Seasonal Variability of Global Semidiurnal Internal Tides

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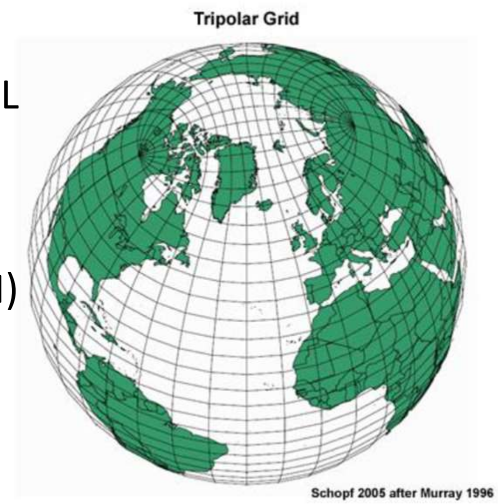
Research Questions

- Which areas in the global ocean have high seasonal variability in total (stationary + non-stationary) semidiurnal internal tides?
- What factors (time variability in tidal forcing, mesoscale currents, and stratification) can be responsible for the seasonal variability of total internal tides?

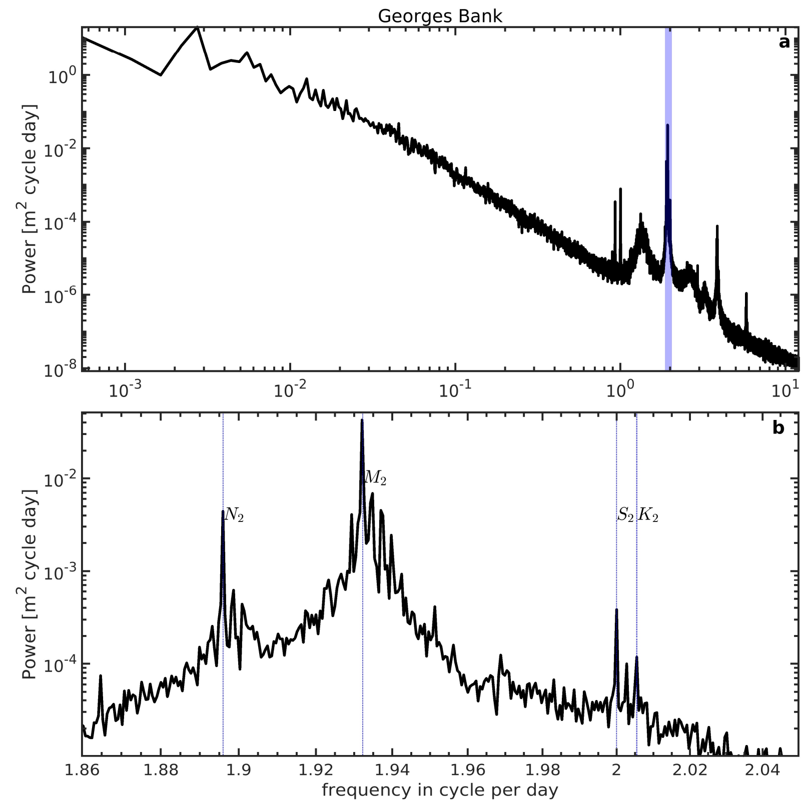
Model

- Steric sea surface height (SSSH) from Hybrid Coordinate Ocean Model (HYCOM) simulation Expt 18.5 is used
  - Forward simulation
  - 8-km horizontal resolution and 32 layers
  - Atmospheric forcing from FNMOC NOGAPS
  - Forced with M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1 tidal constituents and SAL correction
  - 6-year simulation; data output every hour
- Internal tide energetics from Hybrid Coordinate Ocean Model (HYCOM) simulation Expt 06.1 is used
  - Atmospheric forcing from FNMOC NOGAPS
  - Forced with M_2, S_2, N_2, K_1, O_1 tidal constituents and SAL correction
  - 8-km horizontal resolution and 41 layers



Data Analysis

- Five-year time series is divided into one-month segments (60 segments)
- For each one-month segment, SSSH is bandpassed for the semidiurnal frequencies between 1.86 and 2.05 cpd.
- This output is considered as total internal tide
- The zoomed image for semidiurnal frequencies for the Georges Bank area is shown in the bottom panel.



Seasonal Variability in Total Internal Tides

To study the seasonal variation in semidiurnal total internal tide:

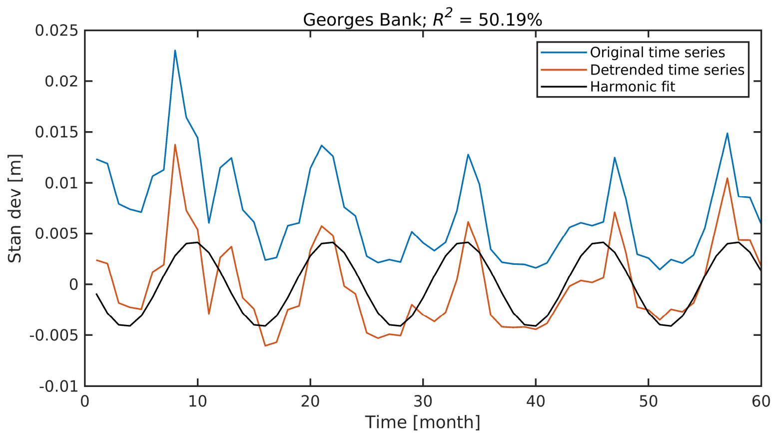
- The standard deviation of bandpassed SSSH time segments is calculated for one-month duration.
- The seasonal changes in standard deviation represent the seasonal changes in total semidiurnal internal tide.
- The annual signal is fitted to time series of monthly standard deviation (y_m) using the least-squares method after removing the linear trend

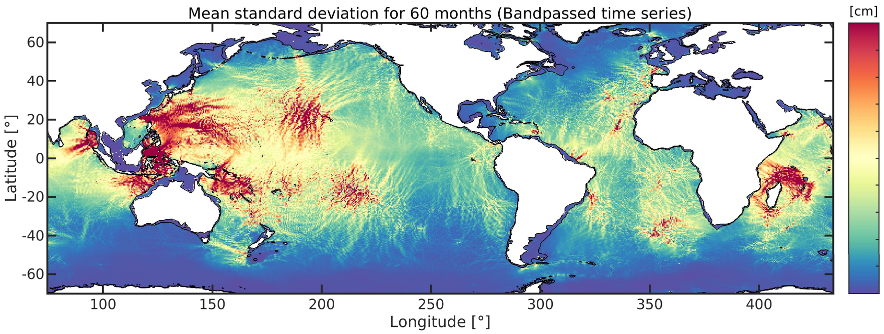
$$\breve{y_m} = y_m - l t_m$$

$$\breve{y_m} = \widehat{y_m} + \epsilon_m$$

$$\widehat{y_m} = y_0 + y_a \cos(\omega_a t_m + \phi_a)$$

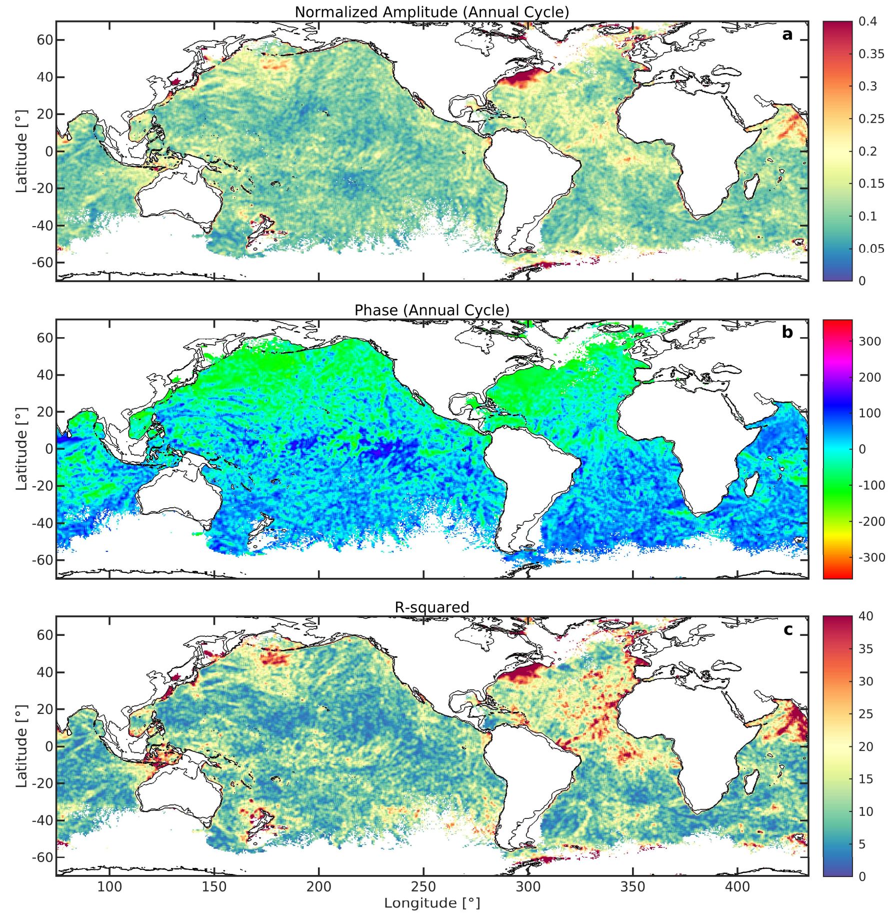
$\breve{y_m}$ - detrended time series	t - time in months
$\widehat{y_m}$ - fitted time series	l - linear trend
y_a - amplitude of annual cycle	y_0 - mean
ω_a - annual frequency	ϵ_m- residual





Seasonal Variability in Total semidiurnal internal tides

- The internal tides generated in coastal areas are showing high seasonal variability - Georges Bank and Arabian Sea
- The Northern and Southern Hemispheres are out of phase which indicates the seasonal variation due to changes in stratification
- The seasonal signal is stronger in the Atlantic Ocean than in the Pacific Ocean



The figure on the right-side shows (a) the normalized amplitude and (b) phase of the annual cycle for the global ocean. (c) The coefficient of determination (R^2) for the fit. The amplitude of the annual cycle is normalized by the mean standard deviation for 60 months. We are using normalized amplitude and R^2 as indicators for the seasonal variability. R^2 gives information about how much of the variance in the time series of the standard deviation can be explained by seasonality. The normalized amplitude specifies how much of the standard deviation varies seasonally compared to the mean standard deviation. If the normalized amplitude is 1, the seasonal cycle's amplitude is equal to the mean standard deviation. If the normalized amplitude is not significant, but R^2 is large, this indicates that the standard deviation is not varying much. Hence, we focus on areas where both normalized amplitude and R^2 are significant.

Factors causing seasonal variability

- Generation - barotropic tides and stratification variability (Buijsman et al. (2012))

$$C = Wp'(z = -h)$$

C : depth-integrated barotropic to baroclinic energy conversion

W : vertical barotropic velocity

$p'(z = -h)$: perturbation pressure at the bottom

- Propagation - The increase in stratification increases the phase speed which further increases wavelength. The increase in wavelength decreases the energy density which should decrease the amplitude of internal tide sea surface height
- Dissipation

Seasonal variation due to wavelength

- We can derive the change in amplitude of internal tide due to the change in wavelength. The total energy in the wavelength is constant for internal tide:

$$\int \mathrm{EdL} = \mathrm{constant}$$

- The total energy density can be expressed as (Zhao et al., 2016):

$$\mathrm{E} = \frac{\mathrm{a}^2 \mathrm{E}_1}{2}$$

$$\frac{\mathrm{a}^2 \mathrm{E}_1}{2} \mathrm{L} = \mathrm{constant}$$

$$\frac{\delta a}{a} = -\frac{\delta L}{2L}$$

E- total energy density

a- amplitude of M2 internal tide

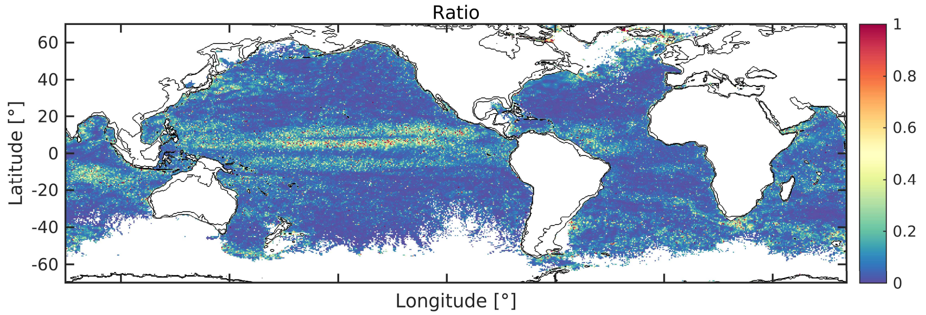
L – wavelength of M2 internal tide

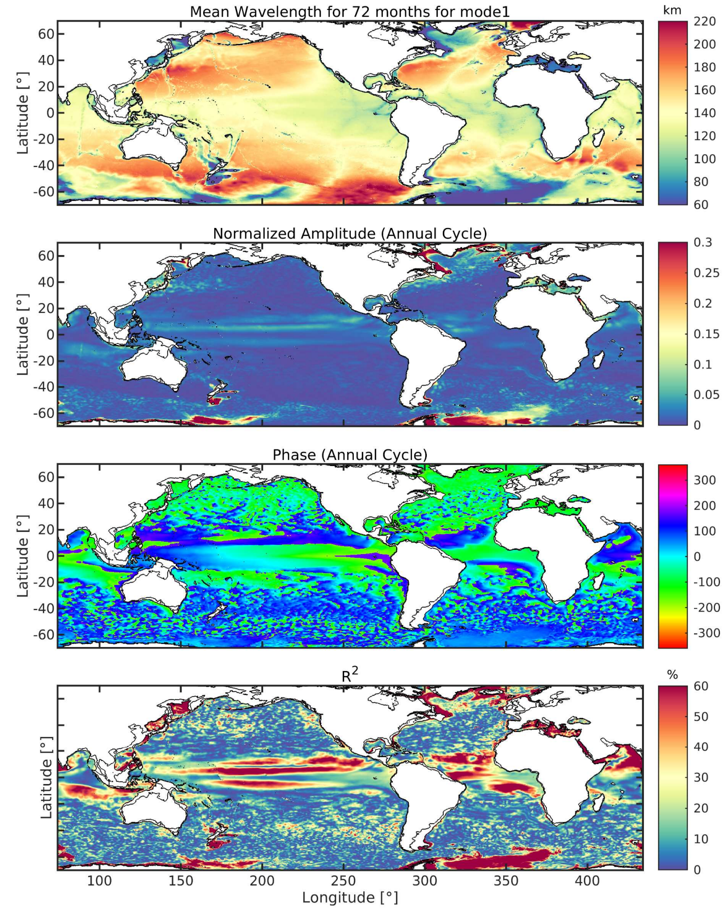
- The minus sign indicates that amplitude and wavelength are out of phase

Seasonal variation due to wavelength

- The monthly standard deviation has same seasonal phase as the wavelength
- The ratio of ($\frac{\delta a}{a}$) and normalized amplitude of seasonal cycle for the standard deviation of bandpassed SSSH time series is not significant
- The observed change in SSSH is not due to the change in wavelength

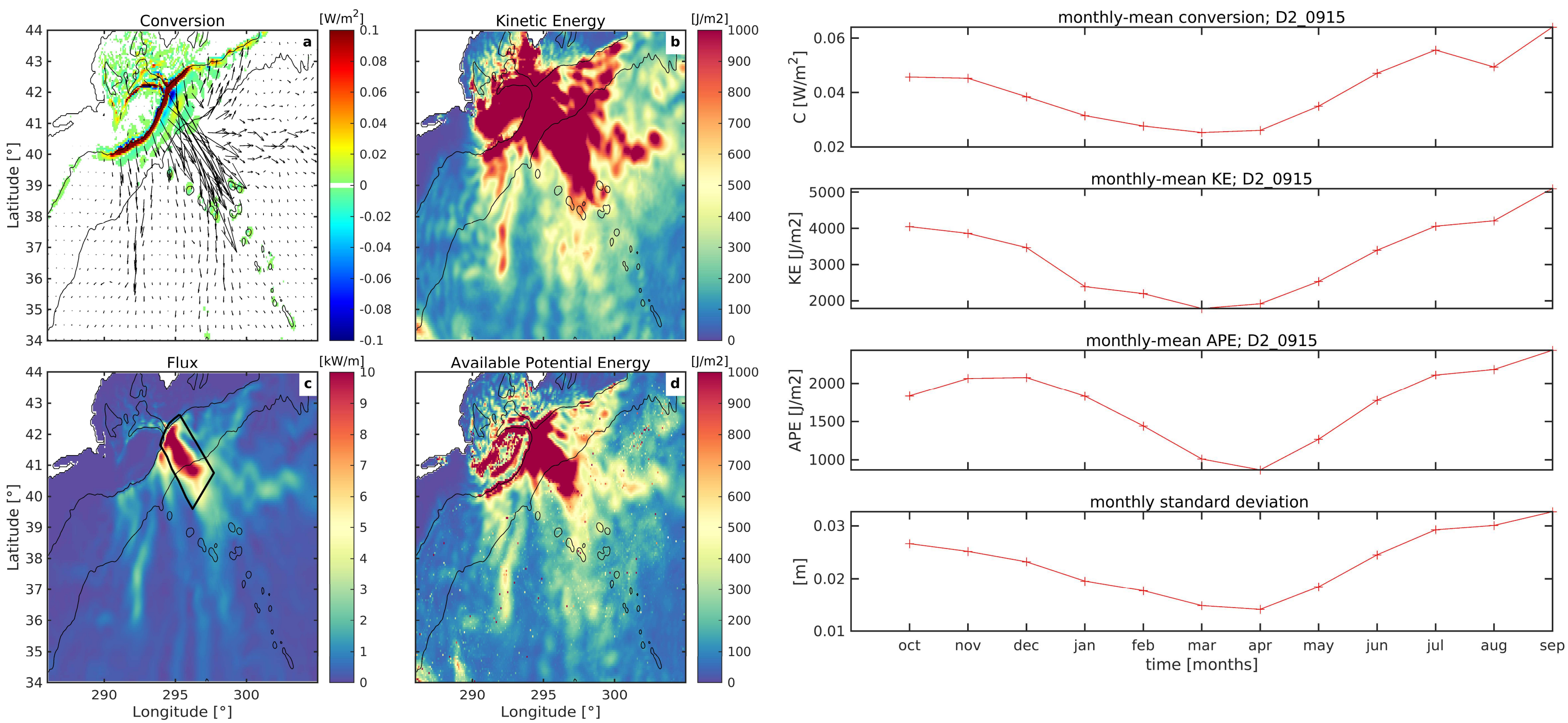
$$Ratio = \frac{\frac{\delta a}{a}}{Normalized\ amplitude\ of\ seasonal\ cycle\ for\ stan\ dev}$$





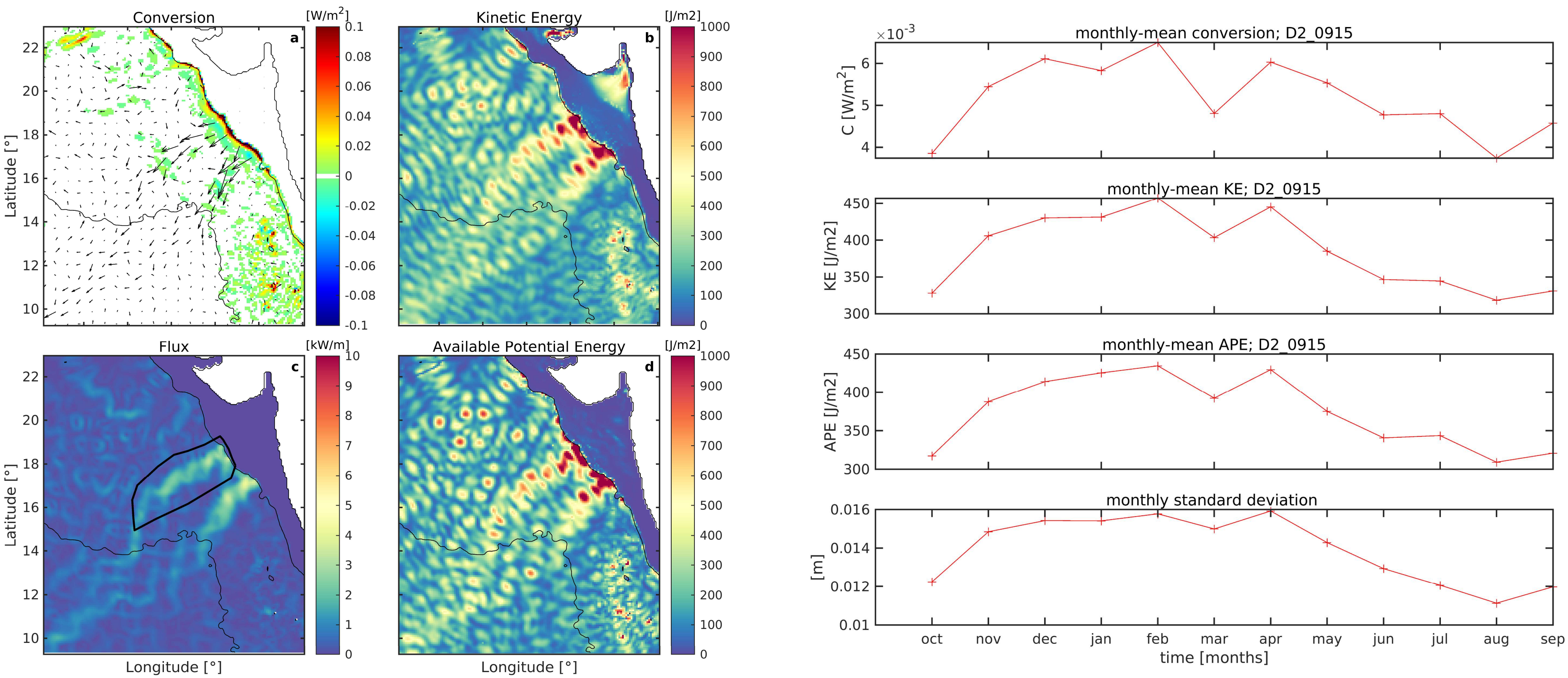
The figure on the right-side shows mean of (a) Mode 1 wavelength over six years. (b) The normalized amplitude and (c) phase of the annual cycle for the mode 1 wavelength. (d) The coefficient of determination (R^2) for the annual seasonal cycle fit for the mode 1 wavelength

Georges Bank



If seasonal variability is present at generation, then conversion should also show the seasonal variability, and its seasonal cycle should be similar to the seasonal cycle present
in the monthly standard deviation of semidiurnal SSSH. For this analysis, we are making a polygon capturing the generation and propagation of the internal tide beam. The area integrated values for conversion, kinetic energy, available potential energy, and monthly standard deviation for polygon for each month are shown in right figure. Same seasonal cycle is observed in their values (conversion, kinetic energy, available potential energy, and monthly standard deviation), showing that the seasonal conversion changes are causing seasonal changes in the total semidiurnal internal tide.

Arabian Sea



For the Arabian Sea, two internal tide beams are present, and strong internal tides are generated at the shelf break. The mesoscale variability is low in this region. Here the conversion rates show a similar seasonal trend as the monthly standard deviation of semidiurnal SSSH. We conclude that seasonal variability is present at the generation site for the Arabian Sea.

Conclusion

- Strong seasonal variability is observed in the total semidiurnal internal tide for two regions : the Georges Bank and the Arabian Sea.
- The seasonal change in barotropic to baroclinic conversion rate due to stratification is the dominant factor causing seasonal variability in the Georges Bank and the Arabian Sea.