Changes in Synoptic Weather Patterns and Greenland Precipitation in the 20th and 21st Centuries

METRO STATE

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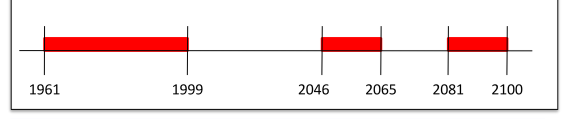
Abstract

Predictions of Greenland precipitation are analyzed using self-organizing maps (SOMs). An ERA-40 sea-level pressure synoptic climatology is used to evaluate 20th century simulations of IPCC AR4 models for the period 1961-1999. The models that best reproduce the North Atlantic surface synoptic climatology and Greenland precipitation in ERA-40 are the CCCMA-CGCM3.1(T63), MIROC3.2(hires), and MPI-ECHAM5. Using these models in a 3-model ensemble, daily SLP and precipitation data from model simulations for time periods 1961-1999, 2046-2065, and 2081-2100 are compared, where future simulations are based on the Special Report on Emissions Scenarios (SRES) A1B climate scenario. Precipitation over Greenland is predicted by this ensemble to increase from 35.8 cm yr^{-1} to 45.8 cm yr^{-1} by the end of the 21st century, a 27.8% increase. This is equivalent to an annual decline in sea level of 0.5 mm yr^{-1}. The precipitation change is attributed to changes in atmospheric circulation and thermodynamics during the future time periods. Results indicate that the North Atlantic storm track is predicted to shift northward through the 21st century, resulting in less precipitation being produced dynamically over the southeast coast of Greenland, but increased precipitation over the remainder of the ice sheet. Thermodynamic changes, explained by a strong increase in temperature and specific humidity predicted by the 3-model ensemble, dominate the future precipitation changes, accounting for 82.5% of the total change. This combination of shifting the mid-latitude cyclones that act as the forcing for Greenland precipitation, while increasing the available precipitable water in the atmosphere, produces more precipitation over Greenland under global warming conditions. These changes are predicted to most dramatically affect the northern and eastern Greenland regions during the first half of the 21st century, then the western, central, and southern regions during the second half of the 21st century.

Master Self-Organizing Map (SOM)

Data to train SOM

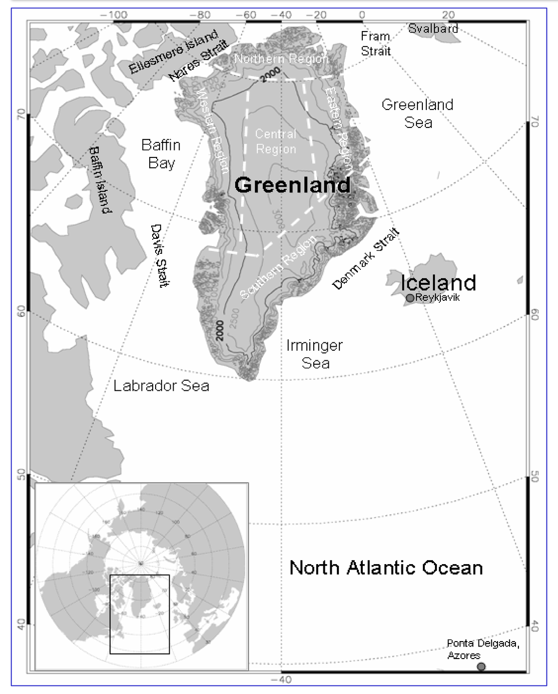
- North Atlantic domain
- Daily sea level pressure (SLP)
  - Daily Precipitation
  - –ERA-40
    - 1961-1999
  - –Output from 15 IPCC AR4 GCMs
    - 1961-1999 (20c3m)
    - 2046-2065 (SRES A1B)
    - 2081-2100 (SRES A1B)
- Over 400,000 daily samples



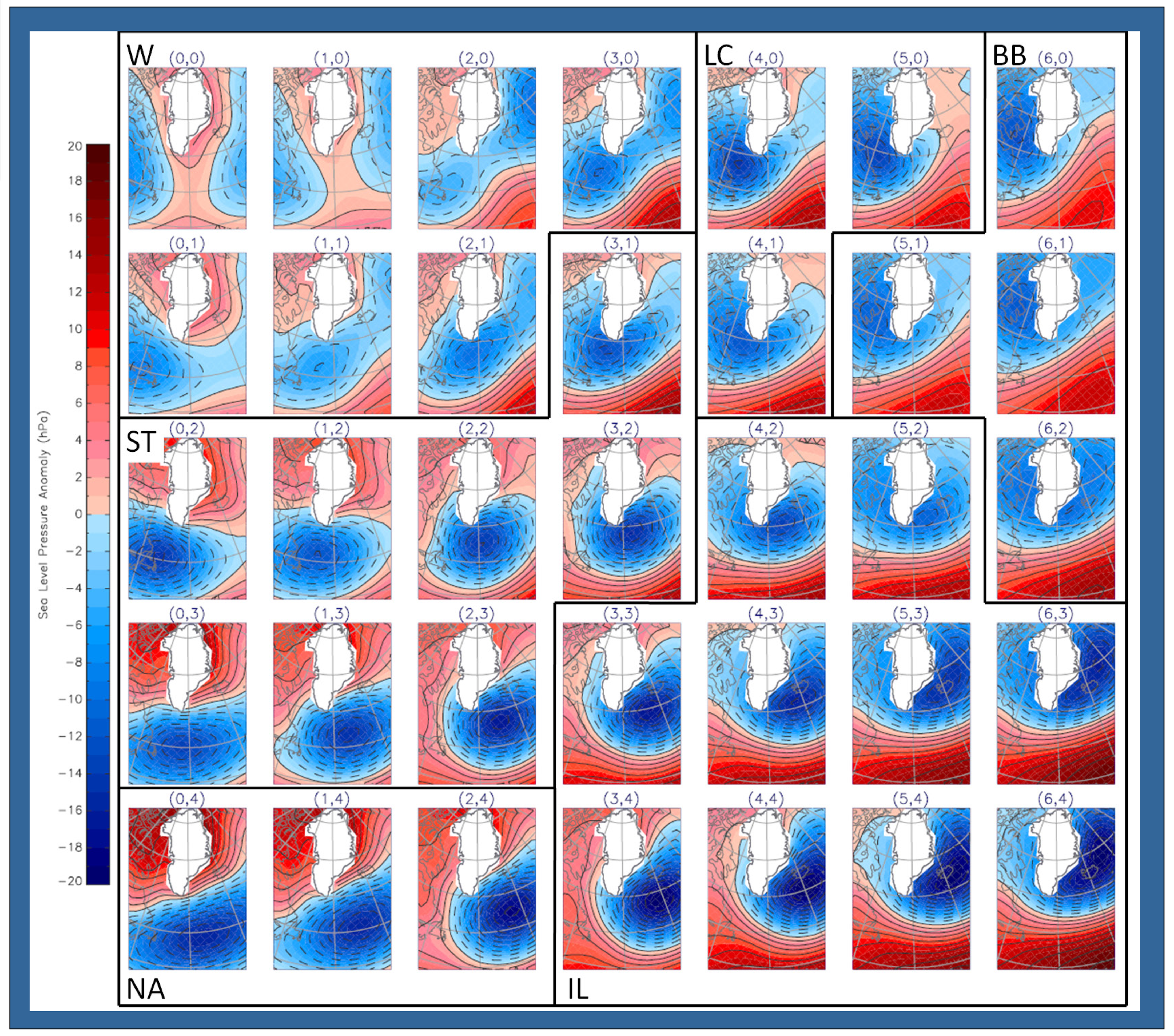
Method

Use self-organizing maps (SOMs) to:

- Objectively identify synoptic weather patterns that occur in region of interest
- Current climate (1961-1999)
  - Identify models that adequately reproduce the frequency of occurrence of these patterns
  - Determine precipitation associated with each pattern
- 21st century
  - Attribute changes in precipitation to:
    - changes in frequency of occurrence of weather patterns
    - changes in amount of precipitation associated with each weather pattern



↑ Domain used in this study. The boundaries of five Greenland regions are indicated on the map by white dashed lines. Elevation is contoured over Greenland every 500 m with a bold black line to represent the 2000 m contour.



Identifying models that reproduce ERA-40 SOM pattern frequency

↓Correlation of ERA-40 node frequency to model node frequency of occurrence.

Model	Correlations					Ranks					Sum of ranks
	Annual	DJF	MAM	JJA	SON	Annual	DJF	MAM	JJA	SON	
3 model ensemble	**0.71**	**0.87**	**0.71**	**0.90**	**0.82**	1	3	5	2	3	14
5 model ensemble	**0.65**	**0.91**	**0.64**	**0.89**	**0.78**	2	1	10	4	4	21
15 model ensemble	**0.59**	**0.76**	**0.72**	**0.78**	**0.91**	3	9	3	7	1	23
MIROC3.2(hires)	**0.56**	**0.81**	**0.73**	**0.85**	**0.69**	5	7	2	5	5	24
CCCMA-CGCM3.1(T63)	**0.54**	**0.87**	**0.71**	**0.75**	**0.65**	6	2	4	8	7	27
MPI-ECHAM5	**0.57**	**0.77**	0.41	**0.91**	**0.83**	4	8	16	1	2	31
GFDL-CM2.1	0.27	**0.64**	**0.66**	**0.63**	**0.66**	10	11	8	10	6	45
NCAR-CCSM3.0	0.47	**0.81**	-0.06	**0.62**	**0.63**	7	5	18	11	8	49
IPSL-CM4	0.45	**0.82**	**0.70**	0.42	0.11	8	4	6	15	16	49
MIROC3.2(medres)	0.25	0.37	0.46	**0.90**	**0.62**	11	14	14	3	9	51
MIUB-ECHO-G	0.20	**0.81**	**0.65**	**0.52**	0.38	12	6	9	14	13	54
CCCMA-CGCM3.1	0.03	**0.74**	**0.57**	**0.60**	**0.53**	15	10	11	12	11	59
MRI-CGCM2.3.2A	0.02	0.42	**0.51**	**0.81**	**0.51**	16	13	12	6	12	59
IAP-FGOALS-g1.0	0.36	0.35	**0.68**	0.37	0.28	9	15	7	17	14	62
CSIRO-Mk3.0	0.03	0.32	**0.50**	**0.74**	**0.61**	14	16	13	9	10	62
GISS-ER	0.11	0.25	**0.74**	0.38	-0.03	13	17	1	16	18	65
GFDL-CM2.0	-0.06	0.50	0.45	**0.56**	0.24	18	12	15	13	15	73
GISS-AOM	-0.03	-0.49	0.31	-0.18	0.09	17	18	17	18	17	87

We wanted to find a model or ensemble of models that best reproduces the ERA-40 SLP synoptic climatology, our best representation of reality. We can't use ERA-40 to forecast the future climate, but if we can find models that best simulate the past climate, we can use those to predict the future.

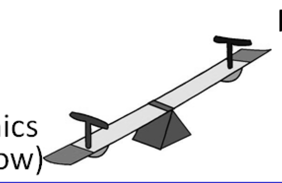
Each model's frequency of occurrence of weather patterns is correlated to the ERA-40 frequency of weather patterns for 1961-1999. Based on these correlations, a 3-model ensemble, consisting of models CCCMA-CGCM3.1(T63), MIROC3.2(hires), MPI-ECHAM5, was chosen.

← Figure: Master SOM of SLP anomalies (hPa) trained from 20th and 21st century data from 15 IPCC AR4 AOGCMs as well as ERA-40 reanalysis data. Anomaly SLP contour interval is 2 hPa. Blue shades and dashed contours represent negative SLP anomalies, while red shades and solid contours represent positive SLP anomalies

- Six groupings, 35 nodes-
  - –W-Weak cyclones
  - –LC-Labrador Sea cyclones
  - –BB-Baffin Bay cyclones
  - –ST-Southern Tip cyclones
  - –NA-North Atlantic cyclones
  - –IL-Icelandic Low cyclones

Motivation:

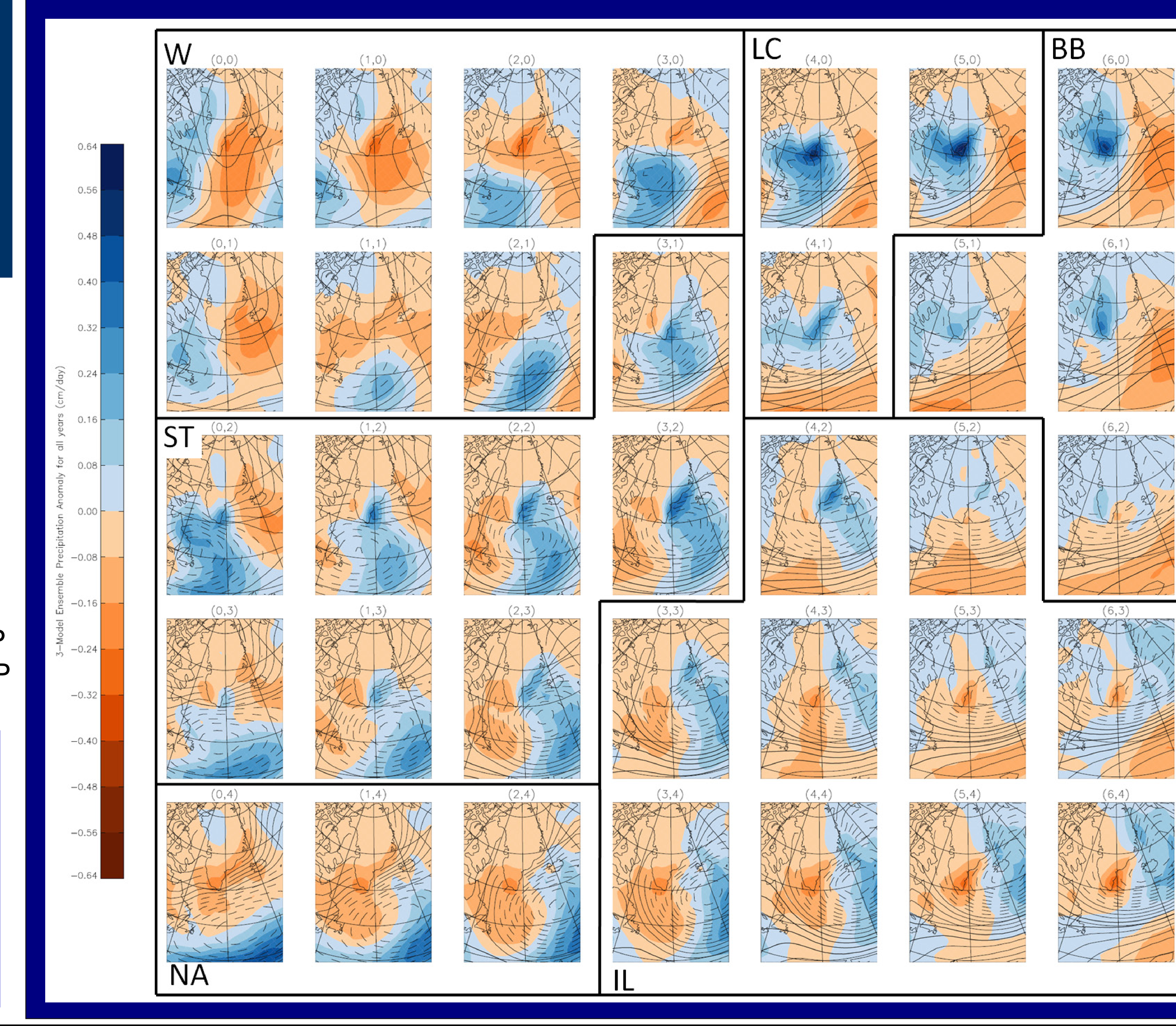
Mass Balance of the Greenland Ice Sheet



Mapping Precipitation to Master SOM

The list of days whose sea level pressure pattern fell into each node was used to create a list of all of the precipitation data that fell into each node. These 3-model ensemble precipitation data were averaged to create a precipitation pattern mapped to a certain node on the master SOM. For example, the precipitation maps for the several hundred days whose synoptic pattern best matched node (0,0) were averaged to create the precipitation expected to happen whenever the synoptic pattern in node (0,0) takes place.

↓ Master SOM node anomaly SLP (solid contour lines for positive SLP anomalies and dashed contour lines for negative SLP anomalies with 2hPa contour intervals) and node averaged 3-model ensemble precipitation anomaly for 1961-1999, 2046-2065, and 2081-2100 (cm day^{-1}) (blue shading indicates positive precipitation anomalies and orange shading indicates negative precipitation anomalies).



Why is Greenland precipitation predicted to change?

Greenland Precipitation Change from 1961-1999 to 2081-2100

- The annual Greenland precipitation is predicted by the 3-model ensemble to increase from 35.8 cm to 45.8 cm (10 cm), a 27.8% increase
  - –To put this into perspective, 10 cm of precipitation over Greenland is equal to 0.5 mm sea level decline
- Two things are predicted to change in the 21st century
  1. Circulation
  2. Precipitation amount from a given weather pattern

Using the SOM, we can evaluate the contribution from each of these and answer the question: *Why is Greenland precipitation predicted to change?*

Attribution of precipitation change

$$P_{annual} = 365\frac{day}{yr}\sum_{n=1}^{35} f_n p_n \qquad f_{future} = (f + \Delta f) \qquad p_{future} = (p + \Delta p)$$

$$P_{future} = 365\frac{day}{yr}\sum_{n=1}^{35} (f_n + \Delta f_n)(p_n + \Delta p_n)$$

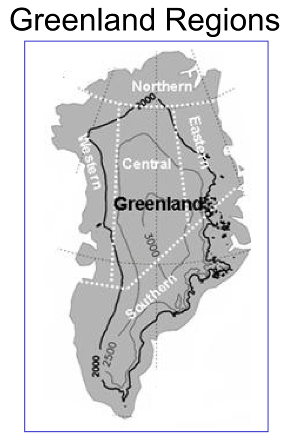
$$P_{future} = 365\frac{day}{yr}\sum_{n=1}^{35} \underbrace{f_n p_n}_{\text{Initial}} + \underbrace{\underbrace{f_n \Delta p_n}_{\text{Intra-Pattern Variability}} + \underbrace{\Delta f_n p_n}_{\text{Frequency Change}} + \underbrace{\Delta f_n \Delta p_n}_{\text{Combined}}}_{\text{Net Change: 10 cm}}$$

n = node

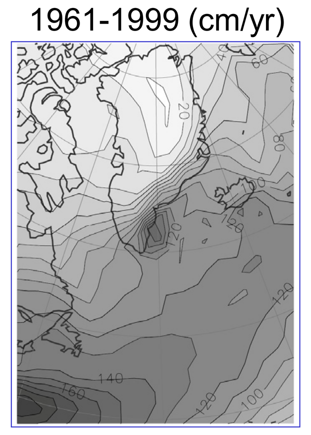
f = number of days occurring

p = precipitation (cm/day)

Greenland Regions



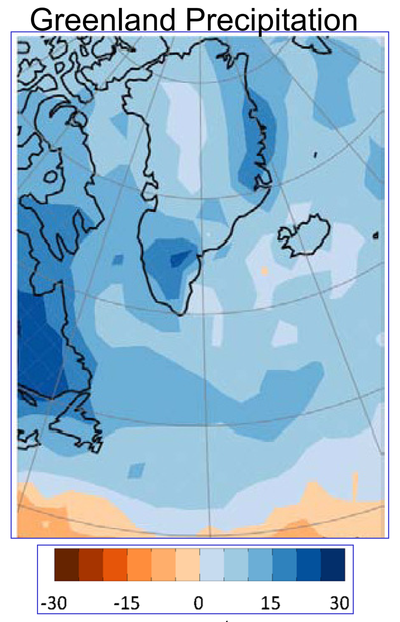
Annual Precipitation 1961-1999 (cm/yr)



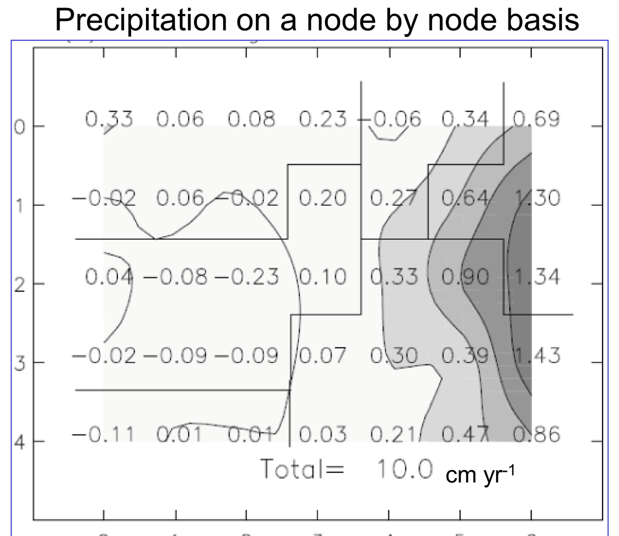
Predicted change in precipitation

Region	Precipitation 1961-1999 (cm/yr)	2081-2100 (cm/yr)	Change (cm/yr)	Percent Change (%)
Greenland	35.8	45.8	10.0	27.8%
Southern	65.0	78.4	13.4	20.7%
Eastern	23.7	37.4	13.7	58.1%
Central	15.6	21.2	5.6	36.2%
Western	25.4	32.1	6.7	26.3%
Northern	16.7	26.7	10.0	60.0%

Predicted Change in Greenland Precipitation



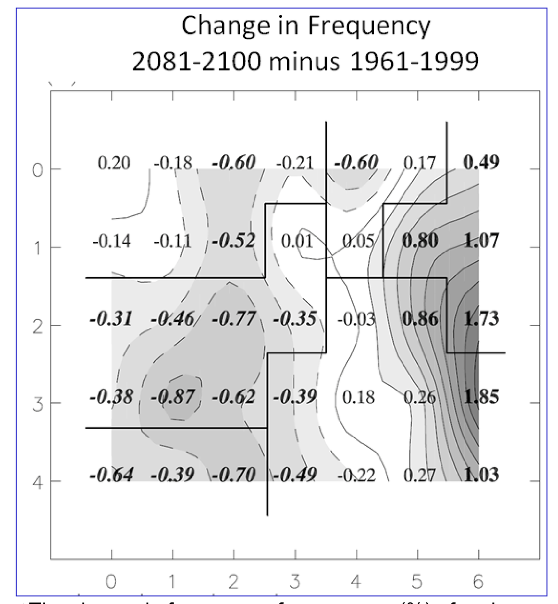
Predicted Change in Greenland Precipitation on a node by node basis



A Northward Shift in Storm Track (13%)

$$\underbrace{\Delta f_n p_n}_{\text{Frequency Change}}$$

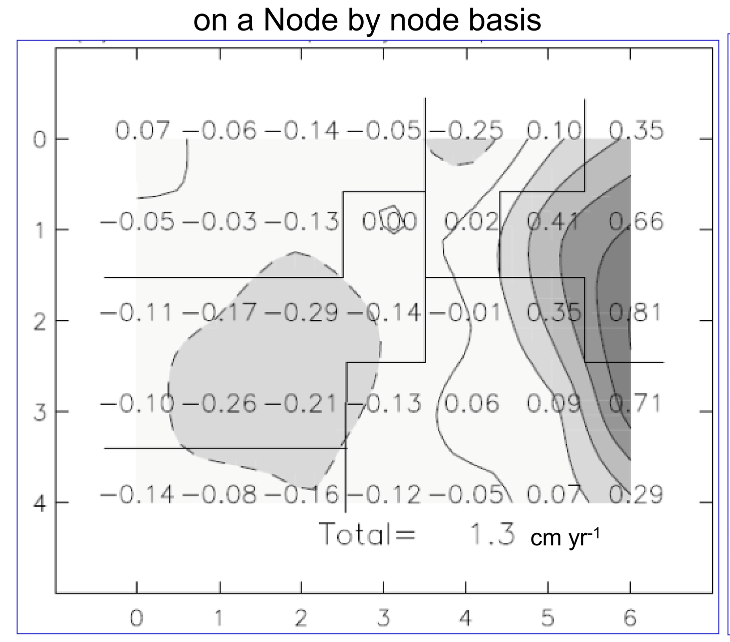
Change in Frequency 2081-2100 minus 1961-1999



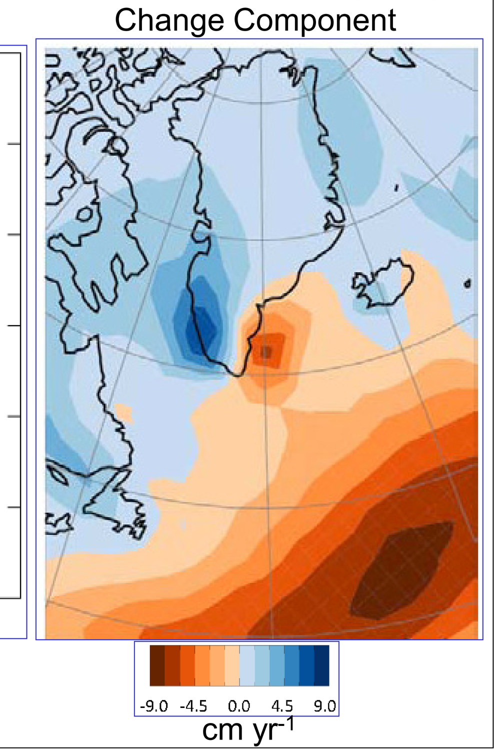
↑The change in frequency of occurrence (%) of nodes on the master SOM. Positive values indicate synoptic patterns that will become more common by the end of the 21st century. Negative values indicate patterns that will become less common over time.

Synoptic patterns on the right side of the master SOM will become more frequent in a warmer climate. These patterns consist of cyclones with centers in the northern portions of the domain, indicating a northern shift in storm track over the 21st century. This change in weather pattern frequency is responsible for 13% of the predicted increase in precipitation. Nodes on the right side of the SOM will contribute more to Greenland precipitation in the future due to this frequency change. This shift will cause southeastern Greenland to receive less snowfall and southwestern Greenland to receive more. This effect, however, is overshadowed by the large increases in precipitation from each event (see box below).

Effect of Pattern Frequency change component on a Node by node basis



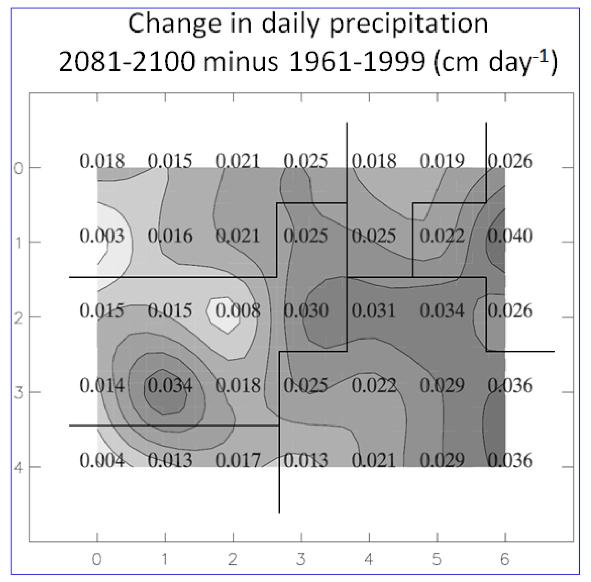
Effect of Pattern Frequency Change Component



More precipitation from each event (82%)

$$\underbrace{f_n \Delta p_n}_{\text{Intra-Pattern Variability}}$$

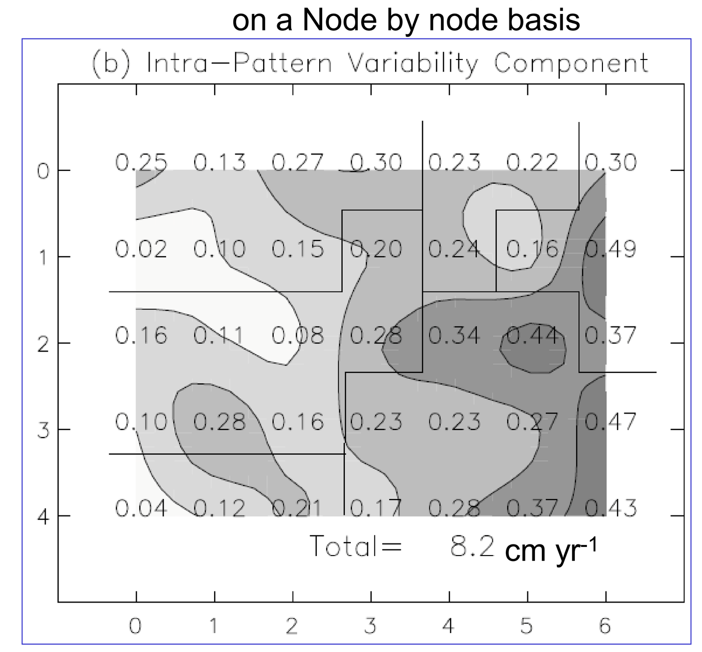
Change in daily precipitation 2081-2100 minus 1961-1999 (cm day^{-1})



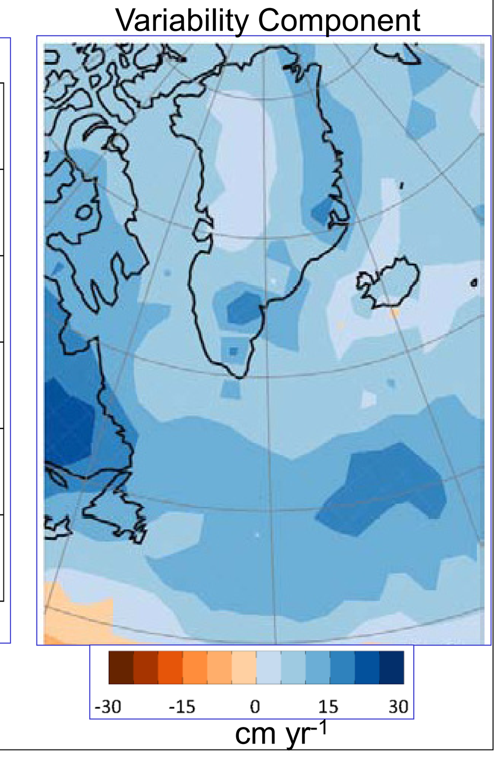
↑The change in average daily Greenland precipitation from each node on the master SOM. Positive values indicate that each synoptic pattern, when it occurs, will produce more precipitation in a warmer climate.

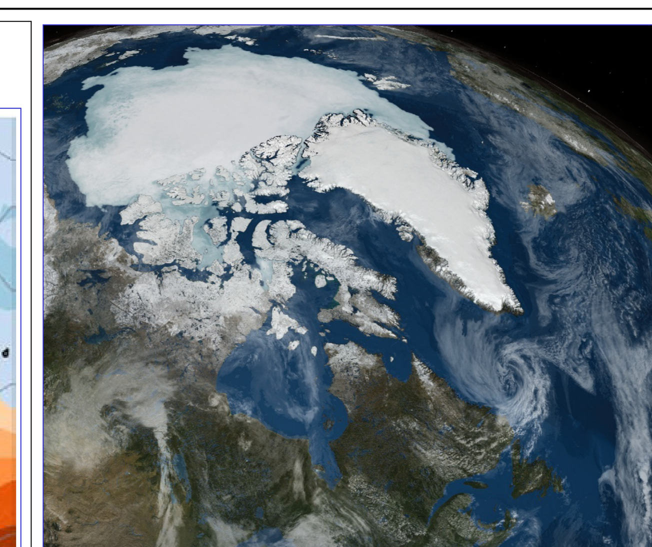
Intra-pattern variability is responsible for 82% of the predicted increase in precipitation. Intra-pattern variability change, or changes in the water cycle that, with increases in global temperatures, will allow for more precipitable water availability in the atmosphere. This change takes place quickly for the northern and eastern regions, allowing their rate of change to be largest over the first half of the 21st century, while the other regions will experience a higher rate of change over the second half of the century.

Effect of Intra-Pattern variability component on a Node by node basis



Effect of Intra-Pattern Variability Component





The interaction between the synoptic circulations and the topography of the Greenland ice sheet creates precipitation.

Conclusions

- Predicted changes over the 21st century (1961-1999 to 2081-2100) using:
  - –A North Atlantic domain
  - –The SRES A1B global warming scenario
  - –A 3-model ensemble consisting of CCCMA-CGCM3.1(T63), MIROC3.2(hires), and MPI-ECHAM5:
    - –A northward shift in storm track is evident from the frequency of occurrence of SOM nodes in the future
    - –Precipitation resulting from any single weather pattern is predicted to be higher in the future
    - –Annual Precipitation over Greenland will increase from 35.8 cm to 45.8 cm (10 cm, 27.8% increase)
      - Precipitation over Northern and Eastern Greenland will increase by up to 60.0%
      - This increase in precipitation is a result of mostly thermodynamic, but also atmospheric circulation (dynamic) changes that will take place under global warming conditions
- The increase in precipitation over Greenland is only equal to 0.5 mm yr^{-1} decrease in sea level, not enough to make up for melt and ice sheet dynamics losses under the same warming scenario. Greenland will lose mass.