Energetics of the Southern Ocean Mode

André Jüling
with
Jan Viebahn, Henk Dijkstra, Sybren Drijfhout & Anna von der Heydt

IMAU
Utrecht University

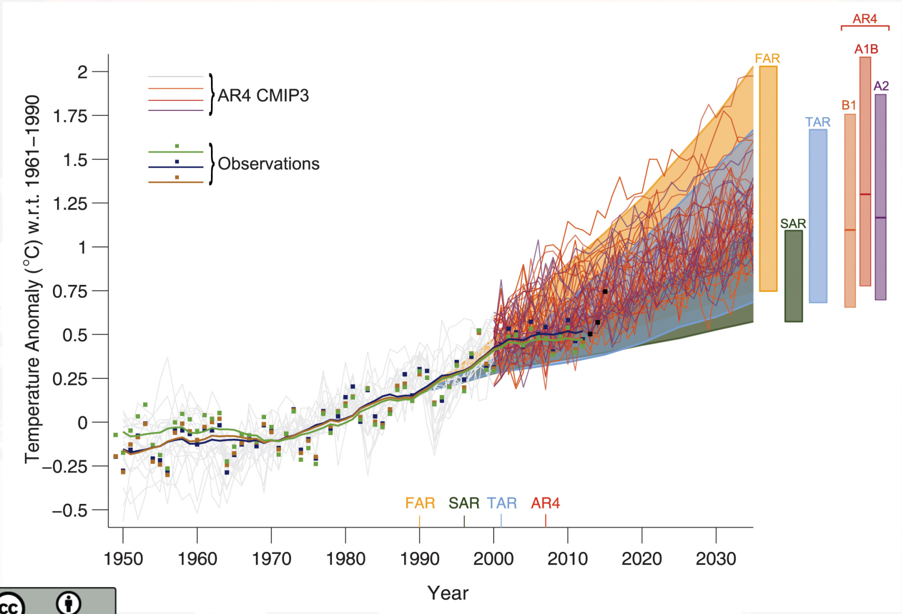
EGU General Assembly
09.04.2018

Utrecht University

IMAU
Institute for Marine and Atmospheric research Utrecht

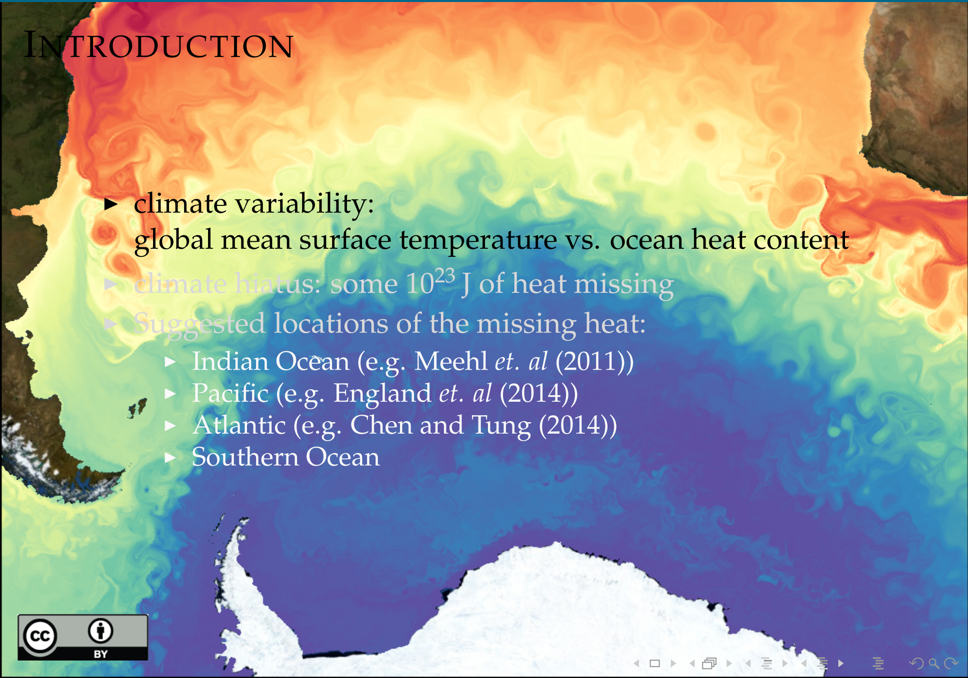
NESSC
NETHERLANDS EARTH SYSTEM SCIENCE CENTRE

CC BY


AR4 CMIP3
Observations
Temperature Anomaly (°C) w.r.t. 1961–1990
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
−0.25
−0.5
FAR SAR TAR AR4
1950 1960 1970 1980 1990 2000 2010 2020 2030
Year
FAR
SAR
TAR
AR4
B1
A1B
A2

CC BY

Introduction



- climate variability:
  global mean surface temperature vs. ocean heat content
- climate hiatus: some 10^{23} J of heat missing
- Suggested locations of the missing heat:
  - Indian Ocean (e.g. Meehl *et. al* (2011))
  - Pacific (e.g. England *et. al* (2014))
  - Atlantic (e.g. Chen and Tung (2014))
  - Southern Ocean

CC BY

Introduction

- climate variability:
  global mean surface temperature vs. ocean heat content
- climate hiatus: some 10^{23} J of heat missing
- Suggested locations of the missing heat:
  - Indian Ocean (e.g. Meehl *et. al* (2011))
  - Pacific (e.g. England *et. al* (2014))
  - Atlantic (e.g. Chen and Tung (2014))
  - Southern Ocean

cc BY

INTRODUCTION

- climate variability:
  global mean surface temperature vs. ocean heat content
- climate hiatus: some 10^{23} J of heat missing
- Suggested locations of the missing heat:
  - Indian Ocean (e.g. Meehl *et. al* (2011))
  - Pacific (e.g. England *et. al* (2014))
  - Atlantic (e.g. Chen and Tung (2014))
  - Southern Ocean

CC BY

Introduction

- climate variability:
  global mean surface temperature vs. ocean heat content
- climate hiatus: some 10^{23} J of heat missing
- Suggested locations of the missing heat:
  - Indian Ocean (e.g. Meehl *et. al* (2011))
  - Pacific (e.g. England *et. al* (2014))
  - Atlantic (e.g. Chen and Tung (2014))
  - Southern Ocean

Introduction

- climate variability:
  global mean surface temperature vs. ocean heat content
- climate hiatus: some 10^{23} J of heat missing
- Suggested locations of the missing heat:
  - Indian Ocean (e.g. Meehl *et. al* (2011))
  - Pacific (e.g. England *et. al* (2014))
  - Atlantic (e.g. Chen and Tung (2014))
  - Southern Ocean

cc BY

Introduction

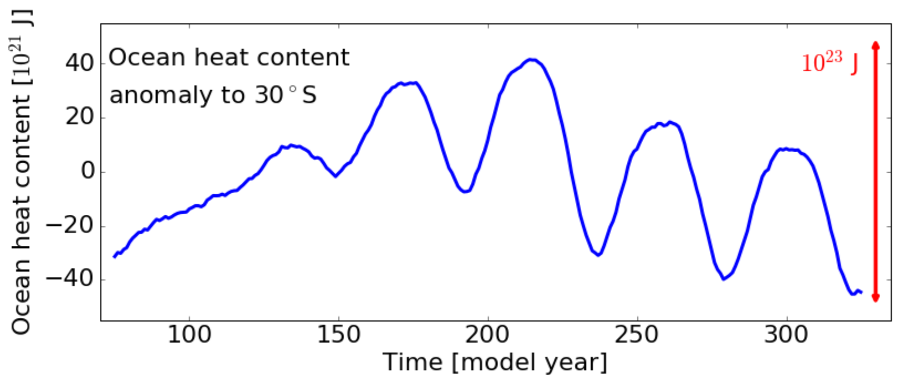
- climate variability:
  global mean surface temperature vs. ocean heat content
- climate hiatus: some 10^{23} J of heat missing
- Suggested locations of the missing heat:
  - Indian Ocean (e.g. Meehl *et. al* (2011))
  - Pacific (e.g. England *et. al* (2014))
  - Atlantic (e.g. Chen and Tung (2014))
  - Southern Ocean

Introduction

- climate variability:
  global mean surface temperature vs. ocean heat content
- climate hiatus: some 10^{23} J of heat missing
- Suggested locations of the missing heat:
  - Indian Ocean (e.g. Meehl *et. al* (2011))
  - Pacific (e.g. England *et. al* (2014))
  - Atlantic (e.g. Chen and Tung (2014))
  - Southern Ocean

CC BY

INTRODUCTION

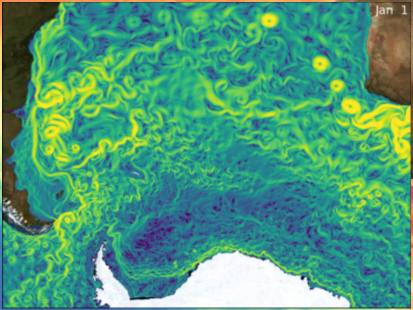


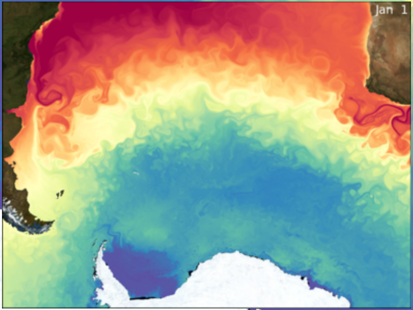
CC BY

Model

Parallel Ocean Program

- high resolution: $0.1° \approx 10\,\mathrm{km}$
  $\Rightarrow$ meso-scale eddies
- ocean only configuration
  $\Rightarrow$ oceanic processes are isolated
- repeated monthly mean climatological forcing
  $\Rightarrow$ every mode of variability that is not diurnal or seasonal is internal
- 325 model years, last 50 full output



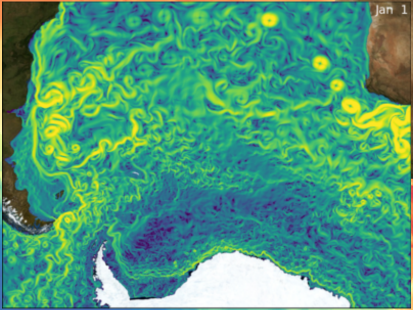


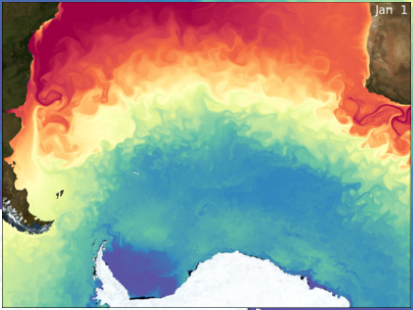
cc BY

Model

Parallel Ocean Program

- high resolution: $0.1° \approx 10\,\text{km}$ $\Rightarrow$ meso-scale eddies
- ocean only configuration $\Rightarrow$ oceanic processes are isolated
- repeated monthly mean climatological forcing $\Rightarrow$ every mode of variability that is not diurnal or seasonal is internal
- 325 model years, last 50 full output



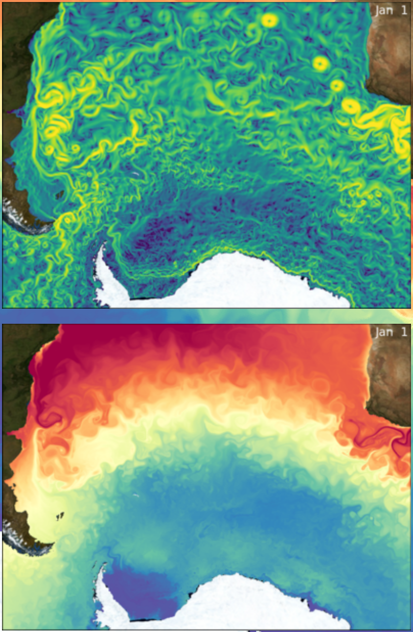


BY

Model

Parallel Ocean Program

- high resolution: $0.1° \approx 10\,\text{km}$
  $\Rightarrow$ meso-scale eddies
- ocean only configuration
  $\Rightarrow$ oceanic processes are isolated
- repeated monthly mean climatological forcing
  $\Rightarrow$ every mode of variability that is not diurnal or seasonal is internal
- 325 model years,
  last 50 full output

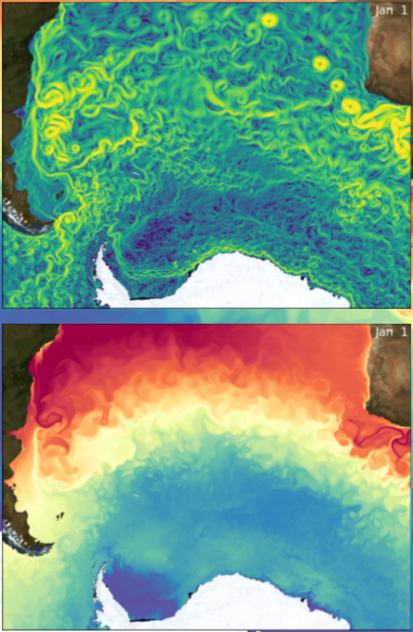


CC BY

Model

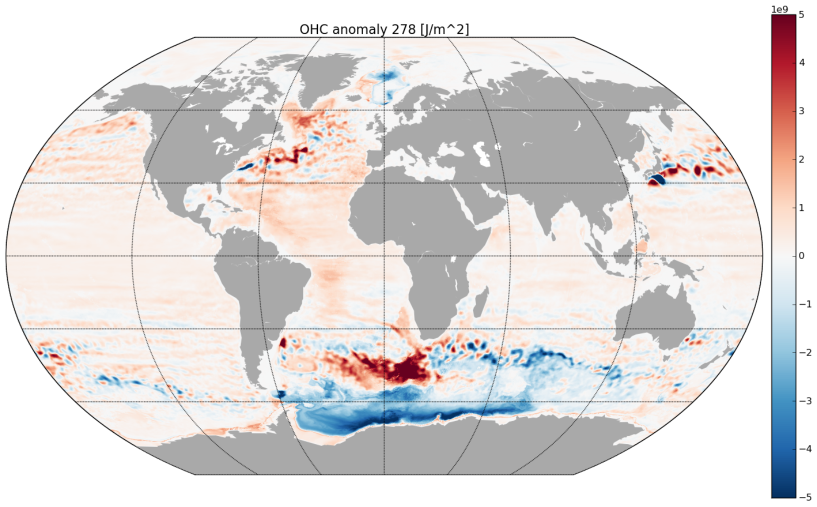
Parallel Ocean Program

- high resolution: $0.1° \approx 10\,\mathrm{km}$
  $\Rightarrow$ meso-scale eddies
- ocean only configuration
  $\Rightarrow$ oceanic processes are isolated
- repeated monthly mean climatological forcing
  $\Rightarrow$ every mode of variability that is not diurnal or seasonal is internal
- 325 model years, last 50 full output



CC BY

Southern Ocean heat content anomaly



Southern Ocean Mode

- 50 yr cycle in ocean heat content
- not seen in low-resolution model ⇒ eddies seem essential

Research question

What causes the Southern Ocean Mode?

Proposed mechanism: eddies – mean flow interaction

- eddies interact with mean flow to alter energy input
- mechanism proposed by Hogg et al. (2005) for quasi-geostrophic model
- description in mechanical energy framework

CC BY

Southern Ocean Mode

- 50 yr cycle in ocean heat content
- not seen in low-resolution model ⇒ eddies seem essential

Research question

What causes the Southern Ocean Mode?

Proposed mechanism: eddies – mean flow interaction

- eddies interact with mean flow to alter energy input
- mechanism proposed by Hogg et al. (2005) for quasi-geostrophic model
- description in mechanical energy framework

CC BY

Southern Ocean Mode

- 50 yr cycle in ocean heat content
- not seen in low-resolution model ⇒ eddies seem essential

Research question

What causes the Southern Ocean Mode?

Proposed mechanism: eddies – mean flow interaction

- eddies interact with mean flow to alter energy input
- mechanism proposed by Hogg et al. (2005) for quasi-geostrophic model
- description in mechanical energy framework

CC BY

Southern Ocean Mode

- 50 yr cycle in ocean heat content
- not seen in low-resolution model $\Rightarrow$ eddies seem essential

Research question

What causes the Southern Ocean Mode?

Proposed mechanism: eddies – mean flow interaction

- eddies interact with mean flow to alter energy input
- mechanism proposed by Hogg et al. (2005) for quasi-geostrophic model
- description in mechanical energy framework

CC BY

Lorenz Energy Cycle

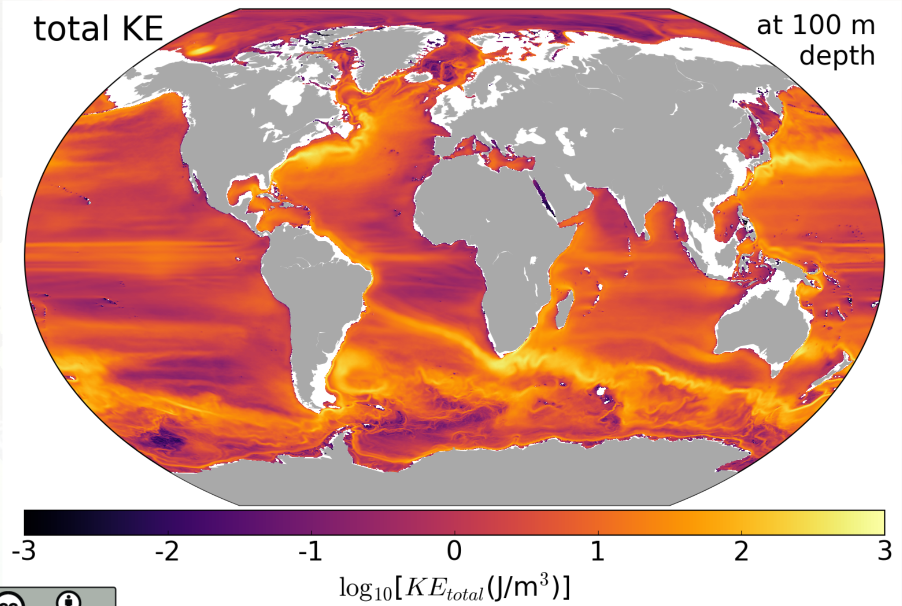
Mechanical energy balance of the ocean

1. Reservoirs
   - Kinetic Energy (KE)
   - Available Potential Energy (APE)
2. Generation
   - KE: wind stress forcing $\propto \vec{u} \cdot \vec{\tau}$
   - APE: buoyancy fluxes (heat and salinity)
3. Conversion
   - APE $\leftrightarrow$ KE: vertical movement of water
4. Dissipation
   - steady state assumption: dissipation = residual

Eddy-mean decomposition: $\overline{xy} = \bar{x}\bar{y} + \overline{x'y'}$ with $\bar{x} = \frac{1}{T}\int_0^T x \, \mathrm{d}t$

- additional eddy-mean conversion terms
  - KE: barotropic instab

CC BY



cc BY

Lorenz Energy Cycle

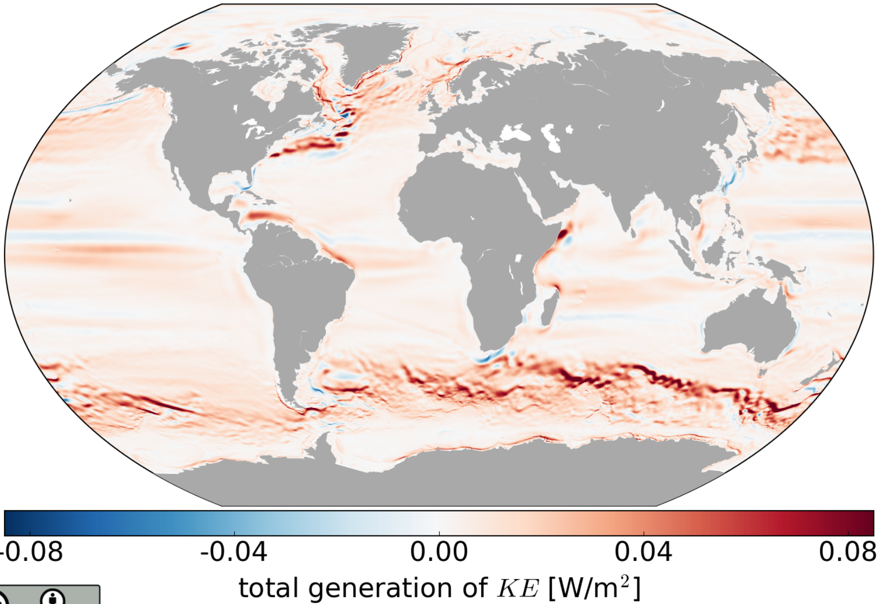
Mechanical Energy Balance of the Ocean

1. Reservoirs
   - Kinetic Energy (KE)
   - Available Potential Energy (APE)
2. Generation
   - KE: wind stress forcing $\propto \vec{u} \cdot \vec{\tau}$
   - APE: buoyancy fluxes (heat and salinity)
3. Conversion
   - APE $\leftrightarrow$ KE: vertical movement of water
4. Dissipation
   - steady state assumption: dissipation = residual

Eddy-mean decomposition: $\overline{xy} = \bar{x}\bar{y} + \overline{x'y'}$ with $\bar{x} = \frac{1}{T}\int_0^T x \, \mathrm{d}t$

- additional eddy-mean conversion terms
  - KE: [illegible]rotropic instab[illegible]

CC BY



CC BY

Lorenz Energy Cycle

Mechanical energy balance of the ocean

1. Reservoirs
   - Kinetic Energy (KE)
   - Available Potential Energy (APE)
2. Generation
   - KE: wind stress forcing $\propto \vec{u} \cdot \vec{\tau}$
   - APE: buoyancy fluxes (heat and salinity)
3. Conversion
   - APE $\leftrightarrow$ KE: vertical movement of water
4. Dissipation
   - steady state assumption: dissipation = residual

Eddy-mean decomposition: $\overline{xy} = \bar{x}\bar{y} + \overline{x'y'}$ with $\bar{x} = \frac{1}{T}\int_0^T x \, \mathrm{d}t$

- additional eddy-mean conversion terms
  - KE: [illegible]rotropic instab

CC BY

Lorenz Energy Cycle

Mechanical energy balance of the ocean

1. Reservoirs
   - Kinetic Energy (KE)
   - Available Potential Energy (APE)
2. Generation
   - KE: wind stress forcing $\propto \vec{u} \cdot \vec{\tau}$
   - APE: buoyancy fluxes (heat and salinity)
3. Conversion
   - APE $\leftrightarrow$ KE: vertical movement of water
4. Dissipation
   - steady state assumption: dissipation = residual

Eddy-mean decomposition: $\overline{xy} = \bar{x}\bar{y} + \overline{x'y'}$ with $\bar{x} = \frac{1}{T}\int_0^T x\,\mathrm{d}t$

- additional eddy-mean conversion terms
  - KE: barotropic instab

CC BY

Lorenz Energy Cycle

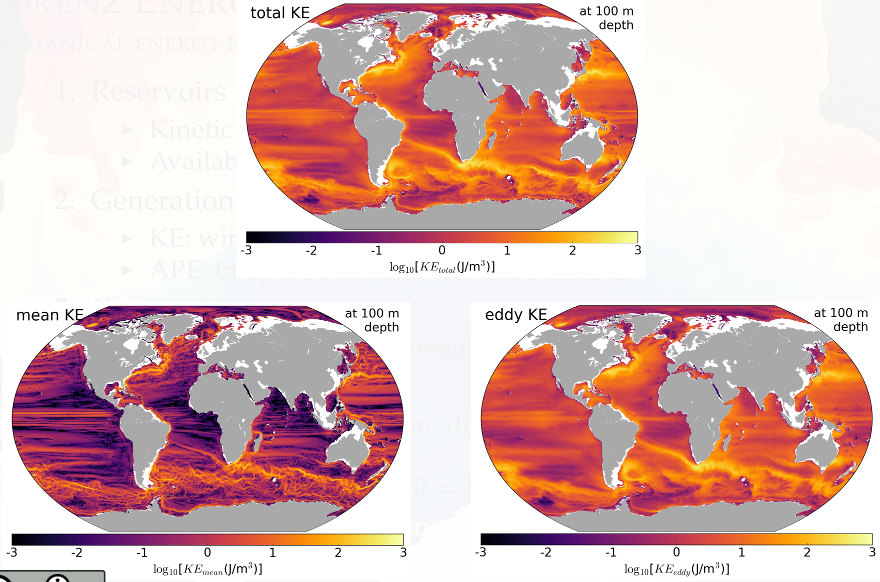
Mechanical energy balance of the ocean

1. Reservoirs
   - Kinetic Energy (KE)
   - Available Potential Energy (APE)
2. Generation
   - KE: wind stress forcing $\propto \vec{u} \cdot \vec{\tau}$
   - APE: buoyancy fluxes (heat and salinity)
3. Conversion
   - APE $\leftrightarrow$ KE: vertical movement of water
4. Dissipation
   - steady state assumption: dissipation = residual

Eddy-mean decomposition: $\overline{xy} = \bar{x}\bar{y} + \overline{x'y'}$ with $\bar{x} = \frac{1}{T}\int_0^T x \, \mathrm{d}t$

- additional eddy-mean conversion terms
  - KE: barotropic instab

CC BY


total KE
at 100 m depth
-3 -2 -1 0 1 2 3
$\log_{10}[KE_{total}$(J/m^3)]
mean KE
at 100 m depth
-3 -2 -1 0 1 2 3
$\log_{10}[KE_{mean}$(J/m^3)]
eddy KE
at 100 m depth
-3 -2 -1 0 1 2 3
$\log_{10}[KE_{eddy}$(J/m^3)]

CC BY

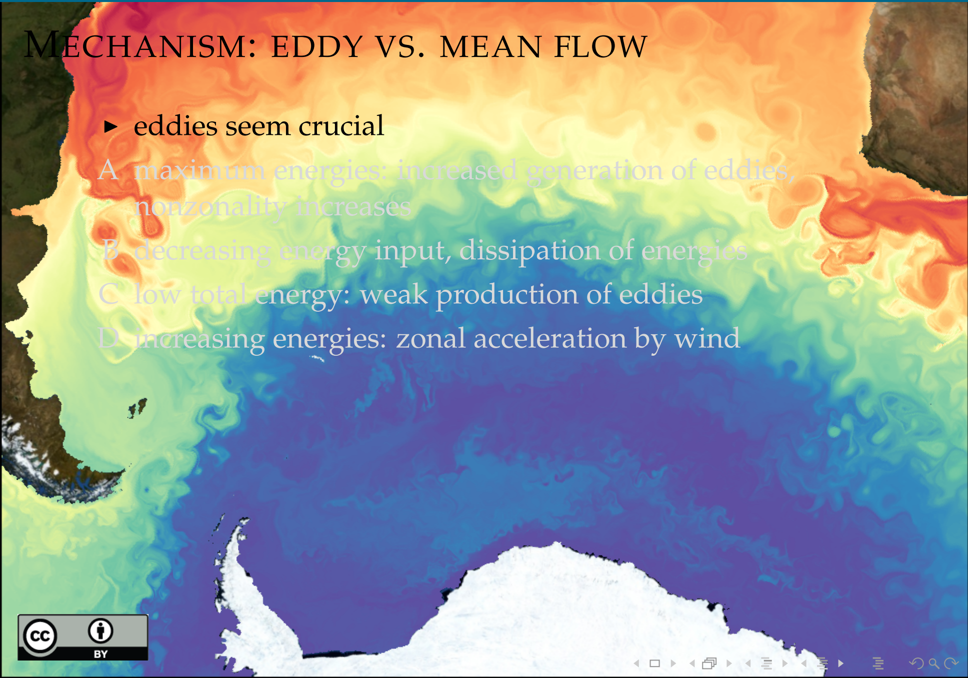
Lorenz Energy Cycle

Mechanical Energy Balance of the Ocean

1. Reservoirs
   - Kinetic Energy (KE)
   - Available Potential Energy (APE)
2. Generation
   - KE: wind stress forcing $\propto \vec{u} \cdot \vec{\tau}$
   - APE: buoyancy fluxes (heat and salinity)
3. Conversion
   - APE $\leftrightarrow$ KE: vertical movement of water
4. Dissipation
   - steady state assumption: dissipation = residual

Eddy-mean decomposition: $\overline{xy} = \bar{x}\bar{y} + \overline{x'y'}$ with $\bar{x} = \frac{1}{T}\int_0^T x \,\mathrm{d}t$

- additional eddy-mean conversion terms
  - KE: barotropic instability



Mechanism: Eddy vs. Mean Flow

- eddies seem crucial

A maximum energies: increased generation of eddies, nonzonality increases

B decreasing energy input, dissipation of energies

C low total energy: weak production of eddies

D increasing energies: zonal acceleration by wind

cc BY

Mechanism: eddy vs. mean flow

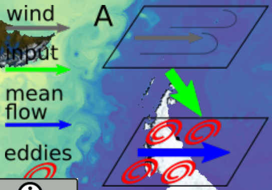
- eddies seem crucial

A maximum energies: increased generation of eddies, nonzonality increases

B decreasing energy input, dissipation of energies

C low total energy: weak production of eddies

D increasing energies: zonal acceleration by wind



CC BY

Mechanism: eddy vs. mean flow

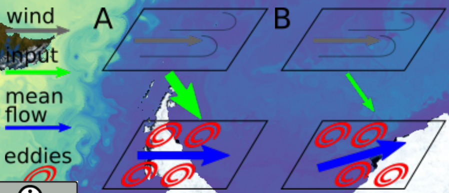
- eddies seem crucial

A maximum energies: increased generation of eddies, nonzonality increases

B decreasing energy input, dissipation of energies

C low total energy: weak production of eddies

D increasing energies: zonal acceleration by wind



CC BY

Mechanism: eddy vs. mean flow

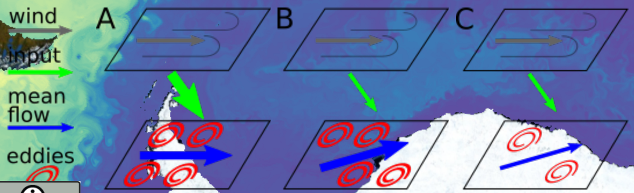
- eddies seem crucial

A maximum energies: increased generation of eddies, nonzonality increases

B decreasing energy input, dissipation of energies

C low total energy: weak production of eddies

D increasing energies: zonal acceleration by wind



cc BY

Mechanism: Eddy vs. Mean Flow

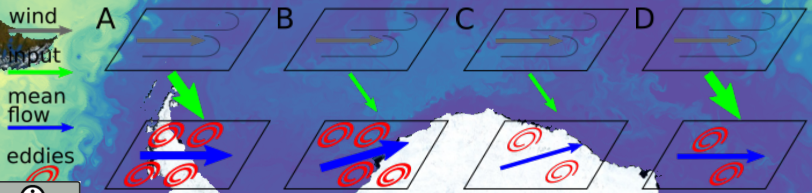
- eddies seem crucial

A maximum energies: increased generation of eddies, nonzonality increases

B decreasing energy input, dissipation of energies

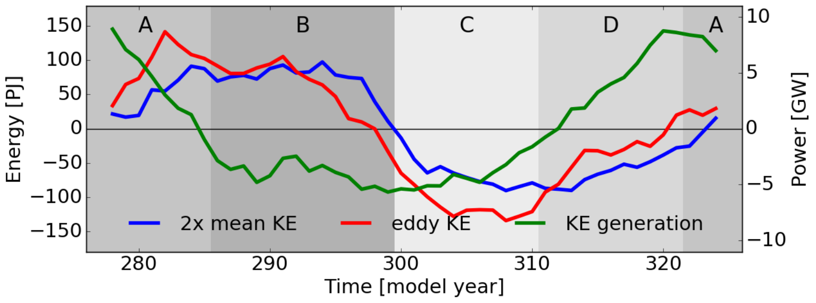
C low total energy: weak production of eddies

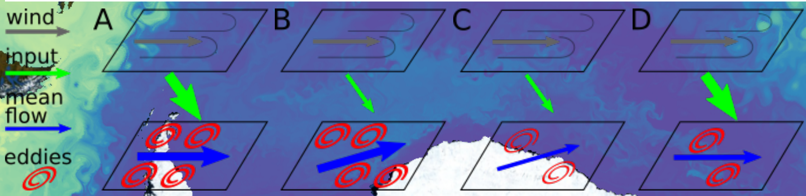
D increasing energies: zonal acceleration by wind



Mechanism: eddy vs. mean flow

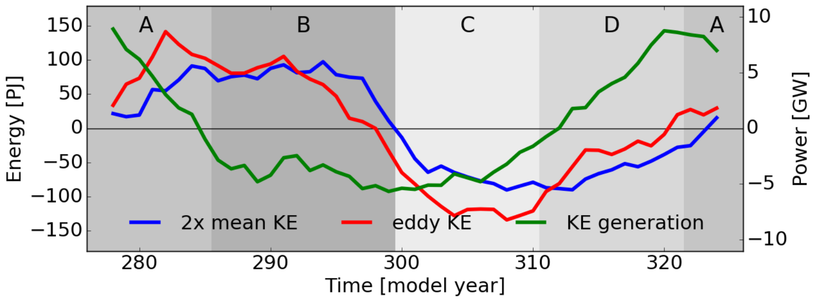
- eddies seem crucial





CC BY

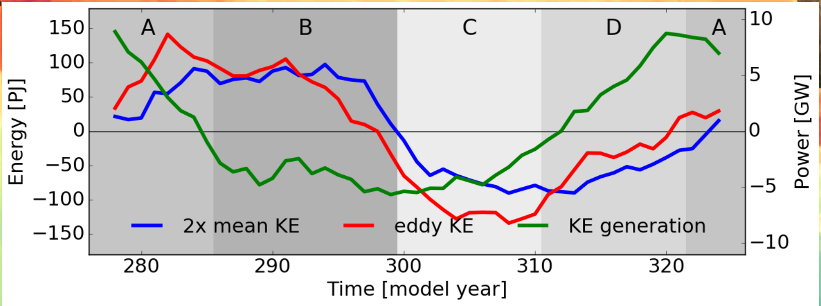
Hypothesis: Eddy vs. Mean Flow



The phasing of energy components supports the eddy-mean flow interaction as the cause of the SOM!

cc BY

Hypothesis: Eddy vs. mean flow



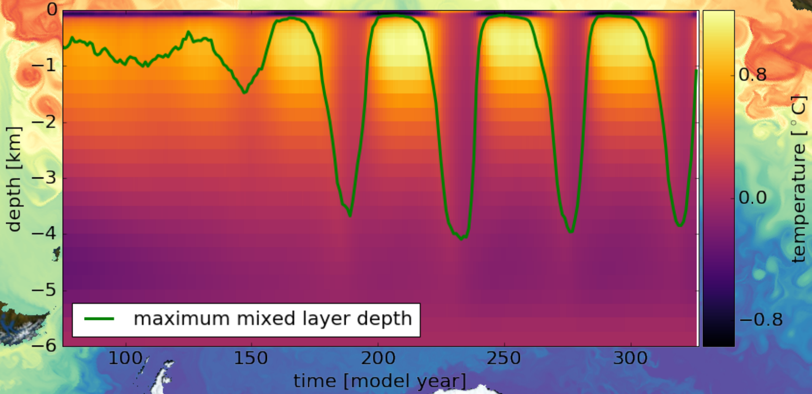
The phasing of energy components supports the eddy-mean flow interaction as the cause of the SOM!

cc BY

SOM consequences

Convection

- temperature in the Weddell gyre



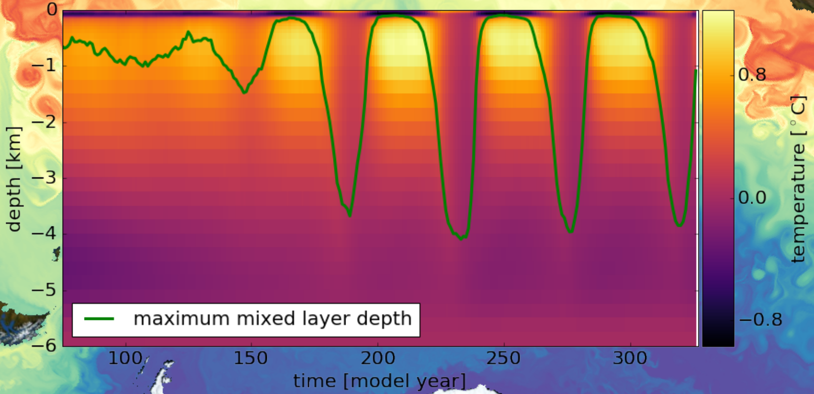
- observations: Weddell Polynya 1974-76 and 2017
- convection explains heat release

CC BY

SOM consequences

Convection

- temperature in the Weddell gyre



- observations: Weddell Polynya 1974-76 and 2017

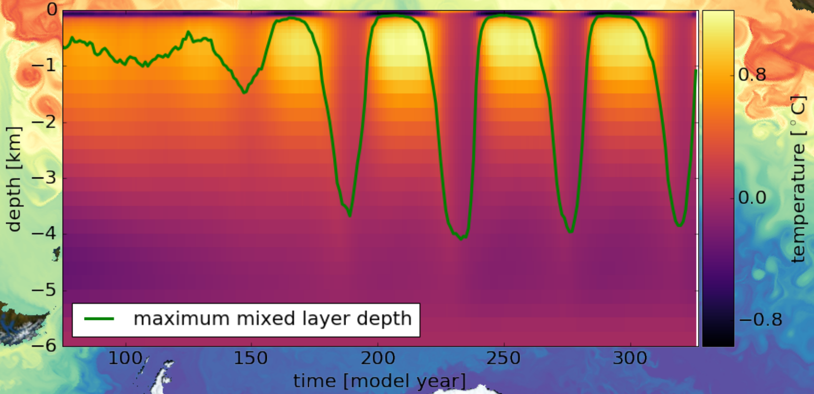
convection explains heat release

CC BY

SOM CONSEQUENCES

CONVECTION

- temperature in the Weddell gyre

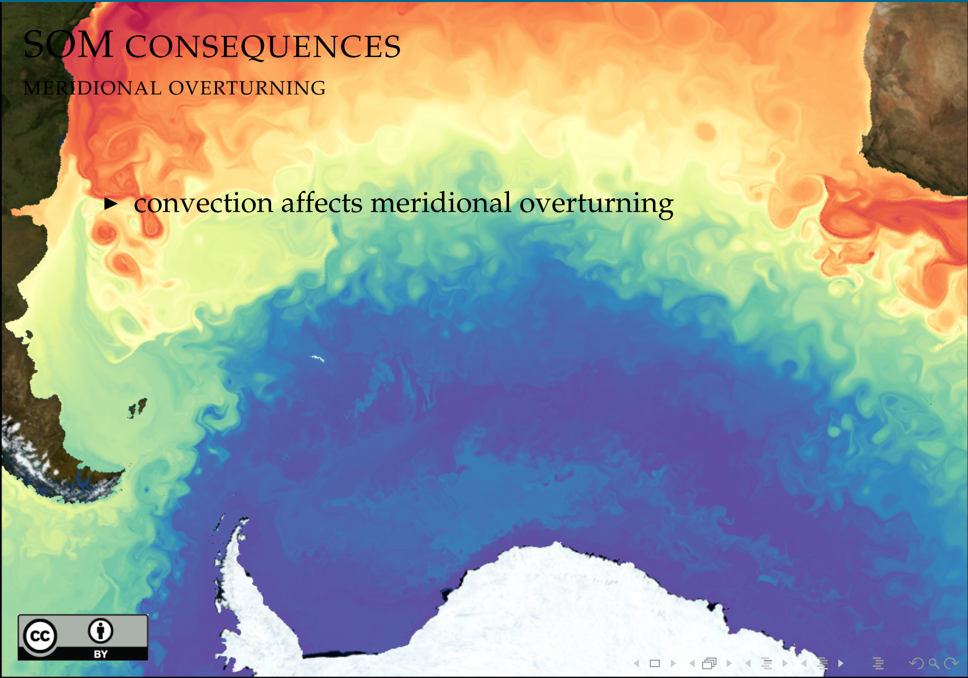


- observations: Weddell Polynya 1974-76 and 2017
- convection explains heat release

CC BY

SOM CONSEQUENCES

MERIDIONAL OVERTURNING



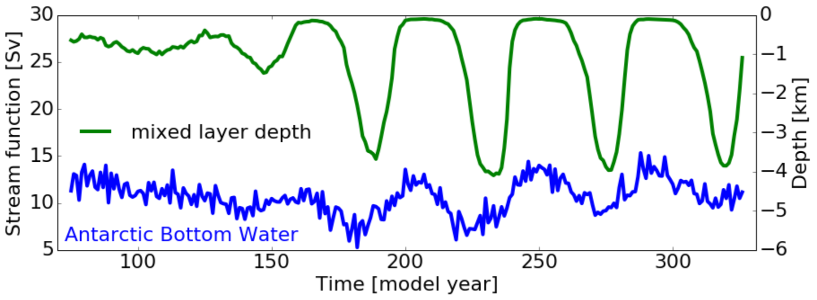
- convection affects meridional overturning

CC BY

SOM CONSEQUENCES

MERIDIONAL OVERTURNING

- convection affects meridional overturning

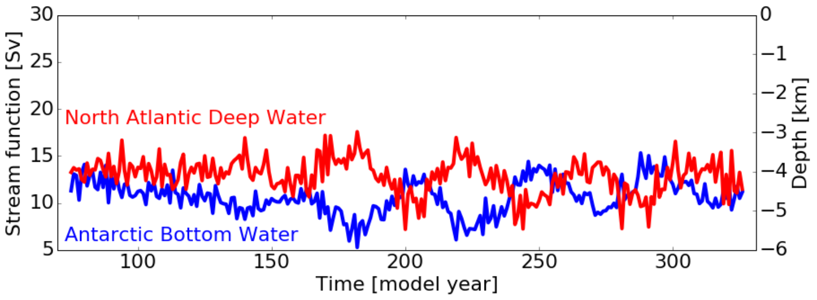


CC BY

SOM CONSEQUENCES

MERIDIONAL OVERTURNING

- convection affects meridional overturning

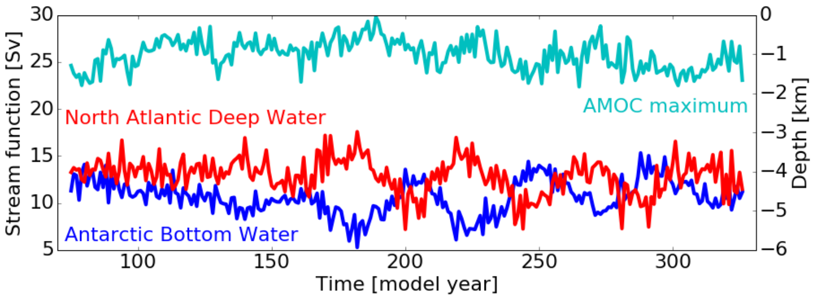


cc BY

SOM CONSEQUENCES

MERIDIONAL OVERTURNING

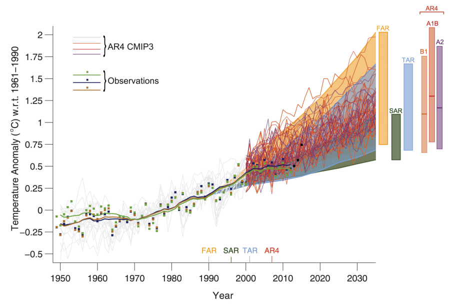
- convection affects meridional overturning



CC BY

Summary

- missing heat of the hiatus
- Southern Ocean Mode
  - 50 year period mode
- mechanical energy cycle
- eddy – mean flow interaction
  - correct phasing of energy components
  - eddies are crucial
- convection and its effects in overturning
  - associated heat release

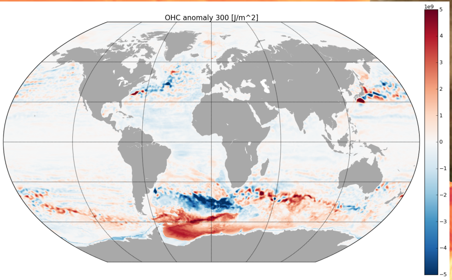


Conclusion

The eddy-mean flow interaction mechanisms likely causes the Southern Ocean Mode.

Summary

- missing heat of the hiatus
- Southern Ocean Mode
  - 50 year period mode
- mechanical energy cycle
- eddy – mean flow interaction
  - correct phasing of energy components
  - eddies are crucial
- convection and its effects in overturning
  - associated heat release



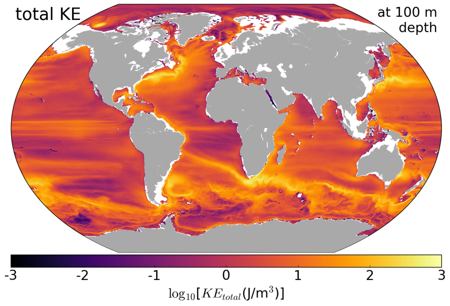
Conclusion

The eddy-mean flow interaction mechanisms likely causes the Southern Ocean Mode.

cc BY

Summary

- missing heat of the hiatus
- Southern Ocean Mode
  - 50 year period mode
- mechanical energy cycle
- eddy – mean flow interaction
  - correct phasing of energy components
  - eddies are crucial
- convection and its effects in overturning
  - associated heat release

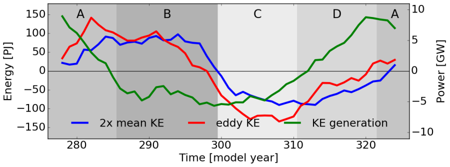


Conclusion

The eddy-mean flow interaction mechanisms likely causes the Southern Ocean Mode.

cc BY

Summary



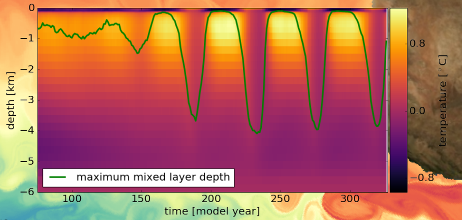
- missing heat of the hiatus
- Southern Ocean Mode
  - 50 year period mode
- mechanical energy cycle
- eddy – mean flow interaction
  - correct phasing of energy components
  - eddies are crucial
- convection and its effects in overturning
  - associated heat release

Conclusion

The eddy-mean flow interaction mechanisms likely causes the Southern Ocean Mode.

CC BY

Summary



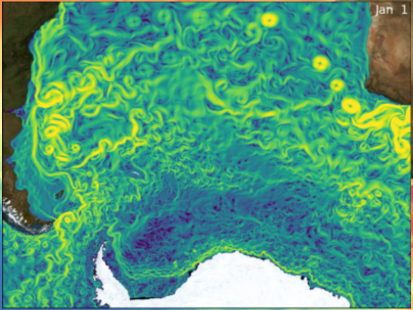
- missing heat of the hiatus
- Southern Ocean Mode
  - 50 year period mode
- mechanical energy cycle
- eddy – mean flow interaction
  - correct phasing of energy components
  - eddies are crucial
- convection and its effects in overturning
  - associated heat release

Conclusion

The eddy-mean flow interaction mechanisms likely causes the Southern Ocean Mode.

CC BY

Summary



- missing heat of the hiatus
- Southern Ocean Mode
  - 50 year period mode
- mechanical energy cycle
- eddy – mean flow interaction
  - correct phasing of energy components
  - eddies are crucial
- convection and its effects in overturning
  - associated heat release

Conclusion

The eddy-mean flow interaction mechanisms likely causes the Southern Ocean Mode.

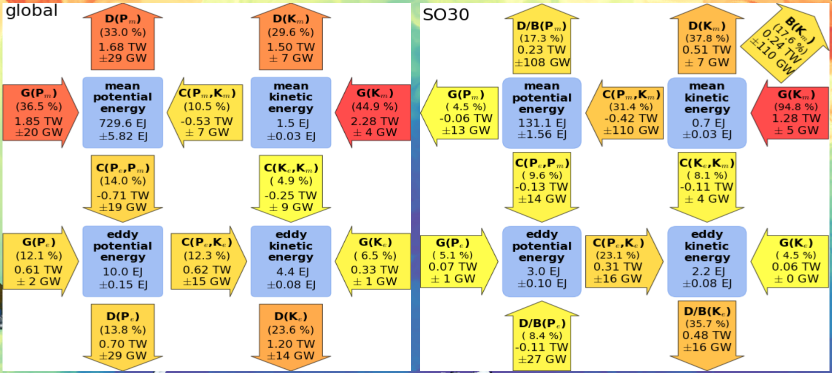
CC BY

Appendix

CC BY

Appendix

Complete Lorenz energy cycle

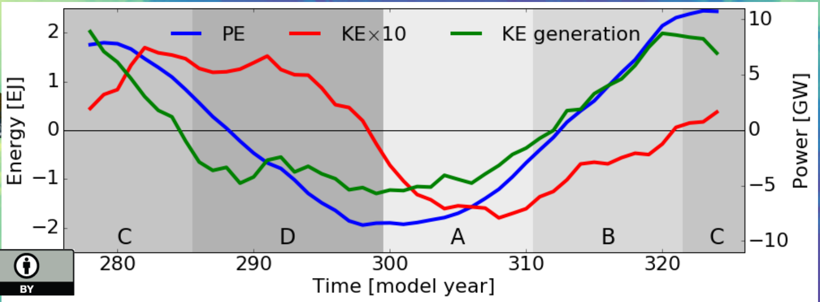


Appendix

APE phasing

different phase naming convention!

- A low total energy: weak production of eddies
- B increasing energies: zonal acceleration by wind & tilting of isopycnals
- C maximum energies: increased generation of eddies, nonzonality increases
- D decreasing energy input, dissipation of energies



CC BY

Appendix

LEC equations: reservoirs

$$P_m = -\frac{g}{2} \int_V \frac{1}{n_0} \bar{\rho}^{*2} \, \mathrm{d}V \tag{1}$$

$$P_e = -\frac{g}{2} \int_V \frac{1}{n_0} \overline{\rho^{*\prime 2}} \, \mathrm{d}V \tag{2}$$

$$K_m = \frac{\rho_0}{2} \int_V \left(\bar{u}^2 + \bar{v}^2 \right) \, \mathrm{d}V \tag{3}$$

$$K_e = \frac{\rho_0}{2} \int_V \left(\overline{u'^2 + v'^2} \right) \, \mathrm{d}V \tag{4}$$

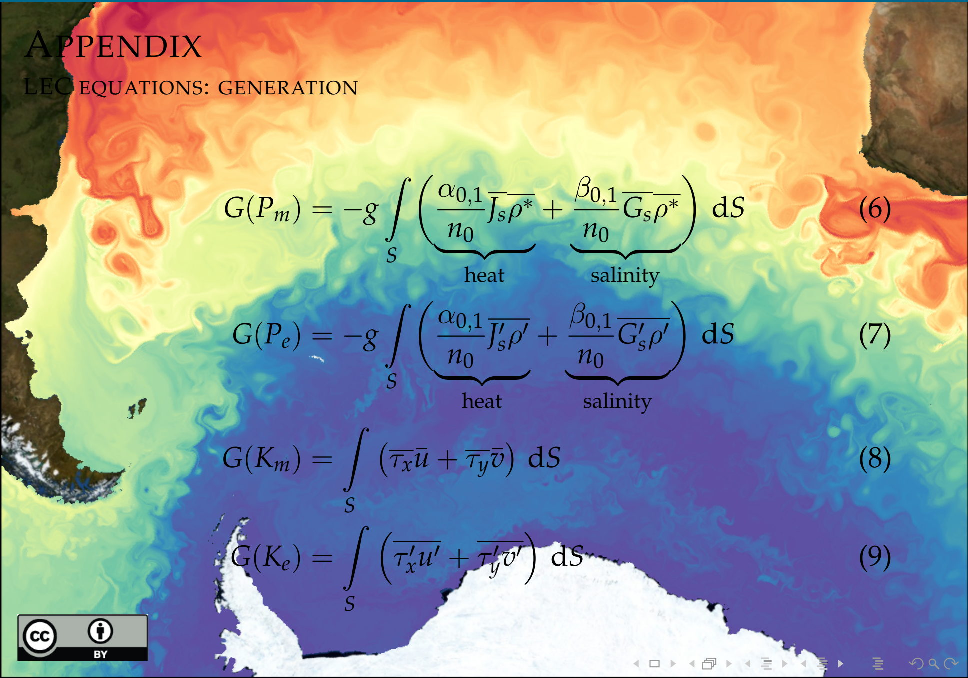
Definition of density anomaly:

$$\rho^*(x, y, z) = \rho(x, y, z) - \rho_{ref}(z) \tag{5}$$

CC BY

Appendix

LEC equations: generation



$$G(P_m) = -g \int_S \left(\underbrace{\frac{\alpha_{0,1}}{n_0} \overline{J_s}\,\overline{\rho^*}}_{\text{heat}} + \underbrace{\frac{\beta_{0,1}}{n_0} \overline{G_s}\,\overline{\rho^*}}_{\text{salinity}} \right) \mathrm{d}S \tag{6}$$

$$G(P_e) = -g \int_S \left(\underbrace{\frac{\alpha_{0,1}}{n_0} \overline{J_s'\rho'}}_{\text{heat}} + \underbrace{\frac{\beta_{0,1}}{n_0} \overline{G_s'\rho'}}_{\text{salinity}} \right) \mathrm{d}S \tag{7}$$

$$G(K_m) = \int_S \left(\overline{\tau_x}\,\overline{u} + \overline{\tau_y}\,\overline{v} \right) \mathrm{d}S \tag{8}$$

$$G(K_e) = \int_S \left(\overline{\tau_x' u'} + \overline{\tau_y' v'} \right) \mathrm{d}S \tag{9}$$

Appendix

LEC equations: conversion

$$C(P_e, P_m) = -\int_V \frac{g}{n_0} \overline{\rho' u'_h} \cdot \nabla_h \bar{\rho} \, \mathrm{d}V \tag{10}$$

$$C(K_e, K_m) = \rho_0 \int_V \left(\overline{u' \mathbf{u}'} \cdot \nabla \bar{u} + \overline{v' \mathbf{u}'} \cdot \nabla \bar{v} \right) \mathrm{d}V \tag{11}$$

$$C(P_m, K_m) = -g \int_V \bar{\rho} \bar{w} \, \mathrm{d}V \tag{12}$$

$$C(P_e, K_e) = -g \int_V \overline{\rho' w'} \, \mathrm{d}V \tag{13}$$

BY

References

Hogg, A. M., P. D. Killworth, J. R. Blundell, and W. K. Dewar
2005. Mechanisms of Decadal Variability of the Wind-Driven Ocean Circulation. *Journal of Physical Oceanography*, 35(4):512–531.

Le Bars, D., J. P. Viebahn, and H. A. Dijkstra
2016. A Southern Ocean mode of multidecadal variability. *Geophysical Research Letters*, 43(5):2102–2110.

Martin, T., W. Park, and M. Latif
2013. Multi-centennial variability controlled by Southern Ocean convection in the Kiel Climate Model. *Climate Dynamics*, 40(7-8):2005–2022.

von Storch, J.-S., C. Eden, I. Fast, H. Haak, D. Hernández-Deckers, E. Maier-Reimer, J. Marotzke, and D. Stammer
2012. An estimate of Lorenz energy cycle for the world ocean based on the 1/10 STORM/NCEP simulation. *Journal of Physical Oceanography*, (1992):120821111920009.

CC BY