Improving the Dynamic Coupling of Sea-ice and Ocean Models

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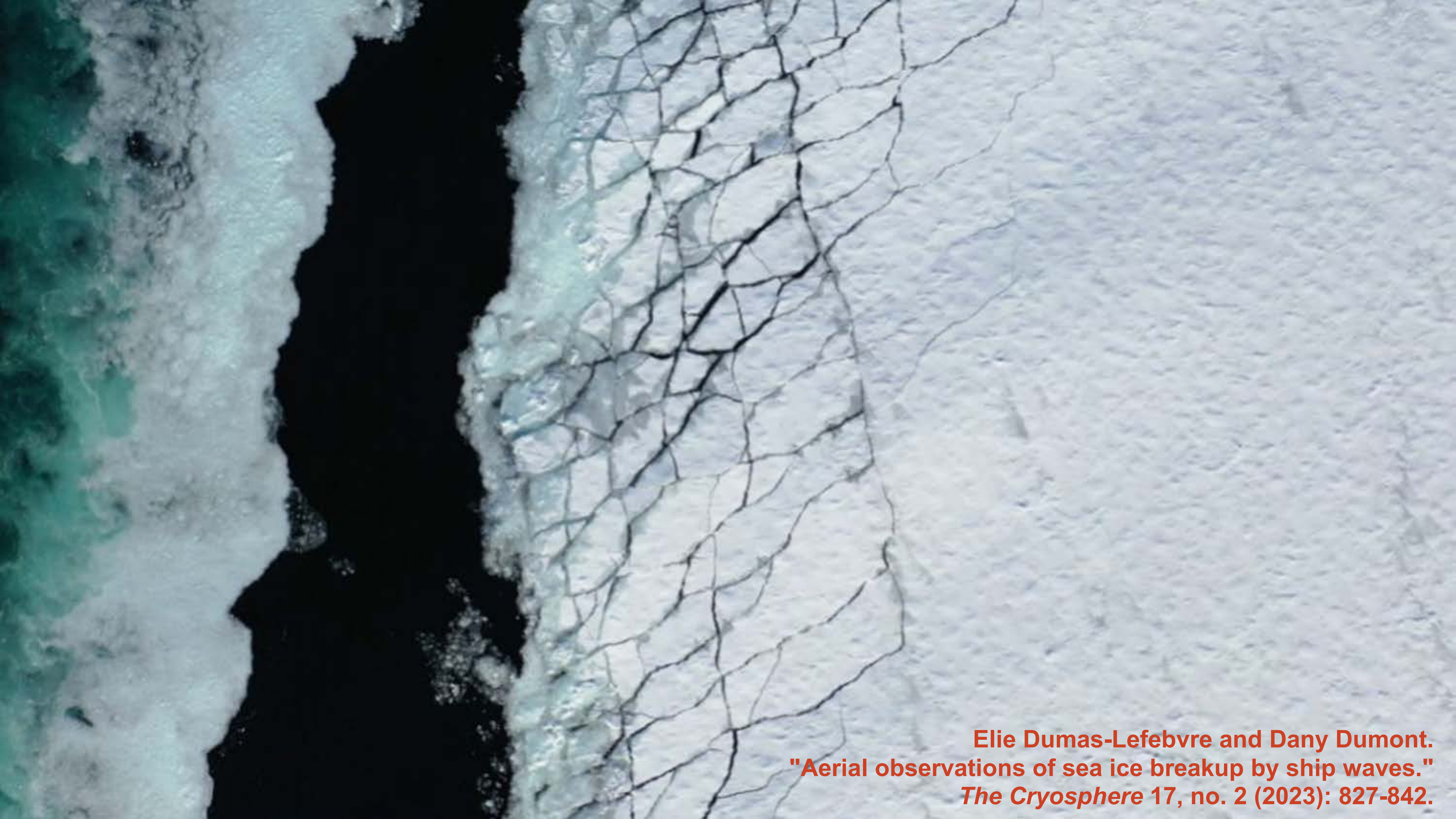
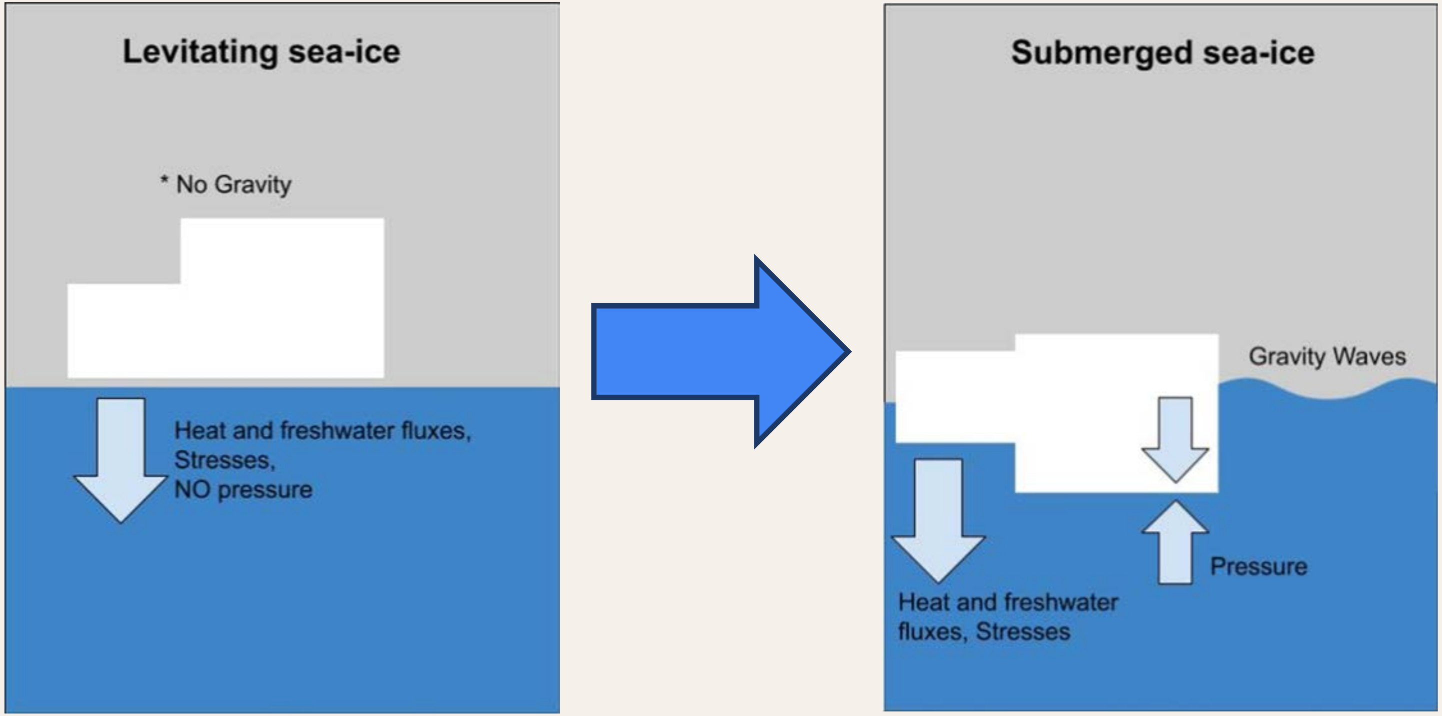


Elie Dumas-Lefebvre and Dany Dumont.
"Aerial observations of sea ice breakup by ship waves."
The Cryosphere 17, no. 2 (2023): 827-842.

Introduction



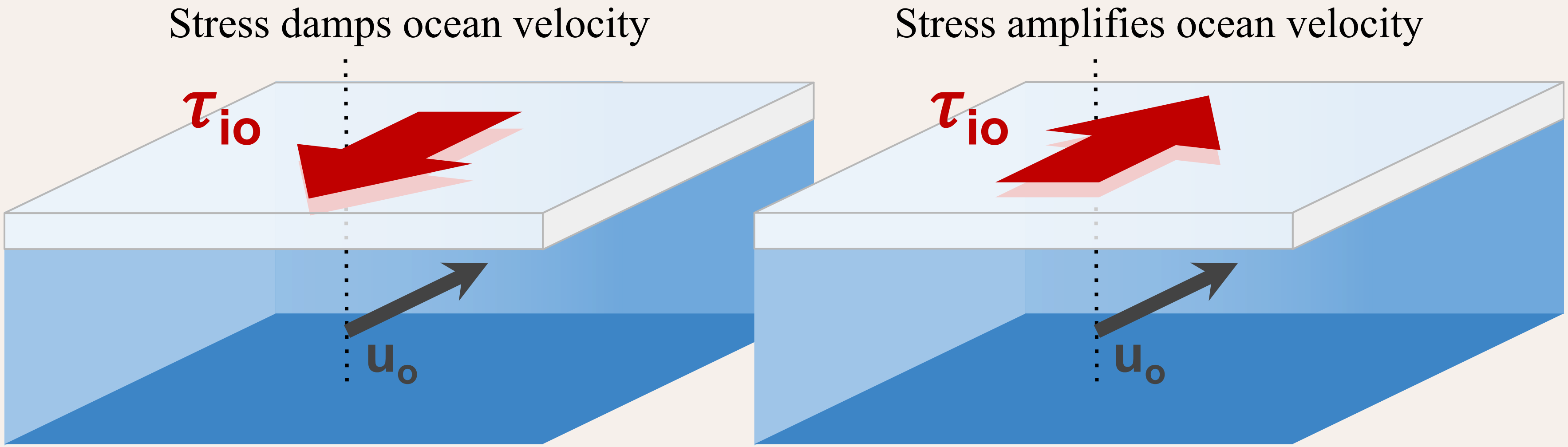
Submerging sea-ice in the ocean so the pressure of sea-ice on the ocean and the gravity waves produced are directly represented

Coupled Ice-Ocean Stress Instabilities

Coupling lag in sea-ice and ocean velocity used to calculate the ice-ocean stress can lead to the stress amplifying, instead of damping, the velocity.

$$\frac{u_i^{n+1} - u_i^n}{\Delta t} - f v_i^{n+1} = -\frac{\lambda}{H_i}(u_i^{n+1} - u_o^n)$$

$$\frac{u_o^{n+1} - u_o^n}{\Delta t} - f v_o^{n+1/2} = \frac{\lambda}{H_o}(u_i^n - u_o^{n-1})$$



Two Proposed Dynamic Coupling Schemes

Solution to Stress Instabilities:

Interspersed coupling
Dynamic updates for the ocean and sea-ice are done sequentially with shorter coupling timestep than the thermodynamic updates

Solution to Gravity waves:

Embedded coupling:
The sea-ice rheology (internal stresses, velocity, concentration) are updated with the barotropic ocean dynamics

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Challenges:

- Sea-ice and ocean must be on the same grid and processors - possible for MOM6/SIS2
- Sea-ice and ocean dynamics must be split from thermodynamics - done for MOM6/SIS2
- Information is usually mediated by “the coupler” - new interfaces must be developed
- Maintaining options to couple MOM6 to other sea-ice models (such as CICE) as we develop these new coupling schemes.

Time stepping in MOM6

- To describe the embedded coupling scheme, we need to understand the different time steps within MOM6 and SIS2
- While these time steps are specific to these models, the concepts could be applied to other coupled ice/ocean models

Time stepping in MOM6

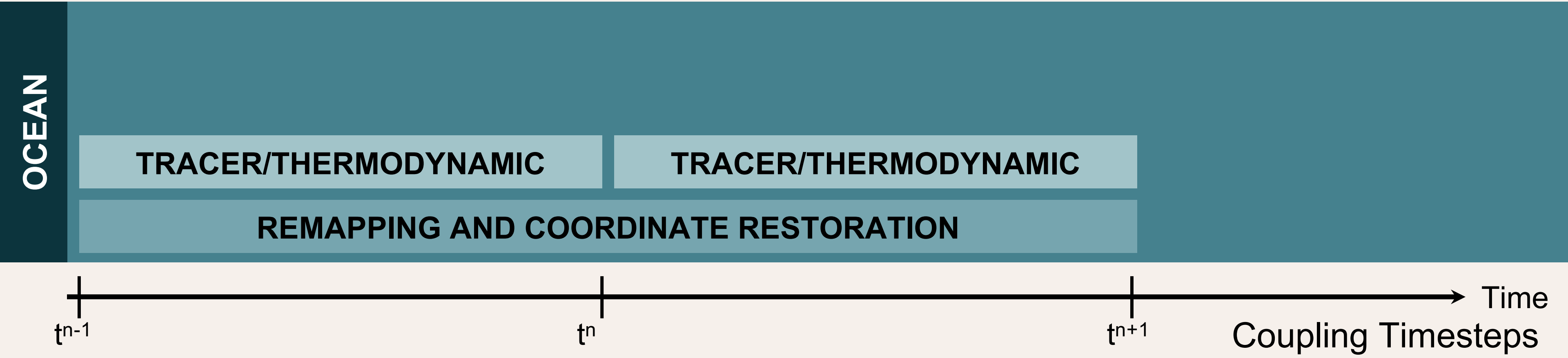
Thermodynamics

(1) Remapping of vertical coordinates (~ 30 minutes-hours)

(2) Tracer Advection, Thermodynamics, and Mixing (column physics)(~30 minutes)

$$\frac{\partial(hk)}{\partial t} = (P - E)_k$$

$$\frac{\partial}{\partial t}(h_k\theta_k)+\nabla_S\cdot(\vec{u}\,h_k\theta_k) = Q_k^\theta h_k+\frac{1}{h_k}\Delta\left(\kappa\frac{\partial\theta}{\partial t}\right)+\frac{1}{h_k}\nabla_s(h_k K\nabla_s\theta)$$



Dynamics

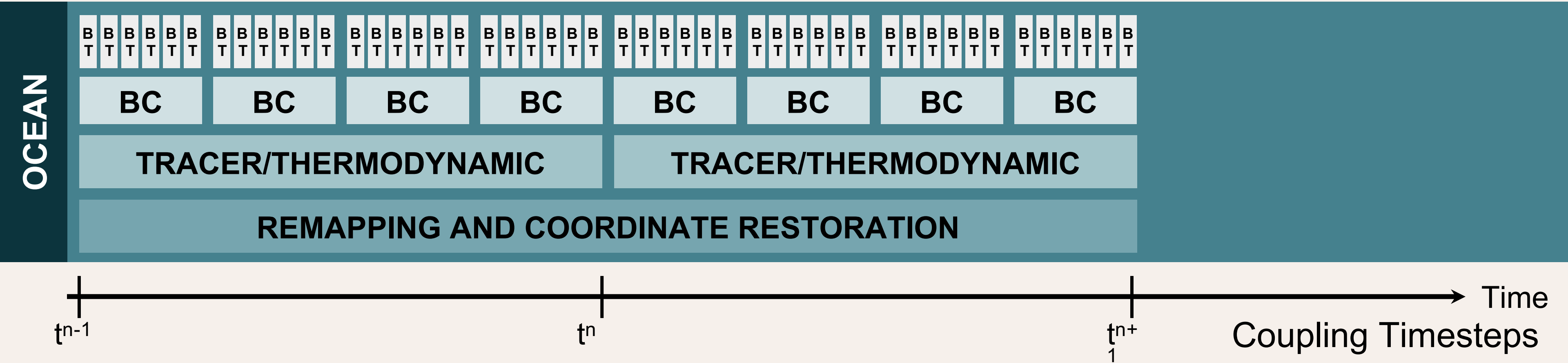
(3) Baroclinic Time Step:

Lagrangian dynamics, 3-D Stacked Shallow Water Equations (~15-30 minutes)

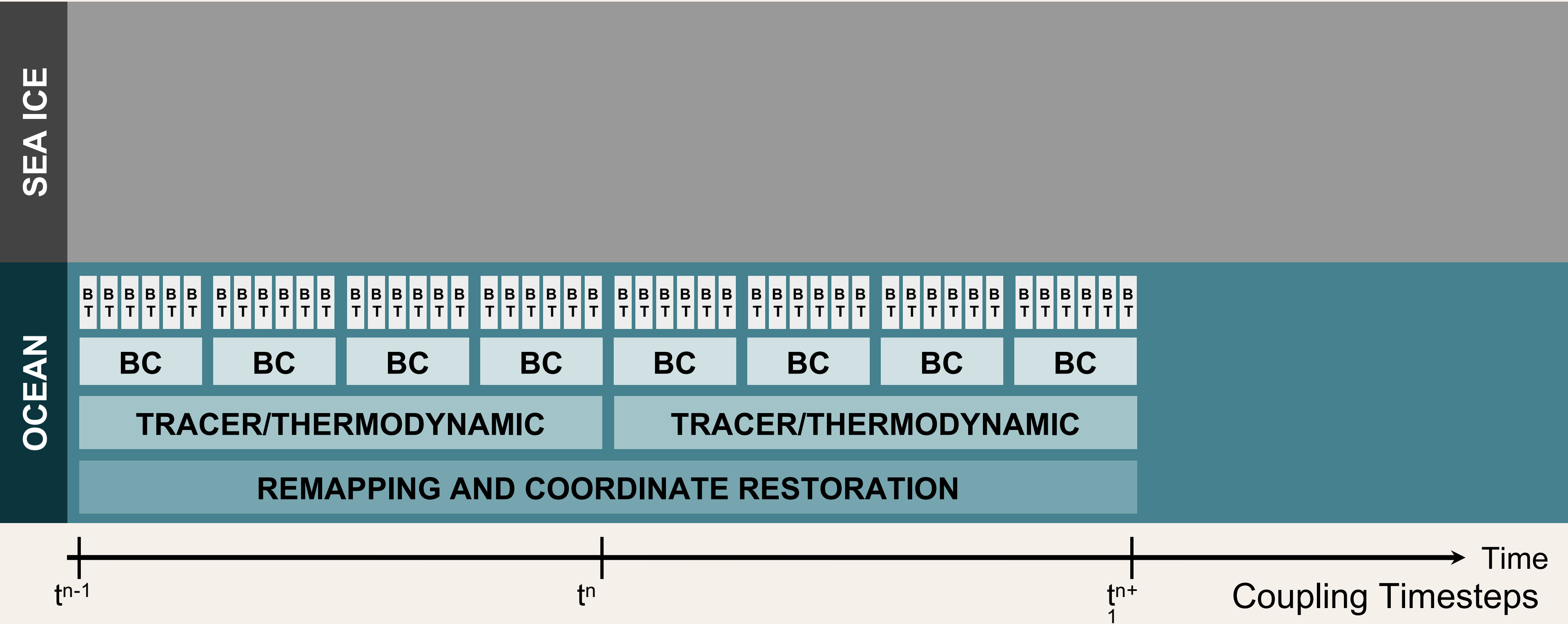
$$\frac{\partial \vec{u_k}}{\partial t} = (f + \nabla_s \times \vec{u_k})\hat{z} \times \vec{u_k}) = -\frac{\nabla_S p_k}{\rho} - \nabla_S(\phi_k + \frac{1}{2}\|\vec{u_k}\|^2) + \frac{\nabla \cdot \tilde{\tau}_k}{\rho} \qquad \frac{\partial(hk)}{\partial t} = \nabla_S \cdot \vec{u}\, h_k$$

(4) Barotropic Time Step: 2-D linear momentum equations and continuity (~90-100 seconds)

$$\frac{\partial \eta}{\partial t} = \nabla \cdot ((D + \eta)\ \overline{U}_{BT}\ )) = P - E \qquad \frac{\partial \overline{U}_{BT}}{\partial t} = -g\nabla\eta - f\hat{z} \times \overline{U}_{BT} + \overline{\mathbf{F}}_{BT}$$



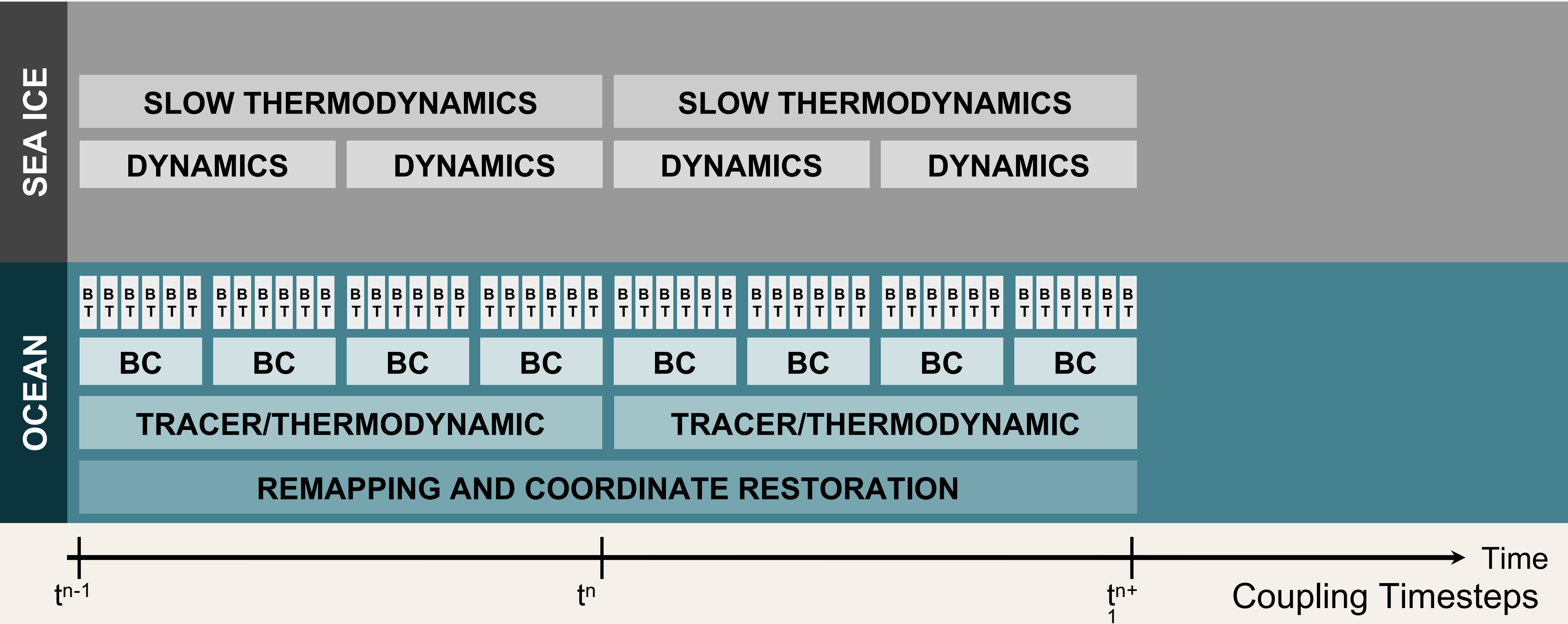
Time stepping in SIS2



Time stepping in SIS2

(1) Slow Thermodynamics: Melting and freezing – thermodynamics between ocean and ice.

(2) Dynamics: convergence, divergence, ice-ocean stresses



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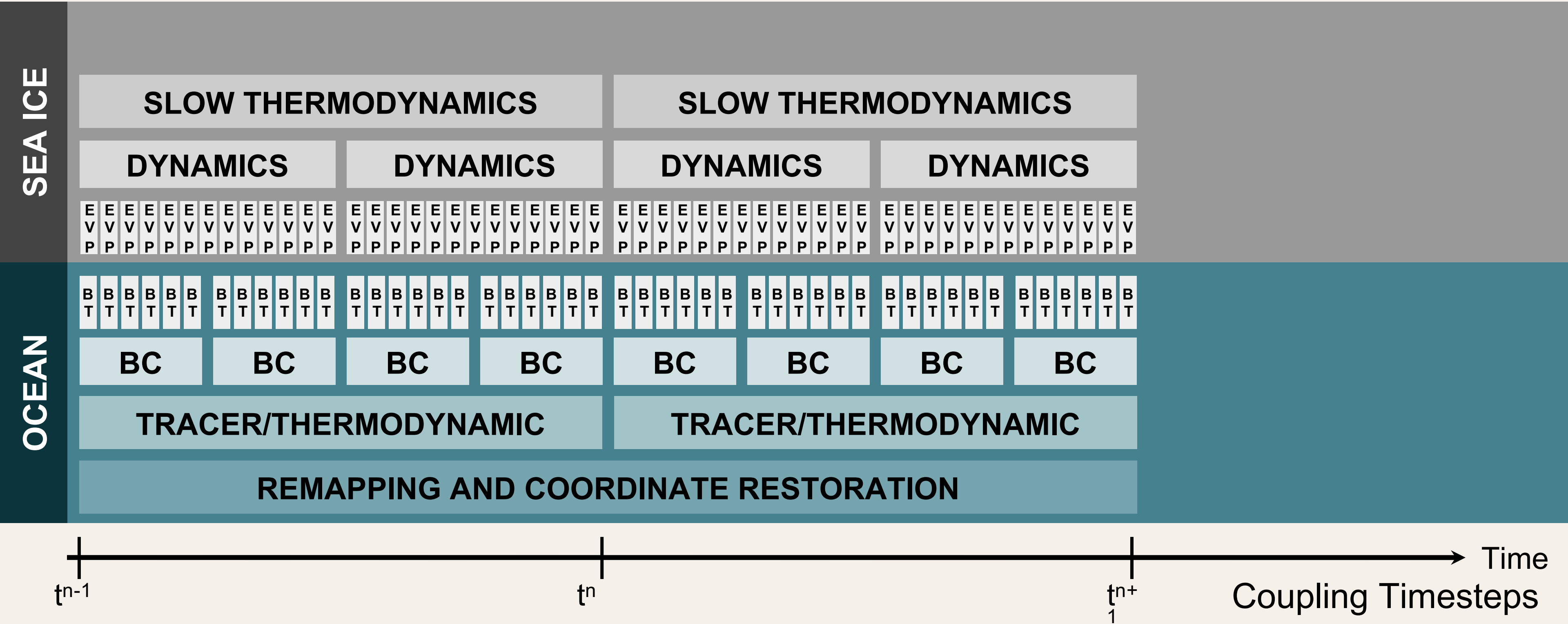
(3) EVP: Rheology



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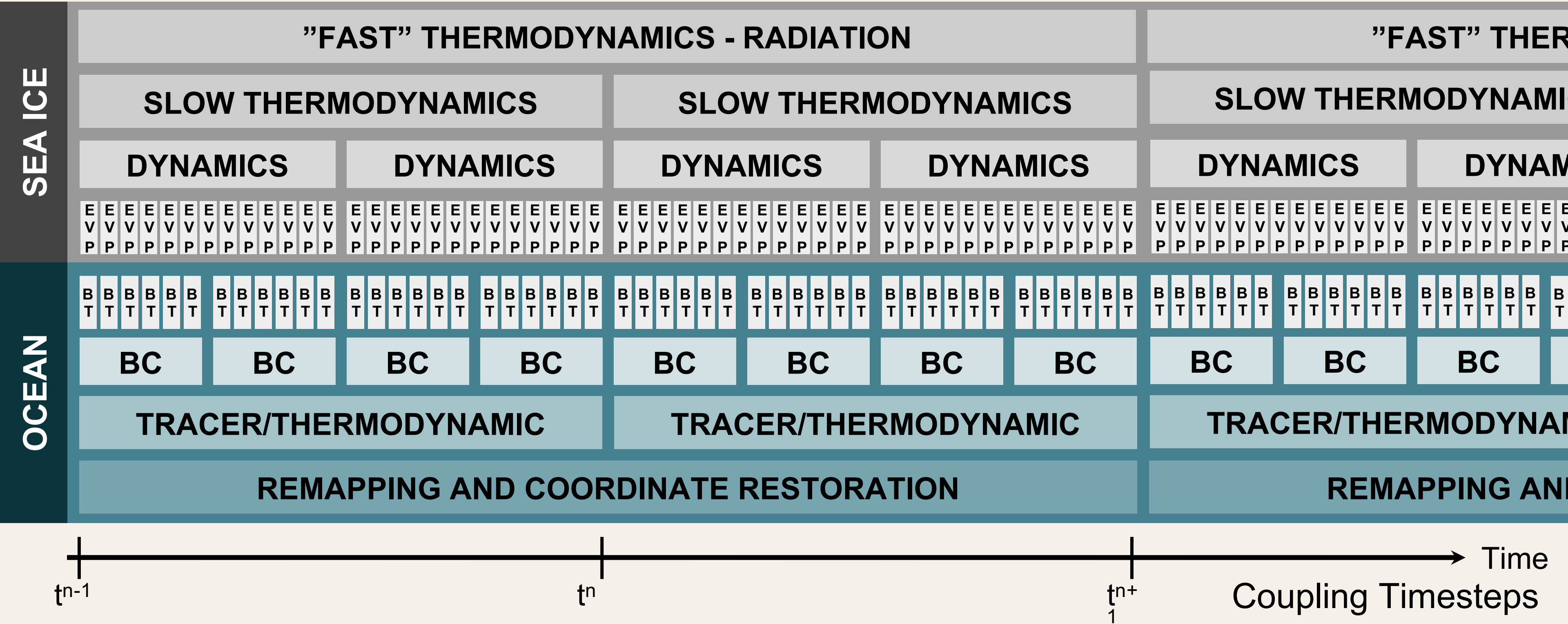
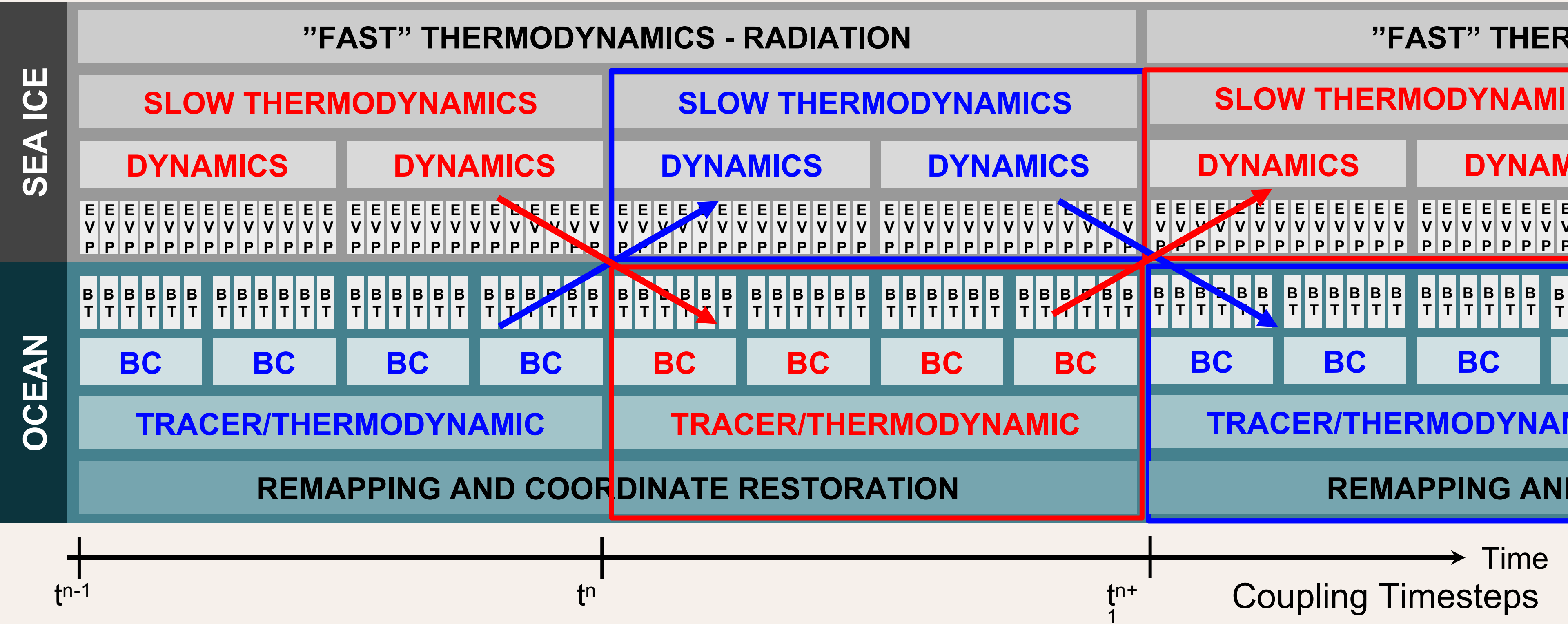


Concurrent Coupling

Sea-ice and ocean components are advanced simultaneously on different processors

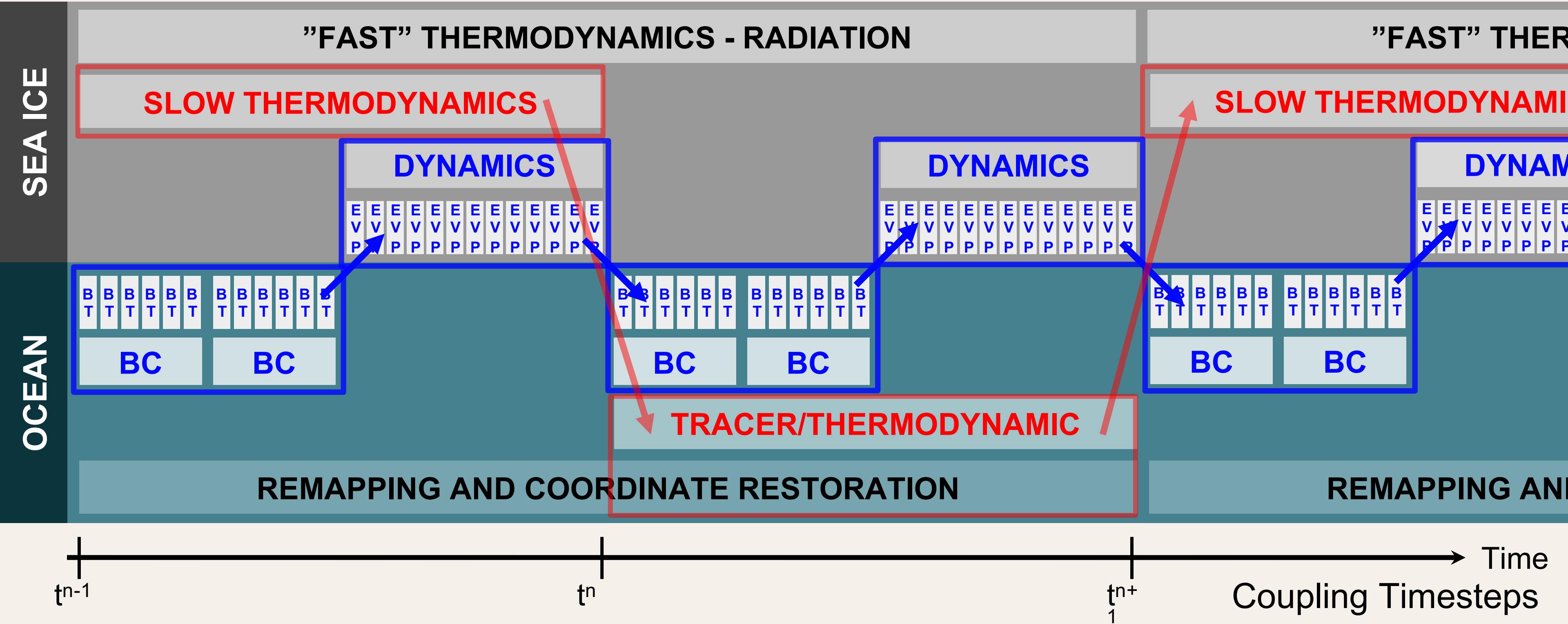
Information is exchanged at the end of each coupling time step

Component state is lagged by one coupled time step



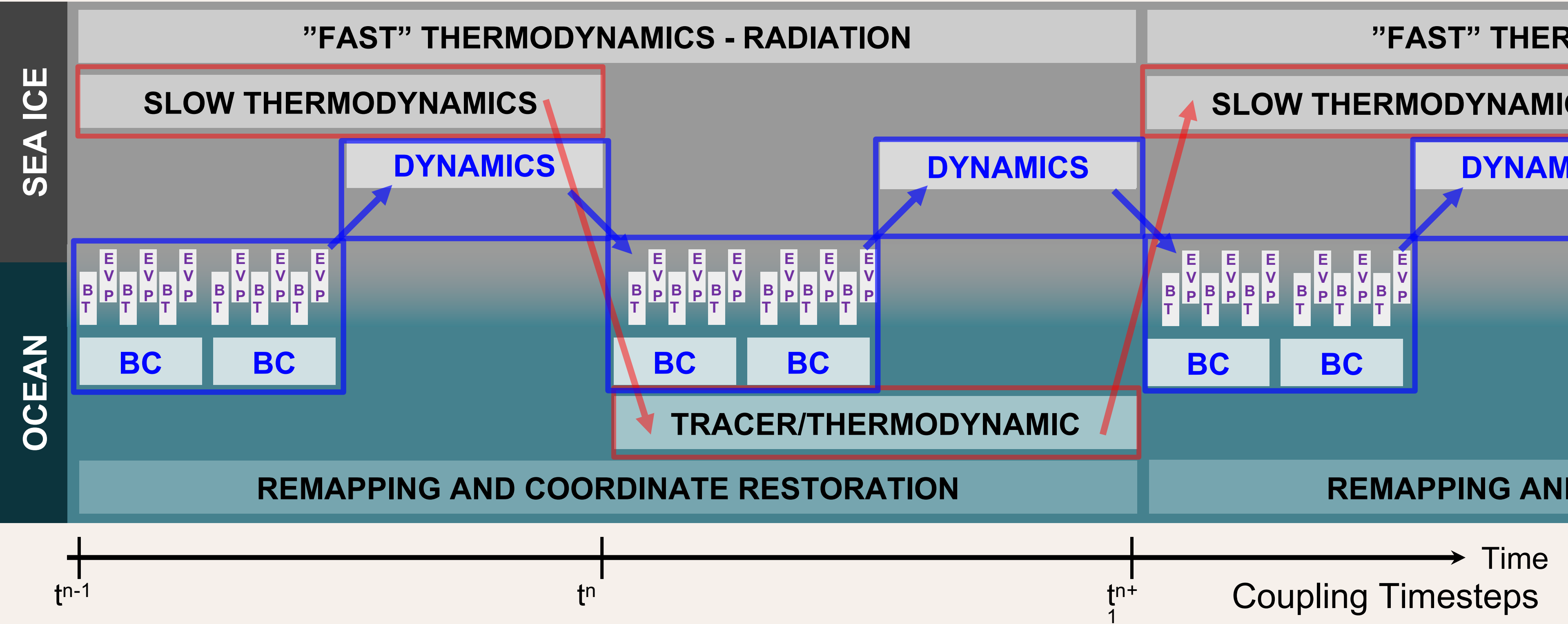
Interspersed Coupling

- Sea-ice and ocean *thermodynamic* components are concurrently coupled
- ***Dynamic* components are coupled more frequently than thermodynamics**
- Reduces the lag between sea-ice and ocean state



Embedded Coupling

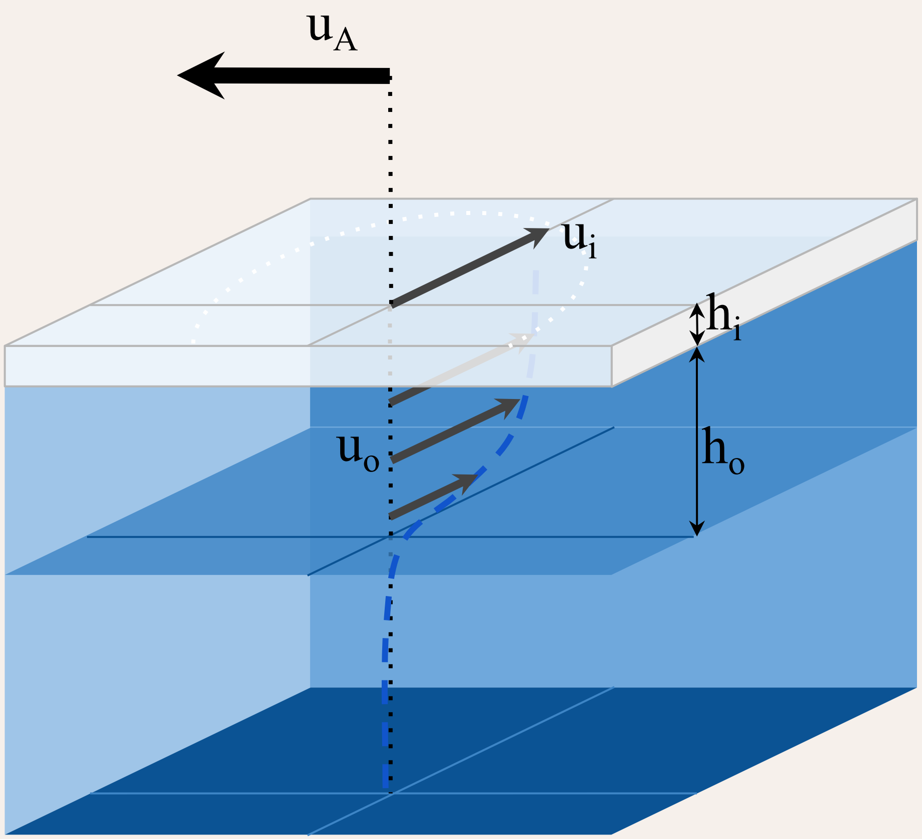
Sea-ice and ocean *thermodynamic* components are concurrently coupled
Dynamic components are coupled more frequently than thermodynamics
Sea-ice rheology is incorporated into barotropic time stepping within the ocean



Results

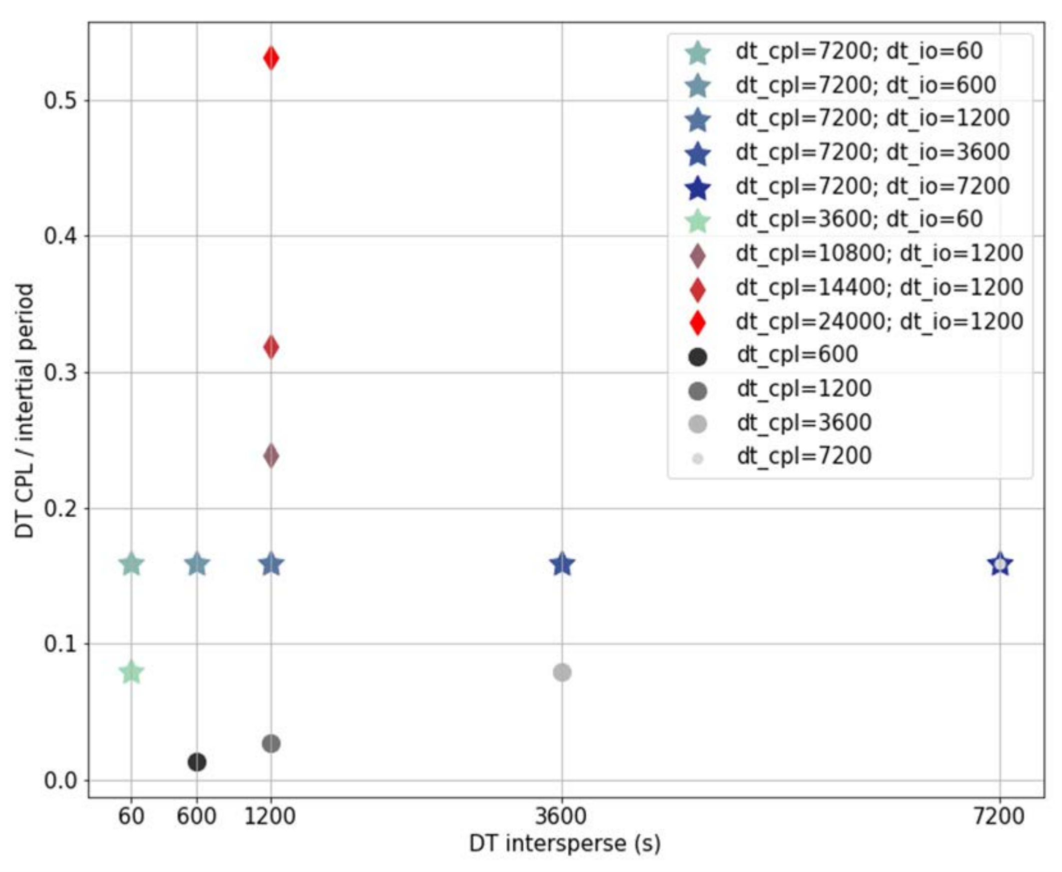
Idealized Uniform Ice and Uniform Winds

- Grid Resolution: ~1/10th degree doubly periodic domain
- Wind Stress: Zonal wind stress -2 N/m2 ; zero meridional wind stress
- Stratification: linear stratification, ocean surface temperature is at freezing temperature
- Flat bottom with 500m depth
- Period of inertial oscillations: ~12 hours
- Simulations are run for 5 days, after approximately 2 days the solution is oscillatory.
- There is some sea ice growth but not substantial changes in the sea ice thickness.



Idealized Uniform Ice and Uniform Winds

- Does coupling time step (dt_{CPL}) or interspersed time step (dt_{IO}) impact the ocean and sea ice state?
- Is the sea ice state the same in an experiment with dt_{IO}=X and dt_{CPL}=X?
- Can we intentionally create instabilities with the concurrent coupling? Can we suppress them with the interspersed coupling?
- At what dt_{IO} does the ice-ocean stress significantly increase? What is the maximum dt_{IO} we can use to get the advantages of interspersed coupling?



Ice-Ocean Timestep vs. Coupling Timestep

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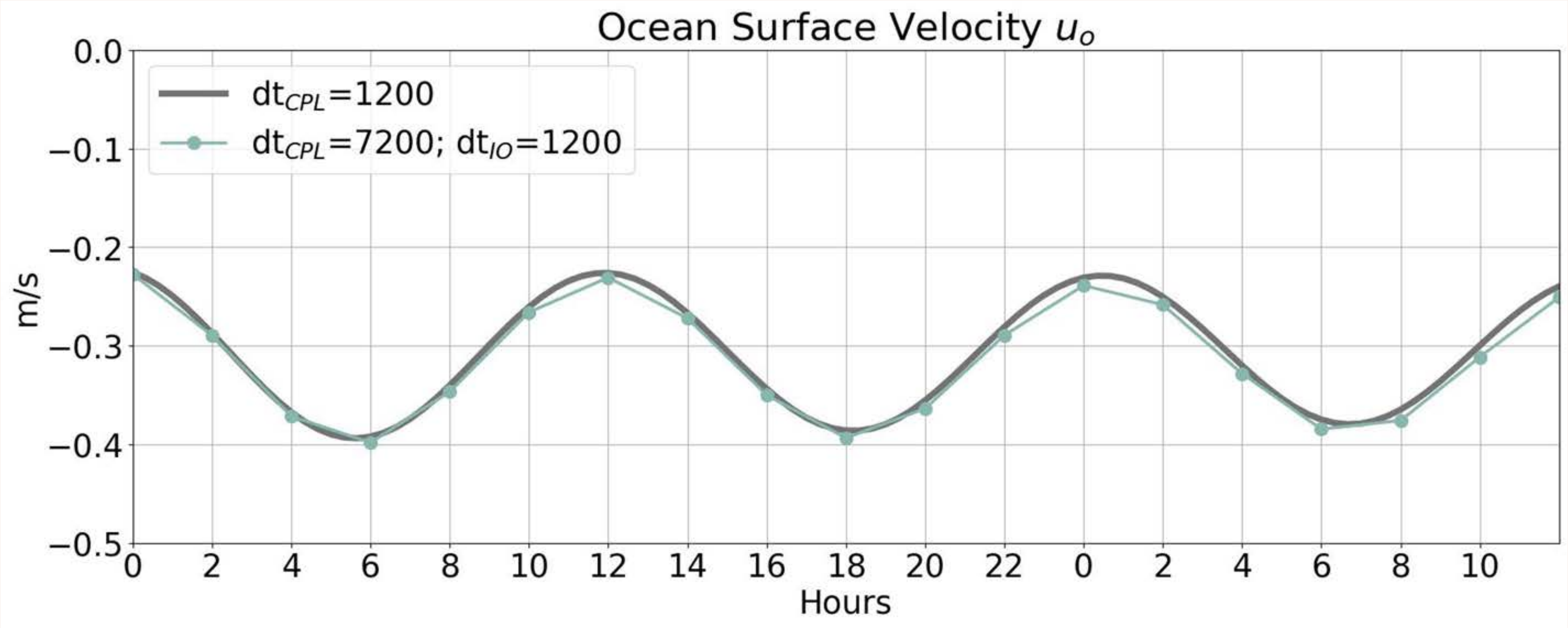
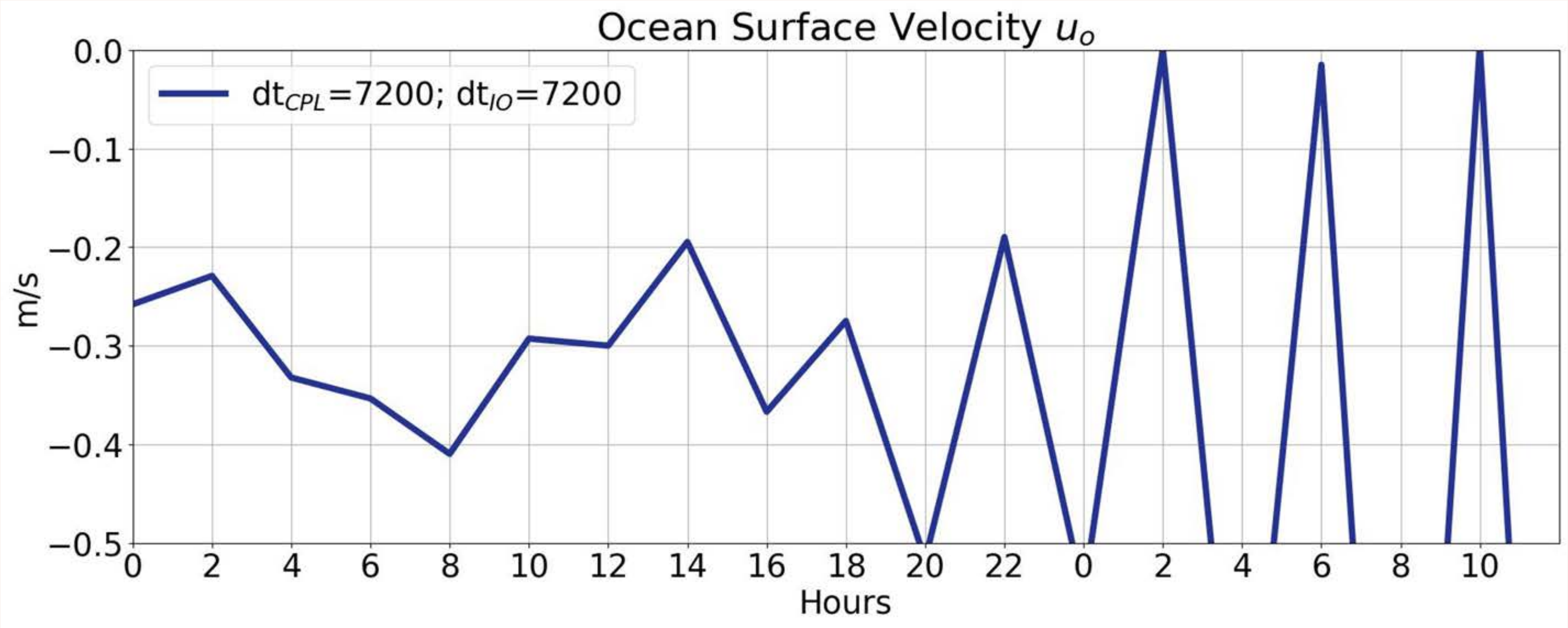


Magnitude of inertial oscillations vs. Timesteps

- Can we intentionally create instabilities with the concurrent coupling? Can we suppress them with the interspersed coupling?



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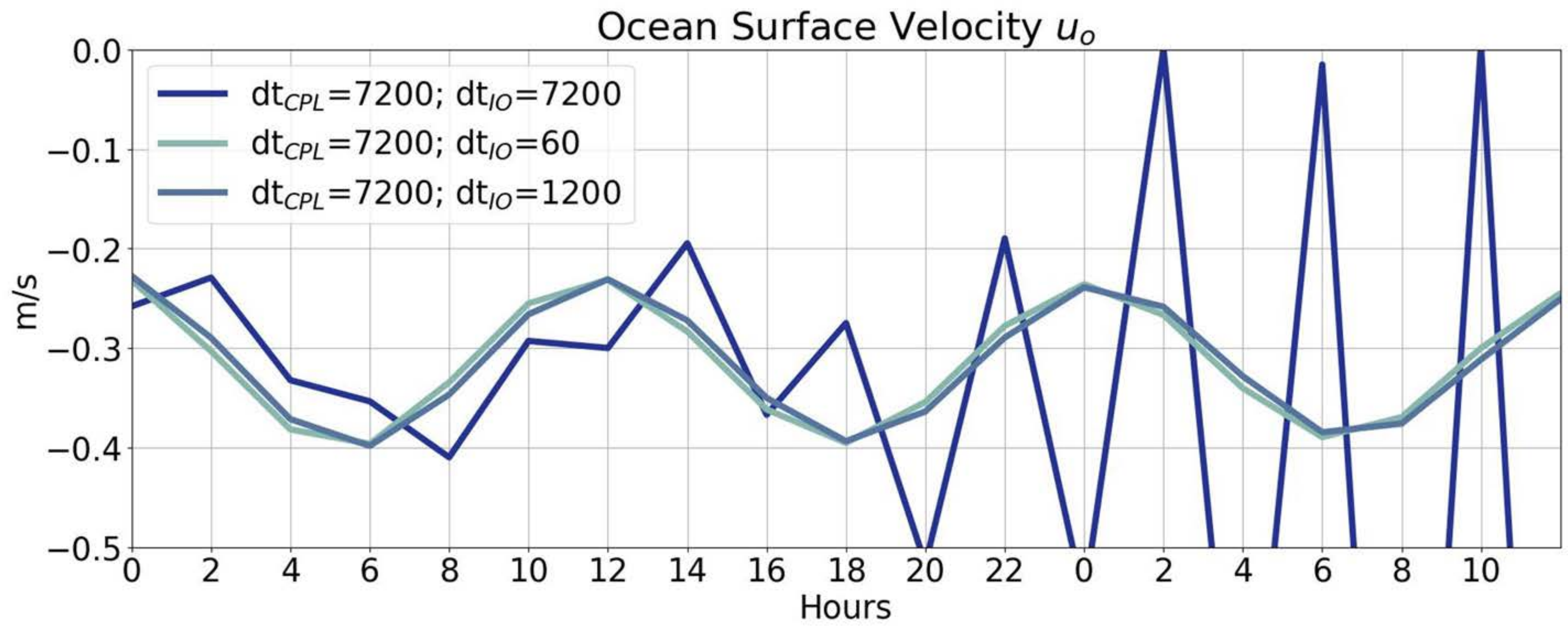

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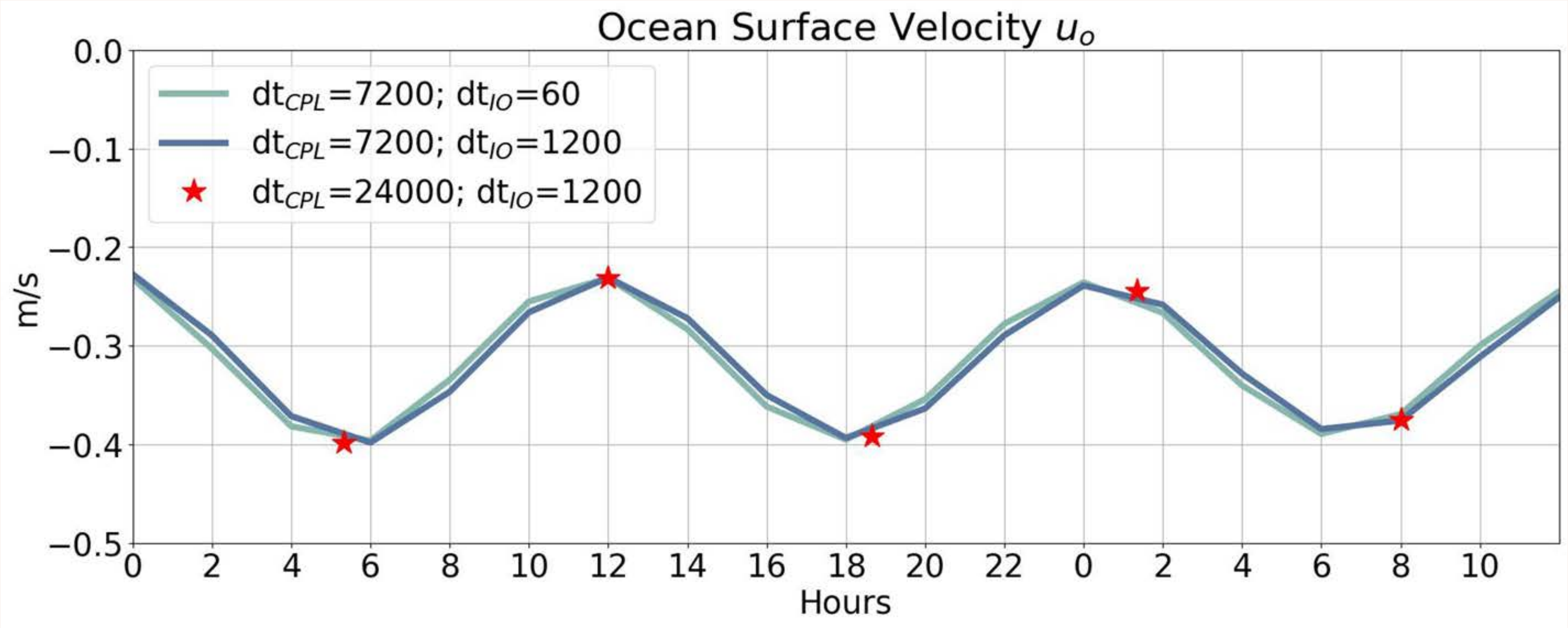
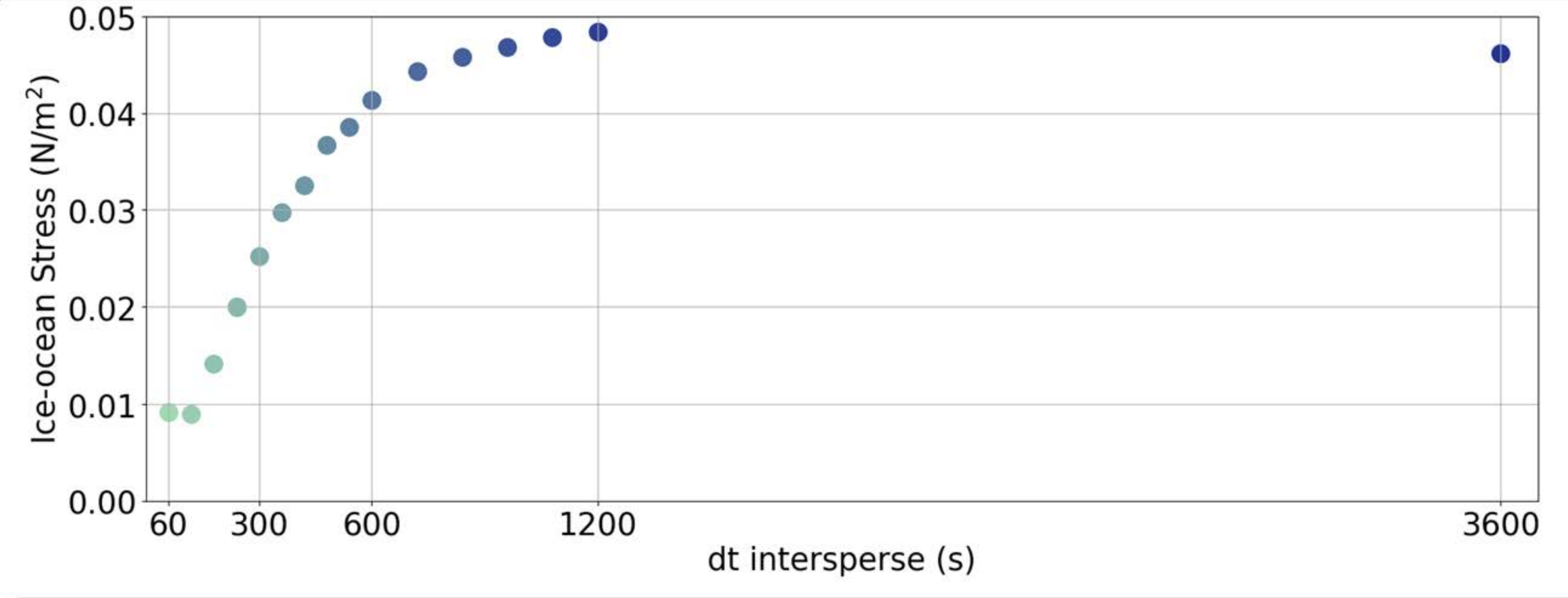


Ice-Ocean Stress vs. Ice-Ocean Timestep

- For a constant coupling timestep dt_{CPL}=7200, how does the ice-ocean stress change?
- Very low stress at embedded limit, increasing with dt_{IO}
- For dt_{IO}=7200, ice-ocean stress is 200 times greater, indicating instability



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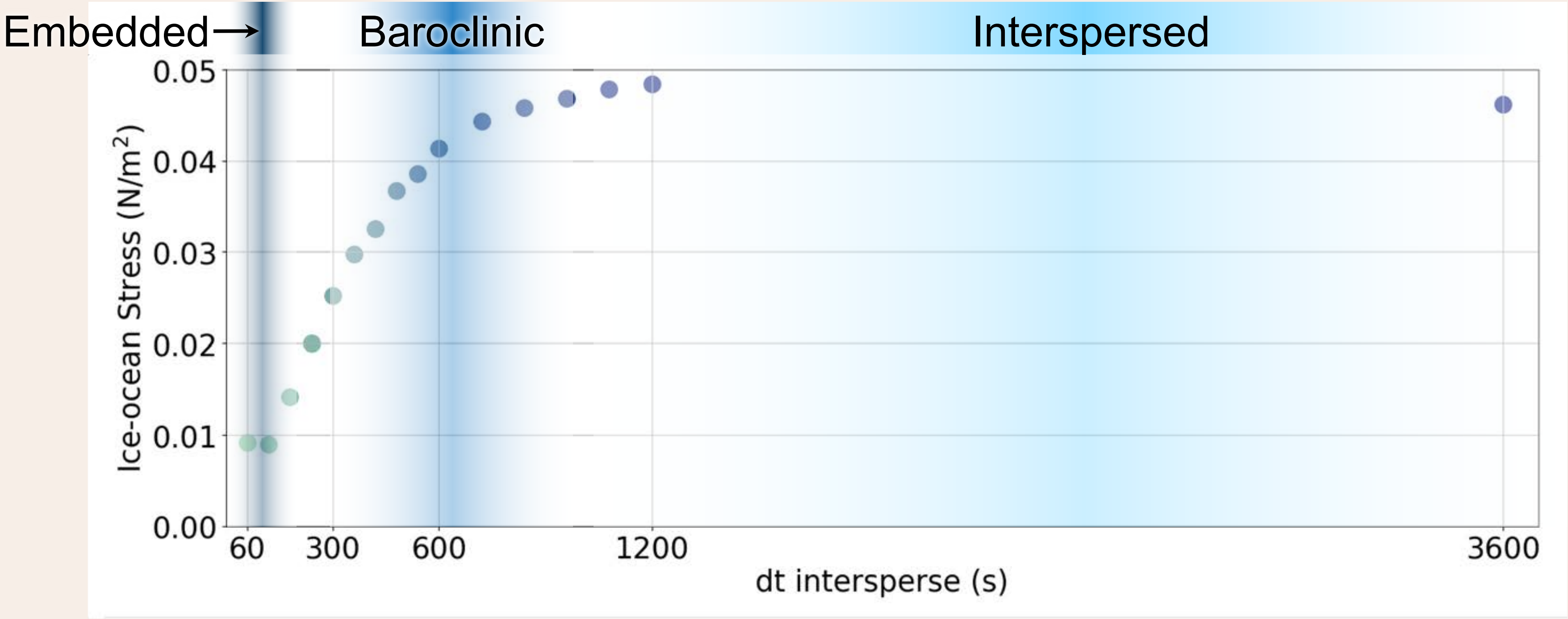
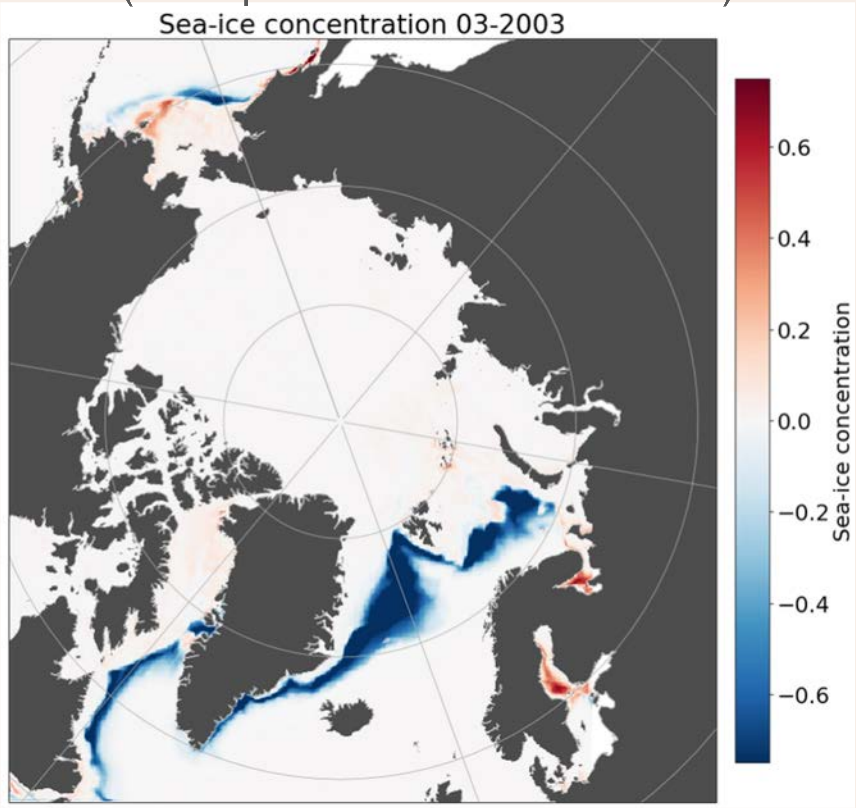


Regional Arctic Model

- Configuration being developed by Katherine Hedstrom
- Compare interspersed and concurrently coupled runs
- 12km horizontal resolution
- Boundary conditions from GLORYS
- Surface forcing from JRA55 Reanalysis
- Initialized in 1993

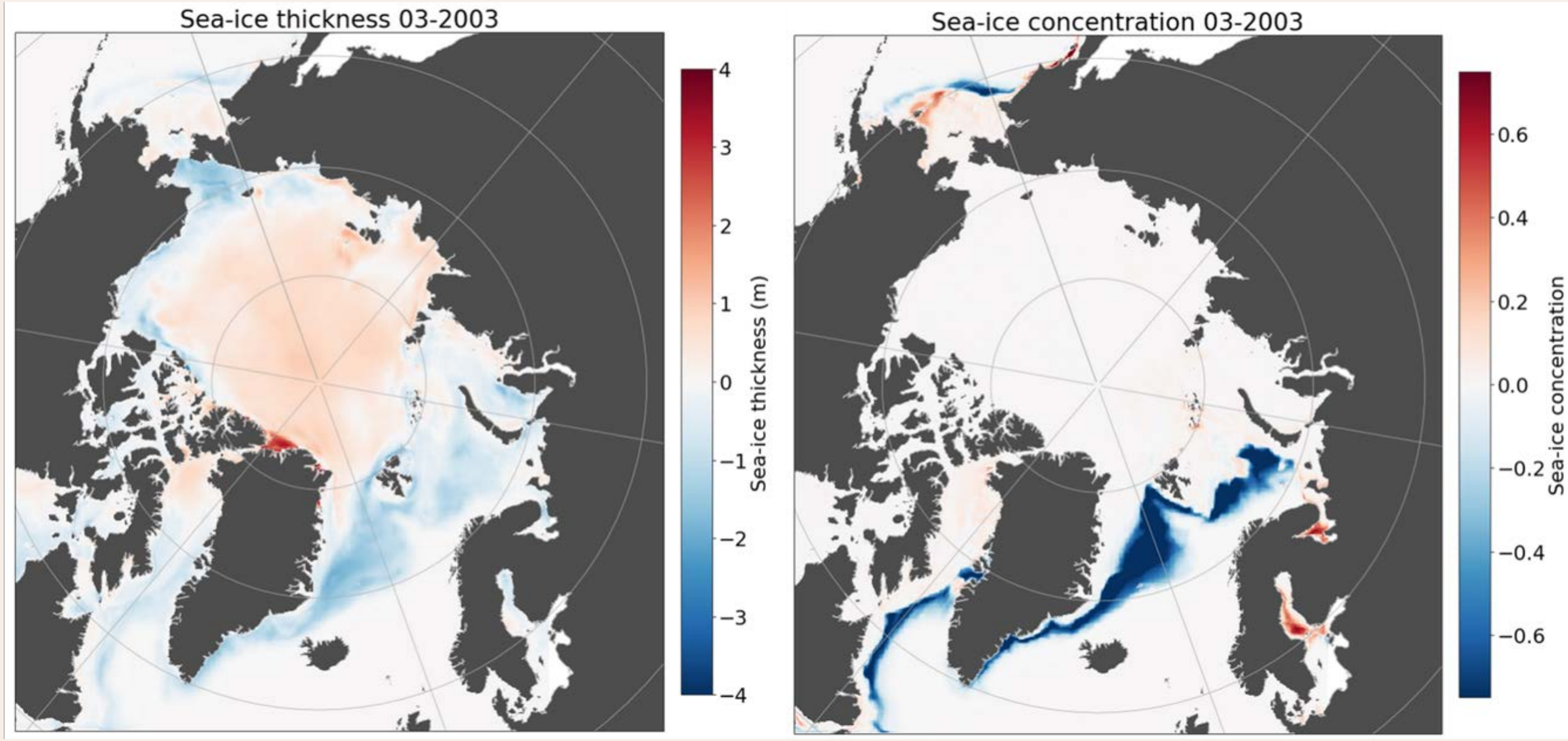
- Reduction of ice in GIN Seas
- Decreased bottom melt, colder SST under ice
- More area with higher ice concentration
- Thicker ice in central Arctic
- Sea-ice speed decreases, u* decreases
- Increasing ice-atmosphere drag can increase ice speed with interspersed coupling

Concentration Difference
(Interspersed minus Concurrent)



Regional Arctic Model

Thickness and Concentration Difference (Interspersed minus Concurrent)



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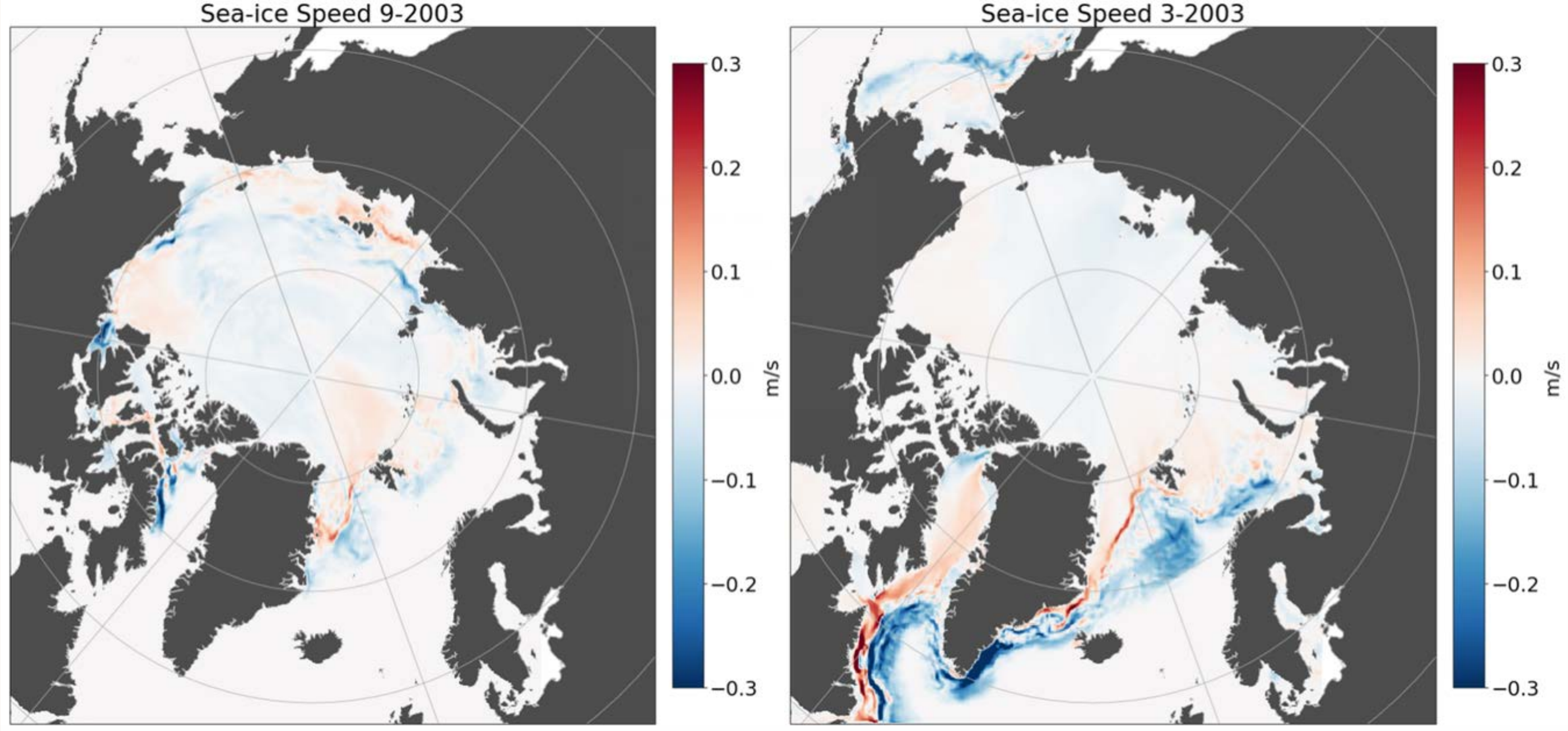

Conclusions

Methods for coupling sea-ice and ocean models

- When coupling sea-ice and ocean models we must ensure the lag is short enough to prevent the growth of coupled stress instabilities.
- To submerge sea-ice (and icebergs!) in the ocean we must resolve gravity waves in the coupling

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Interspersed coupling:
Dynamic updates for the ocean and sea-ice are done sequentially with shorter coupling timestep than the thermodynamic updates

Embedded coupling:
The sea-ice rheology is updated with the barotropic ocean dynamics

Results:

- Interspersed coupling can be used to resolve dynamic process and make unstable solutions stable
- However, interspersed coupling may not be sufficient to reduce ice-ocean stress
- Embedded coupling or coupling at the ocean baroclinic timestep should resolve the ice-ocean stress
- In the Regional Arctic configuration, there is a tendency toward thicker ice with higher concentrations
- More complex idealized simulations are needed to understand all the impacts of interspersed coupling

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