# Sensitivity of Arctic Sea Ice Simulation to Treatment of Sea Ice Dynamics

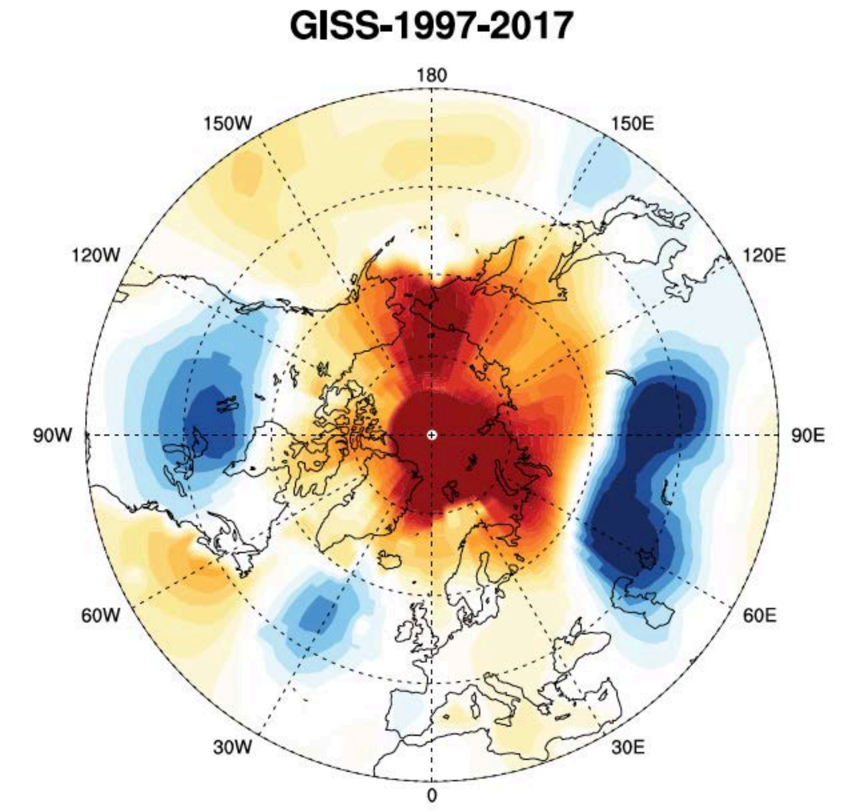
Xiangdong Zhang and Liran Peng
International Arctic Research Center and Department of Atmospheric Sciences
University of Alaska Fairbanks

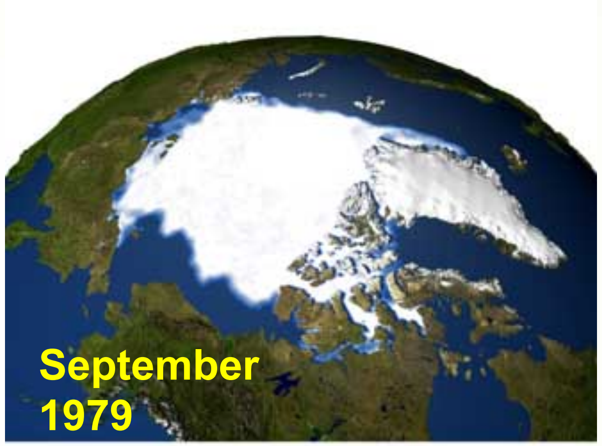
**Blue Waters Symposium, June 3-6, 2019**

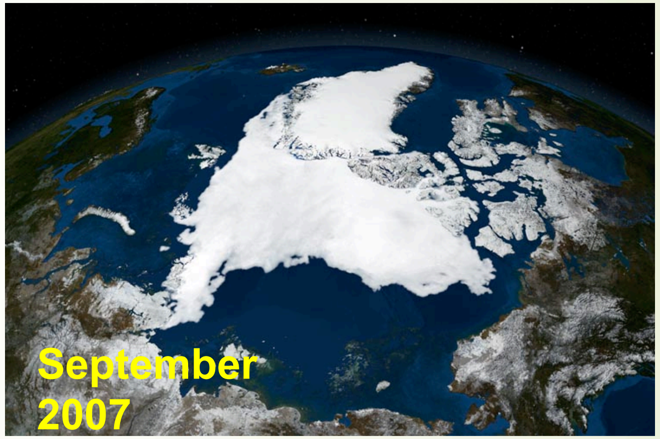
# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

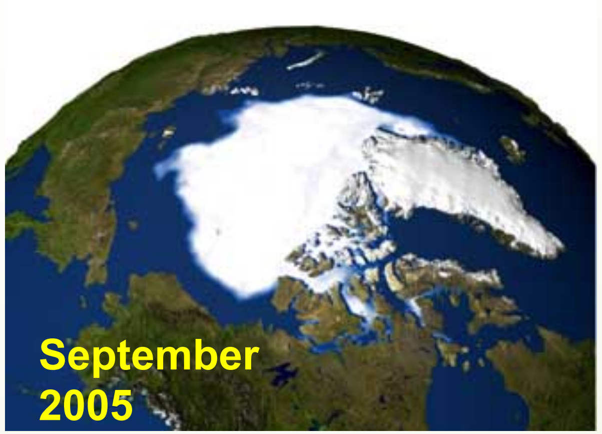
## Motivation

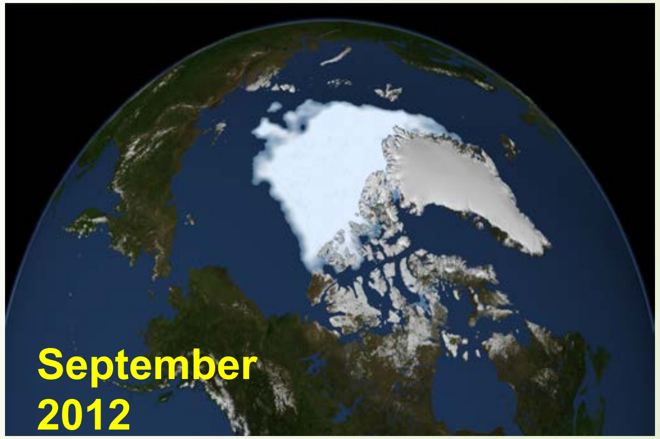
Global warming has been amplified in the Arctic and Arctic sea ice cover has continually reached its record minimum values.



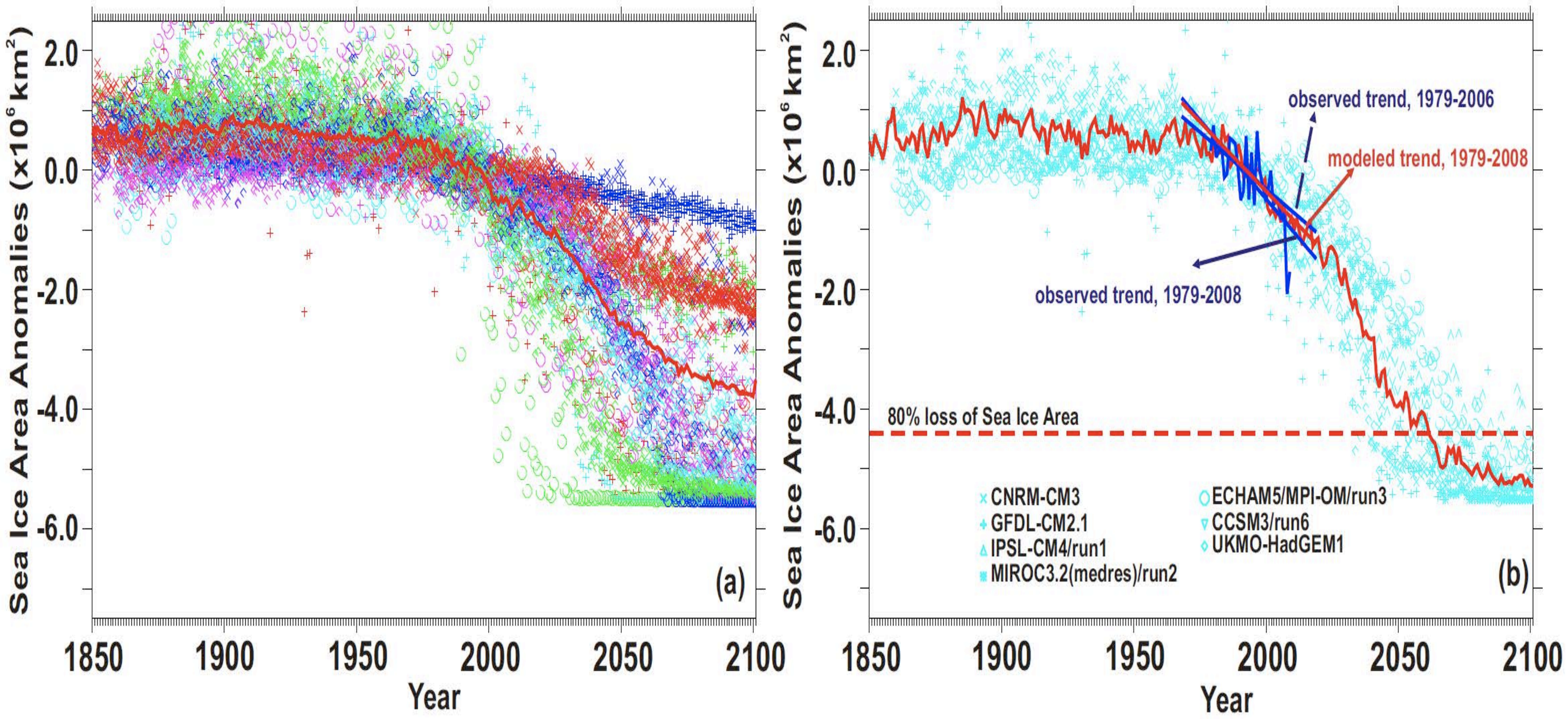




**Note:**
**Winter: No sea ice and snow retreat induced albedo feedback**

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## Motivation

Global Climate model simulations show a large spread, leading to uncertainties in understanding sea ice as well as climate system changes, as well as policy-decision making.




*Zhang and Walsh, J. Climate, 2006; Zhang, Tellus 2010*

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## Motivation

The simulated ice thickness spatial distributions have the largest bias across different climate models, and sea ice dynamics is less investigated using climate models.

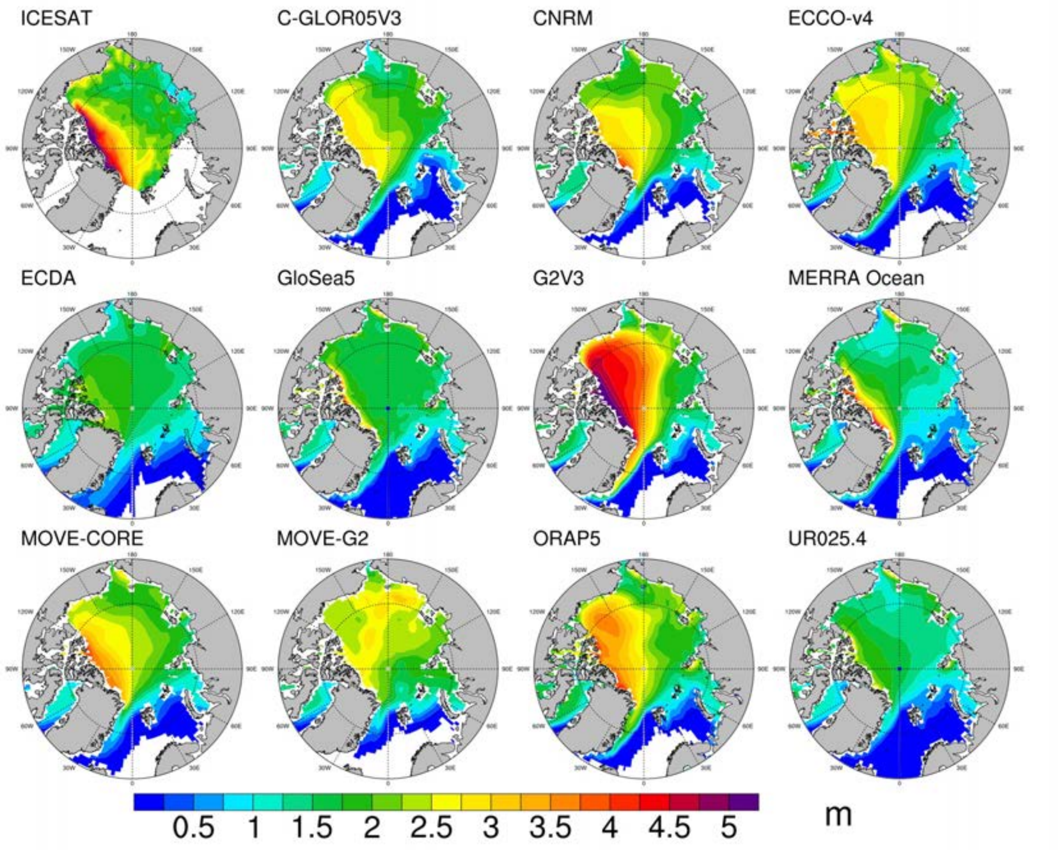



**Fig. 5** March mean sea ice thickness (m), averaged over the period 2003–2007, for all the ORA-IP systems. *Top left* is the estimate from ICESat mean thickness over all February–March campaigns in the period 2003–2007

*Chevallier et al., 2016*

## Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

### Scientific questions

- How do (1) sea ice internal force/strength and (2) air-ice momentum flux impact sea ice motion and thickness distribution?

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## Experiment design

- **Community Earth System Model (CESM 1.2)**
  - Parallel Ocean Program, version 2 (POP2; Danabasoglu et al., 2012)
  - Los Alamos National Laboratory sea ice model, version 4 (CICE4)
- **Horizontal grid**: one-degree displaced the North Pole in Greenland grid
  - Average grid size: 41 km
  - 22.34 km near the East coast of Greenland
  - 61.72 km over the Chukchi Sea
- **Atmospheric forcing data**: ten-year period (1979-1988) averaged ERA-Interim data (Dee et al., 2011)
  - Five atmospheric state variables
    - 10m surface wind components, 2m-air temperature, specific humidity, and the mean sea level pressure
  - Radiation
    - downward long wave and short wave radiation
  - Precipitation

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## Why Blue Waters?

- **Computational Cost for each experiments <Total usage: 405,412>**
  - For CESM2 normal year forcing simulation <~94% of the total usage>
    - Model Cost: 448.56 pe-hrs/simulated year
    - Model Throughput: 5.14 simulated_years/day
  - For CESM2 interannual forcing simulation <~3% of the total usage >
    - Model Cost: 439.56 pe-hrs/simulated_year
    - Model Throughput: 5.24 simulated_years/day
  - For CESM1.2 interannual forcing simulation <~3% of the total usage >
    - Model Cost: 337.88 pe-hrs/simulated_year
    - Model Throughput: 9.09 simulated_years/day

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## Why Blue Waters?

- **Total Storage Used for each experiment**
  - NYF:
    - Ice: 2.5T (monthly and daily outputs)
    - Ocean: 4.08T (monthly and daily outputs)
    - Total: 6.6T
  - IAF:
    - Ice: 3.2T (monthly, daily, and 6-hourly outputs)
    - Ocean: 709G (monthly and daily outputs)
    - Total: 3.9T (1984-2018)
- **Atmospheric forcing data**: 25G

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## CICE4 dynamic workflow <2>

- **Ai-Ice momentum flux:**

$$\tau_{ai} = c_a \rho_a \left|\vec{u}_a\right|^2 \frac{\left(\vec{u}_a\right)}{\left|\vec{u}_a\right|},$$

$C_a$: momentum exchange coefficient (Jordan et al., 1999)

- **Sea ice internal force:**

$$P = C_f C_p \int_0^{\infty} h^2 w_r \, dh,$$

$C_f$: the ratio of total energy losses to potential energy changes.

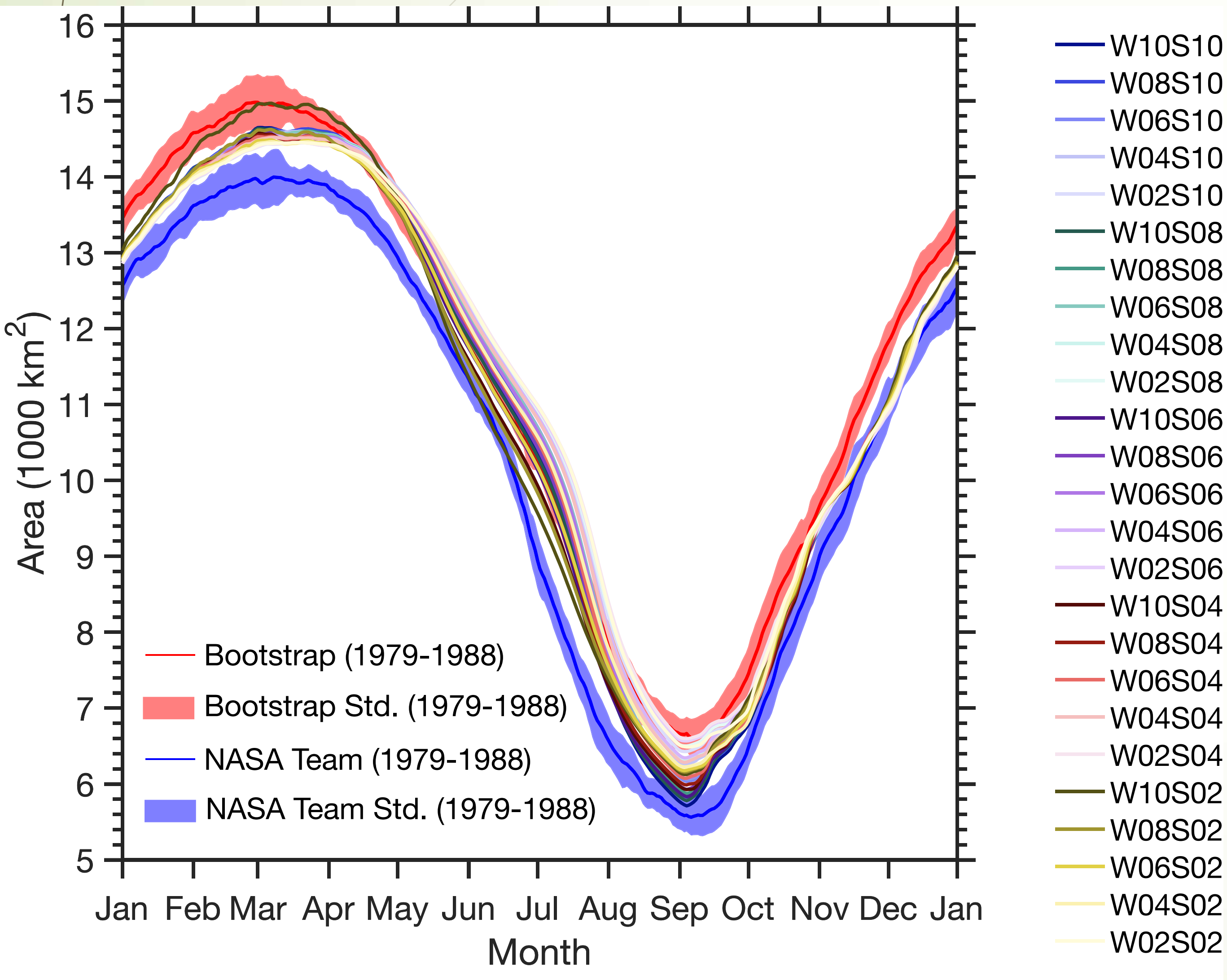
CICE4 dynamic workflow <3>

# There is an uncertainty in defining $C_f$

- No direct observations.
- Hibler (1980) estimated that $C_f$ was between 2 and 10.
- Hopkins and Hibler (1991) and Hopkins (1994) indicated that $C_f$ in the range of 9 to 17.
- Flato and Hibler (1995): $C_f$ 13-43.
- Martin et al., (2016): $C_f$ 10 and 20.
- **Default value: $C_f$ =17 in the model used by the modeling community.**

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## Total sea ice area

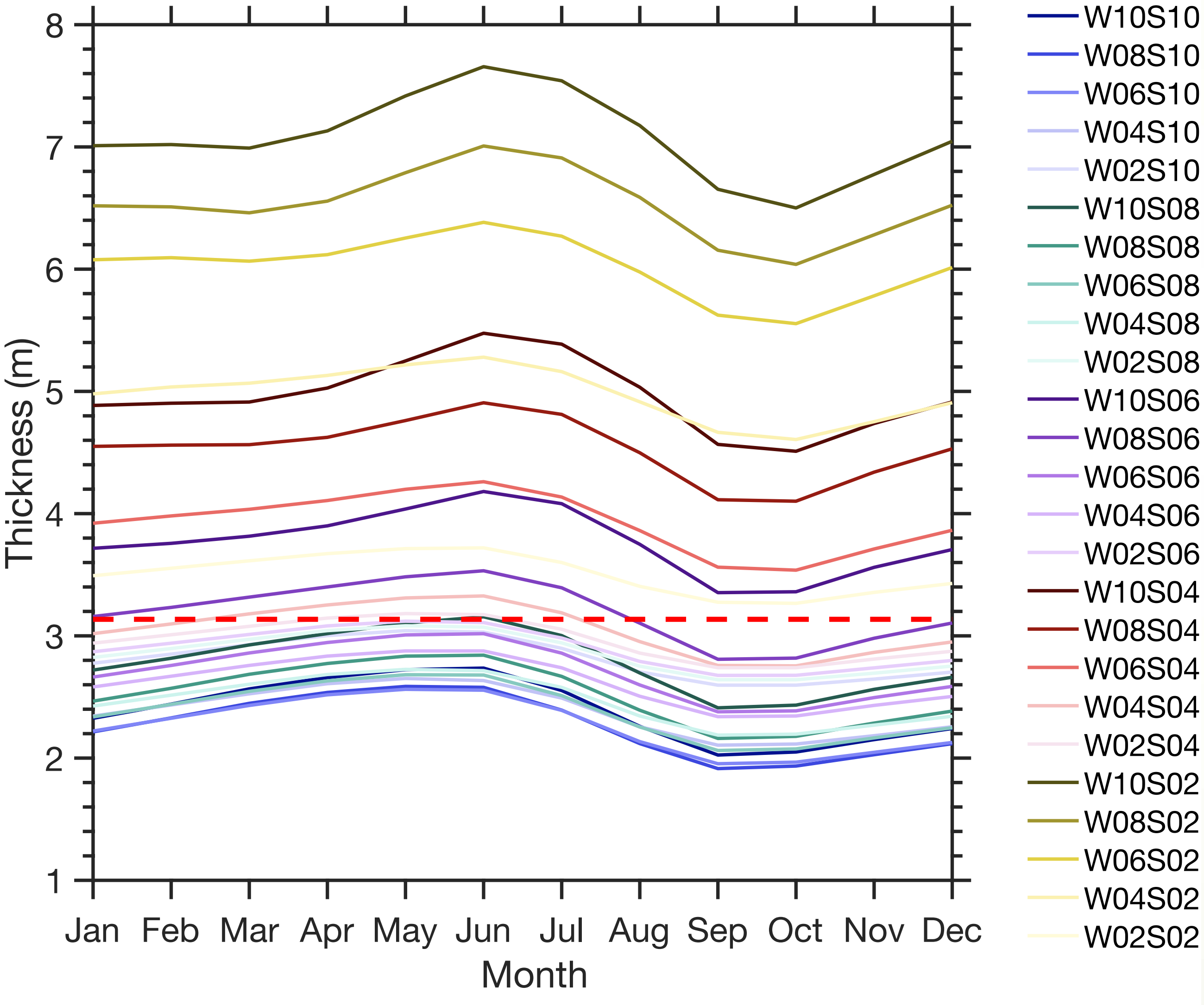



- Each simulation ran 100 year
- 25 sensitivity experiments
- W08S04 refers to $0.8*c_a$ and $0.4*C_f$ conditions

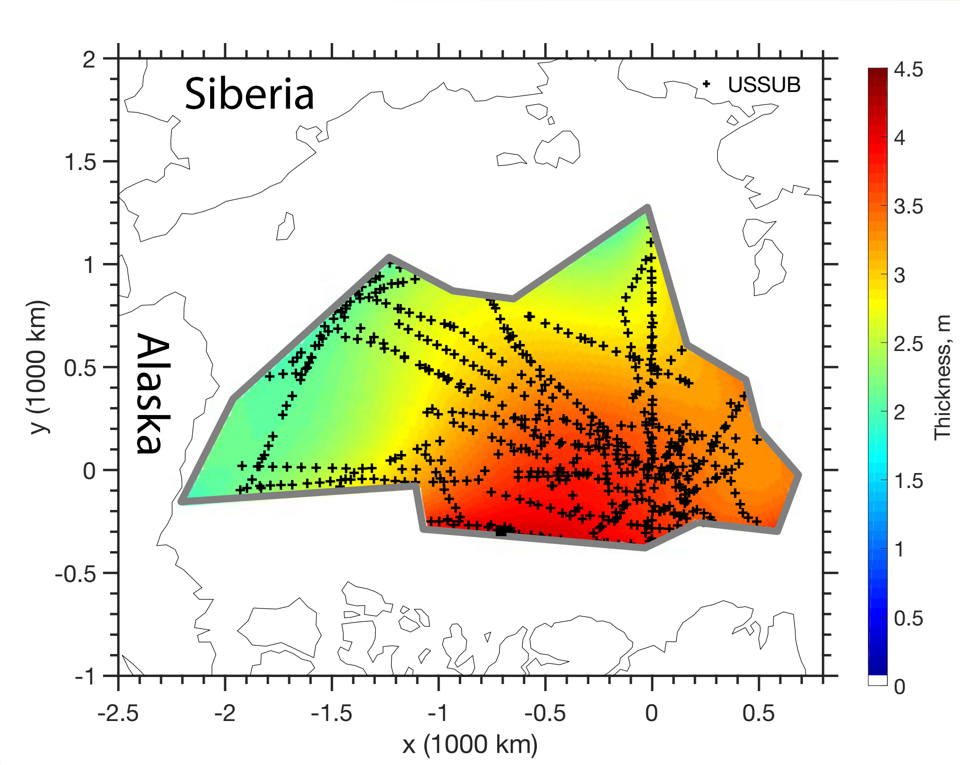
| | $1.0 \cdot C_f$ | $0.8 \cdot C_f$ | $0.6 \cdot C_f$ | $0.4 \cdot C_f$ | $0.2 \cdot C_f$ |
|---|---|---|---|---|---|
| $1.0 \cdot c_a$ | W10S10 | W10S08 | W10S06 | W10S04 | W10S02 |
| $0.8 \cdot c_a$ | W08S10 | W08S08 | W08S06 | W08S04 | W08S02 |
| $0.6 \cdot c_a$ | W06S10 | W06S08 | W06S06 | W06S04 | W06S02 |
| $0.4 \cdot c_a$ | W04S10 | W04S08 | W04S06 | W04S04 | W04S02 |
| $0.2 \cdot c_a$ | W02S10 | W02S08 | W02S06 | W02S04 | W02S02 |

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## Sea ice thickness <1>

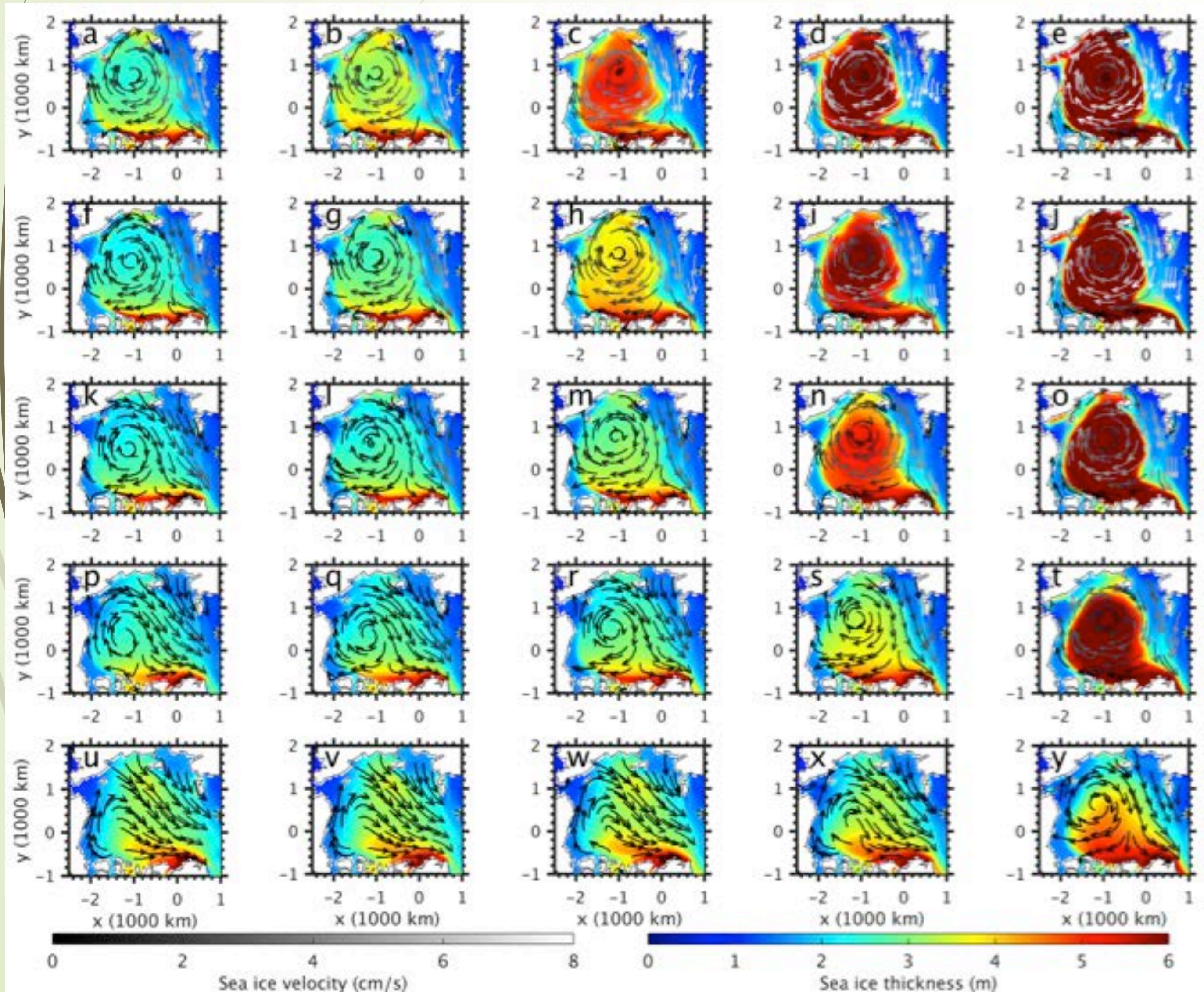



Sea ice thickness are highly sensitive to perturbed air-ice momentum flux and sea ice strength



# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## Sea ice thickness and velocity <March>

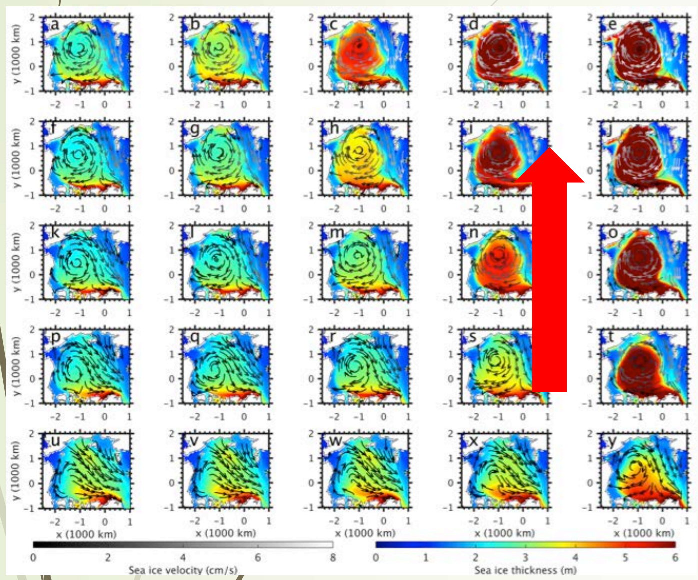


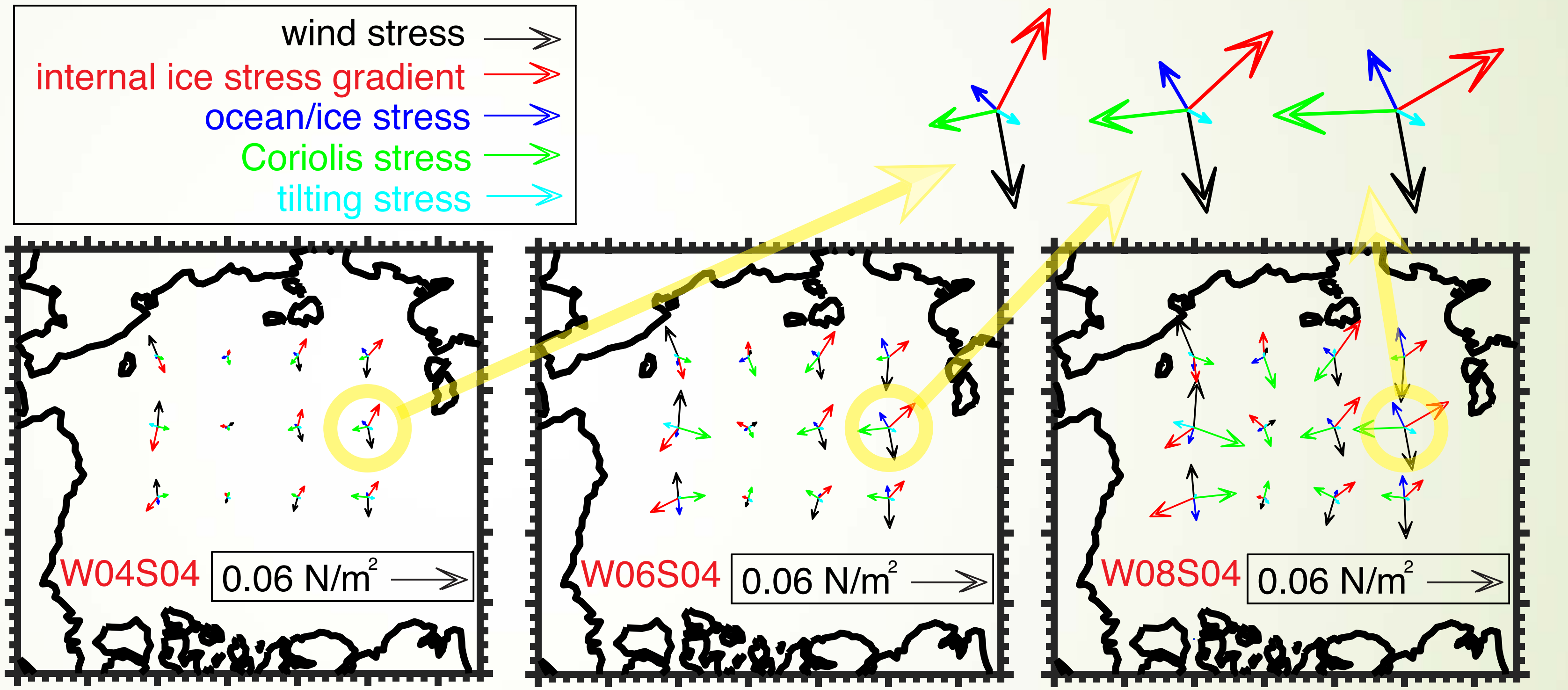

| | $1.0 \cdot C_f$ | $0.8 \cdot C_f$ | $0.6 \cdot C_f$ | $0.4 \cdot C_f$ | $0.2 \cdot C_f$ |
|---|---|---|---|---|---|
| $1.0 \cdot c_a$ | W10S10 | W10S08 | W10S06 | W10S04 | W10S02 |
| $0.8 \cdot c_a$ | W08S10 | W08S08 | W08S06 | W08S04 | W08S02 |
| $0.6 \cdot c_a$ | W06S10 | W06S08 | W06S06 | W06S04 | W06S02 |
| $0.4 \cdot c_a$ | W04S10 | W04S08 | W04S06 | W04S04 | W04S02 |
| $0.2 \cdot c_a$ | W02S10 | W02S08 | W02S06 | W02S04 | W02S02 |

The spatial distribution of the sea ice velocity, and thickness are highly sensitive to perturbed air-ice momentum flux and sea ice strength

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## Increase the air-ice stress

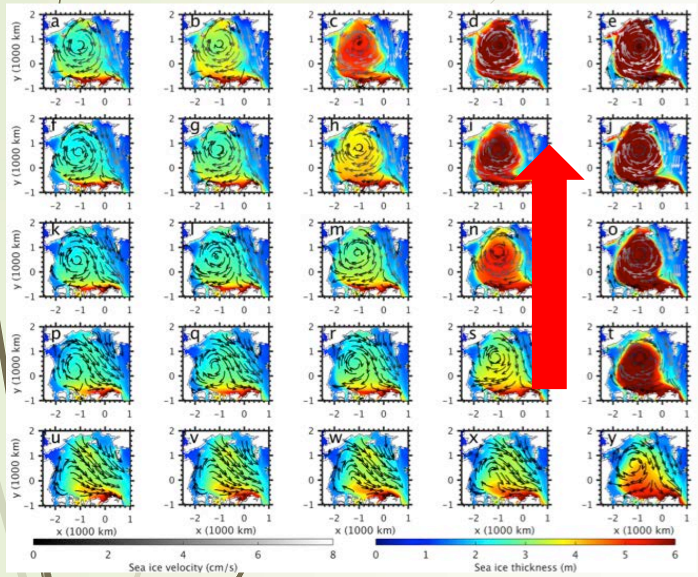


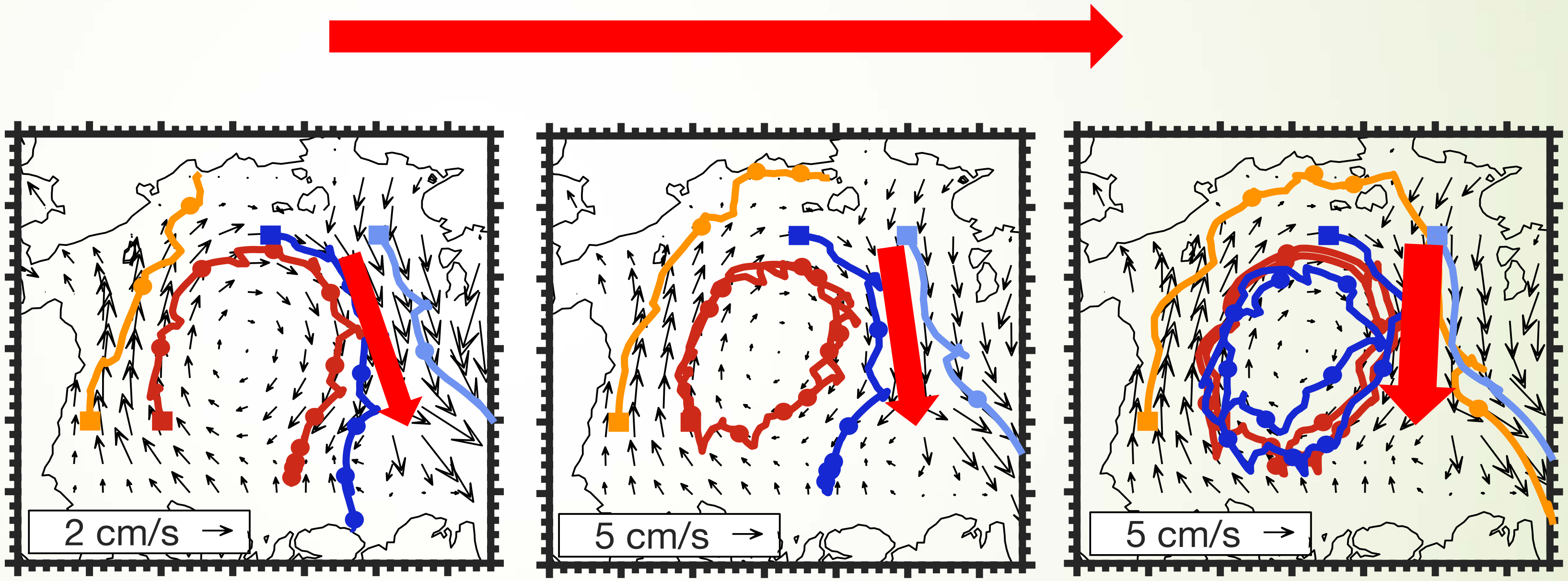




- A larger air-ice stress corresponding to a more extensive kinematic energy gained by sea ice and therefore results in a larger magnitude of sea ice velocity.
- At the same latitude, a larger sea ice velocity leads to a large Coriolis force on sea ice, causing sea ice buildup north of the Canadian Archipelago.

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

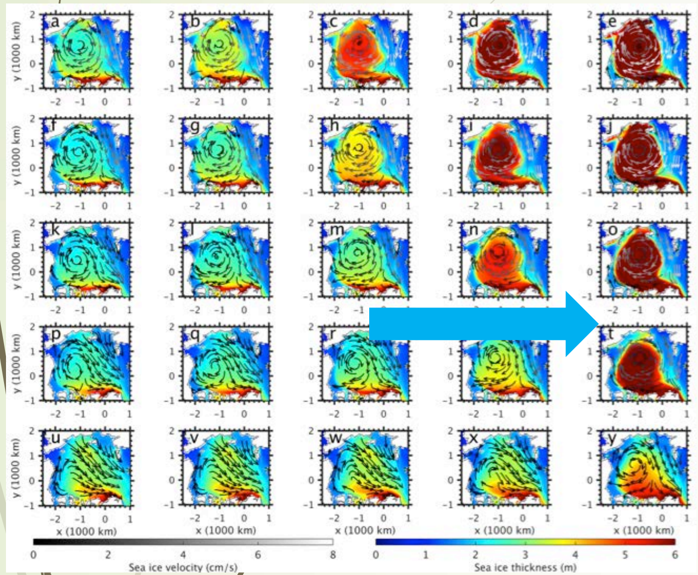
## Increase the air-ice stress



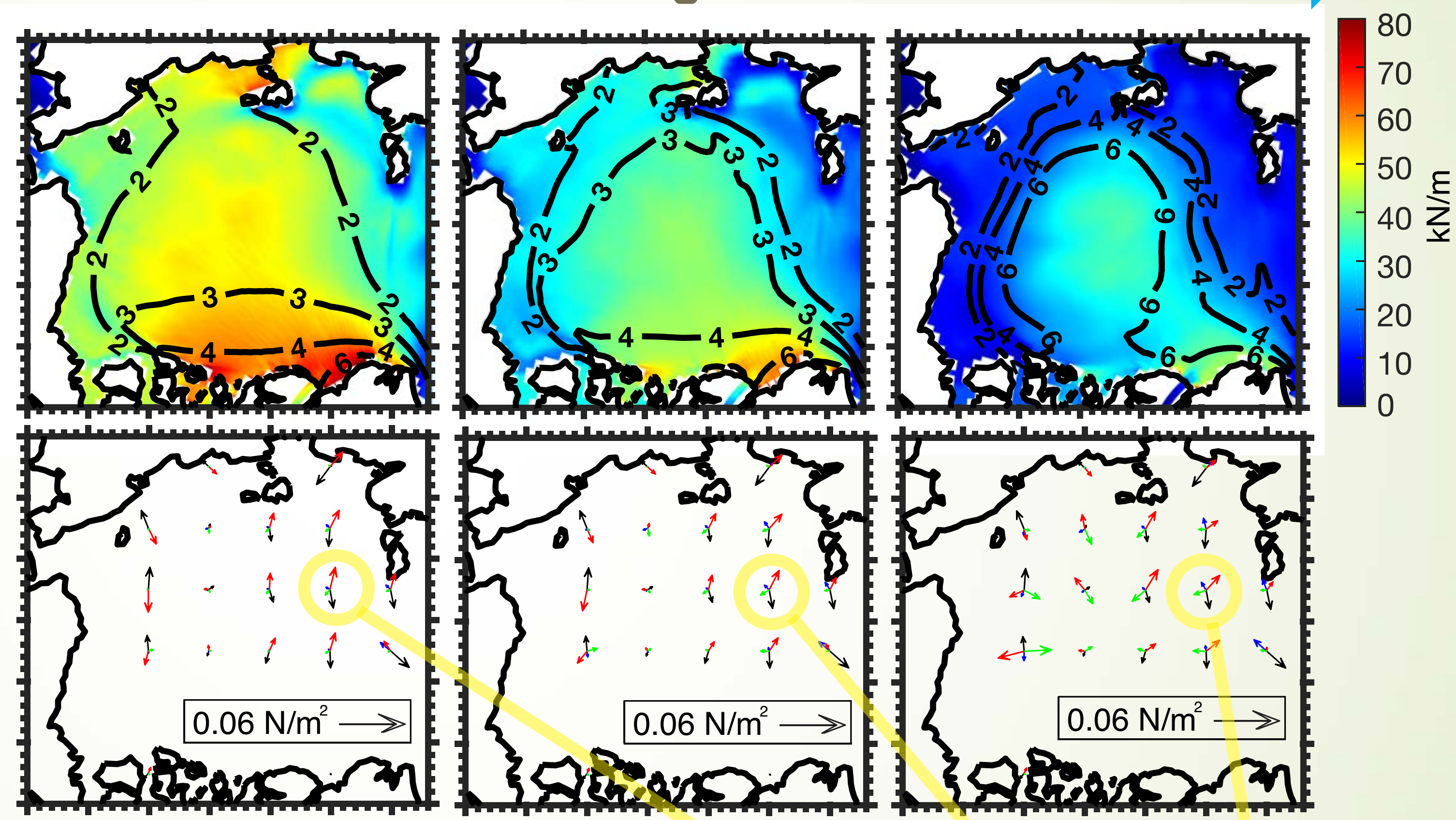




- A larger air-ice stress corresponding to a more extensive kinematic energy gained by sea ice and therefore results in a larger magnitude of sea ice velocity.
- At the same latitude, a larger sea ice velocity leads to a large Coriolis force on sea ice, causing sea ice buildup north of the Canadian Archipelago.

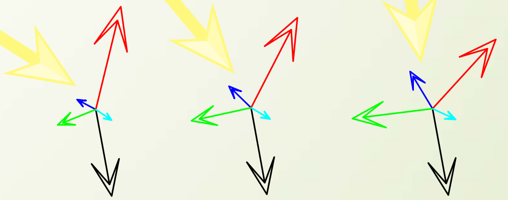
# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics




## Decrease the sea ice strength



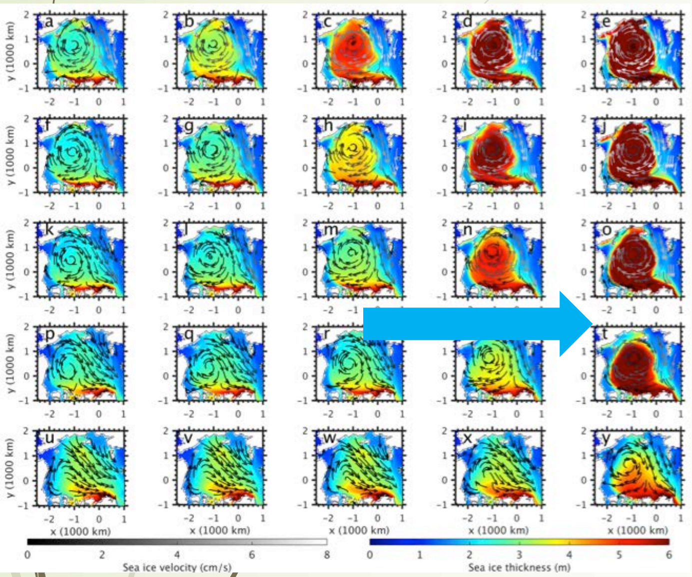

- Following the transpolar drift, sea ice moves across the ice strength contour from low ice strength region to the high ice strength region.

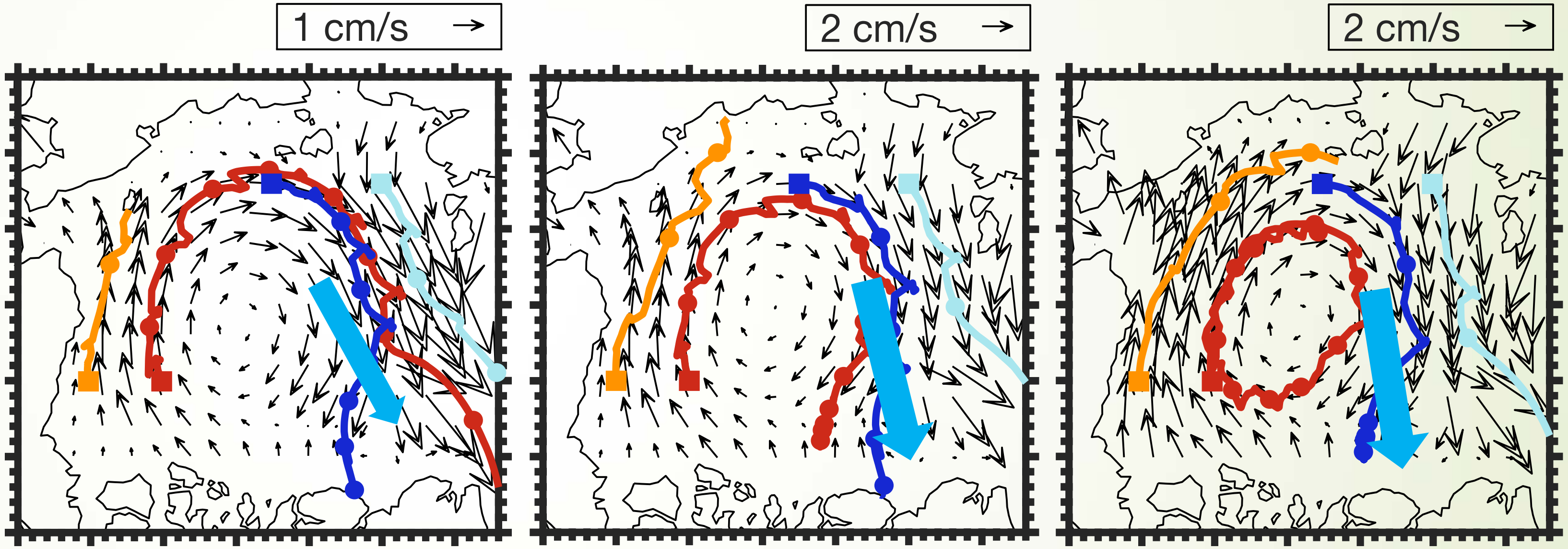


- A larger sea ice strength gradient results in a larger the magnitude of the internal sea ice stress gradient.

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## Decrease the sea ice strength

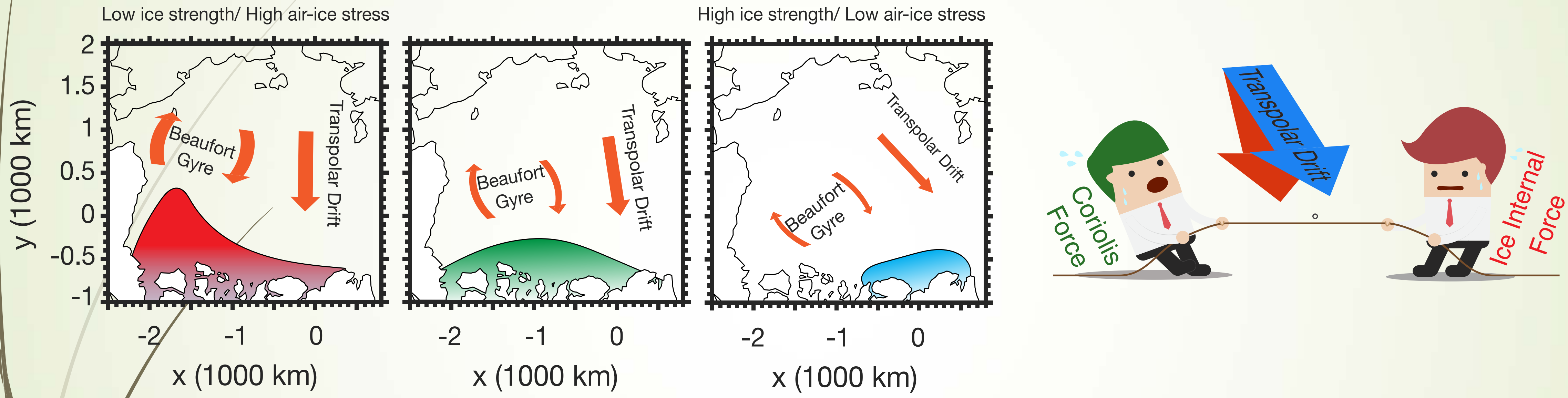



Decrease in sea ice strength results in thicker ice within the center of the Arctic Ocean, and therefore a larger ice volume throughout the year, since more kinetic energy is converted to the potential energy to build sea ice ridge, instead of causing frictional loss.

# Sensitivity of Arctic sea ice simulation to treatment of sea ice dynamics

## Schematics showing sensitivity of sea ice velocity and thickness structures




- Increased sea ice strength or decreased air-ice momentum flux cause a counter-clockwise rotation of the ice transpolar drift, resulting in an increase in sea ice export through Fram Strait and therefore reduction of mean sea ice thickness within the Arctic.
- Sea ice thickness distribution influences energy balance and albedo feedback, and sea ice export via Fram Strait is one of important driving mechanism for Atlantic meridional circulation.