# SAMUDRA

**SA**tellite based **M**arine process **U**nderstanding, **D**evelopment, **R**esearch and **A**pplications for blue economy

# EYES ON WAVES FROM SPACE

# Eyes on Waves from Space

## A Wave Atlas based on Satellite Observations & Numerical Model

**Contributions**

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# FOREWORD

Oceans, one of the most significant constituent of our planet Earth, till date remains the most unexplored of all other earthly resources. With the advent of space-borne satellite instruments like altimeters, synthetic aperture radar and scatterometer we are putting dedicated efforts for better understanding of ocean. SAMUDRA (Satellite based Marine Process Understanding, Development, Research and Applications for blue economy) is a dedicated programme in which we have made earnest efforts to address science questions on various themes including coastal vulnerability, satellite based assessment of potential fisheries zone, satellite data assimilation for ocean state analysis, developing altimeter observation based oil spill tracking, ocean renewable energy etc.

It is remarkable to note that, team SAMUDRA has come up with the wave atlas based on satellite observations and numerical model. This atlas will be of great interest to the scientific community. I congratulate the team for their endeavours.

(डी के दास)
(D K Das)

Ahmedabad
February 4, 2019

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# PREFACE

Ocean plays a vital role in modulating sustainable development of our nation. Thus, ISRO's program SAMUDRA (Satellite based Marine Process Understanding, Development, Research and Applications for blue economy) is formulated to address various criticalities of the ocean. Under this project, satellite data assimilation for ocean state analysis is one of the most important theme.

Ocean surface at any given time and location contains wide range of waves with varying amplitudes. At the first cut, therefore an accurate wave prediction is most important for any oceanographer. Under the above mentioned theme, satellite altimeter observed significant wave height from SARAL/AltiKa, Jason-2 and Jason-3 has been assimilated in the numerical wave model. In this atlas, wave climatology from satellite altimeter and numerical model has been presented. The extreme wave captured by the data assimilative wave model during cyclones from 2014-2016 has been demonstrated. I hope that this atlas will be useful for various institutes working on the same theme.

Raj Kumar

Ahmedabad
February 4, 2019

(Raj Kumar)

# Acknowledgements

The team would like to express their sincere gratitude to Sri. D K Das, Director, Space Applications Centre (SAC), and Sri. N M Desai, Associate Director, SAC for their encouragement and continued support. The motivation from Group Director, Atmospheric and Oceanic Sciences Group, Dr. C M Kishtawal is greatly appreciated. We acknowledge the support provided by Dr. Nitant Dube, Group Head, MOSDAC Research Group and his team. Gridded Satellite derived wave data provided by AVISO for the preparation of the atlas is gratefully acknowledged. Authors are thankful to NCMRWF, MoES, India and ECMWF, UK for providing wind data utilised in the wave model simulation experiments. The team extend their hearty gratitude to WAVEWATCH III developers for the model. We thank MOSDAC and VEDAS for providing altimeter data sets and for hosting science products on wave. Team would also like to thank INCOIS for providing the buoy data sets. Model simulations are performed by utilizing the HPC facility (AKASH) at SAC.


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# Introduction

Surface waves are one of the most prominent features of ocean and its accurate estimation and prediction is very important for various applications such as naval operations, ship routing, fisheries, design of marine structures, offshore industries etc. A wave atlas presents basic wave statistics derived from long-term wave data, which can be obtained from numerical wave model simulations and space-borne altimeter measurements. Advances in ocean wave modelling have resulted in the community standard third-generation models such as WAM, SWAN and WAVEWATCH III. Accuracy of these wave models can be improved by assimilating satellite measured wave information into the model; thereby, making it possible to produce improved wave estimation and prediction.

This atlas is based on WAVEWATCH III version 4.18 (WW3) simulations. 17 years of WW3 simulations (from 2000 to 2016) are used to generate the wave climatology, particularly over the Northern Indian Ocean region at very high spatial resolution (10x10 km). Simulations are carried out by forcing the model with ERA-Interim winds obtained from ECMWF. Merged daily product of wave heights from AVISO for the period from Sep, 2009 to Apr, 2017 is utilized for satellite altimeter based climatology generation at 1x1 degree resolution. The data assimilation using optimum interpolation technique is carried out for simulating waves during 2014 - 2016. Significant Wave Height (SWH) measurements from Jason-2, Jason-3 and SARAL/Altika are used for the assimilation. Model simulations are validated with the buoy observations obtained from Indian National Centre for Ocean Information Services (INCOIS). Inter-annual variability of waves and extreme waves due to tropical cyclones are also presented from the data assimilative wave model simulations. Further, implementation of an ultra high resolution (2.5x2.5 km) data assimilative wave model for the improved wave forecast over the Indian Ocean region is also presented.

# Model Description

WAVEWATCH III is a third-generation wind-wave spectral model developed at NOAA/NCEP with better response to long-range swell propagation and new physics parameterization schemes with capabilities to take large-scale wave-current interaction. It solves the random phase spectral action density balance equation for wave number-direction spectra, which in spherical coordinate is;

$$\frac{\partial N}{\partial t} + \frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\dot{\phi}N\cos\theta + \frac{\partial}{\partial\lambda}\dot{\lambda}N + \frac{\partial}{\partial k}\dot{k}N + \frac{\partial}{\partial\theta}\dot{\theta}_g N = \frac{S}{\sigma}$$

$$\dot{\phi} = \frac{c_g\cos\theta + U_\phi}{R}$$

$$\dot{\lambda} = \frac{c_g\sin\theta + U_\lambda}{R\cos\phi}$$

$$\dot{\theta}_g = \dot{\theta} - \frac{c_g\tan\phi\cos\theta}{R}$$

t is time; λ is longitude; ϕ is latitude; ɵ is wave direction; N is the wave action density spectrum in five dimensions (λ, ϕ, k, ɵ, t); k is the wave number; the overdot symbol denotes the wave action propagation speed in (λ, ϕ, k, ɵ) space; Cg is group velocity; Uϕ and Uλ are current components; R is radius of earth; σ is relative frequency; S is the total of source/sink terms.

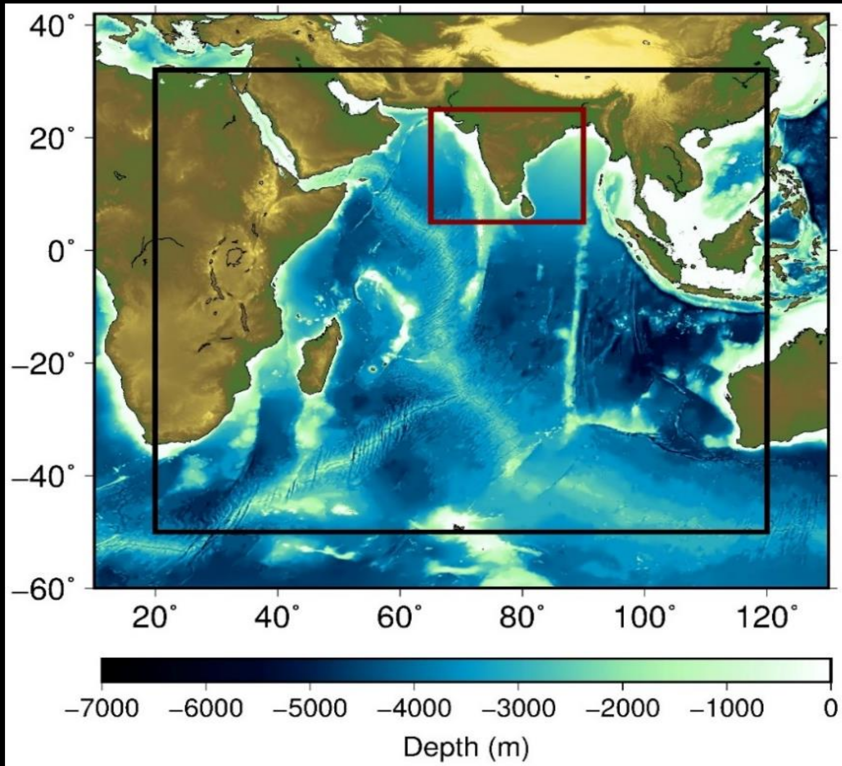
In deep water, term S is,

S= Sin + Snl + Sds

where Sin is wind-wave interaction term, Snl is non-linear wave-wave interactions term and Sds is dissipation term.

In shallow water, additional processes have to be considered, most notably wave-bottom interactions (Sbot) and depth-induced breaking (Sdb).

# Model Configuration




- ❖ WW3 multi-grid model nested domains with two-way interaction
- ❖ It consists of three grids with varying spatial resolutions; including a Global grid, Indian Ocean grid and a Coastal grid
- ❖ Bathymetry is taken from ETOPO1
- ❖ Shoreline data is from Global Self-consistent Hierarchical High resolution (GSHHS) database
- ❖ Spectrum is discretized with 29 frequencies, ranging from 0.0350 to 0.5047 Hz with 1.1 Hz increment factor and 24 directions with a 15-degree increment

| **Grids** | **Resolution** | **Area** |
|---|---|---|
| **Global** | **$1^0$x$1^0$** | **$70^0$ S to $70^0$ N & $0^0$ to $359^0$** |
| **Indian Ocean** | **$0.5^0$x$0.5^0$** | **$50^0$ S to $32^0$ N & $20^0$ E to $120^0$ E** |
| **Coastal** | **$0.1^0$x$0.1^0$** | **$5^0$ N to $25^0$ N & $65^0$ E to $90^0$ E** |

Details of area covered and spatial resolution of each grids

# Satellite Data used for Assimilation

Jason-2 Ocean Surface Topography Mission is a follow-on mission to Jason-1. It was launched at an altitude of 1336 km and 66-degree inclination angle with a repetivity of 10 days covering 95% of ice-free oceans. The altimeter is a dual frequency one operating at a nominal frequency of 13.6 GHz in Ku-band and 5.3 GHz in C-band.

Jason-3 is a joint mission by NASA, NOAA, CNES and EUMETSAT launched on January 17, 2016. It is in line with Jason-2 and is placed at an elliptical orbit with an inclination of 66.05 degree with a perigee of 1331.7 km and apogee of 1343.7 km.

SARAL, a joint ISRO-CNES mission, consists of payloads that include Ka–band high frequency altimeter (AltiKa). The satellite orbit is sun-synchronous with an inclination of 98.55-degree at an altitude of 814 Km. It has a repeat cycle of 35 days. Because of the high frequency, it has very low footprint size and hence is more suitable for coastal studies including assimilation in coastal models.

In the present work, all these three altimeter measured SWH are assimilated in the WW3 model.

Jason-2

Jason-3

SARAL/AltiKa

# Assimilation Scheme

The assimilation aims for best representation of the true wave field by distributing observed data into the model wave field. Optimal Interpolation (OI) technique has been used for the assimilation of altimeter measured SWH into the WW3 model. Here, the analysis field of SWH, $X^a$ is calculated as,

$$X^a = X^b + BH^T(HBH^T + R)^{-1}\,[y^0 - HX^b]$$

where, $X^b$ is the background state and $y^0$ is the observed state. $B$ is the background error covariance matrix and $R$ is the observation error covariance. $H$ is the interpolation operator which maps the model onto observation space.

$B$ is estimated using the formulation, in which the covariance between any two points separated by a distance '$d$' is assumed to have a Gaussian spatial distribution,

$$A\,exp[-(d/l)^2]$$

where $A$ is the model error variance and $l$ is the estimate of correlation spatial scale of model error.

Observation errors are generally assumed to be spatially uncorrelated and can be written as,

$$R = VI$$

where $V$ is the variance value for altimeter SWH and $I$ is an m by m identity matrix (m is the number of observations)

Analysis wave spectrum $F_{an}(f,\theta)$, where $f$ is frequency and $\theta$ is direction, has been calculated from the analysis mean parameter, $SWH_{an}$ by scaling the background model spectra $F_m(f,\theta)$ using the following equation;

$F_{an}(f,\theta) = \left(\frac{SWH_{an}}{SWH_m}\right)^2 F_m(f,\theta)$ where, $SWH_m$ is the background model predicted SWH

# AVISO merged altimeter data

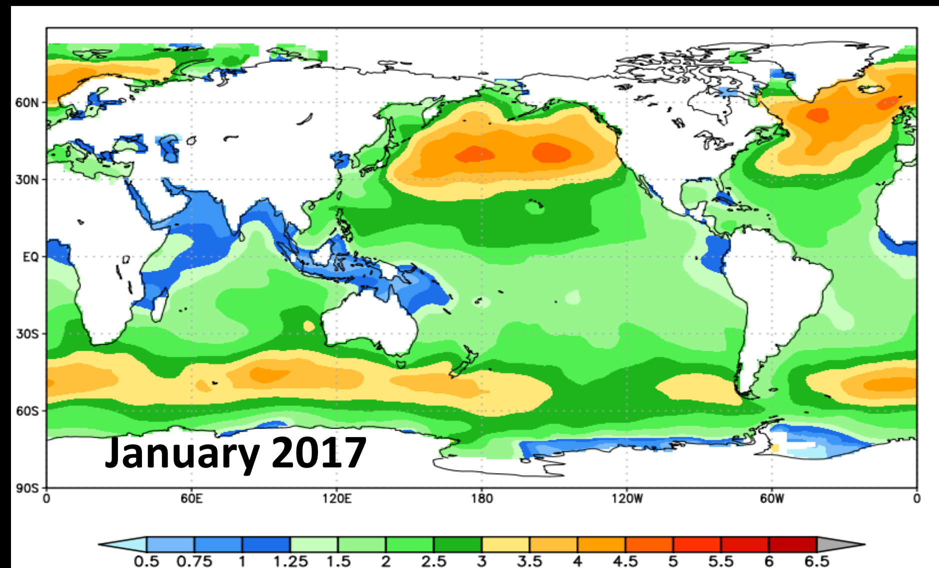
Merged multi-mission daily gridded product at 1° x 1° resolution

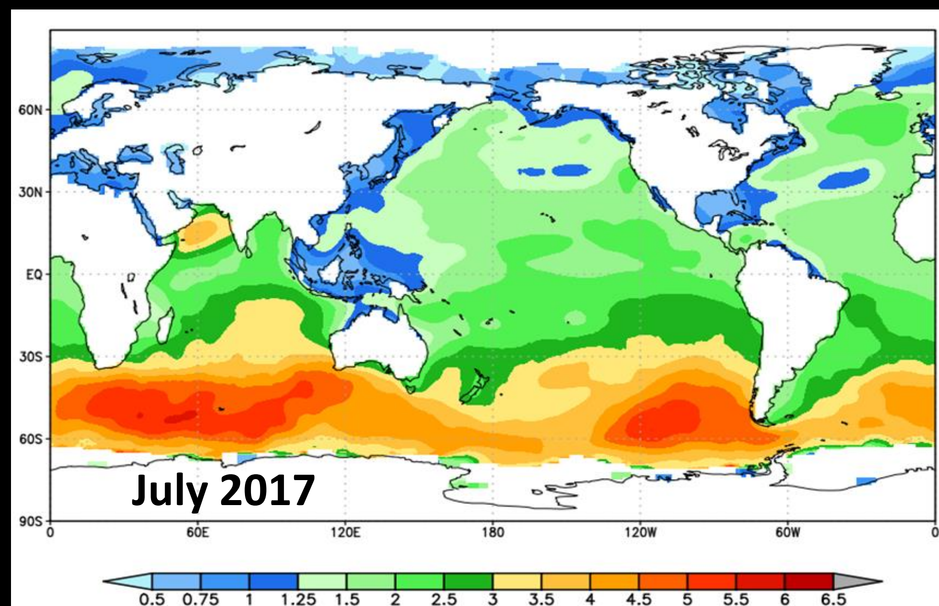
Satellite Altimeters considered
Jason-2
Jason-3
Sentinel -3A
Cryosat-2
SARAL/AltiKa

Data are cross calibrated using OSTM/Jason-2 as a reference mission

Daily merged SWH data product for the period from Sep, 2009 to Apr, 2017 is used for the atlas

Global monthly mean SWH (m) for 2017



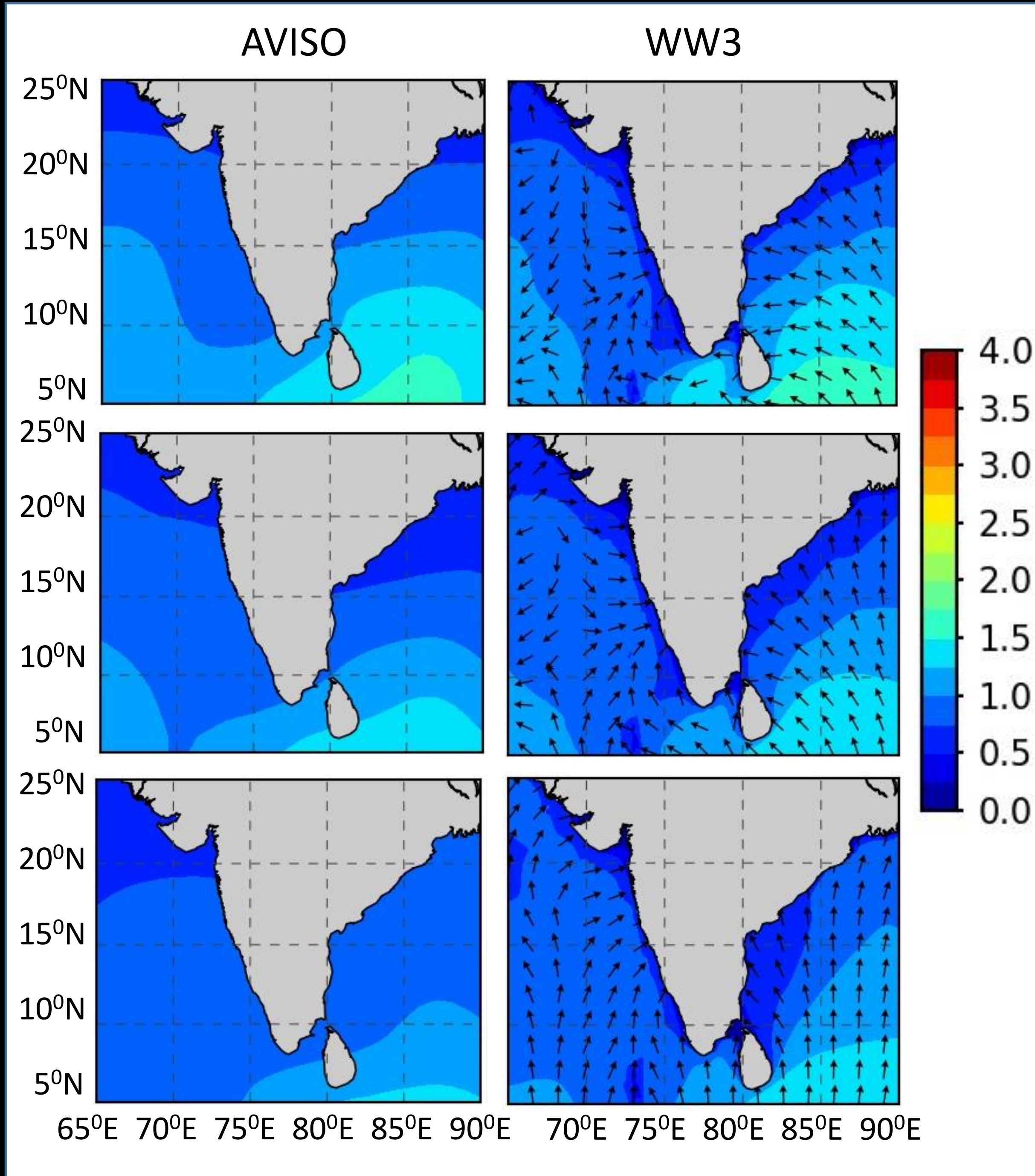
# Monthly climatology derived from AVISO and WW3

# Monthly climatology of SWH (m) and Direction

The SWH (m) climatology for January –March from AVISO (2009-2017) and WW3 simulations (2000-2016)

The climatological pattern of SWH is similar in both AVISO and simulated data sets

During Jan-Mar, eastern side of Indian Ocean exhibits high wave conditions




January

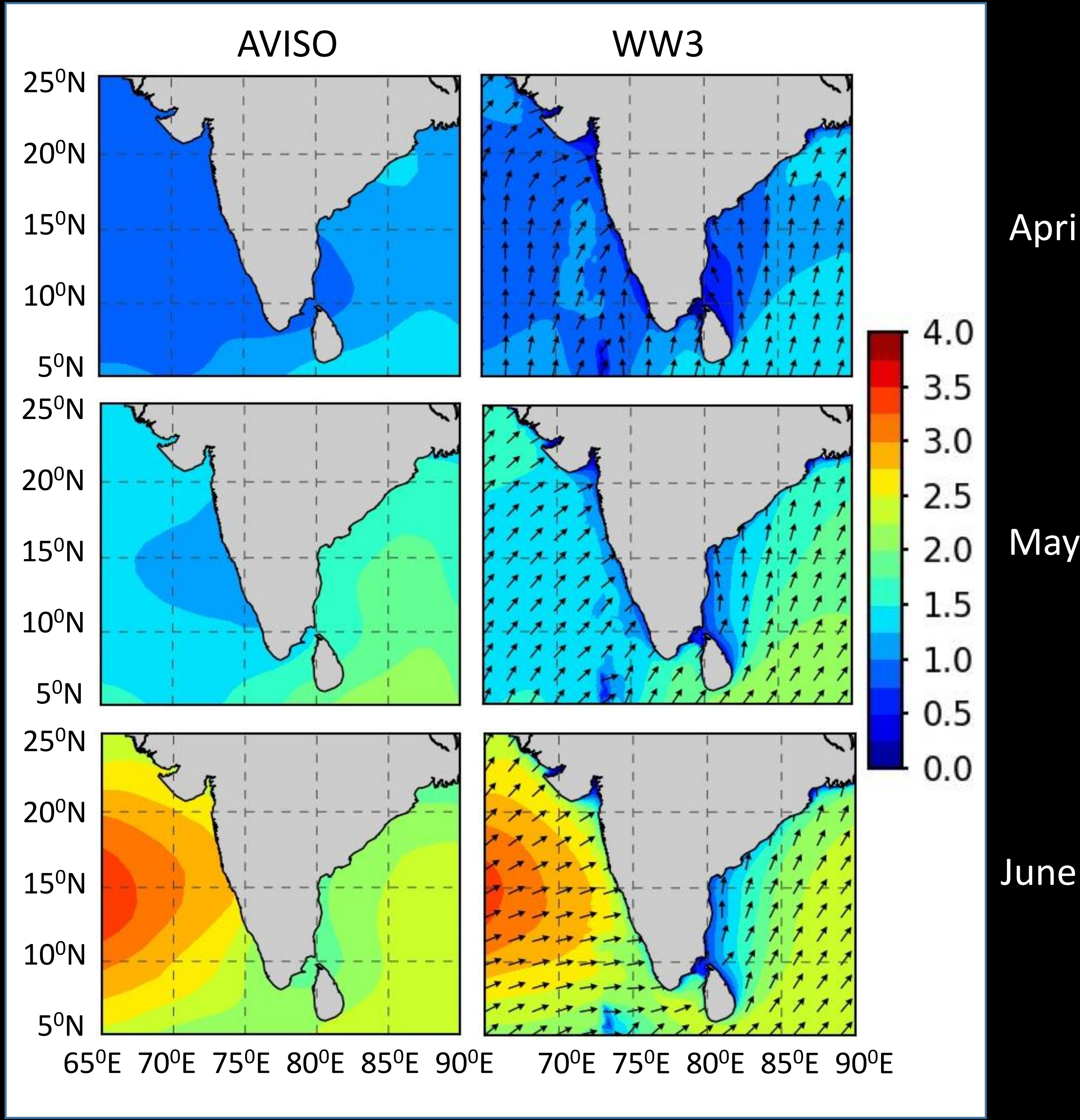
February

March

# Monthly climatology of SWH (m) and Direction

The SWH (m) climatology for April-June from AVISO (2009-2017) and WW3 simulations (2000-2016)

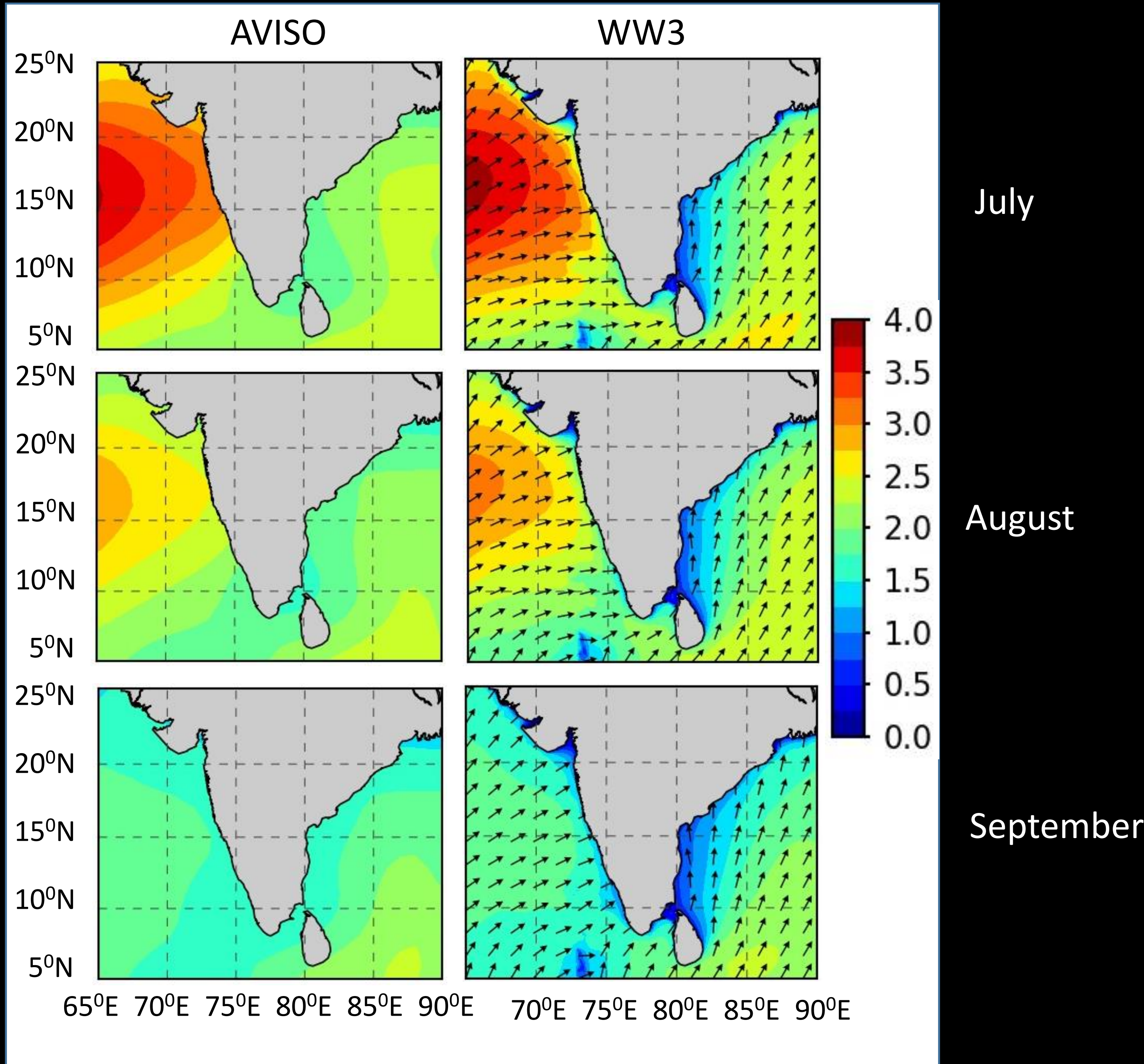
In the month of June, Arabian Sea starts receiving high waves due to cross-equatorial south-west monsoon winds



# Monthly climatology of SWH (m) and Direction

The SWH (m) climatology for July-September from AVISO (2009-2017) and WW3 simulations (2000-2016)

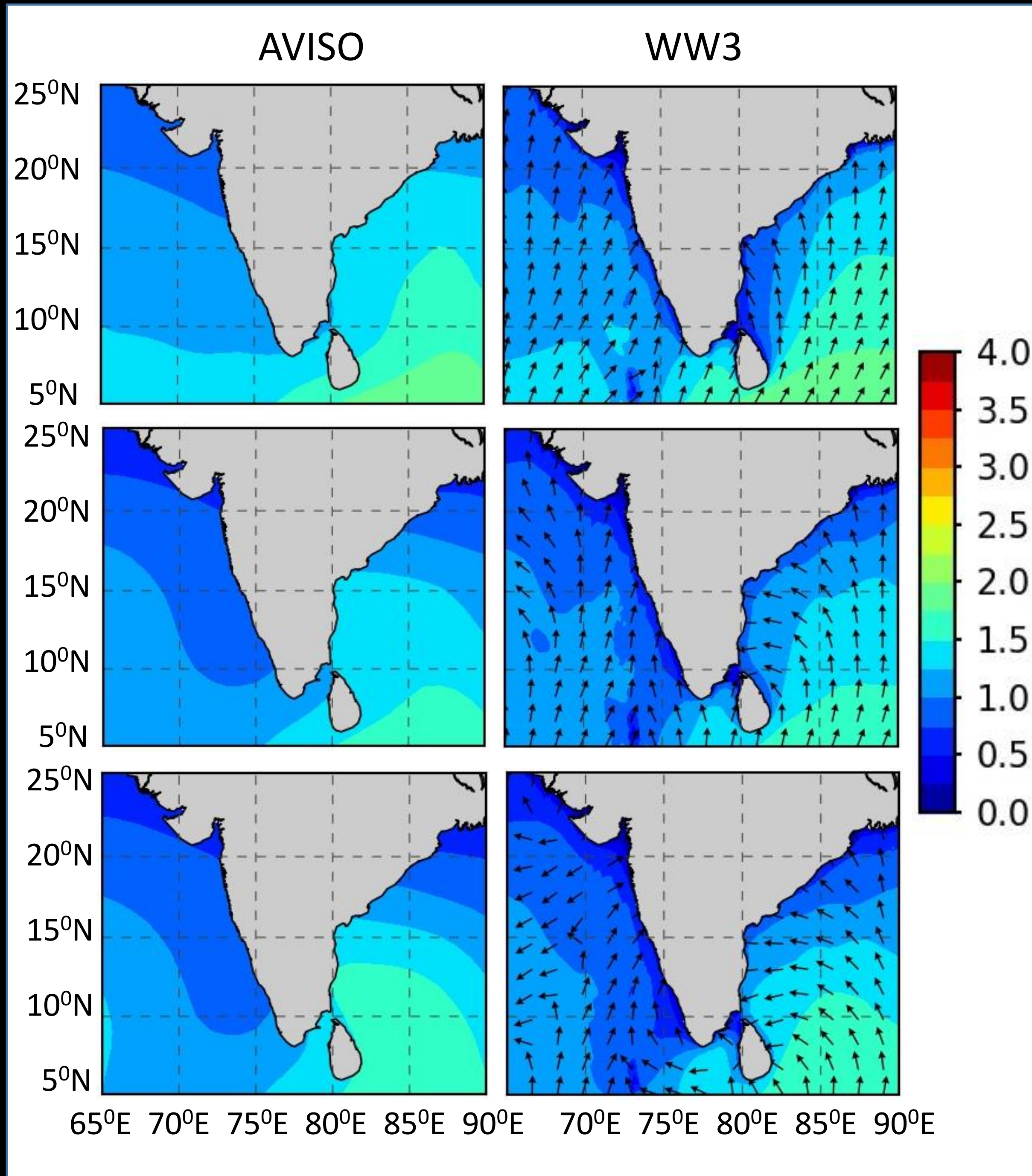
In July, Arabian Sea waves are strongest due to the impact of south-west monsoon winds. Wave conditions are high in Bay of Bengal also.



# Monthly climatology of SWH (m) and Direction

The SWH (m) climatology for October-December from AVISO (2009-2017) and WW3 simulation (2000-2016)

During post-monsoon season (Oct-Dec), Bay of Bengal has higher wave condition as compared to the Arabian Sea due to cyclonic activities.

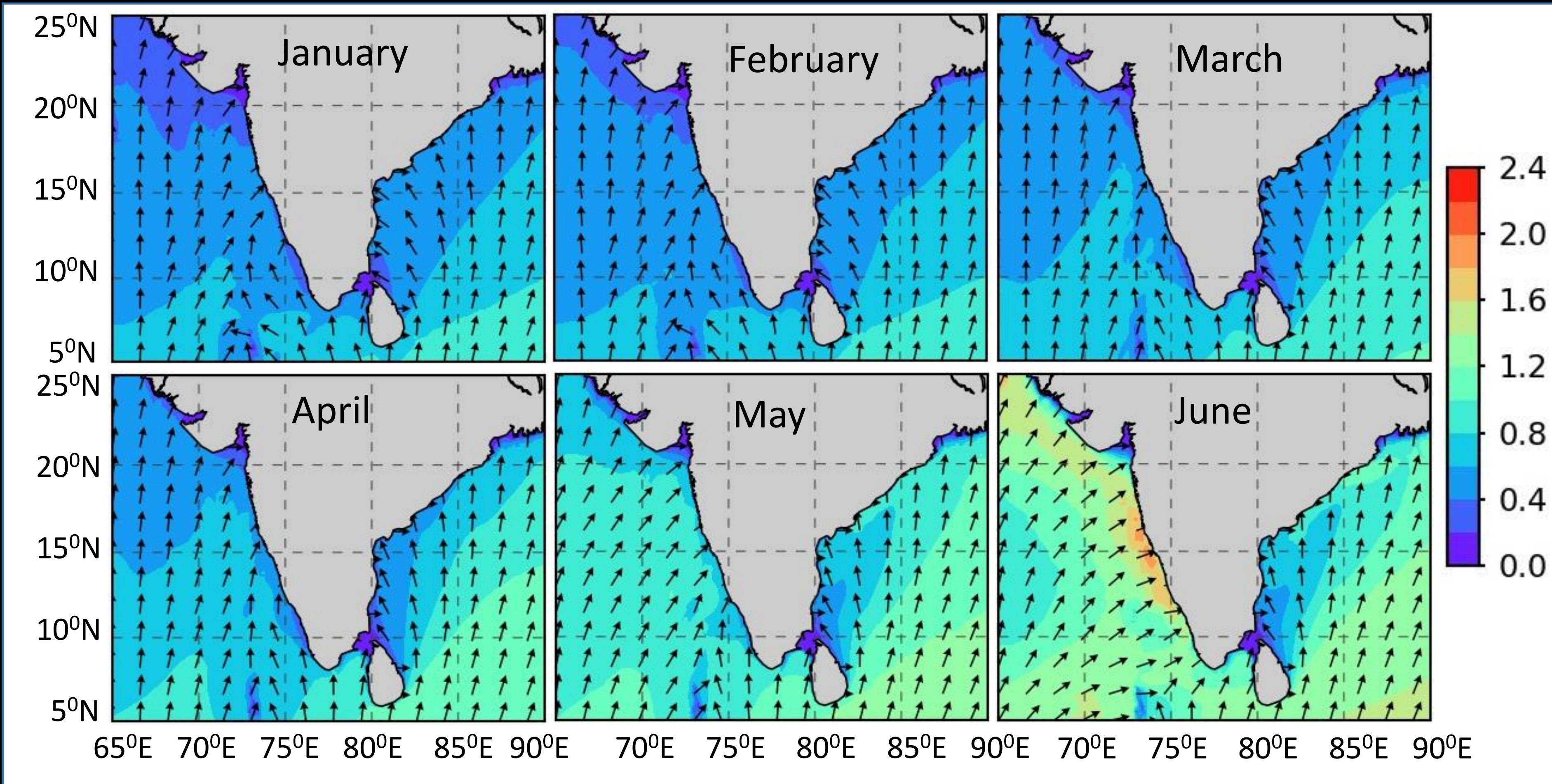



October

November

December

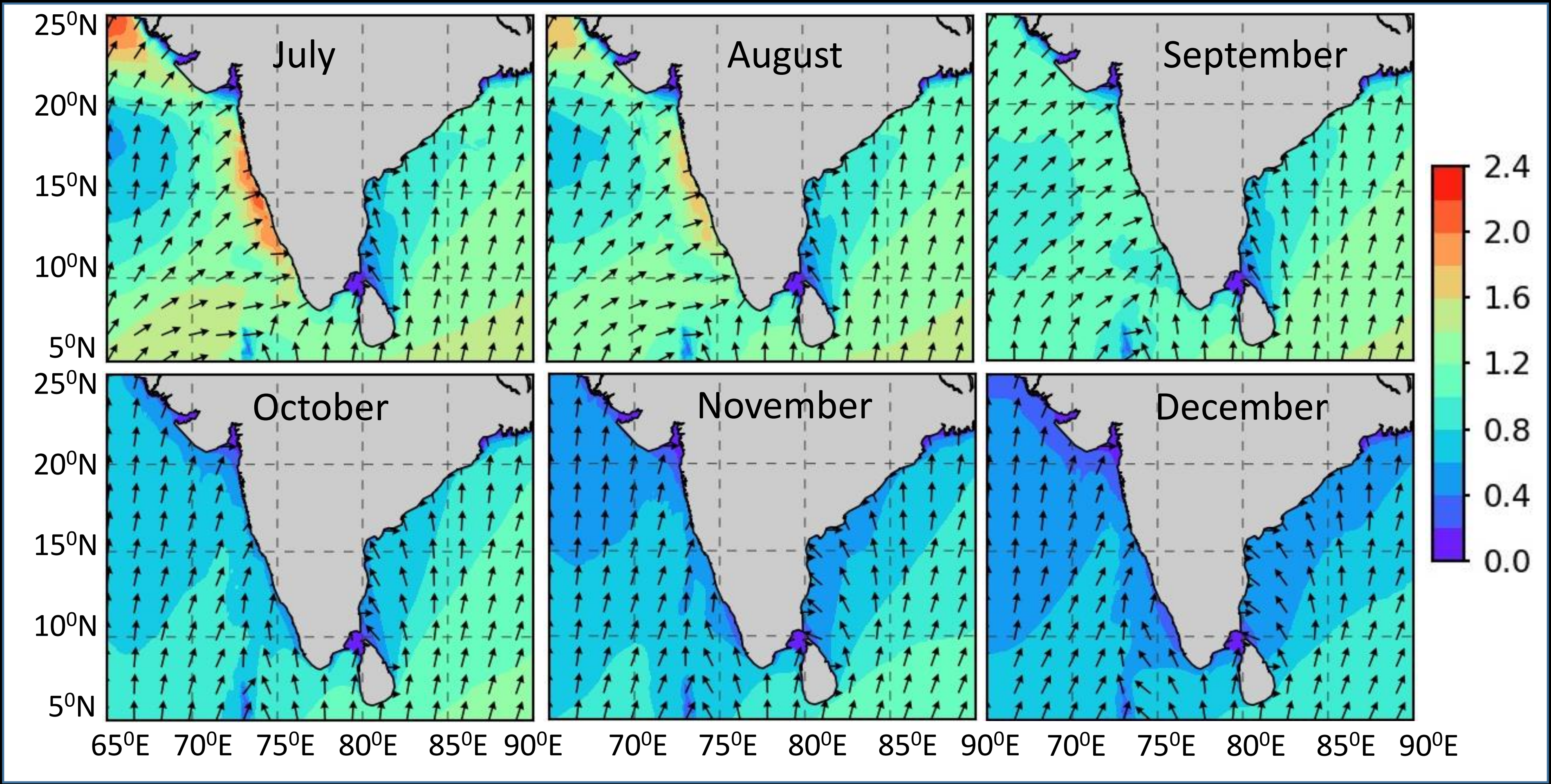
# Monthly climatology of Primary Swell Height (m) and Direction from WW3




High resolution (10x10km) climatology of Primary Swell Wave Height (m) with Primary Swell Direction for January-June from WW3 simulations (2000-2016)

During January–March the swells are less. From pre-monsoon months of April and May, gradually the Arabian sea starts receiving swell from southern Indian Ocean.

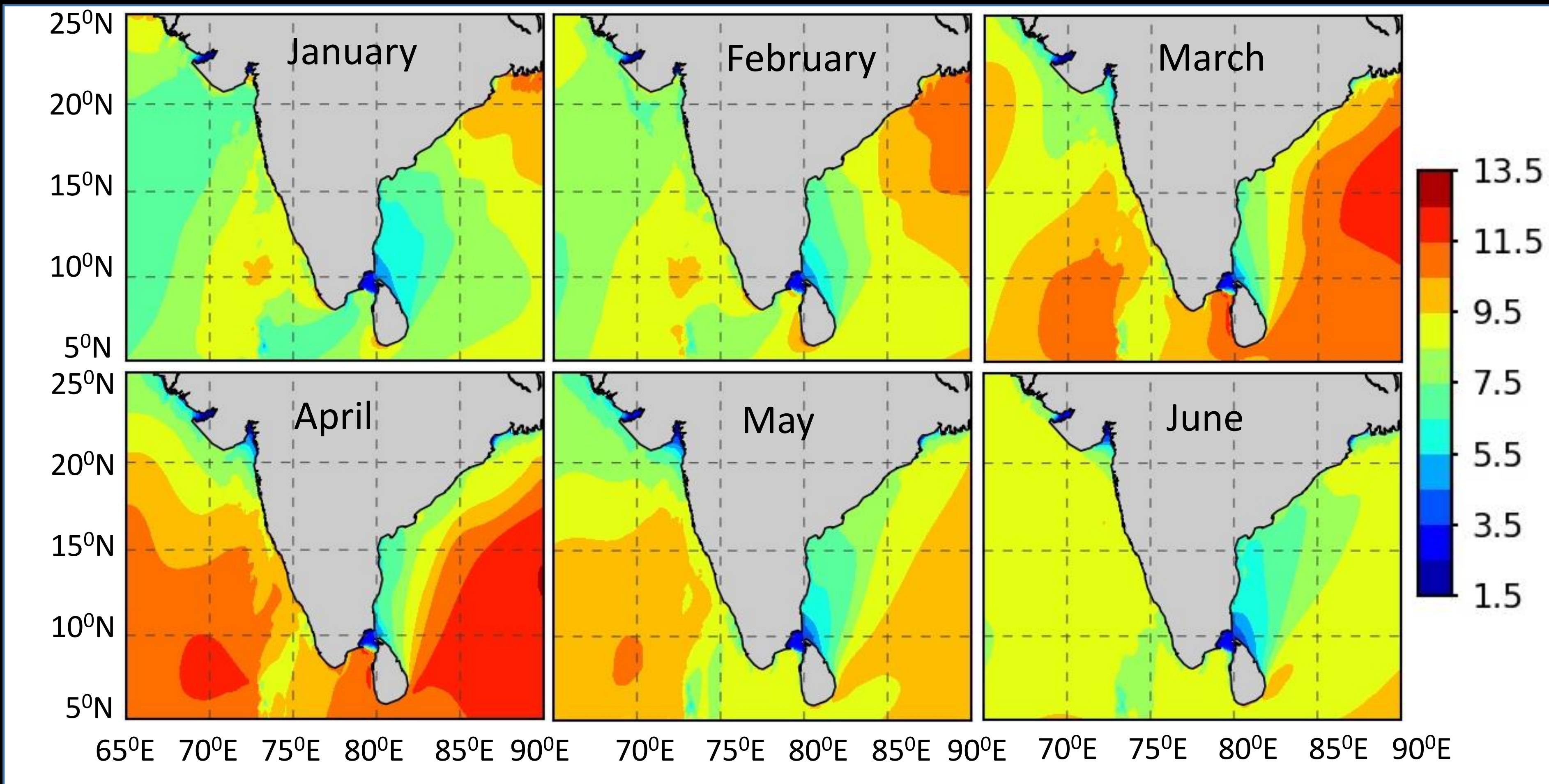
# Monthly climatology of Primary Swell Height (m) and Direction from WW3




High resolution (10x10km) climatology of Primary Swell Wave Height (m) with Primary Swell Direction for July-December from WW3 simulations (2000-2016)

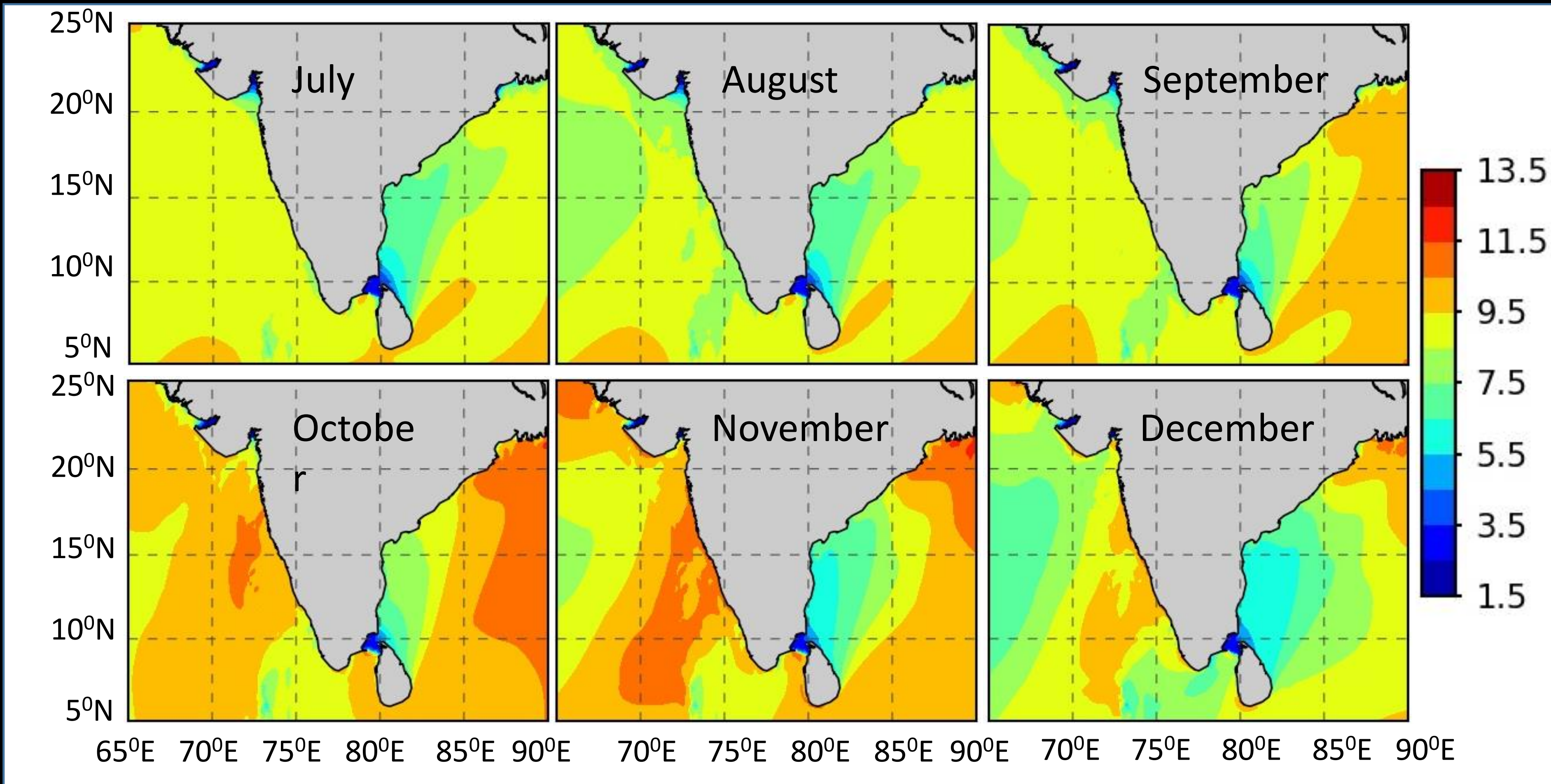
In July, the swells are highest in west coast of India due to the impact of south west monsoon.

# Monthly climatology of Mean Wave Period (s) from WW3



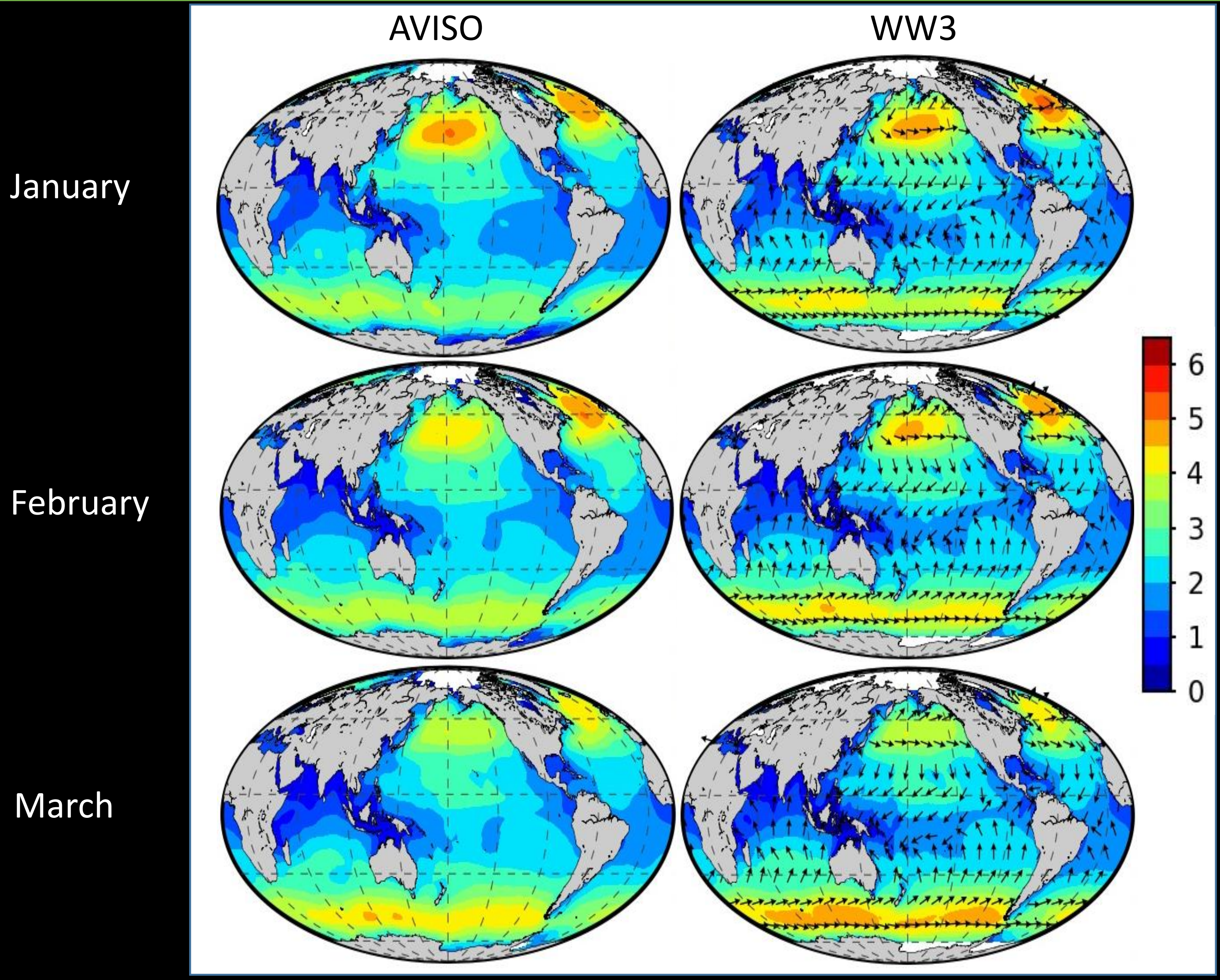

High resolution (10x10km) monthly climatology of Mean Wave Period (sec) for January-June from WW3 simulations (2000-2016)

# Monthly climatology of Mean Wave Period (s) from WW3



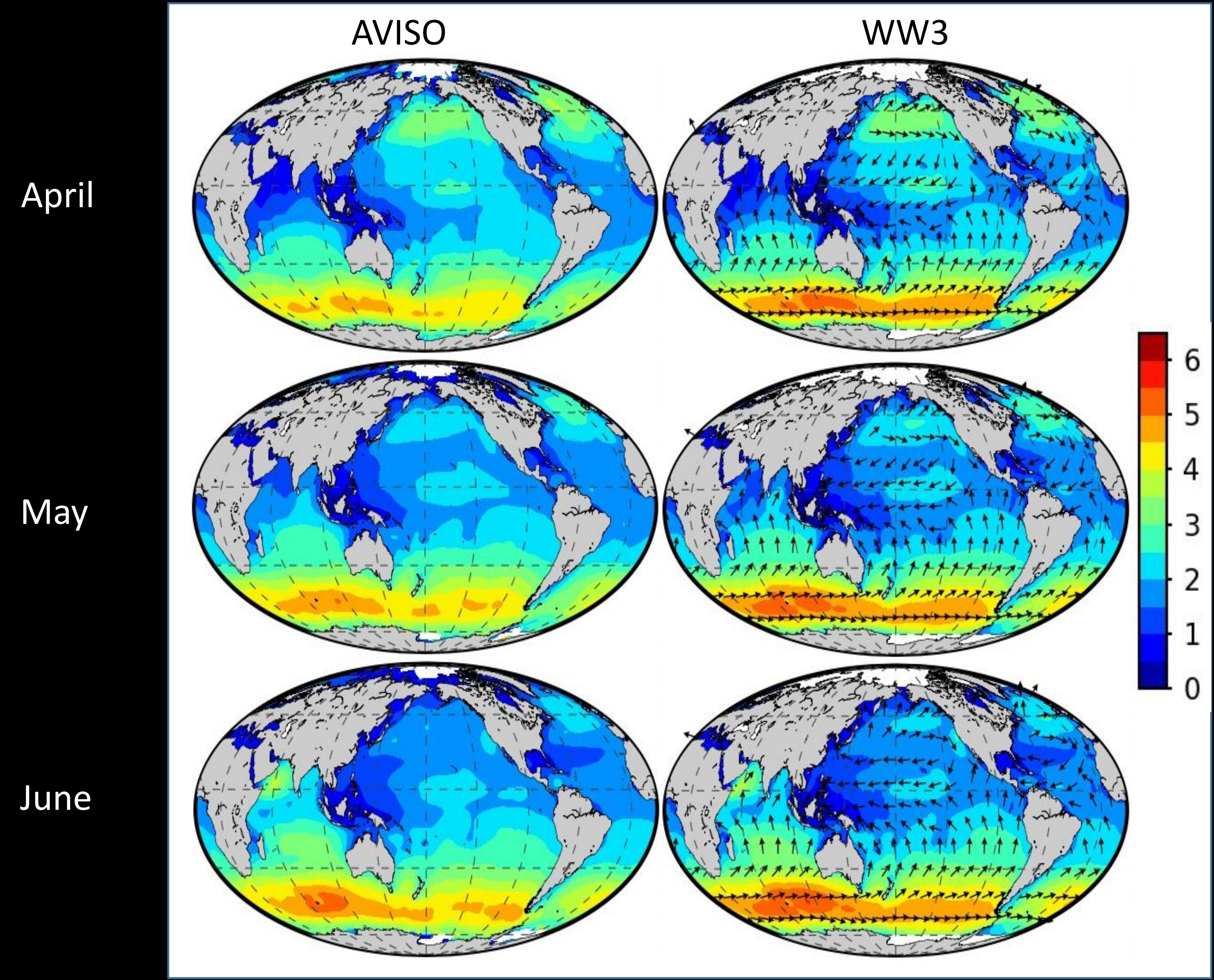

High resolution (10x10km) climatology of Mean Wave Period (sec) for July-December from WW3 simulations (2000-2016)

# Monthly climatology of SWH (m) and Direction- Global



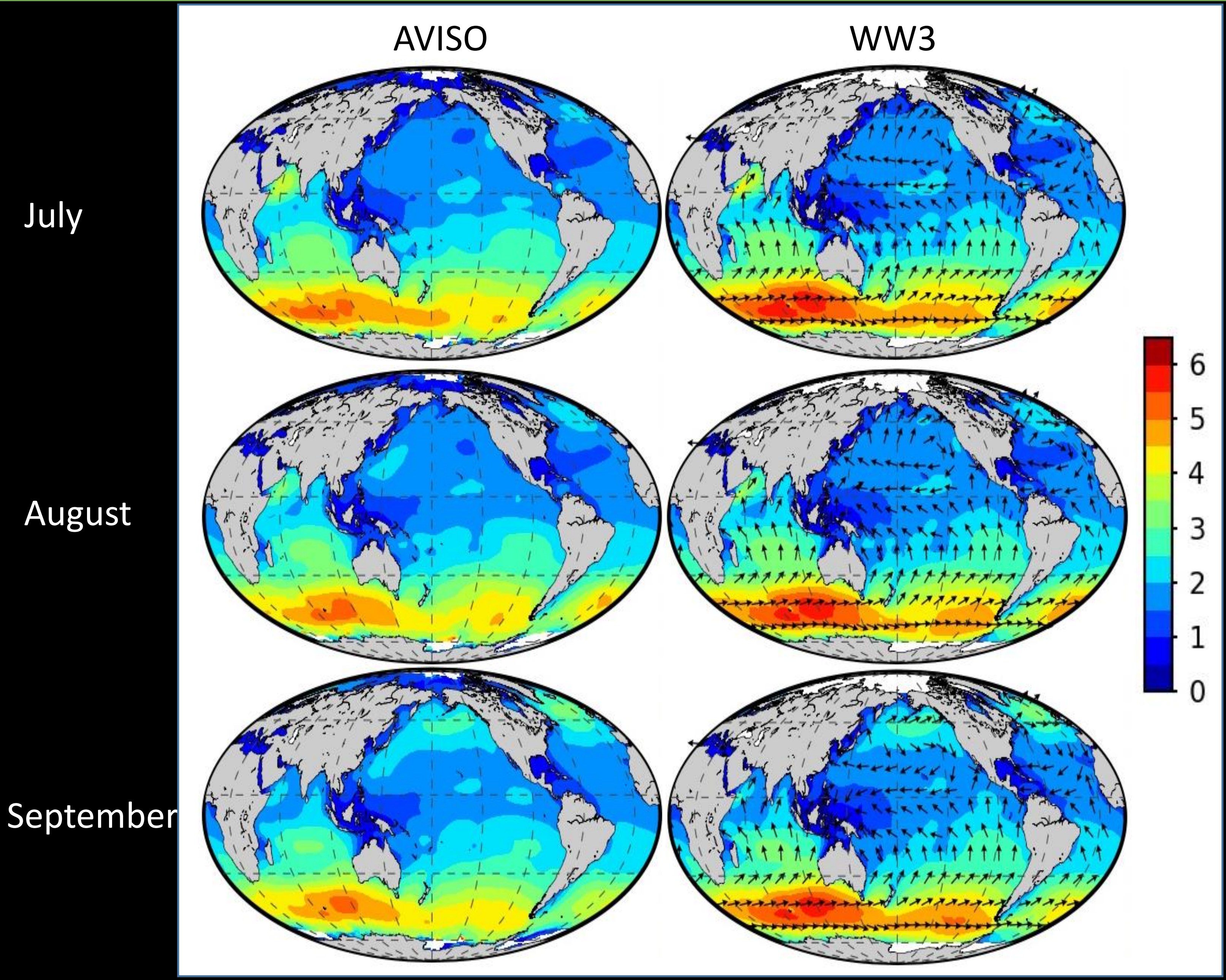

The global SWH (m) climatology at 1x1 degree resolution for January – March from AVISO (2009-2017) and WW3 simulations (2000-2016)

# Monthly climatology of SWH (m) and Direction-Global



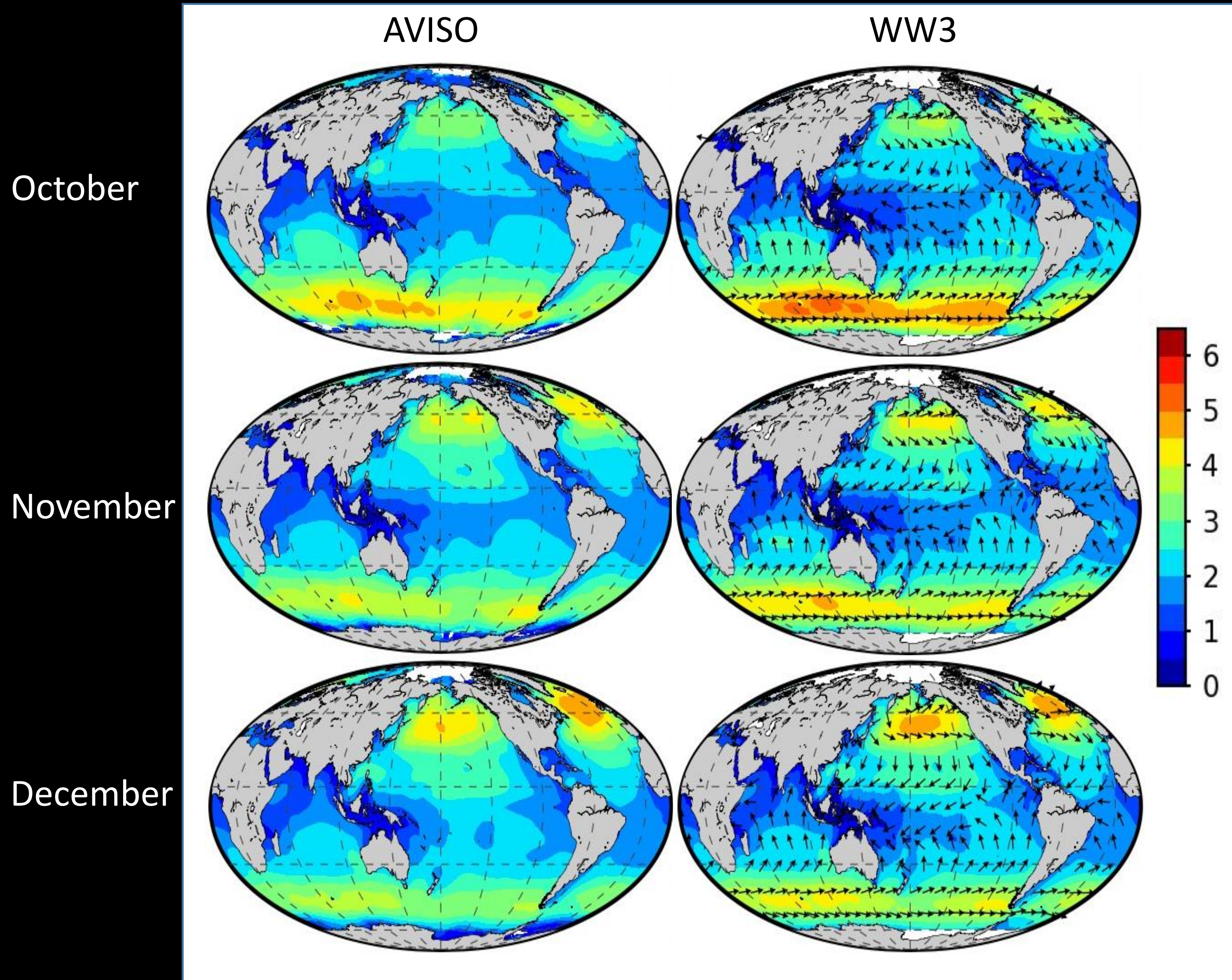

The global SWH (m) climatology at 1x1 degree resolution for April –June from AVISO (2009-2017) and WW3 simulations (2000-2016)

# Monthly climatology of SWH (m) and Direction-Global



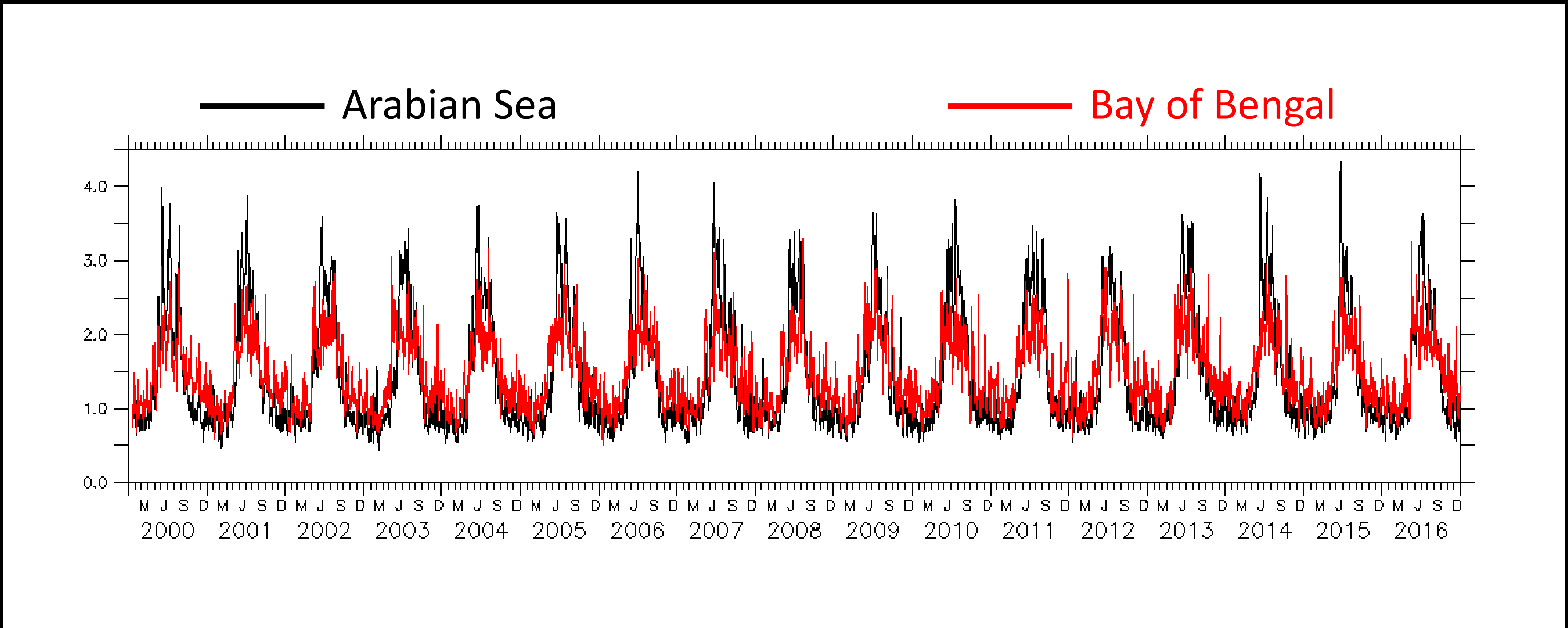

The global SWH (m) climatology at 1x1 degree resolution for July-September from AVISO (2009-2017) and WW3 simulations (2000-2016)

# Monthly climatology of SWH (m) and Direction-Global




The global SWH (m) climatology at 1x1 degree resolution for October-December from AVISO (2009-2017) and WW3 simulations (2000-2016)

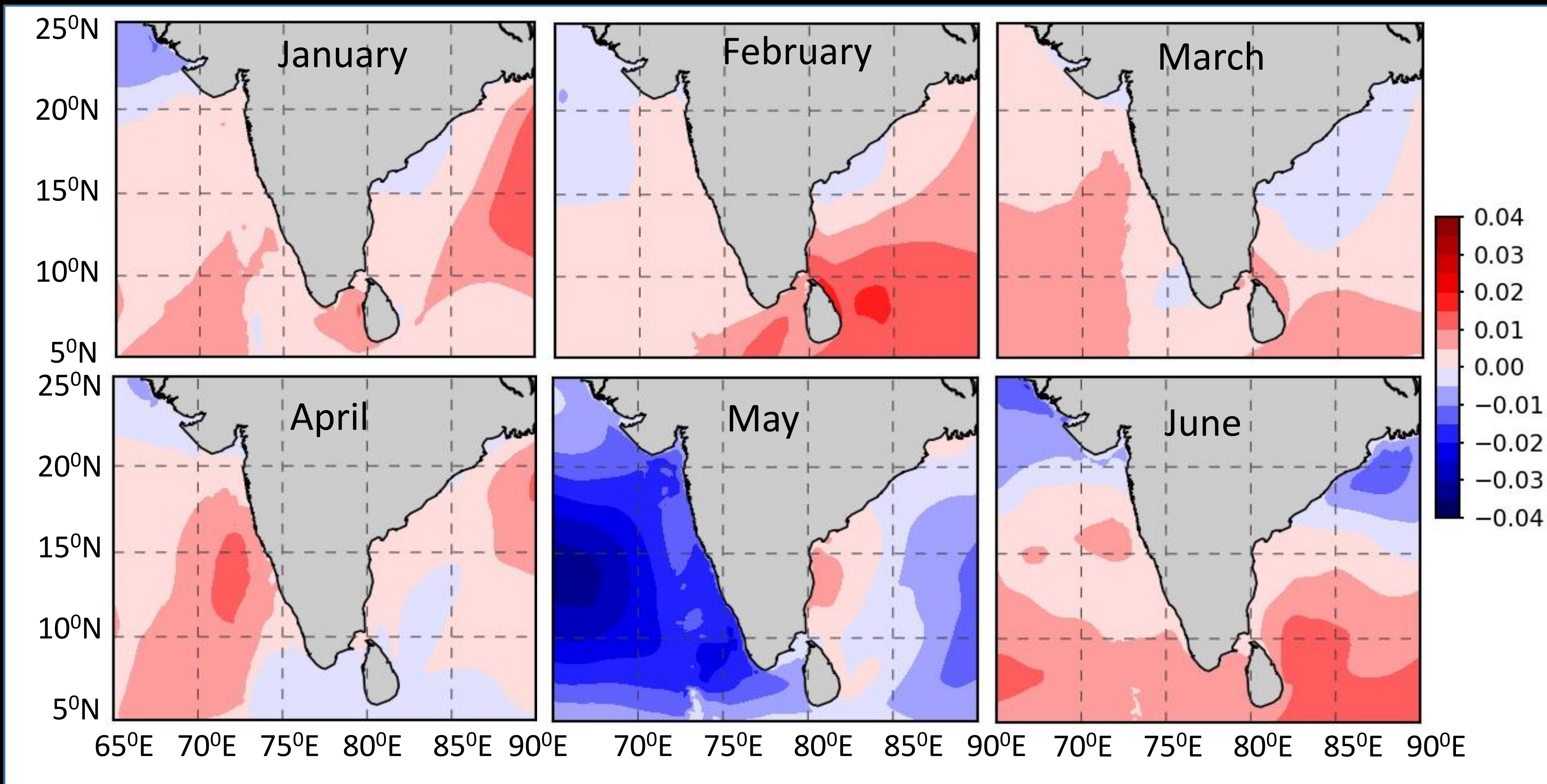
# Time-series of basin-averaged SWH (m) over Arabian Sea and Bay of Bengal




Time-series of basin averaged SWH (m) over Arabian Sea (AS) and Bay of Bengal (BoB) from WW3 simulations (2000-2016)

Waves in Northern Indian Ocean region have a clear seasonal cycle with maxima during the monsoon month of July. AS has more variability compared to that of BoB. SWH in AS during July's of year 2006, 2007, 2014 and 2015 are notably more.

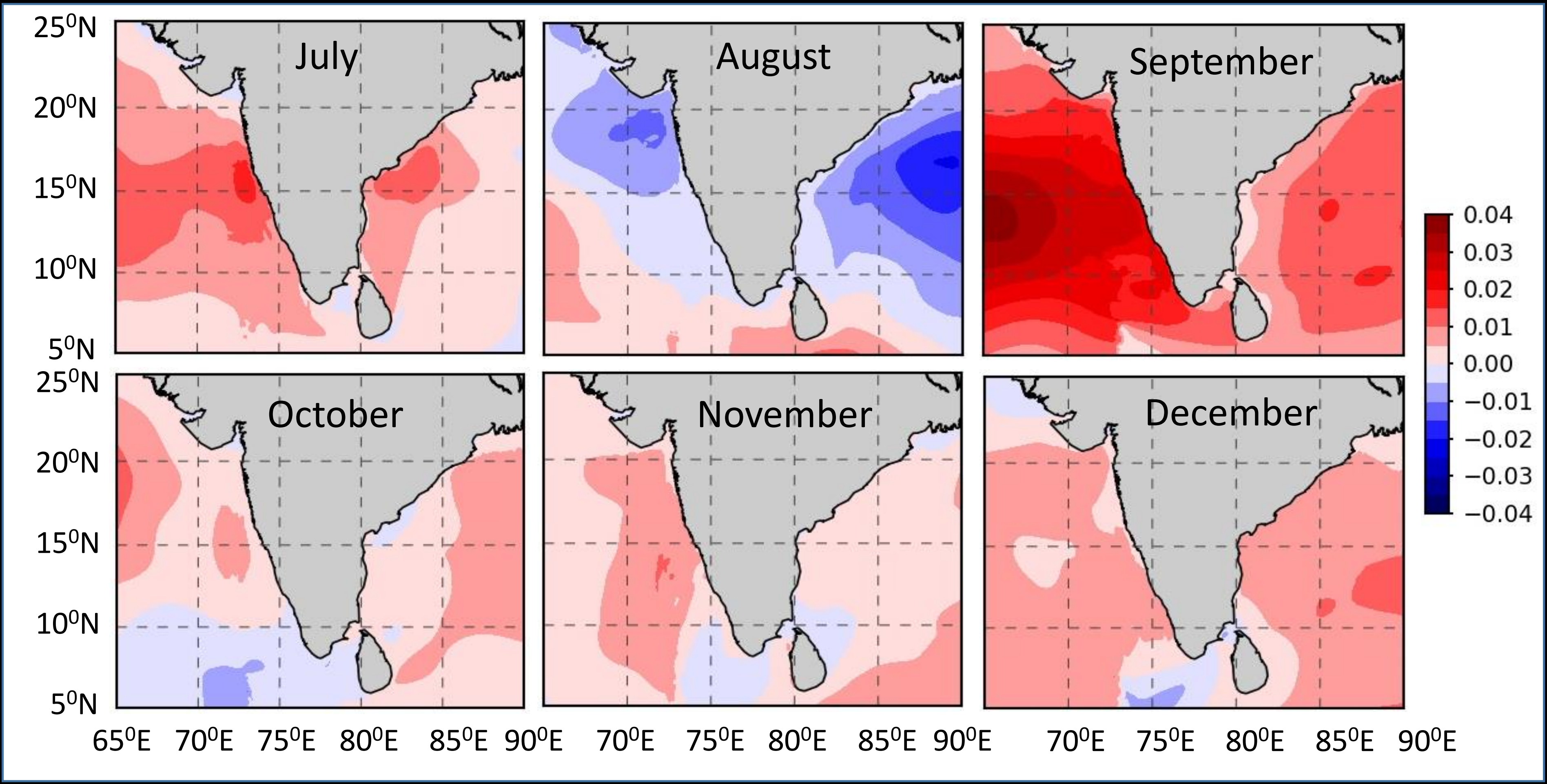
# Monthly Trends in SWH (m/year) from WW3




Monthly trend of SWH (m/year) for January-June from WW3 simulations (2000-2016)

Noteworthy reducing trend up to 4cm/year is observed for the month of May over Arabian Sea

# Monthly Trends in SWH (m/year) from WW3



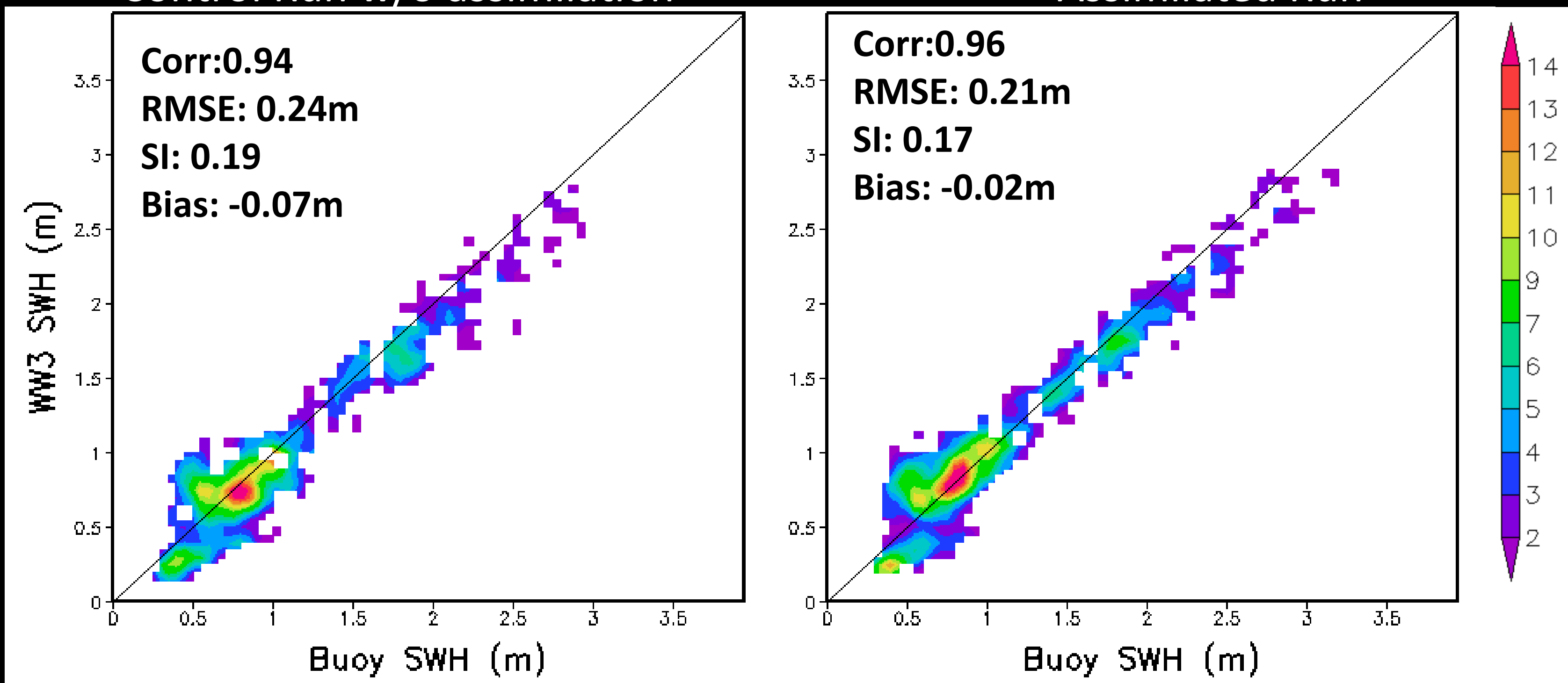

Monthly trend of SWH (m/year) for July-December from WW3 simulations (2000-2016)

A decreasing trend of 3-4cm/year is noticed for the month of August over Bay of Bengal and an increase up to 4cm/year is observed for the month of September over Arabian Sea

# Data Assimilative Wave Model
# (DA WW3)

# Validation of WW3 model simulated SWH (m) with Moored Buoy observations

Control Run w/o assimilation | Assimilated Run

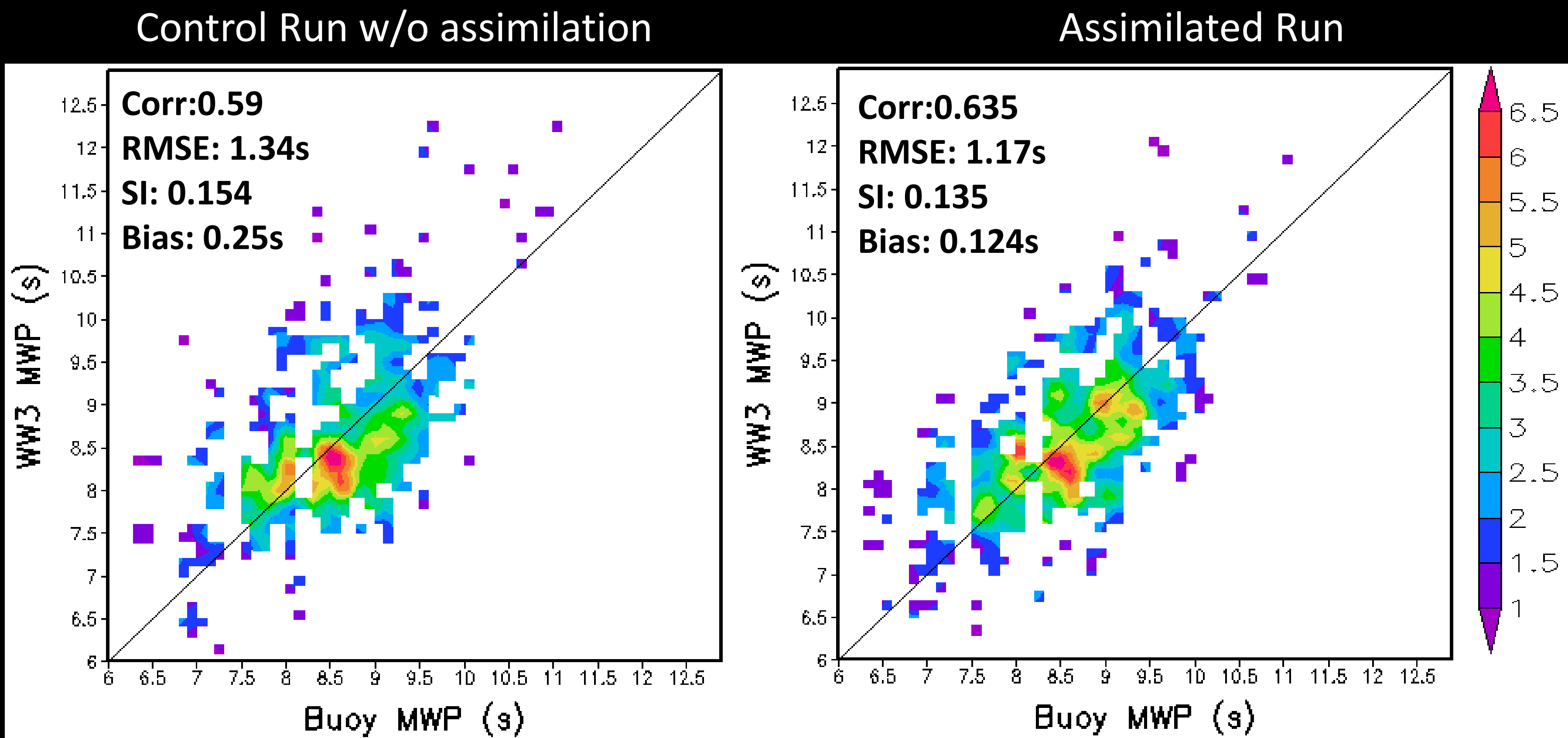



Validation of SWH performed using the available buoy (AD09, CB02 and CB03 ) observations for 2016. The SWH from assimilated run is found to be statistically improved as compared to the control run at the buoy locations. The RMSE is 0.21m for assimilation making skill score of assimilation is ~14%.

List of buoys used for validation

| Buoy ID | Latitude($^0$N) | Longitude($^0$E) | Buoy ID | Latitude($^0$N) | Longitude($^0$E) |
|---|---|---|---|---|---|
| AD06 | 18.99 | 66.98 | BD14 | 8.17 | 85.57 |
| AD07 | 14.99 | 68.88 | CB02 | 10.88 | 72.22 |
| AD09 | 8.25 | 73.30 | CB04 | 15.39 | 73.76 |
| BD08 | 18.16 | 89.67 | CB06 | 13.10 | 80.31 |
| BD11 | 13.50 | 83.99 | | | |

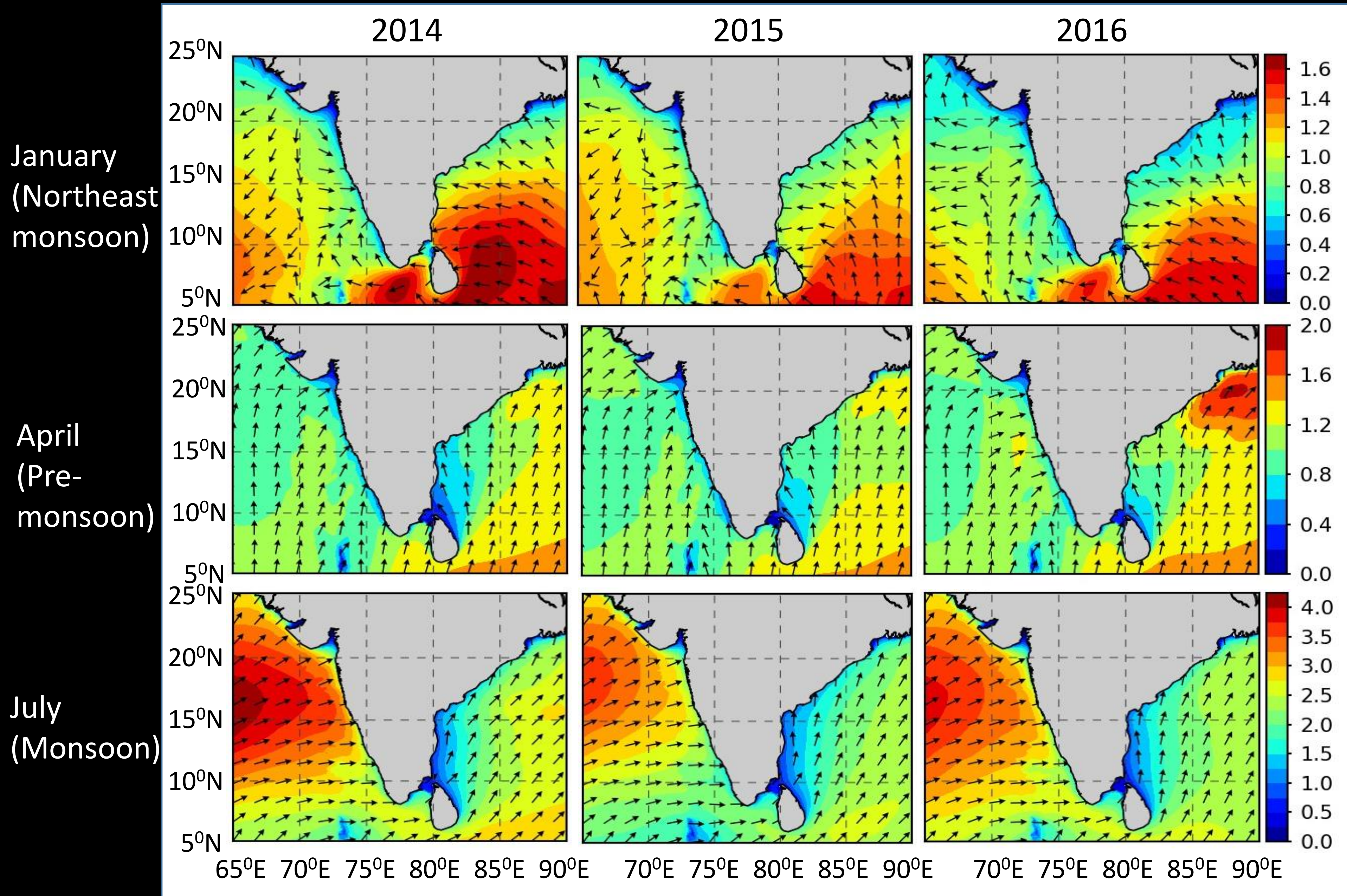
# Validation of WW3 model simulated Mean Wave Period (s) with Moored Buoy observations



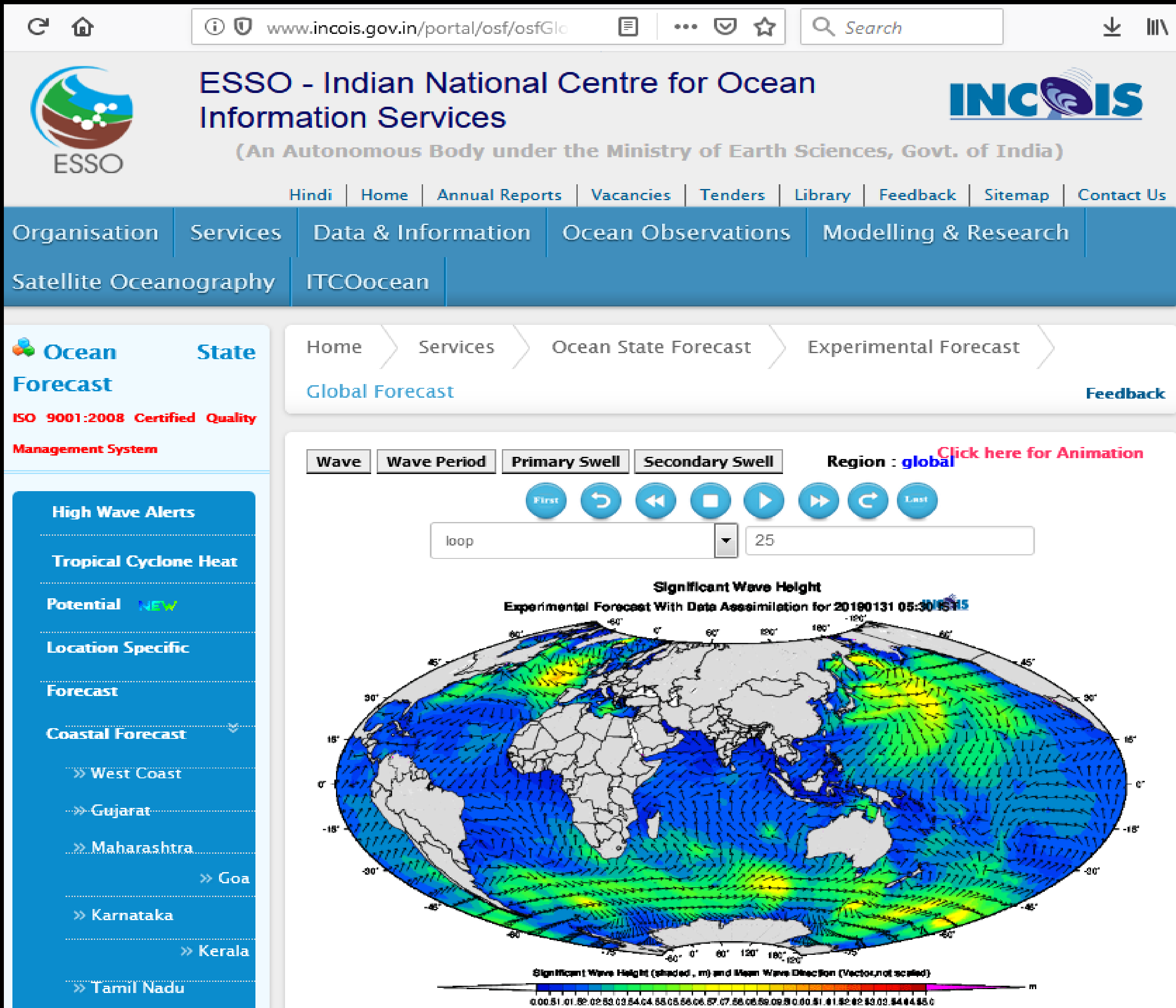

Validation of Mean Wave Period (s) performed using the available buoy (AD09, CB02 and CB03) observations for 2016

The wave period from assimilated run is found to be statistically improved as compared to the control run at the buoy locations with a skill score ~12%

# Inter-annual variability of SWH (m) and Direction from DA WW3

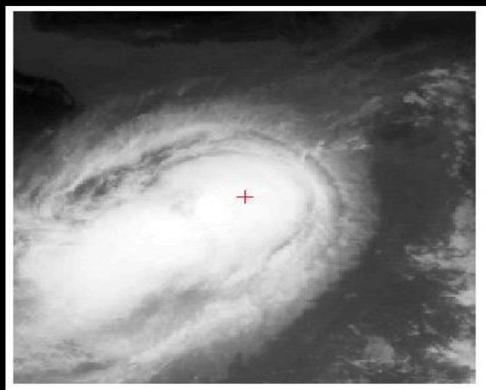
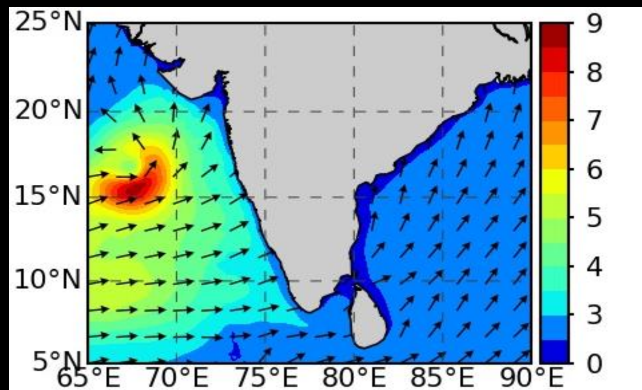


# Hand holding for operational implementation of DA WW3 at INCOIS



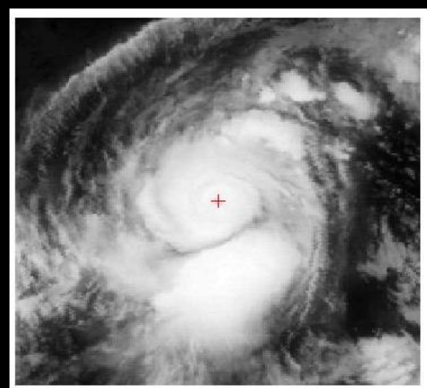
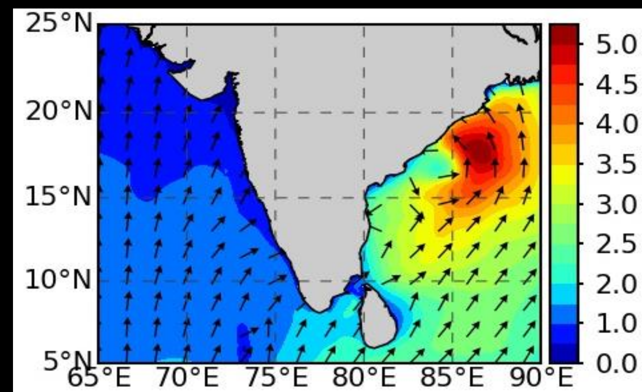

10x10 km WW3 with Jason-2 /3 and SARAL Data Assimilation using optimum interpolation technique implemented at INCOIS, Hyderabad for operational use

# Extreme Waves (SWH in meters and Direction) from DA WW3 during the Cyclones from 2014-2016

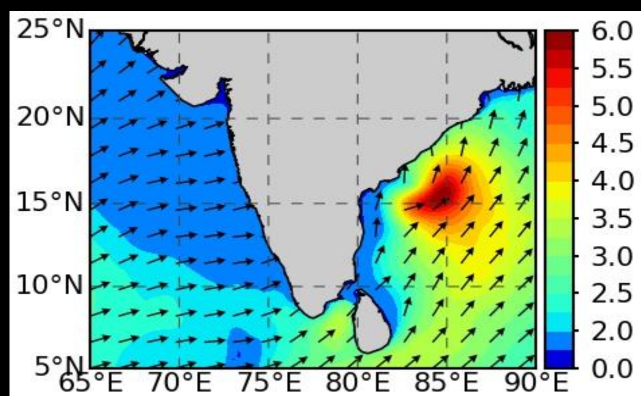




Name: Nanauk
Life time: June 10-14, 2014

Name: Hudhud
Life time: October 7-14, 2014

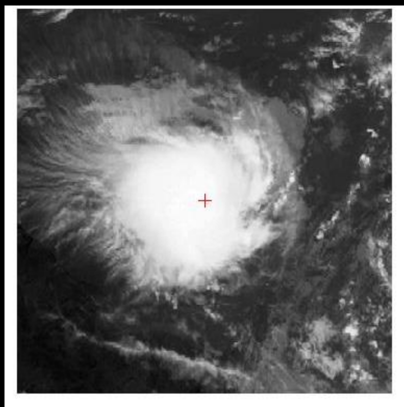


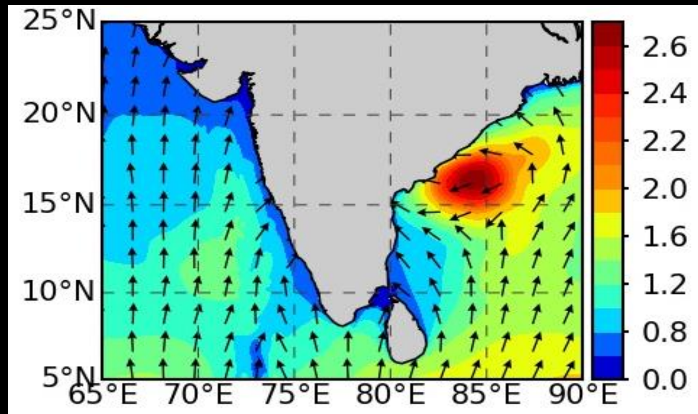



Name: Roanu
Life time: May 17-22, 2016

Satellite images are from Kalpana (Thermal Infra Red)

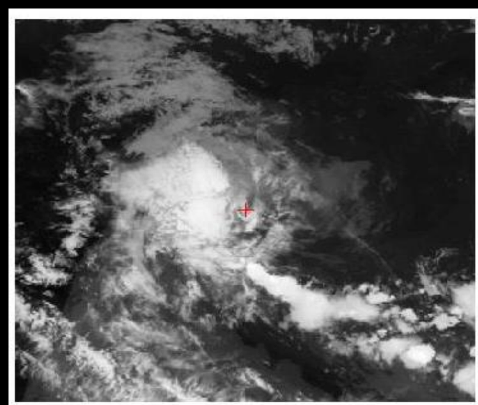
# Extreme Waves (SWH in meters and Direction) from DA WW3 during the Cyclones from 2014-2016

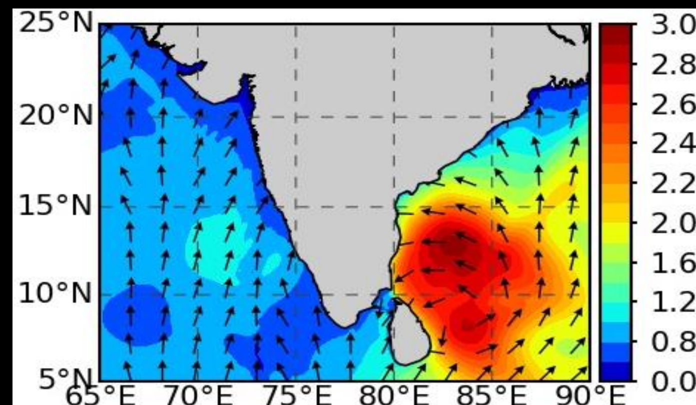


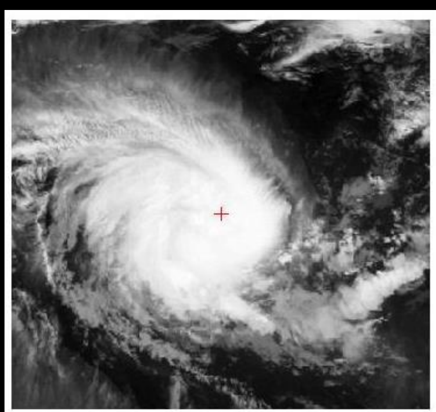


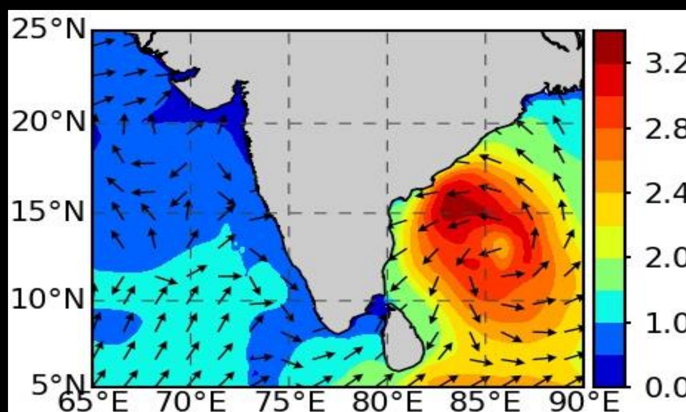

Name: Kyant
Life time: October 21-27, 2016

Name: Nada
Life time: November 29-December 2, 2016








Name: Vardah
Life time: December 6-18, 2016

Satellite images are from INSAT 3D (Thermal Infra Red)

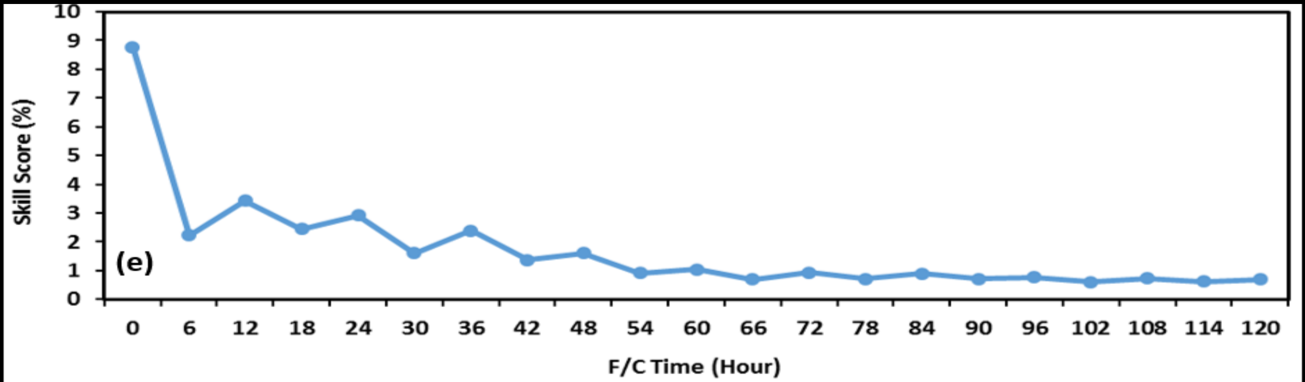
# Step Forward on Data Assimilative Wave Modelling at Ultra High Resolution

- DA WW3 has been configured with a very high resolution (2.5x2.5 km) coastal domain covering the entire EEZ of India.
- SWH observations from SARAL/AltiKa, Jason2 and Jason3 are assimilated into the Indian and NIO domains of the model using OI technique
- Forecasting system uses 10m analysis and forecast wind components obtained from NCMRWF as the forcing field

| Grids | Resolution | Area |
|---|---|---|
| **Global** | $1^0$x$1^0$ | $70^0$ S to $70^0$ N & $0^0$ to $359^0$ |
| **Indian Ocean** | $0.5^0$x$0.5^0$ | $-50^0$ S to $32^0$ N & 20 $^0$ E to $130^0$ E |
| **NIO** | $0.1^0$x$0.1^0$ | $0^0$ to $31^0$ N & $31^0$ E to $114^0$ E |
| **Coastal (Covering EEZ)** | $0.025^0$x$0.025^0$ | $3.6^0$ N to $24^0$N & $65.5^0$ E to $95.8^0$ E |

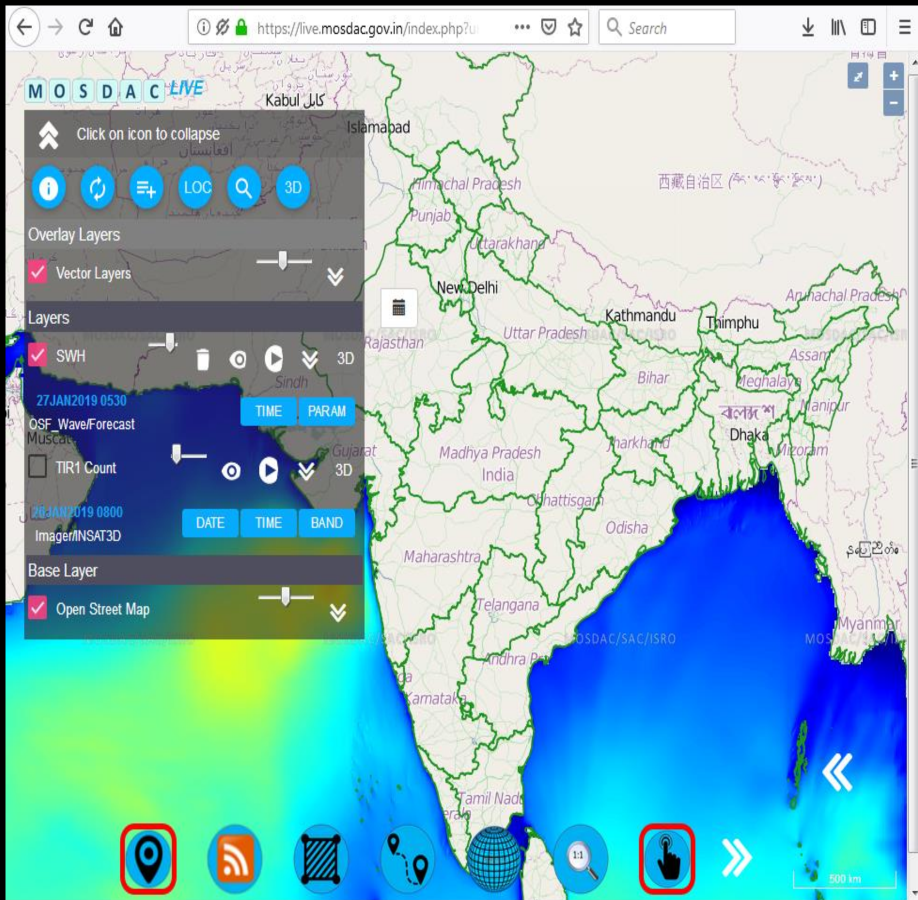
Details of area covered and spatial resolution of model configuration

Impact of assimilation in terms of percentage improvement in SWH F/C




Validation is performed with the available buoy (AD06, AD07, AD09, BD08, BD11, BD14, CB04 and CB06) measurements for the period from 01st June 2018 to 10th June 2018

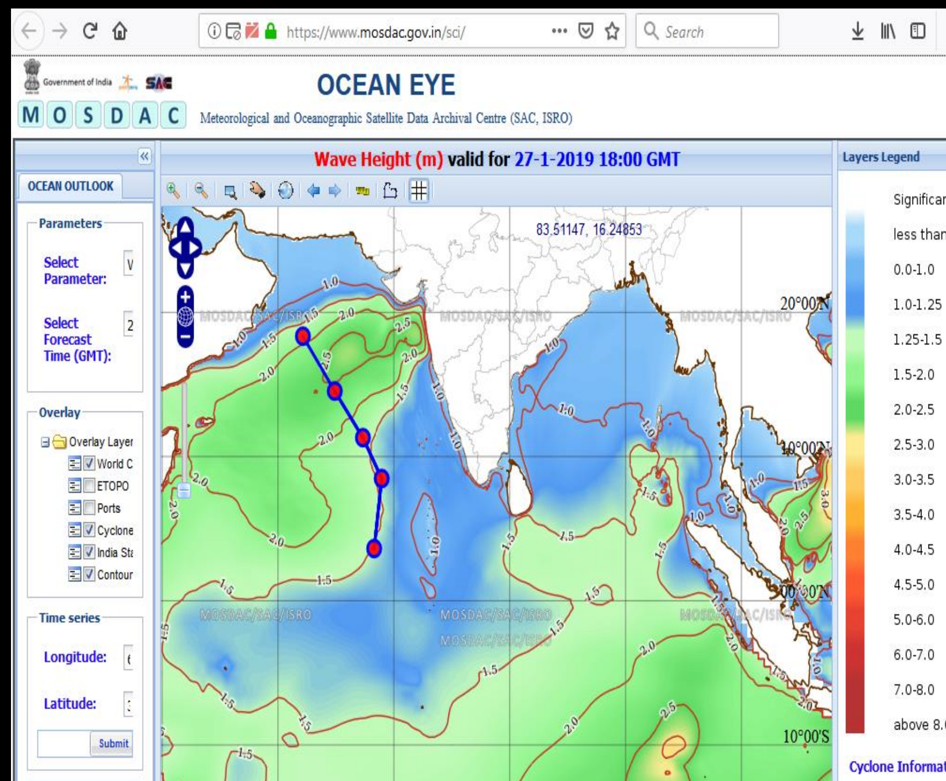
# Dissemination of Wave Forecast




**WW3 at MOSDAC LIVE**

- Ultra high resolution 5- day wave forecasts are being disseminated through LIVE MOSDAC
- Customized dissemination through OCEAN EYE for Shipping Corporation of India (SCI)
- Forecast are also being transferred to other users through MOSDAC

**WW3 at Ocean Eye**

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