Future interannual variability of Arctic sea ice and its implications for marine navigation

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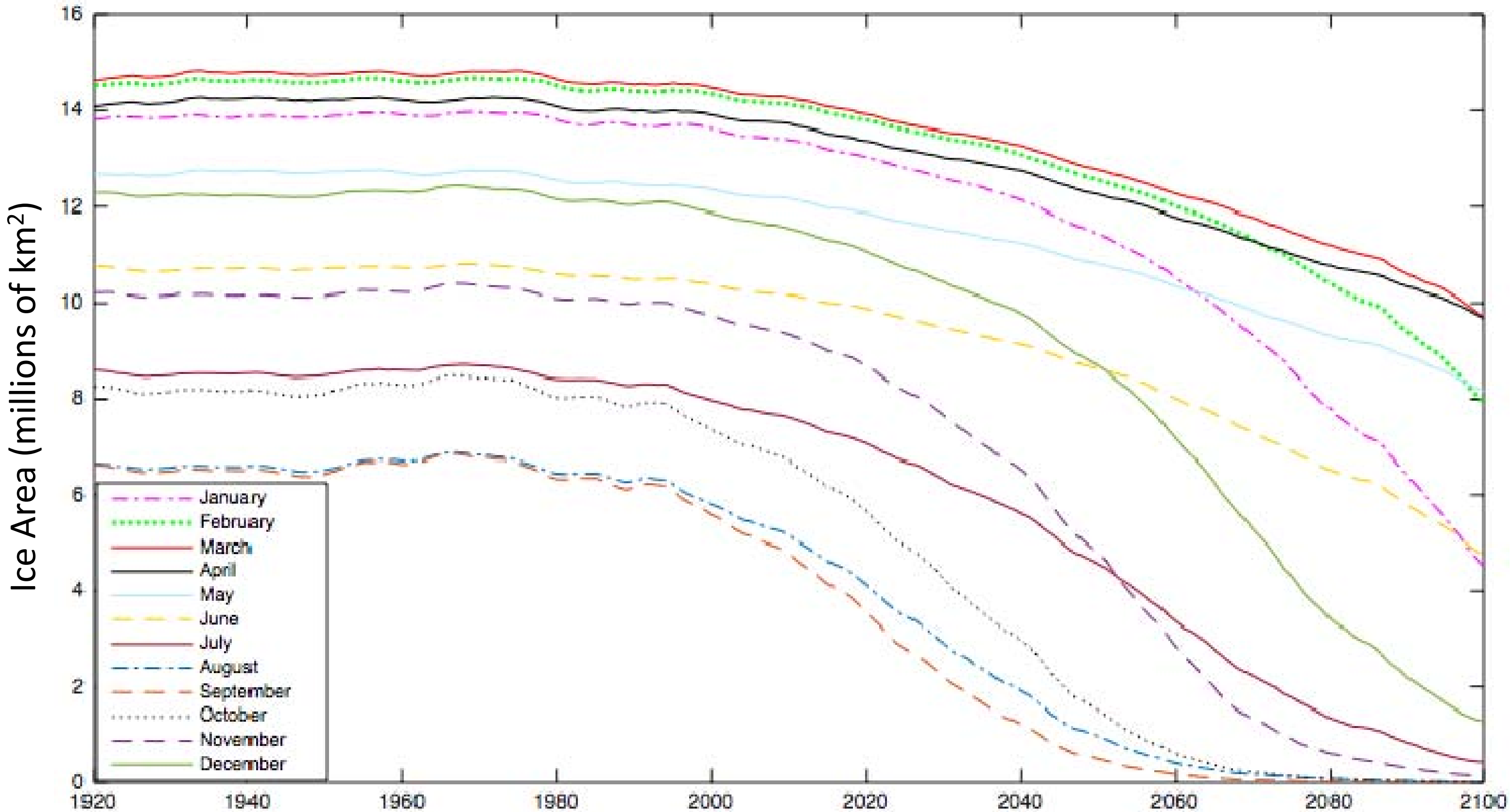
Data

- 40 independent realizations from CESM-LE
    - Past forcing, 1920-2005: observed radiative
    - Future forcing, 2006-2100: RCP8.5 emissions scenario
    - Monthly ice variables; all seasons

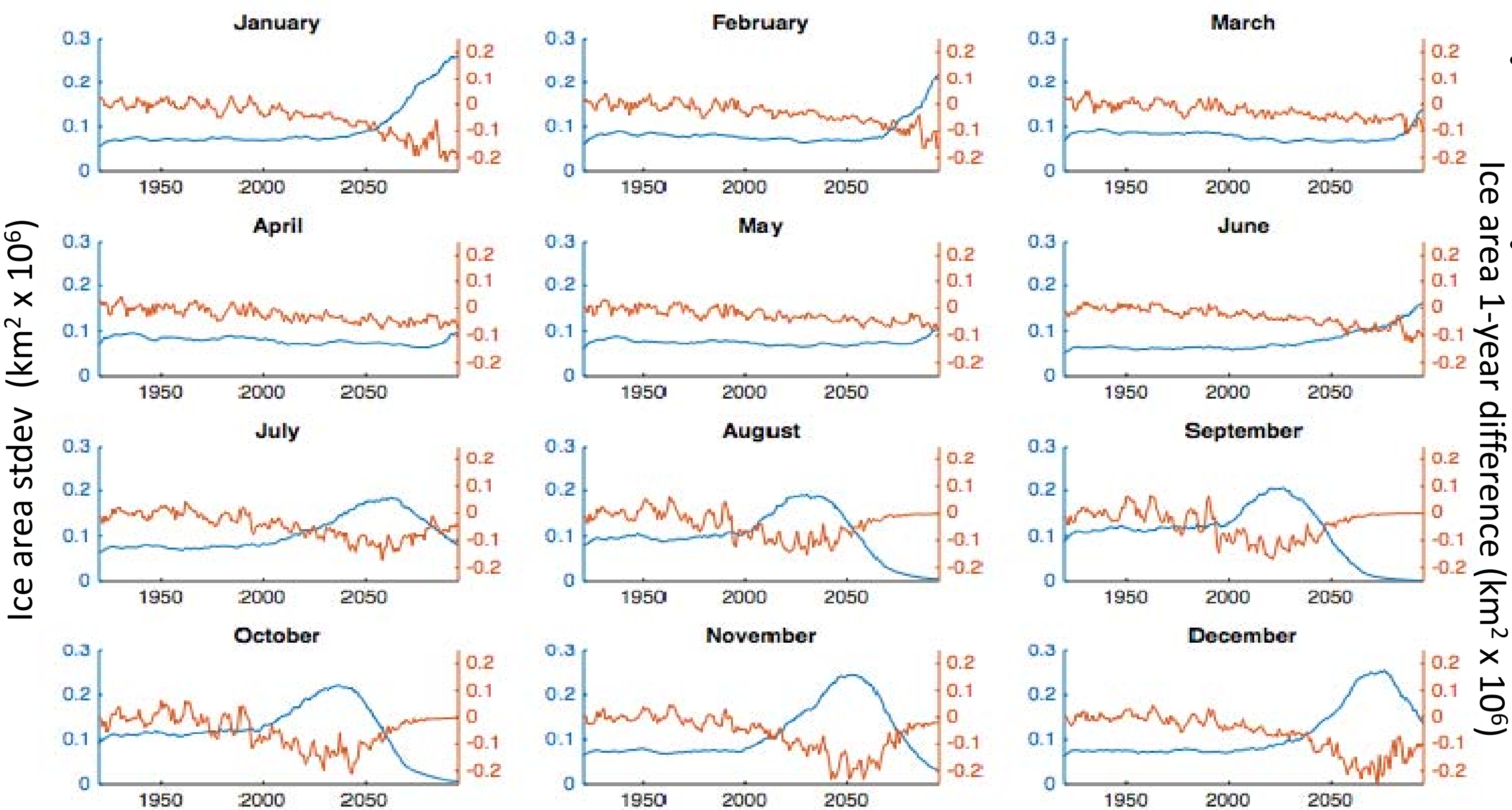
- 33 ensemble members from 12 CMIP5 models

Monthly Sea Ice Area Projections



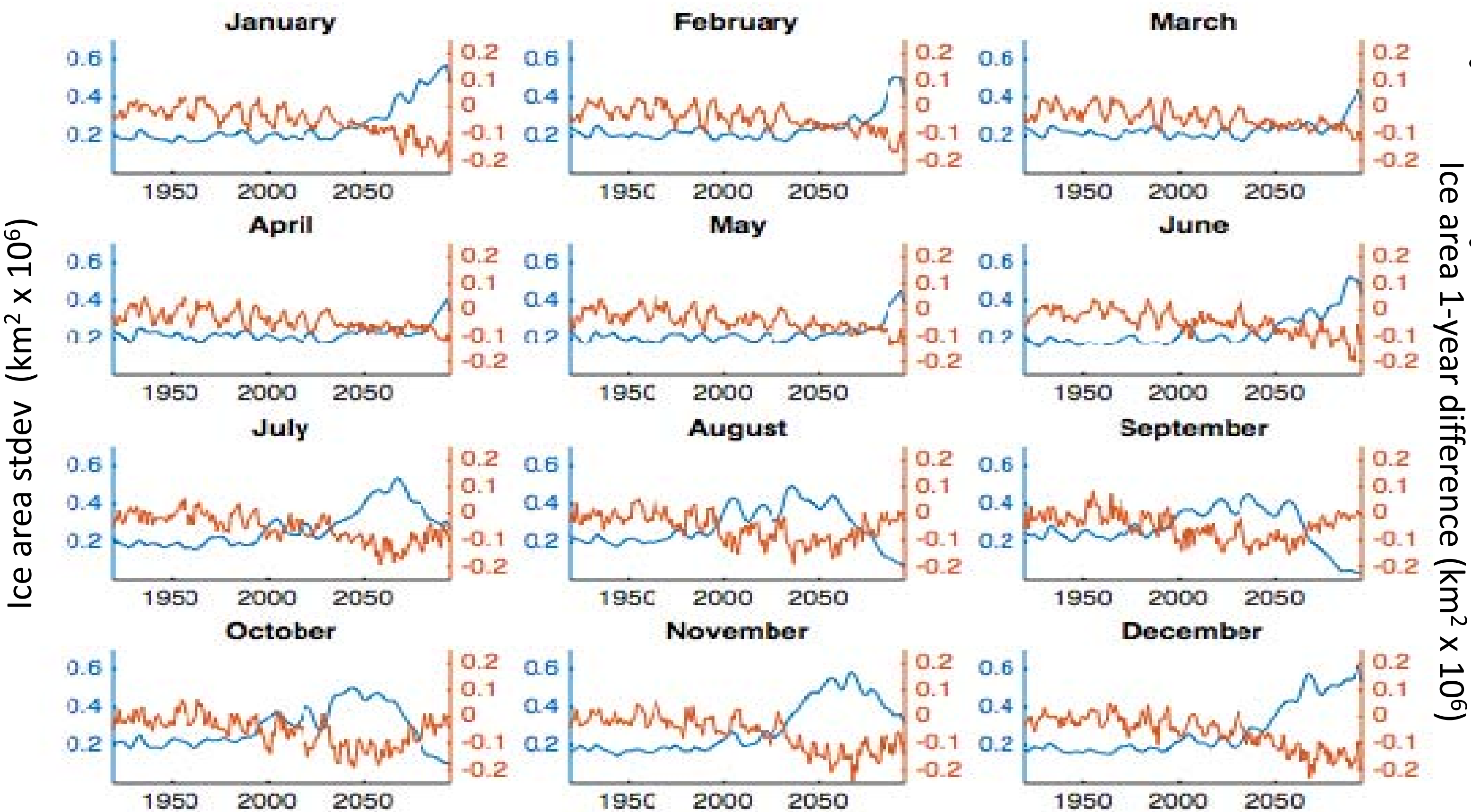
Ensemble mean of 5-year running mean ice area

Ice Area Standard Deviation and Rate of Loss



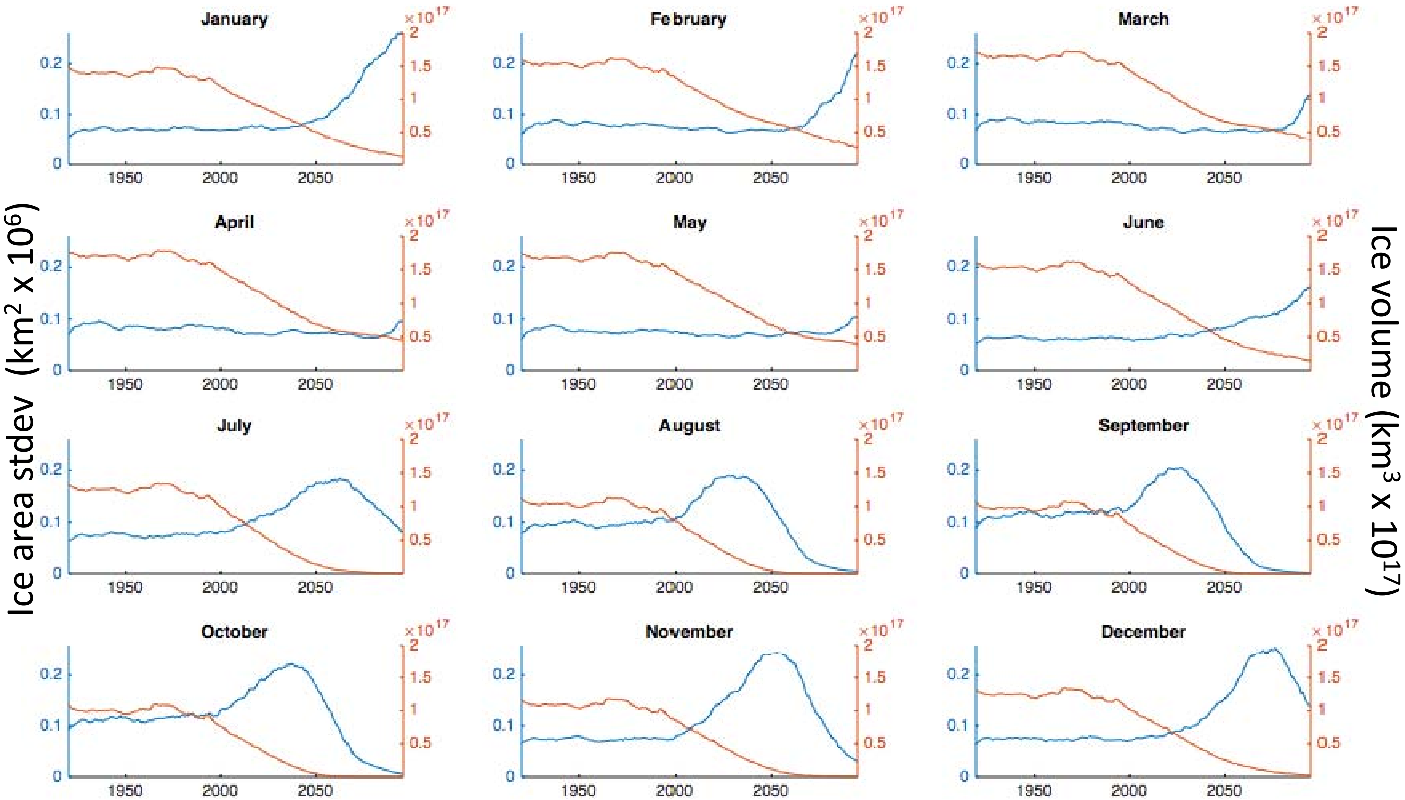
- 10-year running standard deviation applied to running mean of ice area
- 1-year difference in ice area (running mean)

Ice Extent Standard Deviation and Rate of Loss – CMIP5



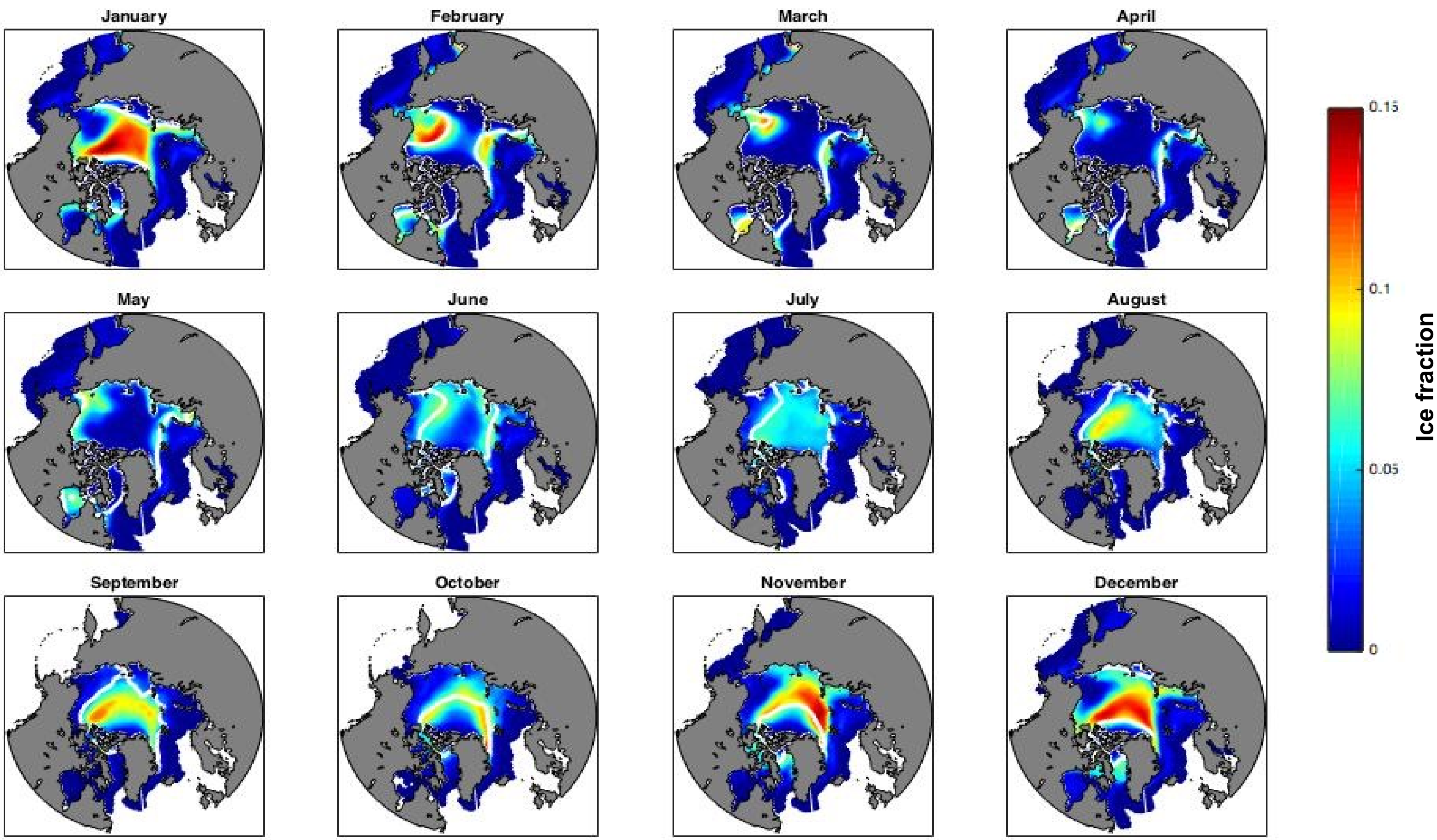
- 10-year running standard deviation applied to running mean of ice area
- 1-year difference in ice area (running mean)

Ice Volume and Standard Deviation of Ice Area



Month	Year of Peak Std. Deviation	Year When Volume < 0.5 x 10^{17} km^2
January	2099	2052
February	2099	2069
March	2099	2081
April	2099	2088
May	2099	2068
June	2099	2048
July	2061	2026
August	2030	2016
September	2026	2013
October	2036	2015
November	2053	2022
December	2076	2023

Standard Deviation of Ice Area in Year when it Peaks



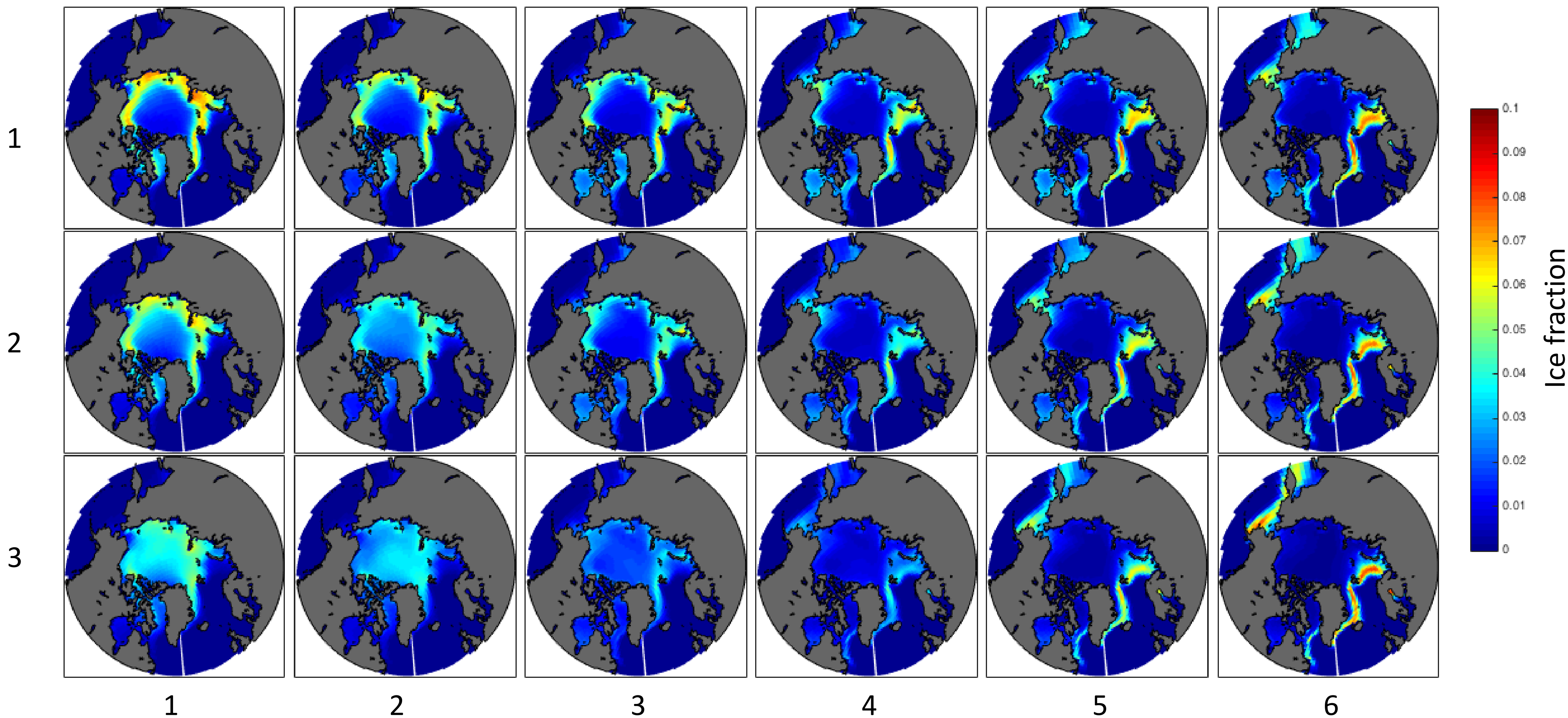
White contour indicates mean 0.25 m thickness

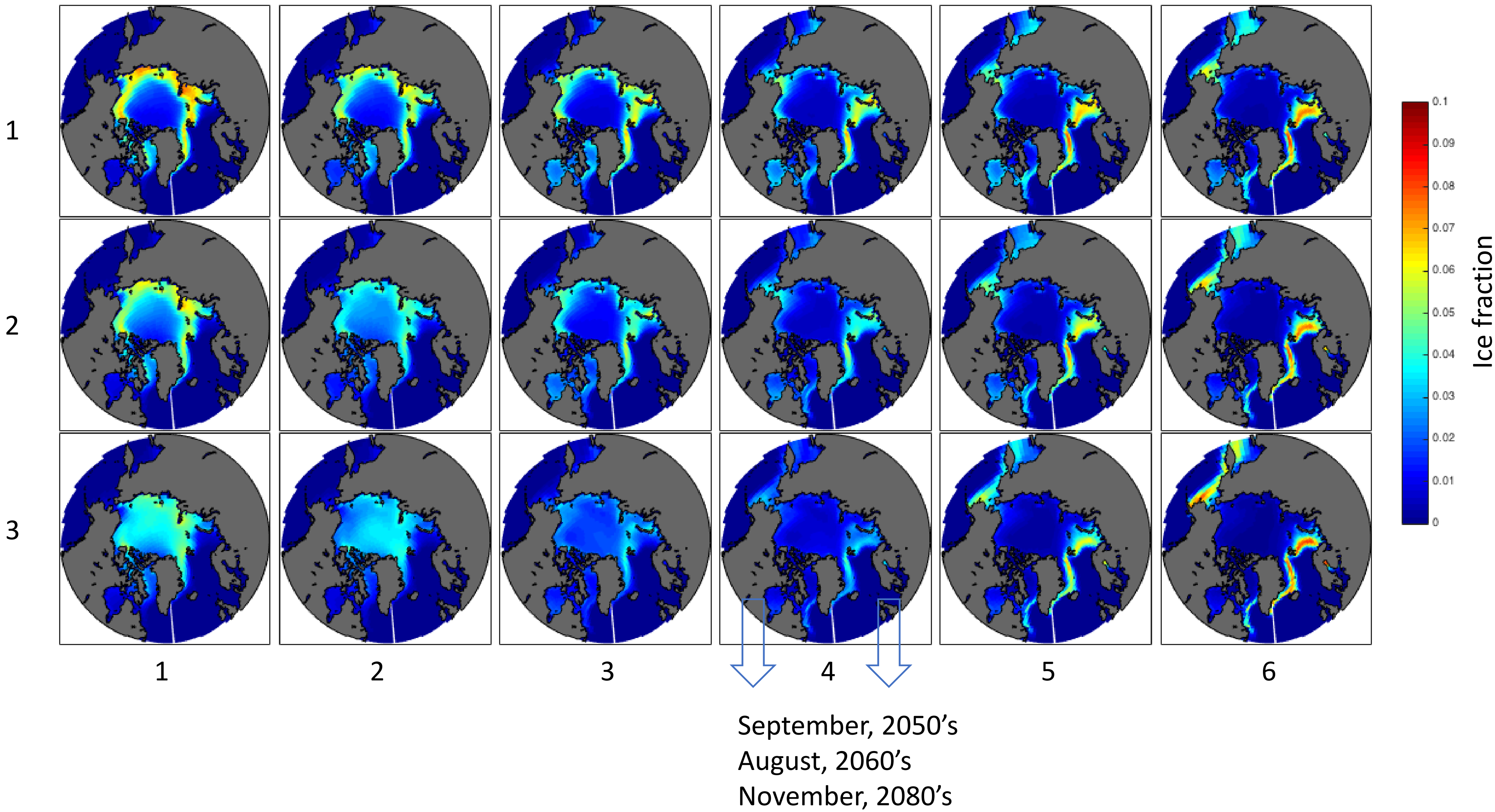
Ice Area Variability – Self Organizing Maps

- Artificial neural network used to separate distinct patterns in the underlying spatial data

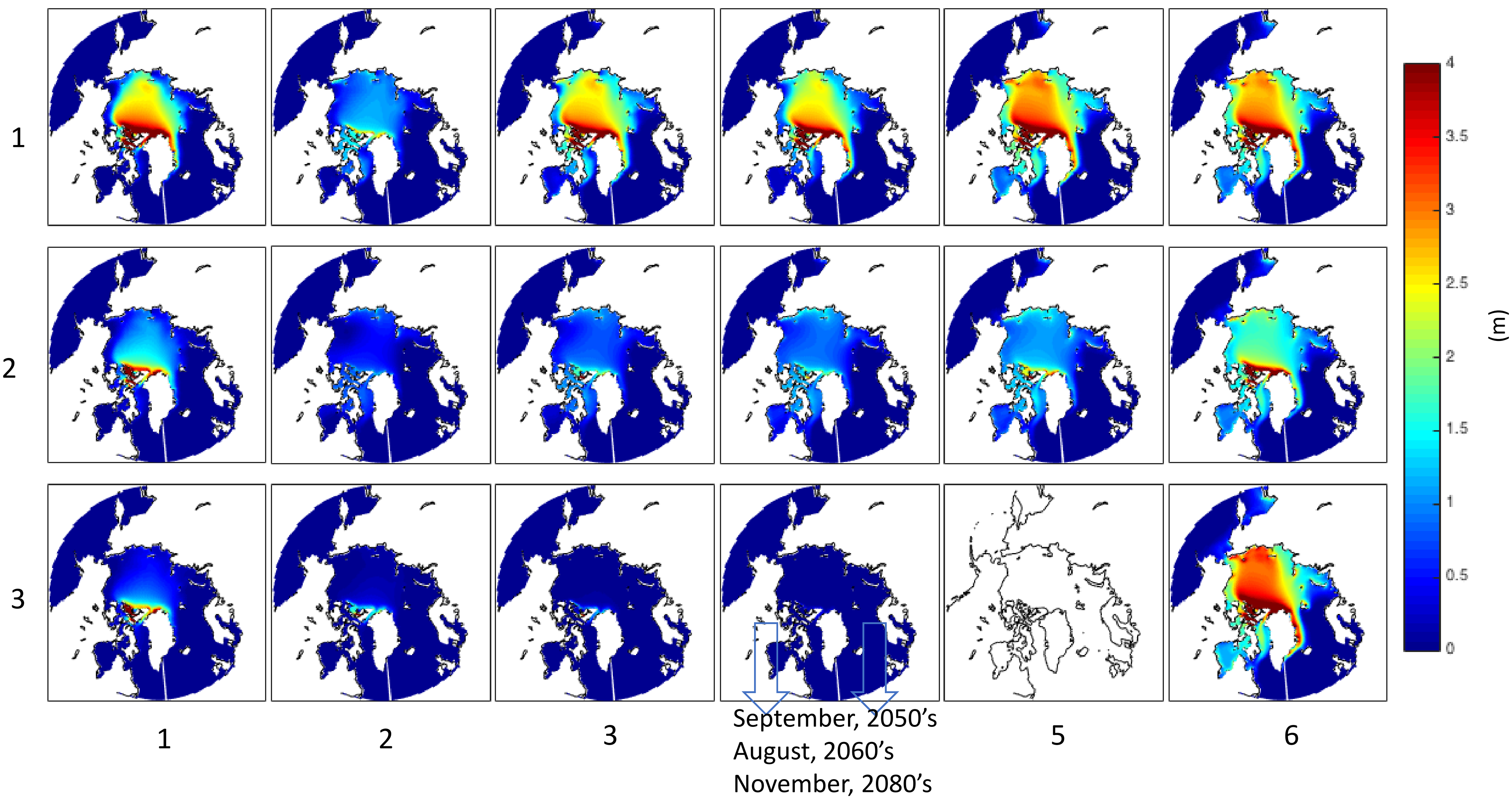
- Monthly sea ice area 10-year running standard deviation
- Input is 12 months x 18 decades (spatial)

Master SOM Map of Ice Area Standard Deviation

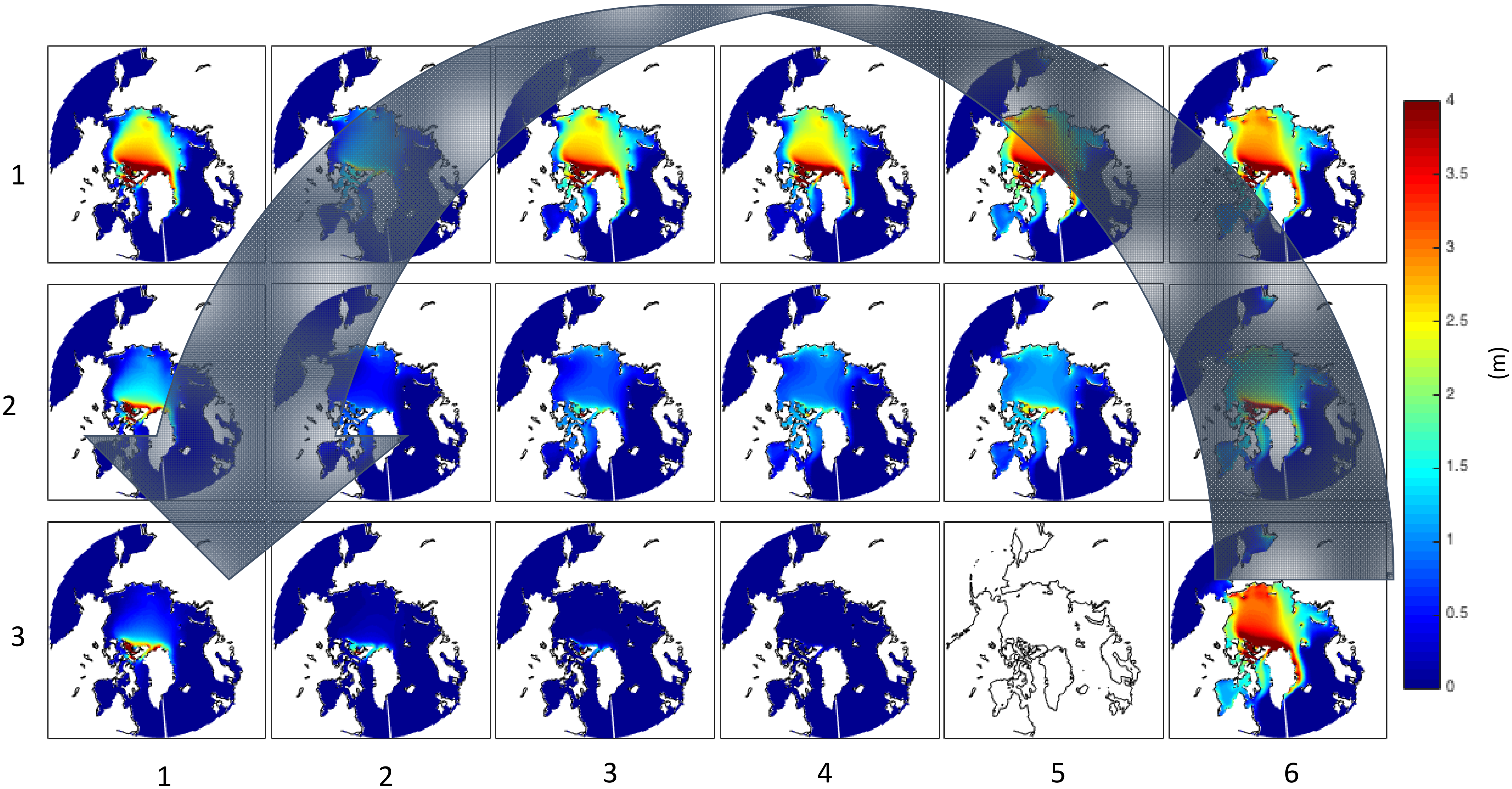


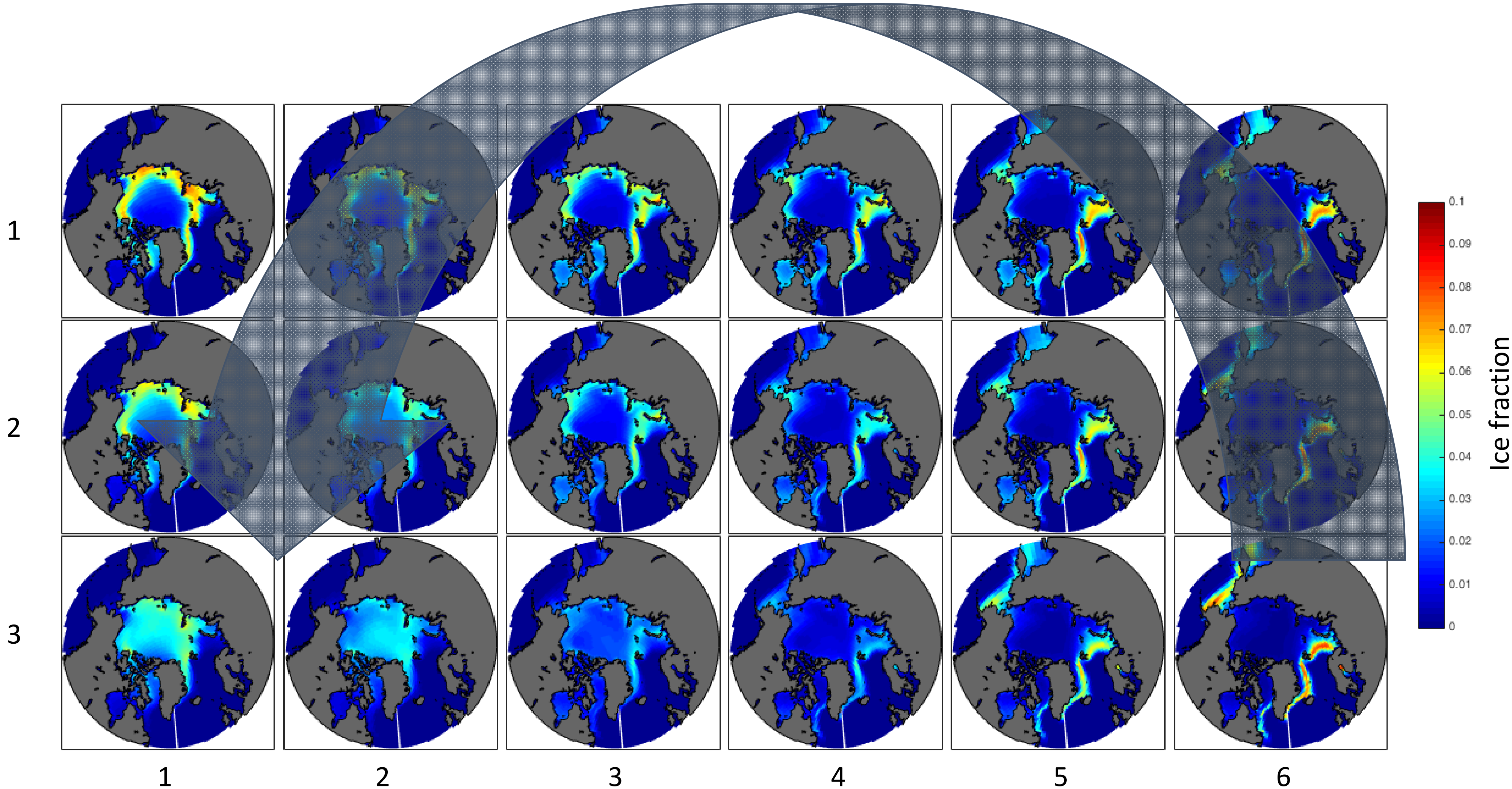

1
2
3
1
2
3
4
5
6
Ice fraction
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
September, 2050's
August, 2060's
November, 2080's

Mean Ice Thickness Mapped to SOM Nodes



Mean Ice Thickness Mapped to SOM Nodes




1
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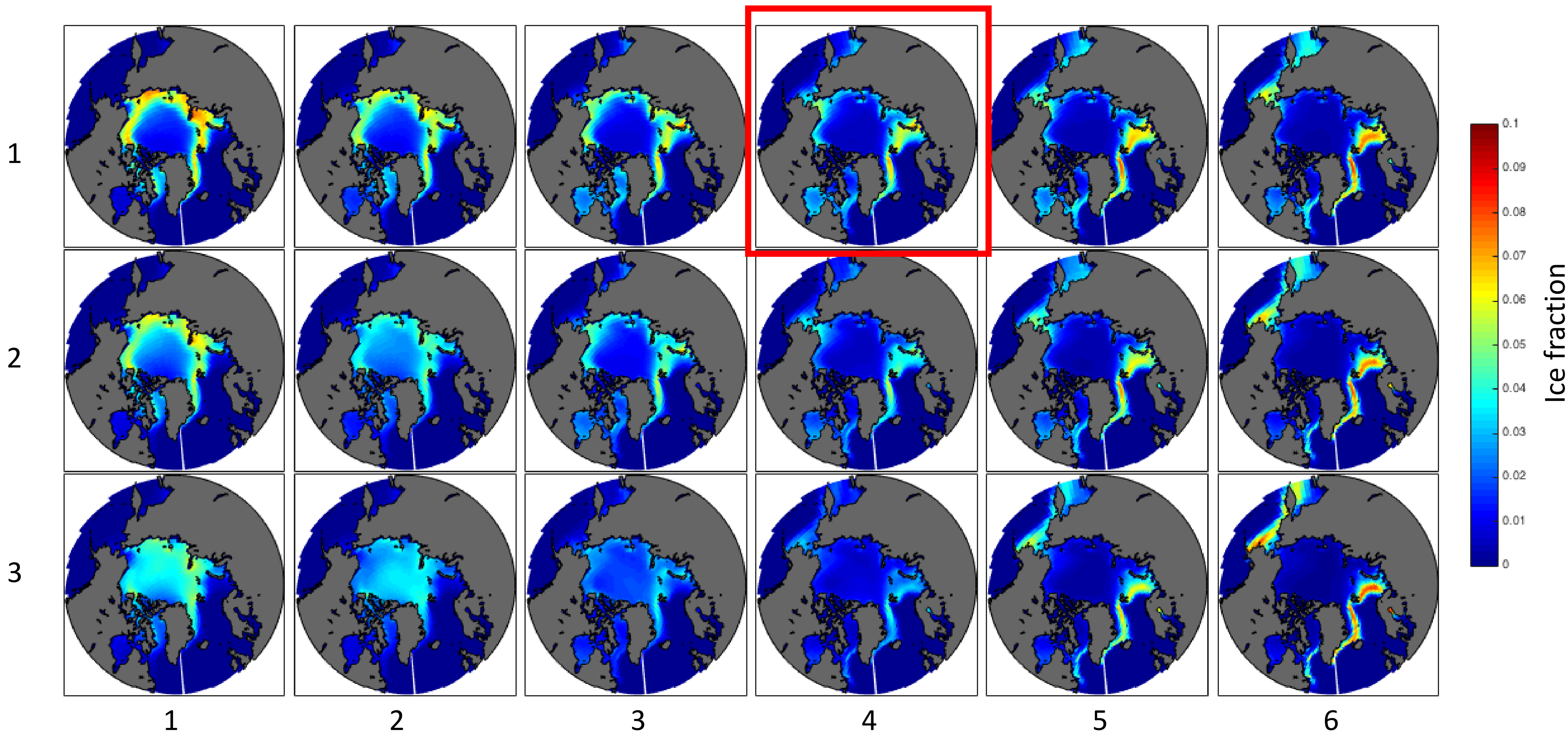
5
6
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Ice fraction

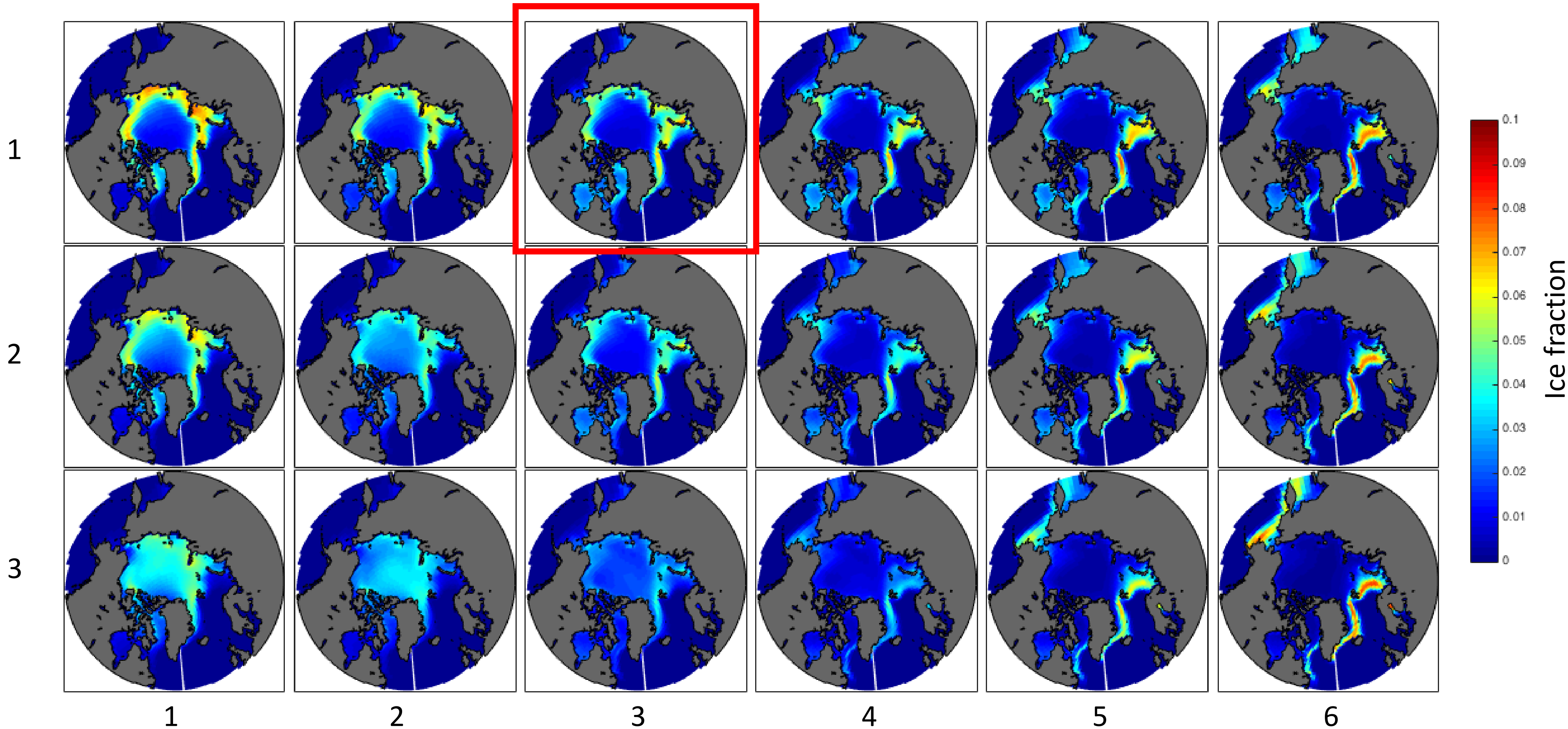
November

1920 - 2000



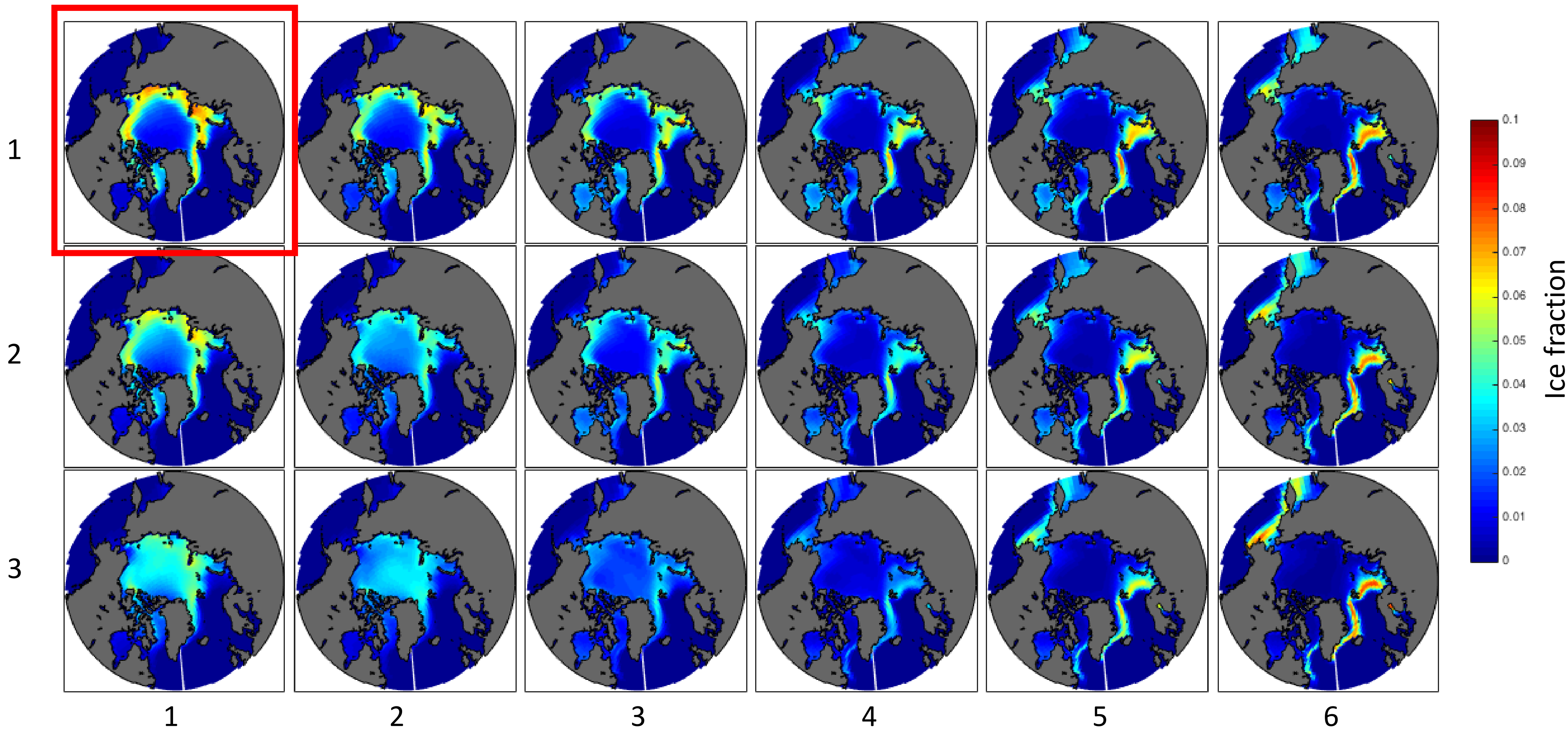
November

2000's



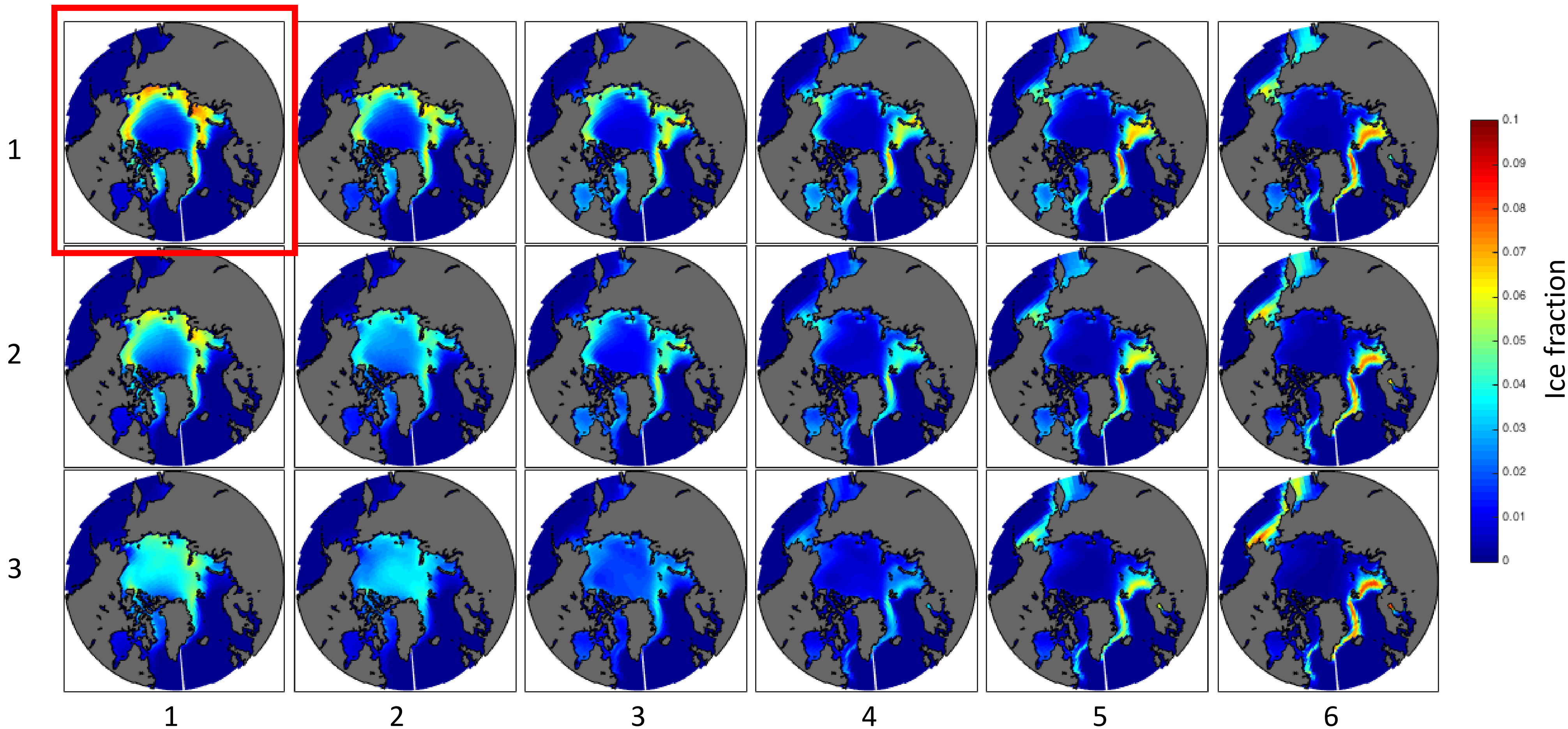
November

2010's



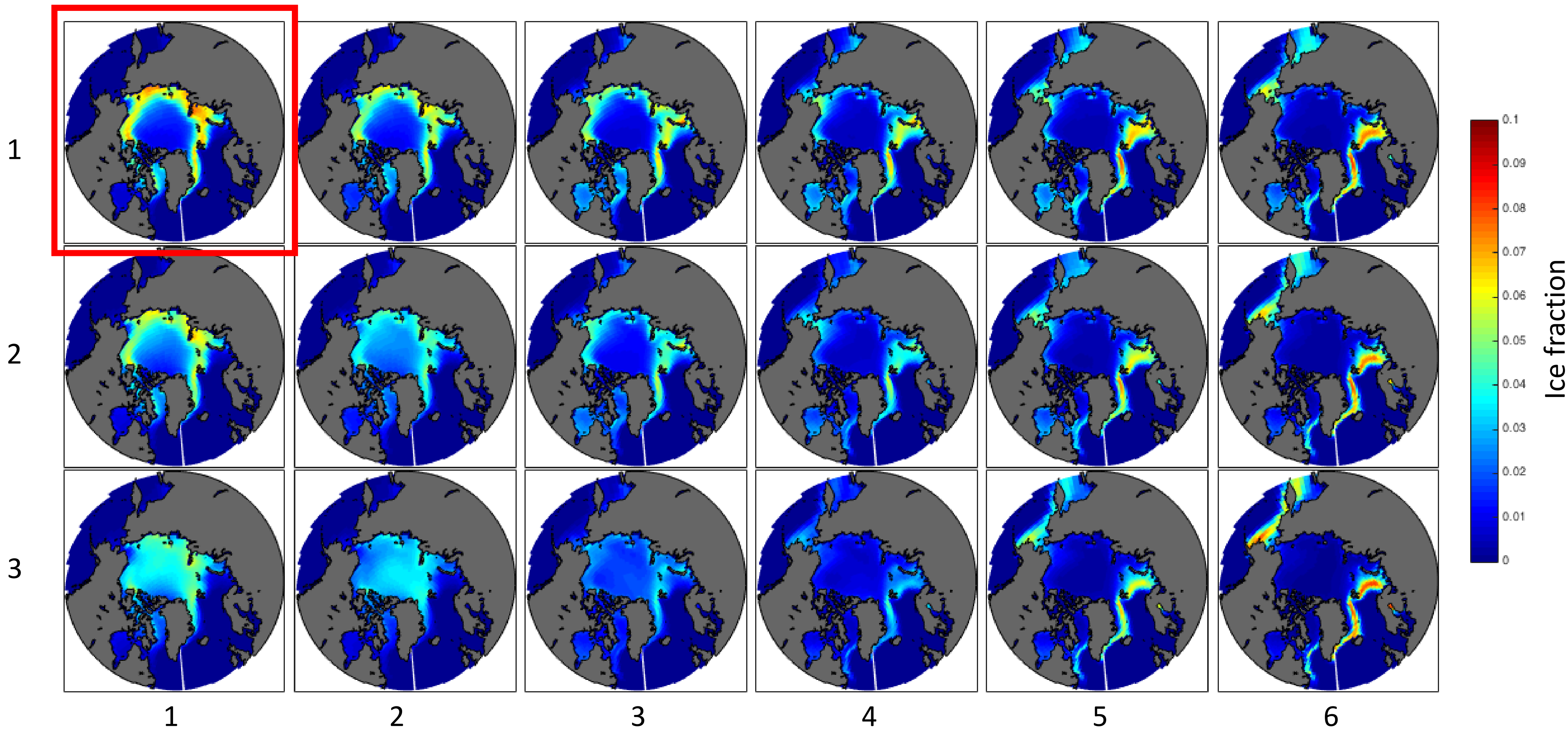
November

2020's



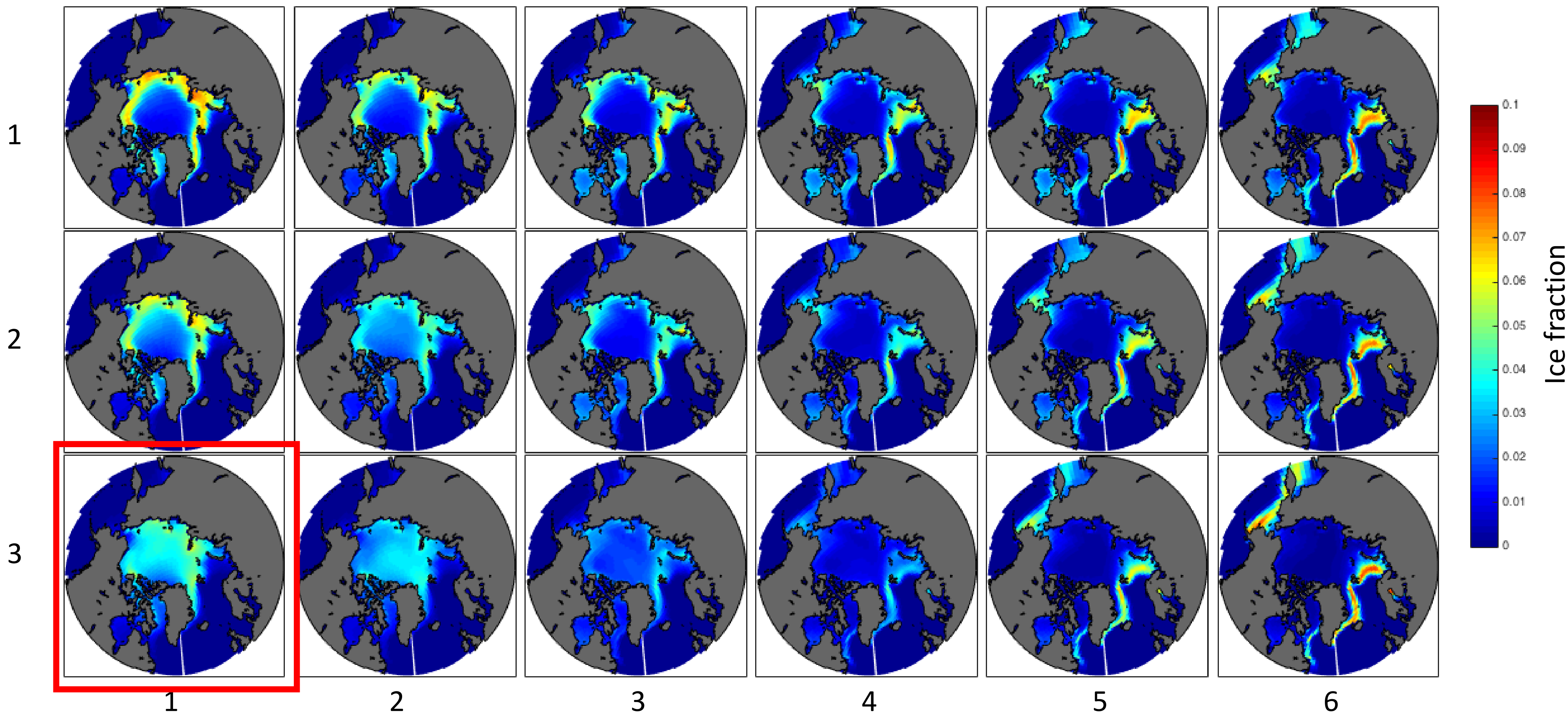
November

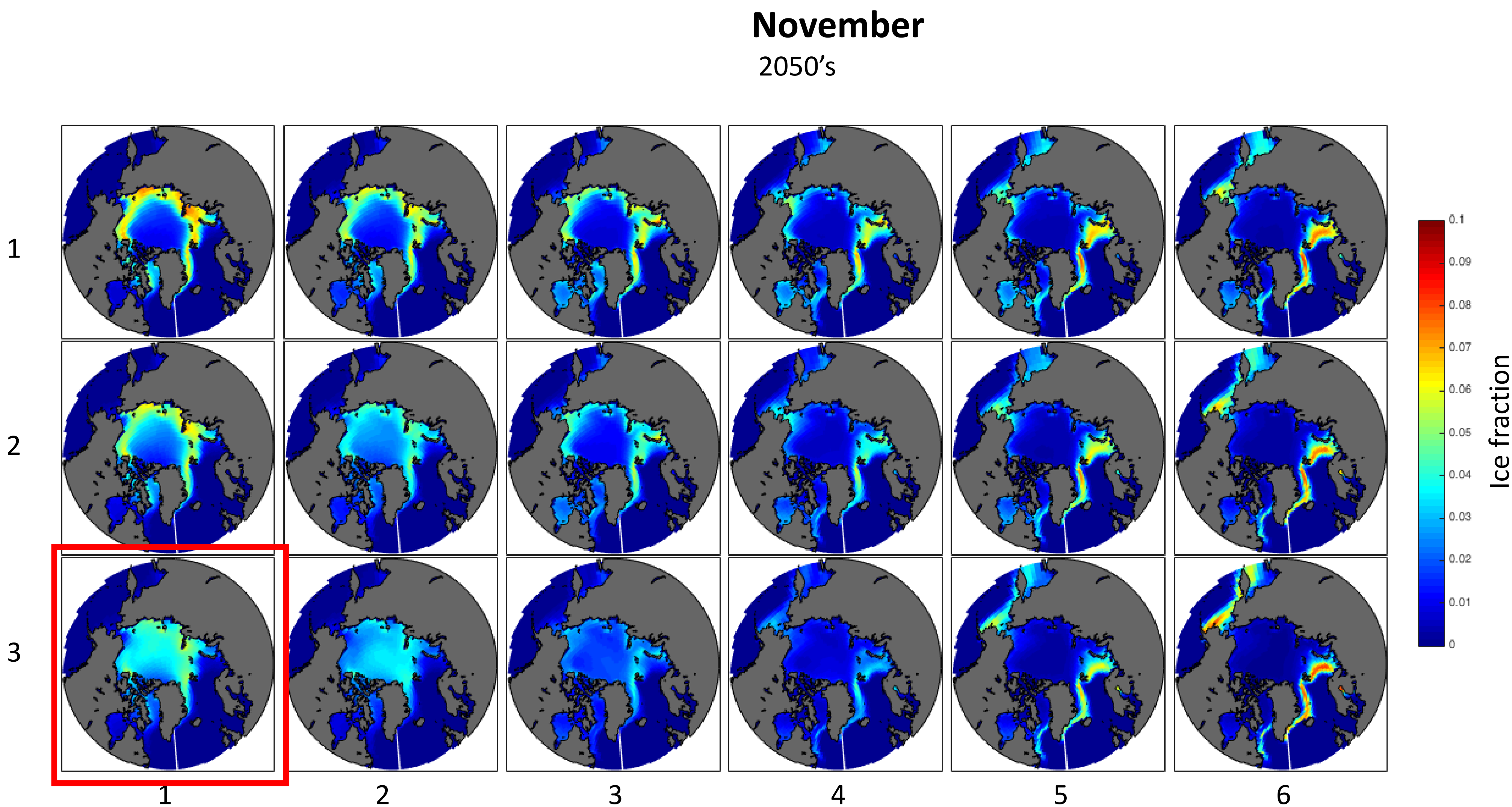
2030's



November

2040's

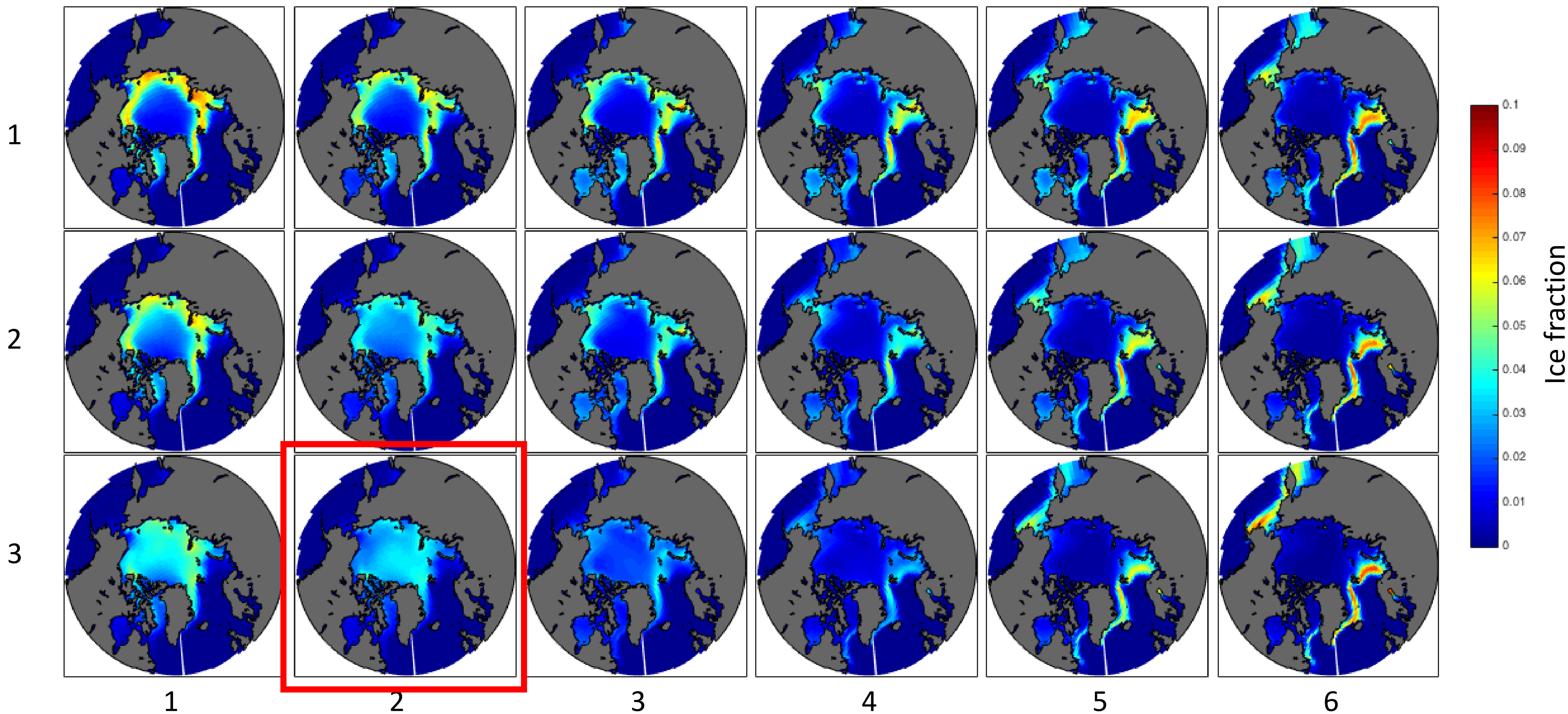




November
2050's
1
2
3
1
2
3
4
5
6
Ice fraction
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

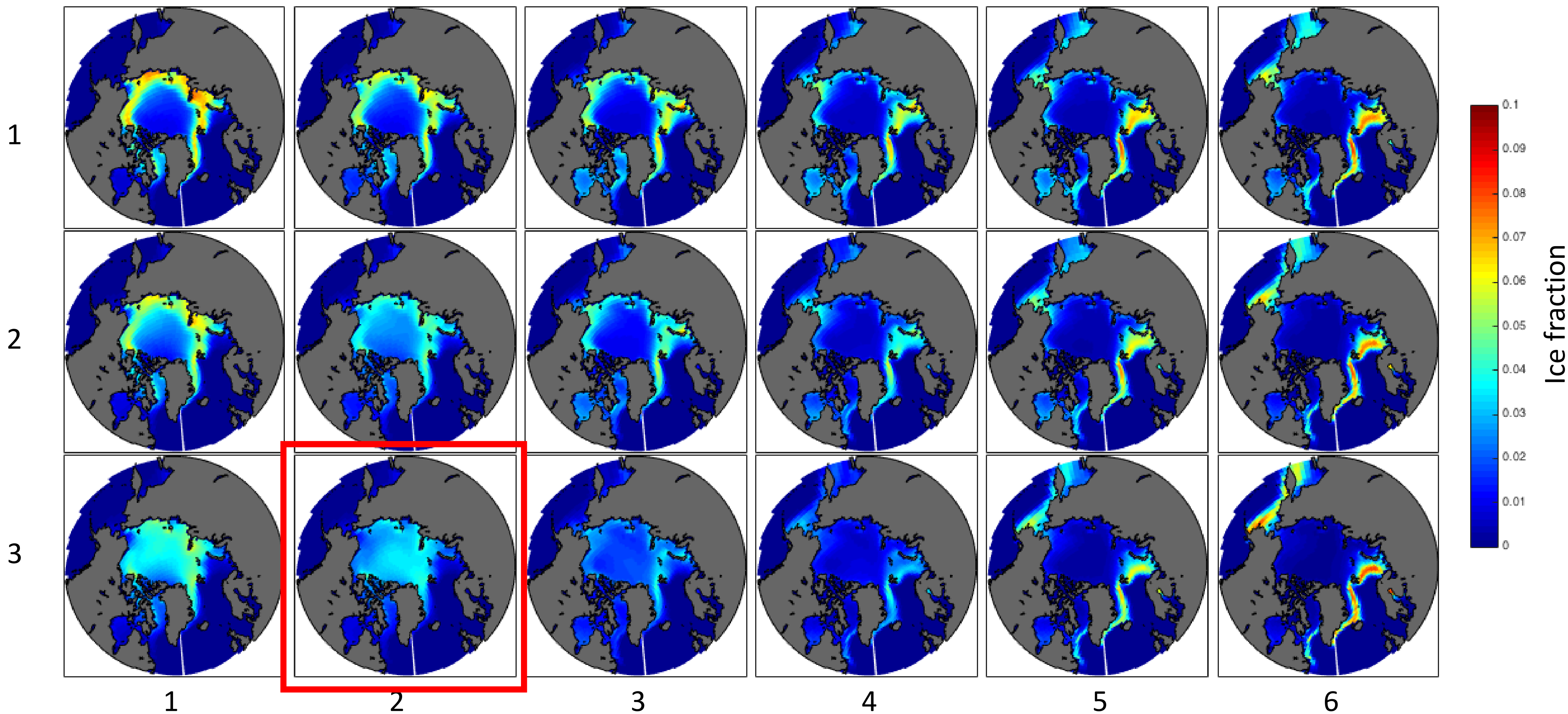
November

2060's



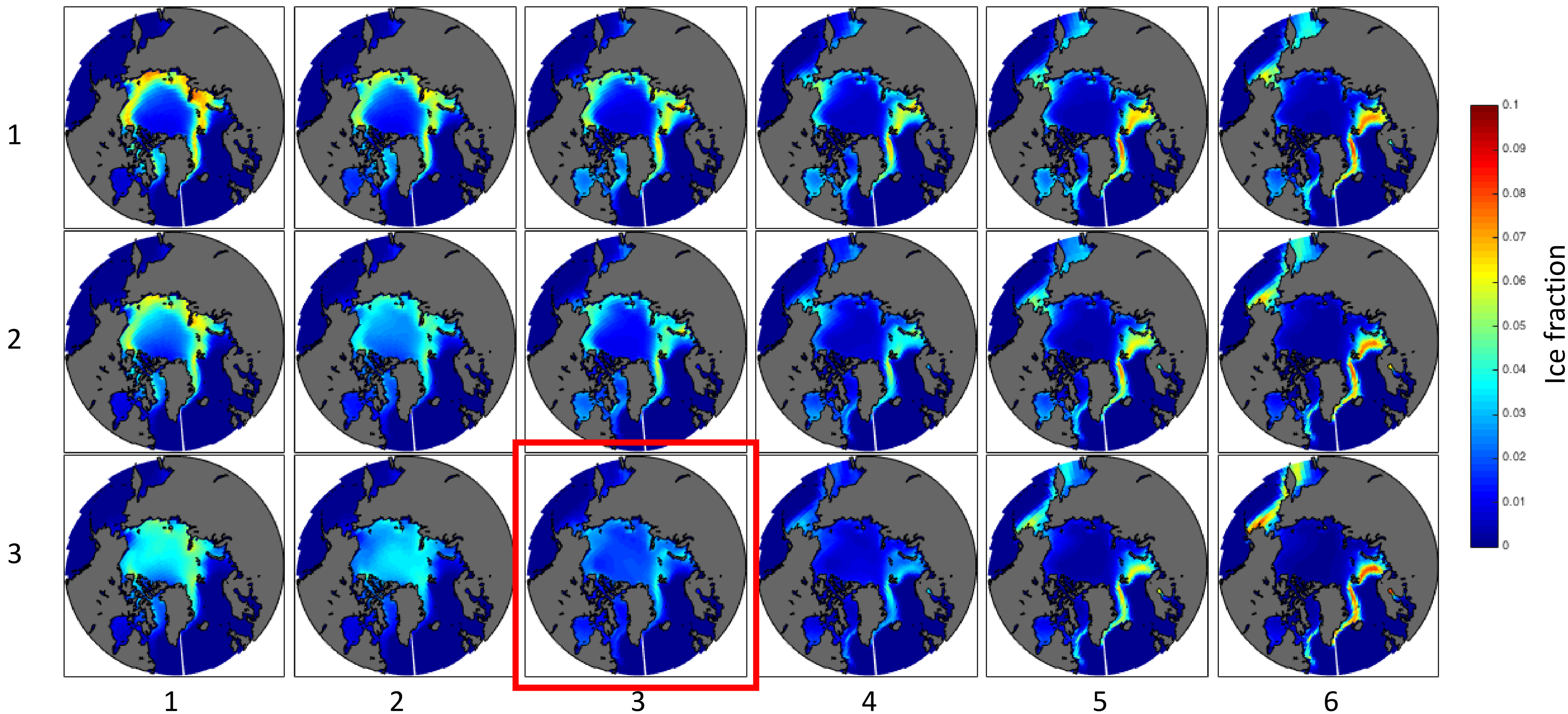
November

2070's



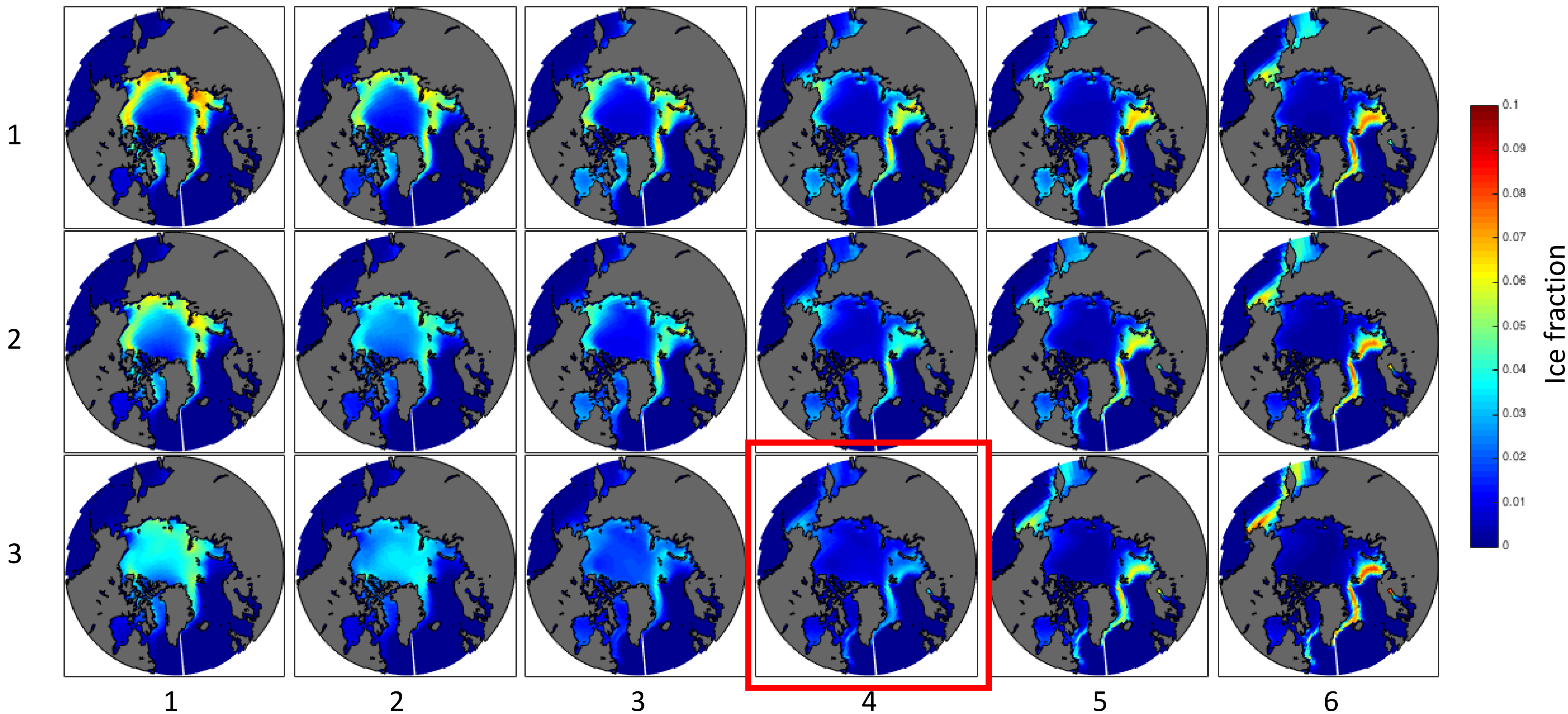
November

2080's



November

2090's



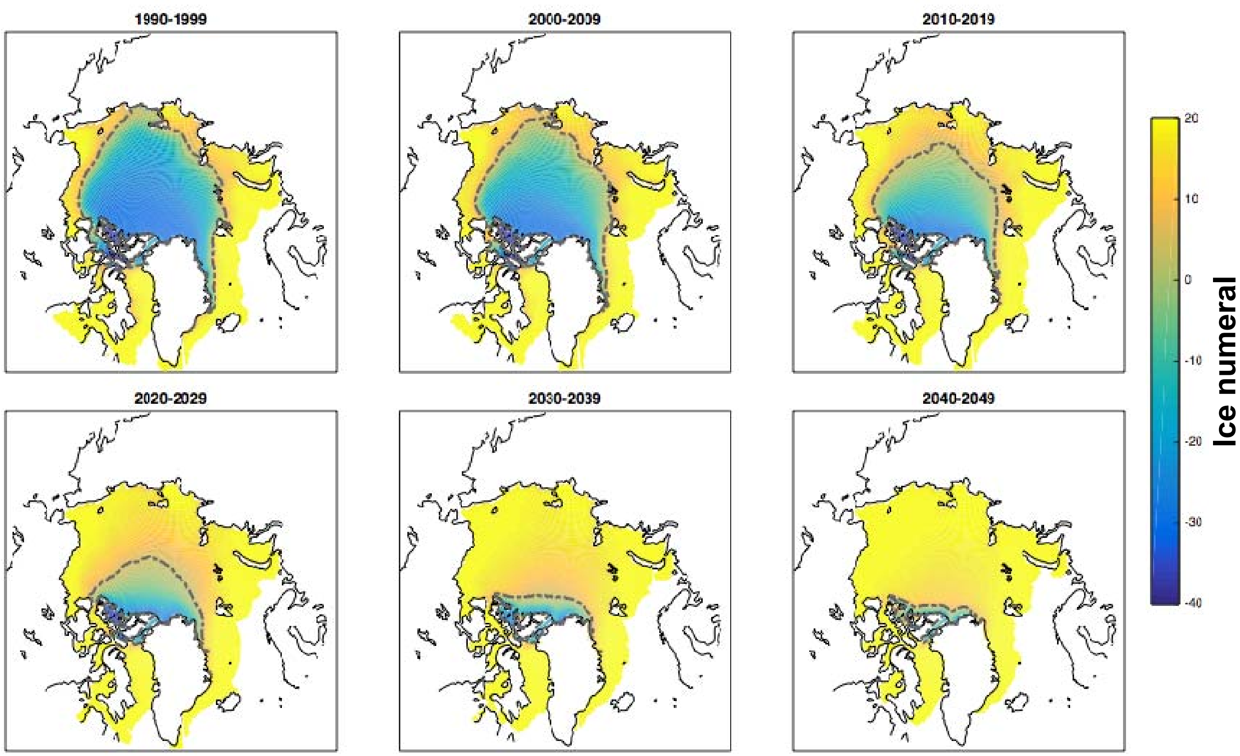
Ice Numeral

- $IN = C_1*IM_1 + C_2*IM_2 + \ldots C_n*IM_N)$

- C_x is ice concentration of type x
- IM_x is the ice multiplier of ice type x (ranging from -4 to + 2)
- 8 ice types ranging from open water to the oldest, thickest ice
- IN < 0 is a significant hazard to ships

- IN calculated for “Type C” vessels – moderately ice-strengthened
- Ensemble-averaged IN calculated for each decade (September only)

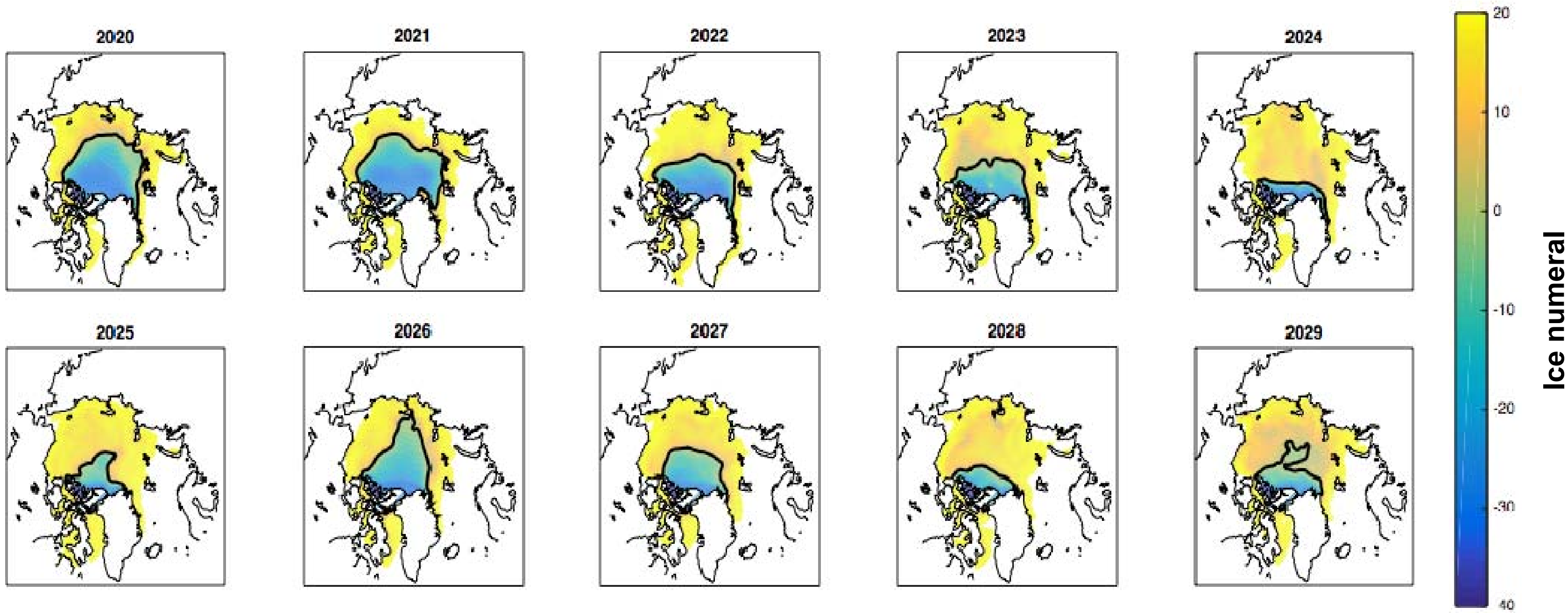
Ice Numeral – September Ensemble Mean



Northern Sea Route becomes navigable on average by 2020's in September

Dashed contour indicates >75% ensemble members agree IN > 0

Ice Numeral – 1 Ensemble, September 2020's



NSR navigability varies by year, despite the downward trend and mean IN < 0

Conclusions

- Arctic sea ice is expected to become more variable in coverage as it diminishes
  - Consistent across seasons and robust among ensembles and CMIP5 models
- Highest magnitude of ice area standard deviation peak occurs Nov-Jan, twice that of spring.
- Relatively consistent spatial pattern of variability that follows the thinning of the ice pack
- Increasingly navigable Arctic is tempered by increased variability