



# **Seasonal and interannual variability of global internal tides**

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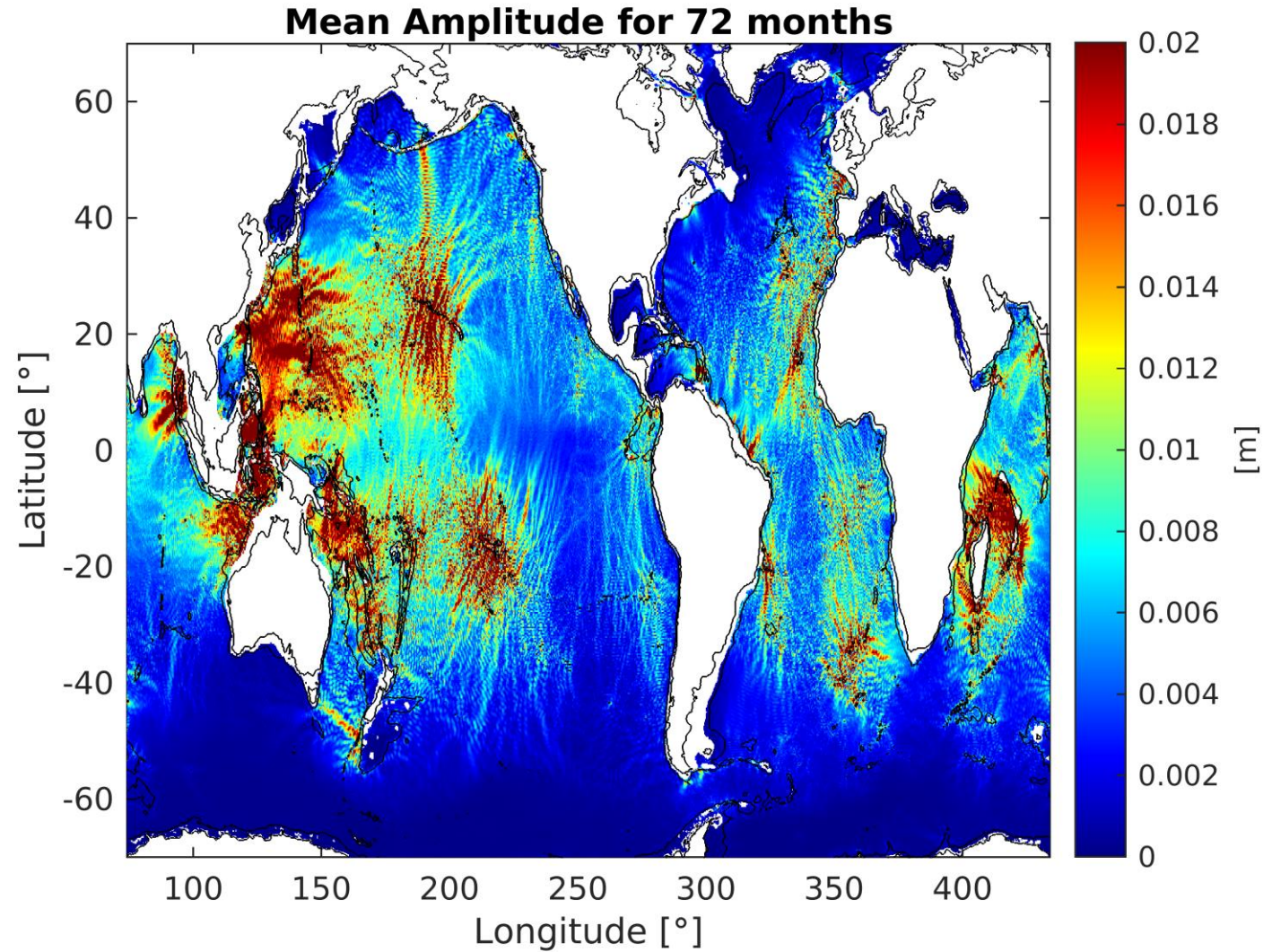
**Maarten Buijsman**

# Introduction and Data

- In this study, we investigate the seasonal and interannual variability of internal tides in the global ocean using a Hybrid Coordinate Ocean Model (HYCOM) due to time varying stratification, mesoscale activity, large-scale shifts in amphidromic points, and changes in ice cover
- Our objective is to analyze the spatial and temporal variability of the amplitude of the semidiurnal  $M_2$  internal tides
- We are using 6 years of steric sea surface height (SSH) extracted from a global HYCOM simulation with a horizontal resolution of 8 km and 32 layers to study the variability of internal tides
- The least-squares harmonic analysis is used to extract complex  $M_2$  harmonic constants over 72 consecutive months for each grid cell
- The SSH amplitude and phase of the  $M_2$  tide is calculated from the complex harmonic constants for each month

# Mean Amplitude for 72 months

This figure shows the areas where strong  $M_2$  internal tides are present in the global ocean



# Seasonal variation of amplitude

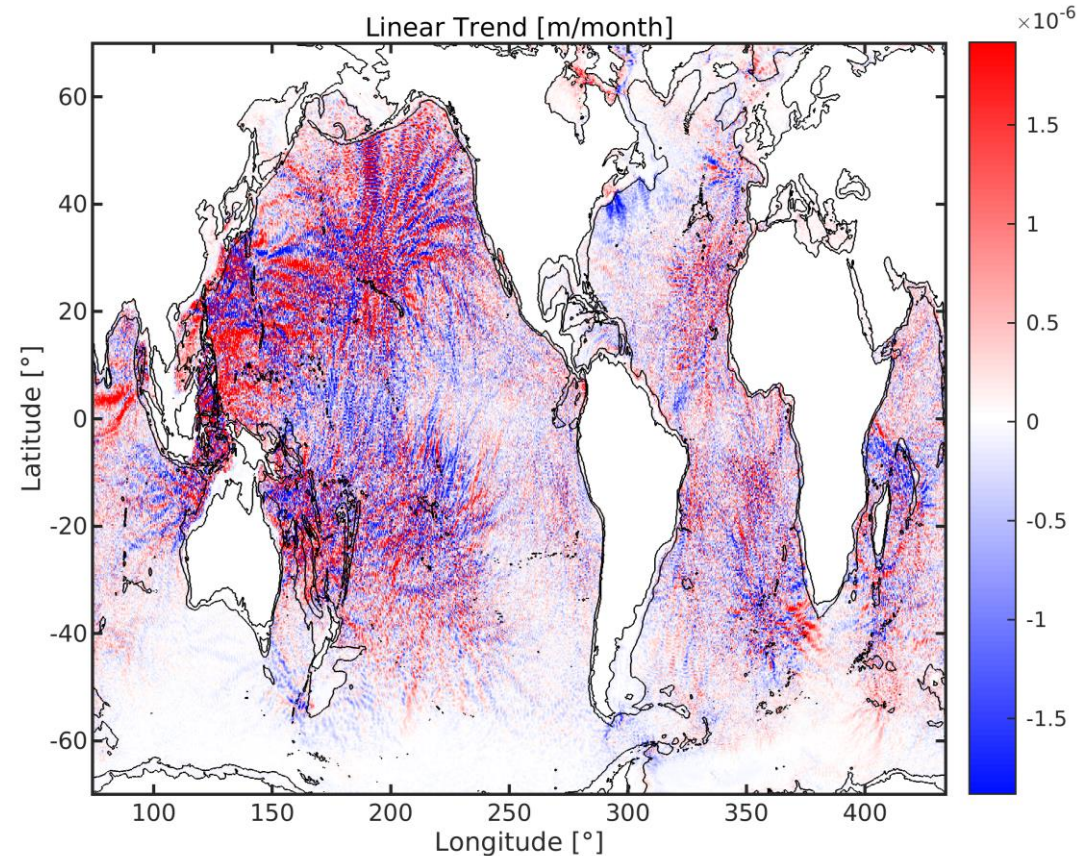
To study the seasonal variation in monthly amplitude for semidiurnal  $M_2$  sea surface height-

- Linear trend is removed using

$$A_{wt}(t) = A(t) - bt,$$

Where  $A$  is time series of SSH  $M_2$  amplitude,  $t$  is time in months and  $b$  is linear trend

- Harmonic and synthetic fits are applied
- Coefficient of determination is calculated for both fits to find the percentage of variance explained by seasonal variations



# Harmonic Fit

- Annual and semiannual seasonal signals are fitted using the least-squares method

$$A_{wt}(t) = A_0 + A_a \cos(\omega_a t + \varphi_a) + A_{sa} \cos(\omega_{sa} t + \varphi_{sa}) + \varepsilon$$

$A_0$  - bias

$A_a$  - amplitude of annual cycle

$\omega_a$  - annual frequency

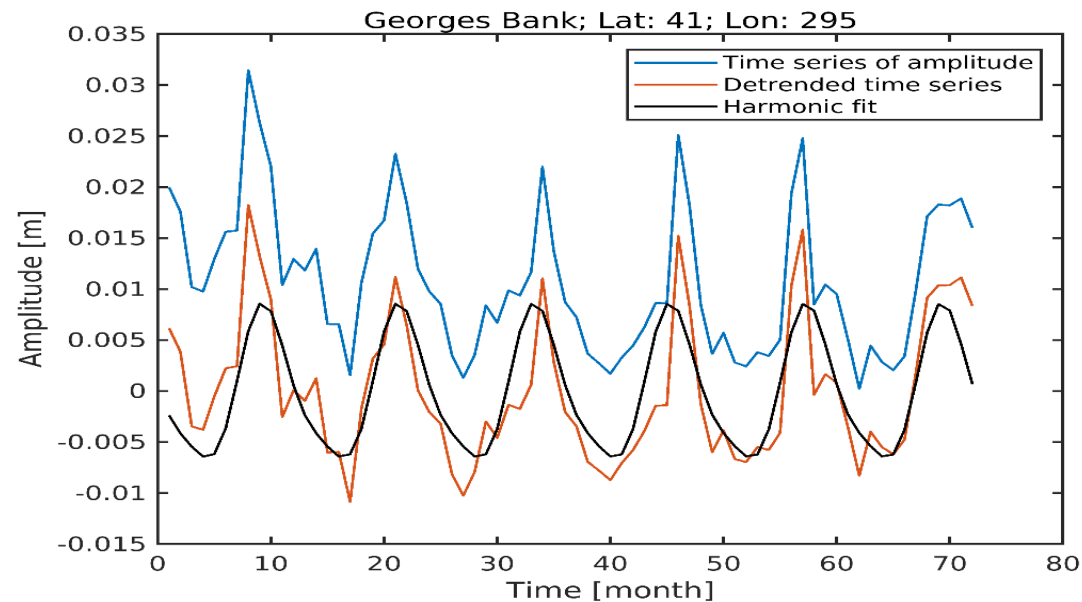
$\varphi_a$  - phase of annual cycle

$A_{wt}$  - detrended time series of SSH  $M_2$  amplitude

$A_{sa}$  - amplitude of semiannual cycle

$\omega_{sa}$  - semiannual frequency

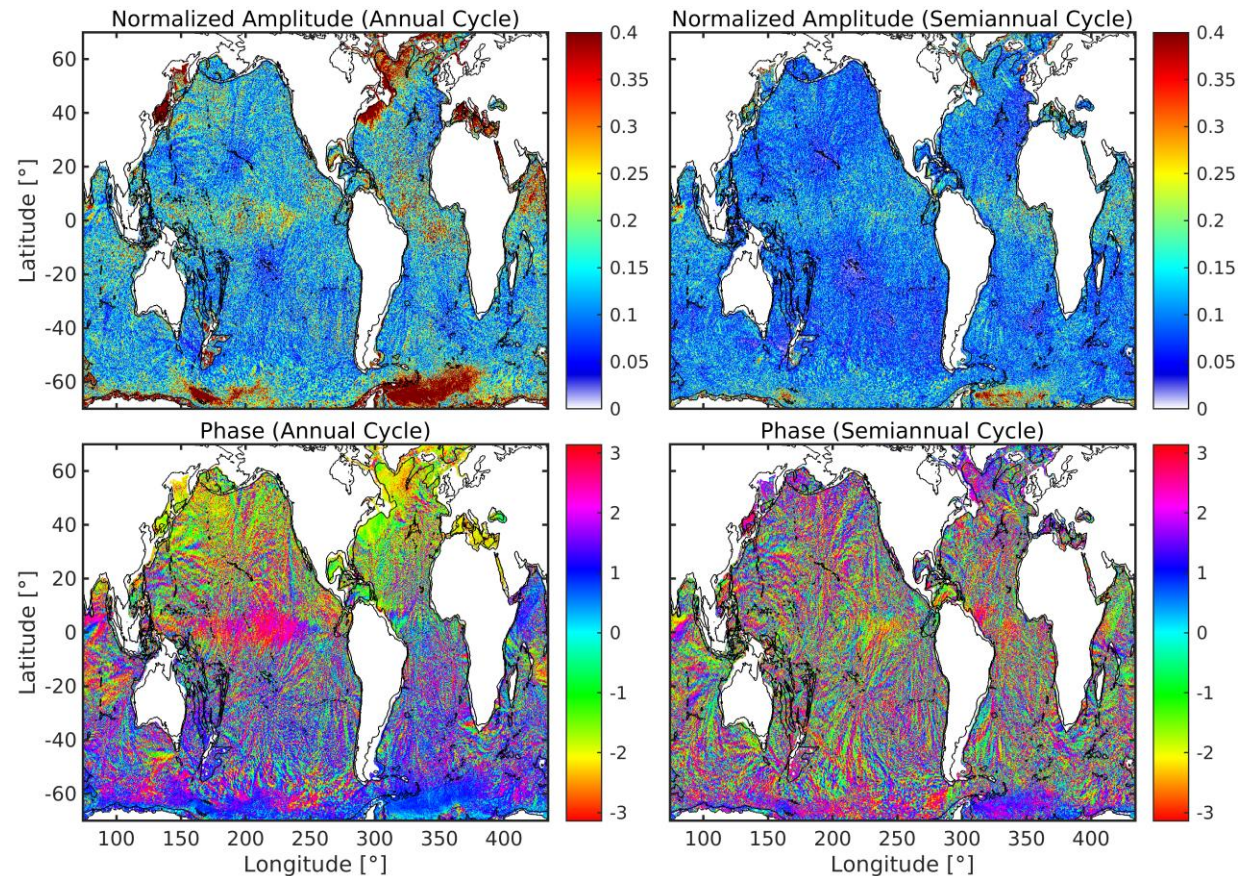
$\varphi_{sa}$  - phase of semiannual cycle



# Harmonic Fit

The amplitude for annual and semiannual cycle is normalized by the mean amplitude of  $M_2$  internal tides for 72 months. Following was observed:-

- The amplitude for annual cycle is higher than the amplitude for semiannual cycle
- The internal tides generated in coastal areas are showing high seasonal variability - Georges Bank, Amazon Shelf, and Arabian Sea
- Seasonal variability is observed in ice covered regions – Arctic Ocean and Southern Ocean, however magnitude of internal tides is small
- The Northern and Southern Hemispheres are out of phase which indicates the seasonal variation due to changes in stratification



# Synthetic Fit

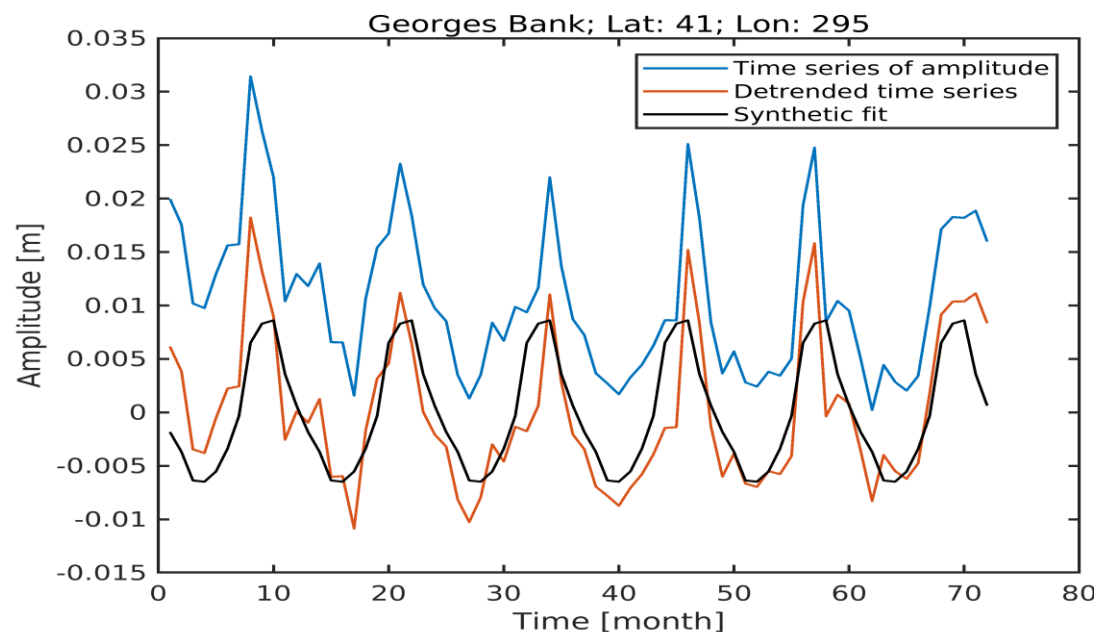
- Mean amplitude for each month is calculated using

$$Y_i = \frac{\sum_{j=1}^6 A_{ij}}{6}$$

Where A is detrended SSH  $M_2$  amplitude for month i and year j

- Fit is constructed by repeating the pattern for 6 years

$$Y_{fit} = ((Y_1, \dots, Y_{12}), (Y_1, \dots, Y_{12}), (Y_1, \dots, Y_{12}), (Y_1, \dots, Y_{12}), (Y_1, \dots, Y_{12}), (Y_1, \dots, Y_{12}))$$



# Synthetic Fit

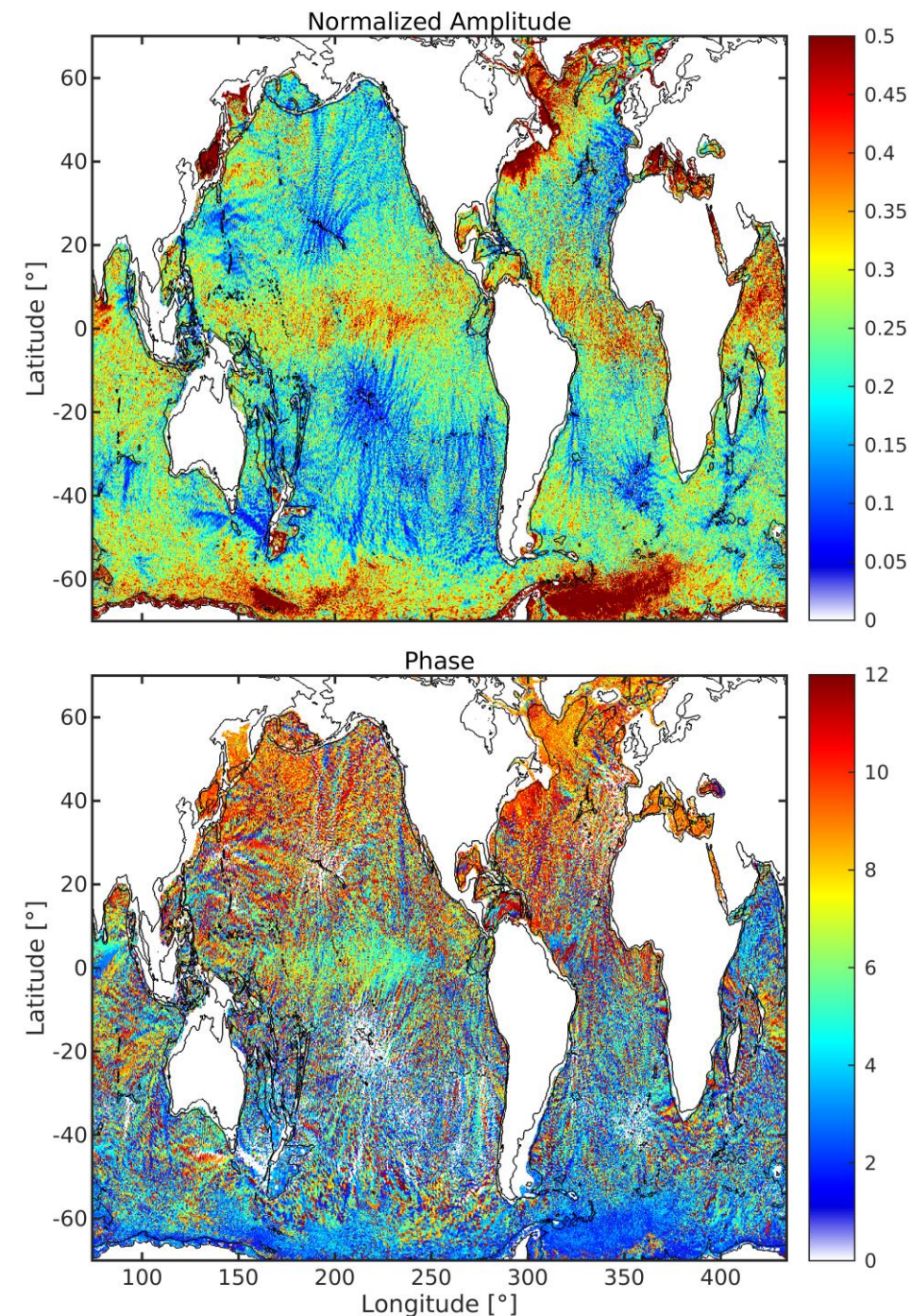
The amplitude of seasonal variation is calculated as follows:

$$A_{fit} = \sqrt{2}\sigma$$

Where  $\sigma$  is standard deviation of  $Y_{fit}$

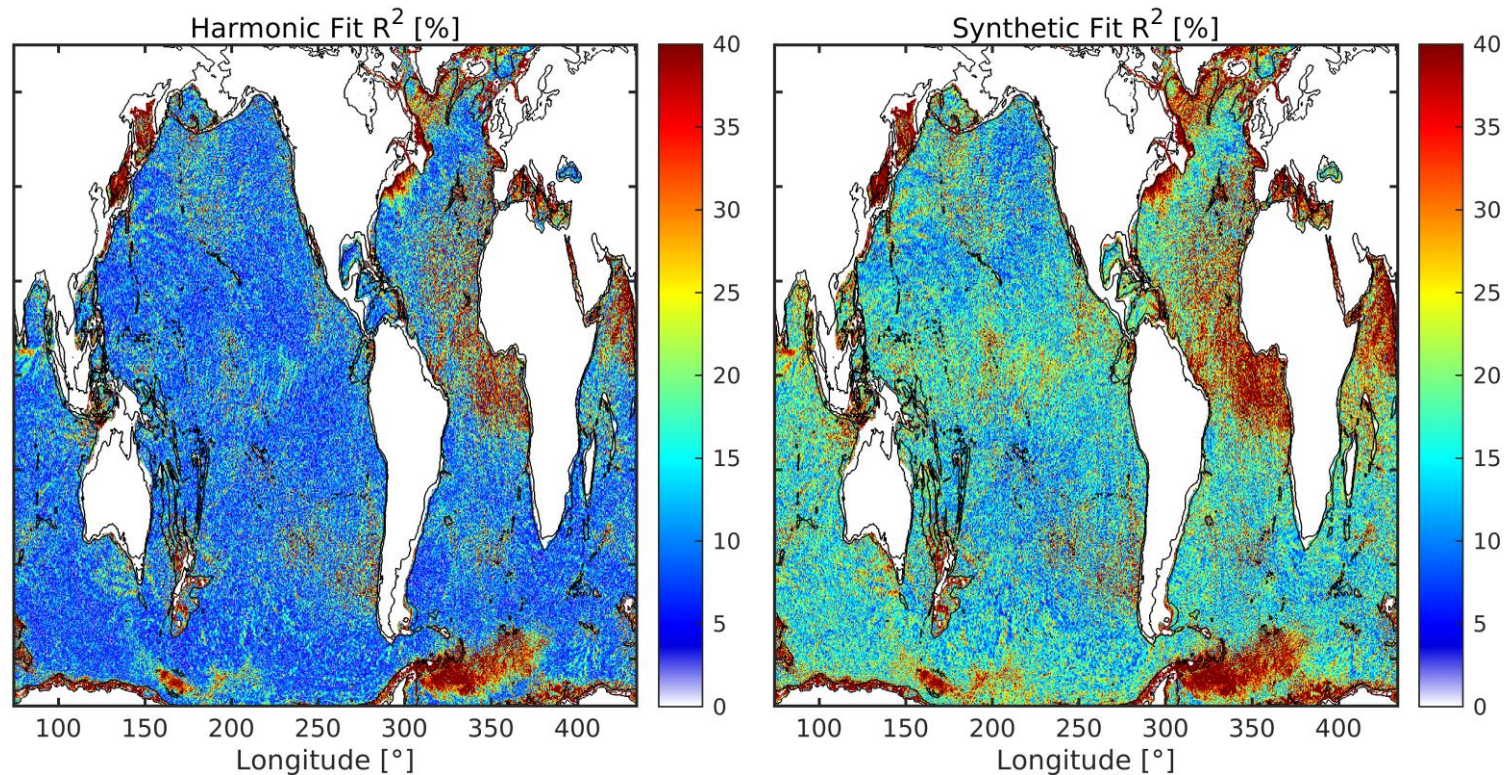
The phase is calculated in months for areas where normalized amplitude is greater than 0.1. The phase is considered as the month in which amplitude is maximum

- This method shows the seasonal variability in the same areas as observed by harmonic fit method
- The phase of seasonal variation indicates the SSH of internal tides is maximum in fall season for respective hemispheres

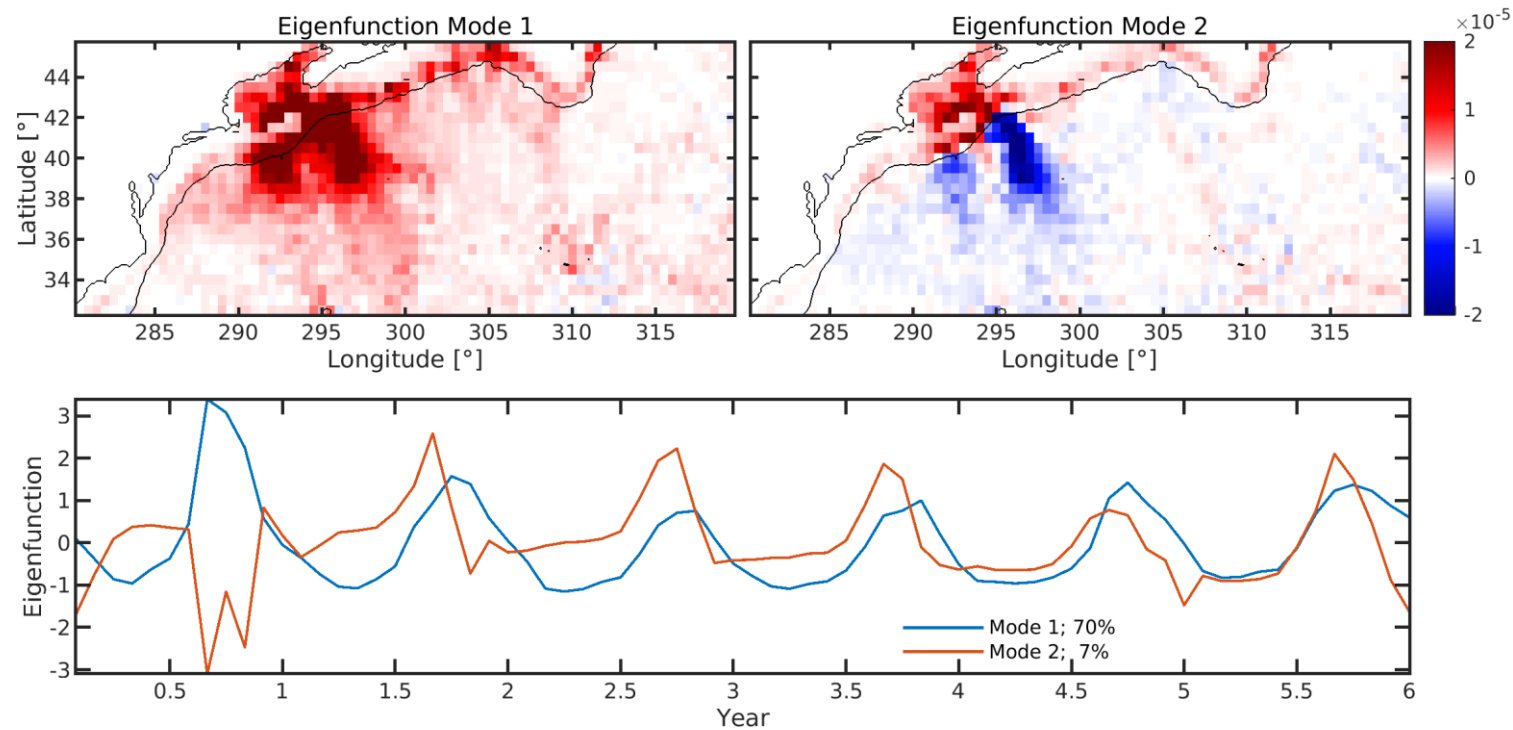


# Comparison of Coefficient of Determination for two fits

The coefficient of determination is higher for synthetic fit as compared to harmonic fit



# Empirical Orthogonal Function for Georges Bank



- The Empirical Orthogonal Function (EOF) mode 1 and 2 eigenfunctions (top) and their time series (bottom) of the monthly  $M_2$  internal tide sea-surface variance
- Mode-1 explains about 70% of the total variability in the monthly  $M_2$  variance, and it displays a strong seasonal variability for Georges Bank

# Stationary amplitude and phase for seasons

- The stationary complex amplitude for each season is given by

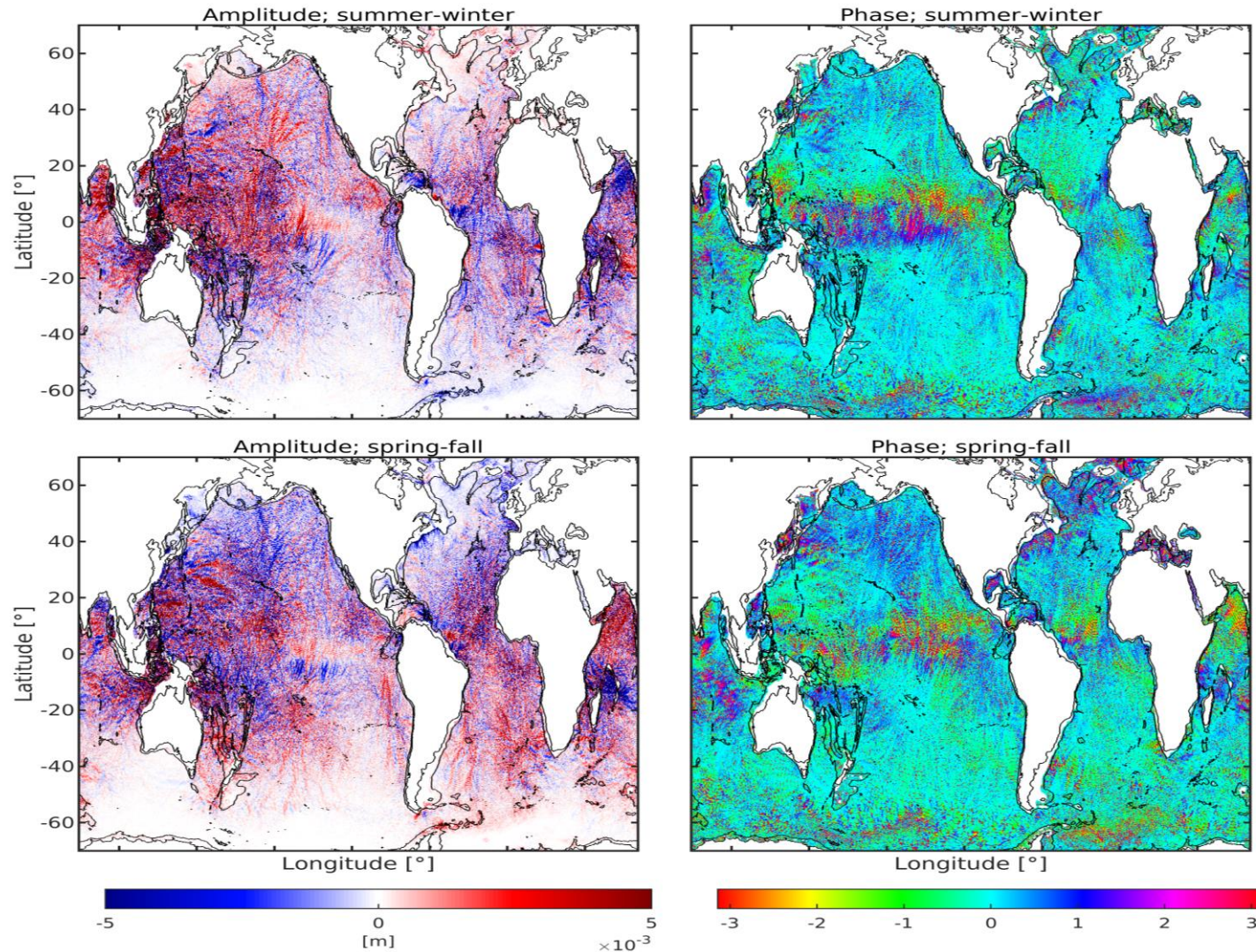
$$\eta_s = \langle \eta_j \rangle$$

Where s and j stands for season and month, respectively.  $\langle . \rangle$  represents the time-mean over the months for each season

The months in each season are defined as below:

- Winter – December, January, February
- Spring – March, April, May
- Summer – June, July, August
- Fall – September, October, November

# Difference between stationary amplitude and phase for seasons



- The difference between spring and fall is higher than summer and winter

In this figure, mean square error (MSE) between the seasons is shown.

MSE is calculated as follows (Shriver et al., 2012):

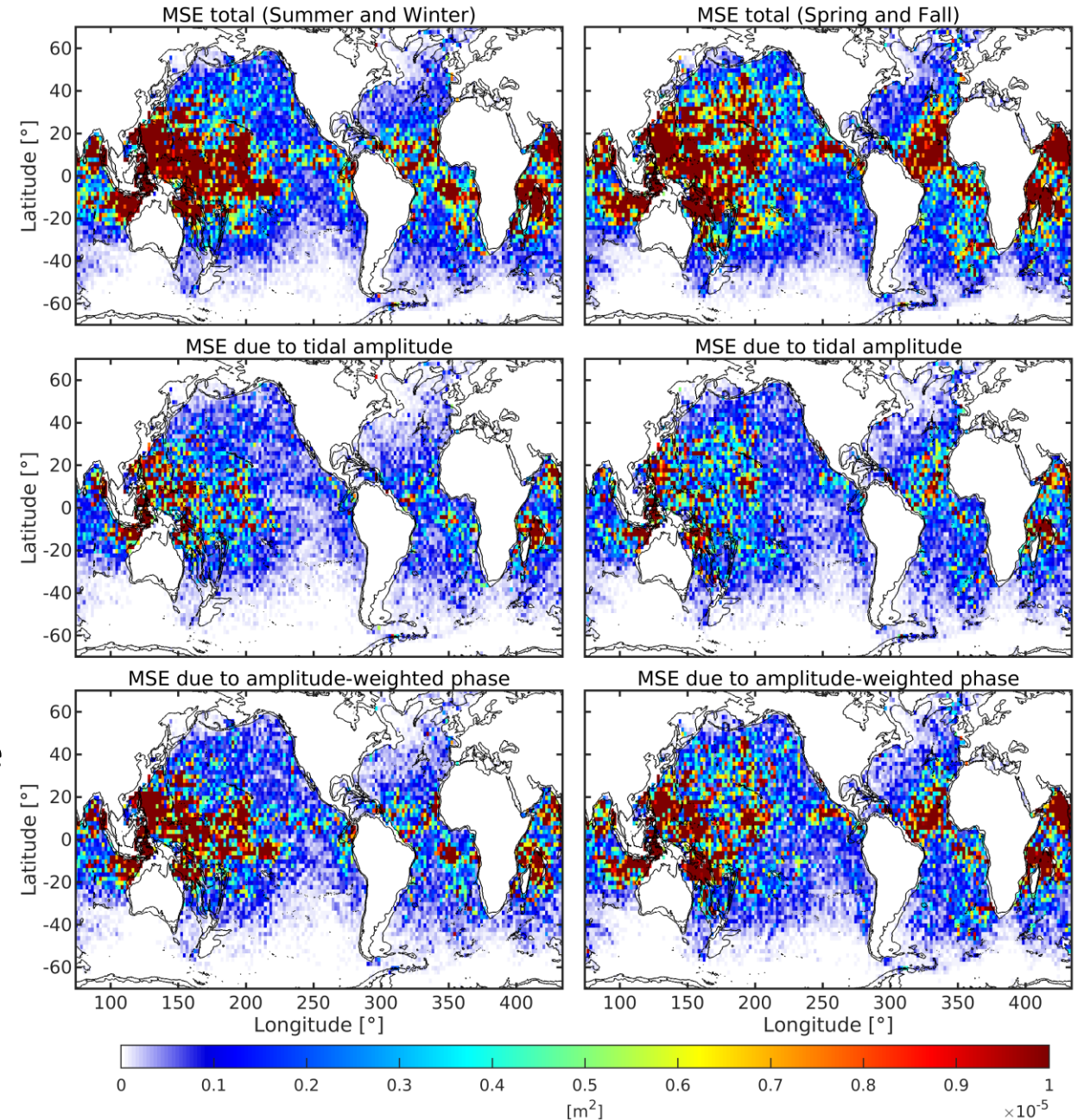
$$\text{Total MSE} = \frac{1}{2} |A_1 e^{i\varphi_1} - A_2 e^{i\varphi_2}|^2$$

$$\text{Tidal amplitude MSE} = \frac{1}{2} (A_1 - A_2)^2$$

$$\begin{aligned} \text{Amplitude weighted phase MSE} \\ = [A_1 A_2 (1 - \cos(\varphi_1 - \varphi_2))] \end{aligned}$$

where  $A_1$  and  $A_2$  are the amplitudes,  $\varphi_1$  and  $\varphi_2$  are the phases for season 1 and season 2, respectively

We can observe that for most of the areas, amplitude weighted phase MSE is higher than Tidal amplitude MSE



# Summary and Conclusion

- We have used harmonic and synthetic fit to understand the seasonal variation in SSH amplitude of  $M_2$  internal tides
- The synthetic fit has a better agreement when compared to harmonic fit
- We have identified three regions with seasonal variability in SSH  $M_2$  amplitude – Georges Bank, Amazon Shelf and Arabian Sea
- The Northern and Southern Hemispheres are out of phase which indicates the seasonal variation due to changes in stratification
- While comparing the stationary internal tides for various seasons, the difference between fall and spring season is higher than winter and summer season. This difference can be attributed mainly to phase