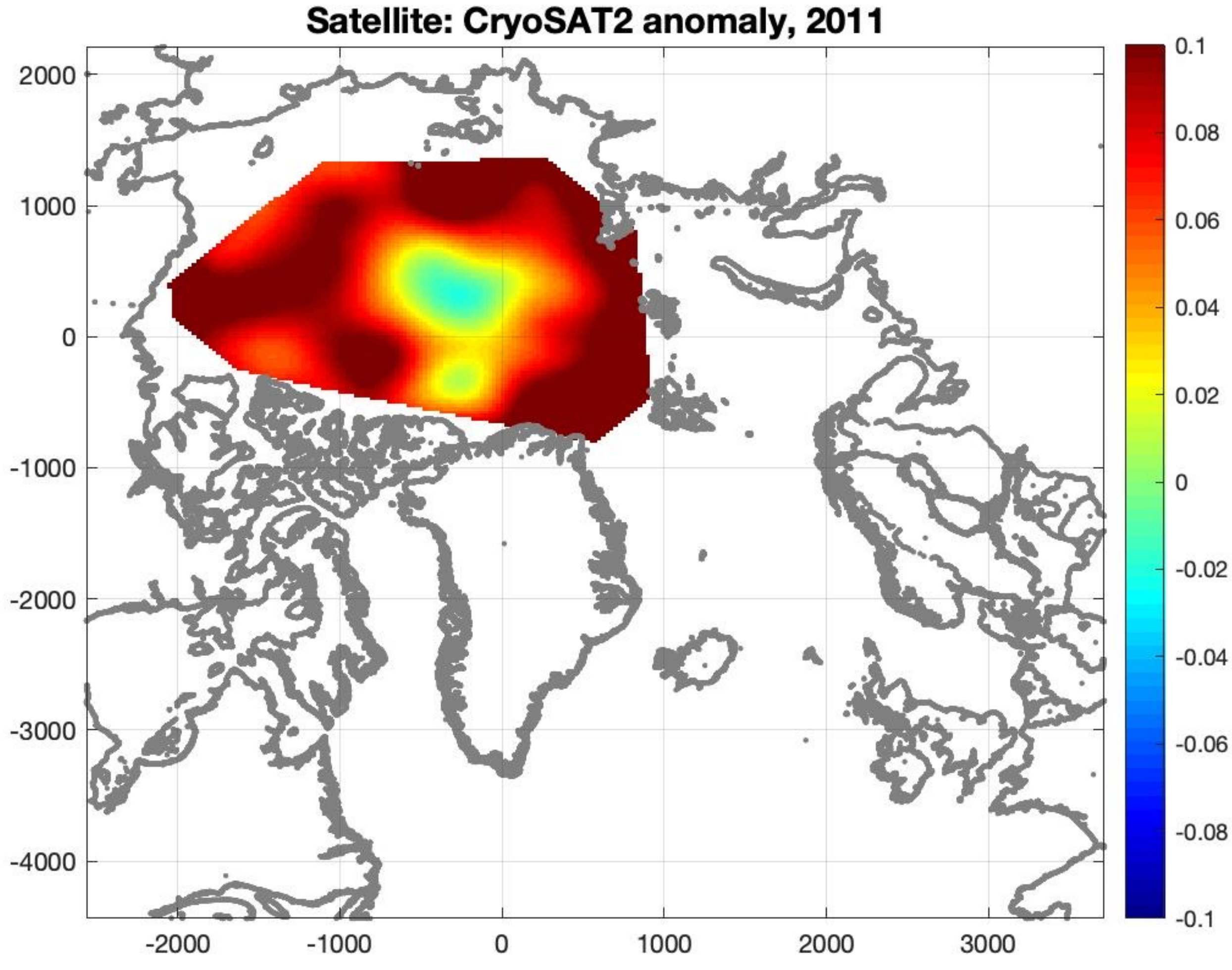

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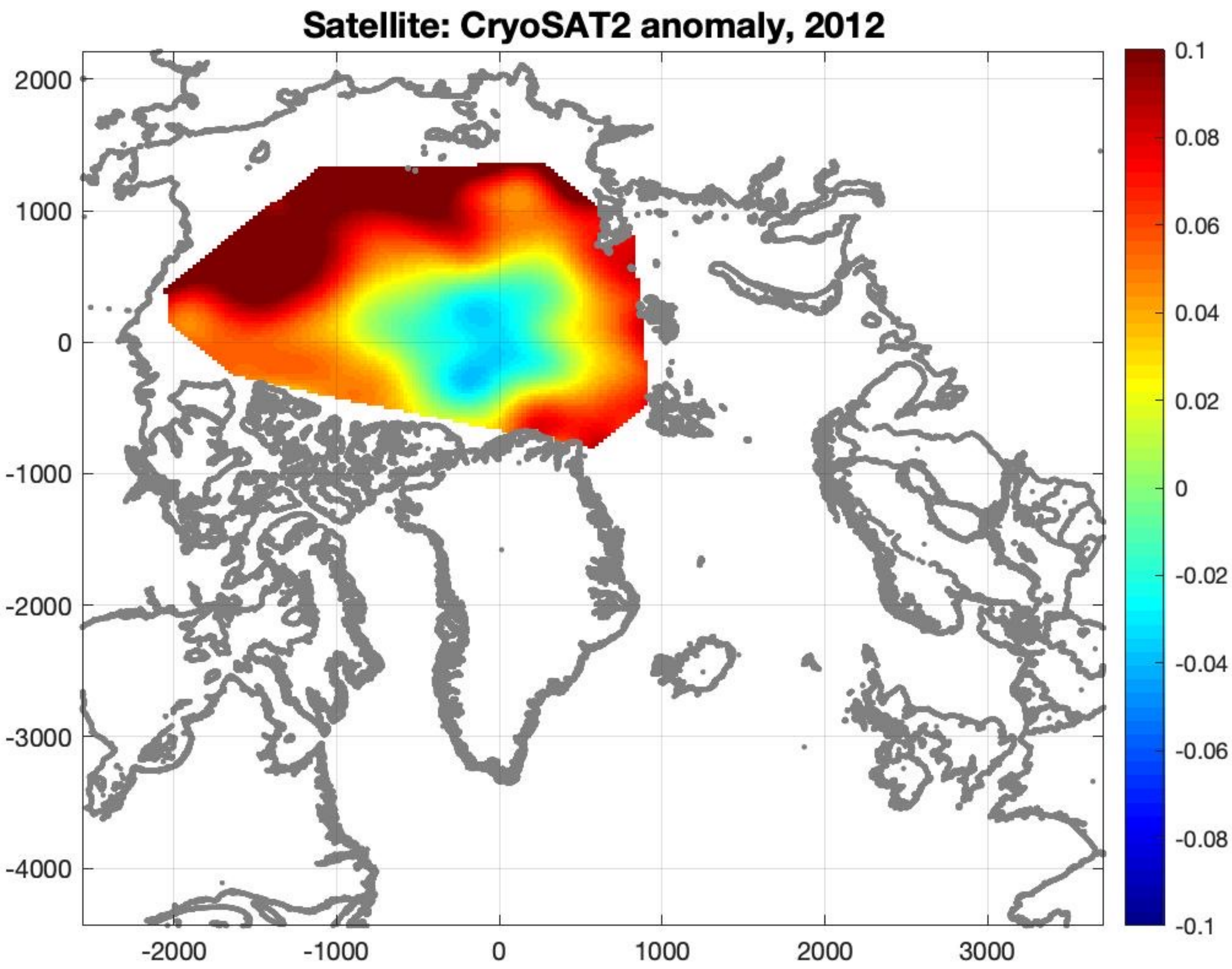

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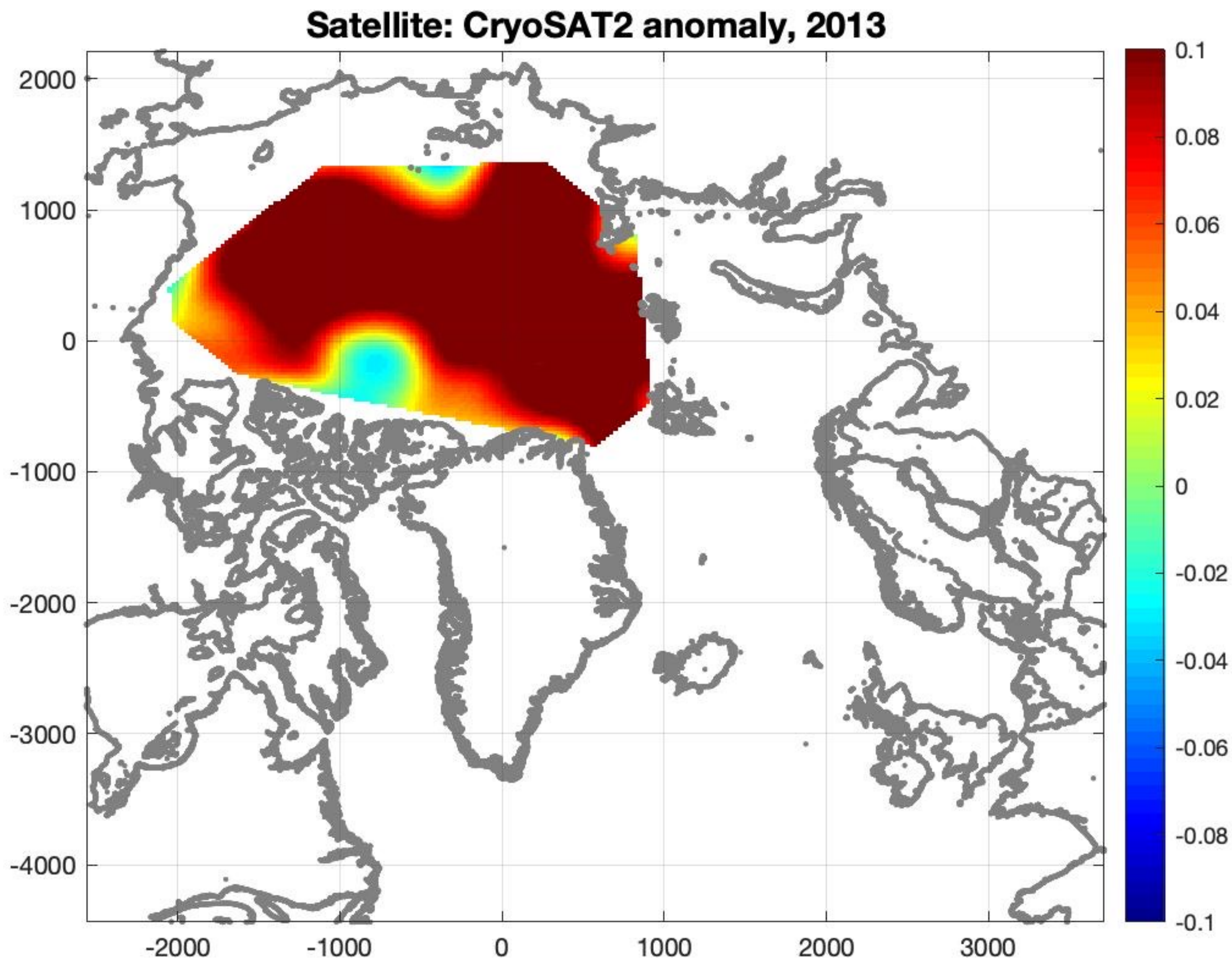

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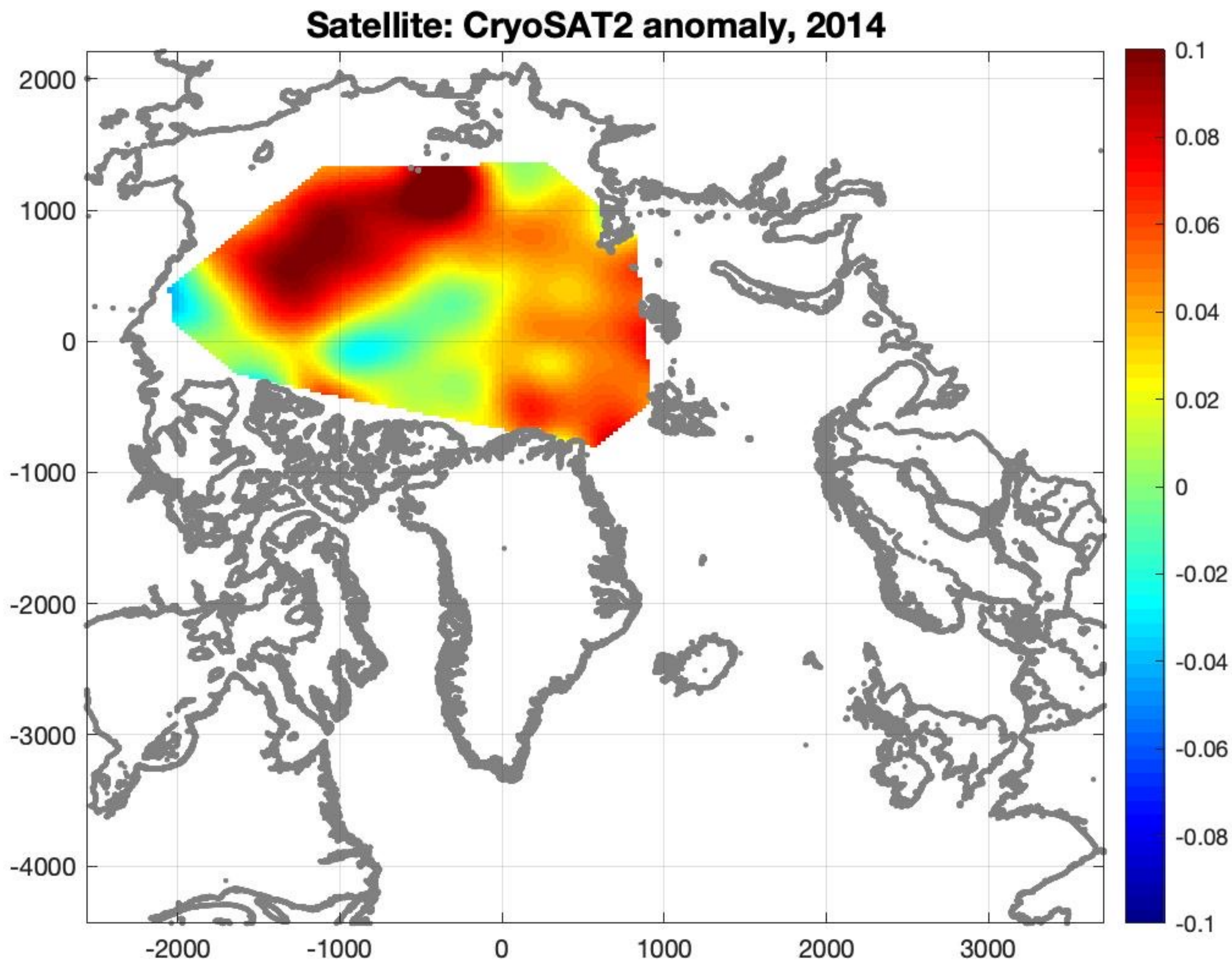

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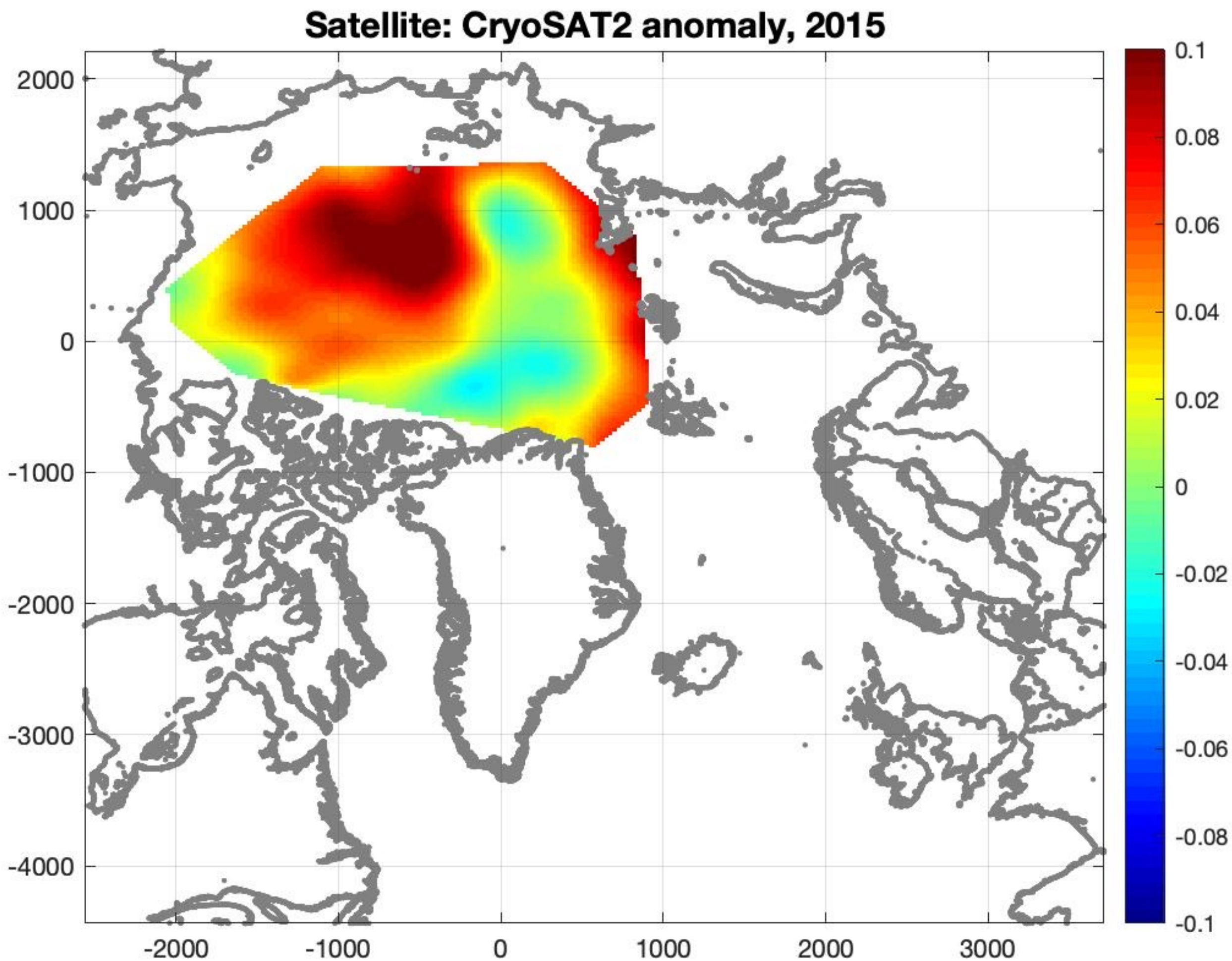


End of subjective impression, On to a more objective analysis.

EOF analysis of historical hydrography and modern satellite altimetry reveal increased cyclonic circulation and a Beaufort Sea observing bias.

In *Morison et al.* [2021] we use

- Historical Hydrography, 1950-1989

- **1950-1989 yearly winter Dynamic Heights (DH) from the US-Russian Arctic Ocean Oceanographic Atlas for the Winter Period**
- **1993 SCICEX, USS PARGO Dynamic Height section**

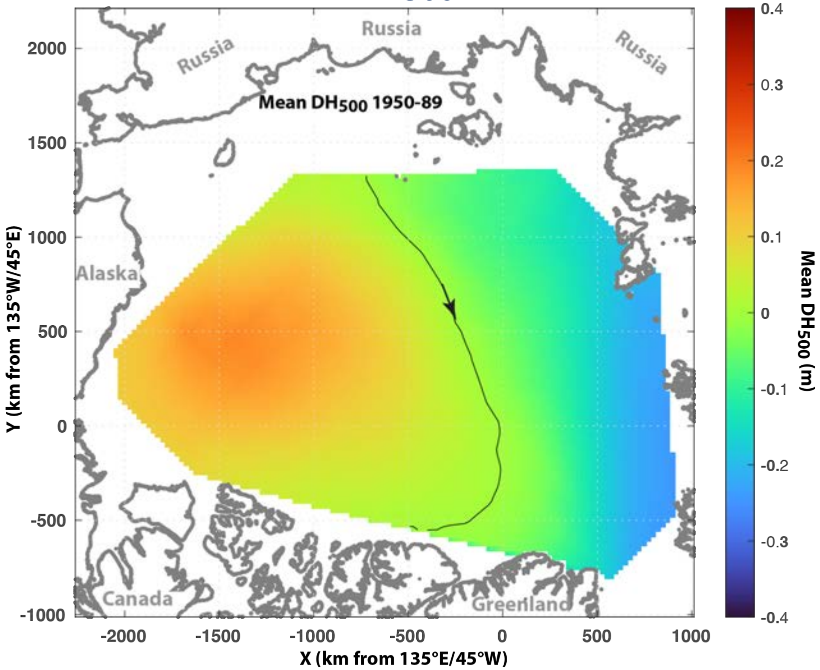
- Satellite Altimetry, 2004-2019

- **2004-2009 ICESat Dynamic Ocean Topography (DOT)**
- **2011-2019 CryoSat-2 Dynamic Ocean Topography**

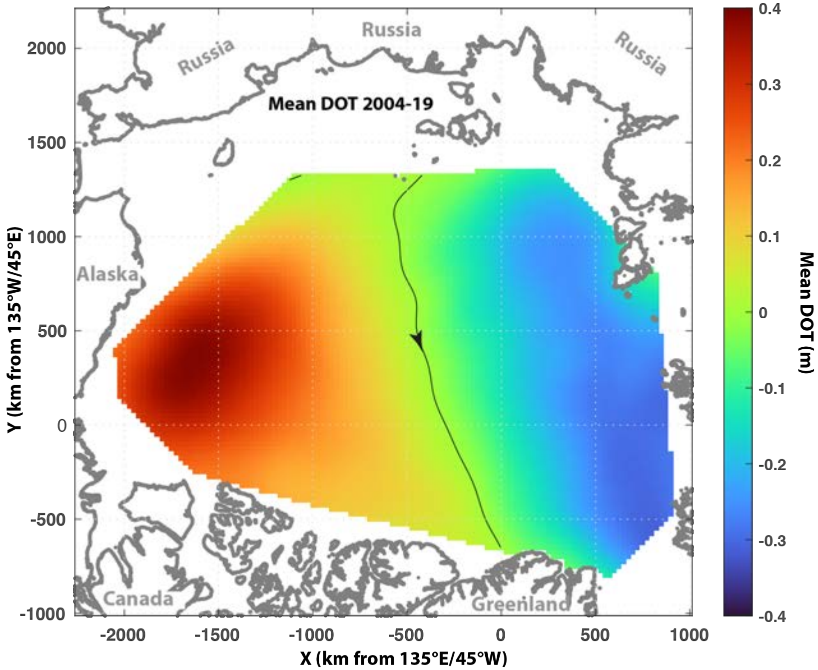
- Prior work (Kwok and Morison, 2011 & 2016) show patterns of variability of ICESat and CryoSat-2 DOT are well correlated (*r*=0.92) with DH_{500} determined by hydrography,

EOF analyses are done of 1950-89 DH and ICESat/CryoSat-2 2004-19 DOT Anomalies Relative to Time-averaged Patterns shown here.

Mean DH_{500} 1950-89



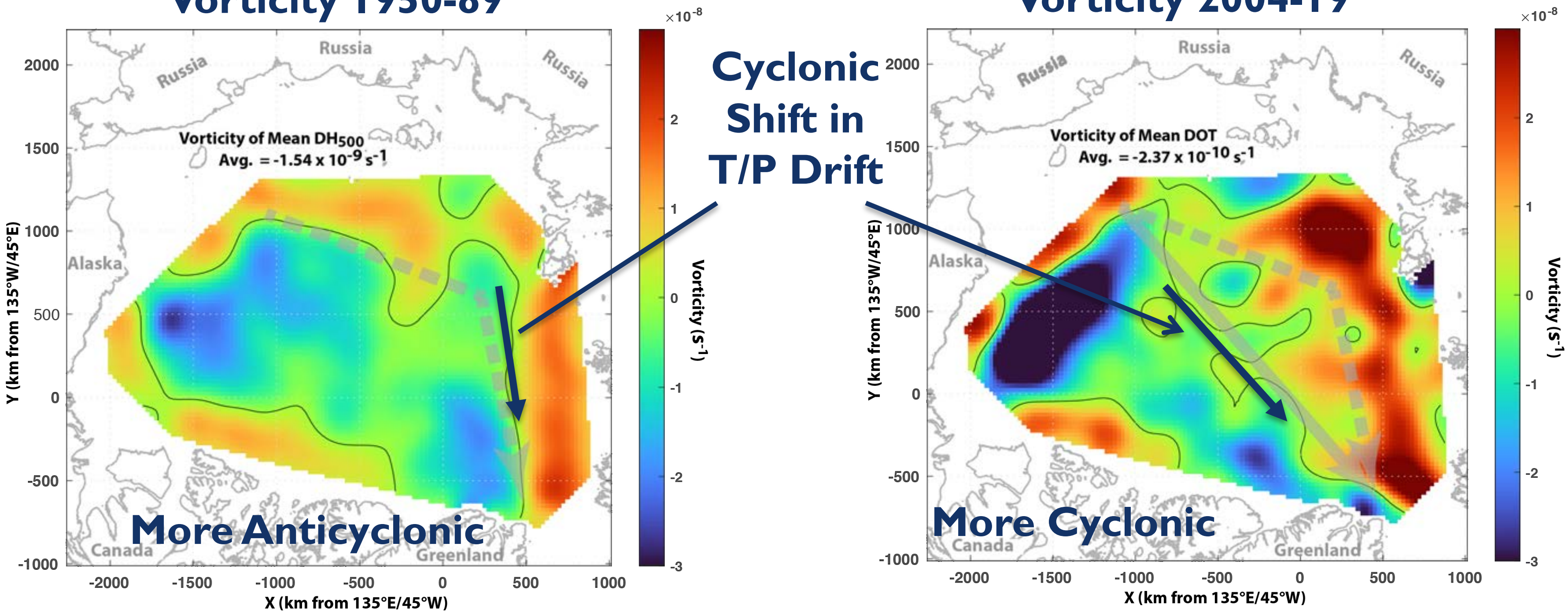
Mean DOT 2004-19



The mean of 2004-19 annual Feb-April DOT (right) is similar to the 1950-89 mean winter DH (left) but the Beaufort Gyre is smaller and more intense, and the Eurasian Basin low is larger and deeper.

Vorticity of surface geostrophic currents associated with the mean winter dynamic heights 1950-89 and DOT 2004-19

Vorticity 1950-89 | Vorticity 2004-19

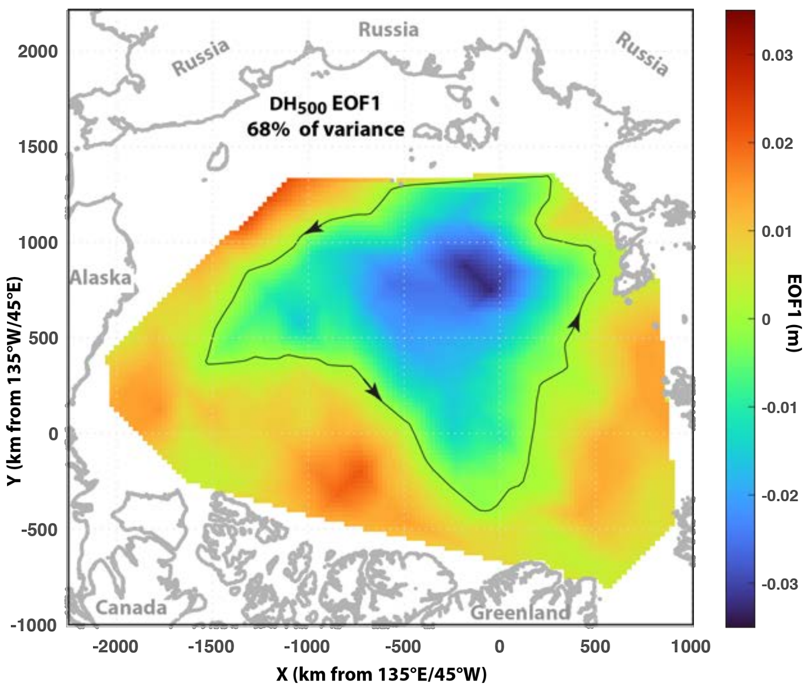


Comparison of vorticity ($\Psi = \frac{g}{f}\nabla^2 h$) of 1950-89 mean DH (left) and 2004-19 mean DOT (right) indicate the Beaufort Gyre intensified, but the cyclonic circulation in the Eurasian Basin also intensified and spread shifting the Transpolar Drift cyclonically

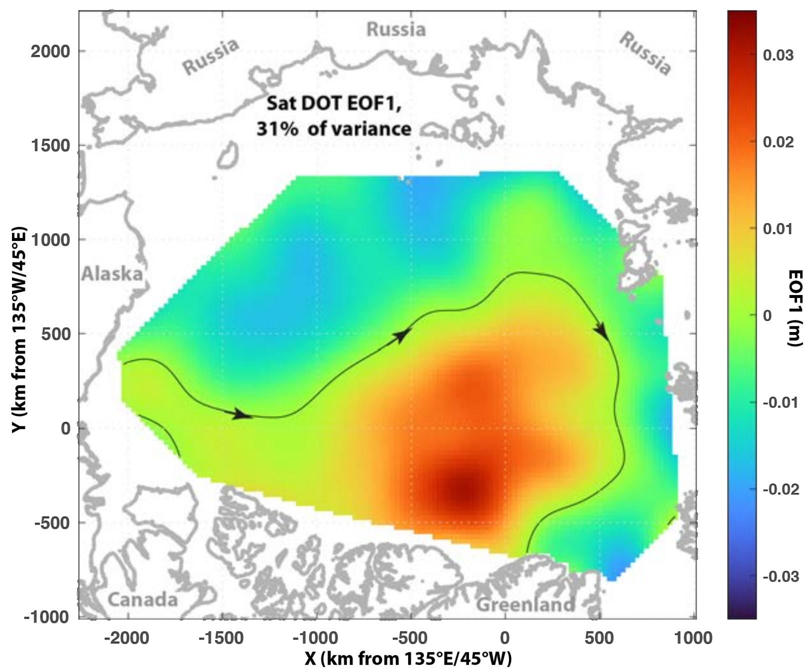
And consistent with increased AO forcing, the average vorticity increased from -15.4 to -2.4 x 10^{-10} s^{-1}. The area of positive vorticity increased from 42% to 55%

The First EOFs of Yearly Dynamic Heights 1950-1989 and Dynamic Ocean Topography 2004-2019

EOF1 1950-89

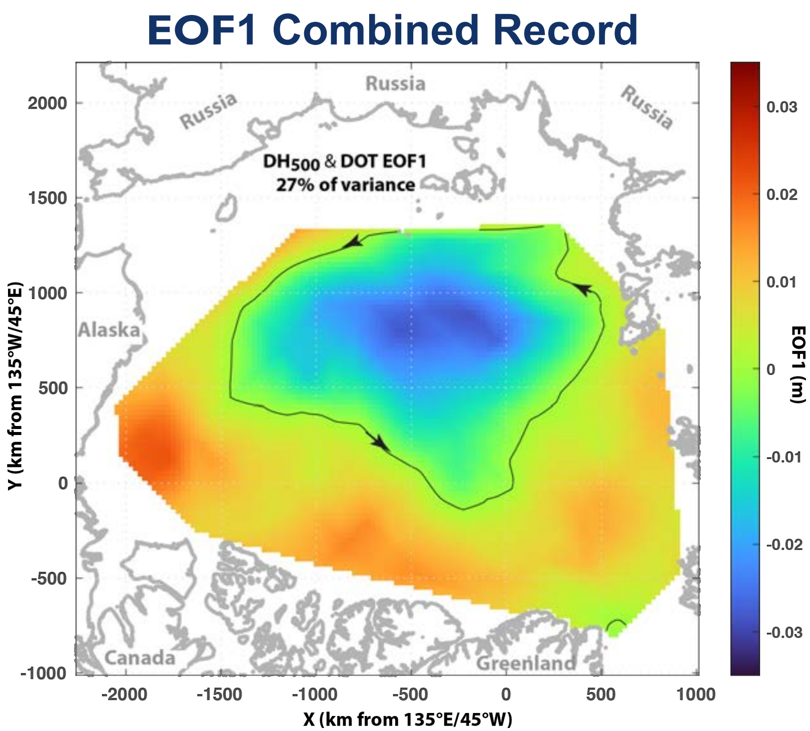


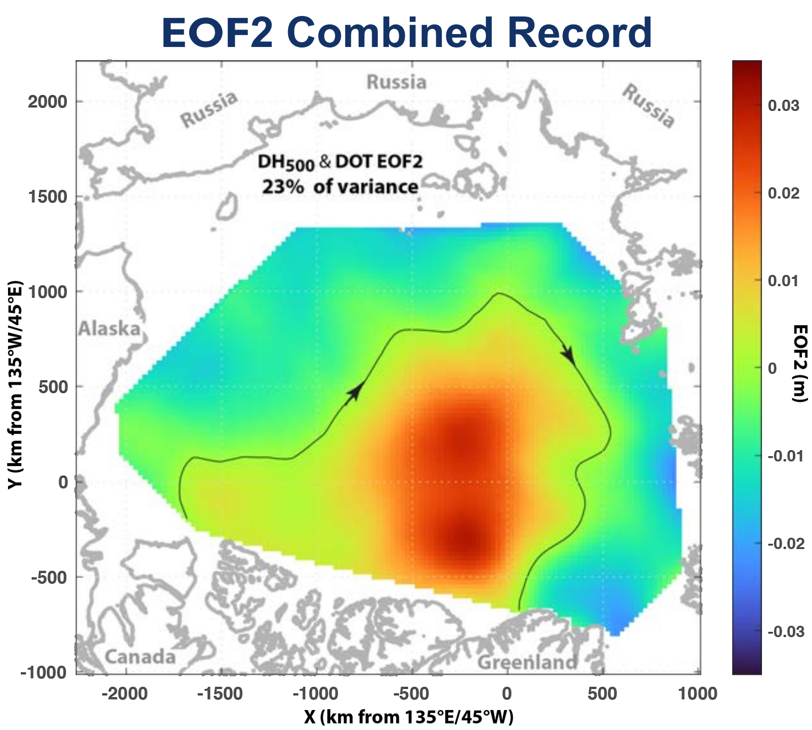
EOF1 2004-19



- EOF1 for 1950-89 DH explaining 68% of variance is dominantly a low over the Makarov Basin.
- EOF1 of 2004-19 DOT explaining 39% of the variance is like EOF1 of 1950-89 DH but has a broader extent along the Russian continental shelf break consistent with the Sokolov [1962] cyclonic mode and as seen in the DOT transitions under changing AO in 2007 and 2010.

The leading EOF for the combined 1950-89 DH_{500} and 2004-19 DOT record is a low centered in the Makarov Basin.



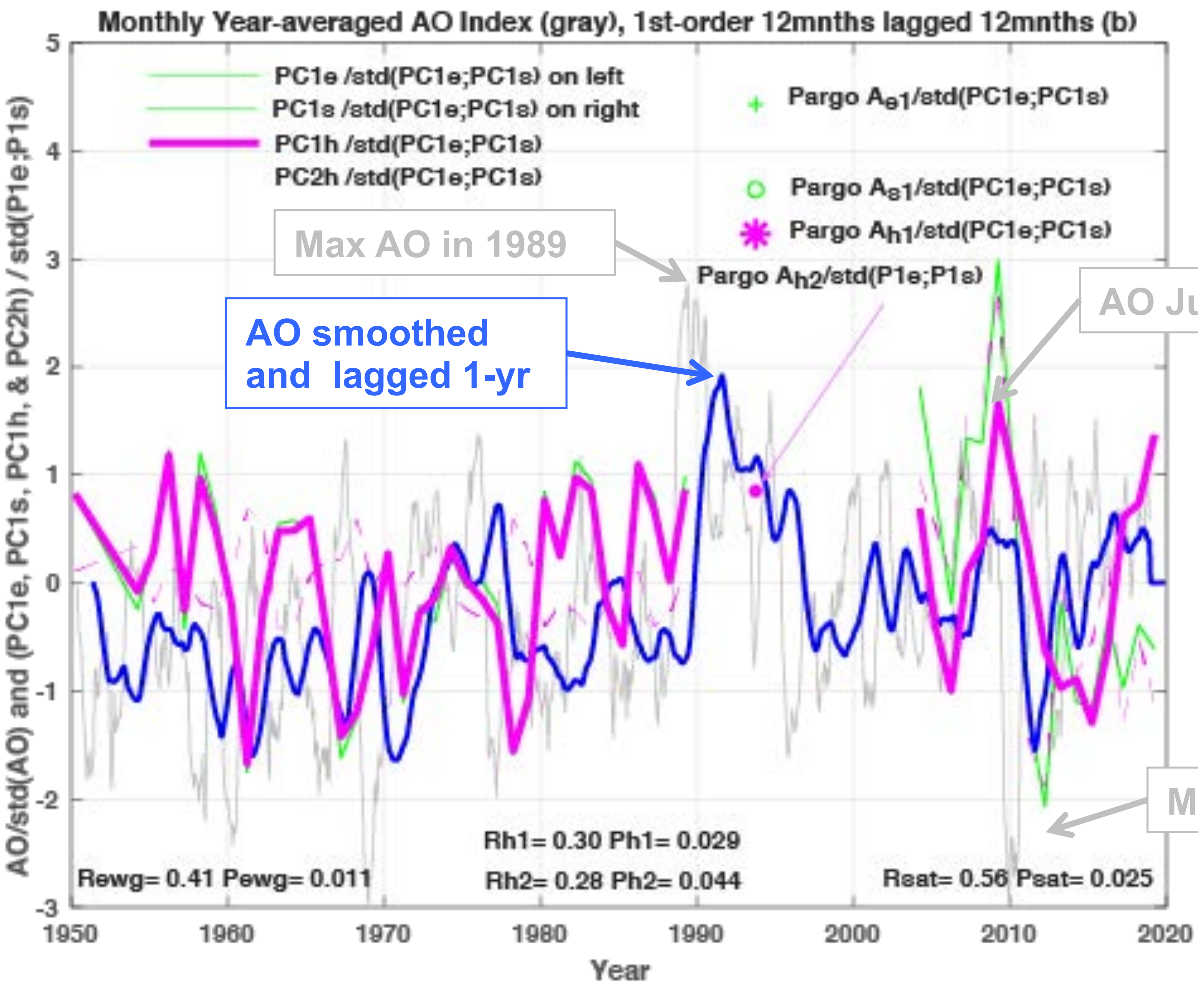


EOF1 of the 1950-2019 combined record ~ EOF1 of 1950-89 record

EOF2 of the 1950-2019 combined record ~ EOF1 2004-19 DOT and has a broader extent along the Russian continental shelf than the 1950-1989 EOF1.

EOF1 and EOF2 reflect a slight difference in first mode structure between 1950-89 and 2004-19.

PC1 for the combined record follows 1st Order (tau=1 yr.) response to the Arctic Oscillation (AO) lagged 1 year

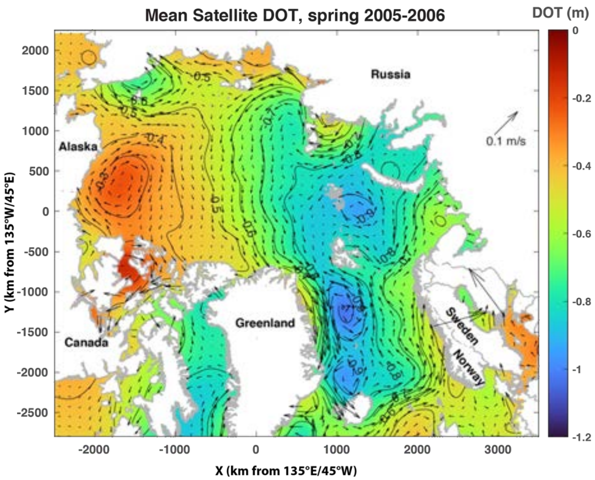


Next slide shows ocean response due to a jump in PC1 in response to an AO increase in 2007

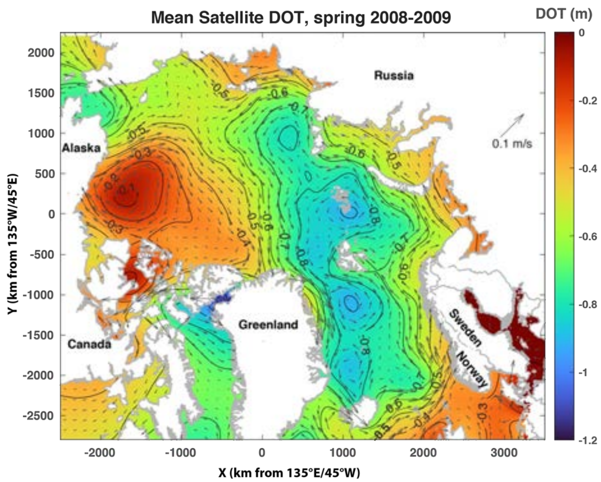
- **Correlations of lagged AO with 1950-89, 2004-19, and combined PC1s are small (0.41, 0.56, 0.3) but significant.**
- **PC1 of the combined record increased with AO after 1990.**

We have continued to find changes to be dominated by shift to cyclonic circulation centered on the Russian side of the Arctic Ocean after increases in winter AO, e.g., 2007.

ICESat 2005-06 DOT

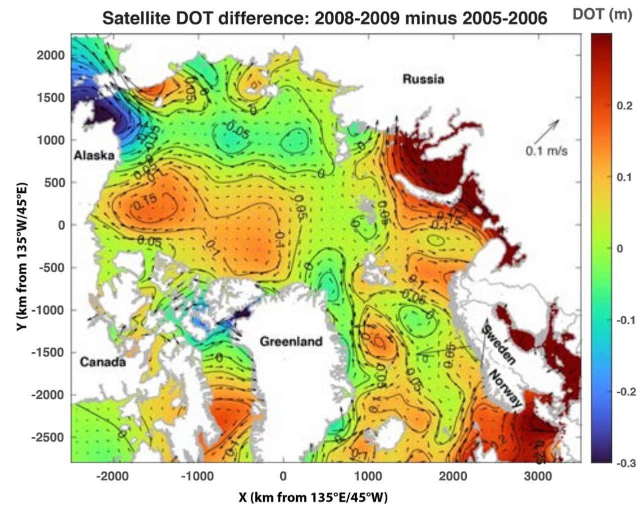


ICESat 2008-09 DOT



ICESat 2008-09 DOT

- ICESat 2005-06 DOT



More cyclonic circulation on the Russian side

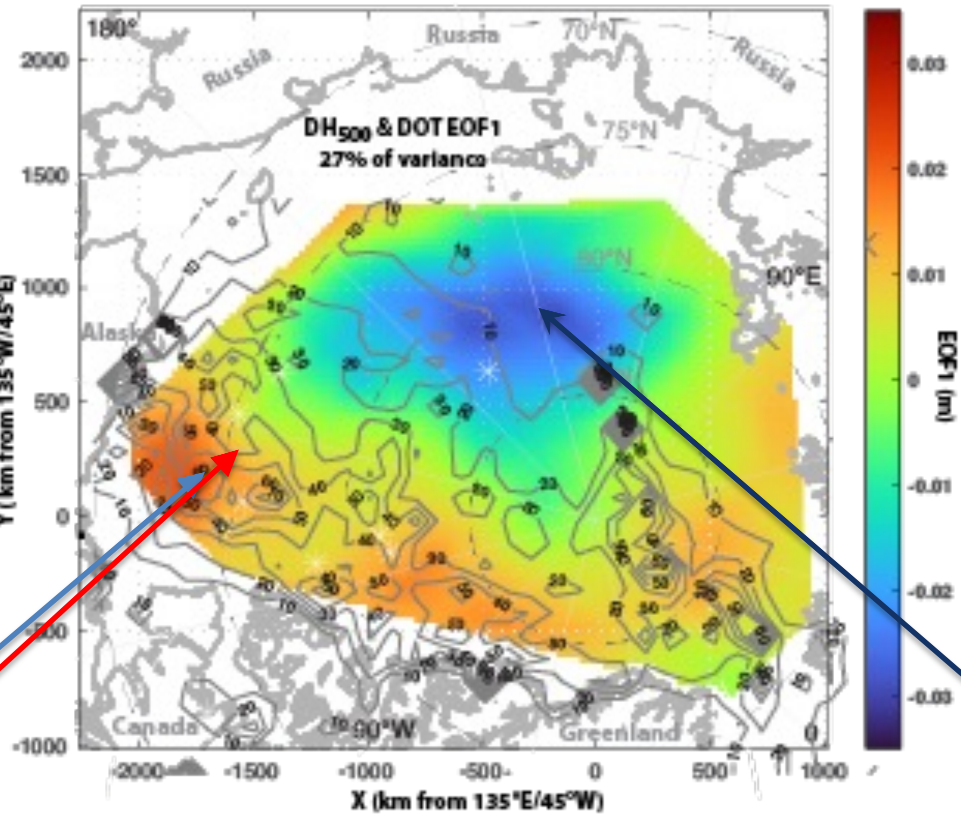
The cyclonic mode is EOF1 in its positive phase. The cyclonic mode and increased AO are important because:

- **Rising AO has been argued to be a characteristic of global warming [e.g., *Fyfe et al*., 1998; *Gillett et al*.., 2017].**
- **High winter AO is correlated with reduced ice extent the following summer [*Rigor et al*., 2002] and the cyclonic mode the following year.**
- **Cyclonic mode and increased vorticity arguably makes the ice pack divergent and more mobile leading to ice-albedo feedback and potentially enhanced ice export [Lindsay and Zhang, 2005].**
- **The cyclonic mode sends Eurasian runoff to the east, weakening the cold halocline layer and allowing Atlantic Water heat to reach the surface [*Steele and Boyd*, 1998; *Morison et al*., 2012, *Polyakov et al*., 2017] .**

But the cyclonic mode is poorly sampled by today's *in situ* observing system.

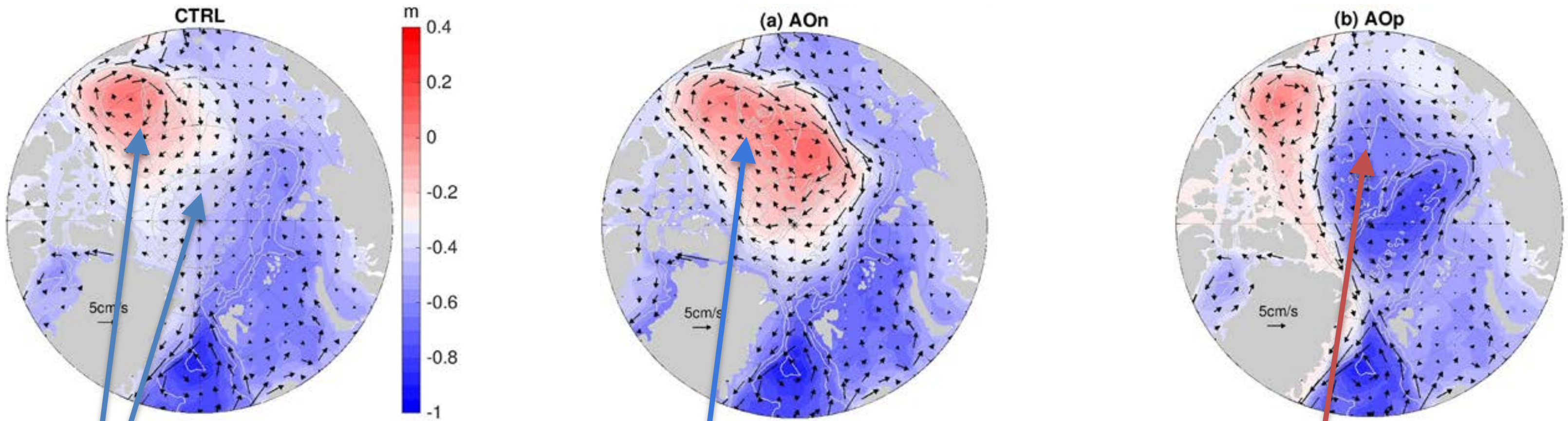
Our In Situ Observations Miss the Fundamental Mode Of Circulation Change

Percent chance of finding an IABP buoy in a 250-km square based on buoy tracks from 2001 to 2021



- The probability contours roughly align with EOF1 contours.
- The odds of finding a buoy inside EOF1's dominant feature are < 10%.
- The odds of finding a buoy inside the Beaufort Sea are 30-60%.
- Worse yet, the EOF is such that vorticity indicated by a small well sampled Beaufort Gyre is the exact opposite of poorly sampled rest of the ocean.

Model results of Wang (2021) capture the Cyclonic Mode and its relation to the AO



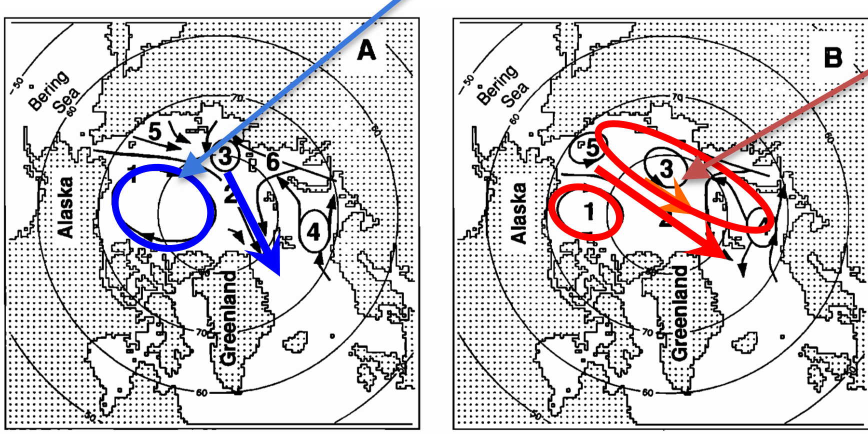
- **Control showing Beaufort Gyre and Transpolar Drift**

- **Under negative AO:**

The Beaufort Gyre expands to nearly fill the basin

- **Under positive AO:**

Cyclonic trough expands on the Russian side and the BG contracts



- **AO+ case is like response to 2007 AO increase mentioned previously and to the anticyclonic and cyclonic modes of Sokolov (1962) related to Icelandic Low.**

Conclusions

- **Changes in Arctic Ocean circulation have a center of action on the Russian side of the ocean.**
- **In the anticyclonic mode the Beaufort Gyre is large, while in the cyclonic mode cyclonic circulation on the Russian side expands, shrinking the size of the BG.**
- **Since about 1990, the Arctic Ocean has been increasingly dominated by the cyclonic mode driven by a one standard deviation positive shift in the AO.**
- **The present *in situ* observing system is effectively blind to the dominant mode of variability, and if we are going to understand circulation change:**
  a) **We need to find ways to make more measurements on the Russian side of the Arctic Ocean, and**
  b) **Devote more modeling effort to the cyclonic mode and its relation to climate.**

Thank You

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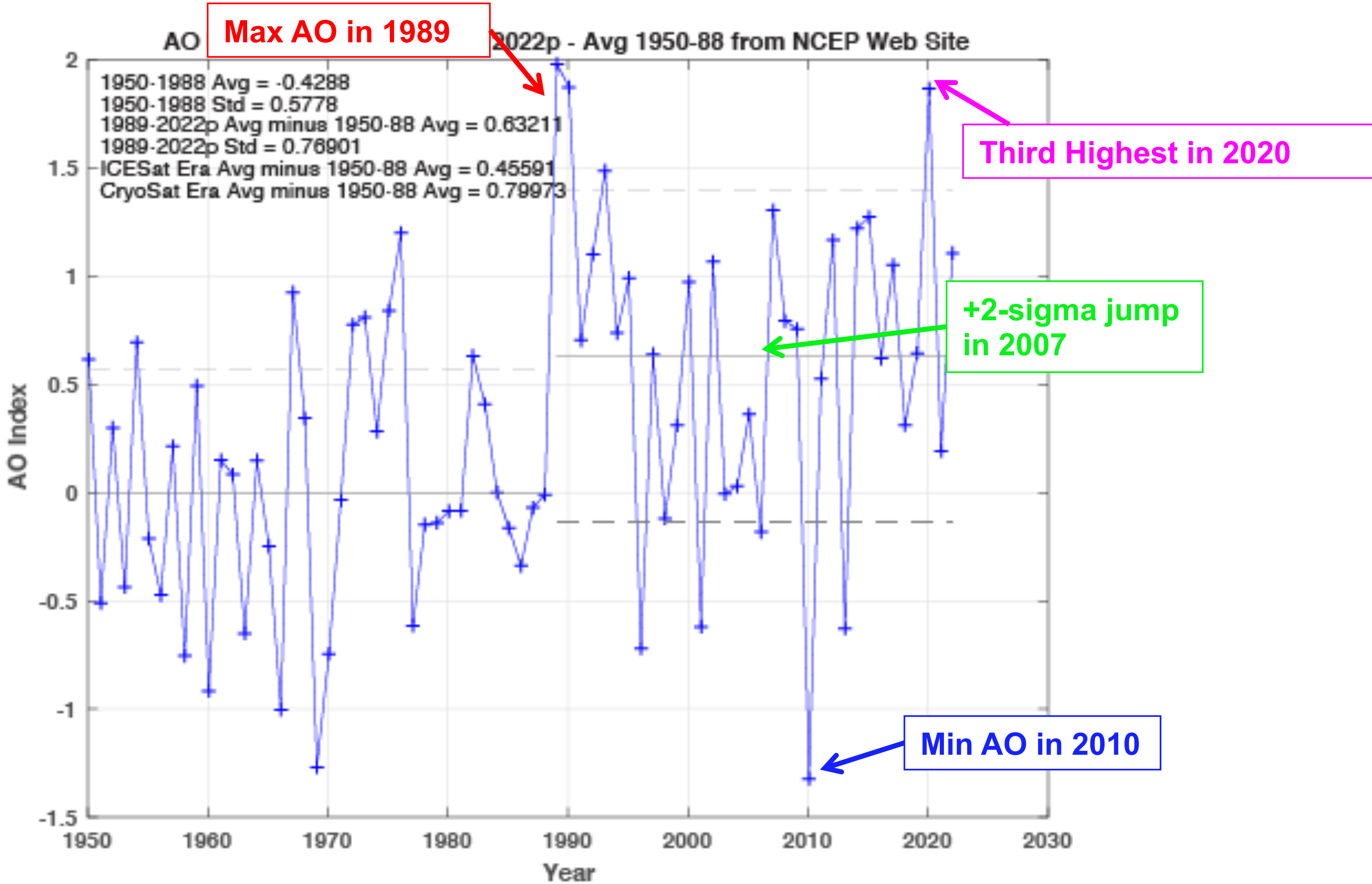
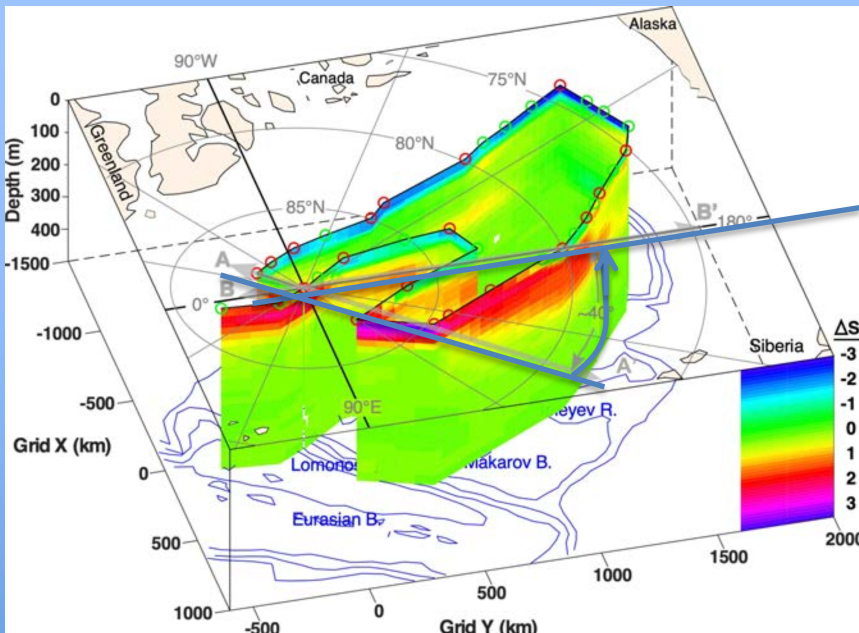
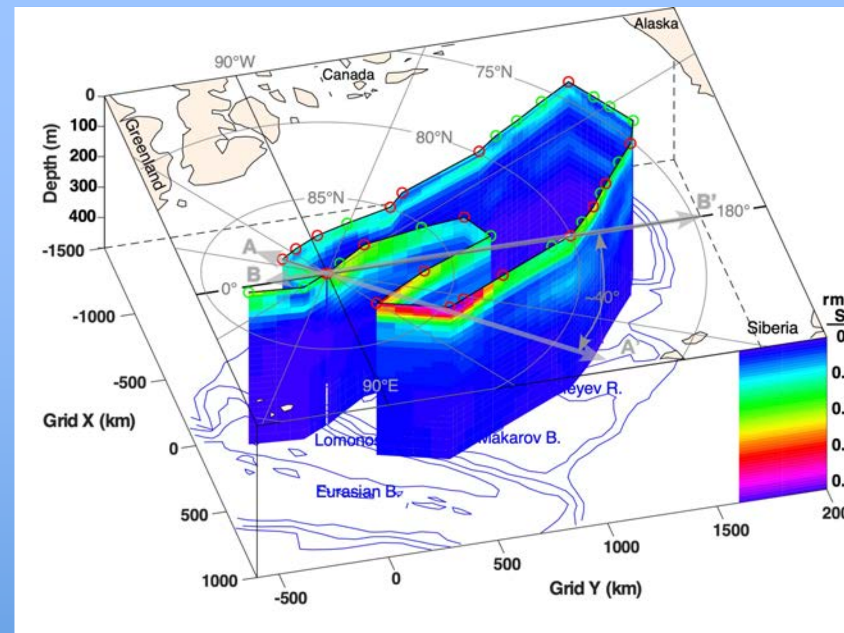
Winter Arctic Oscillation – 1950-89 Average



- **1989 AO Max => Cyclonic forcing and more cyclonic circulation in 1993**
- **1989 AO Max was also beginning of 30+ years of average AO elevated 1-σ**

Comparison of salinity measured by the *USS Pargo* in 1993 and the 1950-1989 summer climatology of the U.S. – Russian Atlas revealed a cyclonic shift in Arctic Ocean circulation driven by a 1989 AO maximum.





<u>*Pargo* '93 Salinity – Summer Climatology</u> **shows a +2 increase in salinity in the central Arctic Ocean and Makarov Basin => a cyclonic shift in the Transpolar Front between Atlantic and Pacific waters.**

The pattern of 1970s RMS salinity variation from US-Russian climatology => this is a fundamental mode of variability

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