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CICE Consortium

The Theory of Coupling for Sea Ice Models

Andrew Roberts and Elizabeth Hunke

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Introduction: An Analytic Form of a CICE Configuration

Atmospheric and Oceanic State

Fundamental Physics

Sea ice thermodynamics

diagnostic: $q(S,T) = \rho C(T_m - T) + \rho L(1 + \mu S/T)$ (energy of melting)

prognostic: $\frac{\partial T}{\partial t} = \left(\frac{k}{\rho C}\right)_{i,s} \frac{\partial^2 T}{\partial z^2}$ (ice temperature)

prognostic: $f(h) = \frac{dh}{dt} = \frac{F_{net}}{-q(S,T)}$ (growth rate)

Sea ice dynamics

diagnostic: $P = \frac{\rho_i g(\rho_w - \rho_i)}{2(1 - c_{fric})\rho_w} \int_0^\infty h^2 w_r dh$ (compressive strength, statics)

diagnostic: $\sigma_{mn} = \zeta \dot{e}_{kk}\delta_{mn} + \mu(2\dot{e}_{mn} - \dot{e}_{kk}\delta_{mn}) - P\delta_{mn}/2$ (internal stress)

prognostic: $m\frac{\partial \tilde{u}}{\partial t} = \tilde{\tau}_w + \tilde{\tau}_a - mf\mathbf{k} \times \tilde{u} - mg\nabla\eta - m\left(\tilde{u}\cdot\nabla\right)\tilde{u} + \frac{\partial \sigma_{mn}}{\partial x_n}$ (velocity)

diagnostic: $\psi(h) = \nabla \cdot \tilde{u} \;\; w_r\left(h, g(h)\right)$ (volume conservation)

Sea ice thickness distribution

prognostic: $\frac{\partial g(h)}{\partial t} = -\nabla \cdot \left(g(h)\,\tilde{u}\right) + \psi(h) + \mathrm{f}(h)$ (continuity equation)

Sea Ice State

Atmosphere, Ocean and Hydrology Update

Introduction: An Analytic Form of a CICE Configuration

Atmospheric and Oceanic State

Some Namelist Settings

Sea ice thermodynamics

diagnostic: $q(S,T) = \rho C(T_m - T) + \rho L(1 + \mu S/T)$ (ktherm=1)

prognostic: $\dfrac{\partial T}{\partial t} = \left(\dfrac{k}{\rho C}\right)_{i,s} \dfrac{\partial^2 T}{\partial z^2}$

prognostic: $f(h) = \dfrac{dh}{dt} = \dfrac{F_{net}}{-q(S,T)}$

Sea ice dynamics

diagnostic: $P = \dfrac{\rho_i g(\rho_w - \rho_i)}{2(1 - c_{fric})\rho_w} \displaystyle\int_0^\infty h^2 w_r dh$ (kstrength=1)

diagnostic: $\sigma_{mn} = \zeta \dot{e}_{kk}\delta_{mn} + \mu(2\dot{e}_{mn} - \dot{e}_{kk}\delta_{mn}) - P\delta_{mn}/2$ (kdyn=1)

prognostic: $m\dfrac{\partial \widetilde{u}}{\partial t} = \widetilde{\tau}_w + \widetilde{\tau}_a - mf\mathbf{k} \times \widetilde{u} - mg\nabla\eta - m\left(\widetilde{u} \cdot \nabla\right)\widetilde{u} + \dfrac{\partial \sigma_{mn}}{\partial x_n}$

diagnostic: $\psi(h) = \nabla \cdot \tilde{u} \;\; w_r\left(h, g(h)\right)$ (kridge=1)

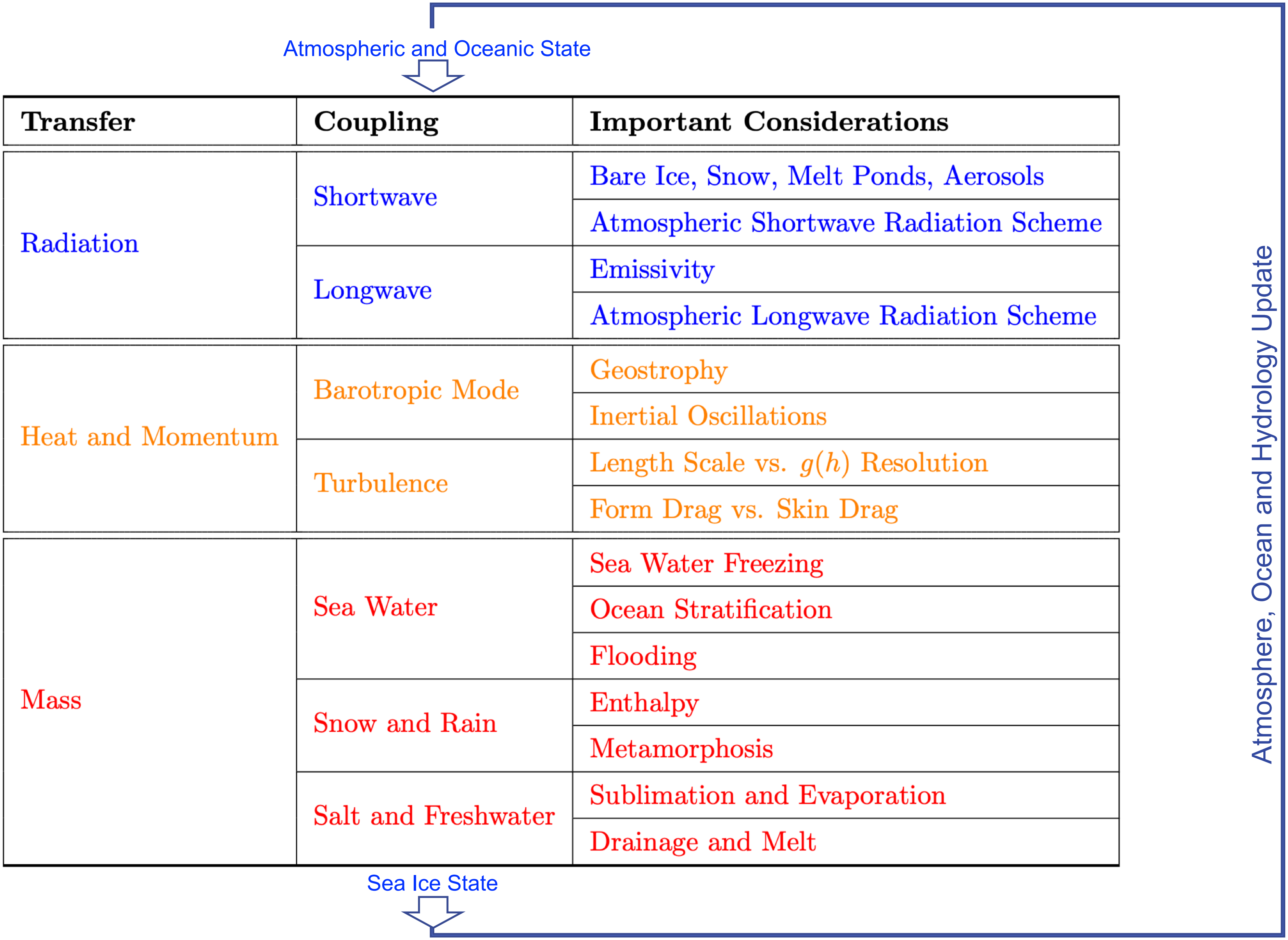
Sea ice thickness distribution

prognostic: $\dfrac{\partial g(h)}{\partial t} = -\nabla \cdot \left(g(h)\,\widetilde{u}\right) + \psi(h) + \mathrm{f}(h)$ (ncat=5)

Sea Ice State

Atmosphere, Ocean and Hydrology Update

Introduction: Fundamental Couplings in a Nutshell



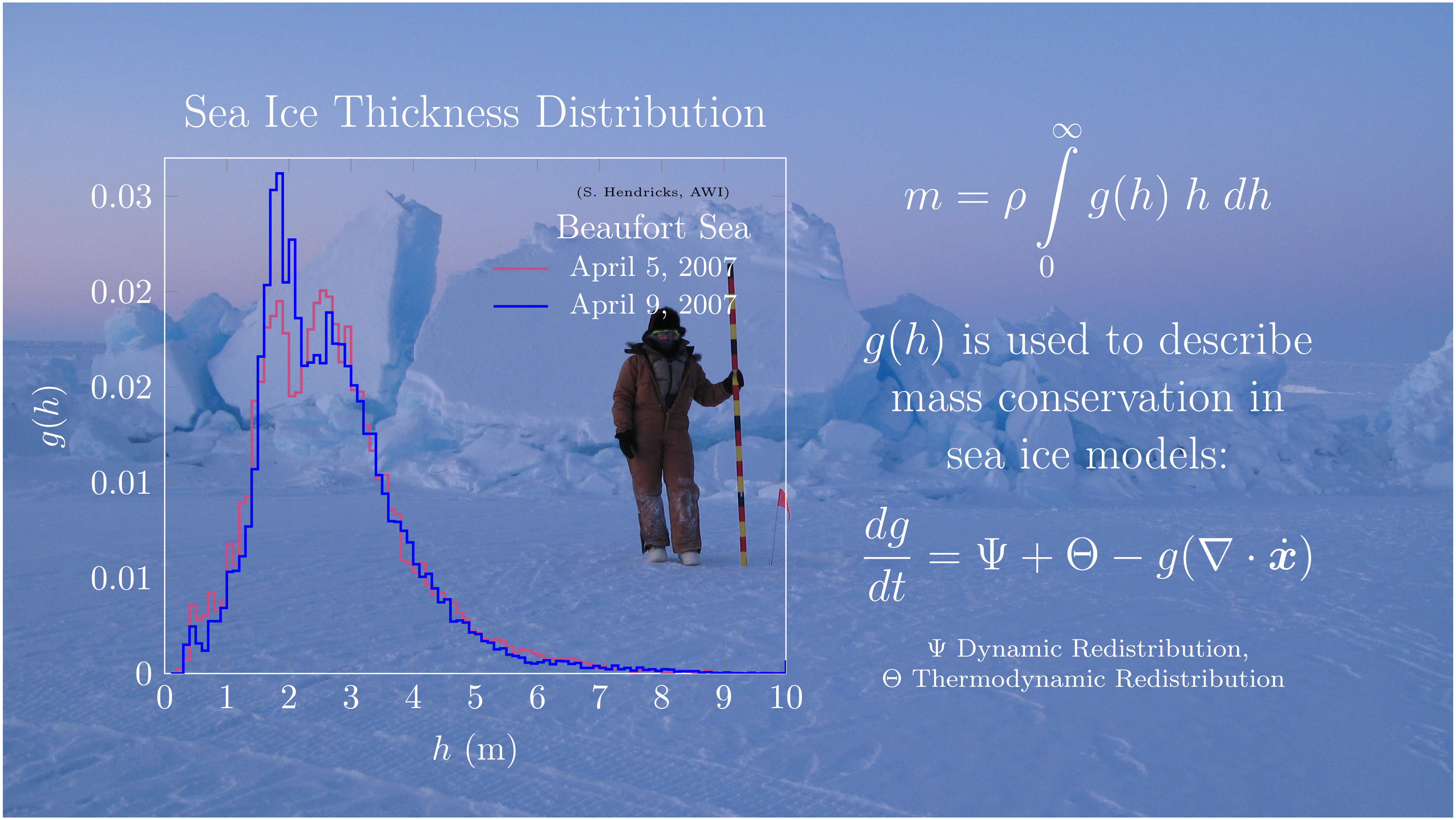
Atmospheric and Oceanic State

Transfer	Coupling	Important Considerations
Radiation	Shortwave	Bare Ice, Snow, Melt Ponds, Aerosols
		Atmospheric Shortwave Radiation Scheme
	Longwave	Emissivity
		Atmospheric Longwave Radiation Scheme
Heat and Momentum	Barotropic Mode	Geostrophy
		Inertial Oscillations
	Turbulence	Length Scale vs. $g(h)$ Resolution
		Form Drag vs. Skin Drag
Mass	Sea Water	Sea Water Freezing
		Ocean Stratification
		Flooding
	Snow and Rain	Enthalpy
		Metamorphosis
	Salt and Freshwater	Sublimation and Evaporation
		Drainage and Melt

Sea Ice State

Atmosphere, Ocean and Hydrology Update

A sea ice model's state space is fundamental to coupling



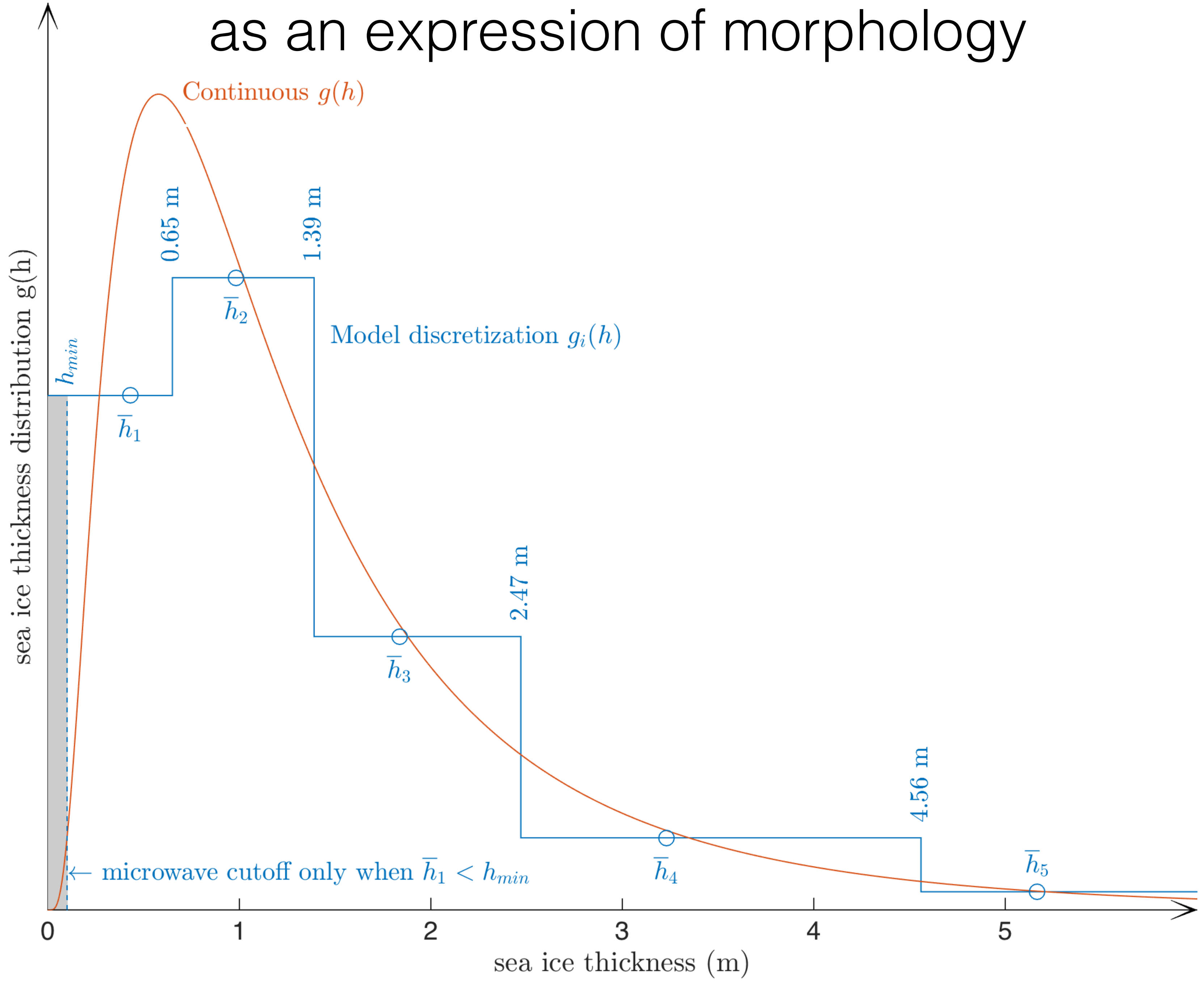
$$m = \rho \int_{0}^{\infty} g(h)\ h\ dh$$

$g(h)$ is used to describe mass conservation in sea ice models:

$$\frac{dg}{dt} = \Psi + \Theta - g(\nabla \cdot \dot{\boldsymbol{x}})$$

Ψ Dynamic Redistribution,
Θ Thermodynamic Redistribution

Sea Ice Thickness Distribution
as an expression of morphology



Radiation Coupling

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Radiation Coupling: The Bulk Equation

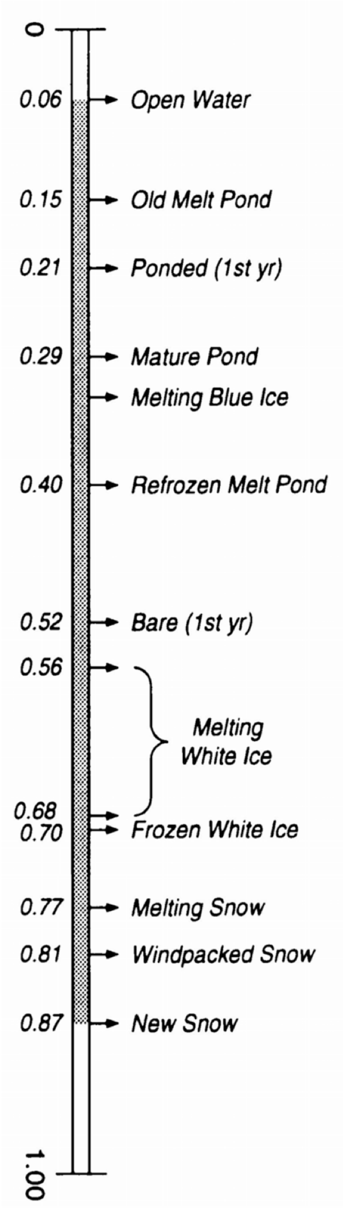
$$\epsilon\sigma T^4_{surf\uparrow} + H + LW_\downarrow + (1-\beta)(1-\alpha)SW_\downarrow = k\left(\frac{\partial T}{\partial z}\right).$$

Symbols and Constants with Rough Estimates

ϵ	Bulk Emissivity (typically 97-99%)
σ	Boltzman Constant
T_{surf}	Surface Temperature
H	Surface Turbulent Fluxes
$LW_\downarrow$	Longwave Down
β	Shortwave penetration fraction (~0.3)
α	Bulk Albedo
$SW_\downarrow$	Shortwave Down
k_i	Thermal Conductivity of Ice (~2.03 W m^{-1} K^{-1})
k_s	Thermal Conductivity of Ice (~0.31 W m^{-1} K^{-1})
T	Depth-Varying Temperature in Sea Ice
z	Vertical Coordinate in a sea ice column

This is the most basic form of thermodynamic coupling.

Radiation: Shortwave: Surface Type



From Perovich 1998

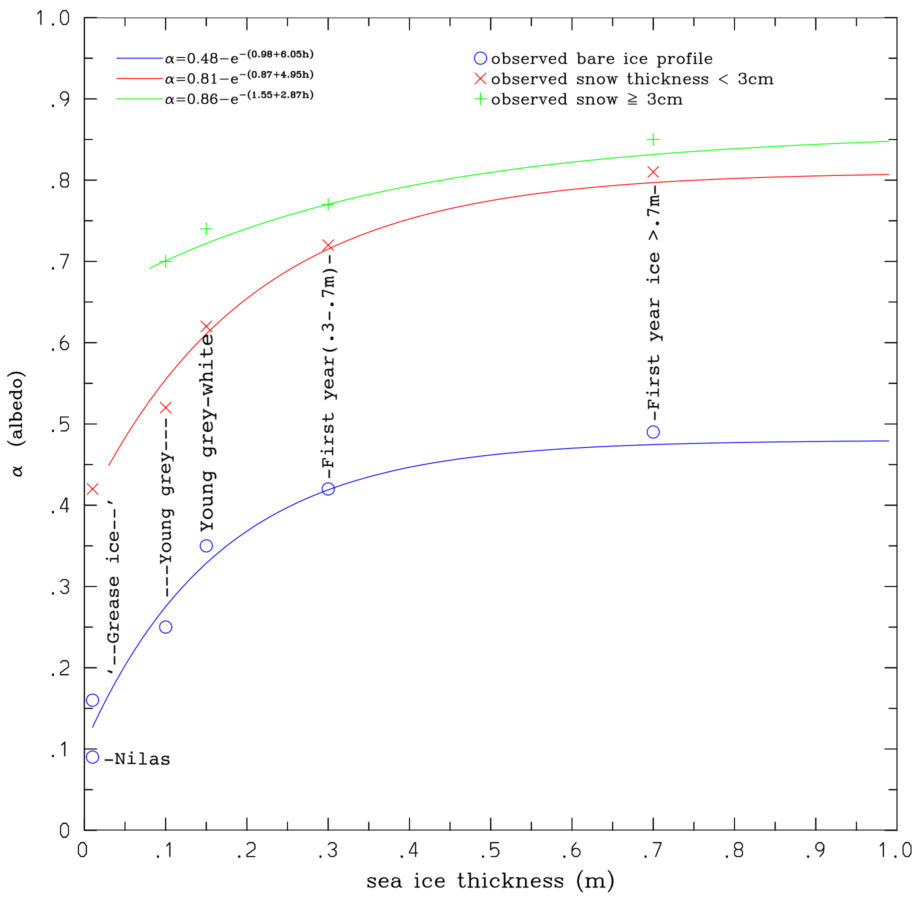
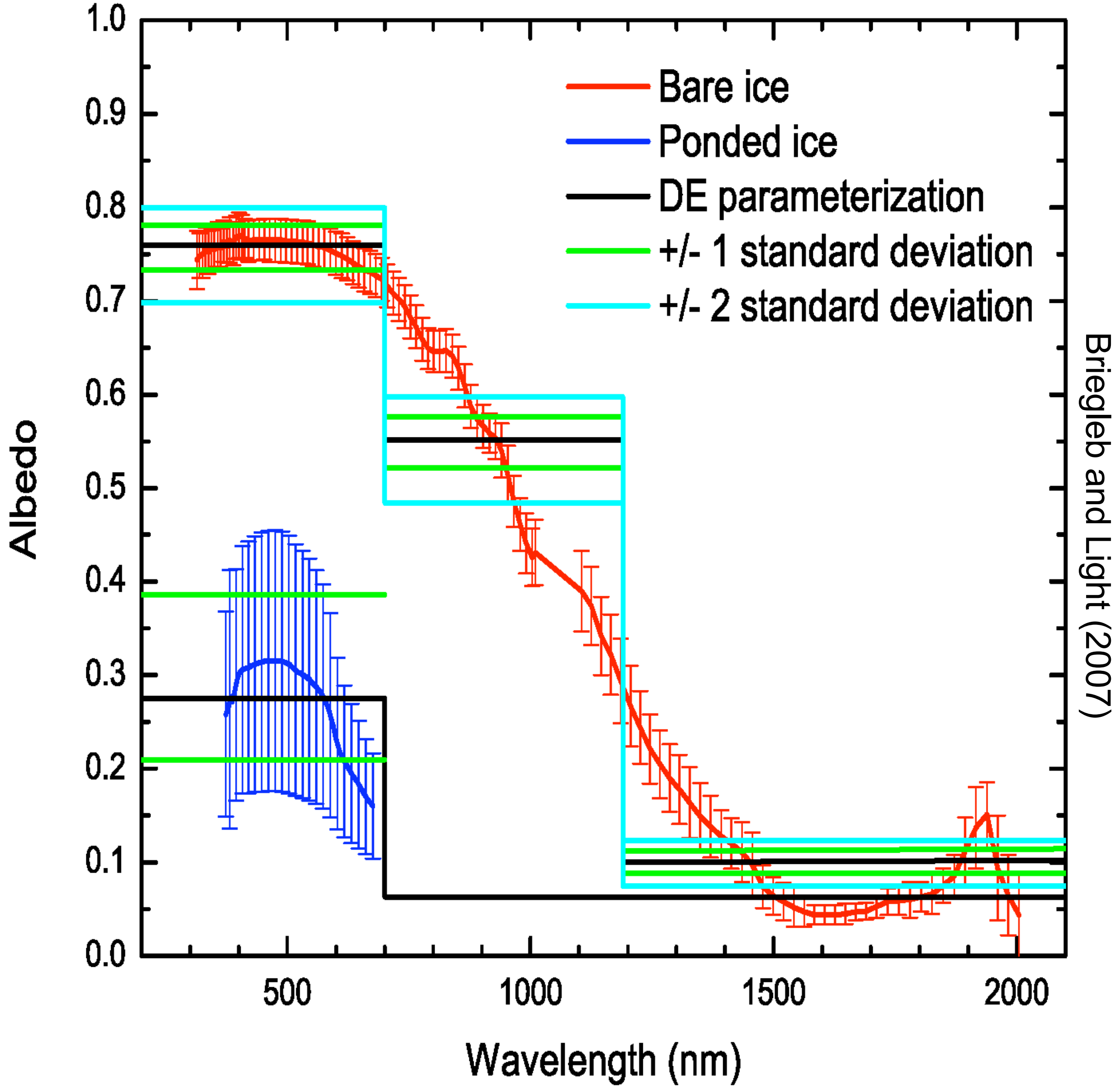


Figure 1.8: Antarctic albedos for bare sea ice and snow covered sea ice relative to World Meteorological Organisation (WMO) classifications indicated at the minimum thickness of each class (after *Brandt et al.* [1999]). Solid lines have been added by the author as suggested model parameterisations, with equations for each line indicated in the key.

Bulk Albedo From Roberts (2005).

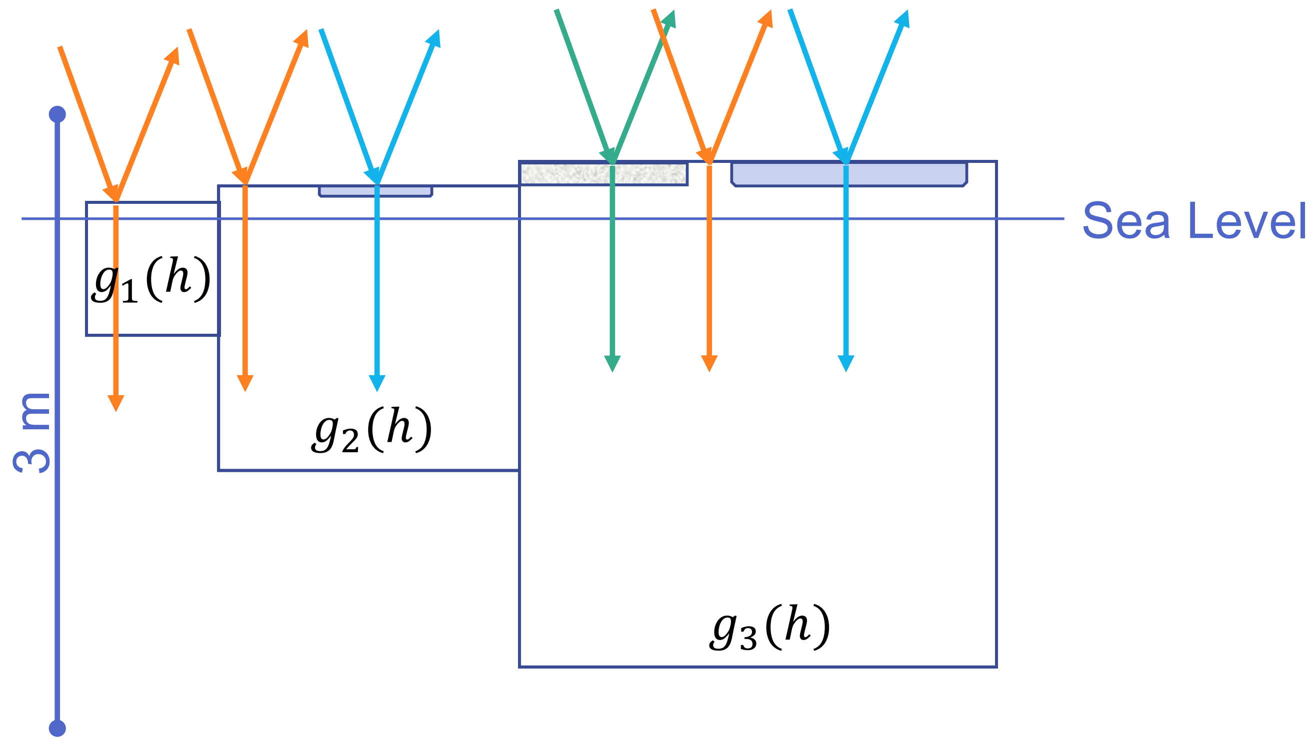
Radiation: Shortwave: Spectral Coupling



Delta Eddington (DE) Radiation Scheme in CICE

Radiation: Shortwave: Surface Type

Coupling in CICE



Radiation Calculations are performed separately for bare ice, snow and melt ponds for each thickness category $g_i(h)$

Radiation Coupling

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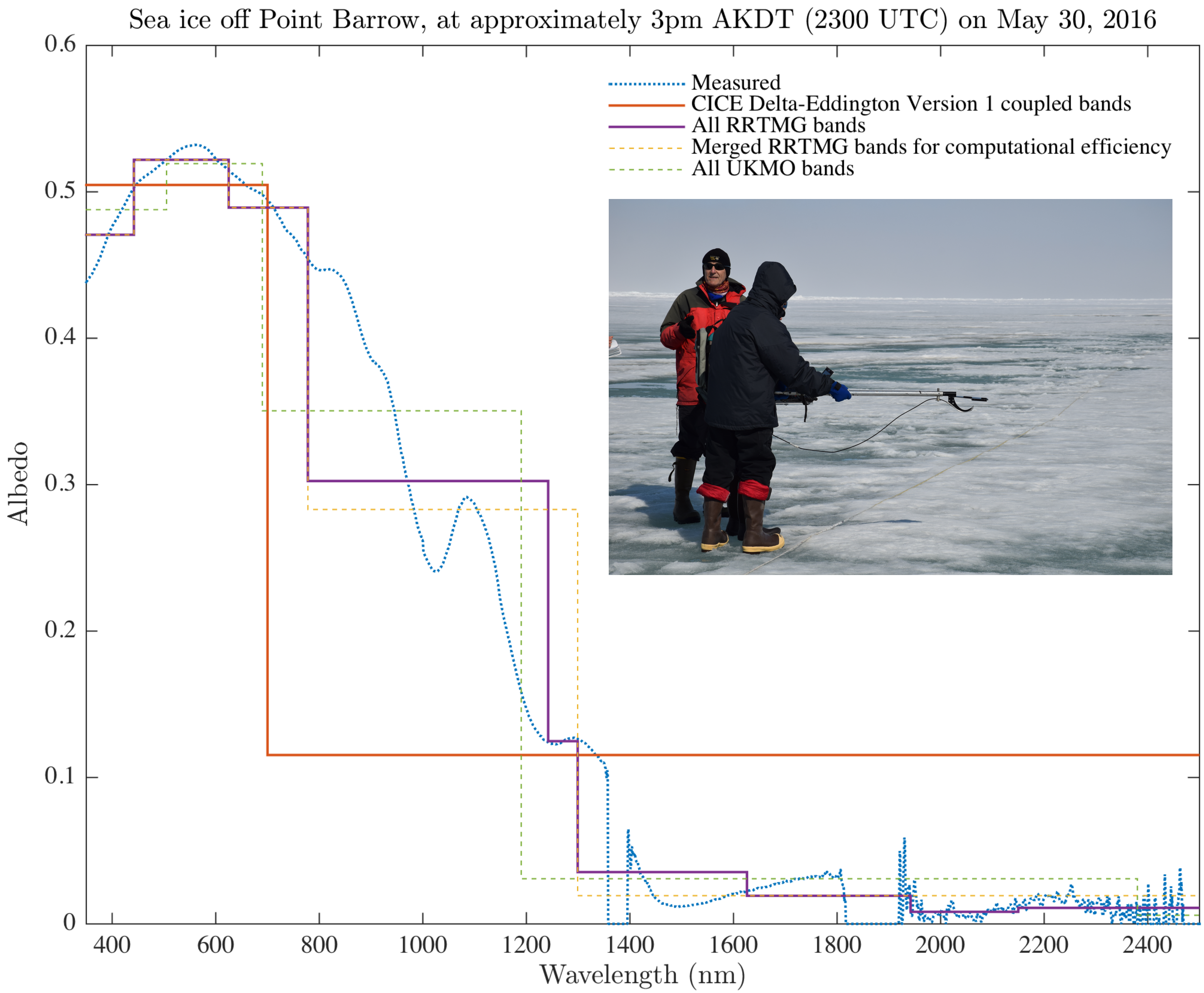
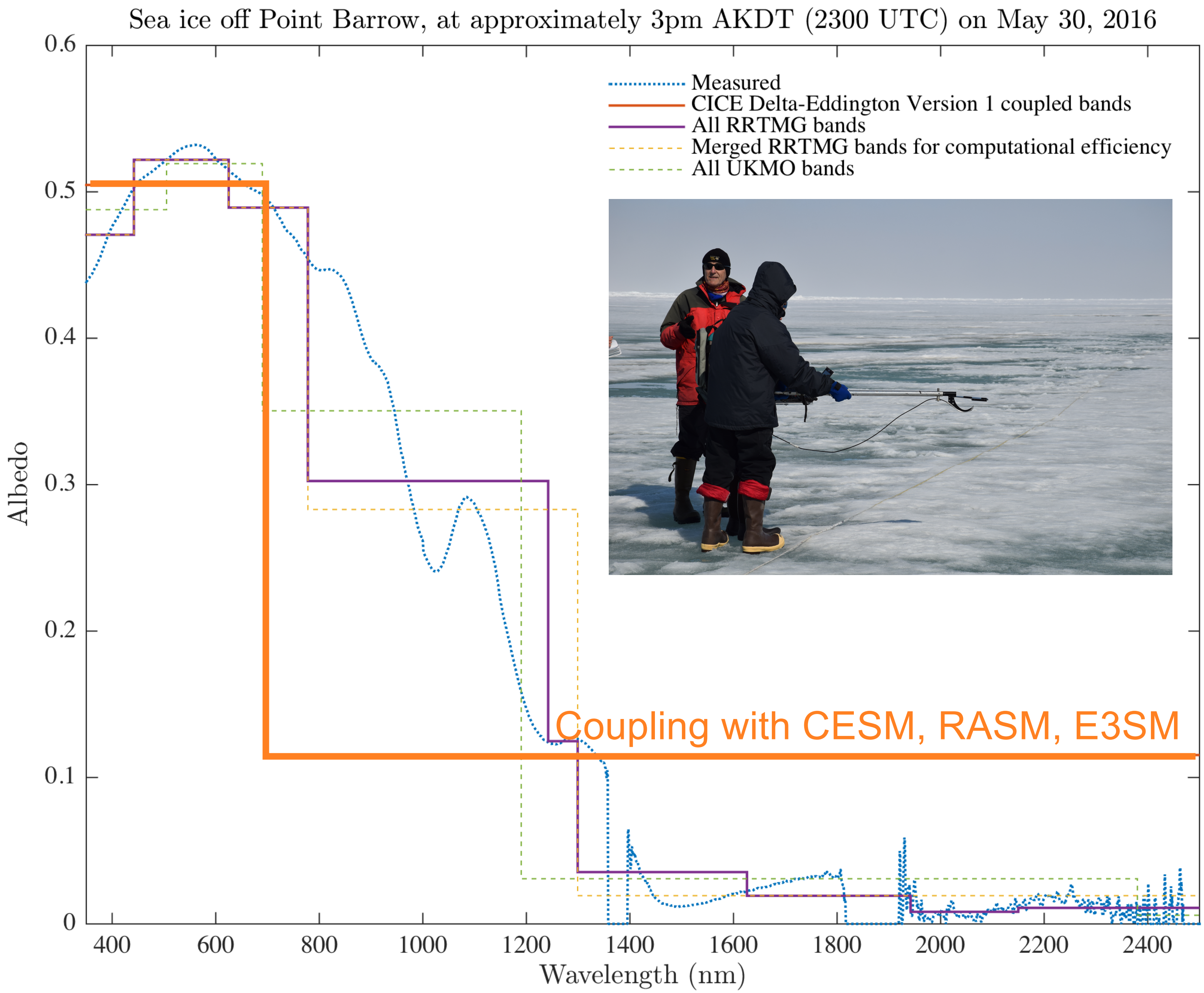
Radiation: Shortwave: Atmospheric Model

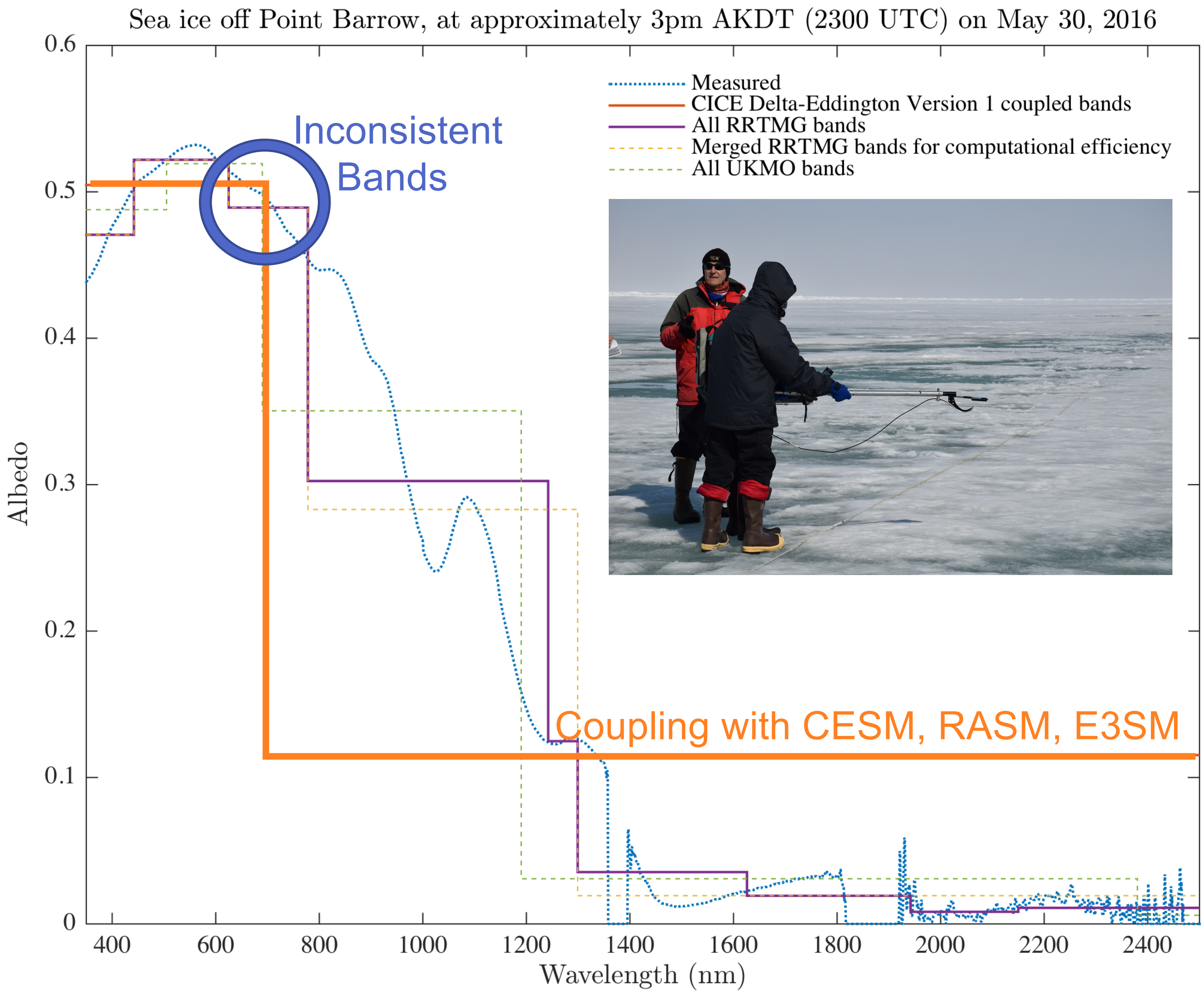


Radiation: Shortwave: Atmospheric Model



Coupling with CESM, RASM, E3SM

Radiation: Shortwave: Atmospheric Model



Sea ice off Point Barrow, at approximately 3pm AKDT (2300 UTC) on May 30, 2016

Inconsistent Bands

Coupling with CESM, RASM, E3SM

Radiation Coupling

Transfer	Coupling	Important Considerations
➡ Radiation	Shortwave	Bare Ice, Snow, Melt Ponds, Aerosols
		Atmospheric Shortwave Radiation Scheme
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T	Depth-Varying Temperature in Sea Ice
z	Vertical Coordinate in a sea ice column

Spectral coupling is being implemented in some models

CICE Consortium

Heat and Momentum Coupling

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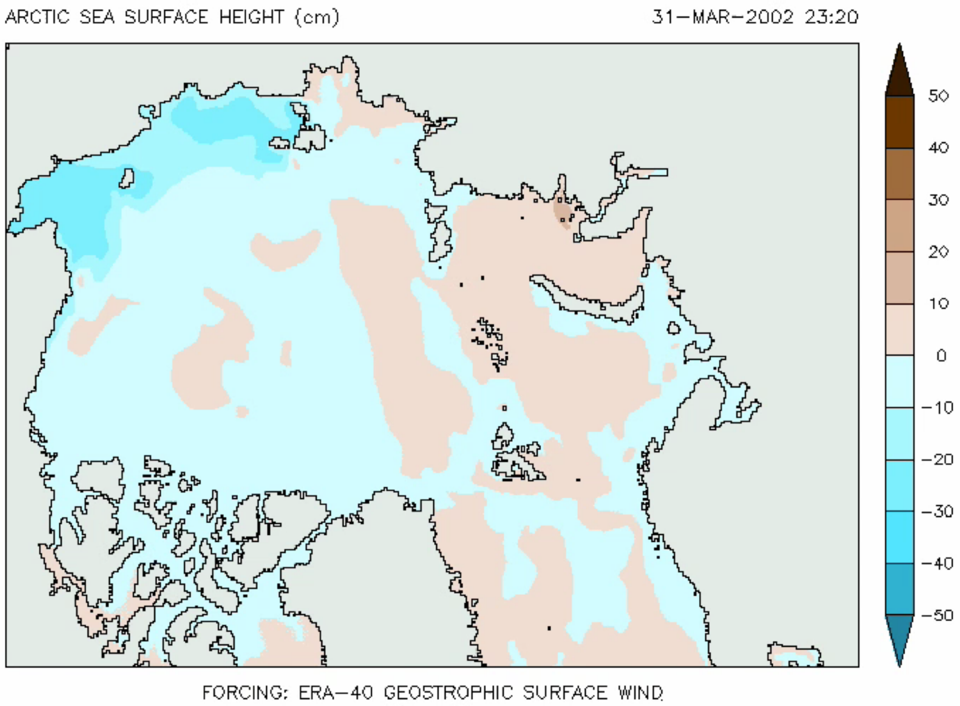
Momentum Coupling: Relationship to Geostrophy

$$m\frac{\partial \widetilde{u}}{\partial t} = \widetilde{\tau}_w + \widetilde{\tau}_a - mf\mathbf{k} \times \widetilde{u} - m\mathrm{g}\nabla\eta - m\left(\widetilde{u}\cdot\nabla\right)\widetilde{u} + \frac{\partial \sigma_{mn}}{\partial x_n}$$

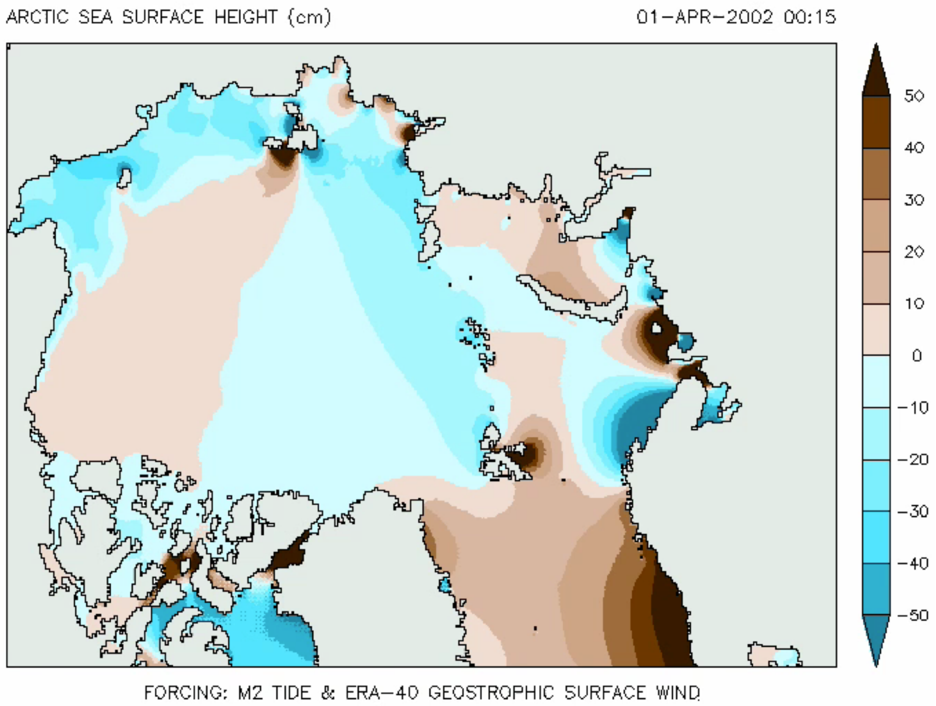
Notation			
constant			
k	unit normal vector upward from the sea surface		
g	acceleration due to gravity	9.80	ms^{-2}
variables			
t	time		
m	ice mass per unit area including freeboard snow		
$\widetilde{u} = (u, v)$	horizontal ice velocity		
$\widetilde{\tau}_w$	surface stress at the ocean-ice interface		
$\widetilde{\tau}_a$	surface stress at the ice-atmosphere interface		
f	Coriolis parameter		
η	sea surface height		
σ_{mn}	internal two dimensional stress tensor	$m, n = 1, 2$	
x_n	two dimensional axes for internal stress		

Momentum Coupling: Relationship to Geostrophy

$$m\frac{\partial \tilde{u}}{\partial t} = \tilde{\tau}_w + \tilde{\tau}_a - mf\mathbf{k} \times \tilde{u} - \boxed{mg\nabla\eta} - m\left(\tilde{u} \cdot \nabla\right)\tilde{u} + \frac{\partial \sigma_{mn}}{\partial x_n}$$



Standard Geostrophic Signal in the Ocean

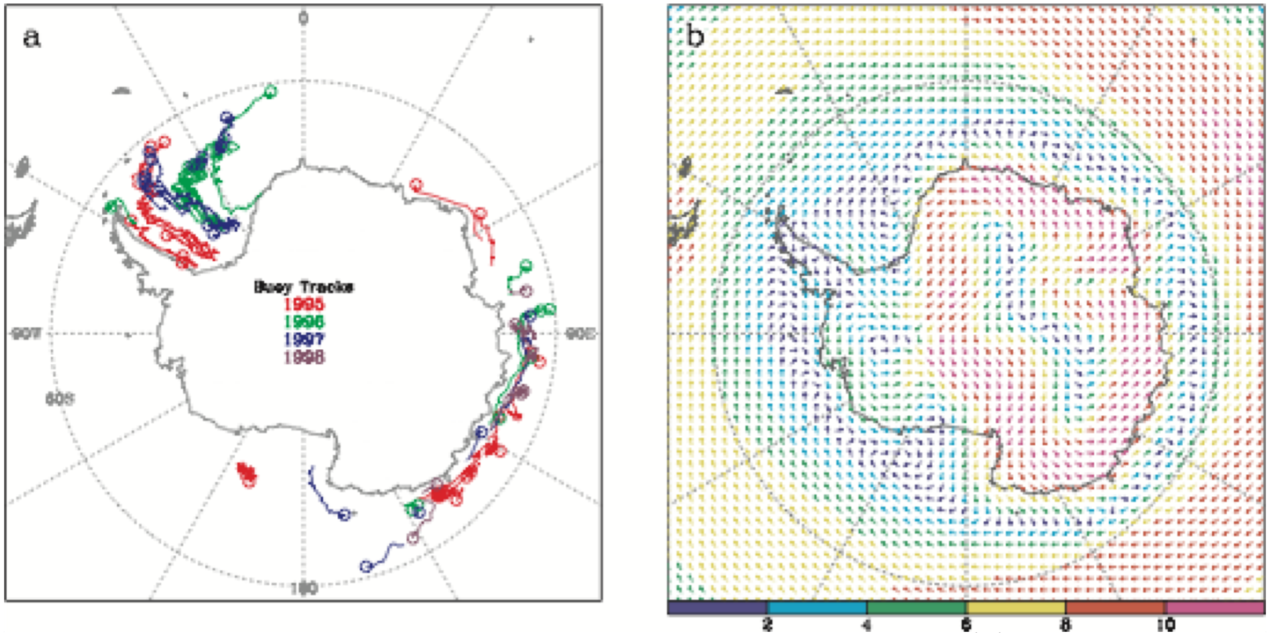


With Tides Added

Barotropic Sea Ice Model: Hibler et al 2006

Momentum Coupling: Relationship to Geostrophy

Nansen [1902] found Arctic ice drifted at approximately 2% of and 30° to the right of the surface wind.



Considerable areas of Antarctic sea ice are close to free drift: (a) Antarctic buoy tracks in ice with concentration exceeding 30% at the start and end of each trace. Circles indicate final position. (b) NCEPR2 10m wind velocity ($\mathrm{m\,s^{-1}}$) averaged from 6hourly fields over the buoy deployment years 1995 through 1998 represented in (a).

Nansen, F., 1902: *The oceanography of the north polar basin.* Vol. 3, 427 pp..

Momentum Coupling: Relationship to Geostrophy

$$m\frac{\partial \widetilde{u}}{\partial t} = \widetilde{\tau}_w + \widetilde{\tau}_a - mf\mathbf{k}\times\widetilde{u} - mg\nabla\eta - m\left(\widetilde{u}\cdot\nabla\right)\widetilde{u} + \frac{\partial\sigma_{mn}}{\partial x_n}$$

$$\widetilde{\tau}_a = \rho_a C_{D_{10}}\,|\widetilde{u}_{10}|\widetilde{u}_{10}$$

$$\widetilde{\tau}_w = \rho_w C_{W_g}\,|\widetilde{u}_{w_g} - \widetilde{u}|\;\left[\left(\widetilde{u}_{w_g} - \widetilde{u}\right)\cos\varphi + \mathbf{k}\times\left(\widetilde{u}_{w_g} - \widetilde{u}\right)\sin\varphi\right]$$

Notation

constants		estimate	
ρ_a	air density	1.2	kg m^{-3}
ρ_w	sea water density	1025	kg m^{-3}
φ	Ekman turning angle	-25	degrees
$C_{DN_{10}}$	neutral 10m wind drag coefficient	0.00175	
C_{W_g}	geostrophic current drag coefficient	0.0034	
variables			
$\widetilde{u}_{10}$	wind velocity 10m above the surface		
$C_{D_{10}}$	stability dependent 10m wind drag coefficient		
$\widetilde{u}_{w_g}$	geostrophic ocean current		

Brunke, M. A., M. Zhou, X. Zeng, and E. L. Andreas, 2006: An intercomparison of bulk aerodynamic algorithms used over sea ice with data from the Surface Heat Budget for the Arctic Ocean (SHEBA) experiment. *J. Geophys. Res.*, **111,** C09001, doi:10.1029/2005JC002907.

Momentum Coupling: Relationship to Geostrophy

$$m\frac{\partial \widetilde{u}}{\partial t} = \widetilde{\tau}_w + \widetilde{\tau}_a - mf\mathbf{k}\times\widetilde{u} - mg\nabla\eta - m\left(\widetilde{u}\cdot\nabla\right)\widetilde{u} + \frac{\partial\sigma_{mn}}{\partial x_n}$$

$$\widetilde{\tau}_a = \rho_a C_{D_{10}}\left|\widetilde{u}_{10}\right|\widetilde{u}_{10}$$

$$\widetilde{\tau}_w = \rho_w C_{W_g}\left|\widetilde{u}_{w_g} - \widetilde{u}\right|\left[\left(\widetilde{u}_{w_g} - \widetilde{u}\right)\cos\varphi + \mathbf{k}\times\left(\widetilde{u}_{w_g} - \widetilde{u}\right)\sin\varphi\right]$$

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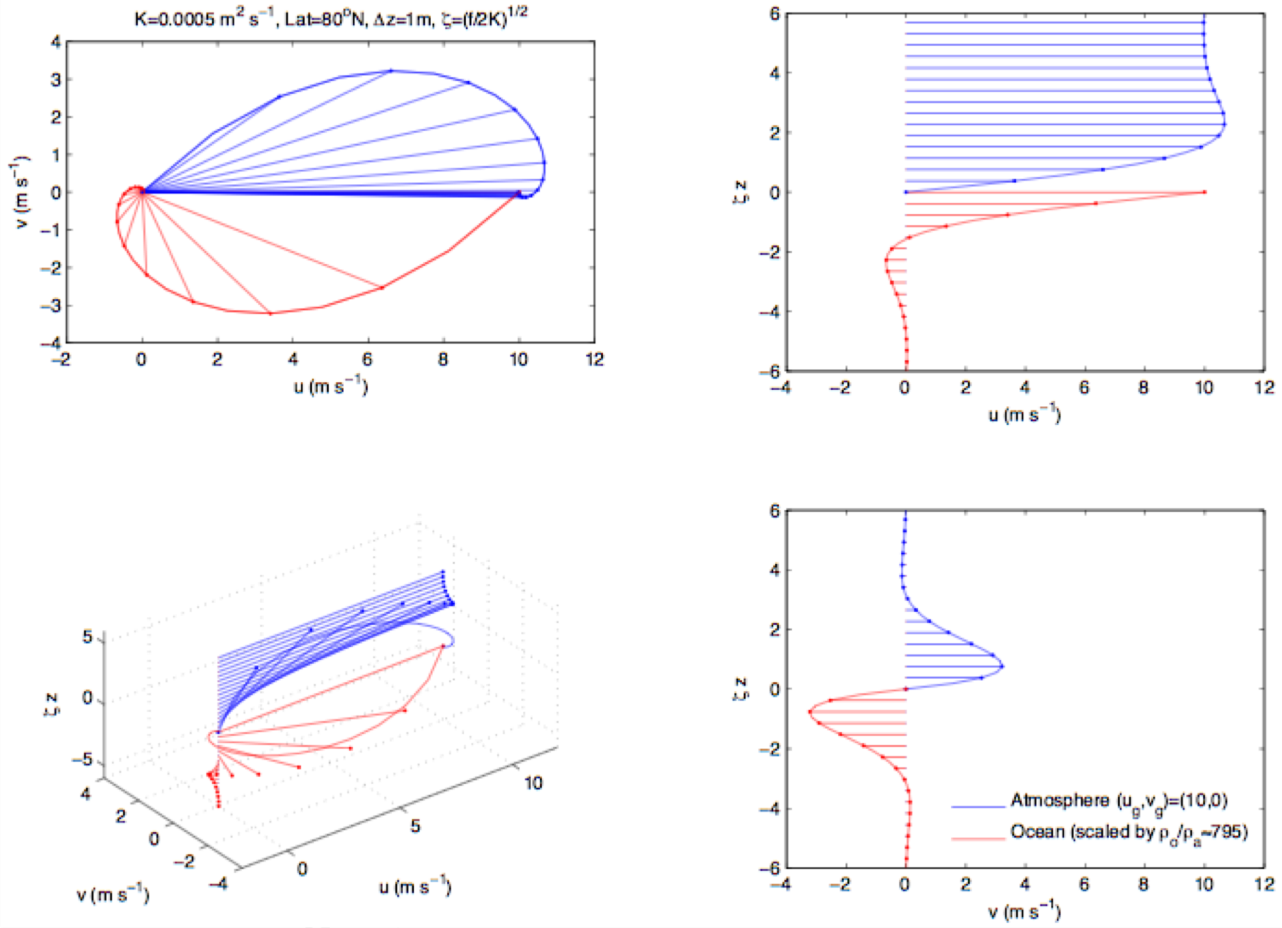
variables	
$\widetilde{u}_{10}$	wind velocity 10m above the surface
$C_{D_{10}}$	stability dependent 10m wind drag coefficient
$\widetilde{u}_{w_g}$	geostrophic ocean current

Why does the ice-ocean stress have a turning angle here, but not the ice-atmosphere stress?

Momentum Coupling: Relationship to Geostrophy



Notation

K	vertical eddy viscosity
ζz	dimensionless Ekman layer depth

ocean magnitudes scaled to atmospheric values
atmospheric heights scaled to oceanic values

Mellor, G. L., 1996: *Introduction to Physical Oceanography.* American Institutde of Physics Press, 260 pp.

Momentum Coupling: Relationship to Geostrophy

$$m\frac{\partial \widetilde{u}}{\partial t} = \widetilde{\tau}_w + \widetilde{\tau}_a - mf\mathbf{k}\times\widetilde{u} - mg\nabla\eta - m\left(\widetilde{u}\cdot\nabla\right)\widetilde{u} + \frac{\partial\sigma_{mn}}{\partial x_n}$$

$$\widetilde{\tau}_a = \rho_a C_{D_{10}}\left|\widetilde{u}_{10}\right|\widetilde{u}_{10}$$

$$\widetilde{\tau}_w = \rho_w C_{W_g}\left|\widetilde{u}_{w_g}-\widetilde{u}\right|\left[\left(\widetilde{u}_{w_g}-\widetilde{u}\right)\cos\varphi + \mathbf{k}\times\left(\widetilde{u}_{w_g}-\widetilde{u}\right)\sin\varphi\right]$$

Notation

constants		estimate	
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variables	
$\widetilde{u}_{10}$	wind velocity 10m above the surface
$C_{D_{10}}$	stability dependent 10m wind drag coefficient
$\widetilde{u}_{w_g}$	geostrophic ocean current

Why is the wind-ice speed difference not included above?

Does it matter?

Momentum Coupling: Relationship to Geostrophy

Let’s answer the previous question by asking another one.

$$\frac{\partial \tilde{M}}{\partial t} = \frac{\widetilde{\tau}_a}{\rho_{iw}} - f\mathbf{k} \times \tilde{M}$$

Notation	
$\widetilde{M} = (M_x, M_y)$	ice-ocean mass transport relative to the geostrophic current
ρ_{iw}	density of the ice-water boundary layer

What does this equation represent?

Momentum Coupling: Relationship to Geostrophy

$$\boxed{m\frac{\partial \tilde{u}}{\partial t} = \tilde{\tau}_w + \tilde{\tau}_a - mf\mathbf{k}\times\tilde{u}} - mg\nabla\eta - m\left(\tilde{u}\cdot\nabla\right)\tilde{u} + \frac{\partial\sigma_{mn}}{\partial x_n}$$

This is the mass-transport version of the free drift equation

$$\frac{\partial\tilde{M}}{\partial t} = \frac{\tilde{\tau}_a}{\rho_{iw}} - f\mathbf{k}\times\tilde{M}$$

Notation

$\widetilde{M} = (M_x, M_y)$	ice-ocean mass transport relative to the geostrophic current
ρ_{iw}	density of the ice-water boundary layer

Heil, P., and W. D. Hibler, III, 2002: Modeling the high-frequency component of Arctic sea ice drift and deformation. *J. Phys. Oceanogr.*, **32,** 11, 3039-3057.

Momentum Coupling: Relationship to Geostrophy

$$\boxed{m\frac{\partial \tilde{u}}{\partial t} = \tilde{\tau}_w + \tilde{\tau}_a - mf\mathbf{k}\times\tilde{u}} - mg\nabla\eta - m\left(\tilde{u}\cdot\nabla\right)\tilde{u} + \frac{\partial \sigma_{mn}}{\partial x_n}$$

A consequence of this is that $\nabla\times\tilde{\tau}_w$ should be conserved

$$\frac{\partial \tilde{M}}{\partial t} = \frac{\tilde{\tau}_a}{\rho_{iw}} - f\mathbf{k}\times\tilde{M}$$

Few models conserve $\nabla\times\tilde{\tau}_w$ in coupling

Notation

$\widetilde{M} = (M_x, M_y)$	ice-ocean mass transport relative to the geostrophic current
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Momentum Coupling: Relationship to Geostrophy

$$\frac{\partial \tilde{M}}{\partial t} = \frac{\widetilde{\tau}_a}{\rho_{iw}} - f\mathbf{k} \times \tilde{M}$$

Can be solved as: $$\frac{\partial^2 M_y}{\partial t^2} + f^2 M_y = -f\frac{\tau_x}{\rho_{iw}},\ \tau_y = 0$$

- Forced harmonic oscillator
- Oscillates with a period of 11.96 hours at the pole
- Linear Time Invariant (LTI) system

Notation

$\widetilde{M} = (M_x, M_y)$	ice-ocean mass transport relative to the geostrophic current
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Heat and Momentum Coupling

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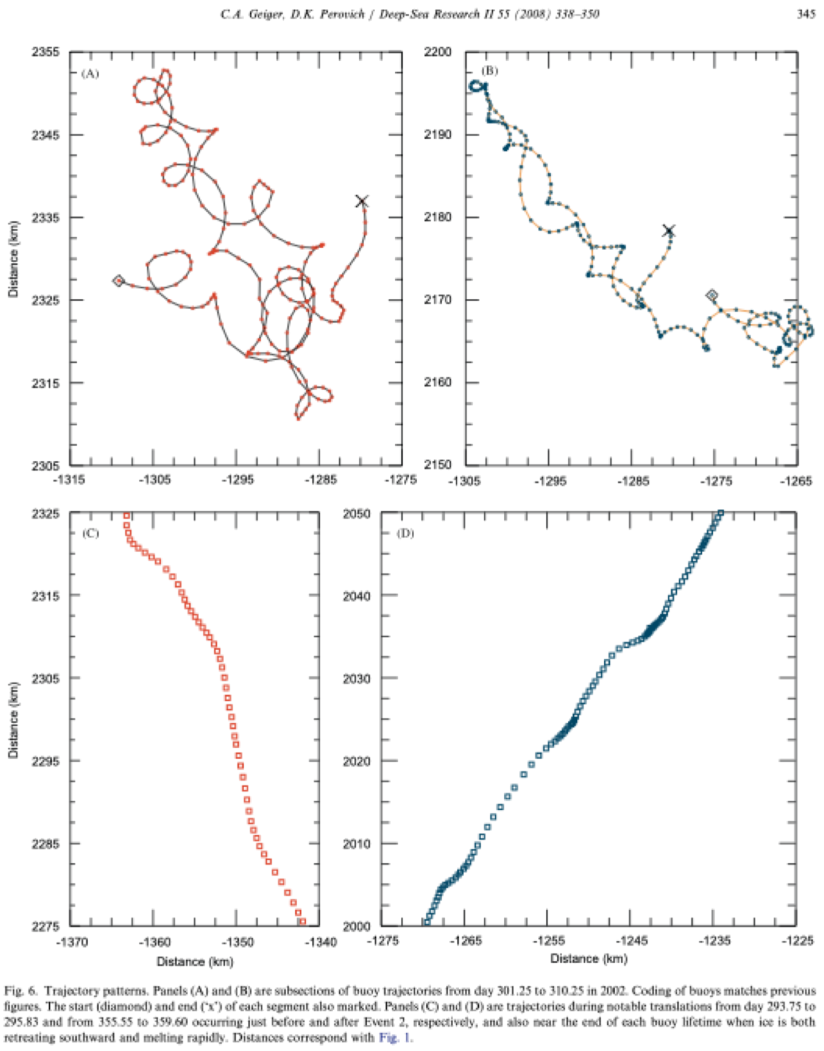
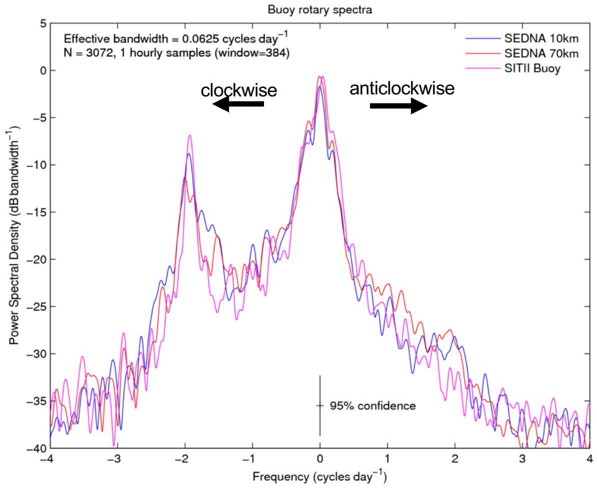
Momentum Coupling: Inertial Oscillations

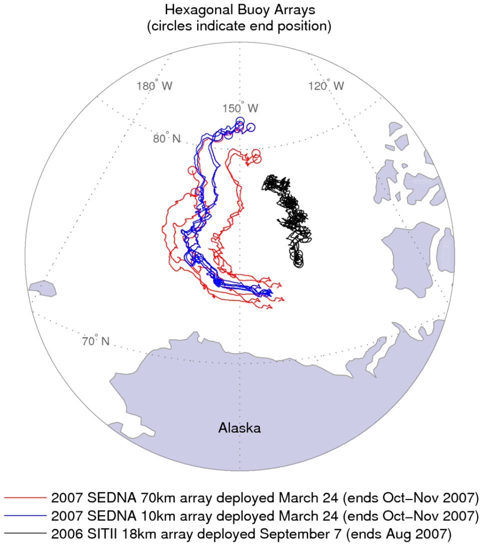


C.A. Geiger, D.K. Perovich / Deep-Sea Research II 55 (2008) 338–350 345

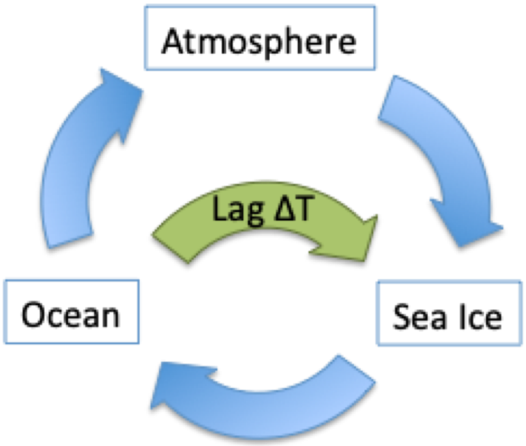
Fig. 6. Trajectory patterns. Panels (A) and (B) are subsections of buoy trajectories from day 301.25 to 310.25 in 2002. Coding of buoys matches previous figures. The start (diamond) and end ('x') of each segment also marked. Panels (C) and (D) are trajectories during notable translations from day 293.75 to 295.83 and from 355.55 to 359.60 occurring just before and after Event 2, respectively, and also near the end of each buoy lifetime when ice is both retreating southward and melting rapidly. Distances correspond with Fig. 1.

Geiger, C. A., and D. K. Perovich, 2008: Springtime Ice Motion in the Western Antarctic Peninsula Region (U.S. GLOBEC contribution number 515). *Deep-Sea Research II*, **55,** 3-4, 338-350.

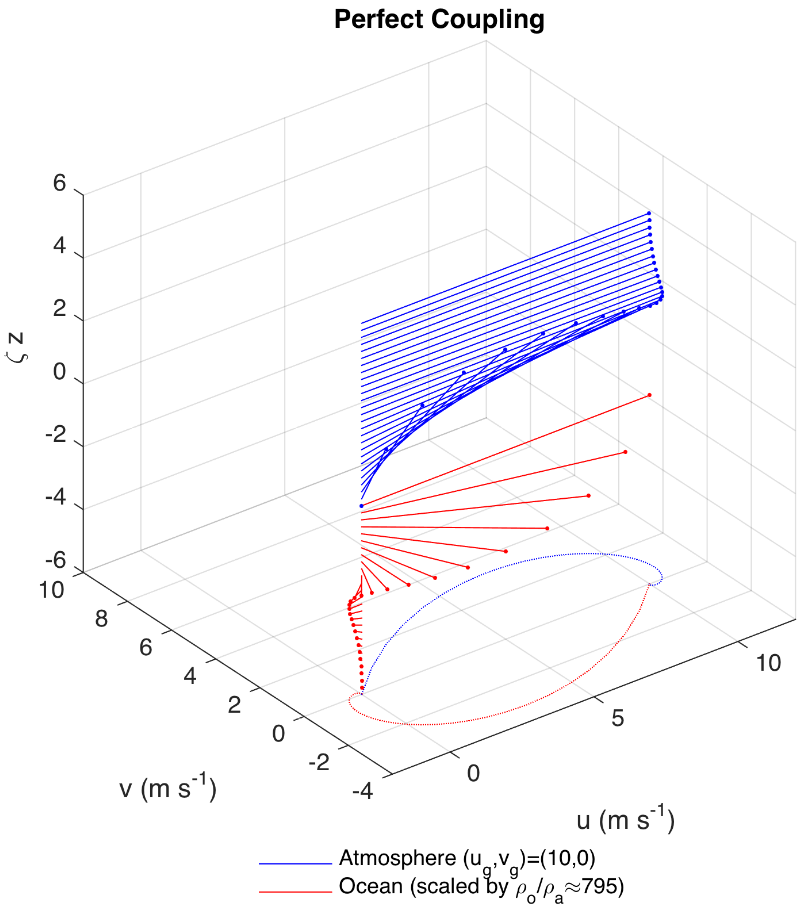




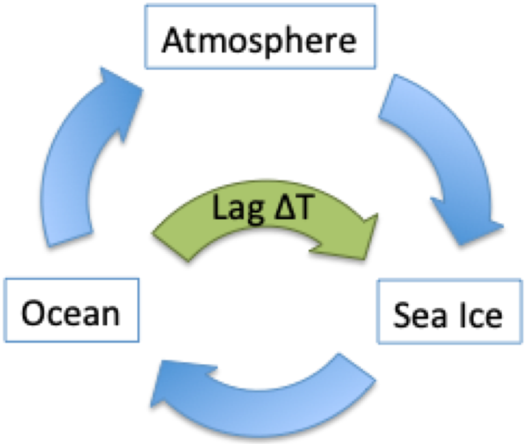
Momentum Coupling: Inertial Oscillations



Lags Inherent in a ring of coupled oscillators with coupling step of ΔT=0



Momentum Coupling: Inertial Oscillations



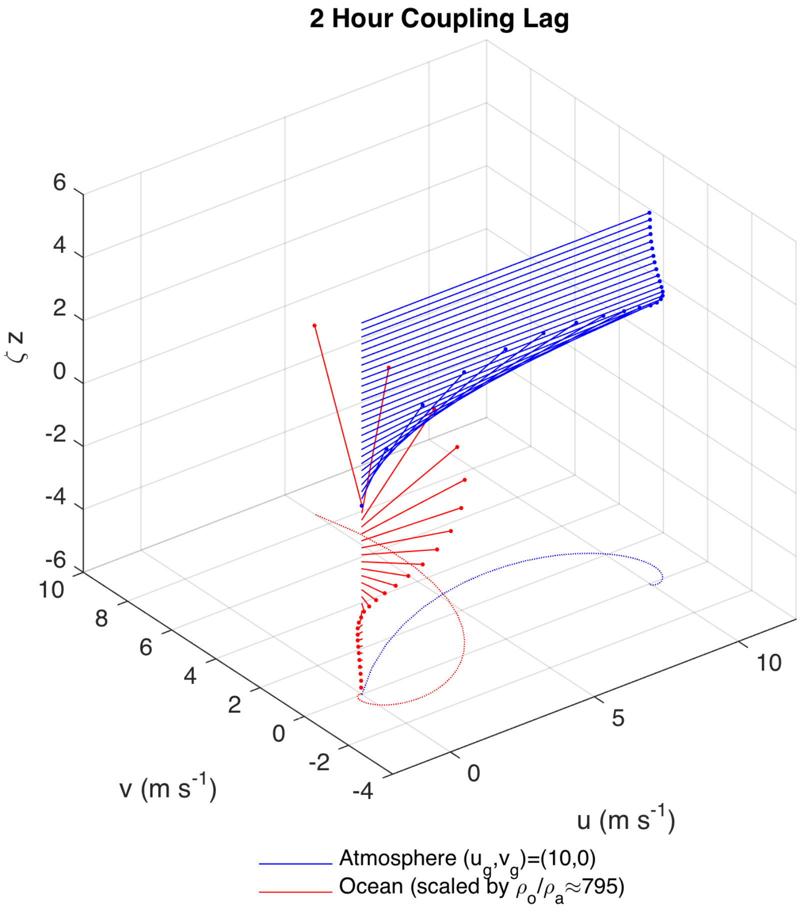
Atmosphere

Lag ΔT

Ocean

Sea Ice

Lags Inherent in a ring of coupled oscillators with coupling step of ΔT>0

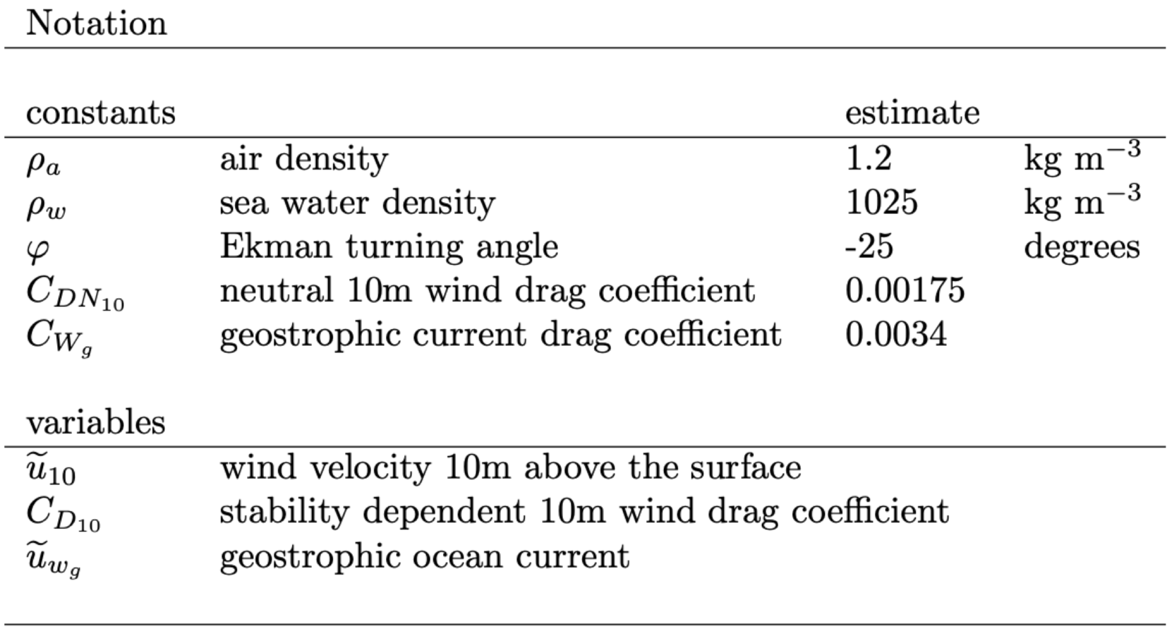


Momentum Coupling: Inertial Oscillations

$$m\frac{\partial \widetilde{u}}{\partial t} = \widetilde{\tau}_w + \widetilde{\tau}_a - mf\mathbf{k}\times\widetilde{u} - mg\nabla\eta - m\left(\widetilde{u}\cdot\nabla\right)\widetilde{u} + \frac{\partial \sigma_{mn}}{\partial x_n}$$

$$\widetilde{\tau}_a = \rho_a C_{D_{10}}\left|\widetilde{u}_{10}\right|\widetilde{u}_{10}$$

$$\widetilde{\tau}_w = \rho_w C_{W_g}\left|\widetilde{u}_{w_g} - \widetilde{u}\right|\,\left[\left(\widetilde{u}_{w_g} - \widetilde{u}\right)\cos\varphi + \mathbf{k}\times\left(\widetilde{u}_{w_g} - \widetilde{u}\right)\sin\varphi\right]$$



Notation

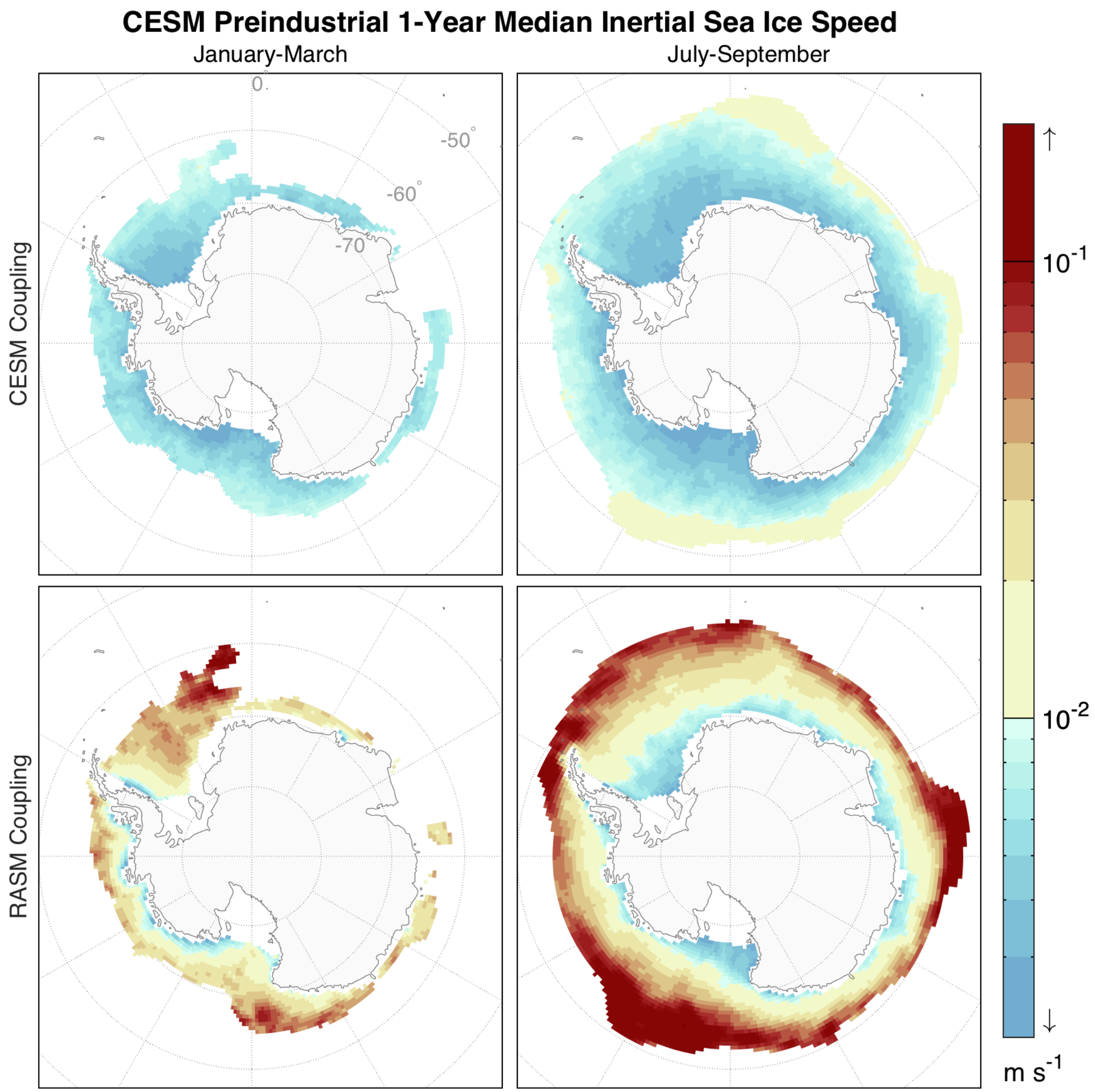
constants		estimate	
ρ_a	air density	1.2	kg m^{-3}
ρ_w	sea water density	1025	kg m^{-3}
φ	Ekman turning angle	-25	degrees
$C_{DN_{10}}$	neutral 10m wind drag coefficient	0.00175	
C_{W_g}	geostrophic current drag coefficient	0.0034	

variables	
$\widetilde{u}_{10}$	wind velocity 10m above the surface
$C_{D_{10}}$	stability dependent 10m wind drag coefficient
$\widetilde{u}_{w_g}$	geostrophic ocean current

Why is the wind-ice speed difference not included above?

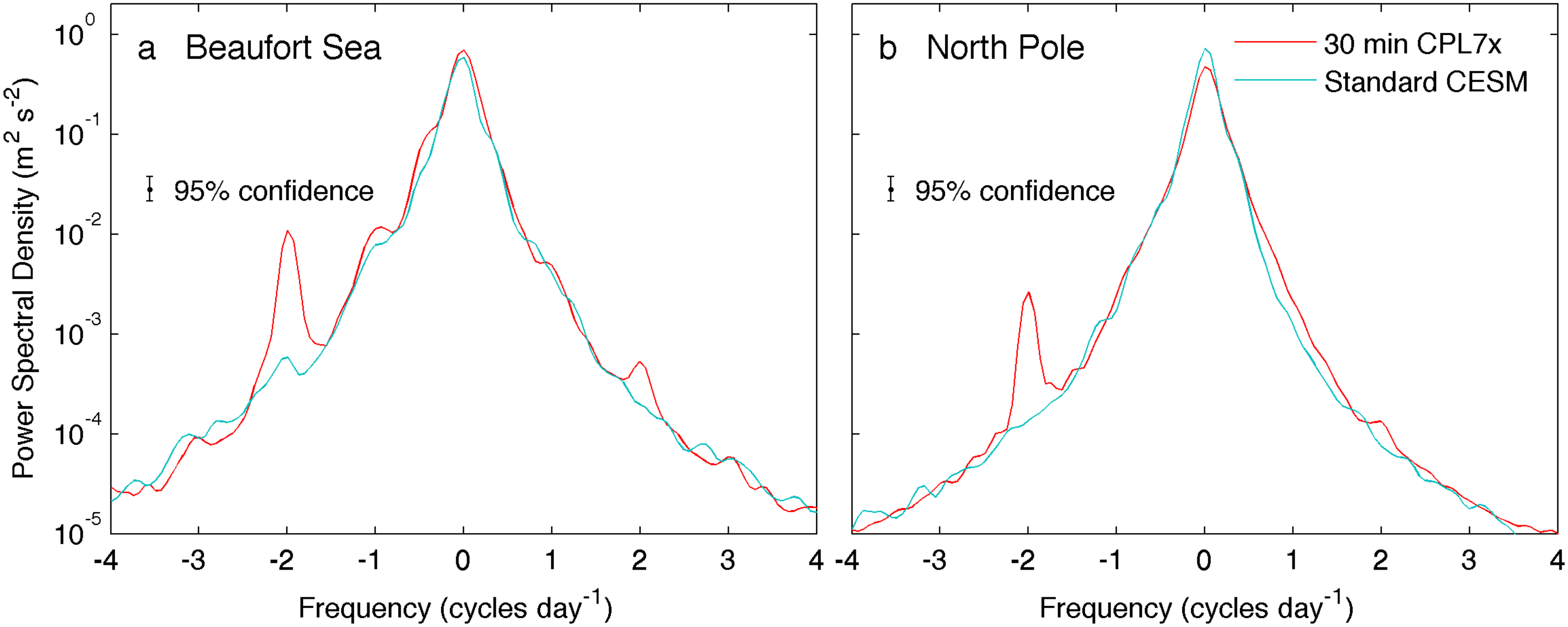
Does it matter? YES

Momentum Coupling: Inertial Oscillations



Roberts et al. 2015

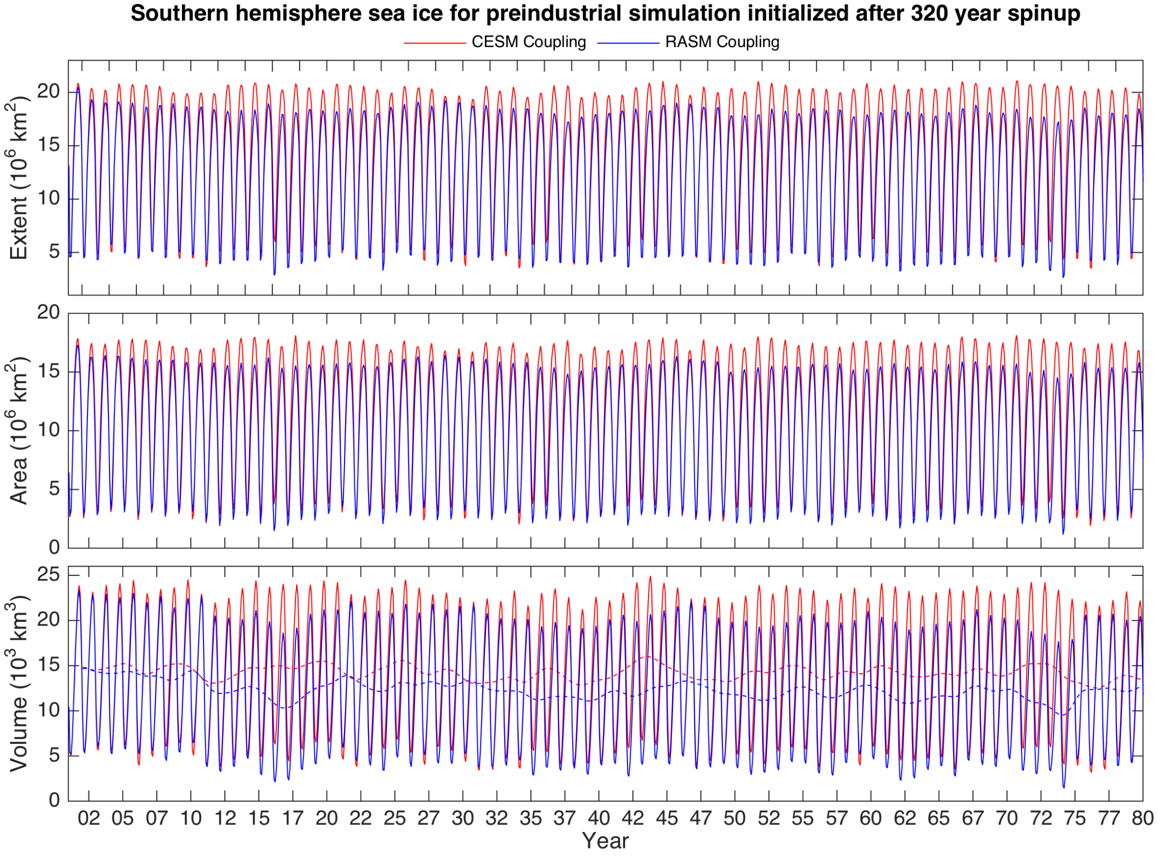
Momentum Coupling: Inertial Oscillations



Result from more frequent ice-ocean coupling in CESM:
30 minutes instead of 1 day

Does it matter?

Momentum Coupling: Inertial Oscillations



Daily oceanic coupling with CPL7 September extent years 30-80	**30 min oceanic coupling with CPL7x September extent years 30-80**	**1979-2013 September Mean**
20.38×10^6 km^2	18.19×10^6 km^2	18.83×10^6 km^2
Difference:	2.19×10^6 km^2	

Does it matter? YES

Heat and Momentum Coupling

Transfer	**Coupling**	**Important Considerations**
Radiation	Shortwave	Bare Ice, Snow, Melt Ponds, Aerosols
		Atmospheric Shortwave Radiation Scheme
	Longwave	Emissivity
		Atmospheric Longwave Radiation Scheme
Heat and Momentum	Barotropic Mode	Geostrophy
		Inertial Oscillations
	Turbulence	Length Scale vs. $g(h)$ Resolution
		Form Drag vs. Skin Drag
Mass	Sea Water	Sea Water Freezing
		Ocean Stratification
		Flooding
	Snow and Rain	Enthalpy
		Metamorphosis
	Salt and Freshwater	Sublimation and Evaporation
		Drainage and Melt

Heat and Momentum Coupling: Turbulence

$$\tilde{\tau}_a = \rho_a C_d \max\left(\mathrm{u}_{min}, \left|\tilde{u}_a - \tilde{u}_i\right|\right)\left(\tilde{u}_a - \tilde{u}_i\right)$$

$$F_s = \rho_a C_s \max\left(\mathrm{u}_{min}, \left|\tilde{u}_a - \tilde{u}_i\right|\right)\left(\theta_a - T_s\right)$$

$$F_l = \rho_a C_l \max\left(\mathrm{u}_{min}, \left|\tilde{u}_a - \tilde{u}_i\right|\right)\left(Q_a - Q_s\right)$$

where the drag coefficient C_d, and transfer coefficients C_s and C_l are dependent upon $\max(\mathrm{u}_\mathrm{crit}, |\tilde{u}_\mathrm{a} - \tilde{u}_\mathrm{i}|)$ for wind velocity $\tilde{u}_\mathrm{a}$ and air density ρ_a at a reference level 10 m above the surface. θ_a and Q_a are the corresponding potential air temperature and specific humidity, given the respective surface temperature T_s and specific humidity Q_s.

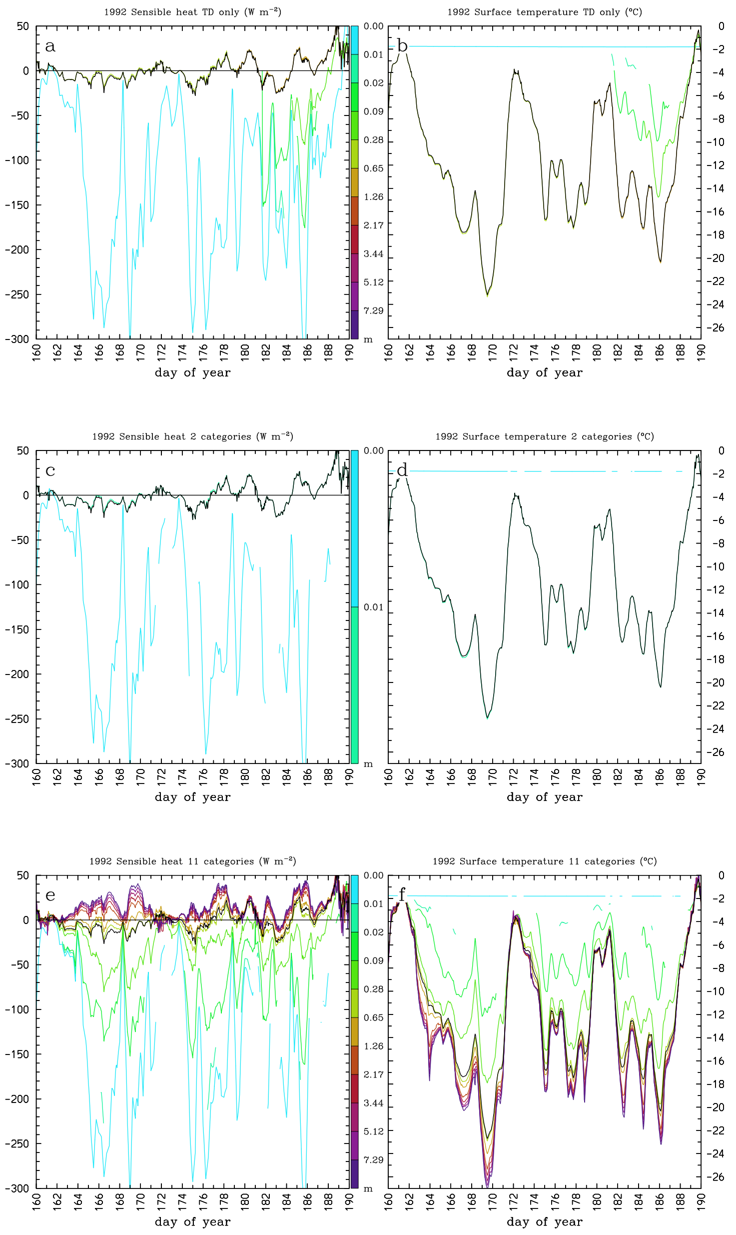
Transfer in the ocean remains a difficult problem

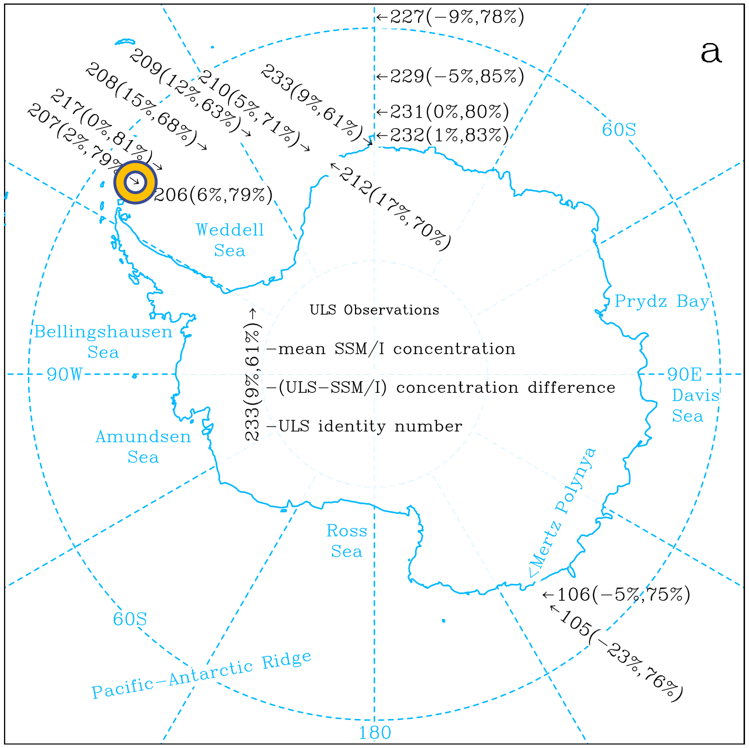
Heat and Momentum Coupling: Turbulence: L vs. $g(h)$

11 cats with thermodynamics only

2 cats with dynamics and thermodynamics

11 cats with dynamics and thermodynamics





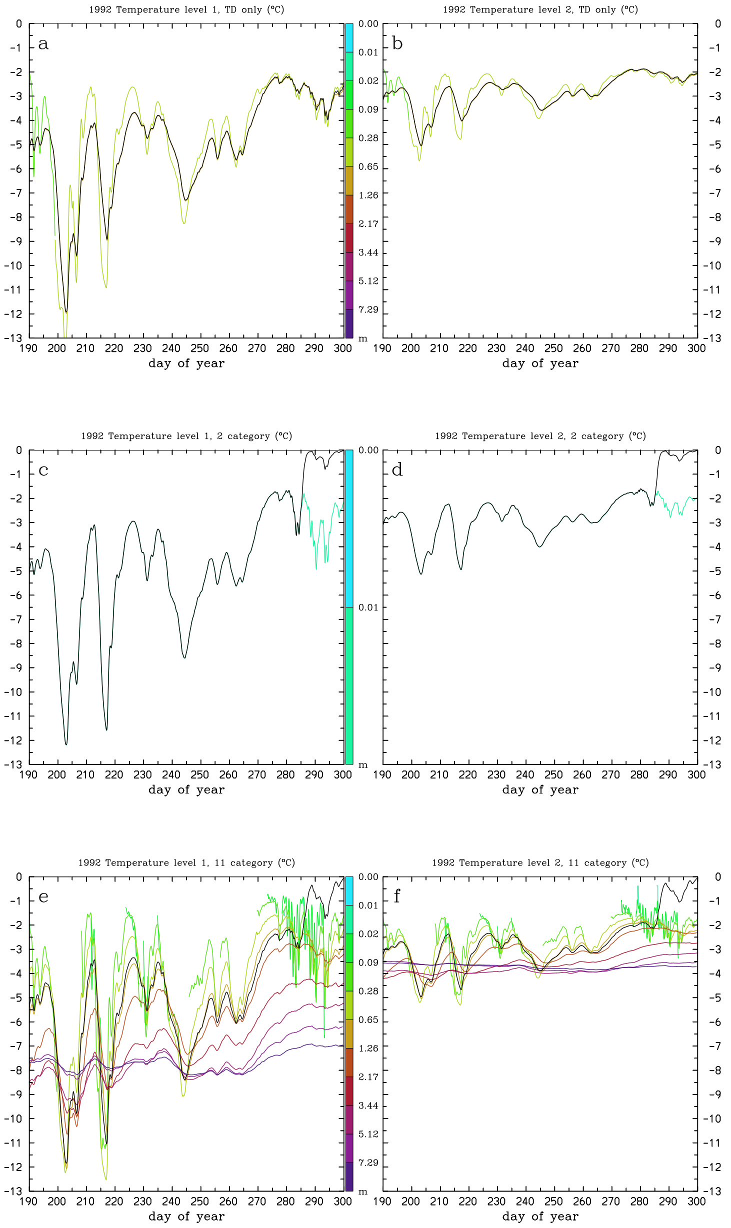
Sensible heat flux and surface temperature in the northern Weddell Sea.

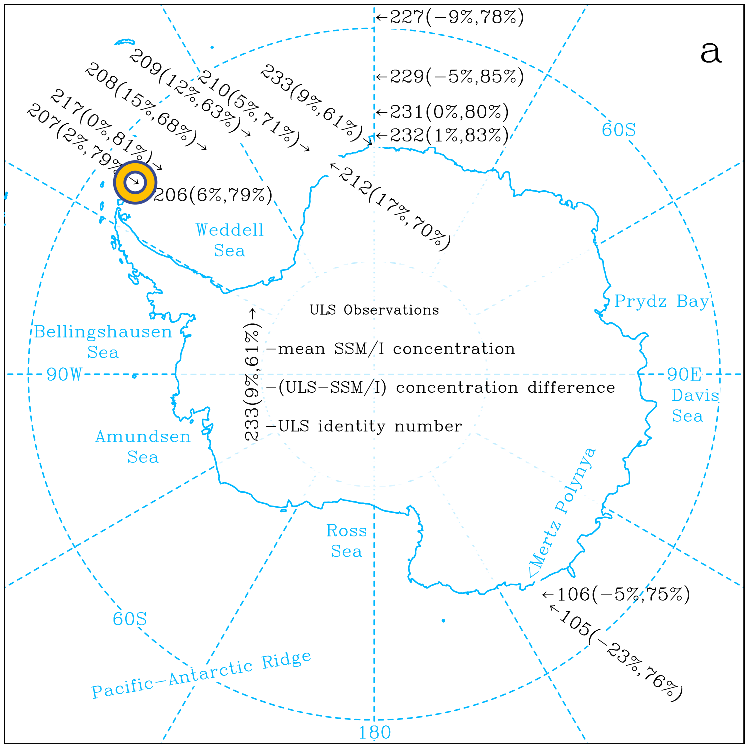
Heat and Momentum Coupling: Turbulence: L vs. $g(h)$

11 cats with thermodynamics only

2 cats with dynamics and thermodynamics

11 cats with dynamics and thermodynamics



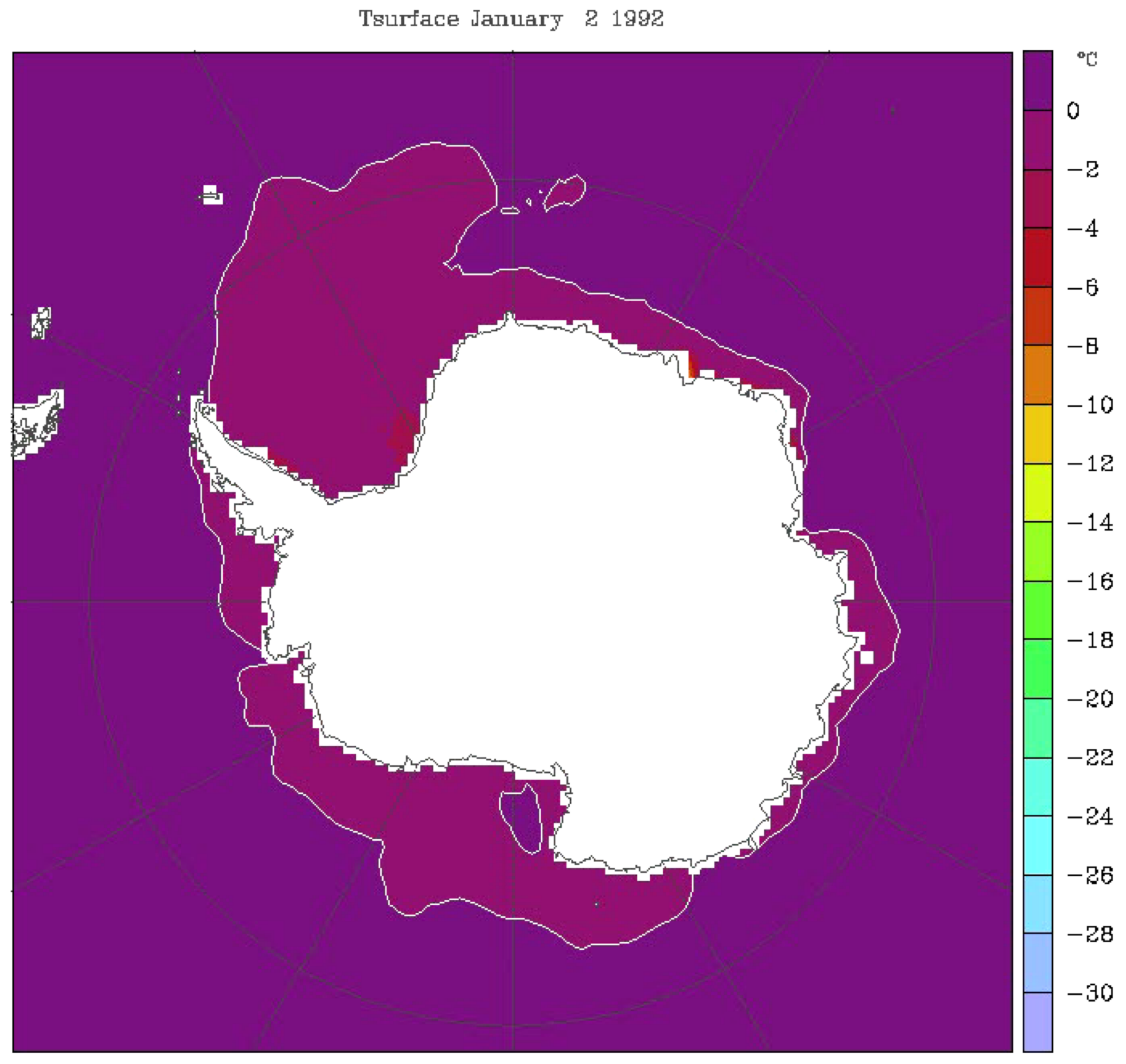


Temperature through the column using Winton (2000) thermodynamics

Heat and Momentum Coupling: Turbulence: L vs. $g(h)$

Surface temperature evolution is inherently noisy, but fluxes in thin thicknesses in g(h) serve to modulate rapid variations over thick sea ice.

Results shown here are from a sea ice forecast model for the Southern Ocean.



Heat and Momentum Coupling

Transfer	**Coupling**	**Important Considerations**
Radiation	Shortwave	Bare Ice, Snow, Melt Ponds, Aerosols
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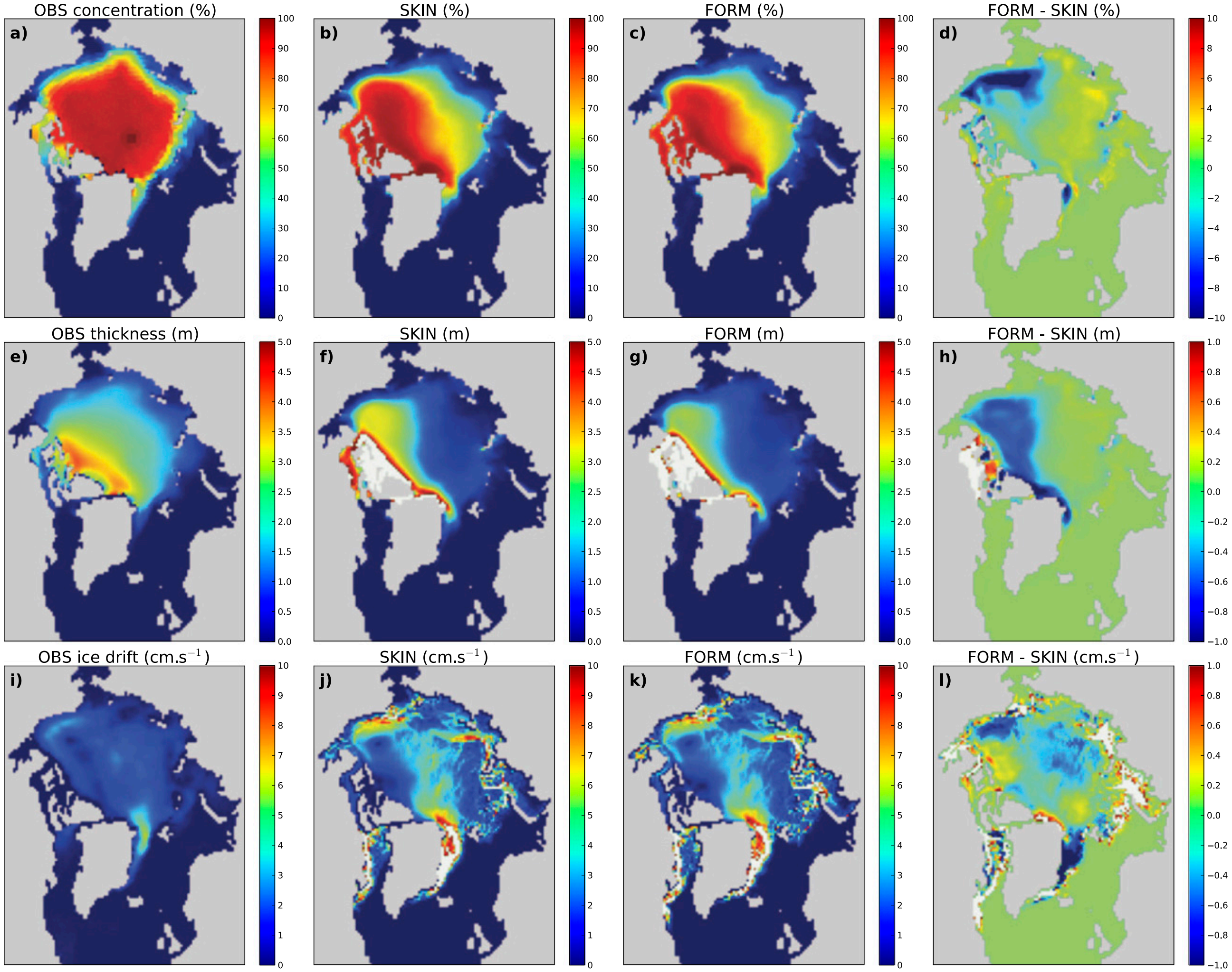
		Flooding
	Snow and Rain	Enthalpy
		Metamorphosis
	Salt and Freshwater	Sublimation and Evaporation
		Drainage and Melt

Heat and Momentum Coupling: Form Drag


OBS concentration (%)

SKIN (%)

FORM (%)

FORM - SKIN (%)

OBS thickness (m)

SKIN (m)

FORM (m)

FORM - SKIN (m)

OBS ice drift (cm.s^{-1})

SKIN (cm.s^{-1})

FORM (cm.s^{-1})

FORM - SKIN (cm.s^{-1})

FIG. 9. Climatological (1990–2012) September ice concentration from (a) HadISST measurements, (b) the SKIN run, (c) the FORM run, and (d) ice concentration difference between the FORM and SKIN runs. Same climatologies for ice thickness from (e) PIOMAS, (f) the SKIN run, (g) the FORM run, and (h) ice thickness difference between the FORM and SKIN runs. Also shown climatologies for the ice drift from (i) Pathfinder, (j) the SKIN run, (k) the FORM run, and (l) ice drift difference between the FORM and SKIN runs. Note that regions where the values exceed the range in the color bar are shown in white.

Tsamados, M., Feltham, D. L., Schroeder, D., Flocco, D., Farrell, S. L., Kurtz, N., et al. (2014). Impact of Variable Atmospheric and Oceanic Form Drag on Simulations of Arctic Sea Ice. *Journal of Physical Oceanography*, *44*, 1329–1353. https://doi.org/10.1175/JPO-D-13-0215.1

Mass Coupling

Transfer	**Coupling**	**Important Considerations**
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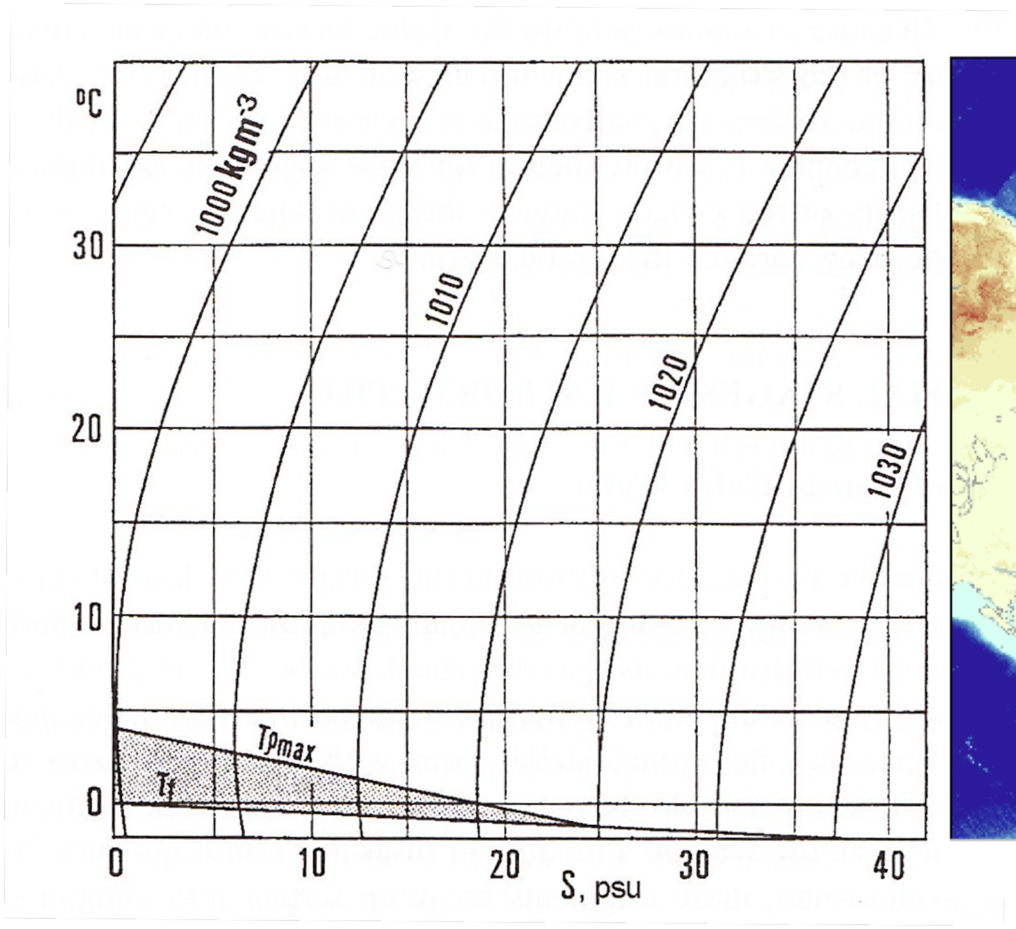
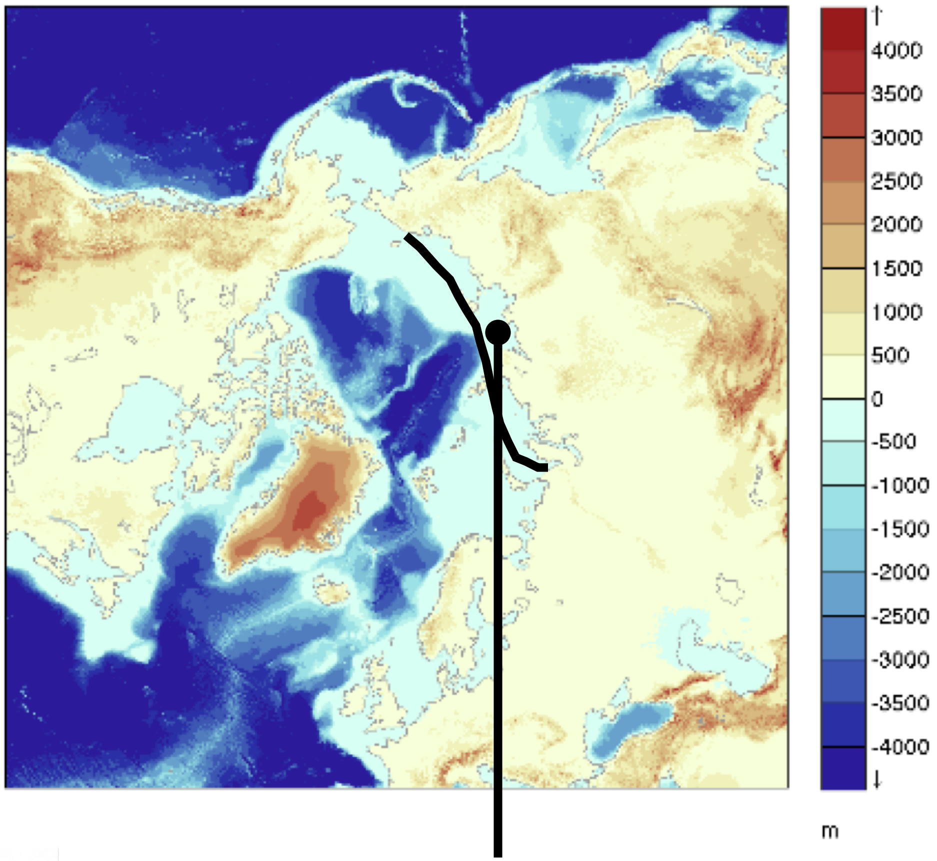
Mass Coupling: Sea Water: Freezing



Temperature of density maximum and freezing temperature of sea ice water from Ono (1965)



This area of the Arctic can have salinities below 24.7 psu due to river outflow. Hence sea ice here may have some characteristics of lake ice and will typically form early during the onset of winter relative to other areas of the Arctic.

Couple Using the Liquidus Temperature

Mass Coupling

Transfer	**Coupling**	**Important Considerations**
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➡ Mass	➡ Sea Water	Sea Water Freezing
		Ocean Stratification
		Flooding
	➡ Snow and Rain	Enthalpy
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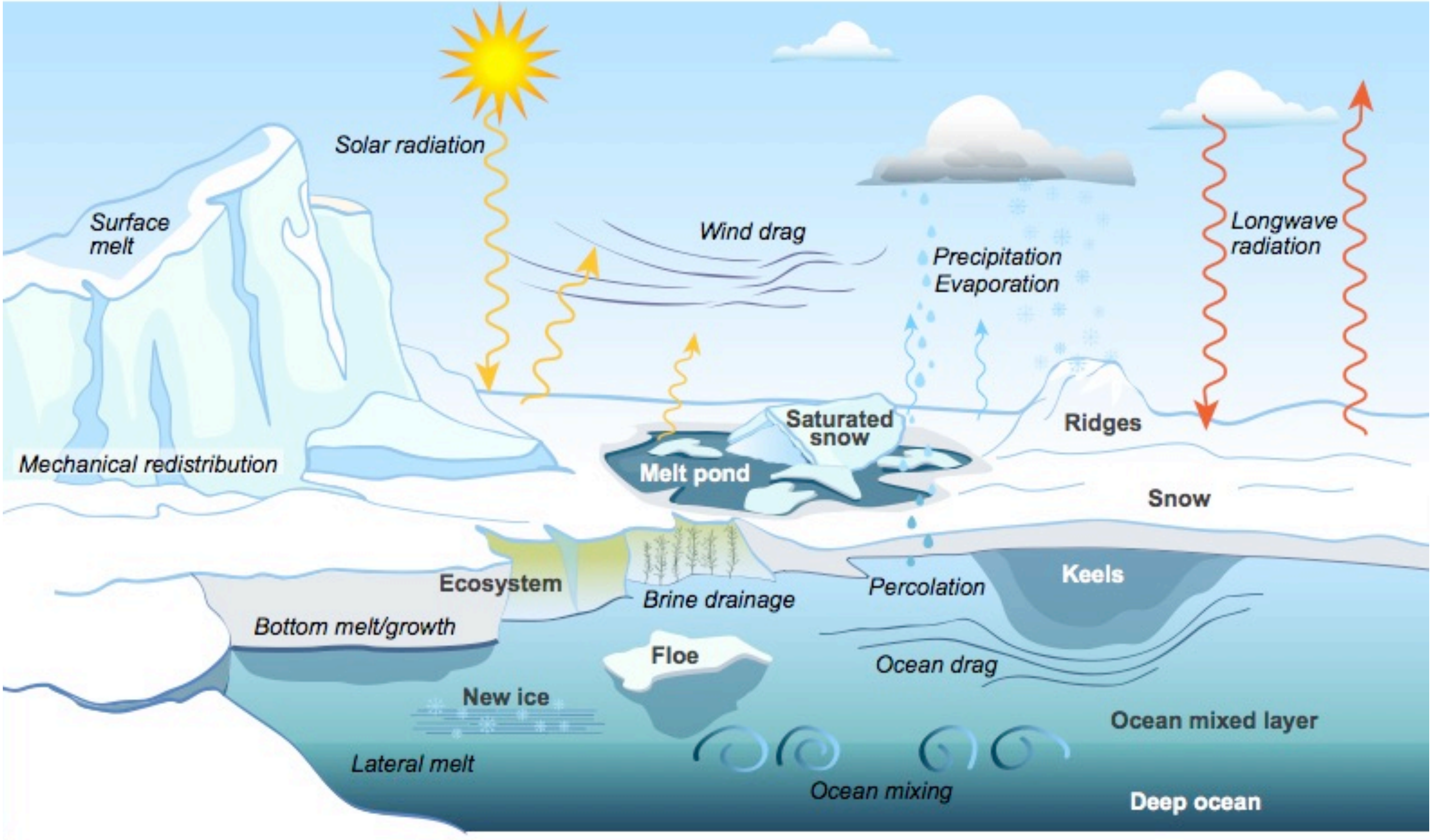
Mass Coupling



Mass Coupling

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CICE Consortium

Conclusion: Limitations of Mass Coupling

- Enthalpy-carrying precipitation and runoff
- Permafrost-sea ice coupling
- Rain and melt-pond water drainage
- Snow metamorphosis

Note that in this talk, I have not discussed wave-ice coupling or biogeochemical coupling, both areas of continued development.