Energetics of the Southern Ocean Mode

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

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Utrecht University



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 climate variability: global mean surface temperature vs. ocean heat content tus: some 10²³ J of heat missing ested locations of the missing heat:
 Indian Ocean (e.g. Meehl *et. al* (2011))
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 Southern Ocean



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Southern Ocean Mode

Lorenz Energy Cycle

Mechanism

Consequences S

MODEL

PARALLEL OCEAN PROGRAM

Visolated

Model

▶ high resolution: $0.1^{\circ} \approx 10 \text{ km}$ ⇒ meso-scale eddies

Processes are

repeated monthly mean dimatological forcing every mode of variability that is not diurnal or seasonal is internal 325 model years, last 501 ml output







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MODEL

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- high resolution: 0.1° ≈ 10 km
 ⇒ meso-scale eddies
 ocean only configuration
 ⇒ oceanic processes are isolated
 - repeated monthly mean dimatological forcing ⇒ every mode of variability that is not diurnal or seasonal is internal 325 model years, last 501 ml output







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- ocean only configuration
 ⇒ oceanic processes are isolated
- repeated monthly mean *g*limatological forcing *⇒* every mode of variability that is not diurnal or seasonal is internal
- 325 model years, last 50 full output









Introduction Model Southern Ocean Mode Lorenz Energy Cycle Mechanism Consequences 0. JUTHERN OCEAN MODE 50 yr cycle in ocean heat content • not seen in low resolution model \Rightarrow eddies seen essenti

ROPOSED 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

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Research question

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LORENZ ENERGY CYCLE

MECHANICAL ENERGY BALANCE OF THE OCEAN

1. Reservoirs

- Kinetic Energy (KE)
- Available Potential Energy (APE)

KE: wind stress forcing $\propto \vec{u} \cdot \vec{\tau}$ APE: buoyancy fluxes (heat and salinity) Conversion

• APE \leftrightarrow KE: vertical movement of water scipation

steady state assumption: dissipation = residual

Eddy-mean decomposition: $\overline{xy} = \overline{xy} + \overline{x'y'}$ with $\overline{x} = \frac{1}{T} \int_0^T x \, dt$ Additional eddy-mean conversion terms KE, rotropic instab

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LOREN MECHANI	NZ EN	NERGY CYCI ergy balance of	LE the ocean	22	2	R
1.	Reserv	voirs				- All
2.	 K A Gener K A 	inetic Energy (KE vailable Potential ation E: wind stress for PE: buoyancy flu	E) Energy (APE) cing $\propto \vec{u}\cdot \vec{\tau}$ xes (heat and sa	linity)	R	
3-	Conve	rsion		.,,	- AL	
E.	► A	$PE \leftrightarrow KE: vertica$	l movement of v	water		
4.	Dissip	ation				
	st st	eady state assum	ption: dissipatio	on = residu	ial _	
	y-mea	n decomposition	$n: \overline{xy} = \overline{x}\overline{y} + \overline{x'}$	$\overline{y'}$ with \overline{x} :	$= \frac{1}{T} \int_0^T x \mathrm{d}t$	
	additi	dhal eddy-mear	n conversion te	rms		
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1.	Reserv	oirs			225	
	► A	vailable Potential	Energy (APE)		29.00	
2.	Gener	ation				3 PAN
	► K	E: wind stress for PE: buoyancy flu	cing $\propto ec{u}\cdotec{ au}$ xes (heat and sa	linity)	N.	
3.	Conve	ersion				
	► A	$PE \leftrightarrow KE: vertica$	l movement of	water		
4.	Dissip	ation				
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	y-meai	n decomposition	n: $\overline{xy} = \overline{x}\overline{y} + \overline{x'}$	$\overline{y'}$ with \overline{x}	$= \frac{1}{T} \int_0^T x \mathrm{d}t$	
	additi	<mark>çma</mark> l eddy-mear	conversion te	rms		
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		Kinet Avail	<mark>tic Energy (KE</mark> able Potential) Energy (APE)		42	
	Z. Gel	· KE: w · APE:	vind stress for buoyancy flu	cing $\propto \vec{u} \cdot \vec{\tau}$ xes (heat and sal	inity)	R	
	3. Co	nversi	on -	movement of w	vator		
	4. Dis	sipatio	on		vater		
K.		stead	y state assumj	otion: dissipatio	n = residu	al	
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	1. 1 2. (Reserv Kii Av Genera KE	oirs netic Energy (KE railable Potential ation E: wind stress for	Energy (APE) cing $\propto \vec{u} \cdot \vec{\tau}$			
	3. (4. 1	 Al Conver Al Dissipation State 	PE: buoyancy flu rsion PE ↔ KE: vertica ation	xes (neat and sa l movement of v	vater	al	
	Eddy	z-mean additi¢	decomposition fol eddy-mear to rotropic inst	n: $\overline{xy} = \overline{xy} + \overline{x'y}$ n conversion te	$\overline{y'}$ with \overline{x} =	$= \frac{1}{T} \int_0^T x \mathrm{d}t$	
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	IZ EN	IERGY CYCI	L E The ocean	22	24	
1. 2.	Reserv Ki Av Genera KI	oirs netic Energy (KE vailable Potential ation E: wind stress for) Energy (APE) cing $\propto \vec{u} \cdot \vec{\tau}$		R	
3. 4.	Conve AI Dissipa	rsion PE ↔ KE: vertica ation	l movement of v	vater		
Eddy	► ste y-mear additic	ady state assum decomposition inal eddy-mear ; barotropic inst	ption: dissipation $\overline{xy} = \overline{xy} + \overline{x'y}$ a conversion termination termina	$\overline{y'}$ with \overline{x} = rms	al = $\frac{1}{T} \int_0^T x \mathrm{d}t$	
	5.			4 D > 4 D		

Model Southern Ocean Mode Lorenz Energy Cycle Mechanism Consequences MECHANISM: EDDY VS. MEAN FLOW eddies seem crucial A maximum energies: increased generation of eddies, onzonality increases decleasing energy input, dissipation of energy energy: weak production of eddies increasing energies: zonal acceleration by wind

Model Southern Ocean Mode 0 00 Lorenz Energy Cycle

Mechanism

Consequences

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MECHANISM: EDDY VS. MEAN FLOW

eddies seem crucial

A maximum energies: increased generation of eddies, nonzonality increases

B W a sing energy input, dissipation of energies by the energy: weak production of eddies 1. Morensing energies: zonal acceleration by wind



Model

Southern Ocean Mode

Lorenz Energy Cycle

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Consequences

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MECHANISM: EDDY VS. MEAN FLOW

- eddies seem crucial
- A maximum energies: increased generation of eddies, nonzonality increases
- **B** decreasing energy input, dissipation of energies

Observation of eddies

meansing energies: zonal acceleration by wind



Model Southern Ocean Mode o oo Lorenz Energy Cycle

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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
 - meansing energies: zonal acceleration by wind



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MECHANISM: EDDY VS. MEAN FLOW

- eddies seem crucial
- A maximum energies: increased generation of eddies, nonzonality increases
- B decreasing energy input, dissipation of energiesC low total energy: weak production of eddiesD increasing energies: zonal acceleration by wind







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









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SOM CONSEQUENCES

convection affects meridional overturning











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

Model Southern Ocean Mode

Lorenz Energy Cycle

Mechanism

Consequences Summary

SUMMARY

- missing heat of the hiatus
 Southern Ocean Mode
 50 year period mode
- Inclusional energy cycle
 Inclusional energy cycle
 Inclusional flow interaction
 Inclusional phasing of
 Prorgy components
 Preddies are crucial
 Provection and its effects in overturning
 Inclusional energy associated heat release

onclusion

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



Introduction Model Southern Ocean Mode Lorenz Energy Cycle Mechanism o o o oo oo oo oo

SUMMARY

missing heat of the hiatus
 Southern Ocean Mode

 50 year period mode

 mechanical energy cycle

 mechanical energy cycle
 mechanical energy cycle
 acorgy components
 eddies are crucial
 convection and its effects in overturning
 associated heat release

total KE -3 -2 -1 0 1 2 3 loging(KE_{weak}(/Jm³)]

Consequences

Summary

onclusion

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



Model Southern Ocean Mode

Lorenz Energy Cycle

Mechanism

Consequences

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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

onclusion

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Model Southern Ocean Mode

Lorenz Energy Cycle

depth [km]

Mechanism

time [model year]

Consequences

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SUMMARY

- missing heat of the hiatus
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- eddy mean flow interaction
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Conclusion

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Model Southern Ocean Mode

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- missing heat of the hiatus
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 - 50 year period mode
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 - eddies are crucial
- convection and its effects in overturning
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 Associated heat
 As

Conclusion

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



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Consequences 00 Summary 0

Appendix





Introduction	Model	Southern Ocean Mode	Lorenz Energy Cycle	Mechanism	Consequences	Summary
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PPENDIX

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



Introduction 0	Model 0	Southern Ocean Mode 00	Lorenz Energy Cycle 0	Mechanism 00	Consequences 00	Summary 0
APPEN	JDIX	BR C	2.00	90	18.4	6
LECEQUA	ATIONS:	RESERVOIRS				R
		$P_m = -$	$\frac{g}{2} \int\limits_{V} \frac{1}{n_0} \bar{\rho}^{*2} \mathrm{d}V$		40	(1)
		$P_e = -$	$\frac{g}{2} \int\limits_{V} \frac{1}{n_0} \overline{\rho^{*/2}} \mathrm{d}V$		R	(2)
	17	$K_m = \frac{\rho}{2}$	$\frac{0}{2}\int\limits_V \left(\bar{u}^2 + \bar{v}^2\right) dv$	₫V		(3)
	G.	$K_e = \frac{\rho}{2}$	$\frac{0}{2}\int\limits_{V}\left(\overline{u^{\prime 2}+v^{\prime 2}}\right)$	dV		(4)
Defi	nition	of density anon	naly:			
СС () ву		$\rho^*(x,y,z)$	$= \rho(x,y,z) - \rho(x,y,z)$	$\rho_{ref}(z)$		(5)₹ २०९२

O Introduction	Model O	Southern Ocean Mode	O Cycle	Mechanism 00	Consequences 00	o Summary
APPEN LEO EQUA	IDIX Ations:	GENERATION	SN	22	220	R
- 10	j.	$G(P_m) = -g \int_{S}$	$\underbrace{\left(\frac{\alpha_{0,1}}{n_0}\overline{J_s\rho^*} + \frac{\beta_0}{n_0}\right)}_{\text{heat}} + \underbrace{\frac{\beta_0}{n_0}}_{\text{s}}$	$\left(\frac{1}{0}\overline{G_s}\overline{\rho^*}\right)$	15	(6)
	1	$G(P_e) = -g \int_{S}$	$\left(\underbrace{\frac{\alpha_{0,1}}{n_0}\overline{J'_s\rho'}}_{\text{heat}} + \underbrace{\frac{\beta_{0,1}}{n_0}}_{\text{sa}}\right)$	$\frac{1}{G'_{s}\rho'}d$	S	(7)
	C.	$G(K_m) = \int\limits_{S} \left(\overline{\tau_x}\right)$	$\overline{u} + \overline{\tau_y}\overline{v}) dS$			(8)
	2	$G(K_e) = \int_{S} \left(\overline{\tau}_{S}^{\prime}\right)$	$(u' + \tau'_y v') dS$		ALL CAL	(9)
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Introduction 0	Model 0	Southern Ocean Mode 00	Lorenz Energy Cycle 0	Mechanism 00	Consequences 00	Summary 0
APPEN	NDIX	Parce	25197	22	24	6
LEO EQUA	ATIONS:	CONVERSION				Su
	13		f a		20	
	Q.	$C(P_e, P_m) = -\int_V$	$\frac{\frac{8}{n_0}}{n_0}\overline{\rho' u'_h}\cdot\nabla_h\bar{\rho}$	dV		(10)
	2	$C(K_e, K_m) = \rho_0$	$\int_{U} \left(\overline{u' \mathbf{u}'} \cdot \nabla \overline{u} + \right)$	$\overline{v'\mathbf{u'}}\cdot\nabla\overline{v}$)	dV ((11)
	58 ($C(P_m, K_m) = -g$	$\int_{V} \bar{\rho} \bar{w} \mathrm{d} V$		AS	(12)
		$\mathcal{C}(P_e, K_e) = -g$	$\int_{V} \overline{\rho' w'} \mathrm{d}V$			(13)
CC ()				10110		

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