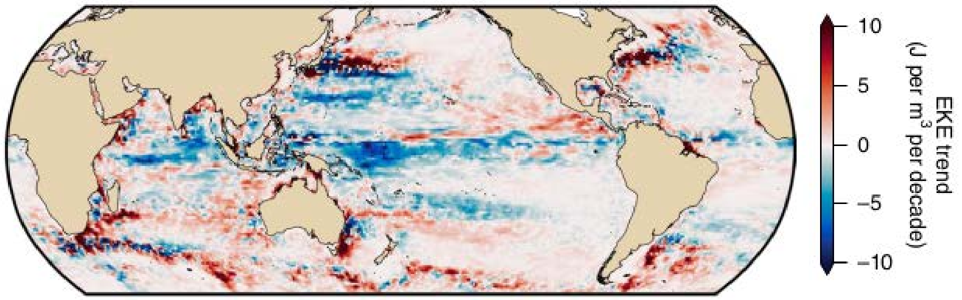
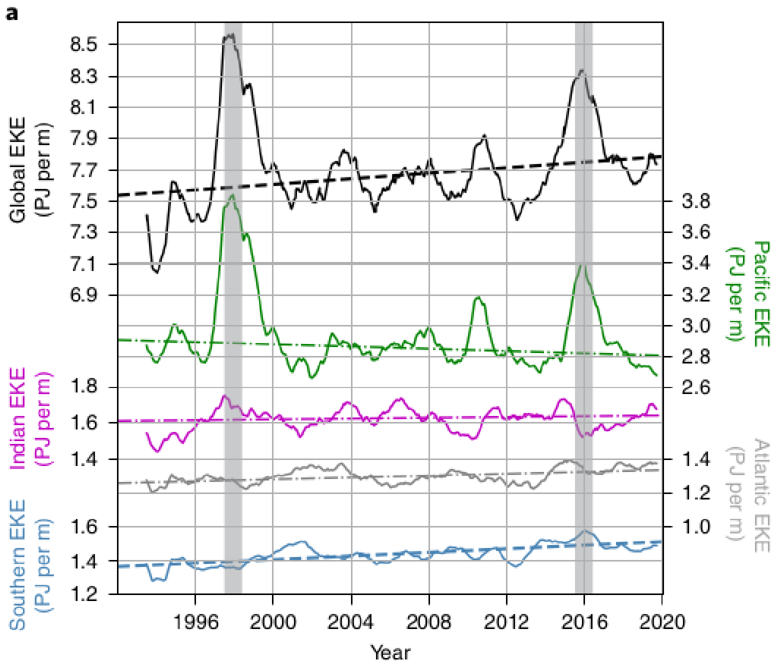
Frequency dependence of ocean kinetic energy and its change over the period 1983-2018

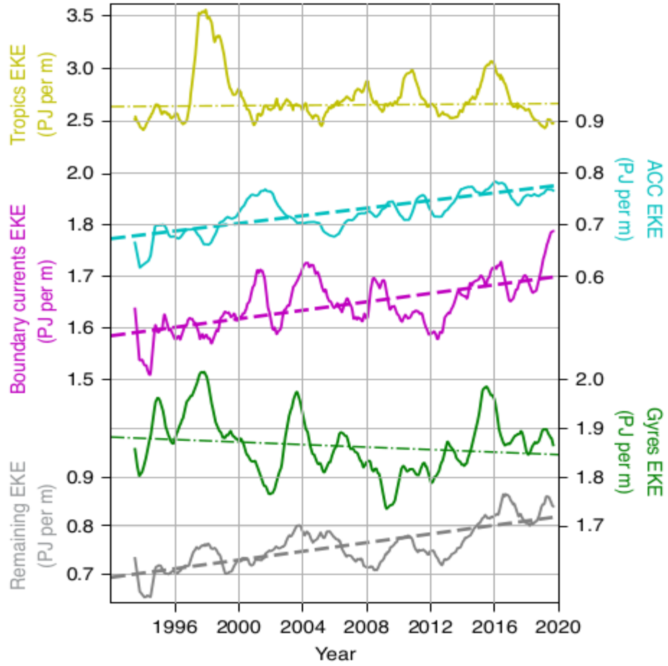
Nuno Serra (Univ. of Hamburg, Germany)
Frank Bryan (NCAR, Colorado, USA)
Detlef Stammer (Univ. of Hamburg, Germany)

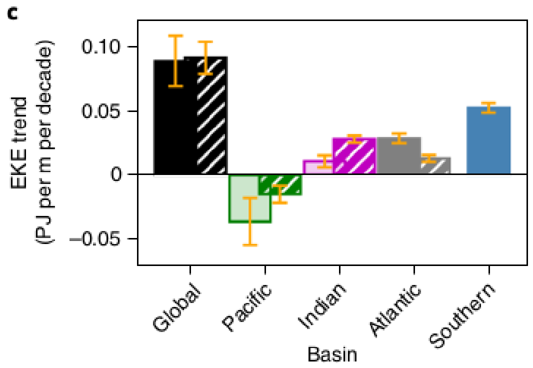
Motivation

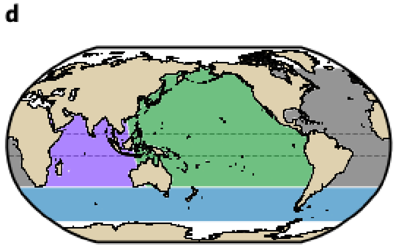
- Positive trends in “eddy” kinetic energy (EKE) have been reported in certain regions (e.g., Southern Ocean) in response to stronger winds (Hogg et al., 2015; Martinez-Moreno et al., 2021).

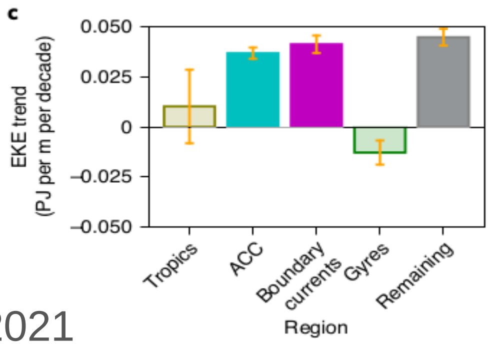


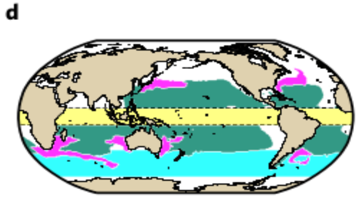








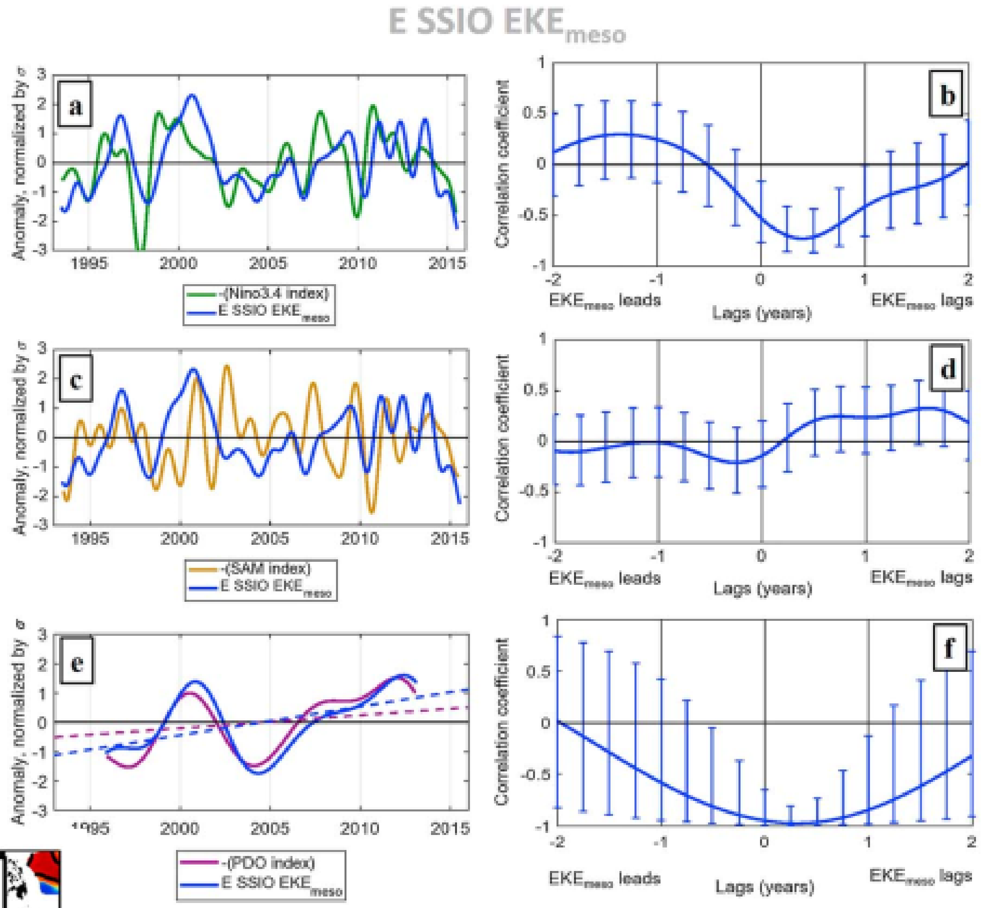


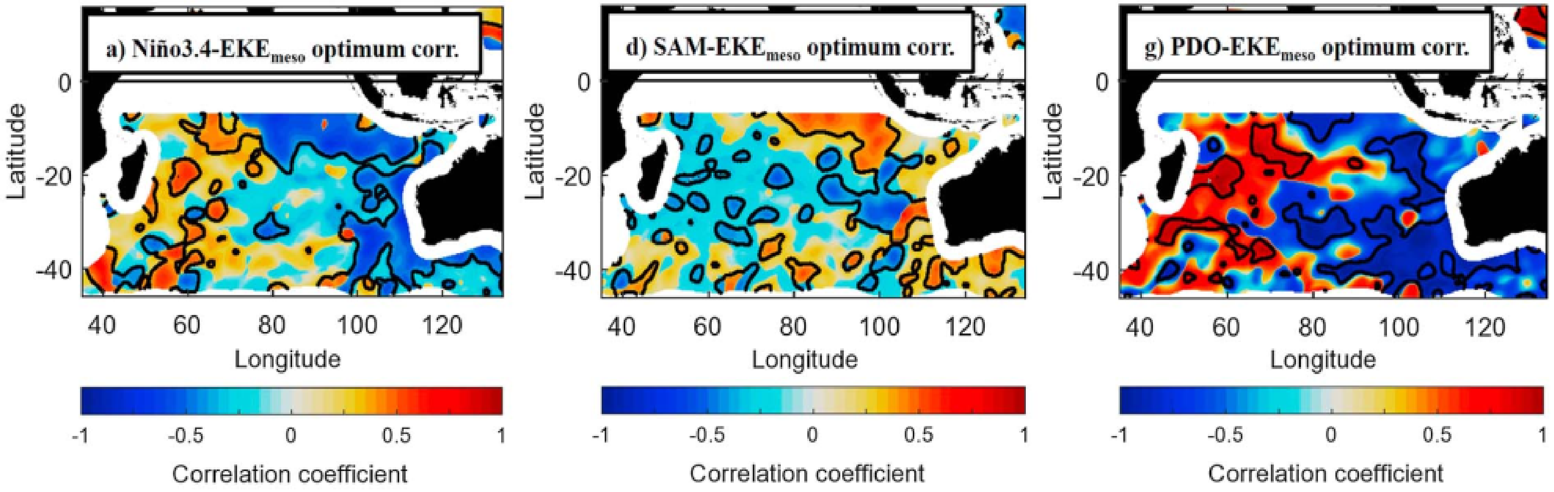


Martinez-Moreno et al., NCC, 2021

Motivation

- Remote influence from the tropical Pacific associated with ENSO and PDO force the EKE of the southeast subtropical Indian Ocean at decadal time scales and also explains multi-decadal trend (Delman et al, 2018, Zheng et al., 2018).

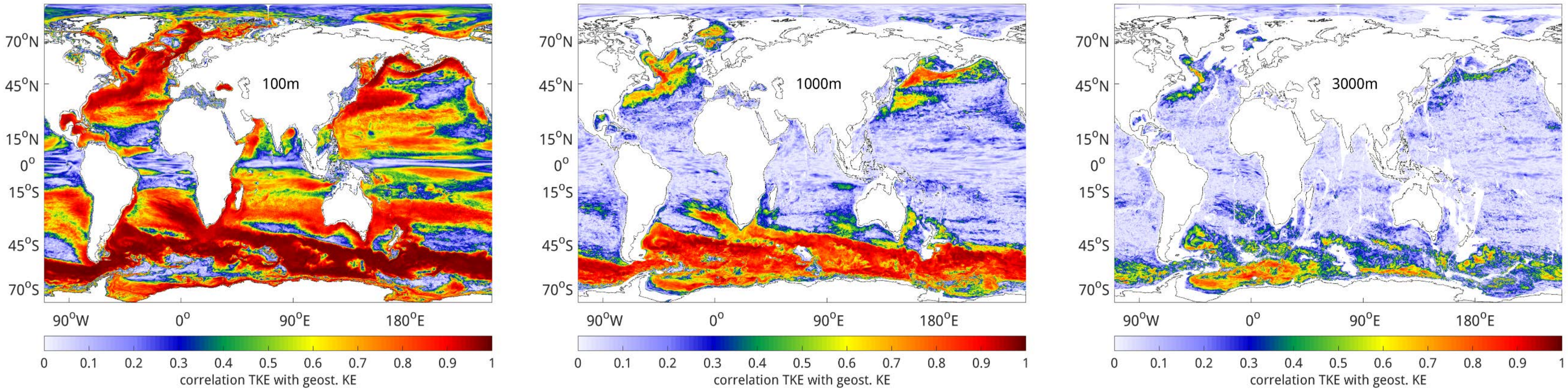




Delman et al., JGR, 2018

Motivation

- Model correlation between total KE and geostrophic KE (from SSH) is absent in tropical regions.
- Correlation decreases fast with depth; altimetry can not monitor interior KE (except in few subpolar regions).
- In situ measurements of interior KE (Luecke et al., JGR, 2020) are too sparse and not long enough.



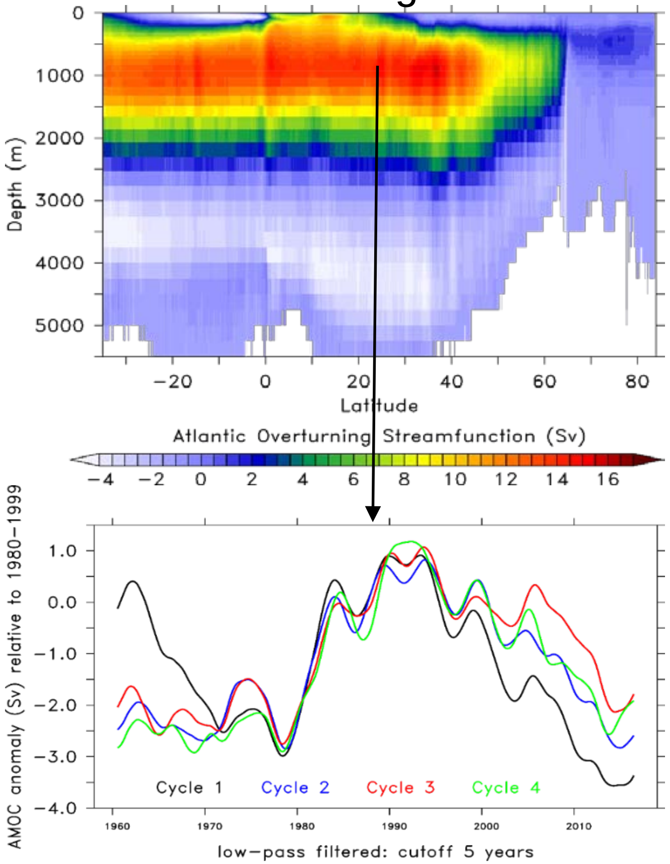
Questions

- How is the ocean kinetic energy distributed in frequency and in depth? What are the relevant processes?
- How did the frequency distribution change in the period 1983-2018? In particular, is the temporal variability at each frequency band related to climate modes?

Model set-up and available integrations

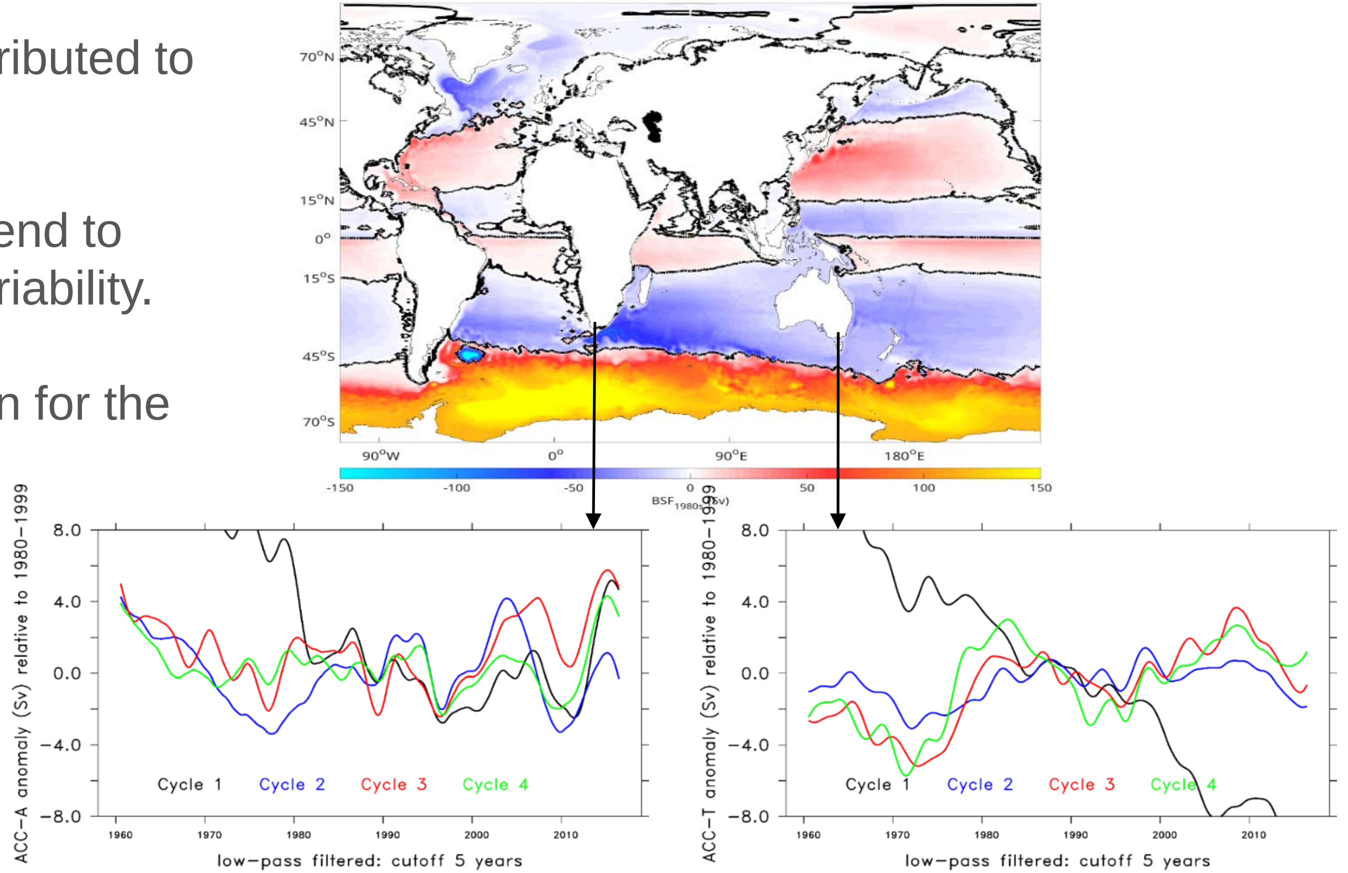
- Global Parallel Ocean Program version 2 (**POP2**) ocean model at **0.1°** resolution with 62 levels. Forced with fluxes from bulk formula + 3-hourly **JRA55-do** atmospheric state (Kobayashi et al. 2015, Tsujino et al., 2017). Details in Bryan & Bachman (2015), Deppenmeier et al. (2021) and Guo et al. (2022).
- 4 repetitions of 1958-2018 JRA55-do forcing with monthly output. Cycles 1 and 3 include 5-day output for 1983-2018. All second moments (e.g., u^2 and v^2) are accumulated online.

Atlantic Overturning Streamfunction



- Cycle 1 trend attributed to model spin-up.
- Cycles 3 and 4 tend to agree in ACC variability.
- Cycle 3 is chosen for the analysis.

Barotropic Streamfunction



Frequency decomposition of kinetic energy

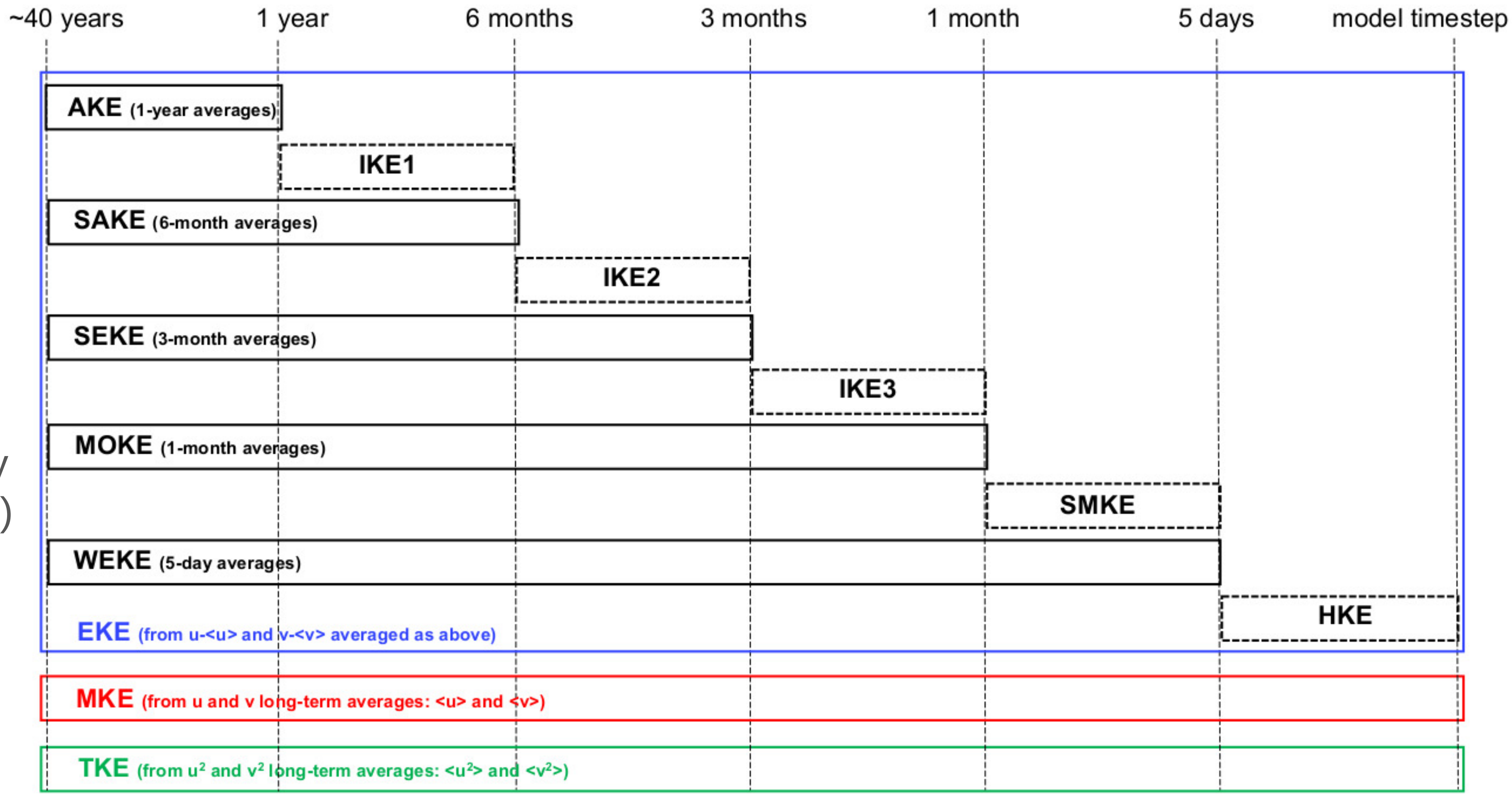
Simple averaging approach:

$$TKE = \frac{1}{2}(\overline{u^2} + \overline{v^2})$$

$$MKE = \frac{1}{2}(\overline{u}^2 + \overline{v}^2)$$

$\overline{(\ )}$ averages over long period (36 or 10 years) of velocity components (u^2,v^2) or (u,v)

$$EKE = TKE - MKE$$



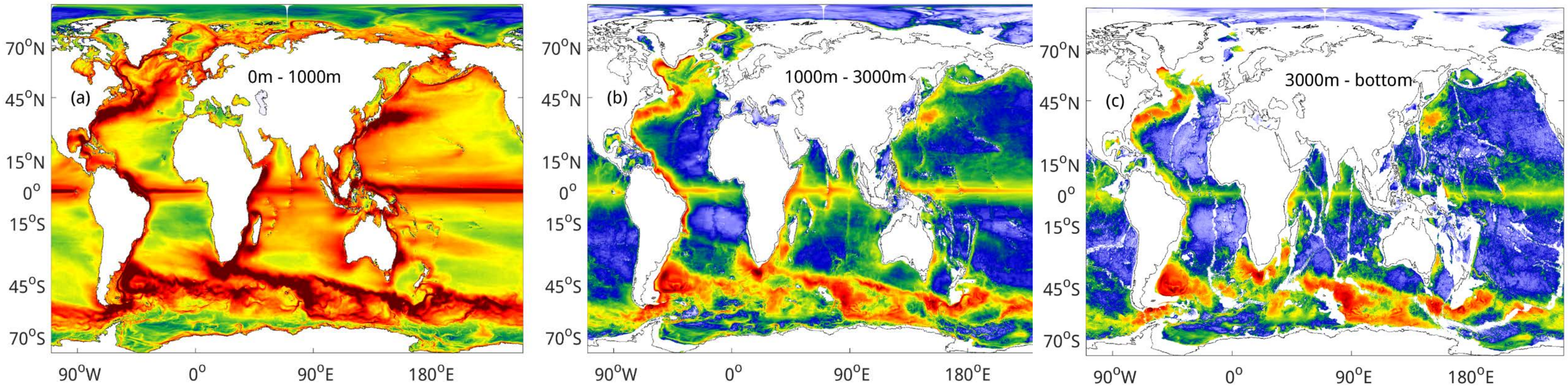
$$xKE = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{M}\sum_{j=1}^{M}\frac{1}{2}[(\bar{u}^{A}{}_{ij} - \bar{u})^2 + (\bar{v}^{A}{}_{ij} - \bar{v})^2]$$

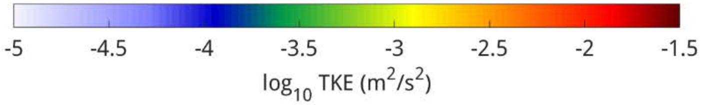
with N = (36, 10) and M = (N, Nx2, Nx4, Nx12, Nx73)

$\overline{(\ )}^{A}$ averages over short period (1yr, 6mo, 3mo, 1mo or 5d)

1983-2018 total (TKE) and mean (MKE) kinetic energy

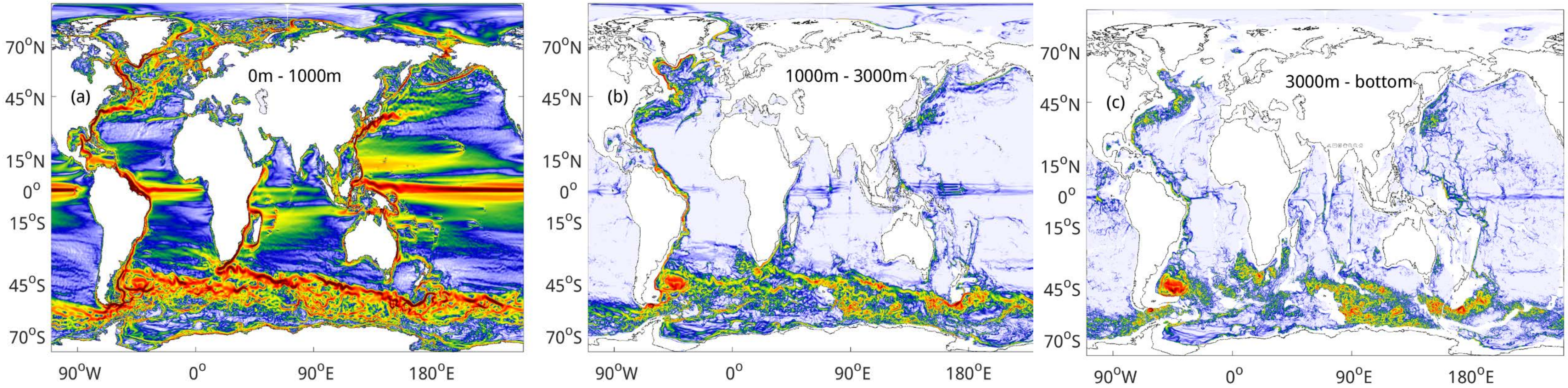
TKE

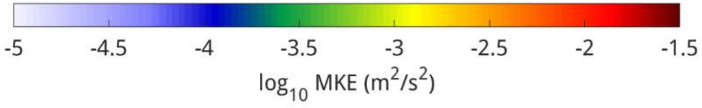




- Accumulation of KE west of Indian and Pacific topographic ridges and seamounts.

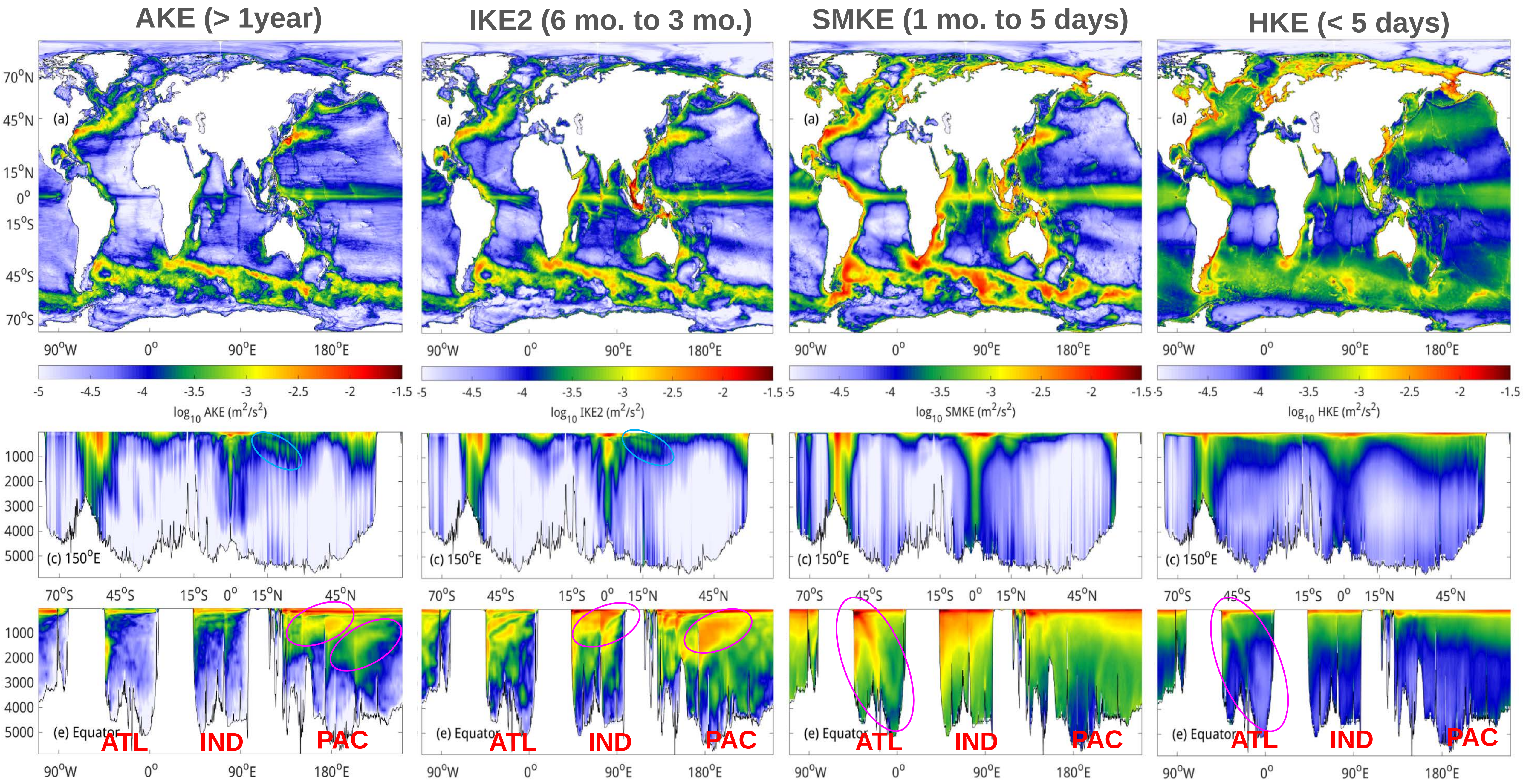
MKE



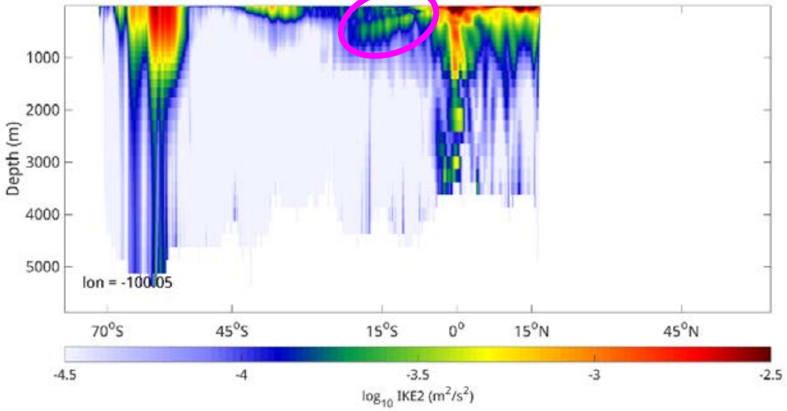


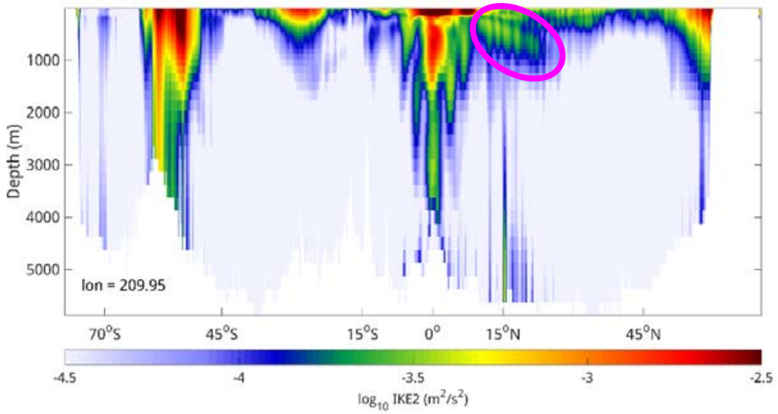
- MKE explains > 70% of TKE in boundary currents, equatorial undercurrents and selected places along the ACC.

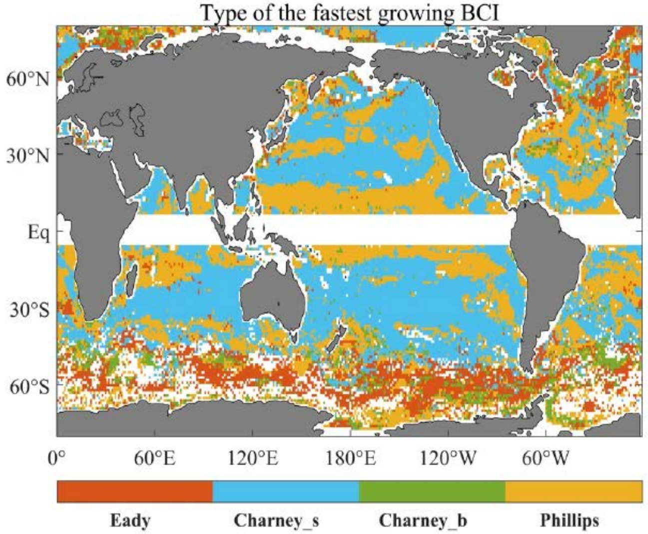
Frequency dependence of transient kinetic energy (EKE)

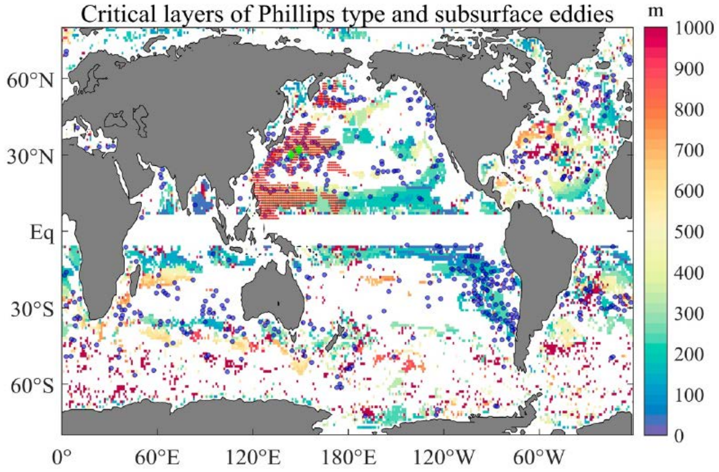


Off-equatorial subsurface EKE maximum at intra-annual frequencies



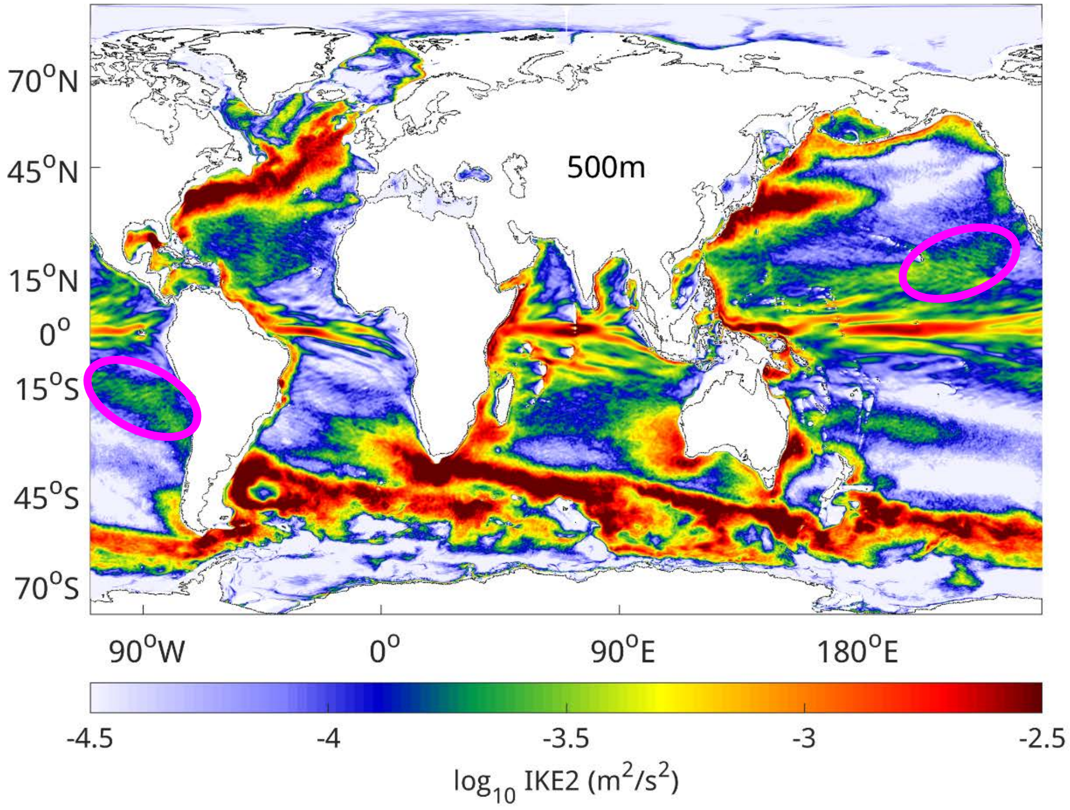






Feng et al, JGR, 2021

- Subsurface maxima seen in all intra-annual KE components due to strong baroclinic instability of the Phillips type and eddy generation (Feng et al., 2021)



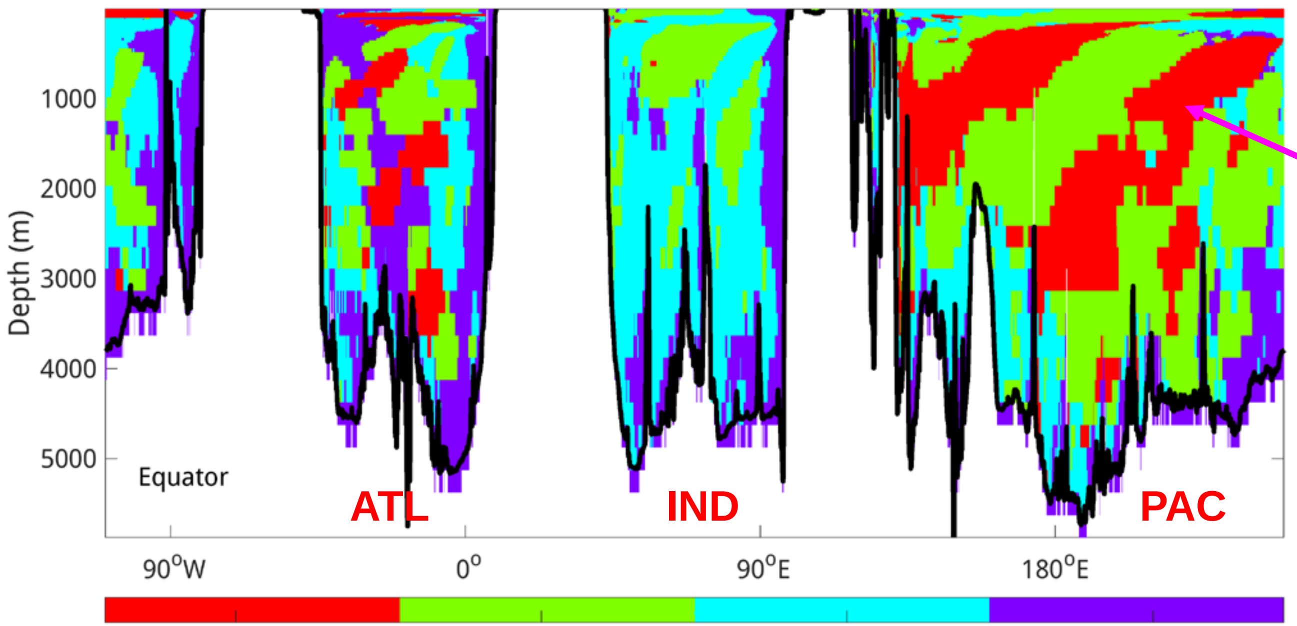
Equatorial Rossby wave activity

- East-west downward slope of intra-annual KE at the equator in all oceans consistent with vertically propagating Rossby waves with upward phase propagation and carrying energy into the deep ocean.

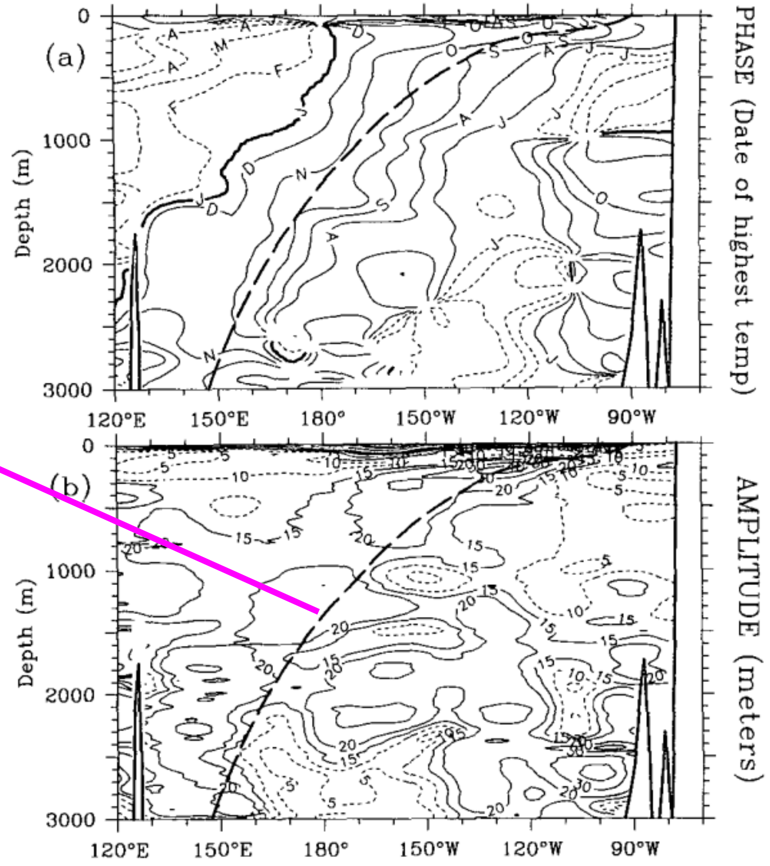
- Generation associated with westward-propagating component of zonal wind (Kessler and McCreary, 1993).

- Indian Ocean has energy at higher frequencies compared to Atlantic or Pacific.

- High-frequency important close to topography and in the Atlantic.

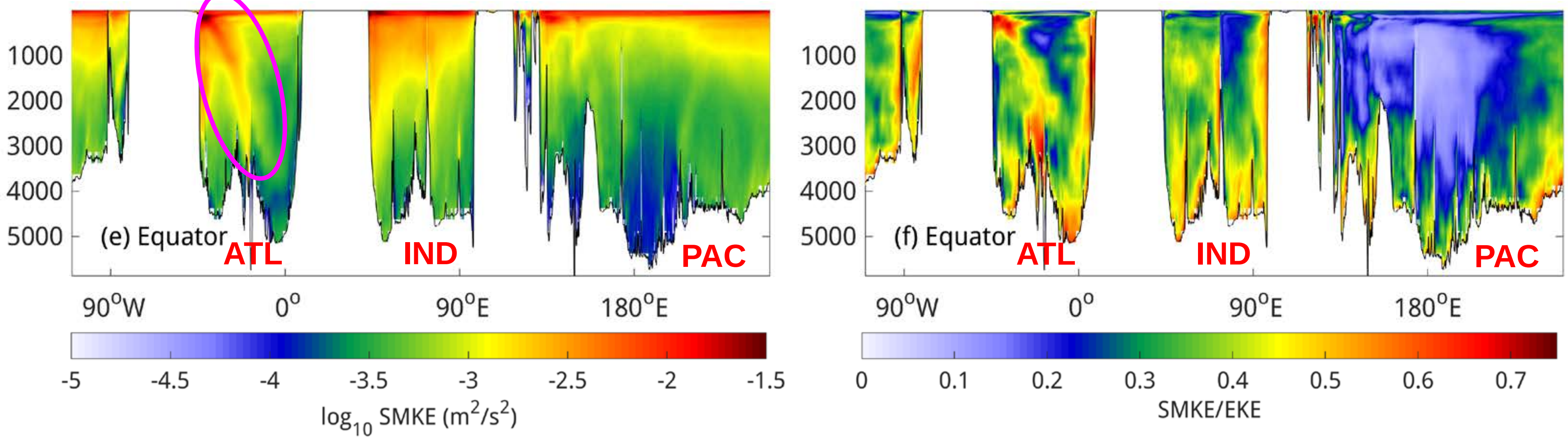


Dominant contribution to EKE

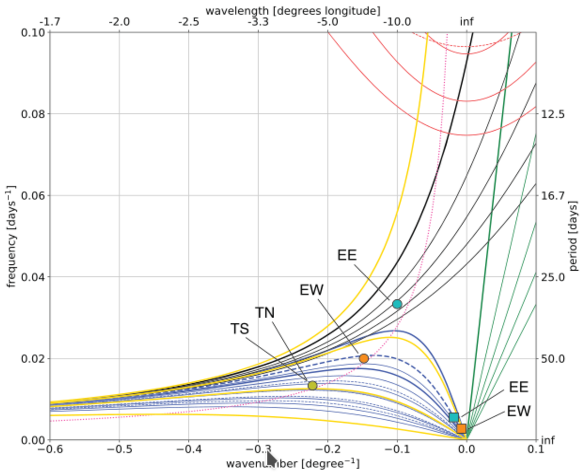


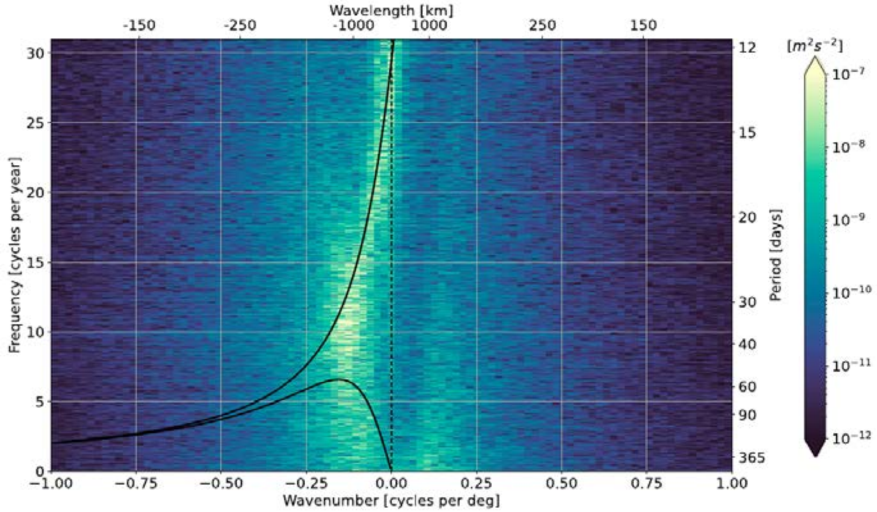
Kessler & McCreary, JPO, 1993

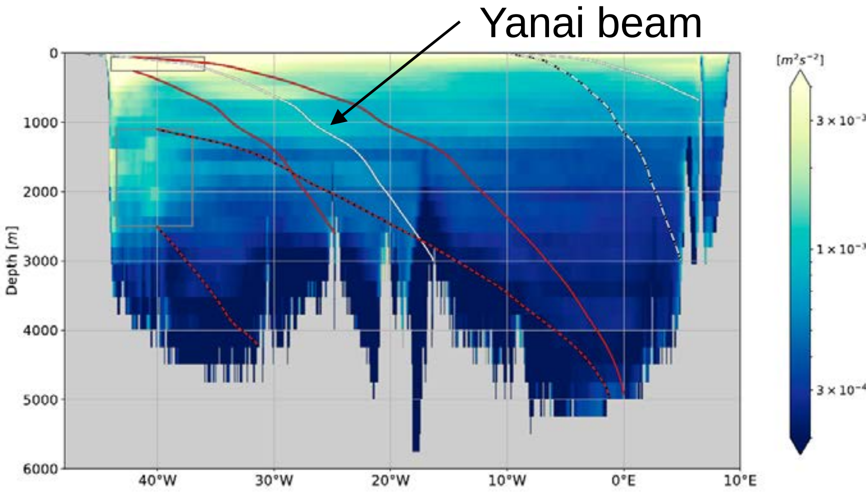
Equatorial Yanai wave activity



- Atlantic Yanai beam in sub-monthly KE related to the interaction between NBC and EUC. Yanai waves are mixed Rossby-gravity waves with downward and eastward energy propagation and upward phase propagation.







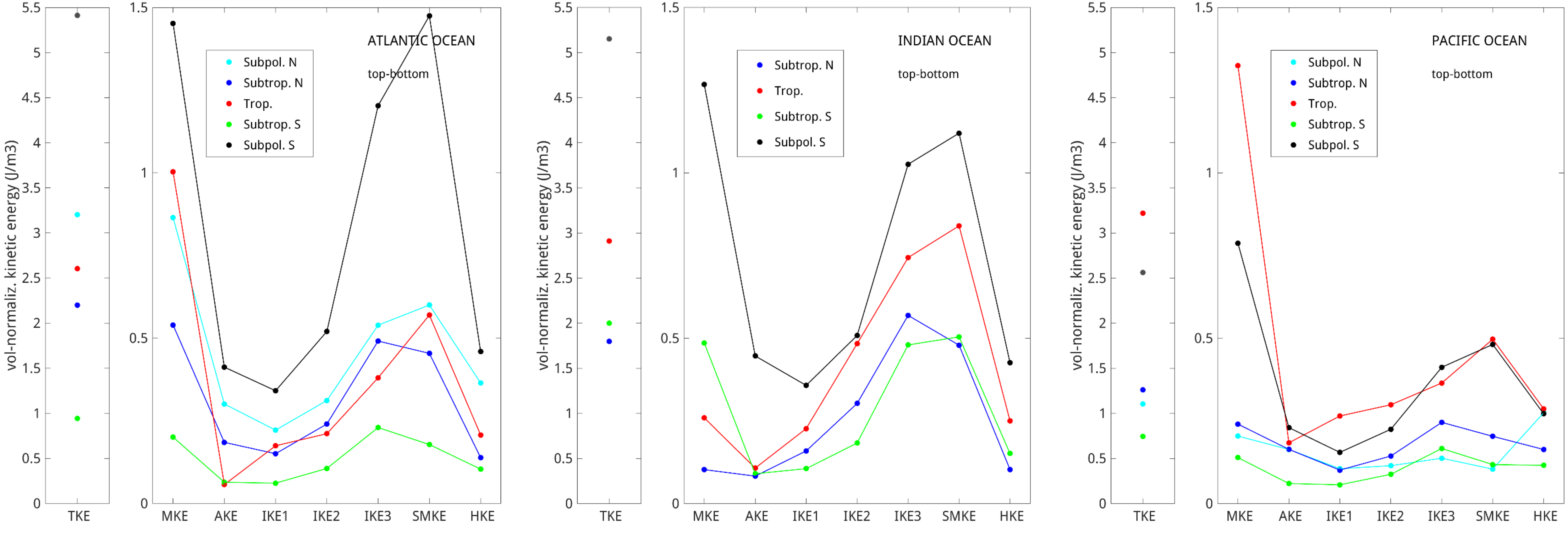
Delpech et al., JGR, 2020

Koerner et al., JPO, 2022

Summary KE "spectra"

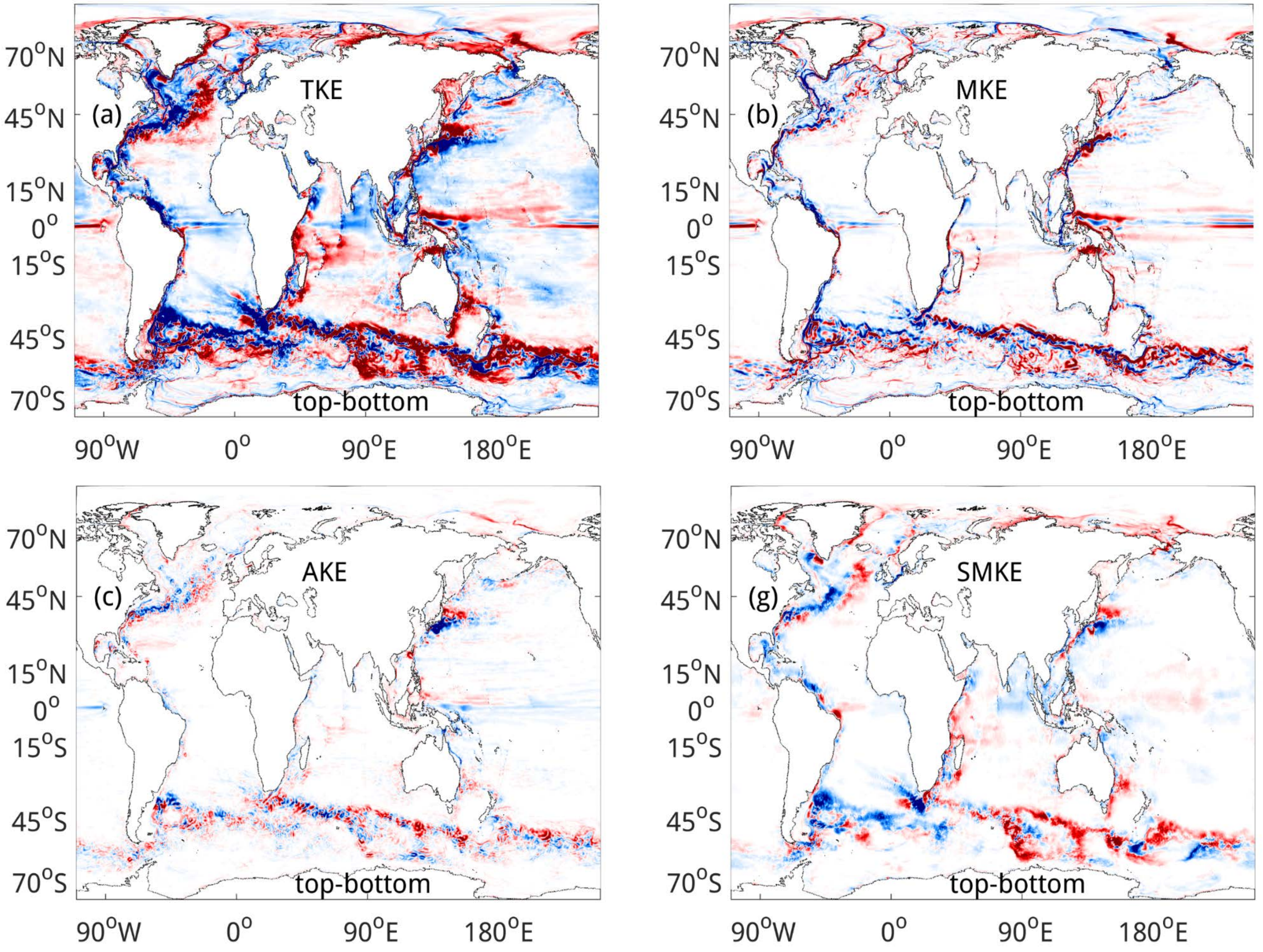
- Larger contributions to EKE from IKE3 and SMKE (except in subtropical regions). Those bands include the strong mesoscale eddy activity.
- MKE comparable or larger than SMKE (except in tropical Indian Ocean).
- HKE levels might be underestimated due to incomplete forcing of internal wave activity.

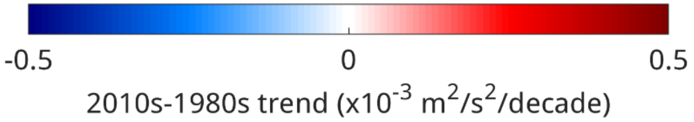
1 yr	<	AKE		
1 yr	>	IKE1	>	6 mo
6 mo	>	IKE2	>	3 mo
3 mo	>	IKE3	>	1 mo
1 mo	>	SMKE	>	5 d
		HKE	<	5 d



Multi-decadal trends: top-bottom

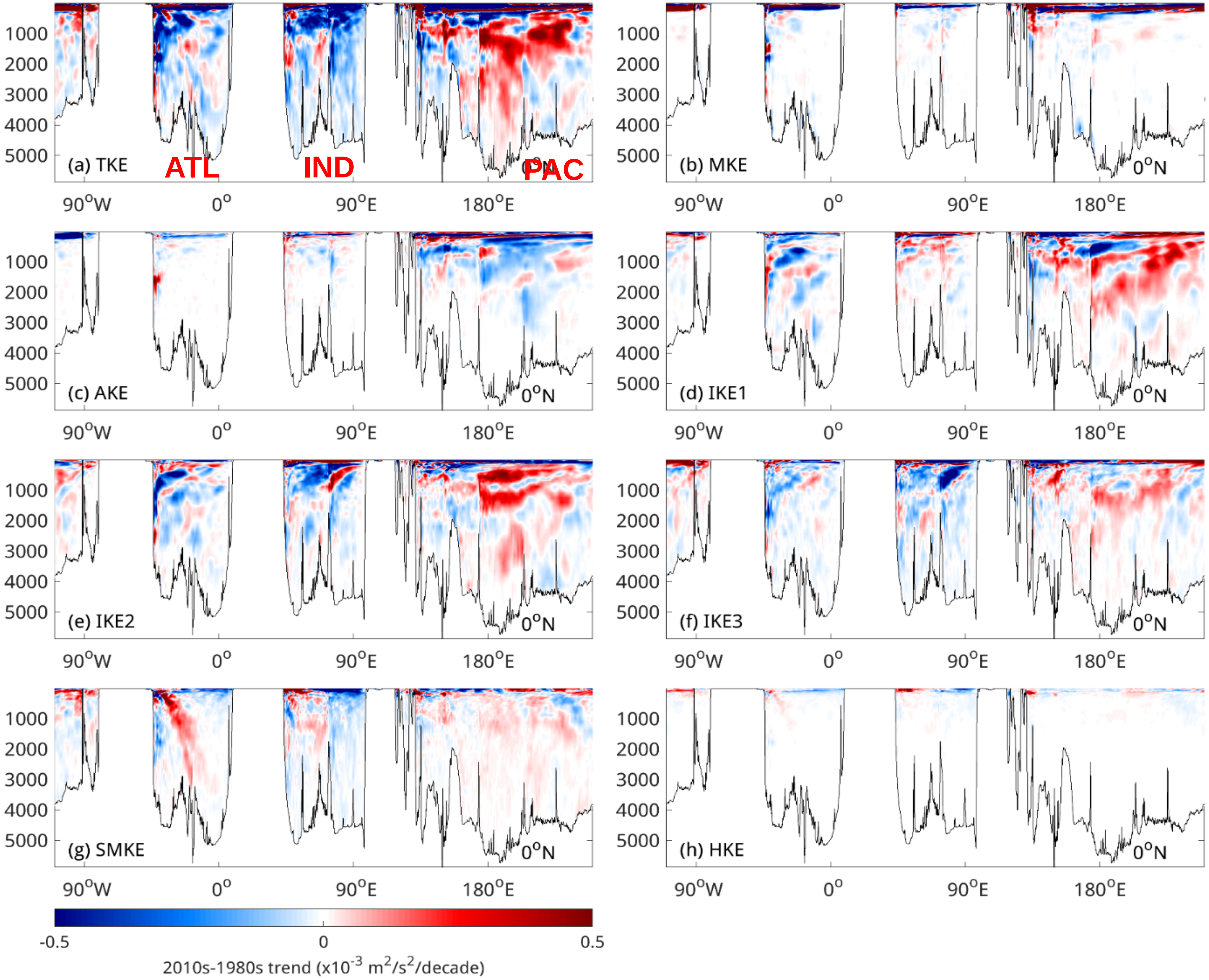
- Atlantic western boundary TKE decrease due to MKE and IKE3-SMKE but increase over the NAC.
- Slow-down of the western subpolar gyre but increase in northeast Atlantic.
- Agulhas leakage decrease (consistent with uncertainty seen by Ruehs et al., 2022).
- Decrease in Atlantic sector of ACC.
- Indian Ocean TKE changes of sub-monthly origin.
- Increase in Equatorial Pacific TKE explained by MKE.
- TKE decrease in Pacific subtropics seen in all bands.



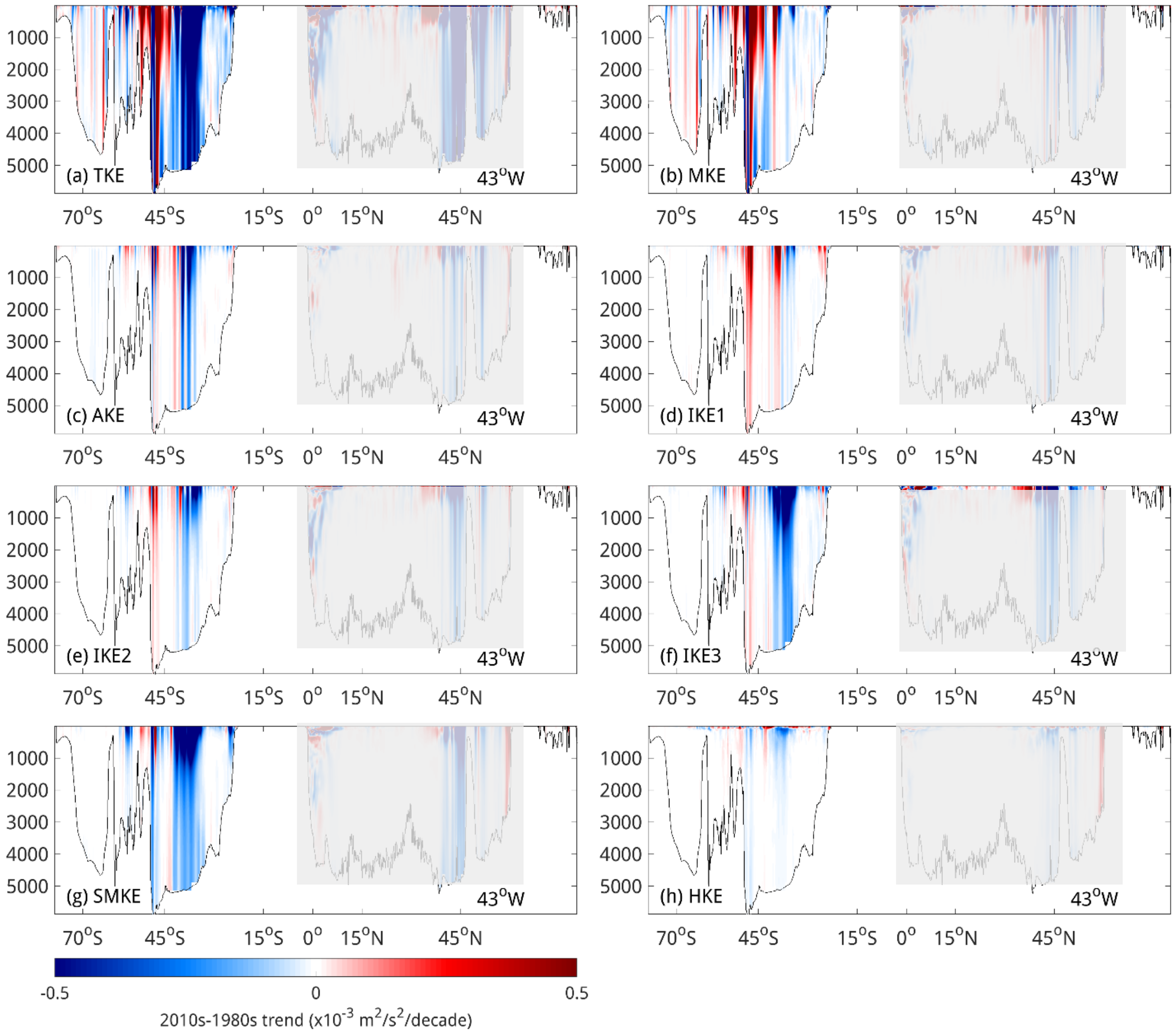


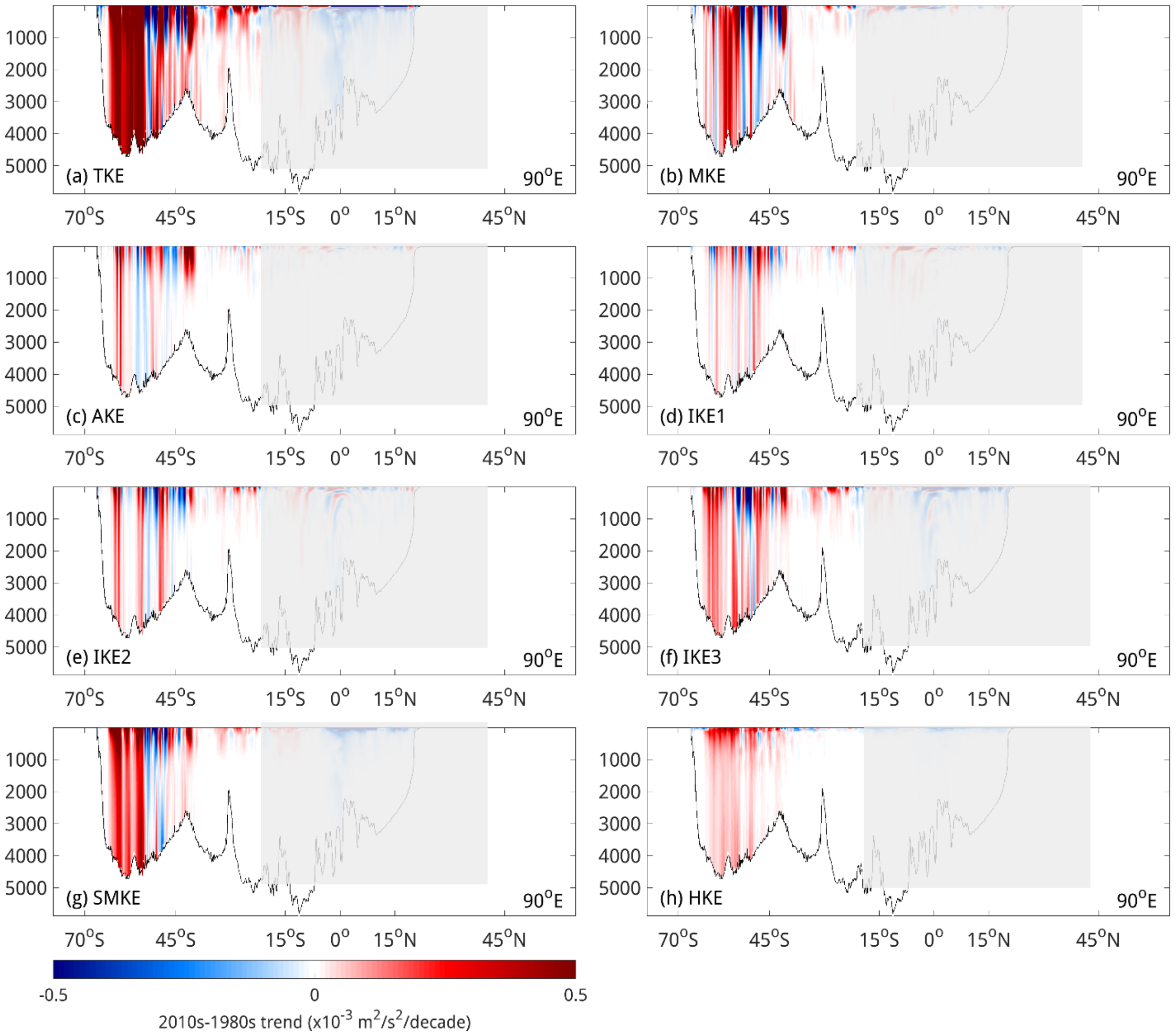
Multi-decadal trends: Equator

- Atlantic EUC reduced in thickness and Pacific EUC deepened, as seen in MKE.
- Central equatorial Pacific: increase in intra-annual (1mo.–1yr) KE and decrease of inter-annual (>1yr) components.
- Yanai wave beam intensified, however masked by decrease in longer intra-annual KE.



Multi-decadal trends: 43°W (ACC Atlantic sector) 90°E (ACC Indian O. sector)



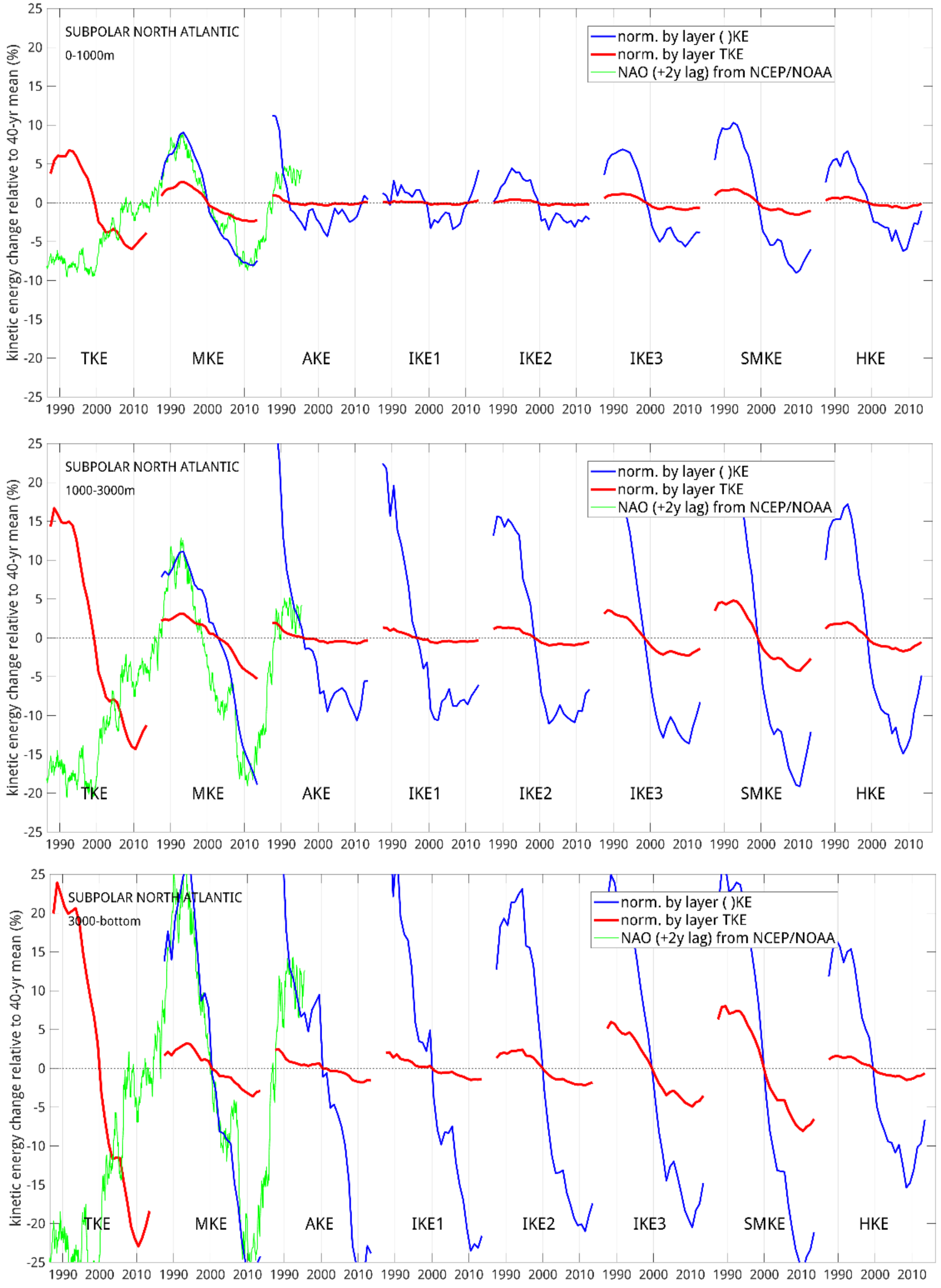


- Strong reduction in TKE in northern part of ACC partly due to inter-annual variations and to sub-seasonal changes.

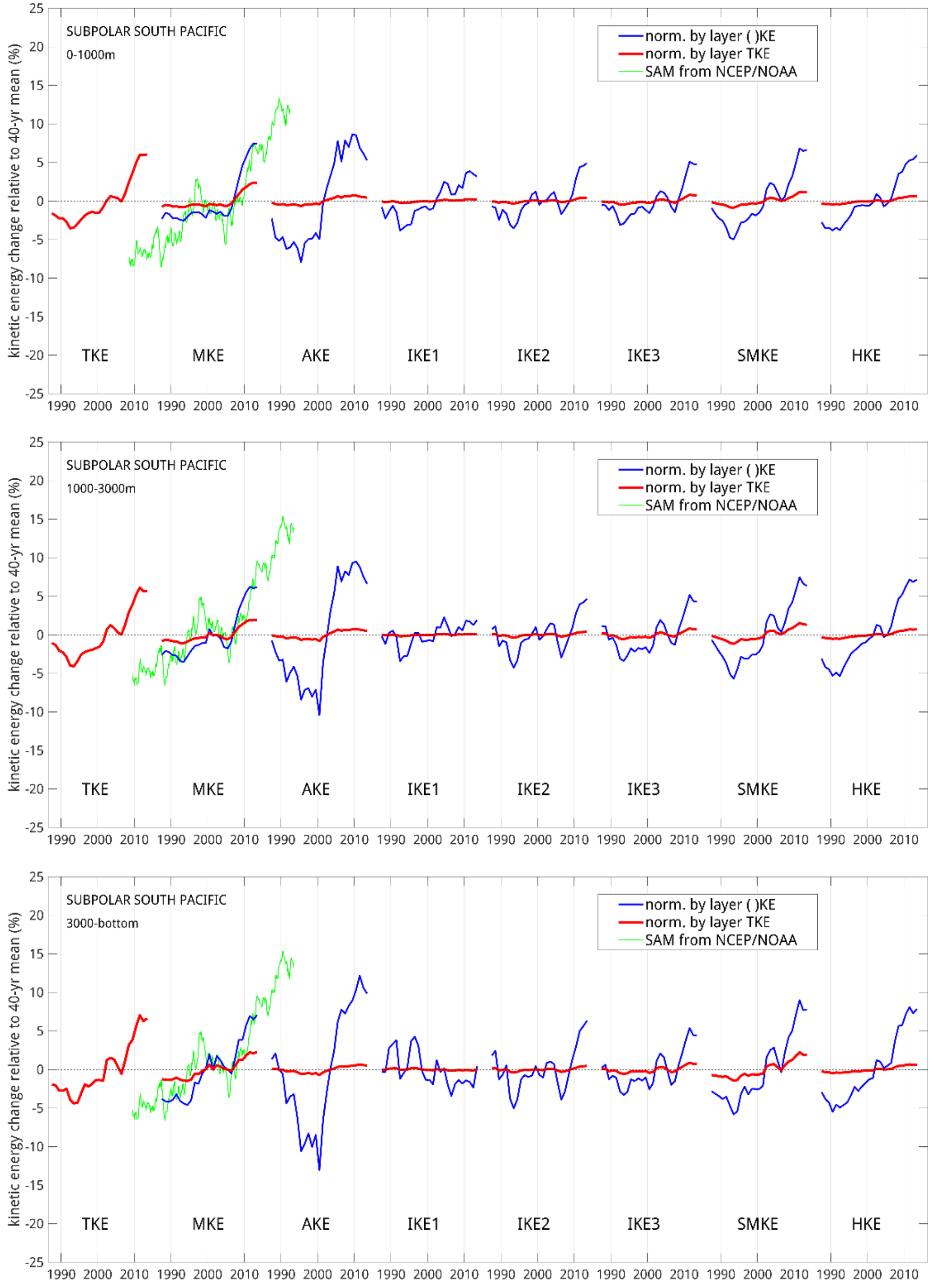
- Strong increase in TKE at and south of ACC axes at all frequencies.

- MKE is correlated with climate modes (NAO and SAM).
- Intra-annual frequencies (IKE1 to HKE) explained by barotropic/ baroclinic instability of the mean flow and eddy generation.
- Sign of forward energy cascade?

Subpolar North Atlantic (> 40ºN)



Subpolar South Pacific (> 40ºS)



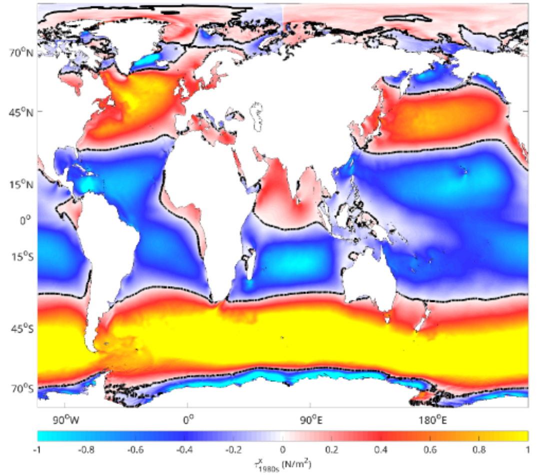
Multi-decadal trends:

- Overall increase in Southern ocean zonal wind responsible by an increase in barotropic transport in the ACC.

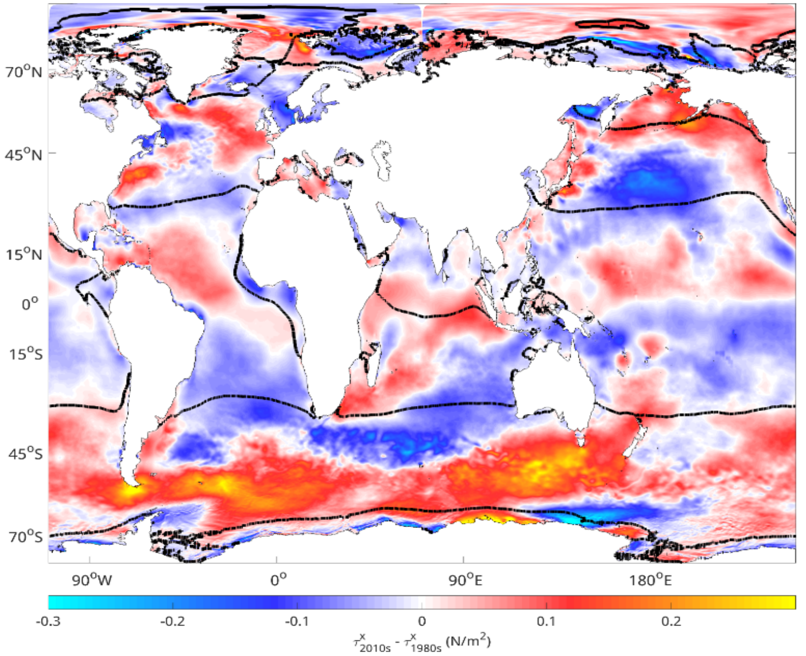
- Zonal wind stress decrease over Agulhas Retroflection region.

Zonal Wind Stress

1980s ave.

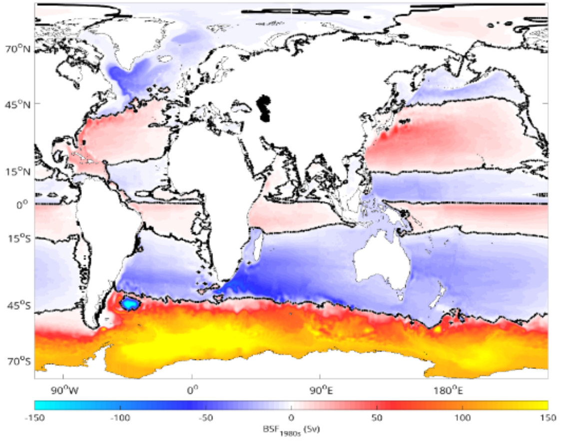


2010s - 1980s

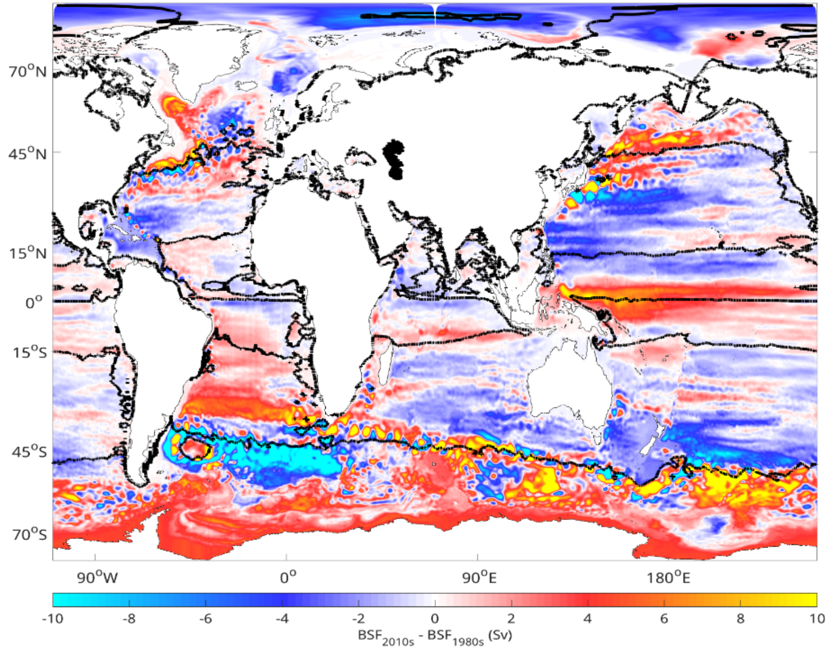


Barot. Streamf.

1980s ave.



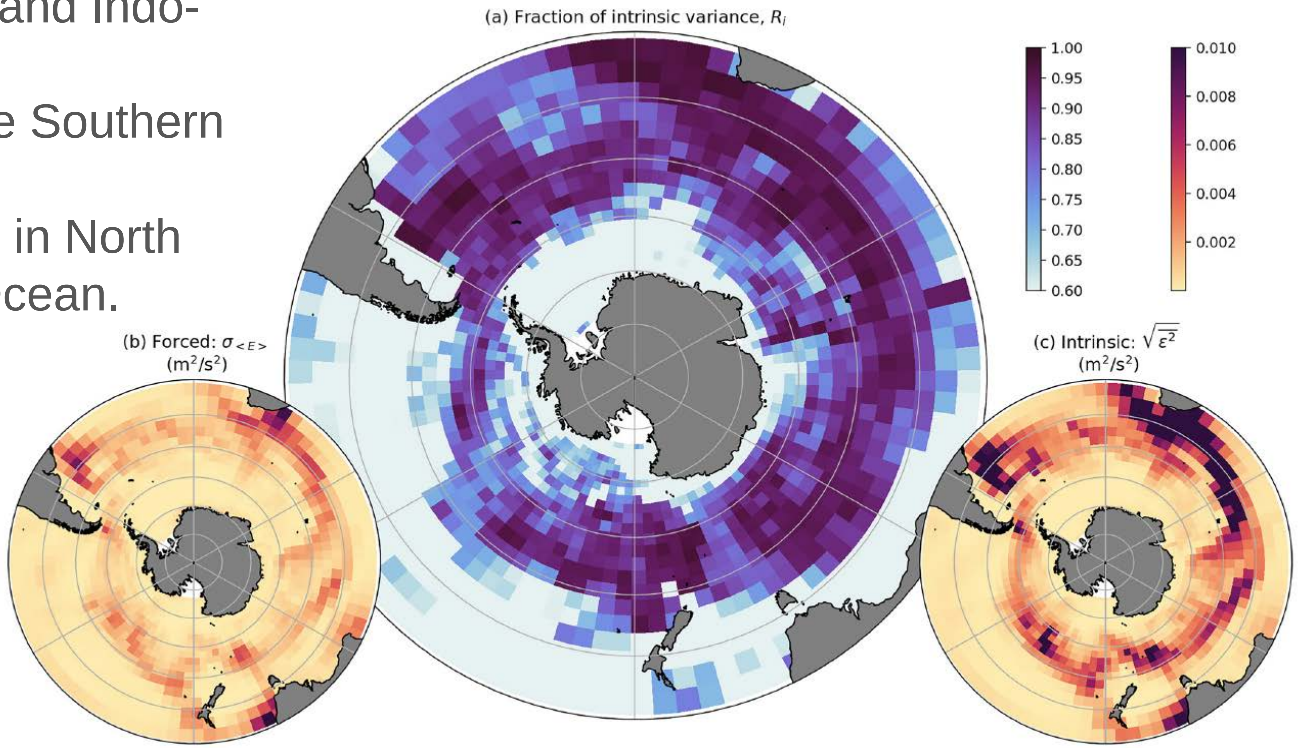
2010s - 1980s



Conclusions

- Accumulation of energy east of topographic seamounts and ridges.
- Vertical structure mostly surface intensified but relevant interior and bottom intensified signals detected.
- Intensification of energy at mid-depth in the equatorial region of all oceans due to Rossby wave activity.
- Downward and eastward energy propagation along a Yanai wave beam in the Equatorial Atlantic connected to the NBC and EUC.
- Largest contribution to transient EKE from intra-seasonal KE (periods between 5 days and 3 months).

- Significant positive trends in KE in Equatorial Pacific and Indo-pacific sectors of Southern Ocean.
- Significant negative trends in the Atlantic sector of the Southern Ocean.
- Temporal changes are correlated with climate modes in North Atlantic and in Indo-Pacific sectors of the Southern Ocean.



Hogg et al., JGR, 2022

Final remarks

- Multi-decadal trends (~40 years) still reflect ocean internal variability.
- Caution since is only one realization of a complex system. The ACC features large intrinsic variations compared to forced variability (Hogg et al., 2022).