

# The Length Scale of Physical Processes on the Antarctic Continental Shelves and Implications of this for Modeling Biogeochemical Cycles

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(with loads of help from: Jenny Graham, John Klinck,  
Dennis McGillicuddy, Walker Smith and Pierre St-Laurent)

February 3, 2015



OLD DOMINION UNIVERSITY

Center for Coastal Physical Oceanography

IDEA FUSION

# The Effect of Model Horizontal Resolution on Physical Processes on the Antarctic Continental Shelves that Impact the Modeling of Biogeochemical Cycles

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# Outline

- Introduction
- Length scales of processes that affect light availability
  - Moving sea ice around
  - Mixed layer depths
- Length scales of processes that affect nutrient delivery
  - Circumpolar Deep Water
  - Glacial Melt Water
  - Benthic sources
  - Melting sea ice
- Conclusions/Questions



# Introduction

While only representing a small percentage of the area of the Southern Ocean, the Antarctic continental shelves have the highest primary productivity per unit area and are extremely important sinks of  $\text{CO}_2$  (e.g. estimate of the Ross Sea  $\text{CO}_2$  sink  $\sim \frac{1}{4}$  of entire (except margins) SO)

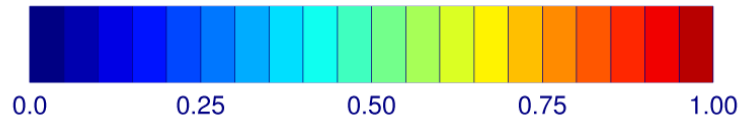
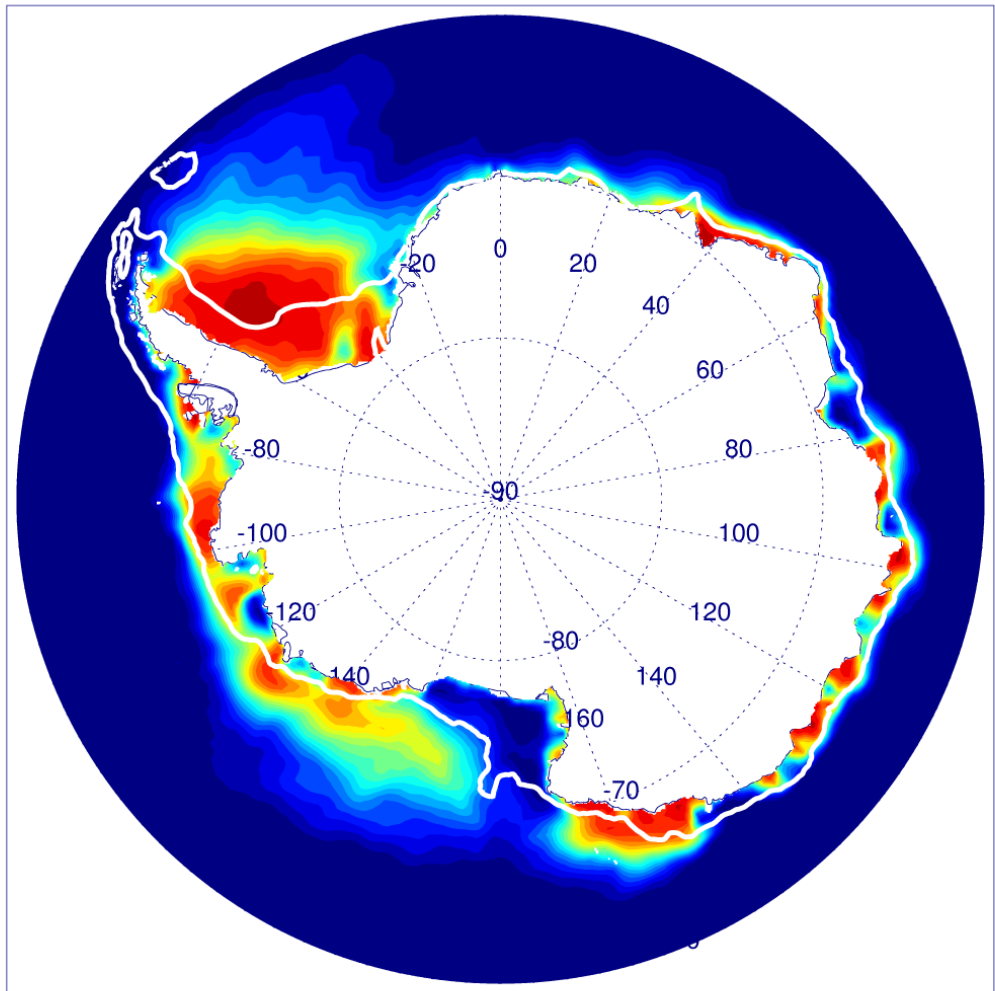
Several factors control primary production on the shelf, but the two most important are light and nutrient limitation

What are the length scales of the important physical processes over the continental shelf in both the ocean and the atmosphere (that we have any chance of resolving in large scale models in the near future...mesoscale or larger) that affect the delivery of light and macro/micro nutrients to the euphotic zone?

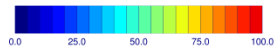
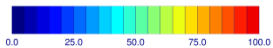
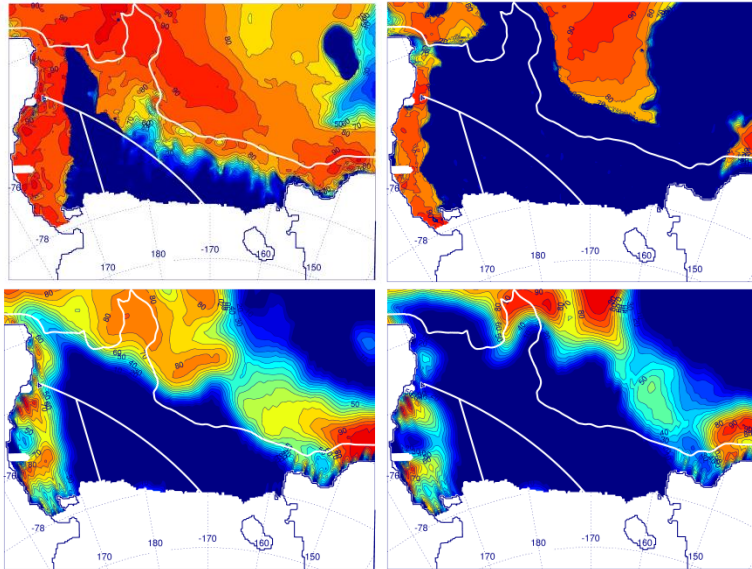
# Light Availability

- Even in summer, much of the continental shelf is still covered with ice and as the production in some summer coastal polynyas is very large, it's important to accurately simulate the summer expansion of these polynyas
- Resolution of the coastal winds (important because of the steep bathymetry) is likely more important than resolution of the ocean for the fall-winter polynya extent (i.e. Petrelli et al., 2008; Mathiot et al., 2012; Hollands et al., 2013), but the wind resolution matters in the summer too
- The mixed layer depths in the polynyas will depend on the winds as well as the changes in the sea ice melt water input

Even in January,  
much of the  
continental shelf  
(white line - 1000m  
isobath) is covered  
by sea ice



# Ross Sea regional model sea-ice area with different wind forcings

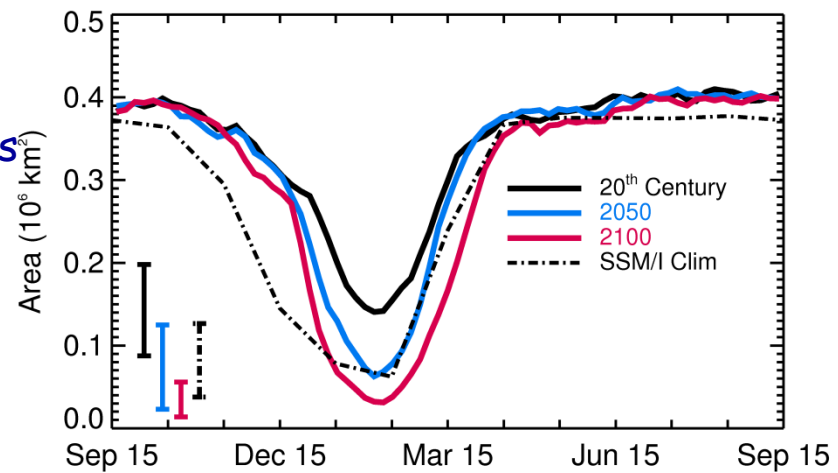


25 Dec 2011

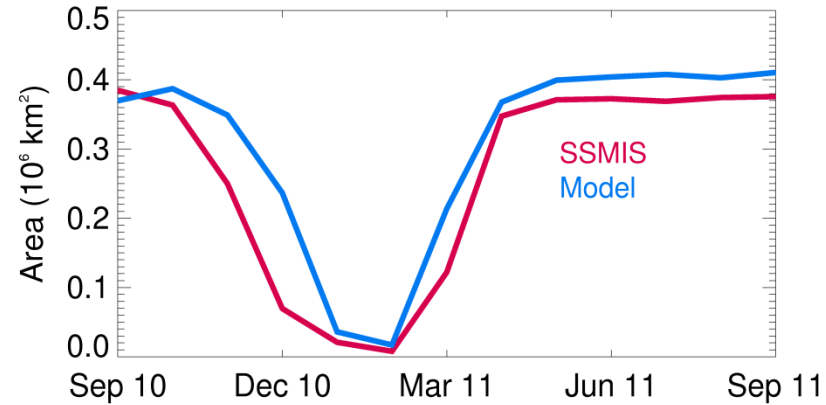
15 Jan 2012

Modeled (top) and observed  
(bottom) sea ice concentration with  
ERA-Interim winds

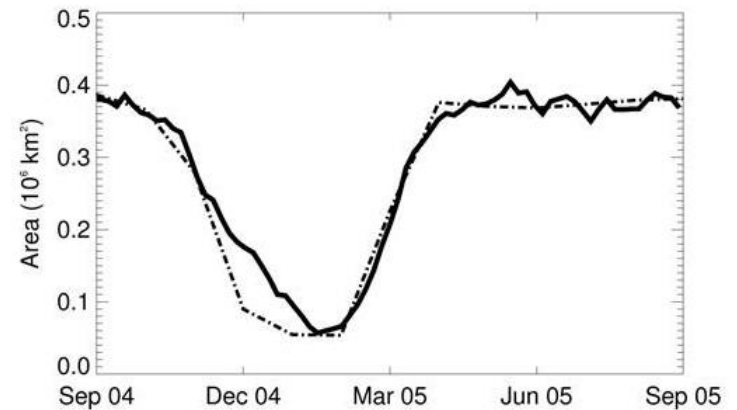
ECHAM5  
climate  
model winds  
(1.875°  
resolution)



ERA-  
Interim  
reanalysis  
winds (~80  
km  
resolution)



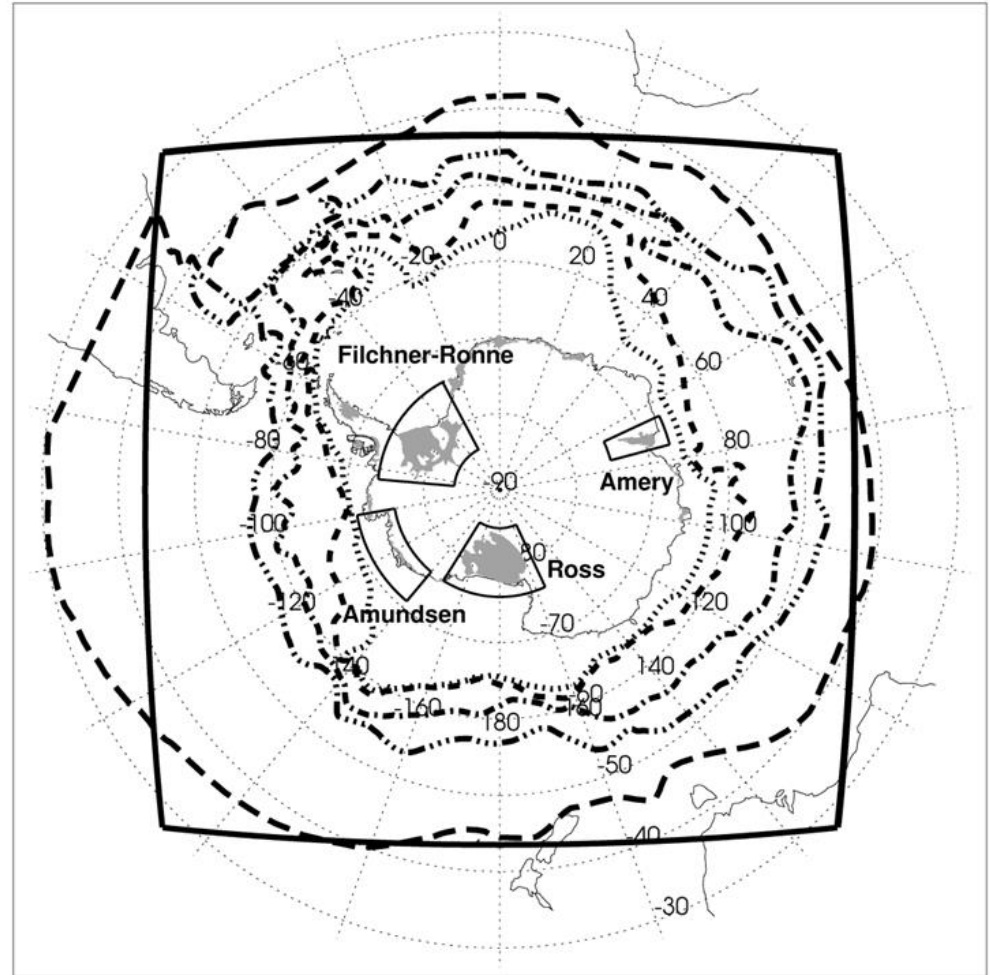
AMPS meso-  
scale atm  
model winds  
(30 km  
resolution)



10 km and 5 km resolution  
circum-Antarctic ROMS  
models with ice shelves

Three simulations:

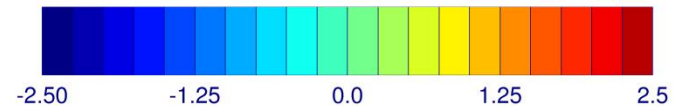
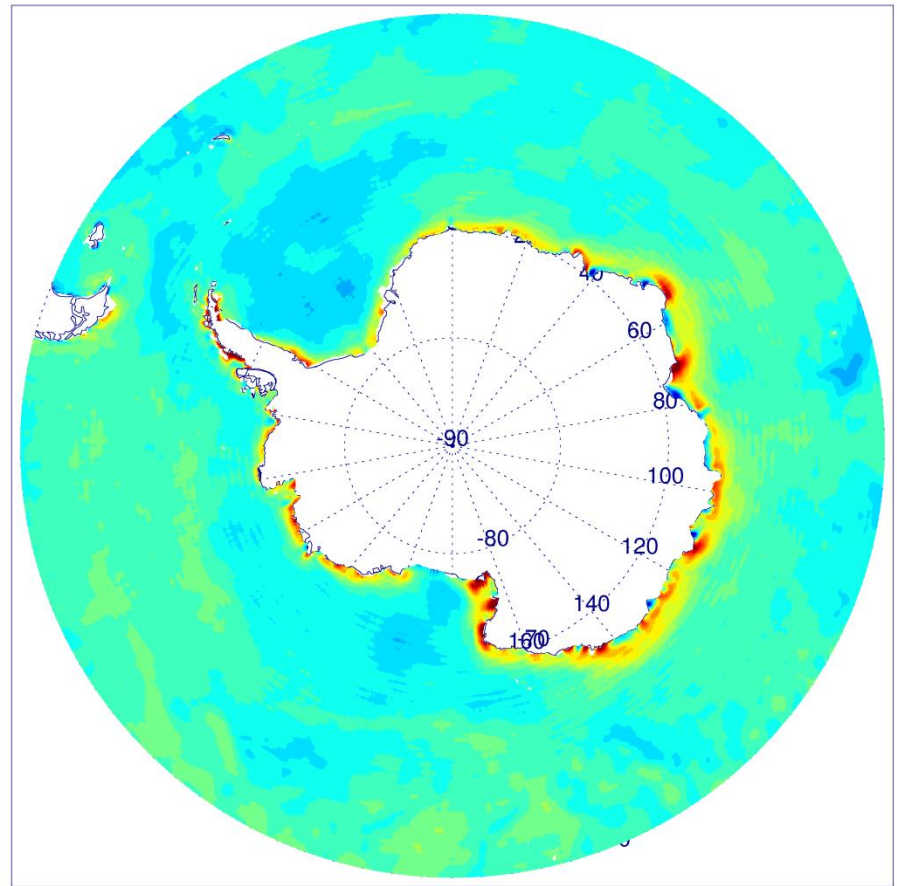
- 1) ERA-Interim reanalysis  
(~80 km) forcing
- 2) 1 + winds from a Polar  
WRF simulation (30 km)  
that was spectrally  
(scales > wave number 7)  
nudged to ERA-Interim
- 3) 1 + winds and  
temperatures from  
Polar WRF (30 km)



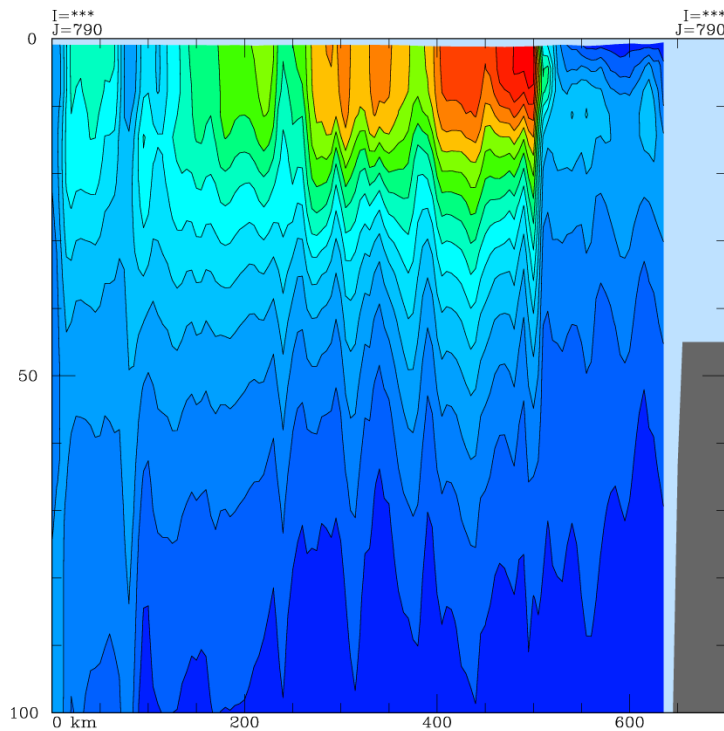


Higher resolution winds are slightly weaker over parts of the open ocean (mostly due to sea ice drag)

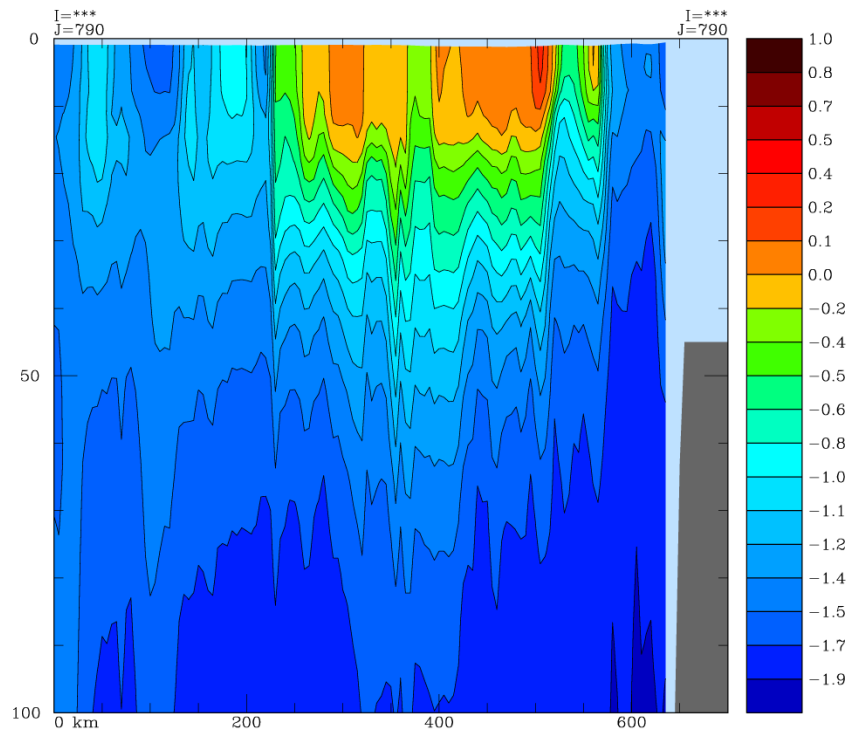
Higher resolution winds are significantly stronger near the coast (due to better resolution of the terrain)



Annual mean of 6 hr 10-m wind speed differences between PWRF and ERA-Interim (positive = stronger PWRF)



ERA-Interim winds (~80km)



PWRP winds (30km)

Temperature cross section (late January, top 100m) looking southward across the central and western Ross Sea from a 5 km circum-Antarctic model

Slightly deeper and cooler summer mixed layers in the western Ross Sea (right side) with higher resolution winds

# Nutrients

- Macro-nutrients: Transported by Circumpolar Deep Water (CDW) onto the shelf and then vertically mixed into the euphotic zone
- Micro-nutrients (dFe): Several possible sources
  - CDW advection onto the continental shelf
  - Glacial melt (ice shelf/iceberg or land based ice)
  - Benthic sources (including nepheloid layers)
  - Melting sea ice
  - Atmospheric deposition
  - Hydrothermal iron
- Eddy effects on vertical fluxes: Not going to really discuss (although we will discuss horizontal advection by eddies) other than to note that, due to weak stratification in Antarctic shelf waters, the radius of deformation is often quite small (4-5 km)

# Circumpolar Deep Water Intrusions

- Much of the CDW is thought to advect onto the continental shelf through troughs and the mean flow/topography interactions may require model resolution on the order of 5 km in some locations (e.g. Nakayama et al., 2014)
- Even worse, the radius of deformation on the shelf can be quite small (4-5 km) requiring model resolution on the order of 1 km to fully resolve baroclinic eddies
- These eddies are likely critical to the CDW transport onto and across the shelf (e.g. Nøst et al., 2011; Martinson and McKee, 2012, Thompson et al., 2014) and significant differences in the CDW transport onto the shelf can occur if these eddies aren't explicitly resolved (St-Laurent et al., 2013; Stewart and Thompson, 2015)

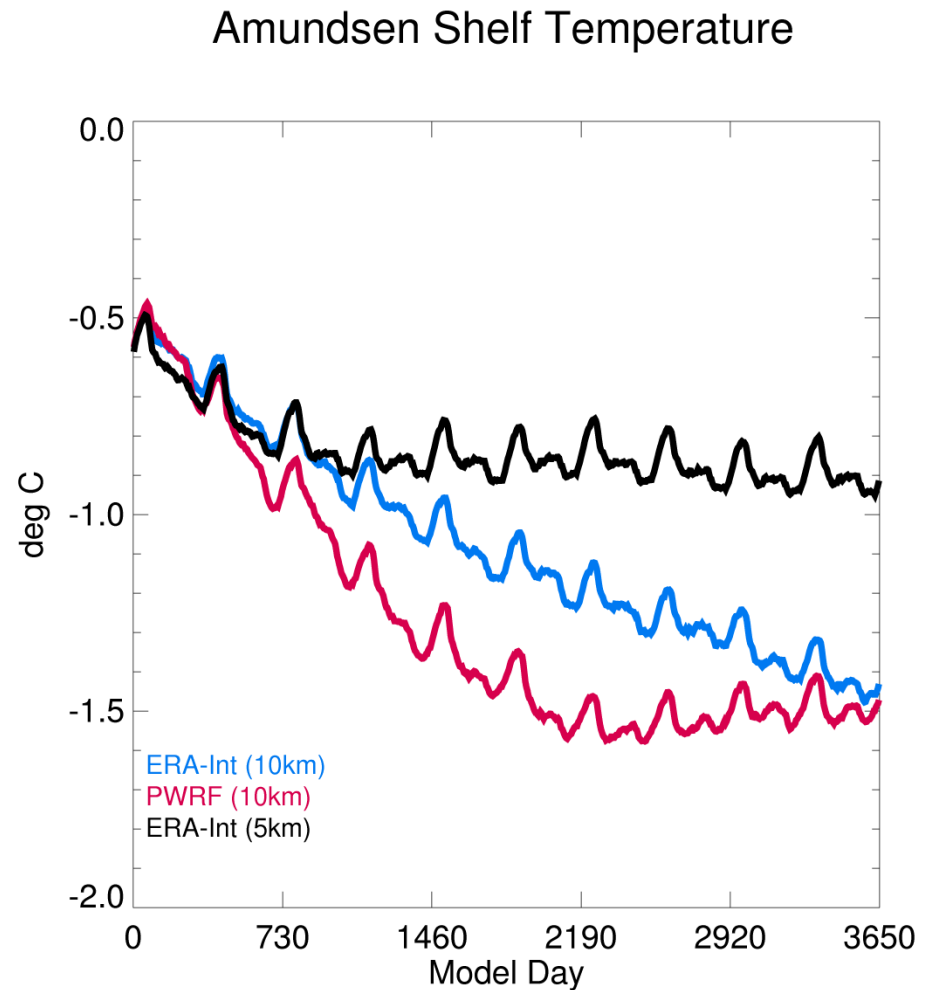


Cold Amundsen shelf is a common problem in models with 10-20km shelf resolution

Average temperature over the entire Amundsen shelf is much too cold in our 10km model

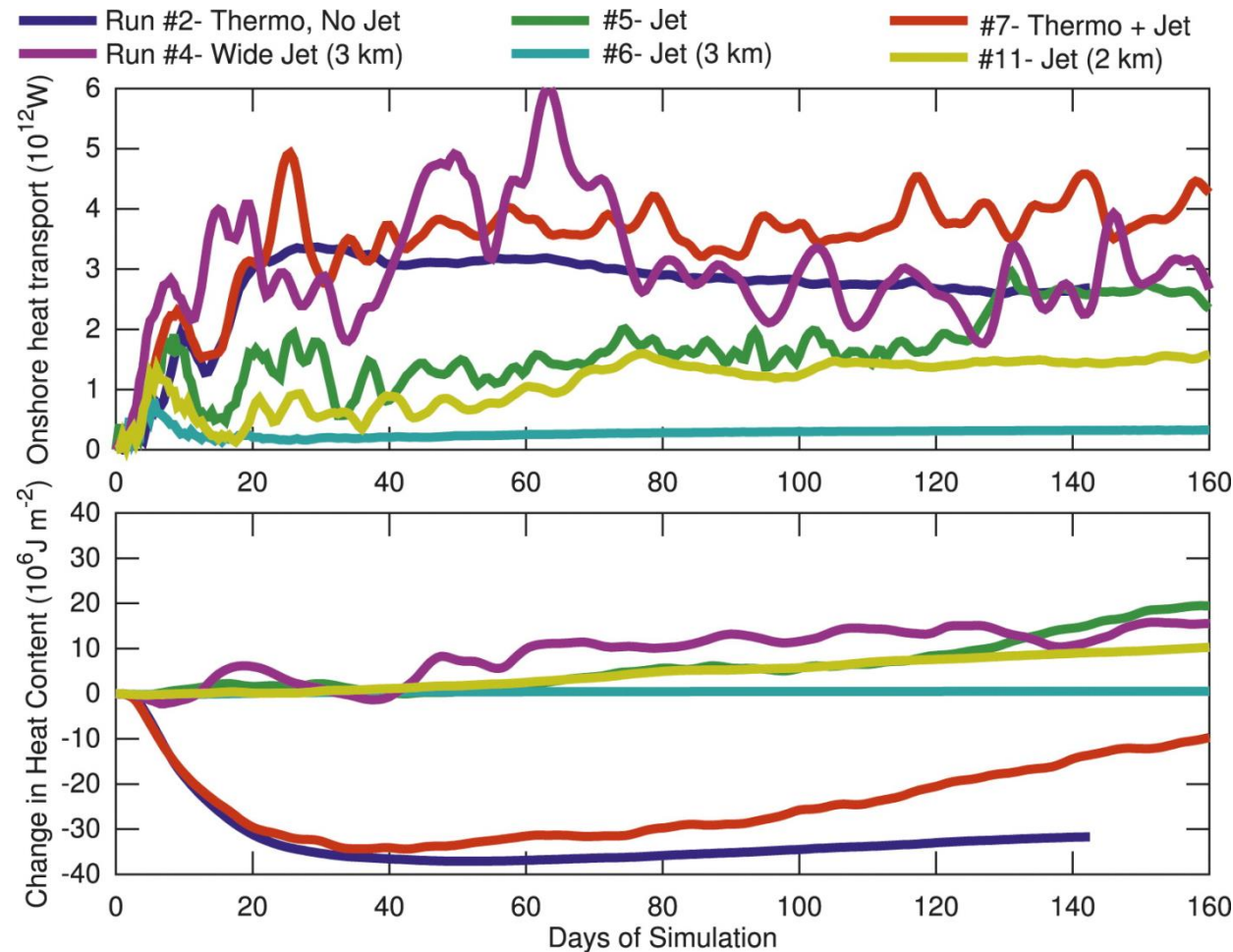
Stronger near shore winds remove heat more rapidly but reach a similar steady state

Higher ocean model resolution improves temperatures dramatically (see also Nakayama et al., 2014)



Idealized simulations of a “warm-water” continental shelf with a trough and an ice shelf showed three mechanisms for transporting heat

The mechanism that relies on eddies (interaction of a Rossby wave with the topography) is diminished when the model resolution is increased from 1 to 2 km and totally shutdown at 3 km

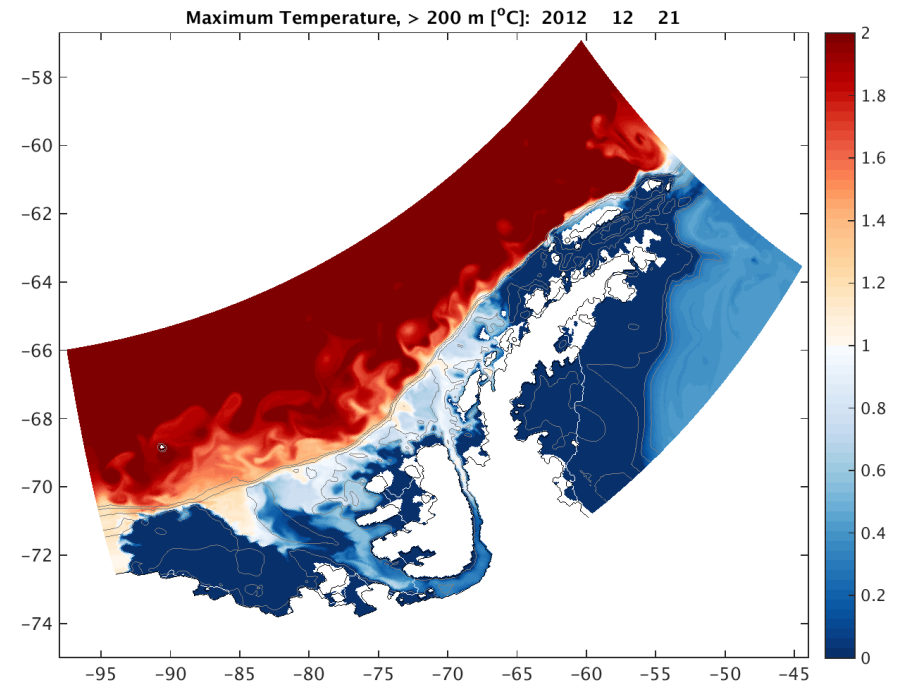
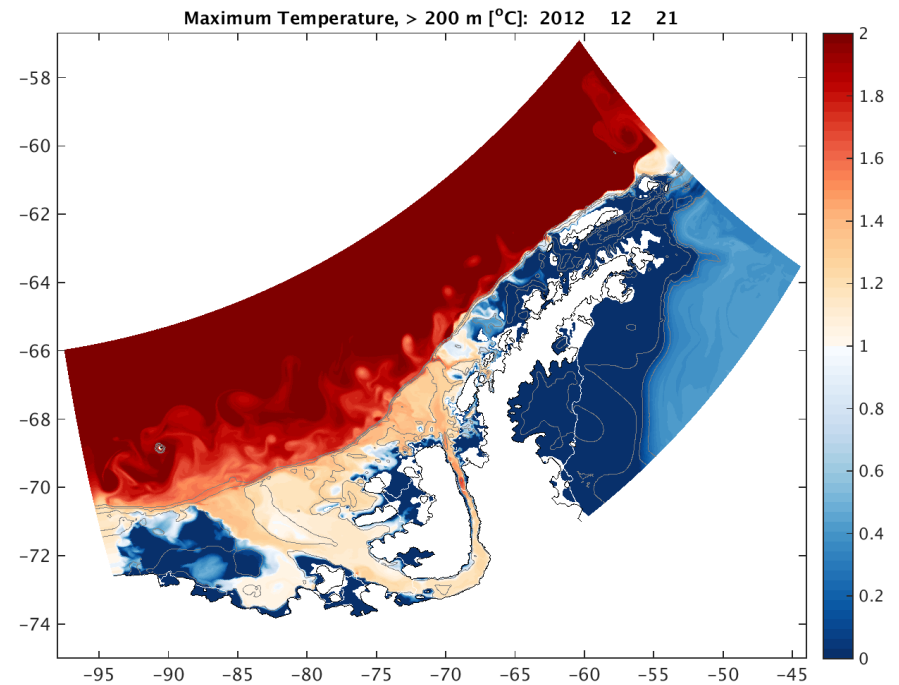


Compare onshore heat transport at 1 km (#5), 2 km (#11) and 3 km (#6) resolution

(St Laurent et al., 2013)

Shelf temperatures are much warmer for 1.5 km resolution (top) vs. 4.0 km resolution (bottom) model of the Bellingshausen Sea, indicating stronger CDW transport along the length of the shelf

(Jenny Graham, et al., in prep)



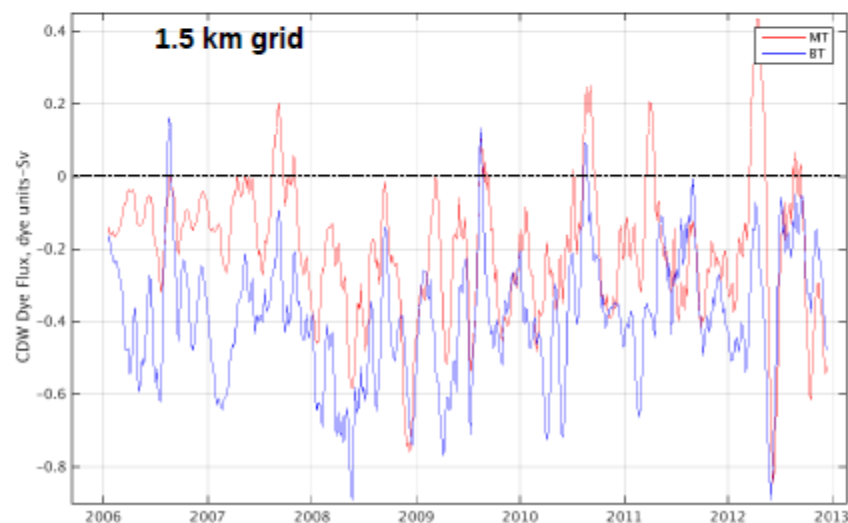
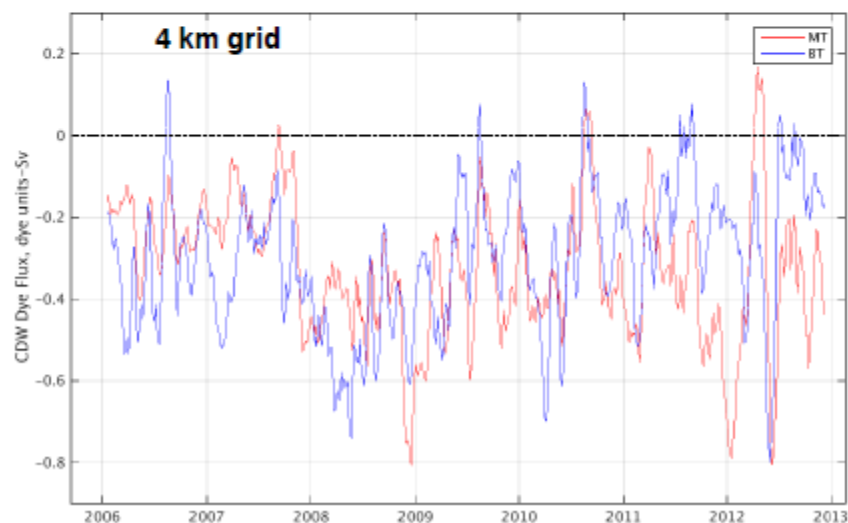
- **Tracer for CDW:** Dye released into all off-shore water  $>0^{\circ}\text{C}$  ( $>200$  m depth).

- **MT = Marguerite Trough**
- **BT = Belgica Trough**

NB. -ve = on-shore.

- Higher fluxes for 1.5 km than 4 km in BT, but not at MT.
- Increased variability at both locations for 1.5 km grid.

[dye units . Sv]	MT	BT
<b>4 km</b>	$-3.28 \pm 2.77$	$-2.99 \pm 3.08$
<b>1.5 km</b>	$-2.03 \pm 3.20$	$-3.85 \pm 3.35$



(Jenny Graham, et al., in prep)



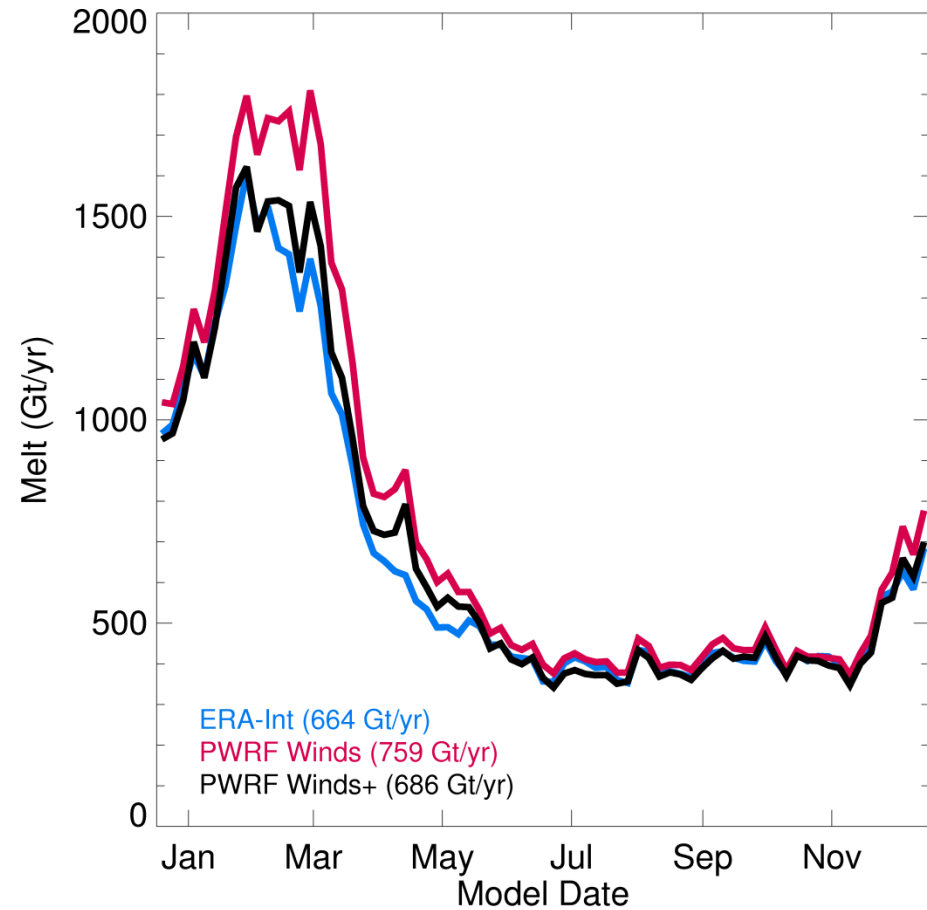
# Glacial Melt Water

- Resolution of coastal wind forcing is important to the ice shelf basal melt
- Besides the resolution needed to get CDW (source of much of the heat melting the floating ice shelves) onto and across the continental shelf to the ice shelves, shelf eddy scale resolution may be needed to get other water masses important to melt underneath the ice shelf
  - e.g. Årthun et al (2013) showed reduced eddy-driven High Salinity Salt Water (HSSW) transport into an ice shelf cavity when the grid resolution was reduced from 0.5 to 2km
- Perhaps more important, melt water (from ice shelves or ice sheet) may come out from under the ice shelves as eddies, impacting how any dFe contained in them will be distributed over the continental shelf

Total base case (10km model) melt rate (664 Gt/yr) is slightly low compared to observational estimates (750-1450 Gt/yr)

Higher resolution winds significantly increase (14%) the total integrated Antarctic basal melt

Total Ice Shelf Basal Melt Climatology (Gt/yr)

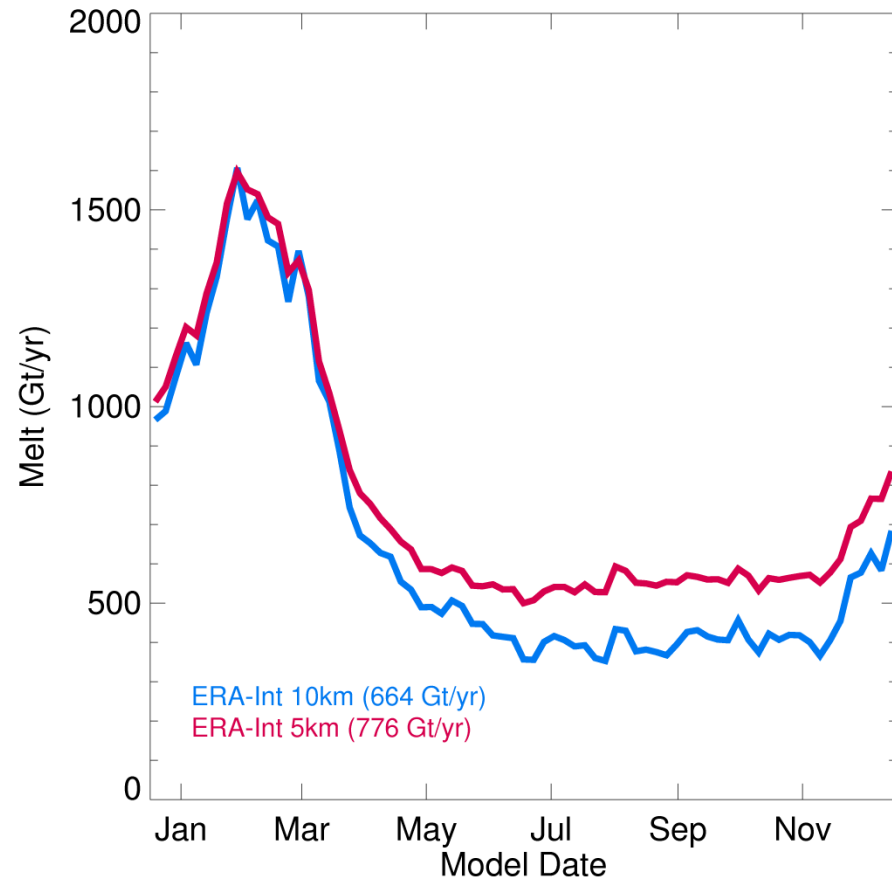


Total basal melt increases by 17% just by increasing the horizontal resolution from 10 to 5km

Greatest increase in melt occurs in winter and early spring

Increase in melt is not spread evenly: Increase over the entire Amundsen sector is ~300%

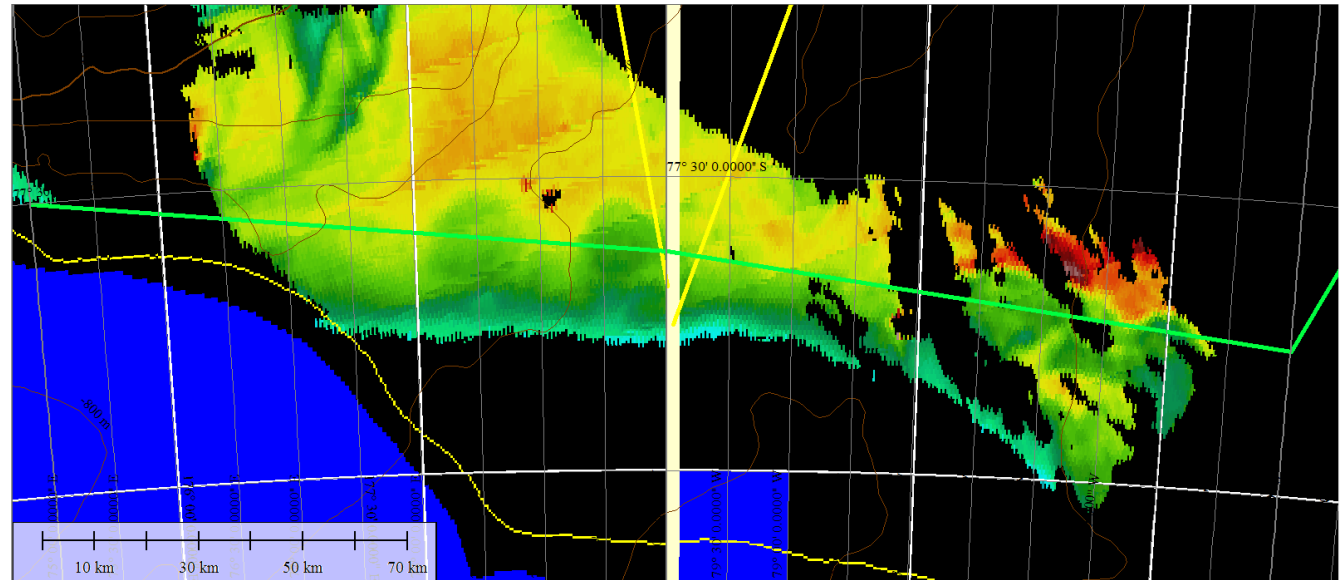
Total Ice Shelf Basal Melt Climatology (Gt/yr)



# Ross Ice Shelf satellite imagery – Jan 25

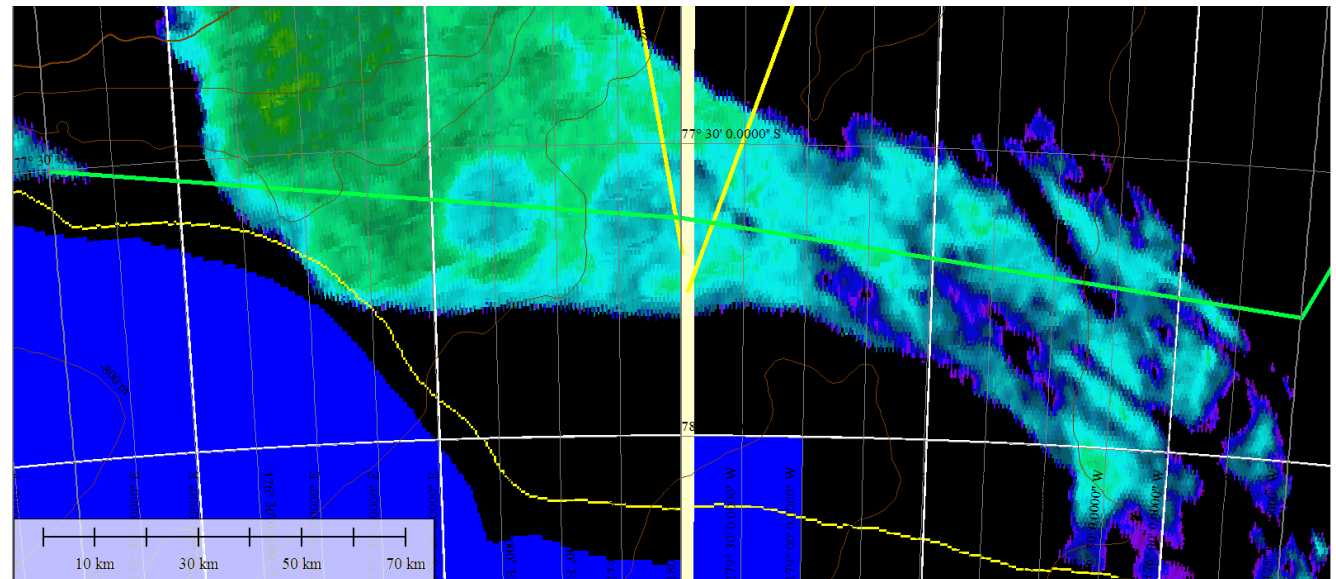
Chl

Eddies were measured to be fresh and have relatively enhanced dFe ( $\sim 0.2$  nM) in the near surface



SST

(courtesy Dennis McGillicuddy and the PRISM-RS project)



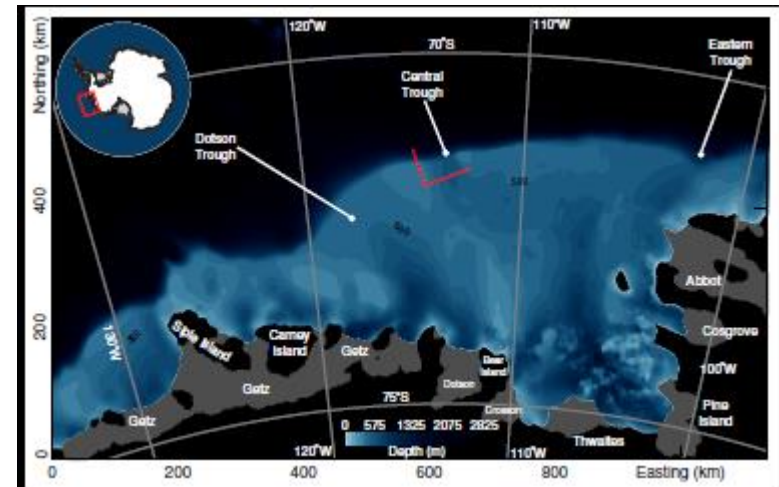
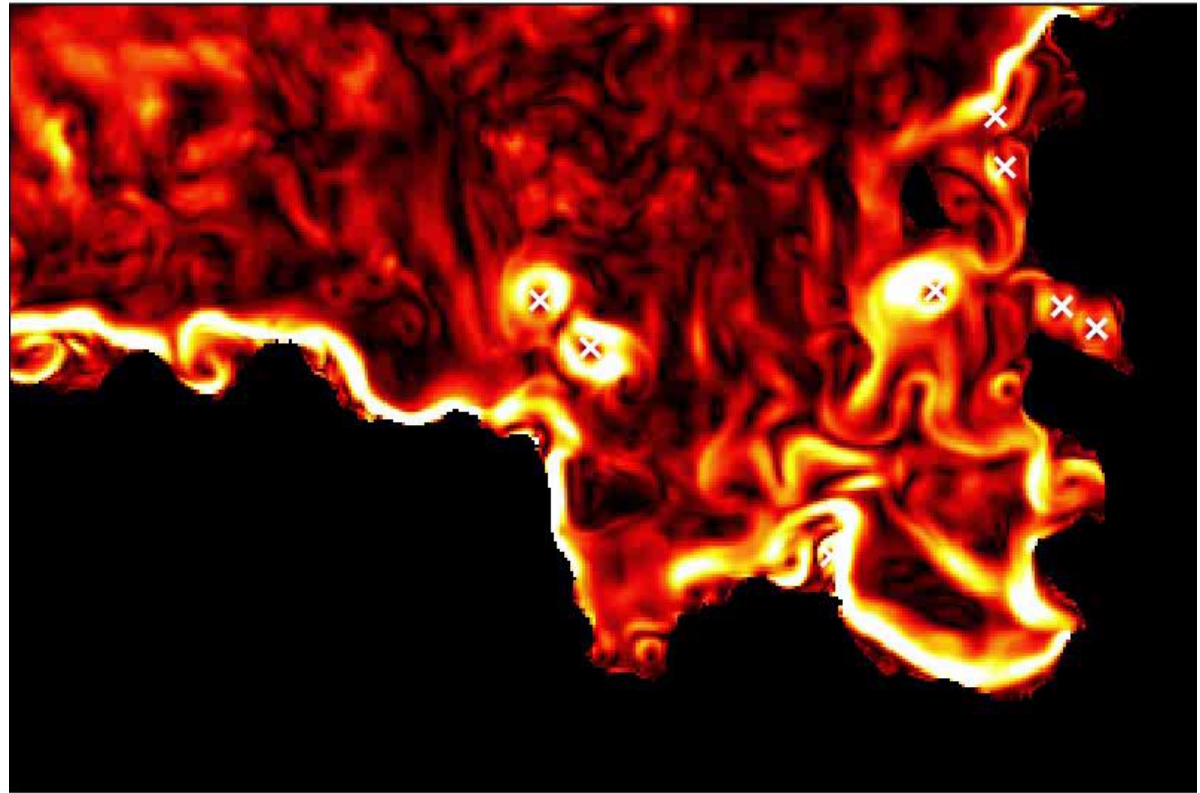


Eddy resolving (1.5 km) simulation of the Amundsen Sea

(Pierre St-Laurent, et al., submitted)

Not only can eddies carry properties to the ice shelves, but they can also transport away from the ice shelves

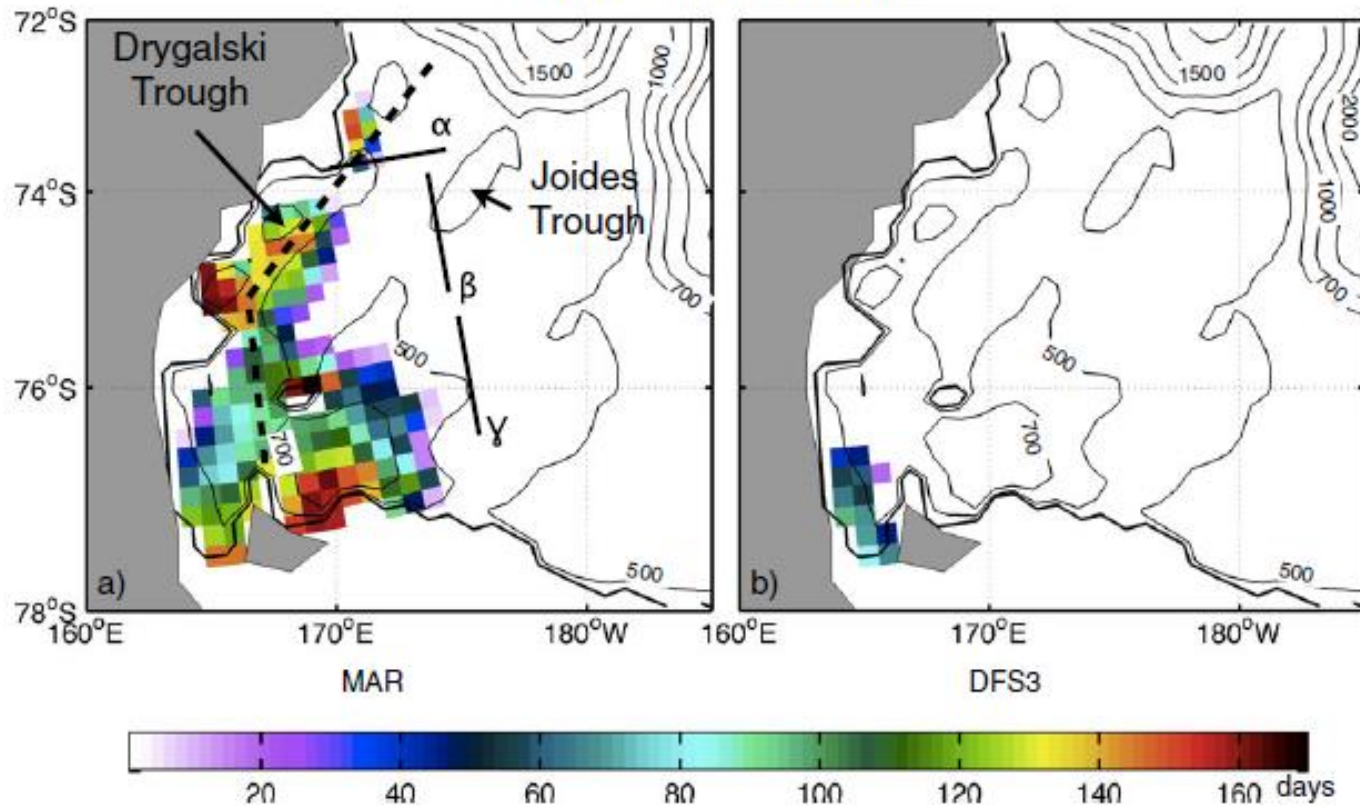
Surface eddies here remove meltwater from the coastal current into the shelf interior



# Benthic Sources

- To get the benthic sources correct, need to get deep mixing on the shelf correct, i.e. HSSW formation in coastal polynyas in fall/winter
- Requires wind resolution fine enough to represent coastal katabatic winds that create/maintain the coastal polynyas

## HSSW formation events



Differences in HSSW formation in a Ross Sea model for MAR (regional atmospheric model: 40 km resolution) and DFS3 (ERA40 plus a parameterization for coastal katabatic winds: 1.125 ° resolution) winds

(Mathiot et al., 2012)

# Melting Sea Ice

- The summer polynya openings are not entirely due to wind blowing the ice away from the coast, there is some in-situ melting which can be a source of dFe
- However, to get the timing of this melt correct, the winds are still critical (earlier slide)



# Conclusions/Questions

- Higher resolution winds ( $\sim 30\text{km}$ ) than the current generation of climate models and reanalyses (although some reanalyses are getting close) improve simulated sea ice along the Antarctic coast and increase ice shelf basal melt
- CDW transport onto the continental shelf may require resolution of  $\sim 1.5\text{km}$  (eddy resolving) on the shelf and shelfbreak
- Glacial melt water processes may require a similar resolution
- We can always find something that requires better resolution...how fine do we really need to go?
- Can some of this be parameterized?

# Acknowledgements

- Thanks to everyone who supplied the different computer codes and data bases (ocean and ice shelf bathymetry, atmospheric forcing, ocean conditions) needed
- Computer facilities and support provided by the Center for Coastal Physical Oceanography and the High Performance Computing group at Old Dominion University
- Financial support from the U.S. National Science Foundation (OCE-0927797, ANT-0944174, ANT-0944223 and ANT-1049089)