Ocean-(ice)-air interactions

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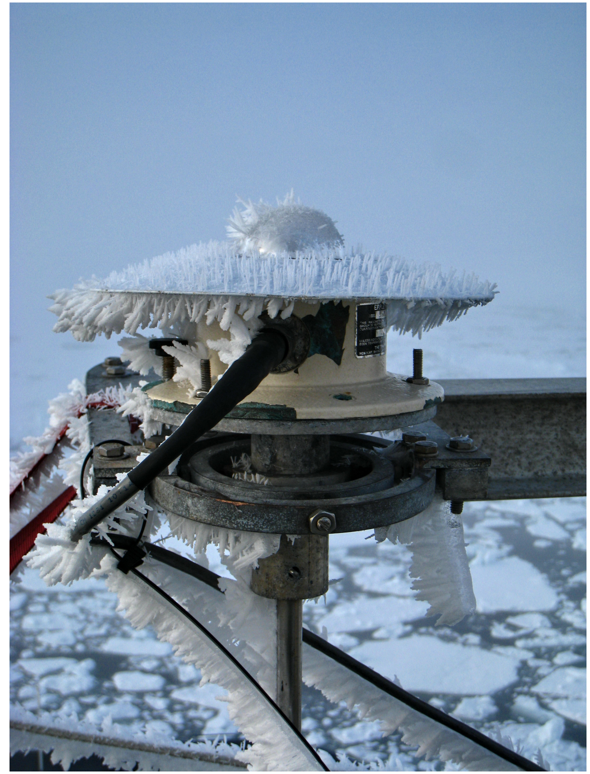


Riming on Eppley pyranometer, 21 Aug 2009
photo credit: Michael Tjernström, Stockholm University

Outline: Challenges for assessing fluxes

- Basics of upper ocean processes: heat budgets, wind and surface heat flux
  - — Large-scale seasonal budgets
- Extending our perspective to upwelling, nutrients, and chlorophyll
  - — Full Southern Ocean
  - — Local effects near Kerguelen
- Moving forward: adding fluxes to the observing system

HIGH-LATITUDE OCEAN AND SEA ICE SURFACE FLUXES: CHALLENGES FOR CLIMATE RESEARCH

BY MARK A. BOURASSA, SARAH T. GILLE, CECILIA BITZ, DAVID CARLSON, IVANA CEROVECKI, CAROL ANNE CLAYSON, MEGHAN F. CRONIN, WILL M. DRENNAN, CHRIS W. FAIRALL, ROSS N. HOFFMAN, GUDRUN MAGNUSDOTTIR, RACHEL T. PINKER, IAN A. RENFREW, MARK SERREZE, KEVIN SPEER, LYNNE D. TALLEY, AND GARY A. WICK

High latitudes present extreme conditions for the measurement and estimation of air–sea and ice fluxes, limiting understanding of related physical processes and feedbacks that are important elements of the Earth's climate.

High-latitude climate change can manifest itself in astonishing ways. Arctic sea ice extent at the end of the melt season in September is declining at a mean rate of 12% per decade, with record seasonal minima in 2007 and 2012 (Comiso et al. 2008; Shawstack 2012). In 2001/02, the Larsen B Ice Shelf on the Antarctic Peninsula collapsed in a matter of months (Rignot et al. 2004), and in 2008, the Wilkins Ice Shelf collapsed equally quickly (Scambos et al. 2009). Ocean heat content is rising rapidly in high-latitude regions of both hemispheres (e.g., Gille 2002; Karcher et al. 2003; Bindoff et al. 2007; Purkey and Johnson 2010). The observed trends are expected to continue and are broadly consistent with projections of anthropogenic climate change reported in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Randall et al. 2007). A common element in high-latitude climate changes is a dependence on surface fluxes; we focus on the exchange of energy, momentum, and material between the ocean and atmosphere and between atmosphere and sea ice (the basic concepts defining surface fluxes are outlined in "Primer: What is an air–sea flux?"). Surface fluxes at high latitudes

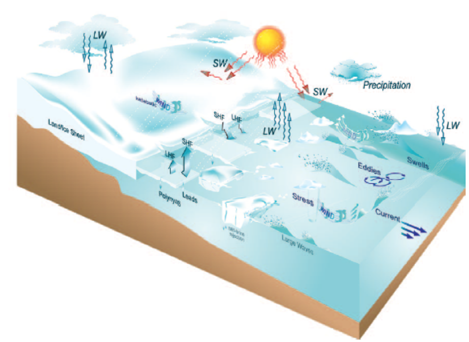
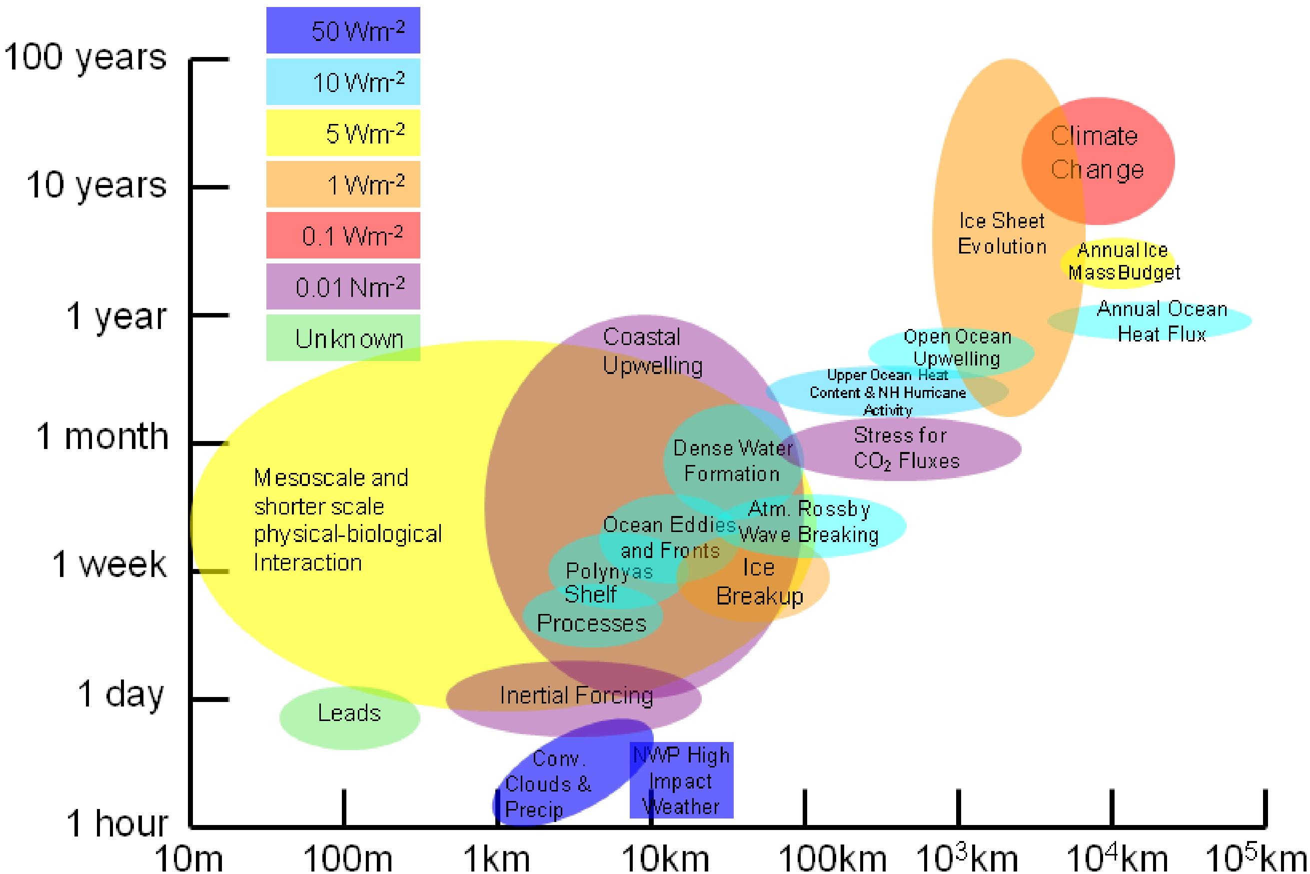


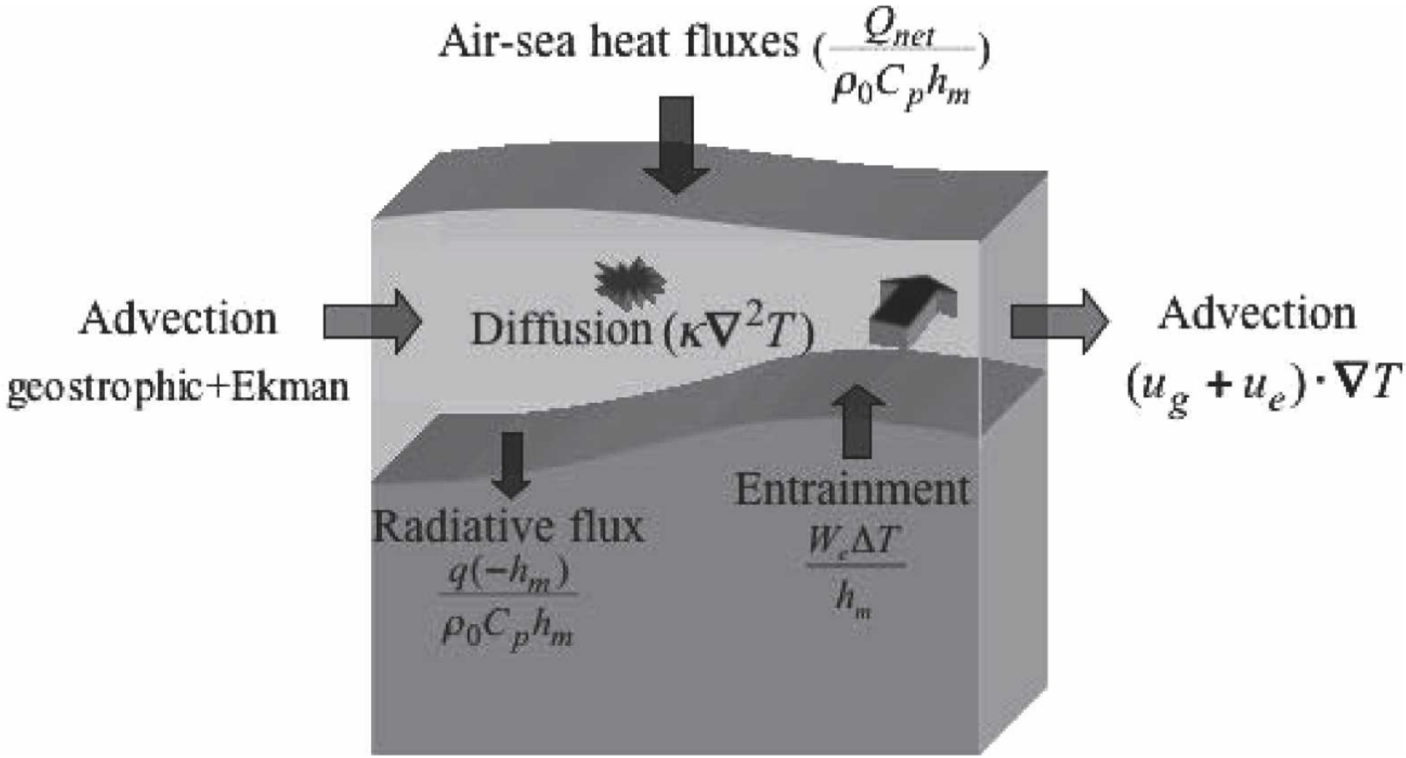
FIG. 1. Schematic of surface fluxes and related processes for high latitudes. Radiative fluxes are both SW and LW. Surface turbulent fluxes are stress, SHF, and LHF. Ocean surface moisture fluxes are *P* and *E* (proportional to LHF). Processes specific to high-latitude regimes can strongly modulate fluxes. These include strong katabatic winds, effects due to ice cover and small-scale open patches of water associated with leads and polynyas, air–sea temperature differences that vary on the scale of eddies and fronts (i.e., on the scale of the oceanic Rossby radius, which can be short at high latitudes), deep and bottom water formation, and enhanced freshwater input associated with blowing snow.

Flux Accuracies and High Latitude Applications



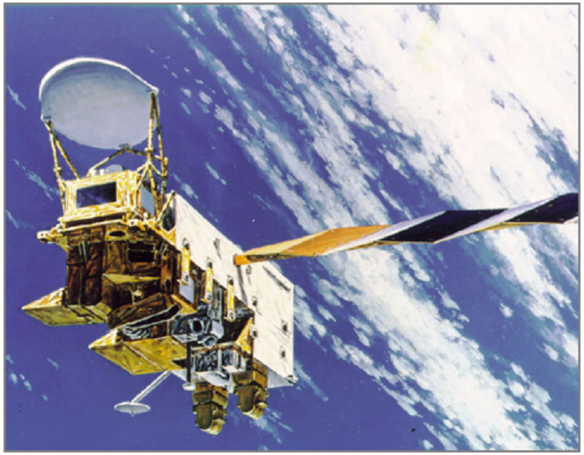
Bourassa et al, BAMS, 2013

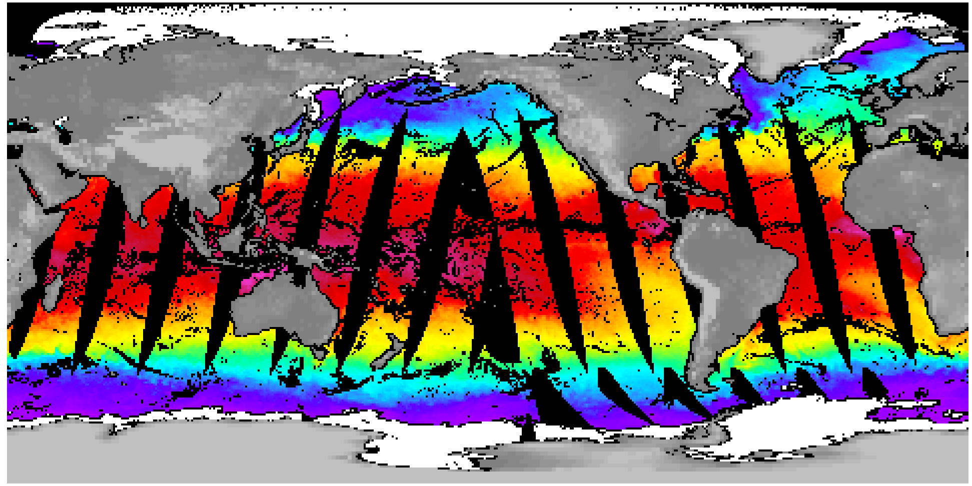
Upper-ocean air-sea exchange: Processes in the mixed layer



Dong et al, 2007

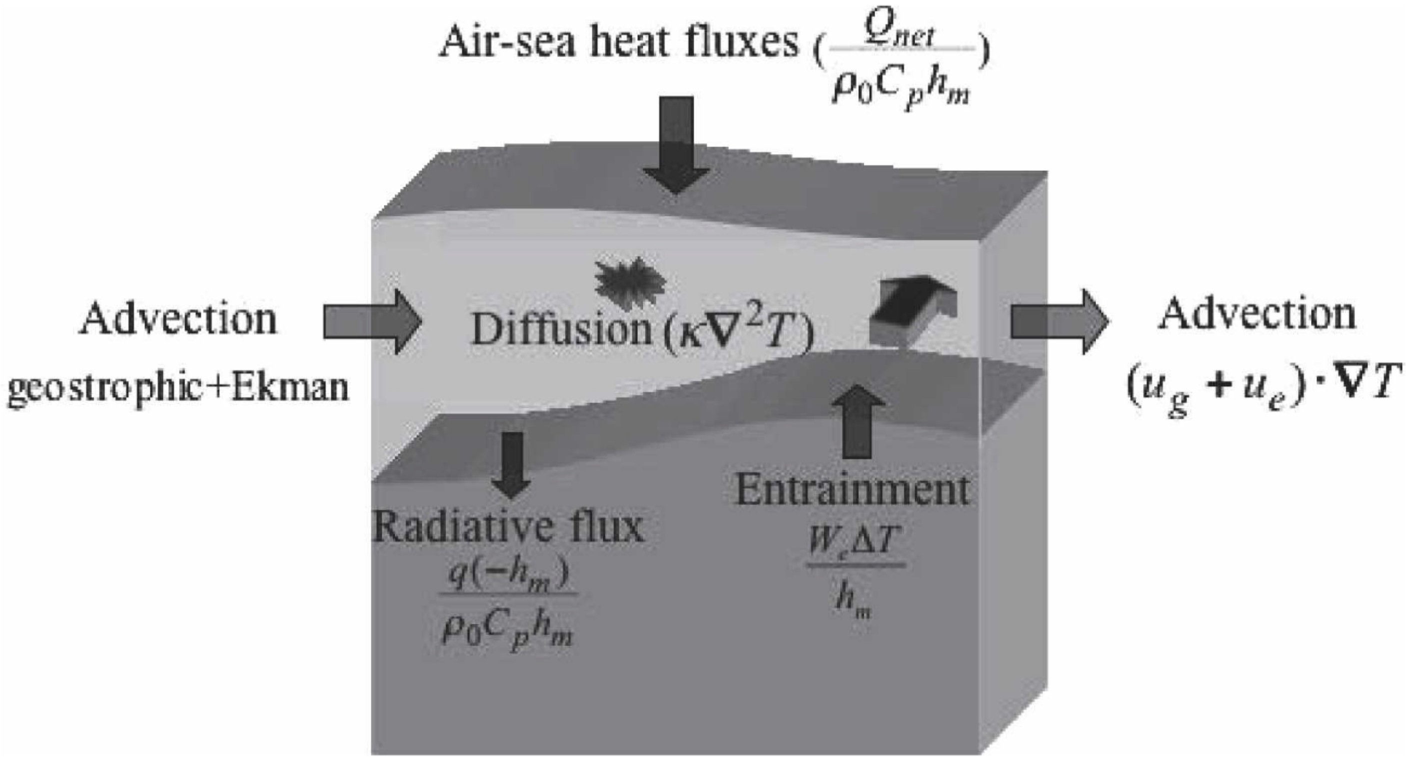
Detecting the upper ocean: SST from AMSR-E





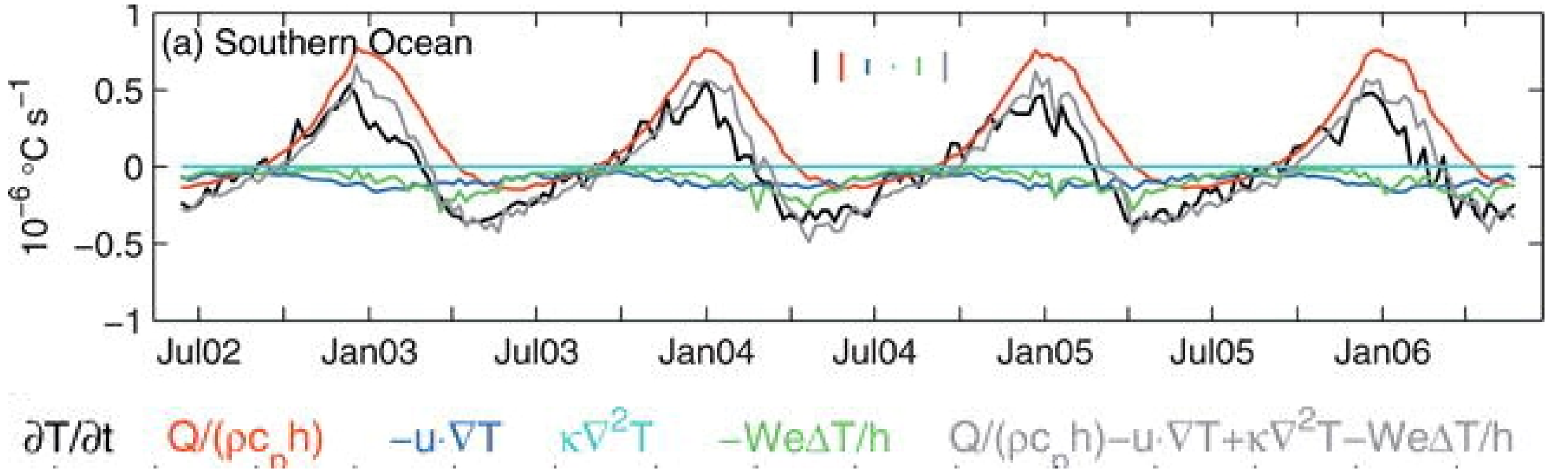
AMSR-E microwave SST, 1 January 2003, Remote Sensing Systems

Upper-ocean air-sea exchange: Processes in the mixed layer



Dong et al, 2007

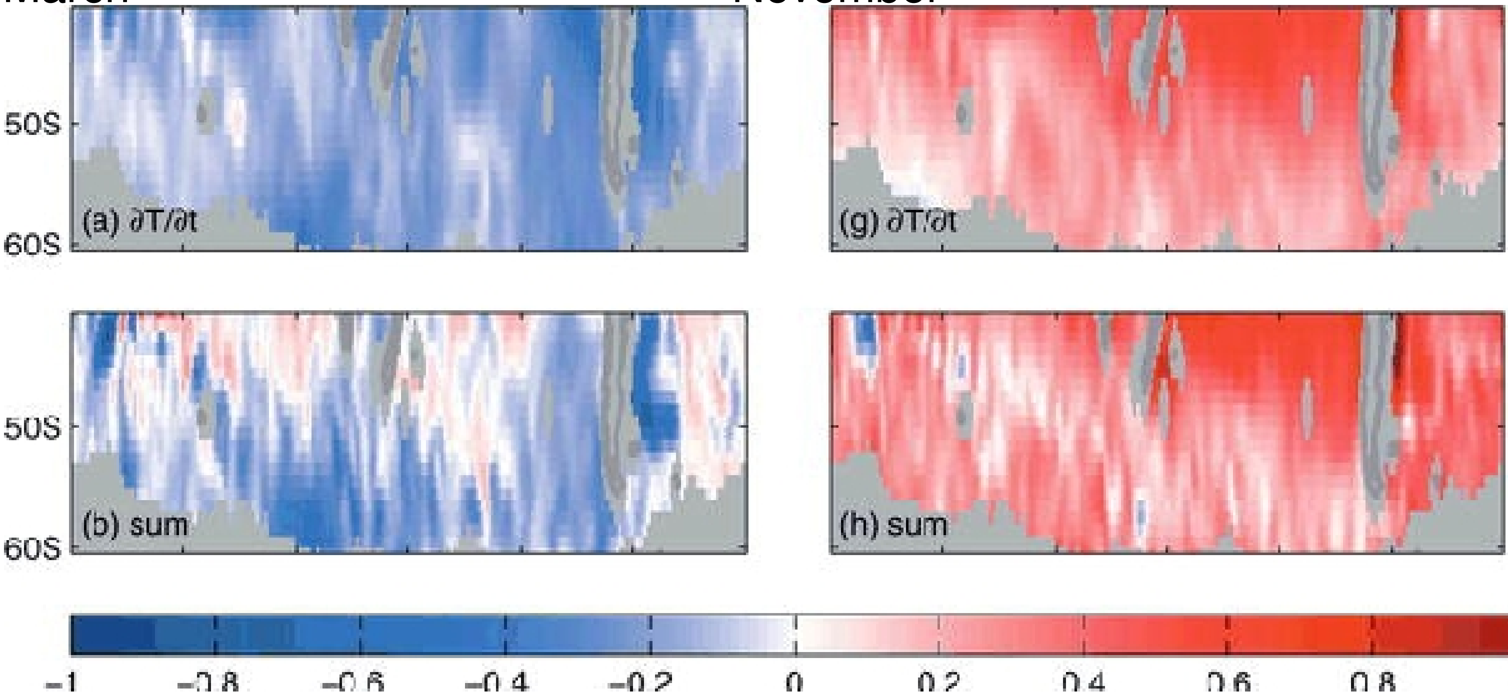
Upper-ocean heat budget



Dong et al, 2007

Regional upper ocean heat budget: Imbalances

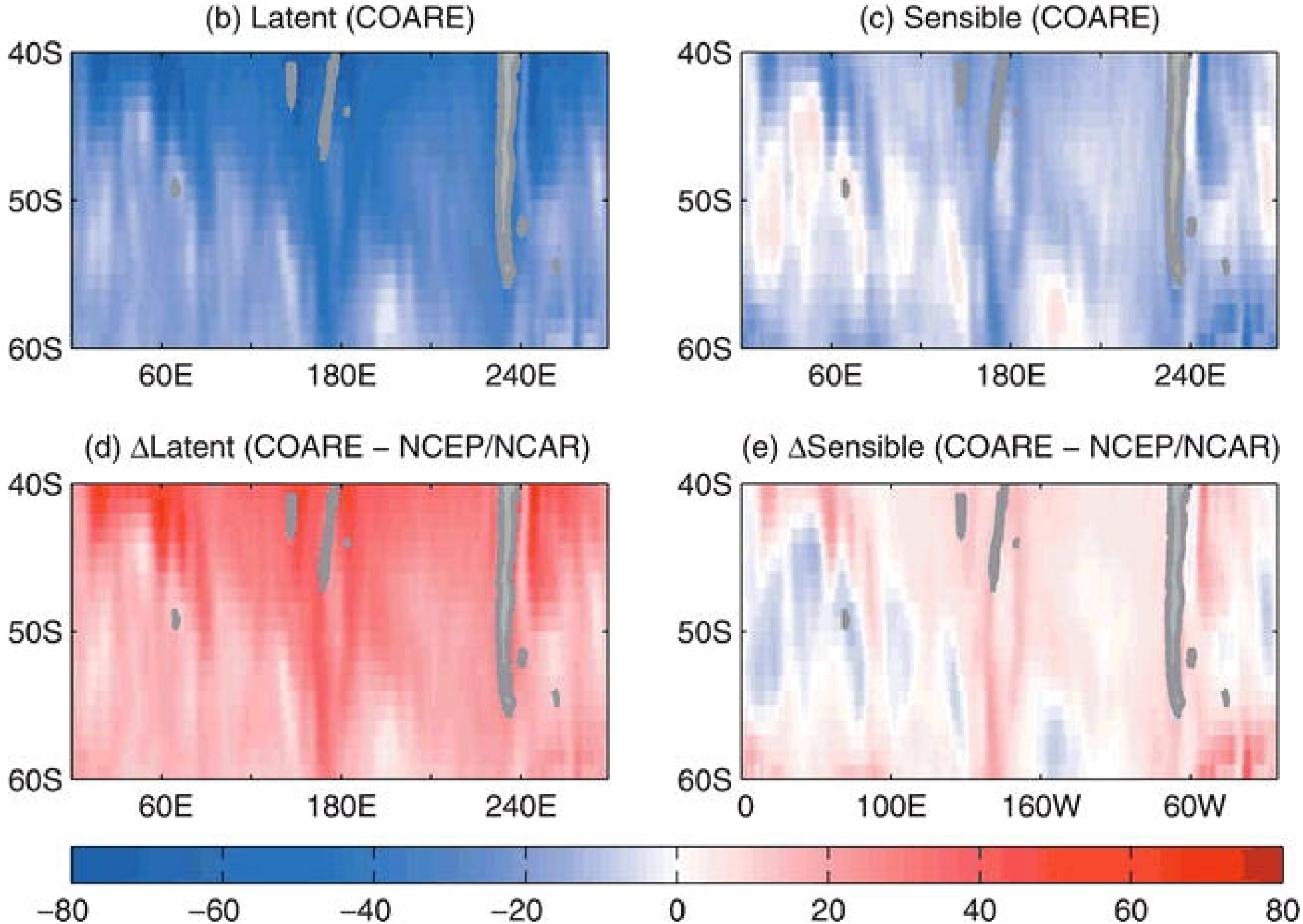
March November



10^{-6} °C s^{-1}

Dong et al, 2007

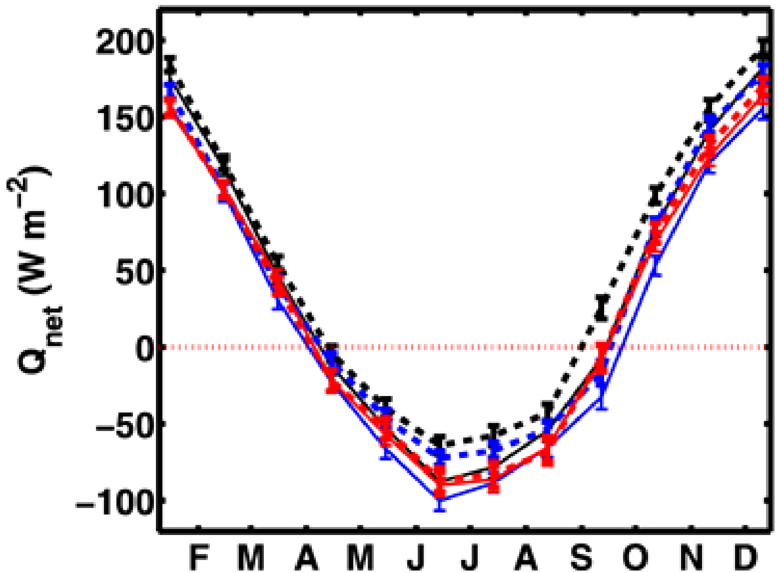
Disagreement among fluxes: June averages



W m^{-2}

Dong et al, 2007

Closer examination in Drake Passage: Seasonal variations in air-sea flux



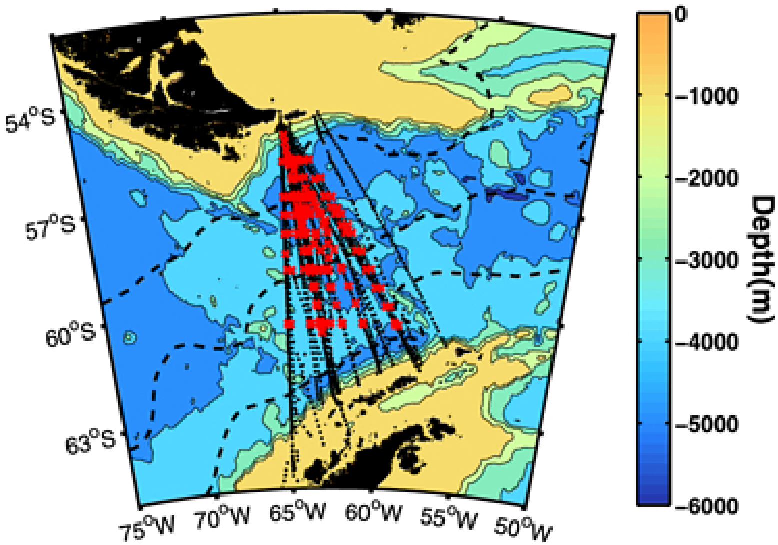
Stephenson et al, JGR-Oceans, 2012

OAFlux: black
NCEP: red
J-OFURO: blue

north of Polar Front: solid
south of Polar Front: dashed

- Seasonal cycles roughly agree for different flux products,
- ... even though means differ substantially.

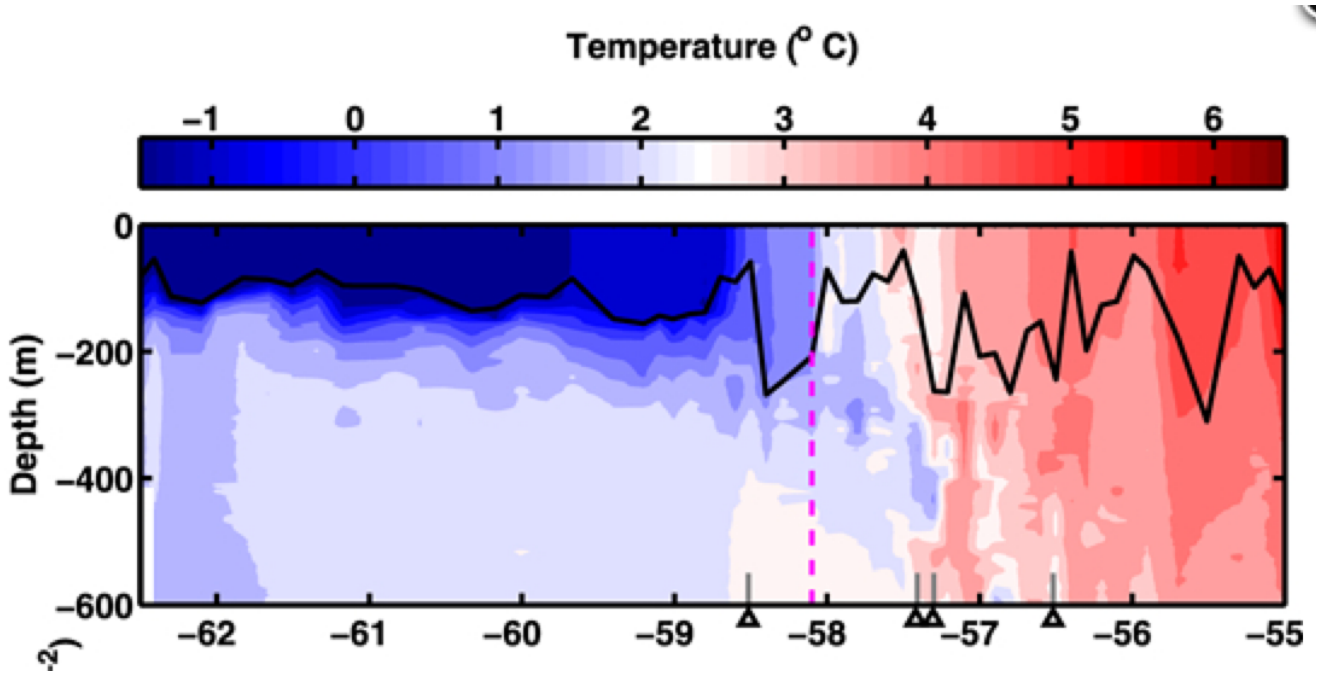
Drake Passage eXpendable BathyThermograph (XBT) data



Stephenson et al, JGR-Oceans, 2012

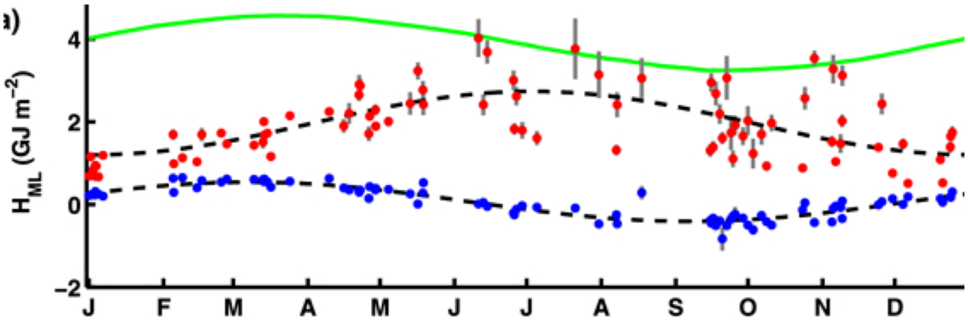
- Gould is US Antarctic program used to ferry supplies to Palmer Station year-round
- Since 1996, 6-7 Drake Passage crossings per year with XBT data.
- A total of 20-22 crossings per year with meteorological data, thermo-salinograph, upper ocean velocity (ADCP), and pCO_2.

Upper ocean section (September 2009)



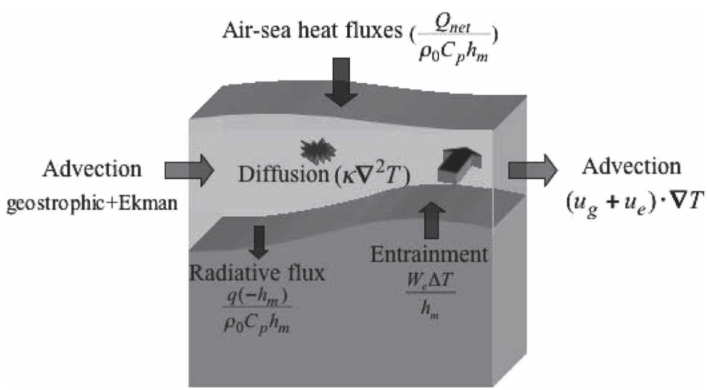
Stephenson et al, JGR-Oceans, 2012

Ocean mixed-layer heat budget



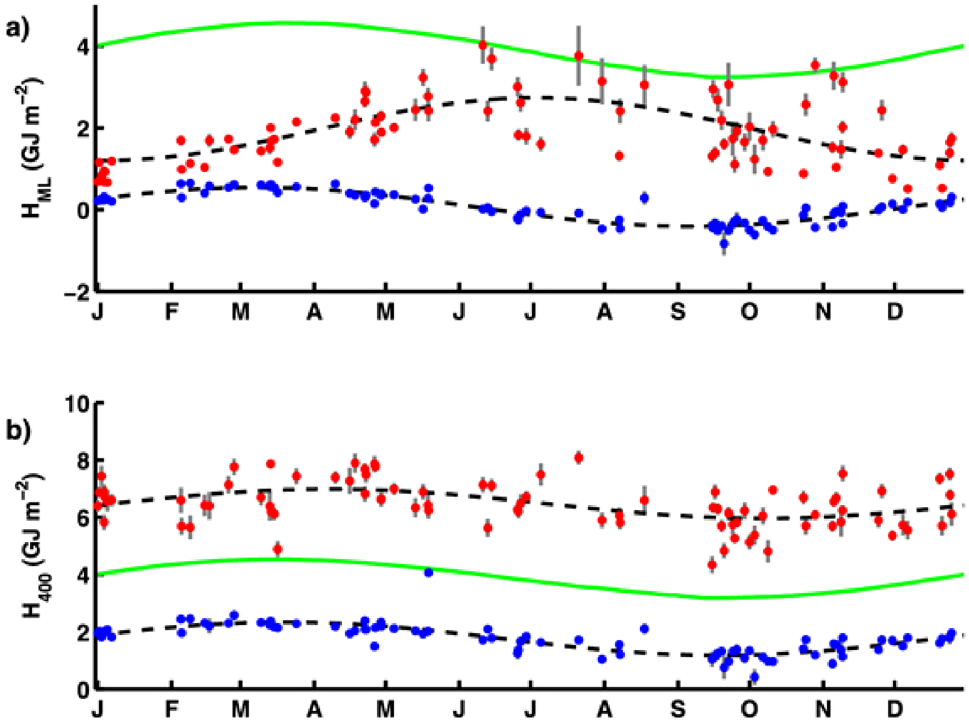
Stephenson et al, JGR-Oceans, 2012

- Climatological seasonal cycles.
- Integrated heat flux (green) disagrees with mixed-layer heat content both north (red) and south (blue) of Polar Front.



Dong et al, 2007

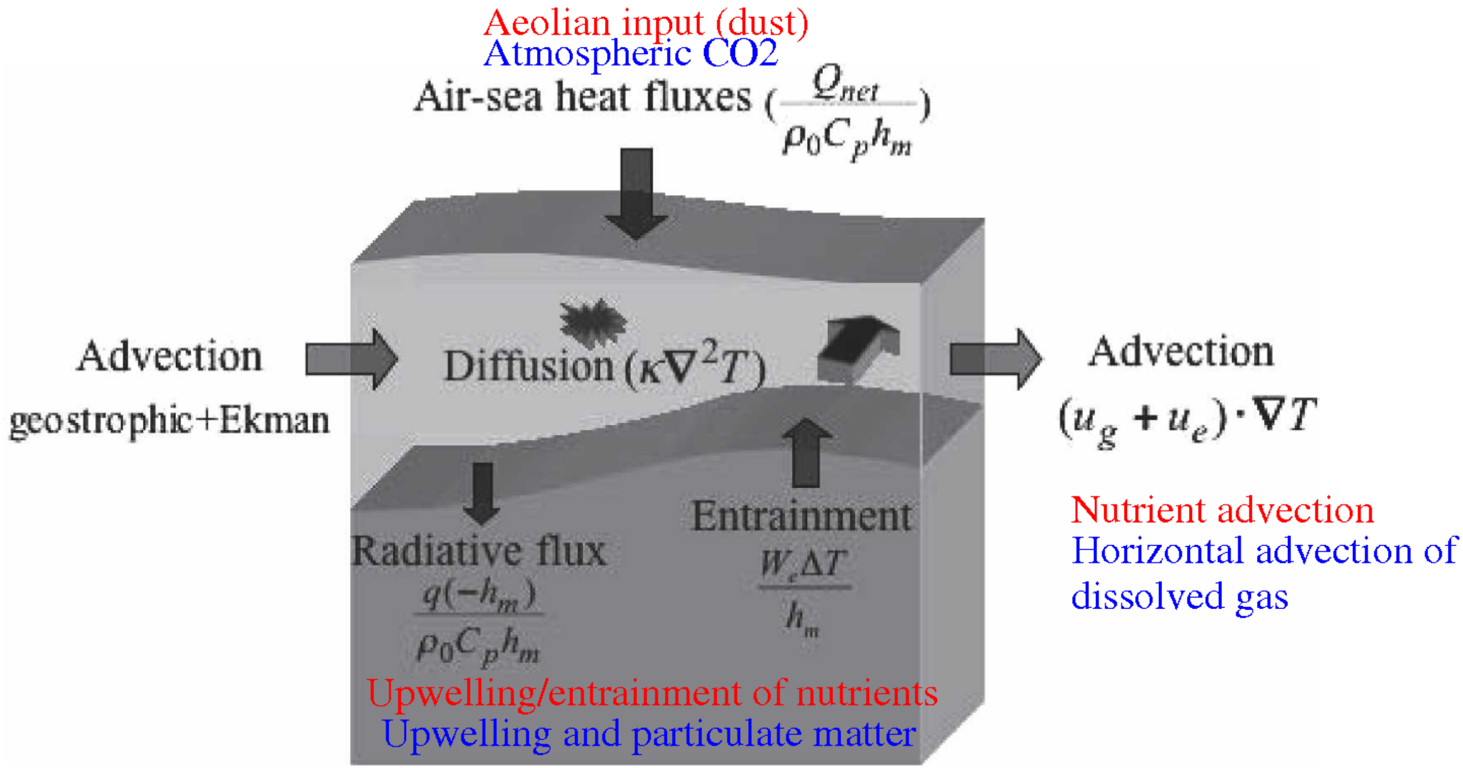
Ocean mixed-layer heat budget



Stephenson et al, JGR-Oceans, 2012

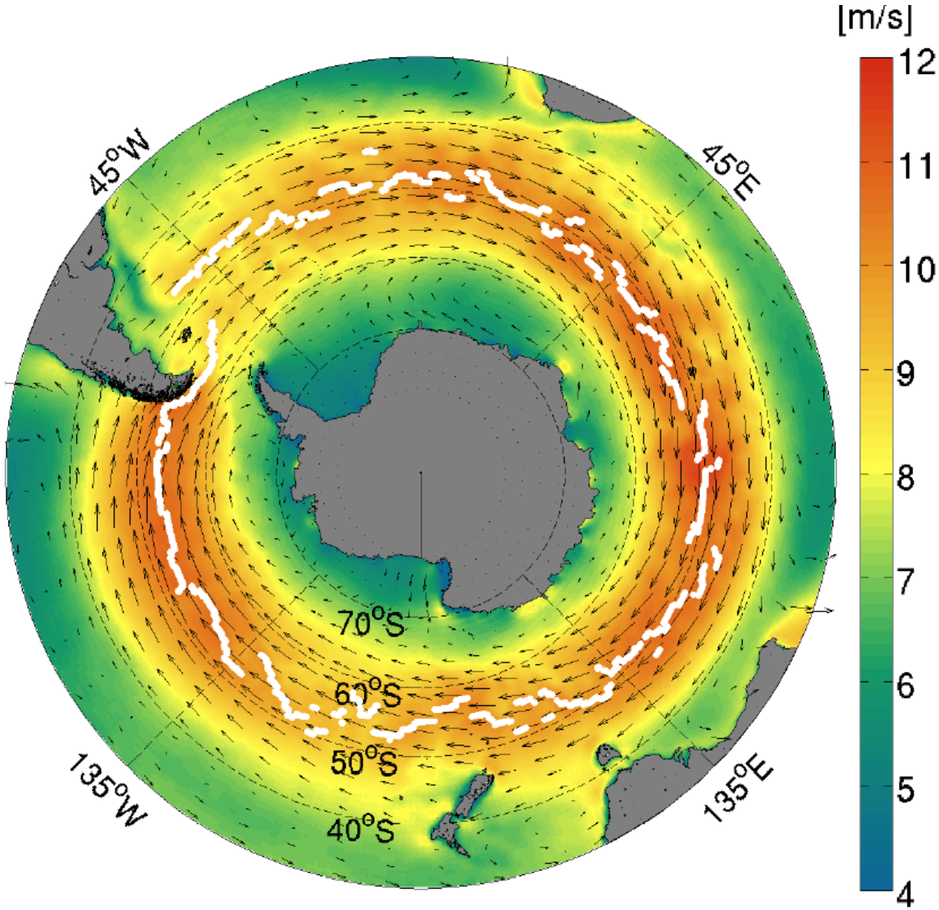
- Climatological seasonal cycles.
- Integrated heat flux (green) disagrees with mixed-layer heat content both north (red) and south (blue) of Polar Front.
- Surface fluxes consistent with heat content in top 400 m.
- Lesson: base of mixed layer exchanges heat with deep ocean.
- Largest factor explaining non-seasonal part: eddies.

Extending to carbon: gas and nutrient exchange



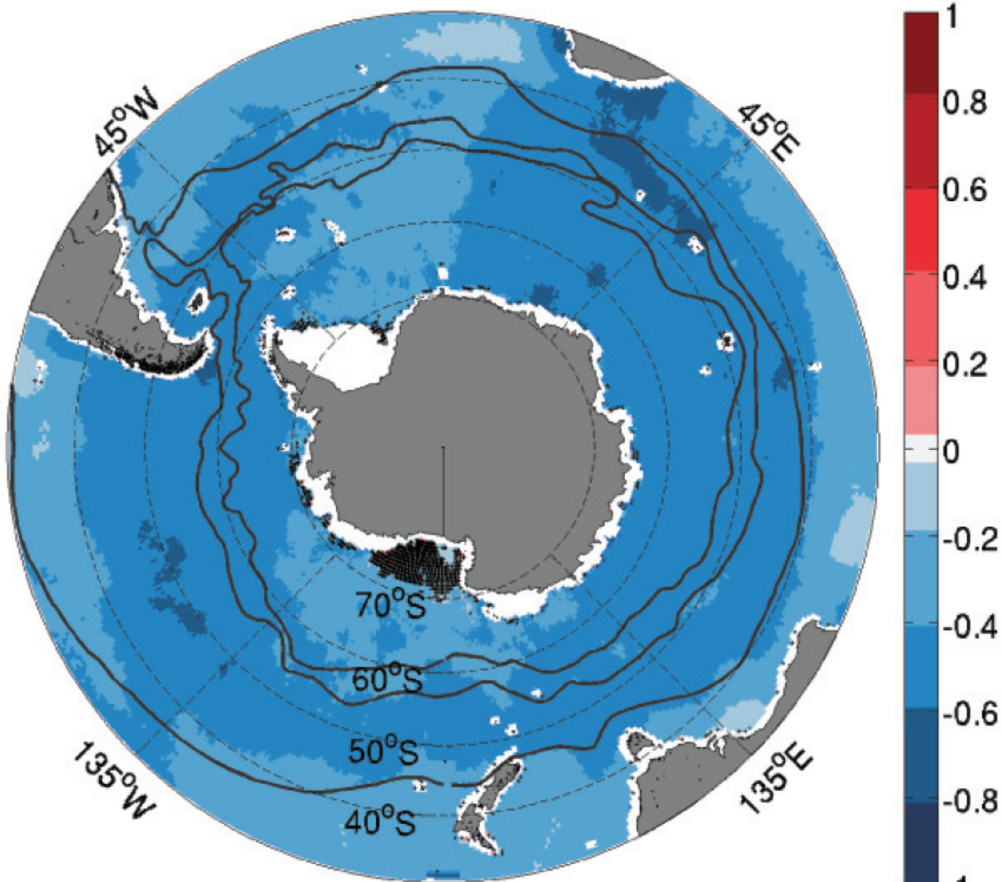
adapted from Dong et al, 2007

Can wind-stress drive nutrient availability?



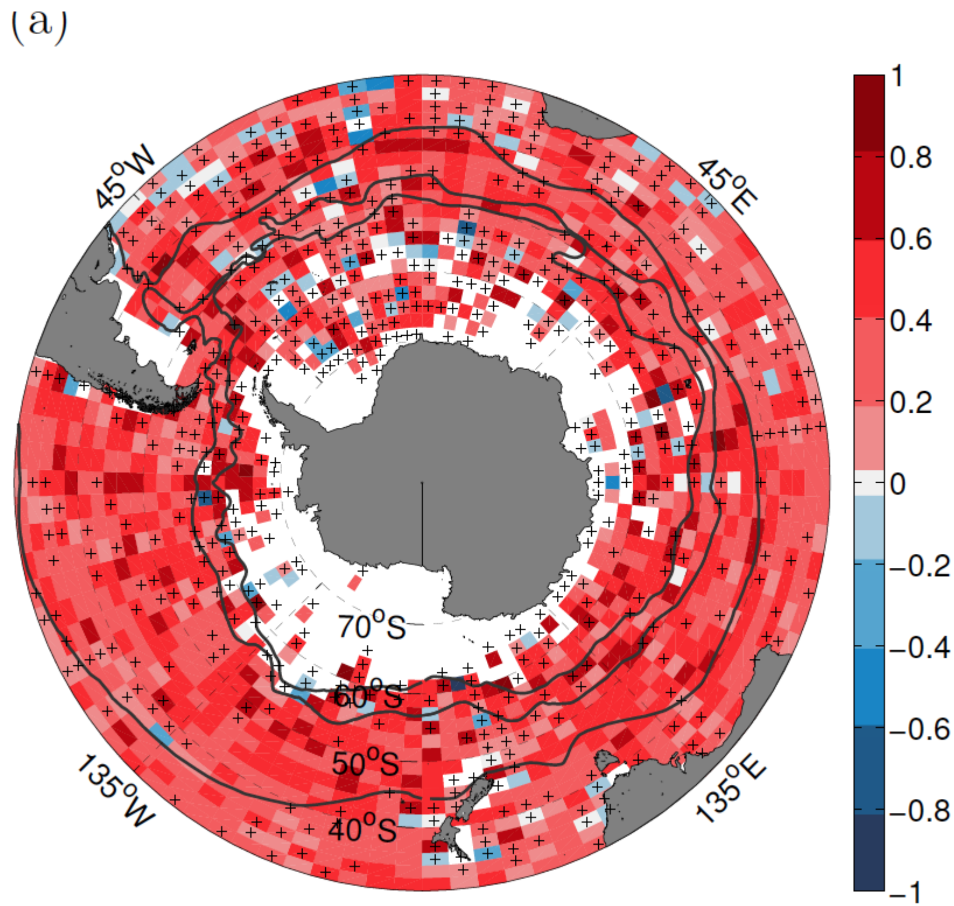
Mean wind speed, Carranza and Gille, 2014, JGR, in press

In summer, high winds imply cold temperatures



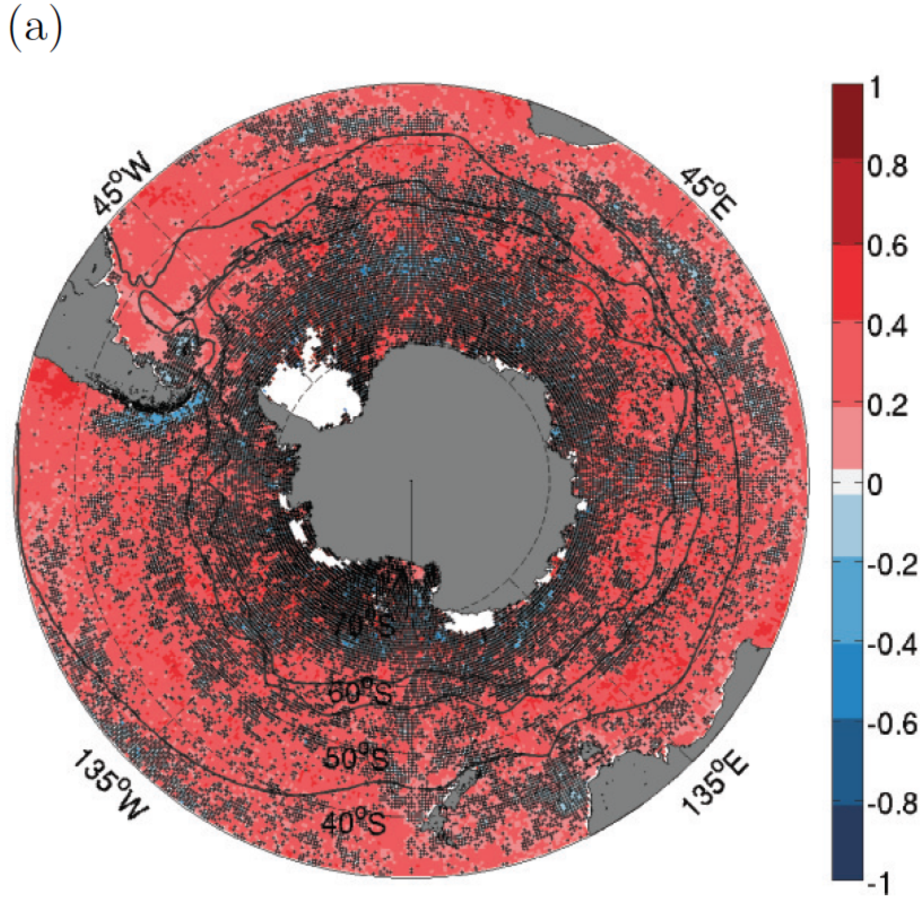
Partial correlation: wind stress vs SST, controlled for surface flux, Carranza and Gille, 2014, JGR, in press

High winds imply deep summer mixed layers



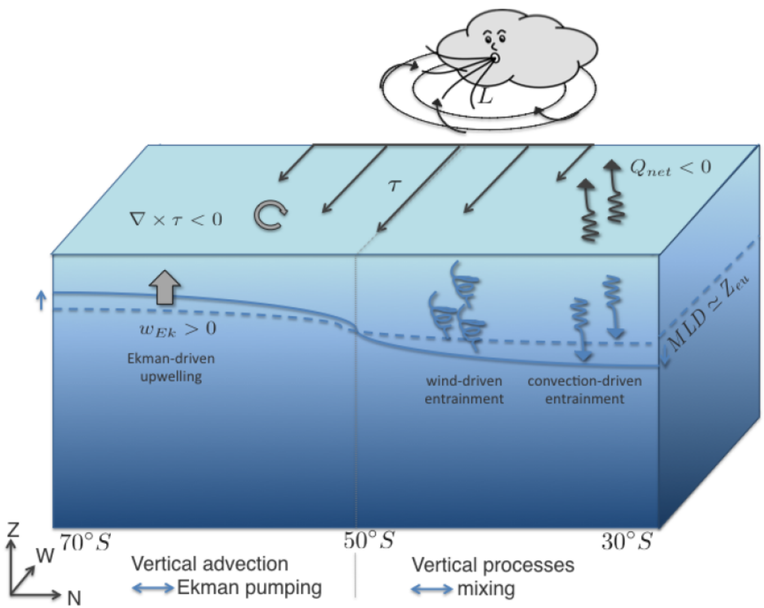
Correlation: wind stress vs mixed-layer depth, Carranza and Gille, 2014, JGR, in press

High winds imply high summer chl-a



Correlation: wind stress vs chl-a, Carranza and Gille, 2014, JGR, in press

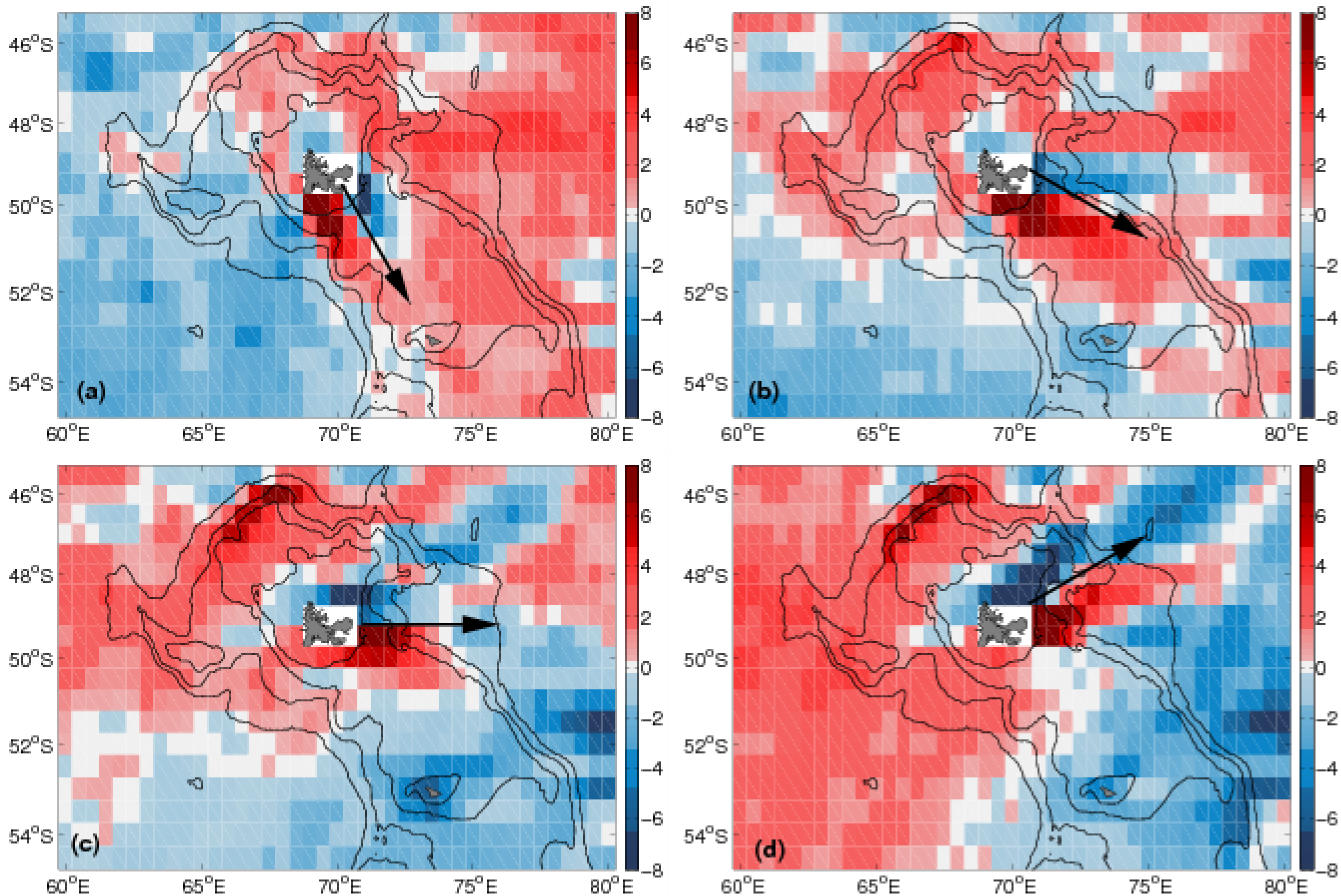
Winds, heat fluxes and Chl-a



Carranza and Gille, 2014, JGR, in press

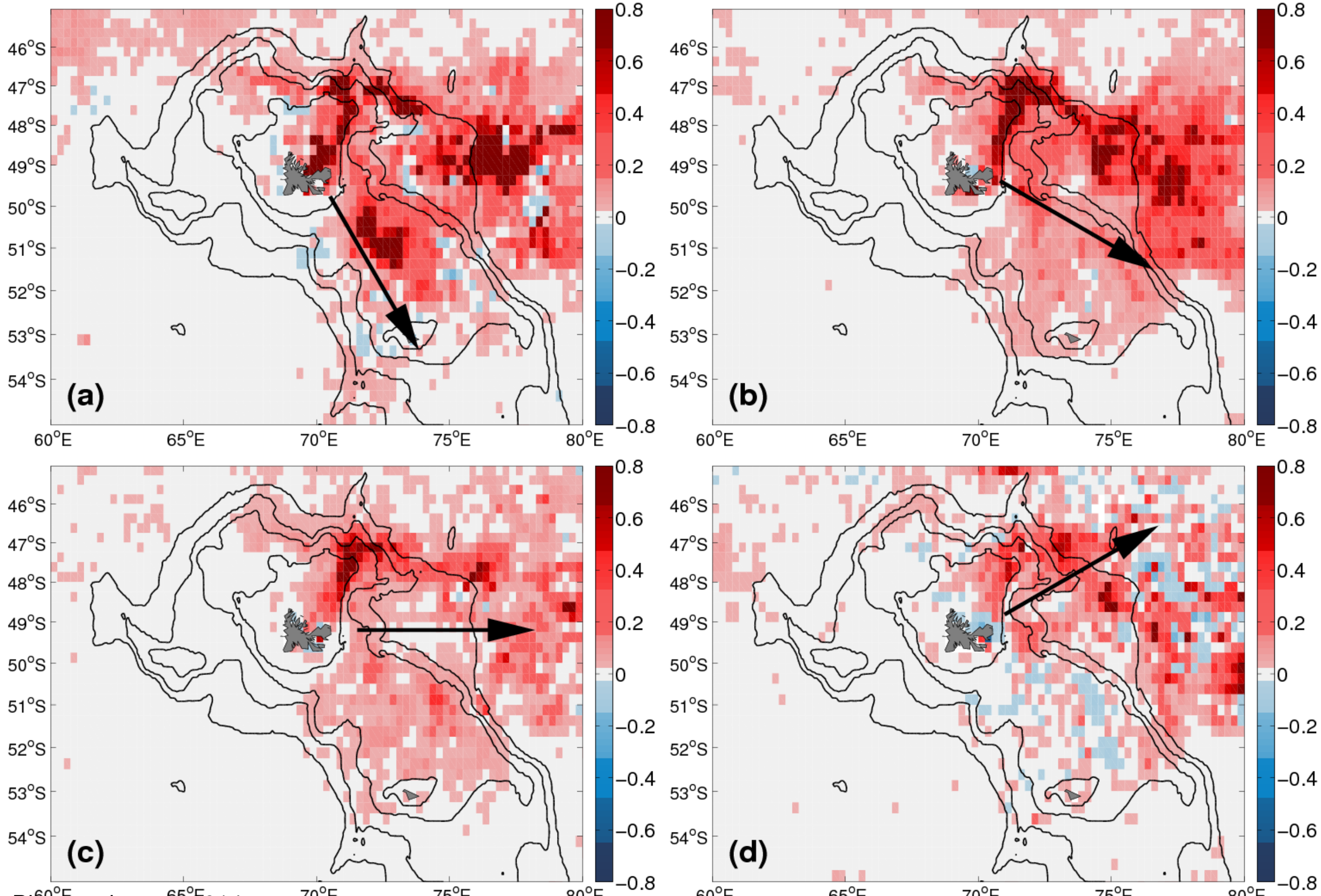
- In summer, stronger winds deepen the mixed layer, resulting in colder SSTs, (nutrient upwelling), and higher Chl-a
- Air-sea fluxes control SST and Chl-a as well, but play a slightly smaller role.
- Year-round averages (not shown) differ from summer values, presumably because mixed layer and stratification are different in winter.

Wind-stress curl shifts with changing wind direction



Kerguelen Island—-Gille et al, Biogeosciences, 2014

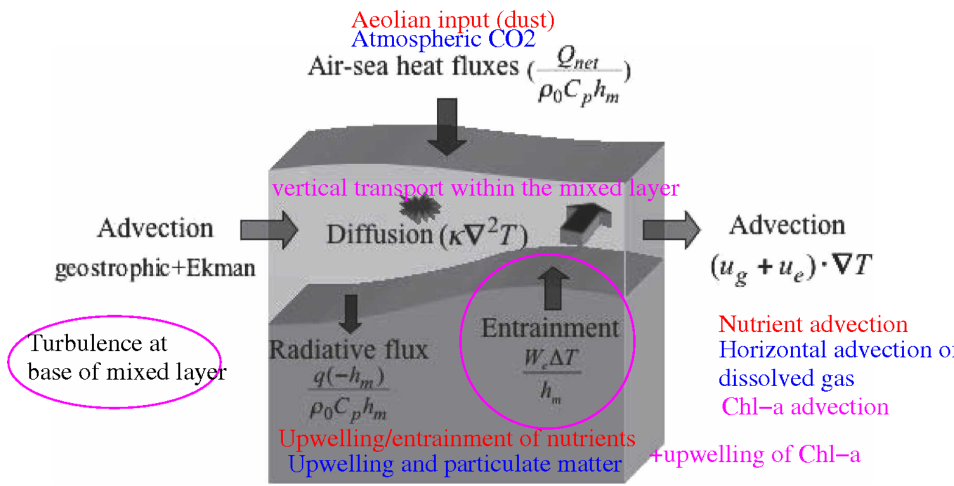
Spring-summer chl-a anomalies higher in areas of curl-induced upwelling



Gille et al, Biogeosciences, 2014

Summary: What aspects of this matter for Southern Ocean carbon?

- Atmospheric inputs of heat (and dust) have substantial uncertainties.
- Upper ocean heat budget strongly depends on entrainment; for heat we can integrate deeper but for biological processes we might need to characterize entrainment.
- Mixed-layer may not always be as homogenized as we hope when we look at satellite data; turbulent exchanges at the base of the mixed layer will need examination.



What would it take to improve air-sea flux estimates?

- **Ship-based observations:**
  - — Auto-flux measurement system used in UK, but not on US ships.
  - — Flow distortion serious problem for Gould, and not yet characterized.
  - — Scott Miller (SUNY Albany) operated from Palmer in test mode....
- **Aircraft:**
  - — Challenges with icing and grounding.
  - — Limited duration campaigns.
- **UAVs/Drones:**
  - — Can take make risks than aircraft (maybe),
  - — ... but technology still developing.

RVIB N. B. Palmer,

photo credit: CDRAKE project, Scripps Inst. Oceanography

What would it take to improve air-sea flux estimates?

- **Moorings:**
  - — Challenging to keep deployed in high wind/wave conditions.
  - — Traditionally measure meteorological variables for bulk formulae but not turbulent fluxes.
  - — Bulk formulae not fully characterized, particularly for high wind/wave conditions.

IMOS mooring, Eric Schultz, Australian Bureau of Meteorology,

from SOOS Science Strategy document

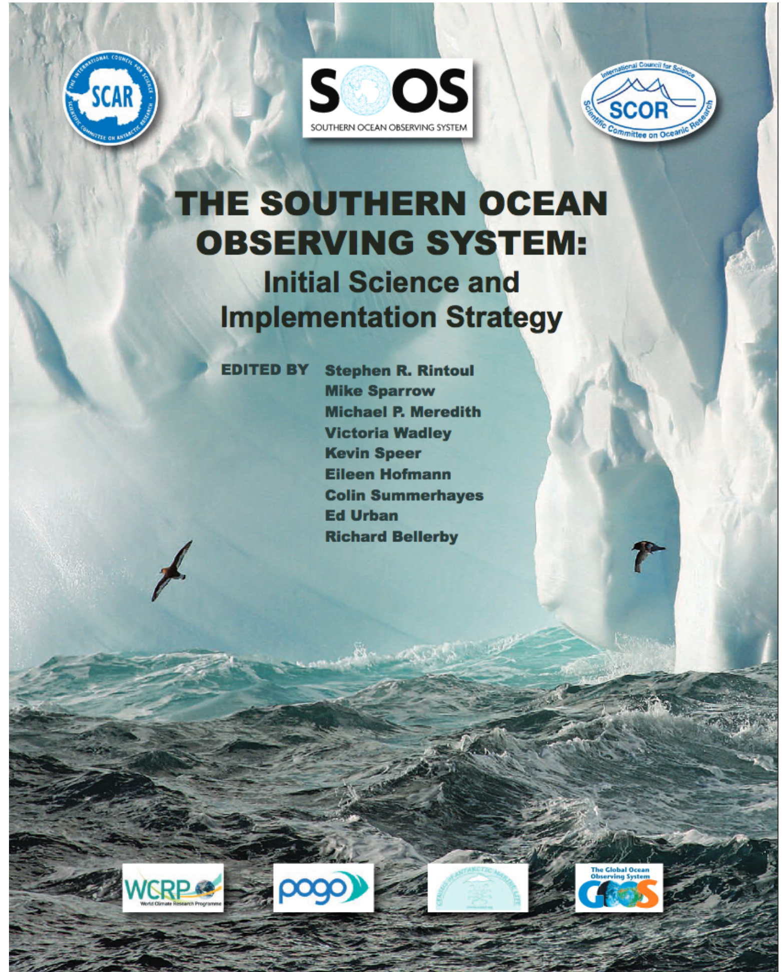
What's Next? Ocean Observatories Initiative moorings

- Ocean Observatories Initiative moorings: Deployment in February and March 2015 in southeast Pacific and Argentine Basin
  - — surface fluxes (bulk)
  - — surface fluxes (direct covariance)
  - — CO_2 flux
  - — surface wave spectra
- SOCRATES: Southern Ocean Clouds, Radiation and Aerosol Transport Experimental Studies (2016/17 or 2017/18)

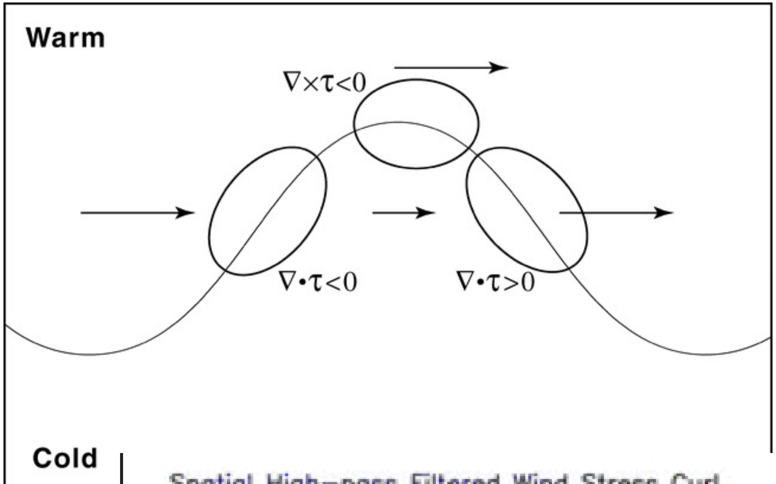
What's Next? Towards Improved Southern Ocean Air-Sea Fluxes

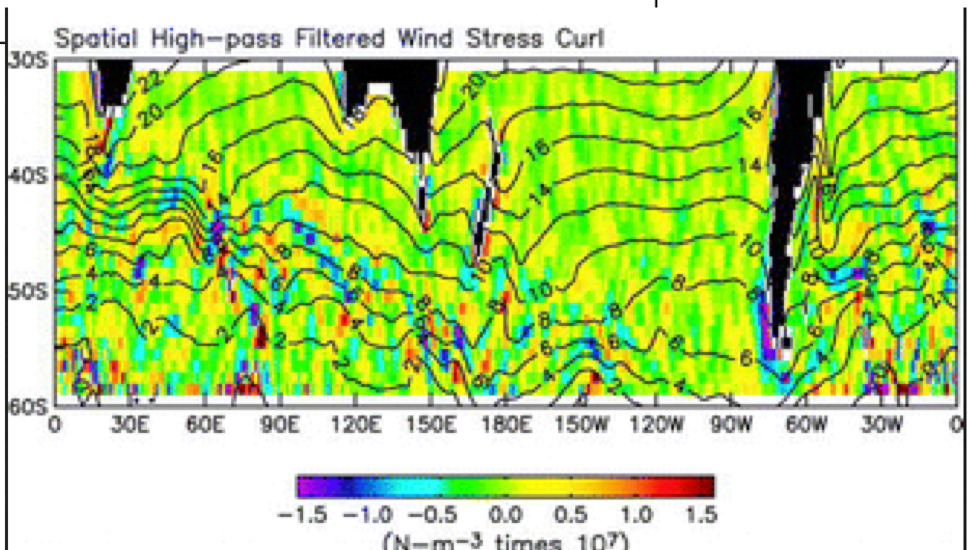
Southern Ocean Observing System (SOOS) coordinating workshop.

- tentatively Frascati, Italy in September 2015, hosted by ESRIN
- prospectus has been drafted
- input and participation welcome
- marginal ice zone and open ocean
- 3 pronged effort:
  - — in situ observations
  - — remote sensing
  - — reanalysis/assimilation/coupled assimilation



SST modulates wind

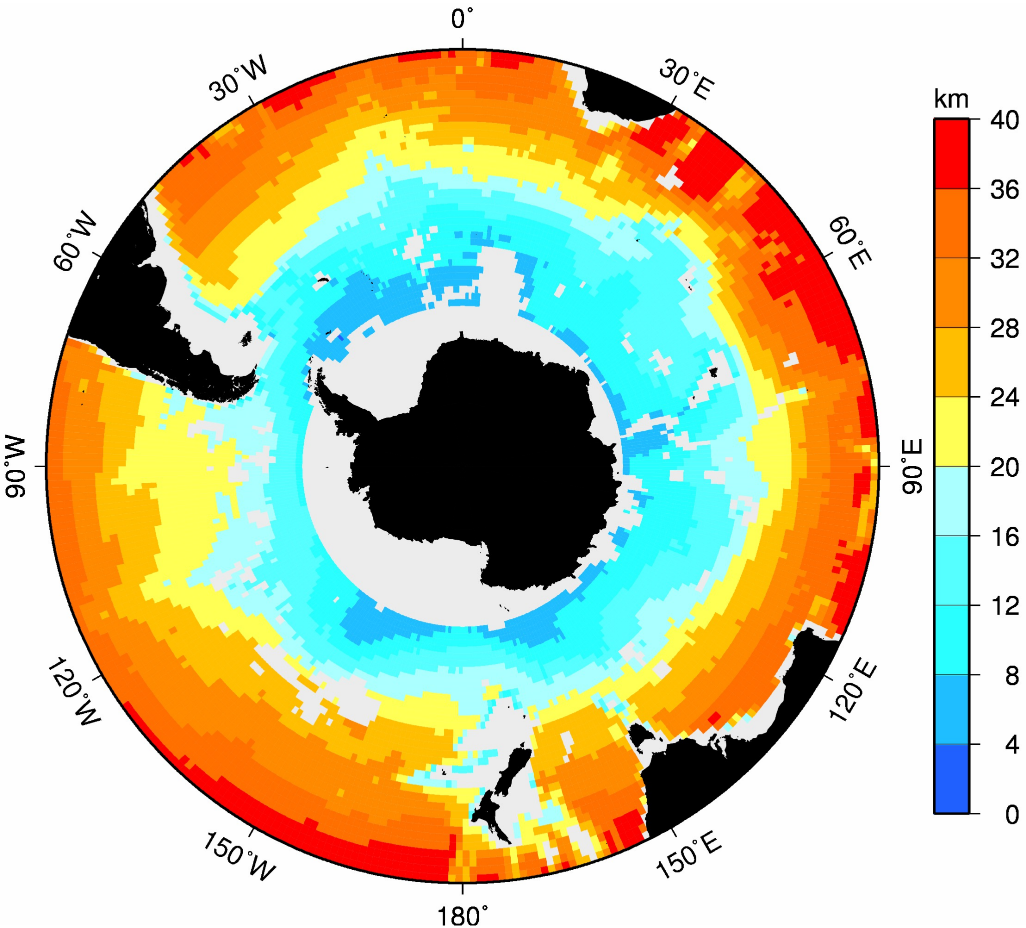




- Wind accelerates over warm SSTs, leading to enhanced gradients in wind stress (and wind-stress curl)

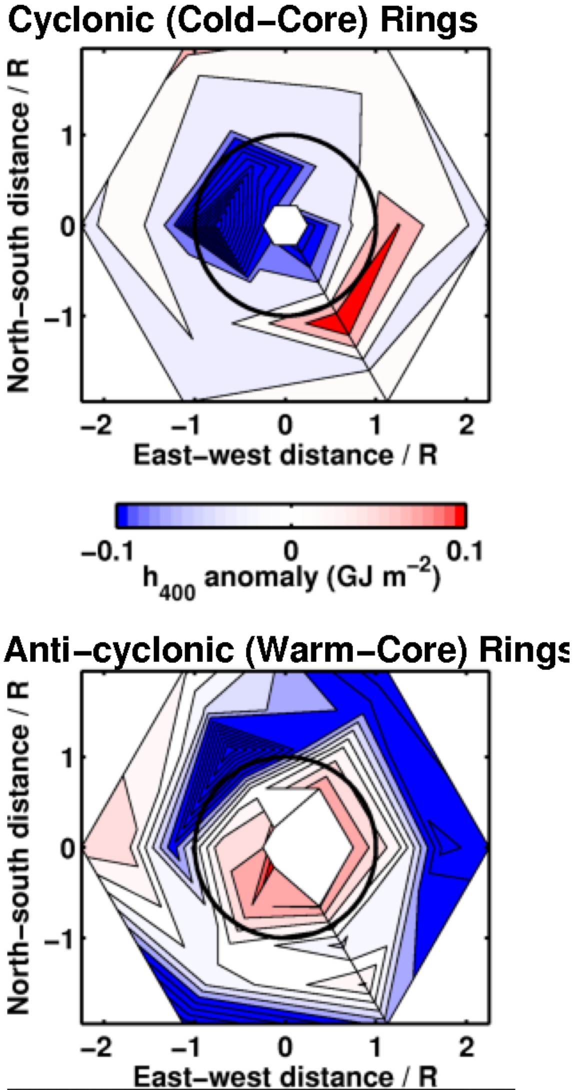
O'Neill et al, J. Climate, 2003

Air-sea exchange at the eddy scale



adapted from Chelton et al, JPO, 1998

- Southern Ocean Rossby radii: O(5-20 km).
- At limits of observing system.
- Small-scale structures can modulate air-sea fluxes.



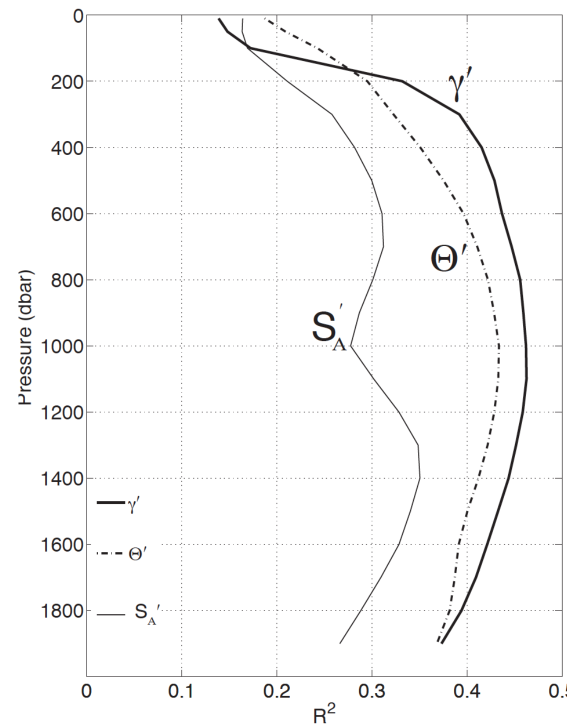
Ocean eddies modulate SST

- Cyclonic and anti-cyclonic eddies both have east-west asymmetry.
- Similar results for ocean color.
- Suggest eddies could influence air-sea temperature difference at sub-mesoscale.

Stephenson et al., JGR-Oceans, 2013

Upper-ocean heat budgets: where we stand

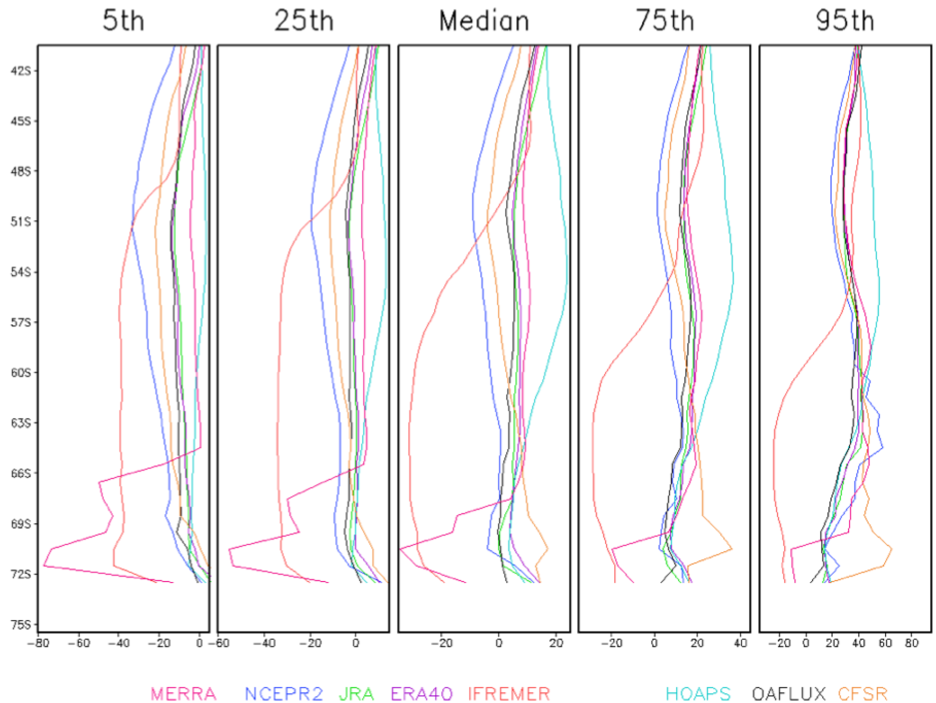
- Upper-ocean heat budget depends on air-sea fluxes and entrainment effects.
- Air-sea fluxes are hard to measure.
- Entrainment issues can be skirted by integrating deeper in the water column.
- Eddies are the biggest non-seasonal process.



Correlation coefficients: sea surface height and Argo

Zajaczkovski and Gille, in prep, 2014

Can we close upper ocean heat budget better by measuring fluxes?



Bourassa et al, BAMS, 2013

- Sensible heat flux estimates disagree in median and in higher moments.
- Latent heat flux and radiative fluxes show similar ranges.