पृथ्वी विज्ञान मंत्रालय
MINISTRY OF EARTH SCIENCES
सत्यमेव जयते

INCOIS

An Assessment of Marine Energy Resource Potential from the Indian EEZ

ESSO-INCOIS-OMARS-TR-08 (2024)



Indian National Centre for Ocean Information Services
"Ocean Valley", Pragathi Nagar, Hyderabad-500 090
Ministry of Earth Sciences, Government of India

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October, 2024

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FOREWORD

The government of India has outlined ambitious plans for long-term economic growth and sustainable development over the next 25 years, driven by innovation, technology, and clean energy. The vision of Vikasit Bharat of the government is to create a $5 trillion economy by 2025 and $10 trillion by 2047. This projected growth is expected to result in an increase in GDP growth rate at 8-9% per annum, enhanced contribution of the manufacturing sector to GDP, increased use of technology for agricultural productivity, and development of infrastructure, transportation networks and smart cities. With the projected economic growth, the energy demand is expected to triple by 2047, with electricity demand reaching 4,000 TWh by 2047.

The government of India has plans to reduce fossil fuel usage, transition to clean energy, and reduce its carbon footprint. India has made significant progress in renewable energy, particularly solar and wind power. The country has already achieved over 100 GW of renewable energy capacity and aims to become a global leader in clean energy. Internationally, marine energy resources are becoming increasingly popular, with countries worldwide investing heavily in this field to reduce their fossil fuel footprint and lower greenhouse gas emissions.

There is an increased interest in marine renewables due to their zero greenhouse gas emissions, predictability, reliability, higher energy density, and diversification, which reduce dependence on a single source. India has a coastline of 7516.6 km, including 2094 km of island territories and 5422 km of mainland coastline. Thus, we are naturally gifted with ample marine energy resources which can contribute significantly to the country's growing economy.

I am glad to learn that the Indian National Centre for Ocean Information Services under the Ministry of Earth Sciences has taken up this ambitious project to estimate the theoretical energy potential from both marine met and hydrological resources, which is one of the unique estimates made so far from the Indian EEZ. I congratulate the team INCOIS for preparing these estimates, which can boost the country's efforts towards developing the blue economy.

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FOREWORD

The development of a blue economy is essential for long-term sustainable development, and it has a fundamental principle that envisions the interplay between the economic, social, and ecological sustainability of the ocean. Globally, there is an increasing interest in investment in next-generation maritime or blue technologies. Under the blue economy framework, ocean energy is envisaged as an emerging sector and considered along with their marine meteorological counterparts, which are the offshore wind and solar resources and generally named 'offshore renewables'. Marine energy technologies convert energy from ocean waves, tides, ocean currents and temperature and salinity gradients to electricity.

Marine energy resources are geographically diverse, sizable, predictable, reliable, and can be developed in an environmentally responsible manner. India's blue economy policy aligns well with its targets to reduce dependence on fossil fuels, and blue energy generation is one of its essential components. India is naturally gifted with an extensive coastline, and estimating blue energy reserves from its Exclusive Economic Zone (EEZ) is one of the preliminary steps in achieving the larger goal of increasing blue energy share in its future clean energy mix.

To expand India's blue energy share, investing agencies need preliminary information about the availability of marine energy resources to focus on areas with highly economically viable potential. Such information will allow them to identify suitable areas for project implementation and detailed surveys regarding environmental impact assessment and techno-commercial feasibility studies using direct field measurements. Marine Energy reserves from the Indian EEZ provide crucial information in this context. I congratulate the INCOIS team for their painstaking efforts in bringing out this report on the availability of theoretical marine energy resource potential from the Indian EEZ. I am sure this report can provide hitherto unavailable insights about ocean energy potential from the Indian EEZ and extend guidance for Indian Industries to establish energy converters along the Indian EEZ and contribute to the nation's Net-Zero target.

We would be delighted to receive feedback from Industries/ end-users about the findings of this report. I want to record my deep appreciation for all those who have contributed to this project's success.

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Dr. T. Srinivasa Kumar
Director



PREFACE

Indian National Centre for Ocean Information Services, since its inception in 1999, has been contributing to India's blue economy through its flagship programs like Potential Fishing Zones (PFZ), Ocean State Forecasts (OSF) and Tsunami Early Warning Services (TEW). INCOIS has also been the national and regional warehouse for oceanographic data spanning in-situ platforms, satellite sensors, and model-simulated products. Taking advantage of the availability of such long-term scientific datasets, INCOIS has taken up the challenge of estimating the marine energy potential from the Indian EEZ. An integrated evaluation of marine meteorological (solar and wind) and hydrological (wave, tide, currents, ocean thermal, and salinity gradients) energy forms has been undertaken for the first time in the country and presented in the form of an Atlas. The Atlas identifies areas with high potential for energy generation and will serve as an extremely valuable reference for policy makers, industry and researchers, as our nation moves towards harnessing the rich energy resources available in the Indian EEZ. INCOIS prepared the annual, monthly, and daily energy estimates of different marine energy components following standard methods that can be visualized through a WebGIS interface at 5 km grid resolution. I thank Secretary, MoES for his guidance in scoping and implementing this important initiative and congratulate Team INCOIS who devoted their time and expertise for this important work.

We strongly believe that this Atlas provide hitherto unavailable insights for long-term planning of the country's energy requirements and contribute to the development of Blue Economy. I look forward to receiving feedback from all relevant stakeholders including industry partners in the energy sector. INCOIS will be happy to undertake any future upgrades to the Atlas including site specific studies based on user needs.

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PREAMBLE

The relevance of blue energy initiatives lies in their ability to harness the vast and untapped energy resources of the world's oceans. According to the International Renewable Energy Agency report, G20 countries collectively account for 81% of total renewable energy and about 100% of Ocean energy. Offshore renewable energy, such as solar, wind, wave, tidal, ocean thermal energy conversion, ocean currents and salinity gradient represent largely untapped potential for renewables. It can significantly aid in the energy transition and developing a global blue economy. The first step towards harnessing the blue energy potential is to estimate the available reserves of various forms of energy within the country's Exclusive Economic Zone (EEZ). Towards this, INCOIS has now developed an Integrated Ocean Energy assessment of the Indian EEZ.

These estimates are prepared using various data sets, which include satellite measurements and model-simulated parameters verified using observations. This report can be used as a guidance for industries to identify potential energy pockets before taking detailed field work for project implementation. INCOIS prepared the annual, monthly, and daily energy estimates of ocean energy components following standard methods that can also be visualized through a WebGIS interface at 5 km grid resolution. INCOIS has estimated integrated ocean energy of 9.2 Lakh TWh within the EEZ of India.

1 Introduction

Blue energy initiatives and the concept of a blue economy are both quite relevant in the context of sustainable development and environmental conservation. Blue energy typically refers to the energy derived from the ocean, including tidal, wave, salinity gradient, ocean currents and ocean thermal energy. It is considered as a renewable and clean energy source with great potential to contribute to the global energy mix while minimizing environmental impacts. It will be a fast-track enabler for achieving net-zero targets as part of global mitigation of climate change effects.

The relevance of blue energy initiatives lies in their ability to harness the vast and untapped energy resources of the world's oceans. Oceans cover a significant portion of the Earth's surface, and by tapping into their energy potential, we can reduce our dependence on fossil fuels and decrease greenhouse gas emissions. The use aligns with the global efforts to transition towards more sustainable and environment friendly energy sources.

The analysis of the International Renewable Energy Agency (IRENA) report (2021) [24] showed that globally, G20 countries are leading the development of renewable energy, and they collectively account for 81% of renewable installed capacity and 75% of deployment potential for the 2010 – 2030 period. In offshore renewables, they account for 99.3% of offshore wind and 100% of ocean energy installed capacities. As the mitigation of climate change is global, G20 countries are responsible for using this leading position to enable the deployment of these technologies in non-G20 countries by sharing their experience and lessons learnt within dedicated collective instances and platforms like the IRENA.

Offshore renewable energy tapping infinite resources in the atmosphere above the sea surface, such as solar and wind (fixed and floating foundations), which have already matured technologies and are being cost effectively harnessed, however, ocean energy (wave, tidal, ocean thermal energy conversion, salinity gradient, ocean currents), represents a still largely untapped potential for renewables and can significantly aid in the energy transition and the development of a global blue economy [24].

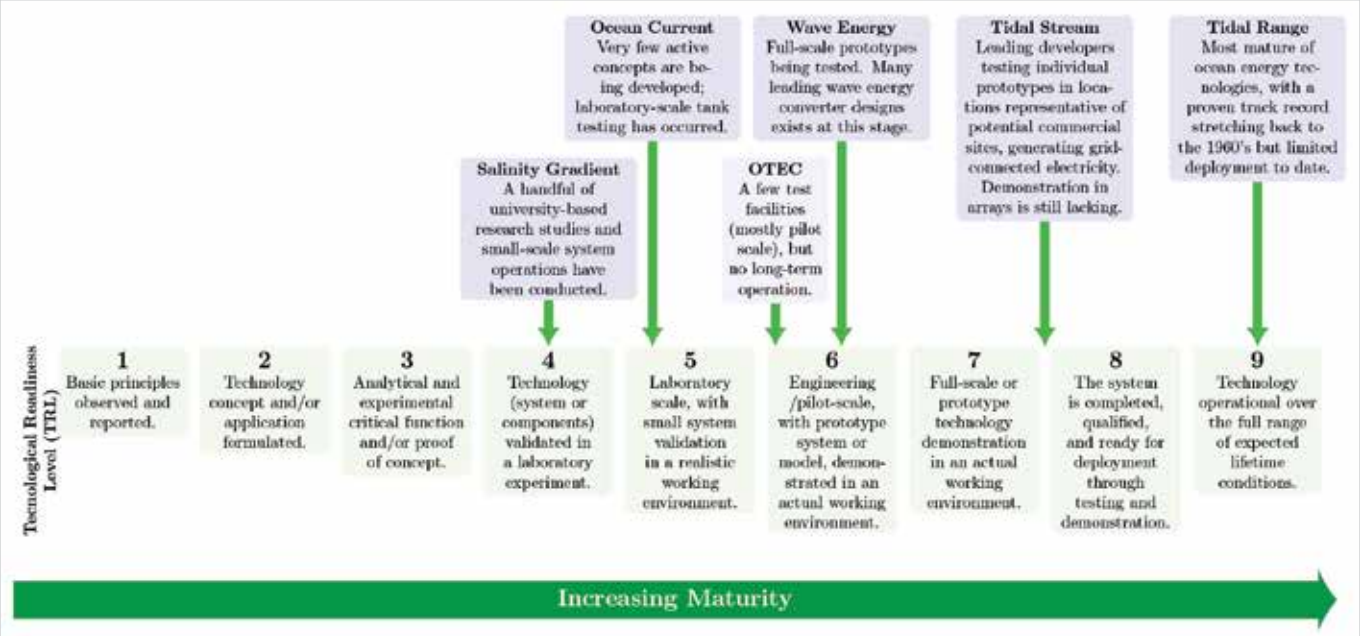


Figure 1: Technological readiness level of different forms of marine energy, reproduced from [23].

Although some technologies for marine energy are in their infancy, there is considerable worldwide interest from academic and industry researchers and policymakers in developing these clean energy resources. Marine energy

has several forms, including tidal energy, wave energy, ocean thermal, ocean current and salinity gradient in the decreasing order of technological maturity [23]. According to IRENA, report 2014 [23], wave energy has a global potential of 8000 to 80,000 TWh per year, followed by ocean thermal energy, with 10,000 TWh per year, osmotic energy (salinity gradient) with 2000 TWh per year, ocean current energy, over 800 TWh per year, and tidal energy, of more than 300 TWh per year.

With the increasing global interest in clean energies and the fast phase of technology developments in this sector, marine energy is expected to occupy a significant component in the global energy mix. Figure 1 shows the Technological Readiness Level (TRL) of different forms of marine energy as of 2014. In the present work, we have incorporated purely marine energy forms, including energy from Wave, Tide, Ocean thermal and salinity gradients, ocean currents, and marine meteorological energy forms, including offshore wind and solar.

1.1 General Disclaimer and Guidance for Usage

While global marine Energy potential has been significant, around the world harnessing the energy at an affordable cost is still in a nascent stage owing to capital investments and long term sustainability; it is only appropriate India starts it's strides in marine energy report preparation concurrently when the world at large is looking at the same innovating affordable technologies which would protect earth both from climate change as well as decarbonising the human global energy needs. However it is needless to record that this report is based on scanty measured data and data derived from available satellite based macro-meteorological models and digital simulation models of oceanic processes. When conceiving any marine/offshore project detailed site specific measurements, corroborations, and data analysis would have to be carried out to this broad based theoretical energy potential to estimate the realisable technical available marine energy potential involving comprehensive EIA environmental impact assessment studies.

Previously there were attempts to independently prepare estimates of different forms of marine energy resources. However, this is the first time the Indian National Centre For Ocean Information Services (INCOIS) has prepared a report on Integrated Marine Energy in the country. This effort aims to bring all such estimates of energy under one umbrella to provide a broader picture of available energy resources from the Indian Exclusive Economic Zone (EEZ). This report can help industries focus on areas in the EEZ where a single form of energy is available predominantly or multiple forms of energy availability can be tapped using hybrid technologies, an upcoming approach in this sector.

- This report's main objective is to provide a broader understanding of marine energy resources from the Indian EEZ. These estimates are prepared using various data sets, which include satellite measurements and model-simulated parameters verified using observations. This report can be used as a guide for industries in identifying potential energy pockets.
- Specific localized zones of EEZ field study need to be undertaken before implementing any projects, considering tecno-legal, tecno-commercial, sea-bed permissions and leasing risks, comprehensive impact assessment studies including existing environment, marine biodiversity and marine/coastal livelihood.
- The estimates in the report are obtained based on the efficiency of presently available methods/tools/technologies and can be different with improvement in the knowledge domain/technology.
- Under a climate change scenario, the present estimates may no longer be valid in the future, and the estimate may require revisions in such a situation as and when the updated field is benchmarked and measured or when model data becomes available.

- The model simulations and satellite data used for the estimates are of different spatial resolutions and interpolated to a uniform 5 km grid in the final product for immediate cross-comparison of different marine renewable energies. The validation of the model products is carried out on the source data field wherever observations are available with respect to the nearest grid point, which needs to be considered while using these estimates.
- The energy resource estimates presented in this report are intended for expert's use in their respective fields, predominantly for further research in the direction of tapping blue energy. INCOIS shall not be responsible for any financial losses due to the misinterpretation of the results presented in this report and its use for purposes other than what it is intended for.

2 Solar Energy

Among the renewables, solar energy has the maximum potential of all renewable energy sources. Approximately 0.7 million km^2 area is needed for ten billion people, assuming a capacity factor of 16% and panel efficiency of 20% [48]. However, the land area appears to be a manageable size compared to other types of land use; densely populated countries may find it challenging to find a place to set up solar farms. Further, floating solar panels have the advantage of lesser shades and high energy yield due to the cooling effect of water.

Until 2020, cumulative installed floating solar PV capacity was around 2.6 GW from active projects in more than 35 countries globally. The installed capacity has more than doubled since 2018, with 1.1 GW installed capacity. Currently, 338 floating solar PV projects are installed in 35 countries, mainly on freshwater artificial reservoirs. The top 10 projects are in China, Japan and the Republic of Korea. The largest plant globally is located in China, with 150 MW. The future demand for floating solar PV is expected to be driven by Asian countries. India plans a project of 1 GW, while the Republic of Korea plans one of 2.7 GW in the Yellow Sea. European countries also aim for several GW in coming years [48].

Hence, it is of vital importance to estimate solar power generation potential along the Indian coastline, not only in calm sea bays, also in nearshore seas. However, there are existing technological limitations for installing plants in cyclone areas and regions experiencing more significant wave heights. A recent global study [48] shows that sites that do not experience waves higher than 6 meters or winds stronger than 15 m/s are suitable for generating power up to one million TWh per year. However, environmental viability is an essential factor to be considered here; with presently available commercially viable technologies, floating solar panels are ideal for calm seas, such as equatorial regions devoid of tropical cyclones and high waves.

2.1 Data and Methods

Computing the electricity generation potential of solar energy from coastal ocean areas involves assessing the solar radiation, available space, and other relevant factors. Coastal regions can offer unique opportunities for solar energy generation, such as floating solar arrays or integrated coastal development projects.

We have used insolation data of the Kalpana satellite from 2011 to 2017 to compute solar energy potential, which has a spatial resolution of ≈8 km (0.072°). The satellite data takes the effect of clouds into account. Kalpana-I, insolation data is given in [MJ m^{-2} day^{-1}]. A default solar panel efficiency of 21.5% has been considered. This has been converted into [kWh m^{-2} day^{-1}] and [MWh km^{-2} day^{-1}].

Computation:

Energy Equation:
Energy (E) = Area (m^2) * Solar Radiance on Horizontal Plane (GHI) * Efficiency

Unit Conversions

$$1MWh = 3600MJ \implies 1MJ = \frac{1}{3600}MWh$$

$$1\frac{MWh}{m^2\ day} = 1,000,000\frac{MWh}{km^2\ day}$$

$$\implies 1\frac{MJ}{m^2 day} = \frac{1,000,000}{3600}\frac{MWh}{km^2\ day}$$

2.2 Results

Many researchers from the 1980s used ground-level solar radiation from satellites [35,7,41]. Since then, solar radiation estimates at ground level have been made using geostationary and polar-orbiting satellites, and the data sets cover virtually the whole planet, albeit with immensely varied spatial and temporal resolution [3]. Several solar radiation data sets have been collected using information from the Meteosat series of European geostationary satellites. While some of these data are available with free of cost, some are licensed on a paid basis. The individual data set's commercial/free status may vary over time. However, to our knowledge, there are currently no publicly accessible high-resolution solar radiation data from the Meteosat satellites located over the Indian Ocean. Therefore, we have used irradiance data from the Kalpana-I satellite, which is made available by the Space Application Centre (SAC) through their MOSDAC website.

We have estimated different energy forms from the Indian EEZ and divided the EEZ as North-East, South-East, North-West, South-west and Andaman-Nicobar sectors. Solar energy potential computed from daily data and is presented as annual average (Figure 2(a)), annual cumulative energy above > 4 kWh/m^2/day (Figure 2(b)), number of days solar energy is above 4 kWh/m^2/day (Figure 2(c)), and sector wise percentages of annual average (Figure 2(d)). The monthly solar energy maps show that the potential varies during different months, and the maximum potential is seen for March, April & May, followed by September and October.

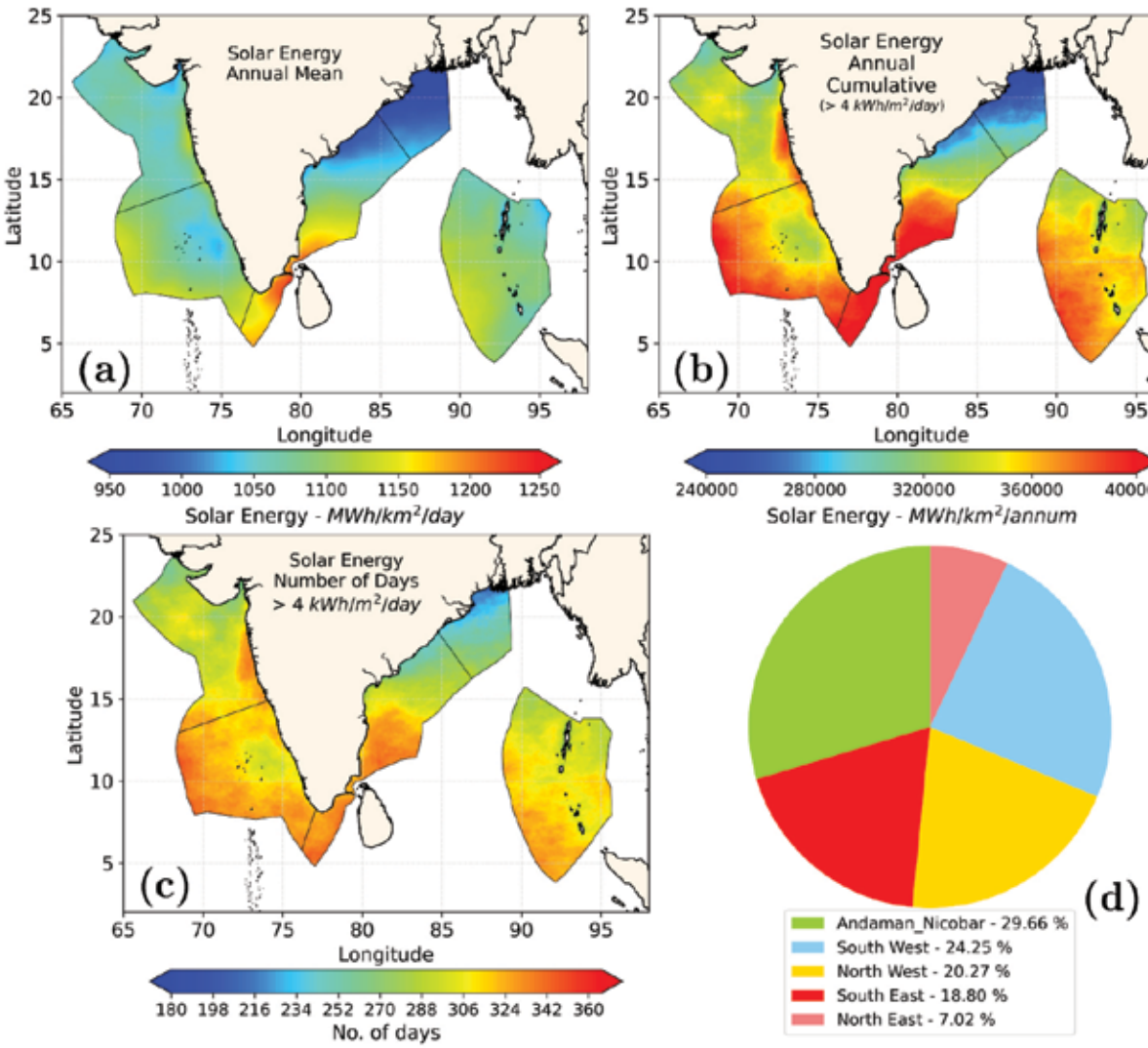


Figure 2: Estimated annual mean solar energy (a), Cumulative 4 kWh/m^2/day (b), Number of days above 4 kWh/m^2/day solar energy from the Indian EEZ (c), Percentage of solar energy available from different sectors (d).

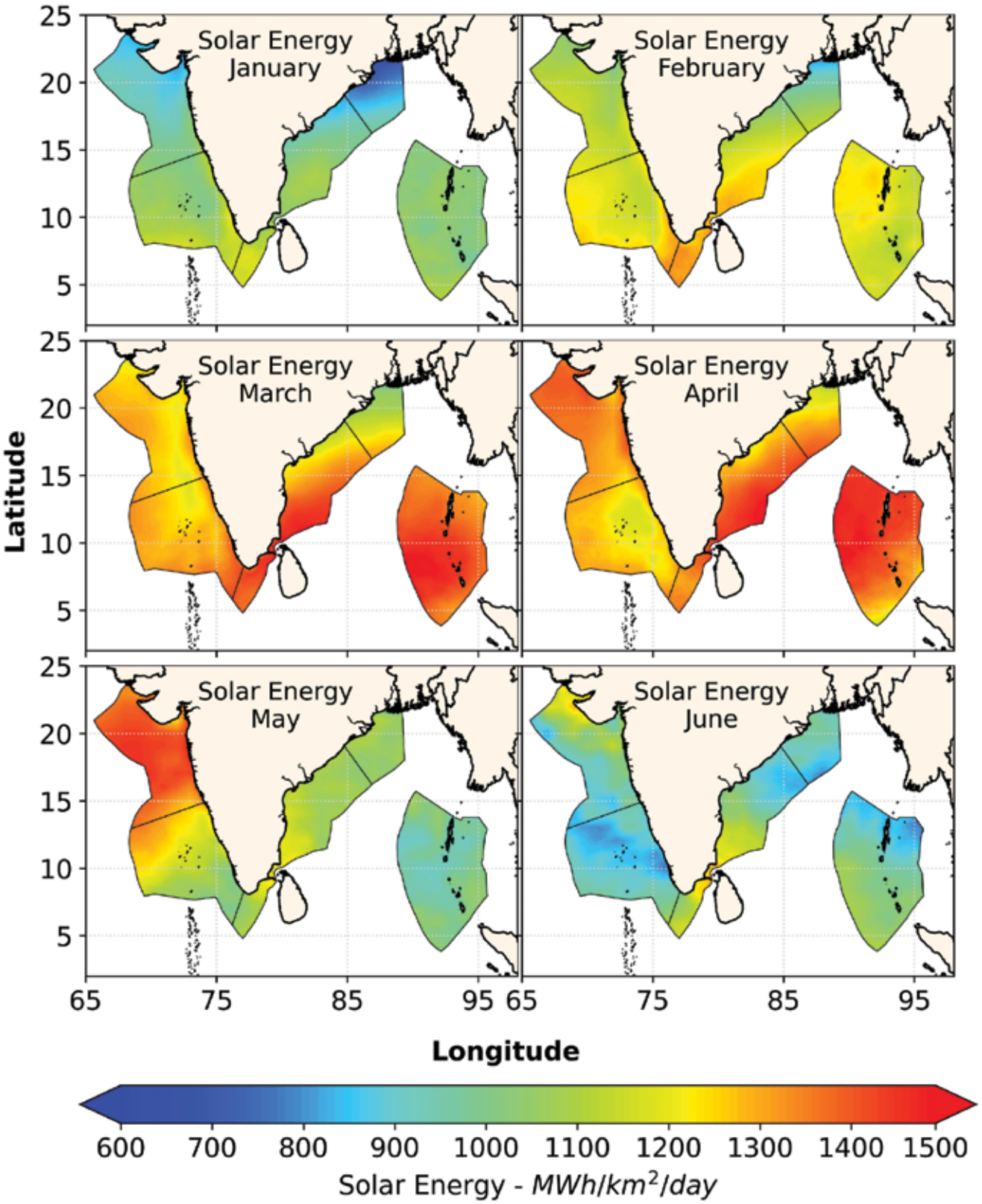


Figure 3: Estimated monthly mean solar energy from the Indian EEZ (January – June).

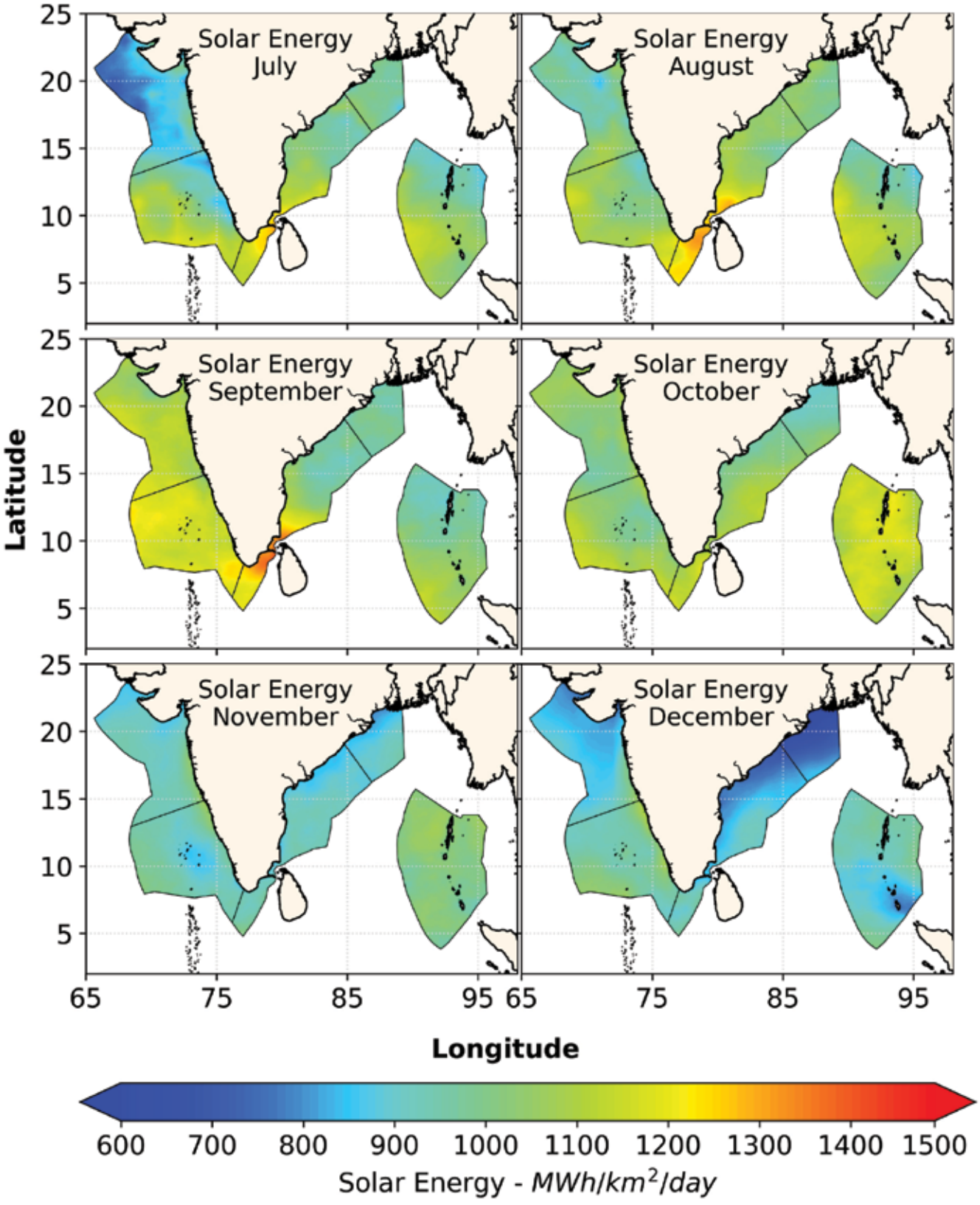


Figure 4: Estimated monthly mean solar energy from the Indian EEZ (July – December).

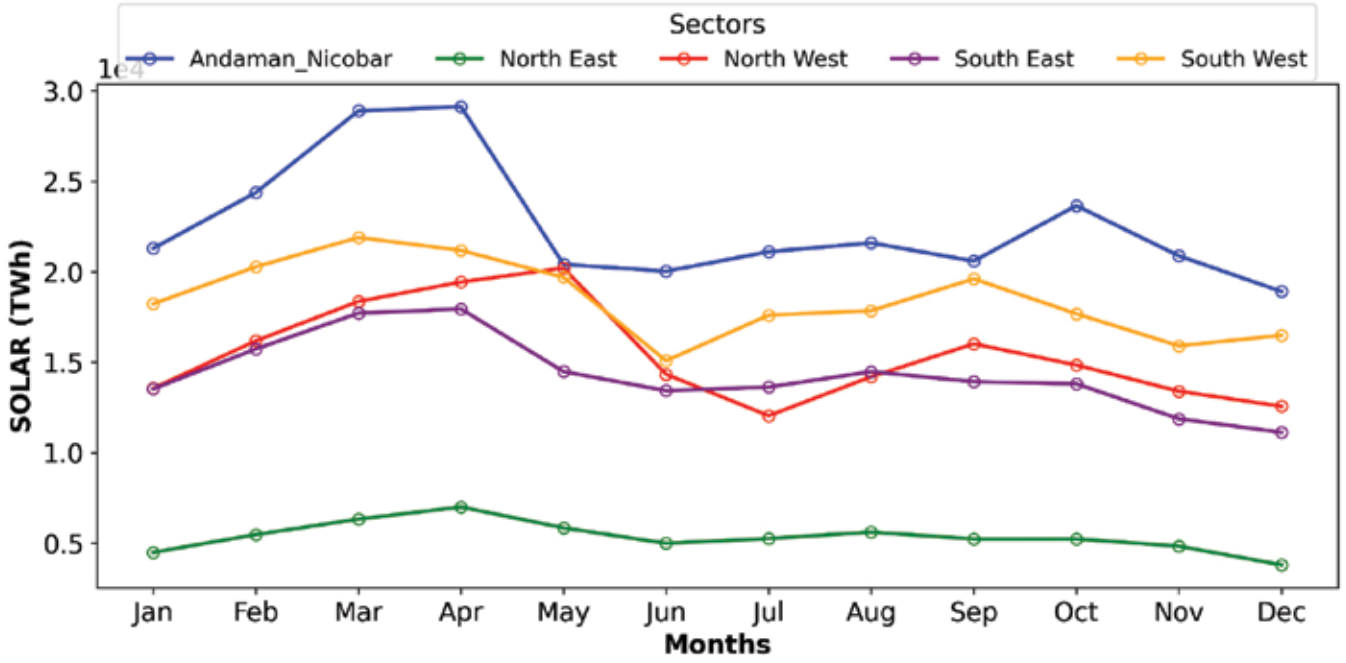


Figure 5: Monthly mean solar energy from five sectors identified from Indian EEZ.

It is evident from Figures 3 to 5 that there is seasonal amplification of solar energy in the Indian EEZ with first peak during April-May and second peak during September-October. This seasonality is more evident in Andaman-Nicobar sector followed by North-west and South-east sectors and seasonality and solar energy magnitude are minimum in North-east sector.

3 Wind Energy

The Indian EEZ is known for its sustained high winds. Over the last decade, emerging technologies evolved drastically in connection with offshore wind farming through fixed type or floating or anchored platforms. In this context, the Indian National Centre for Ocean Information Services prepared a high-resolution wind climatology for the Indian coasts. The climatology can help to assess the potential areas for coastal wind farms and to locate them appropriately. The winds from Cross-Calibrated Multi-Platform wind vector analysis (CCMP) with 0.25 deg X 0.25 deg over the sea are used in the present study. We have evaluated CCMP winds along the Indian Ocean coastal regions using coastal buoy data. Wind characteristics varied remarkably during the last decade compared to the previous decades, as evidenced by the analysis. We have used data spanning 2010 to July 2023 to prepare the current wind energy assessment.

3.1 Data and Methods

Wind data from the Cross-Calibrated Multi-Platform (CCMP) wind vector analysis is used as the base data for the current study. The CCMP wind analysis is a near-global, high spatial and temporal resolution gridded dataset of surface wind vectors spanning the last 30 years. The input data combines inter-calibrated satellite data from numerous radiometers, scatterometers, and in-situ data from moored buoys. An algorithm finds a best-fit solution to all available observations, using the ERA-interim reanalysis winds as a first guess. Wind data from six NIOT/ MoES coastal buoys in and around the Indian coastline are also used to fine-tune the coastal data.

CCMP data has been evaluated using six coastal buoys. Uncertainties in the coastal winds were removed using the average bias-correction technique following [20]. For Industries to assess the potential of wind farming, the availability of winds at 80 m above sea level is usually preferred. Hence, the standard wind data available at 10 m level were converted to 80 m height following the logarithmic relation of [34] and [51]. The bias-corrected winds extrapolated to 80 m height were then used to derive the daily, monthly and annual climatology of winds as well as the Wind Power Density (WPD), following the procedure suggested in Centre for Wind energy Technology-CWET-Chennai, 2010, Energy Pattern Factor (Weightage factor) Indian Wind Atlas, using below Equation. Using average wind speed, we have taken Epf = 1.5 following CWET, 2010, for the Indian scenario. Also, daily climatology of winds at 80 m height was used to construct wind potential maps indicating the number of days on which the wind speed exceeded 6 ms^{-1}. National Institute of Wind Energy- NIWE (former CWET) Chennai has completed a desktop study project on First offshore Wind –"FOWIND" in collaboration with EU with specific reference to Tamil Nadu and Gujarat and prepared detailed multilevel wind measurements using met-tower and Lidars. NIWE as an Institution is mandated to be a single wind clearing agency for offshore wind projects in India.

The average wind speed in Indian EEZ is ≈ 7m/s. Based on the NREL method described for wind energy, a turbine has been designed to produce 3 MW at the mean speed of wind. This corresponds to a turbine with diameter $D = \Phi_{130}$m. An area of 10.5D × 10.5D was suggested for one turbine. Appropriate wake loss has been considered. Also, a Weibull distribution has been taken into account for the wind distribution. An efficiency of 50% is considered by default for the wind turbines. The potential of winds estimated is presented by converting the units to [MWh km^{-2} day^{-1}].

Computation:

$$WPD = 0.5 \times \rho \times V^3 \times Epf$$

where:
WPD is the Wind Power Density (watts/sq.m)
ρ is Air density in kilograms per cubic meter (kg/m^3)
V is Wind speed in meters per second (m/s)
Epf is the energy pattern factor (1.5)

Wind Energy (E) is the cumulative amount of energy generated by a wind turbine over a certain period of time. The wind energy formula is derived by integrating the wind power formula over time.

$$Wind\ Energy\ (E) = \int [0.5\ x\ A\ x\ \rho\ x\ V^3\ x\ Cp] dt$$

where:

E: Wind energy in joules (J) or kilowatt-hours (kWh)
A, ρ , Cp: Constants as defined in the wind power formula
V: Wind speed in meters per second (m/s)
dt: Time interval over which the integration occurs

Specific details of the assumptions made in the computation of wind energy is presented below. For estimating the theoretical power density available at any location, the kinetic power density is considered.

Assumptions made:

- Average wind velocity corresponding to 80m is considered appropriate for the majority of wind turbines.
- This wind velocity is assumed to be constant from an altitude of 40m to 120m (for 80 m vertically above mean sea level (MSL)).

3.2 Results

The coast of Tamil Nadu and Gujarat has the maximum number of windy days. The coast of Tamil Nadu experiences winds above 6 ms^{-1} for more than 310 days, while that for Gujarat's west coast is more than 270 days Figure 6(c) and for the rest of the coastline, including that of Andaman & Nicobar Islands has only up to 220 days. Other parts of the east coast show winds >6ms^{-1} days for more than 200 days in a year Figure 6(c). The coast of Tamil Nadu has an average annual wind power density of 540 Wm^{-2} (20 KWh km^{-2} day^{-1}), and the coast of Gujarat has a value of 420 Wm^{-2} (15KWh km^{-2} day^{-1}) (Figure 6 (a&b)). The coasts of north Andhra Pradesh, Odisha, west coast of Andaman & Nicobar Islands, Maharashtra and Goa have an average WPD of up to 190 Wm^{-2} (18KWh km^{-2} day^{-1}).

It is important to note that the WPD exceeds 500 Wm^{-2} along the southern Tamil Nadu coast for about 8 months in a year (Figure 6(b)&c). However, it exceeds that value only for 4 months along the Gujarat-Maharashtra coast. Regarding WPD and the number of windy days, Tamil Nadu and Gujarat's west coast have maximum wind potential and viability for coastal/offshore wind farms. Kerala, Karnataka, and Lakshadweep Island coasts have minimal potential compared to other parts of the Indian coastline. It is also worth mentioning here that, though there is some potential available (especially during May through September) for the other east

coastal parts, viz., North Andhra Pradesh and Odisha, as the continental shelf is steep, setting up of wind farms are difficult, compared to the west coast.

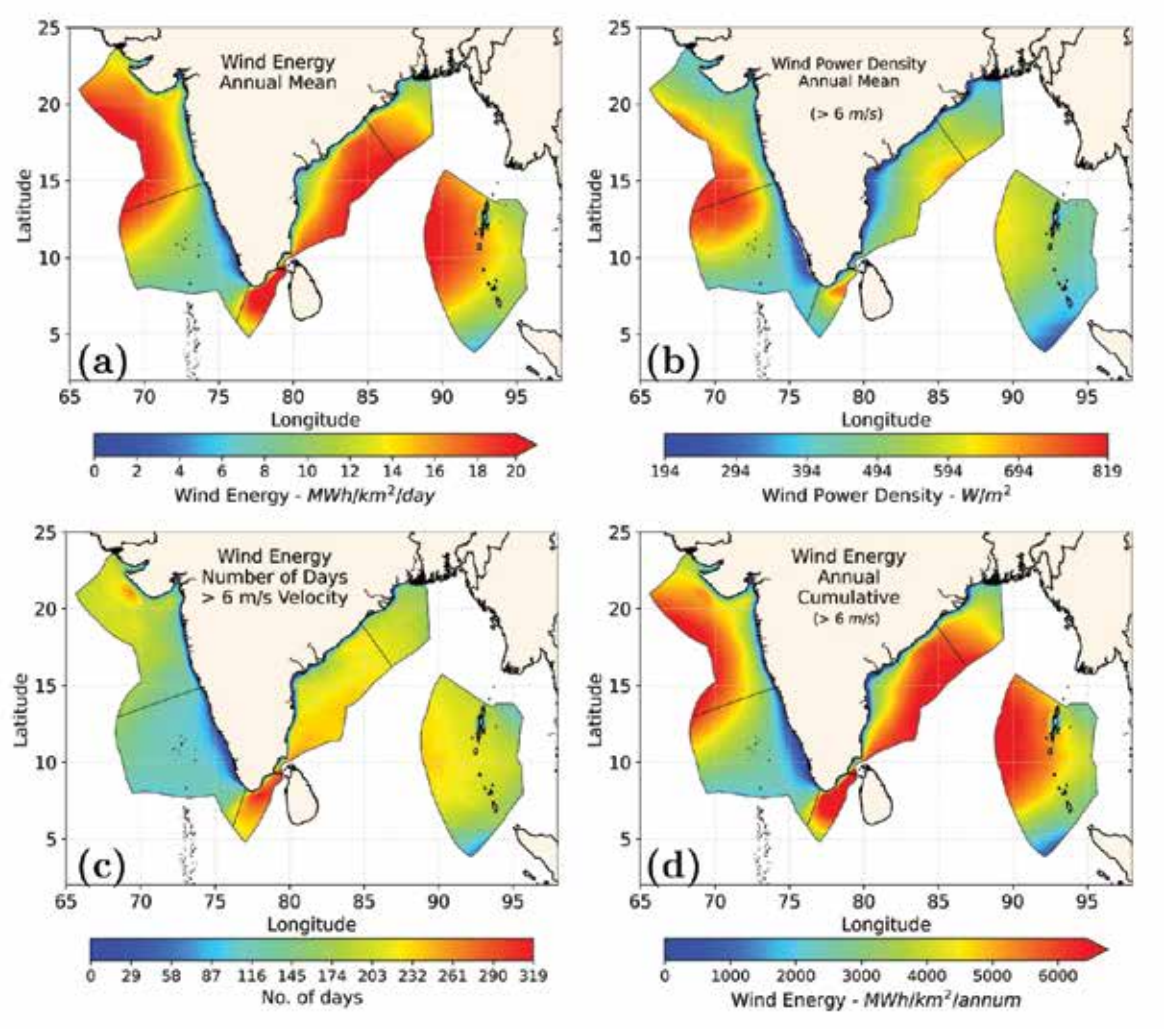


Figure 6: Estimated annual mean of wind energy (a), Wind power density (b), Number of days having > 6 m/s winds from the Indian EEZ (c) and Cumulative wind energy > 6 m/s (d).

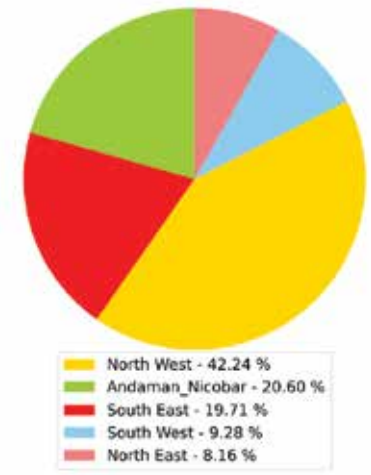


Figure 7: Percentage of wind energy (<1300 m depth) available from different sectors

Figure 7 shows the percentage of wind energy (<1300 m depth) available from North-east, North-west, South-east, South-west and Andaman and Nicobar sectors.

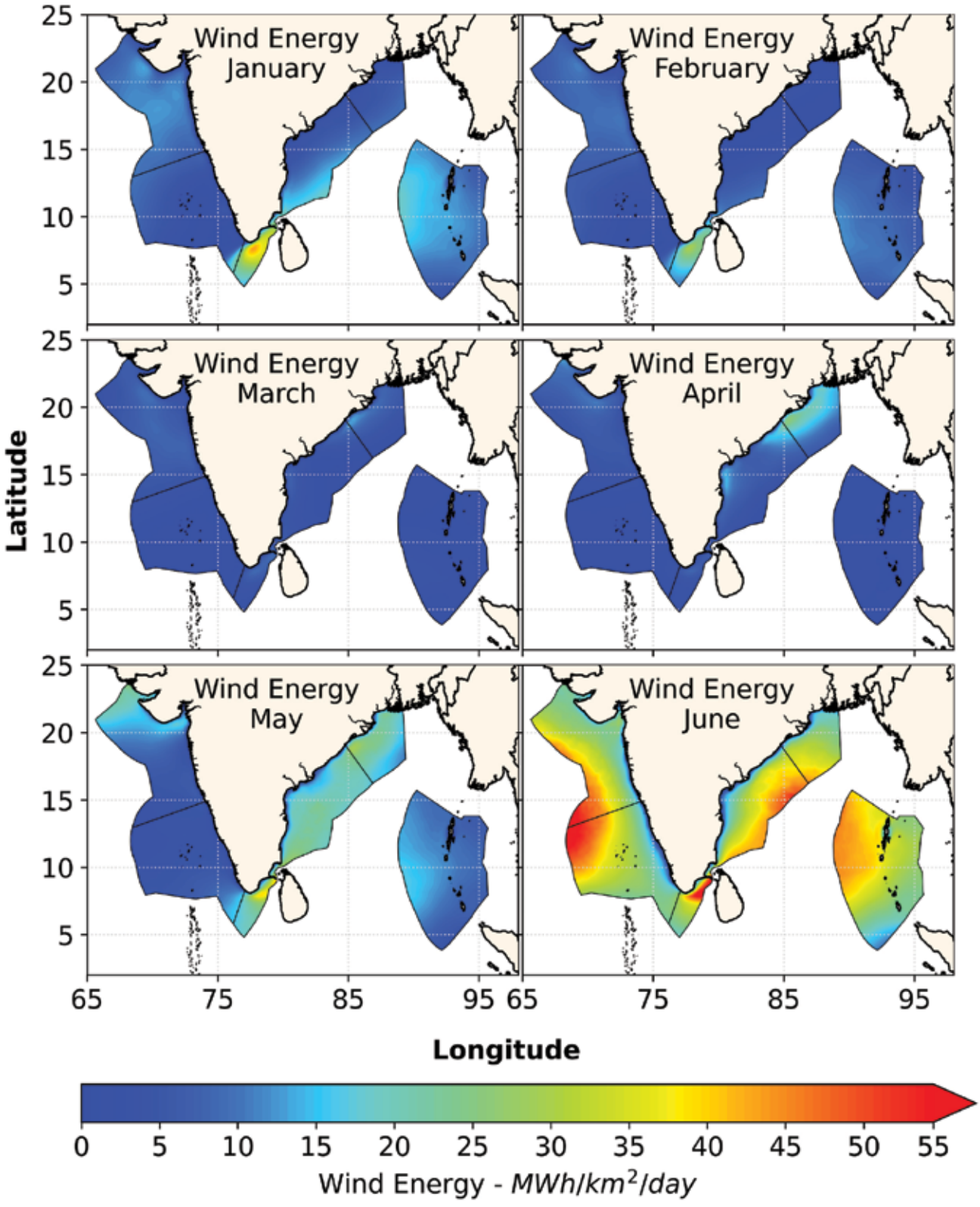


Figure 8: Estimated monthly mean wind energy from the Indian EEZ (January – June).

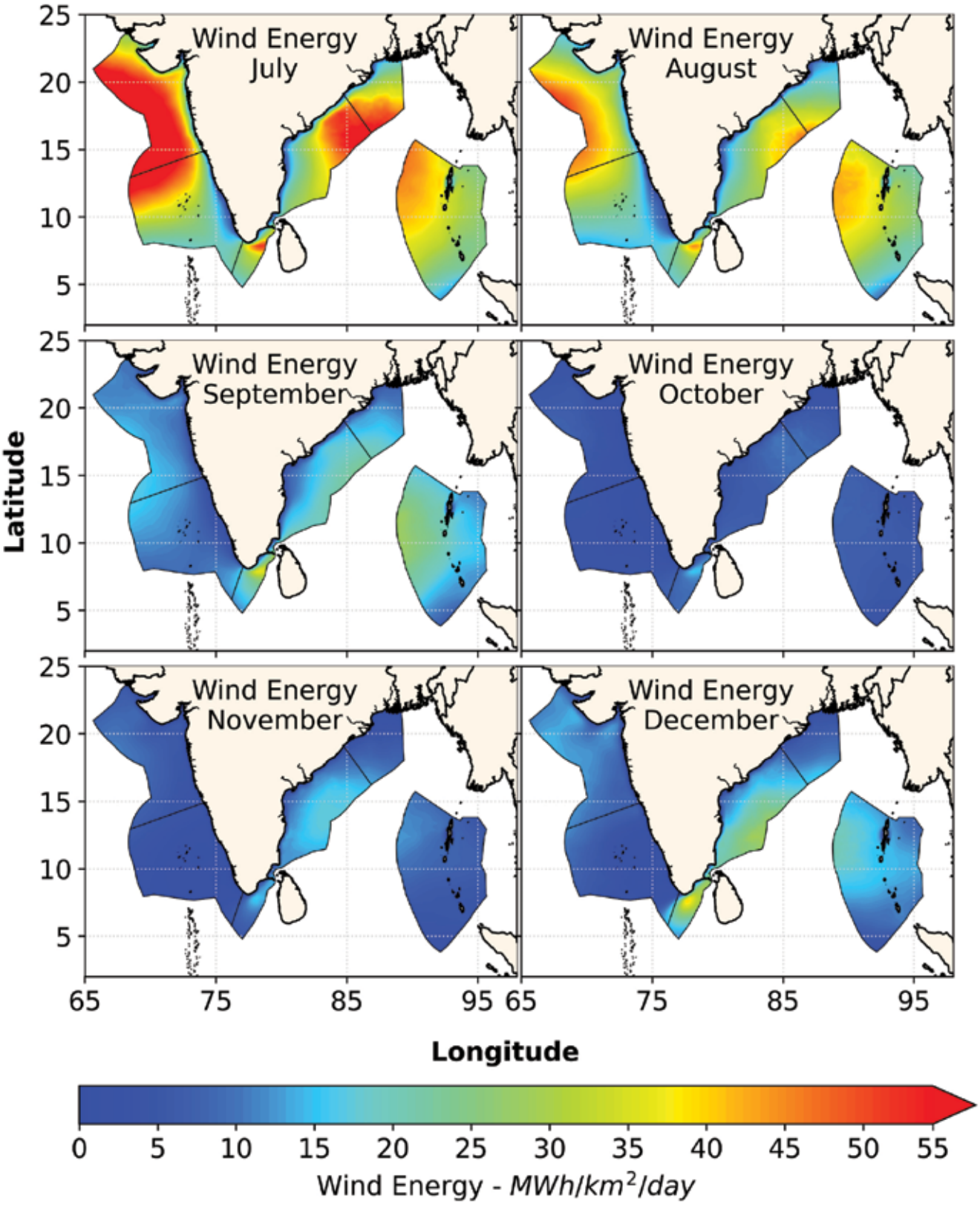


Figure 9: Estimated monthly mean wind energy from the Indian EEZ (July – December).

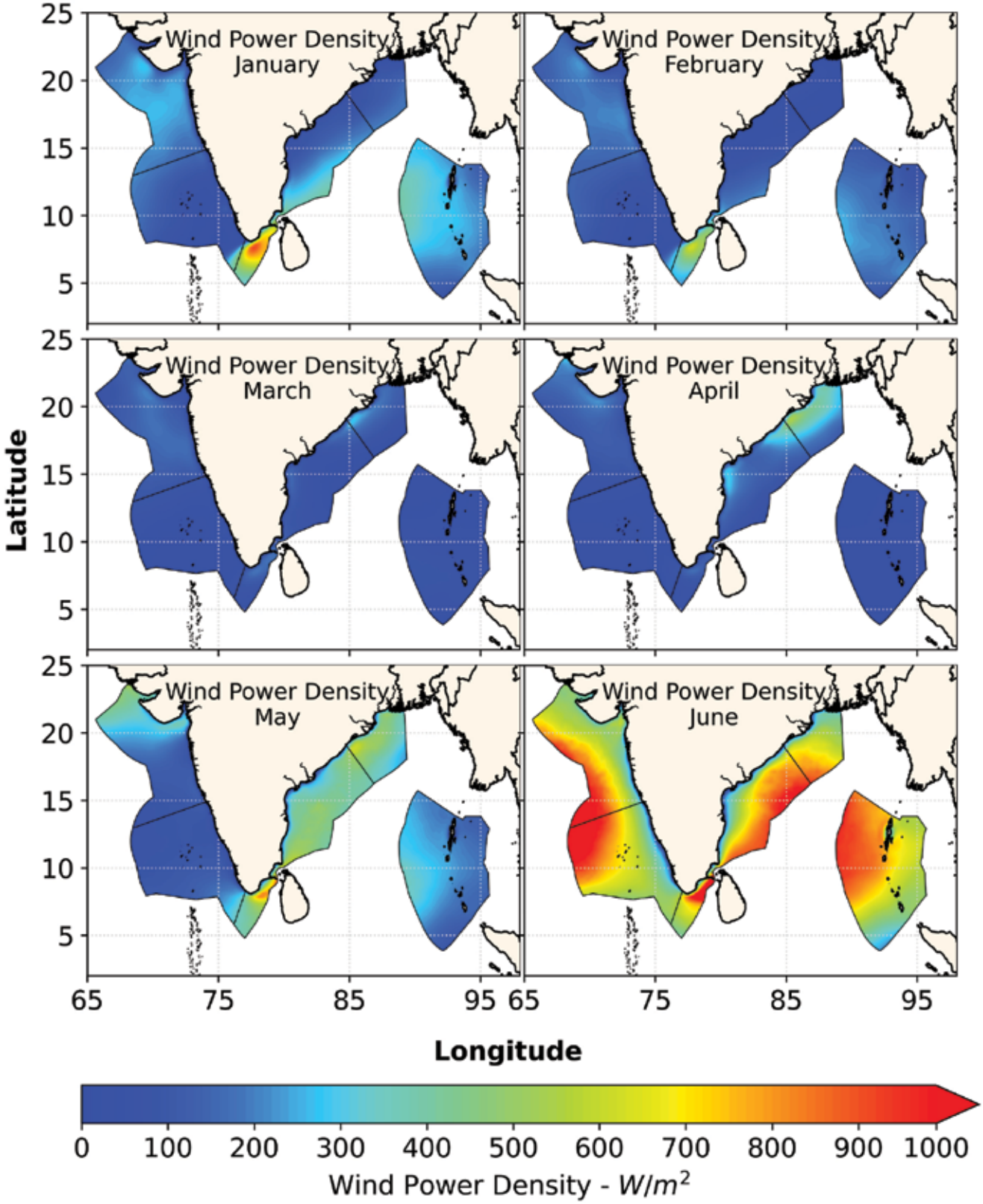


Figure 10: Estimated monthly mean wind power from the Indian EEZ (January – June).

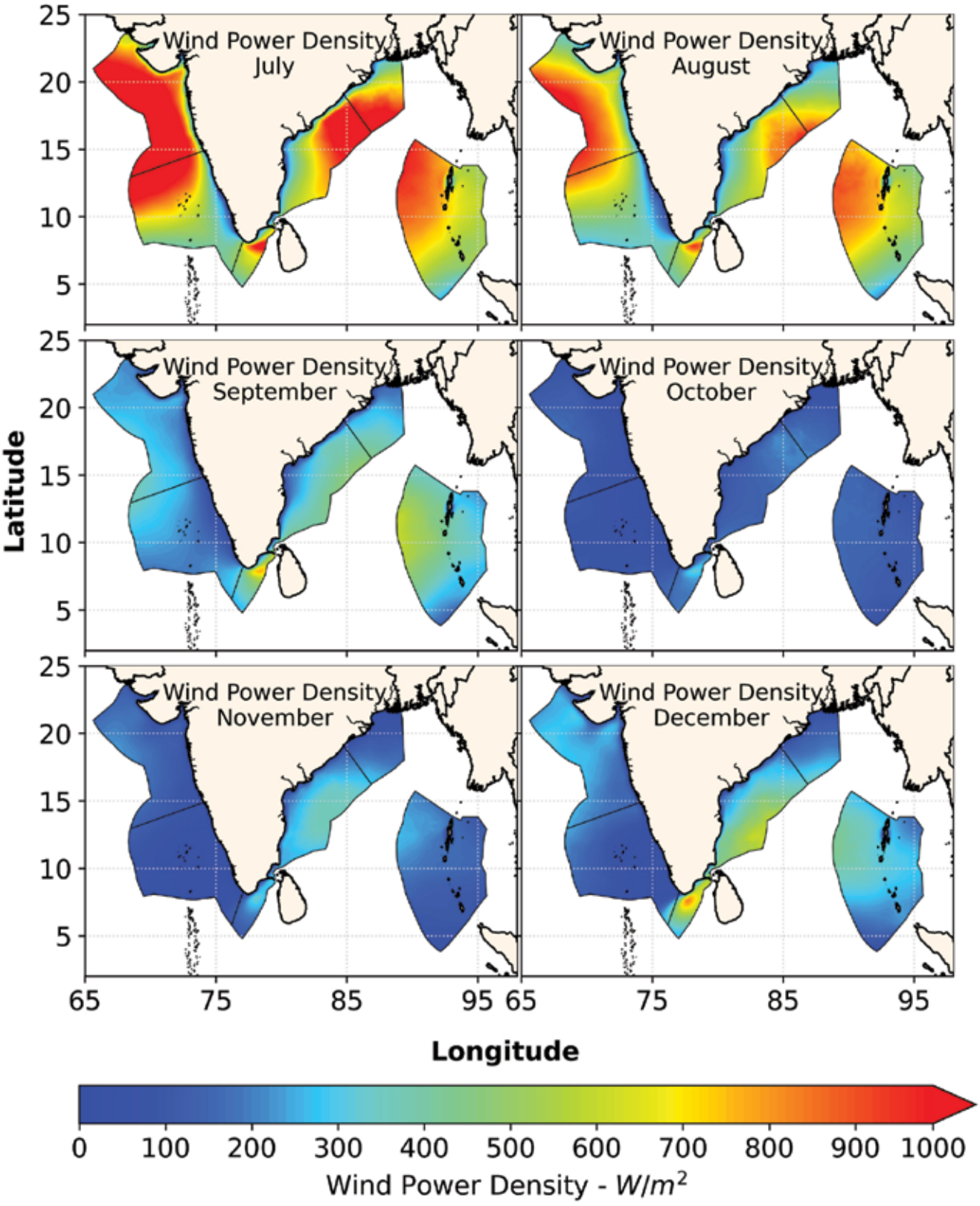


Figure 11: Estimated monthly mean wind power from the Indian EEZ (July – December).

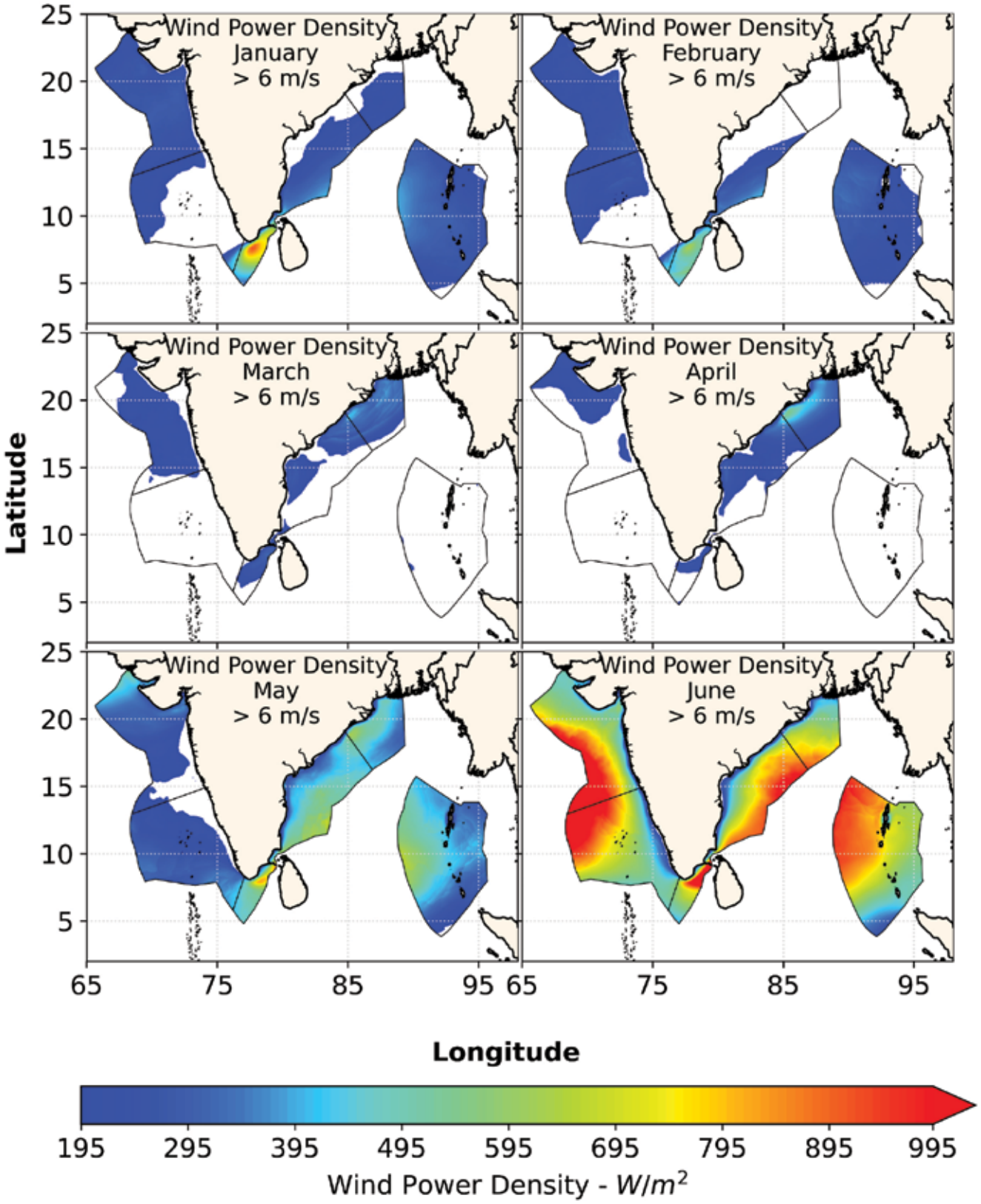


Figure 12: Estimated monthly mean wind power (>6 m/s) from the Indian EEZ (January – June).

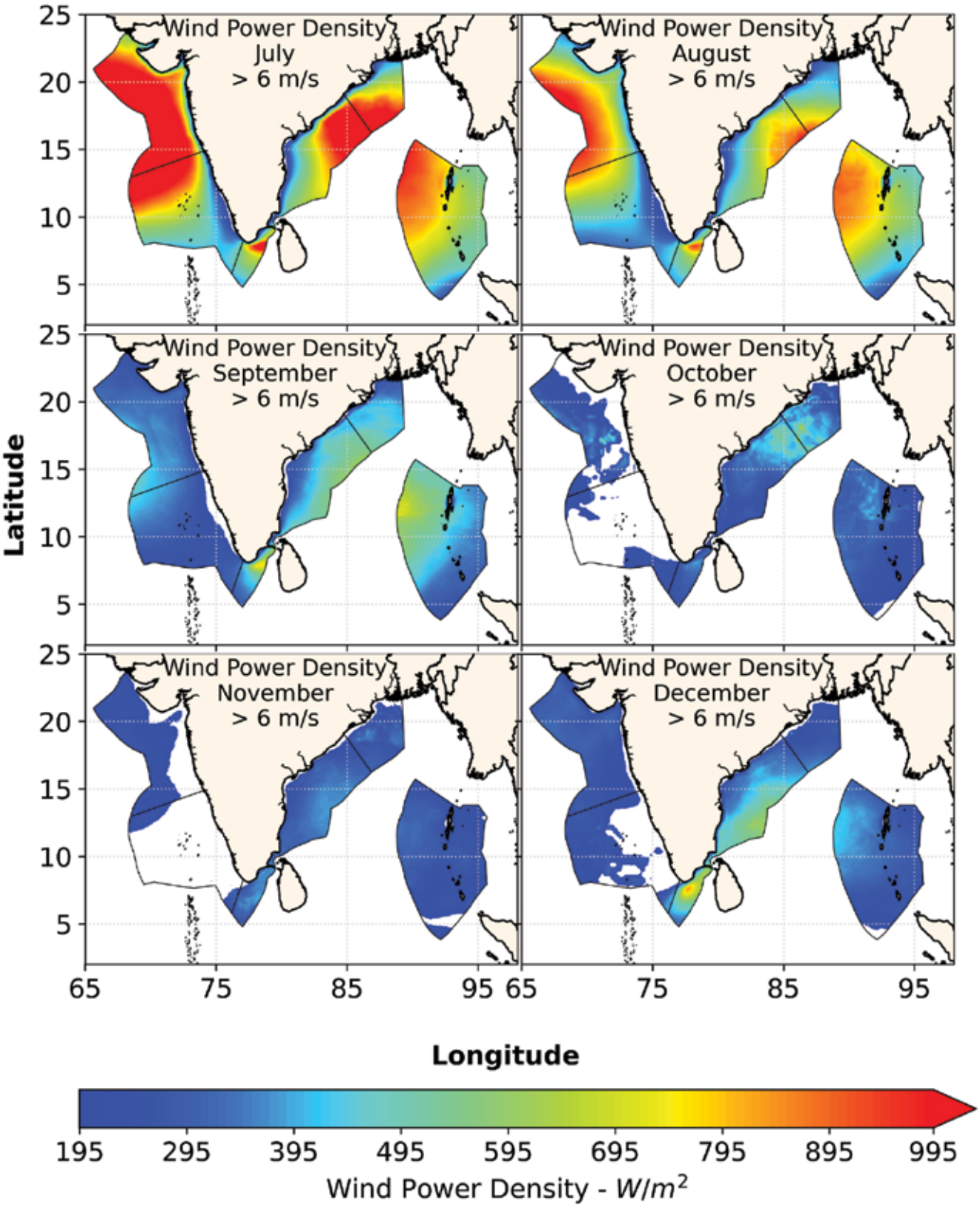


Figure 13: Estimated monthly mean wind power (>6 m/s) from the Indian EEZ (July – December).

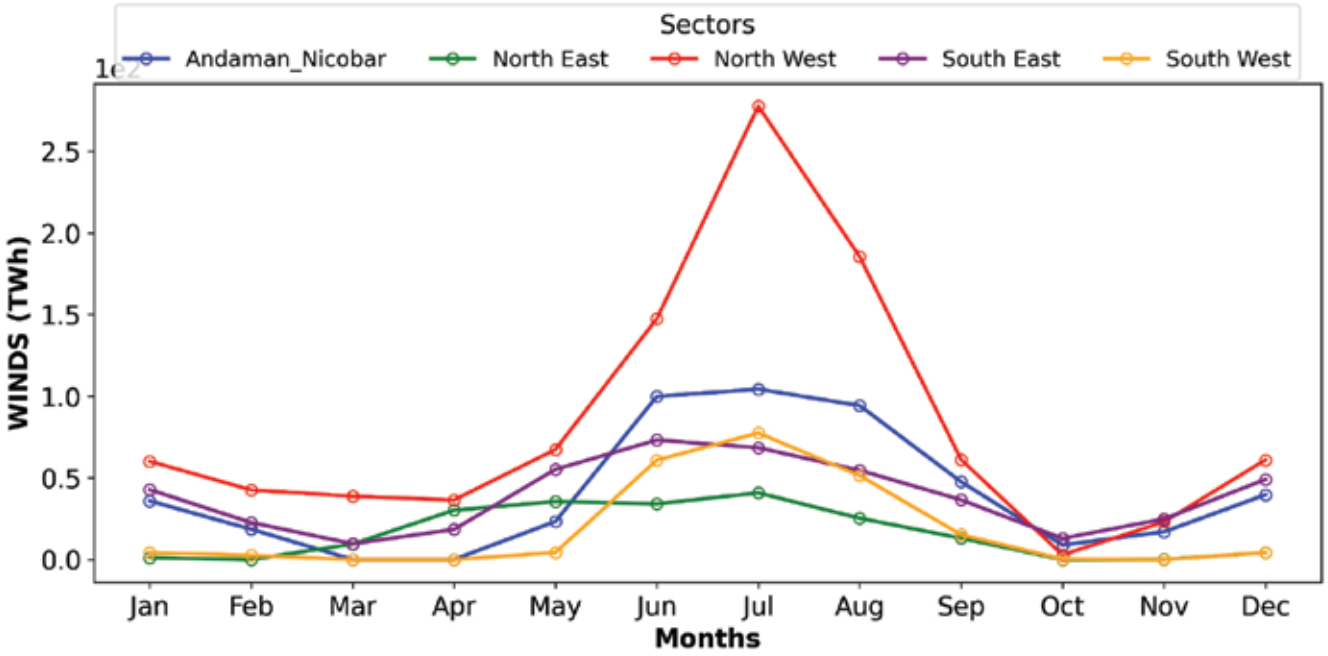


Figure 14: Monthly mean wind energy (from <1300 m depth) from five sectors identified from Indian EEZ.

It is evident from Figures 8, 9 and 14 that there is an annual amplification of wind energy in the Indian EEZ with a peak from June to August. This annual cycle is more evident in the Northwest sector, followed by the Andaman-Nicobar and Southeast sectors, and wind annual variability and magnitude are overall minimal in the Northeast sector.

In wind energy, the standard industry unit is wind power density. However, to keep consistency with other energies, we have estimated wind energy in Terra Watt Hours (TWh) and presented in this report Figures 8 and 9. Nevertheless, we have also presented wind power density monthly maps without any threshold and with a threshold (>6 m s^{-1}) in Figures 10 to 13.

4 Wave Energy

As a source of renewable energy, interest in wave energy is growing considerably [9,18]. Wave energy benefits from its natural concentration near the ocean surface and widespread availability across the globe [46]. However, effectively harnessing wave energy necessitates precise assessments of potential wave energy resources to identify suitable locations and the appropriate wave energy converters. This becomes especially crucial for a country like India, which is bordered by oceans on three sides. Evaluating the wave power potential can play a pivotal role in managing the ever-increasing energy demands of its population. In this study, we utilized 30 years of INCOIS-WAVEWATCH III data to gain insights into the average estimates of wave power availability within India's Exclusive Economic Zone (EEZ).

4.1 Data and Methods

We have used WAVEWATCH III (WW3) version 6.07 [53], with a new parameterization scheme ST4 [4,43], to generate the wave fields during 1993 – 2022 (30 years). The model uses a multigrid approach with a global grid of 1° spatial resolution, a regional grid of the Indian Ocean (0.125° × 0.125°) and a finer coastal grid around the Indian mainland (0.05° ×0.05°). The model was forced with 3-hourly European Centre for Medium-range Weather Forecast (ECMWF) winds with a spatial resolution of 0.25° × 0.25°.

In this study, we used wave power density or wave energy flux (P_{mod}), direct output parameter of the model, for wave energy assessment. It is given as an omnidirectional wave power per unit crest length (kW/m) for any bathymetric depth and is typically represented as below:

Computation:

$$P_{\text{mod}} = \rho g \int_0^{\infty} c_g(f,d) \times S(f) df \tag{1}$$

where:
$c_g(f,d)$ is the group velocity
f is frequency
d is bathymetric depth
$S(f)$ is non-directional wave spectrum

Most previous assessments used wave power computation based on derived wave power, P_{dw}, from the wave parameters, significant wave height, H_s, and wave energy period, T_e. The derived wave power can be given as,

$$P_{\text{dw}} = \frac{\rho g^2}{64\pi} \times T_e \times H_s^2 \tag{2}$$

where:
H_s is the Significant wave height
T_e is the Wave energy period
$\rho = 1024\ \text{kg/m}^3$ is the density of seawater
$g = 9.81\ \text{m/s}^2$ is the acceleration due to gravity

The above approach is not advocated for analysing nearshore regions as they do not allow the influence of bathymetric depth on wave power computation. However, we used this approach only for model validation purpose to compute wave power density from wave rider buoy data as it is not an observed parameter.

In this report, WW3 simulations are processed for preparing annual and monthly climatologies and are used to provide estimates of the annual and monthly mean of wave power potential in the entire EEZ. We have also mapped potential regions for wave energy based on the number of days in a year where the wave power density falls within the feasible range of 2–50 kW/m along the EEZ. This approach is essential for the Indian EEZ which experiences seasonal variations within a year. The prescribed maximum limit we followed is based on WEC limitations [31]. Considering the low energy ocean state scenario on Indian waters, we adopted the minimum extractable wave power as 2 kW/m following [39] and [29].

To get a representative estimates and to be consistent with the units followed by other marine energy resources in preparing the integrated energy estimates, we follow the methodology below to yield wave energy from wave power density, P_{mod} (in units kW/m). We have used daily mean climatology data for this purpose. Assuming that the mean wave power density uniformly crosses the square grids of 5 km × 5 km, we multiply P_{mod} by 5000 m to get wave power, P, crossing each square grid length. It is given by,

$$\mathrm{P\ (kW)} = \mathrm{P_{mod}\ (kW/m)} \times 5000\ \mathrm{(m)}. \tag{3}$$

Then, we compute the wave energy crossing the grid length for a day by,

$$\mathrm{E\ (MWh/day)} = \mathrm{P/1000\ (MW)} \times 24\ \mathrm{(hours)}. \tag{4}$$

Now, we assume that the entire square grid area had this energy for each day, and thus allowing to write the final output data as wave energy per unit grid area per day,

$$\mathrm{E_{grid}\ (MWh/km^2/day)} = \frac{\mathrm{E\ (MWh/day)}}{5 \times 5\ \mathrm{(km^2)}} \tag{5}$$

4.2 Results

Model validation using wave rider buoy data (2020 – 2022) has been carried out for nine locations along the Indian EEZ to ensure the reliability of the simulated wave power. Figure 15 shows validation of wave parameters with buoy wave parameters for two representative locations Karwar (west coast) and Visakhapatnam (east coast). As evident from Figure 15, all the model simulated parameters and calculated wave power agree with the observed variables. Detailed statistical evaluation is presented in Table 1. All the crucial wave parameters shows good agreement with observed values with low error and high correlation. In the context of derived wave power, the statistics results show good agreement and a low scatter index for the western counterpart than the eastern location. Overall, the performed validation affirms the reliability of simulated wave parameters and hence the energy assessment.

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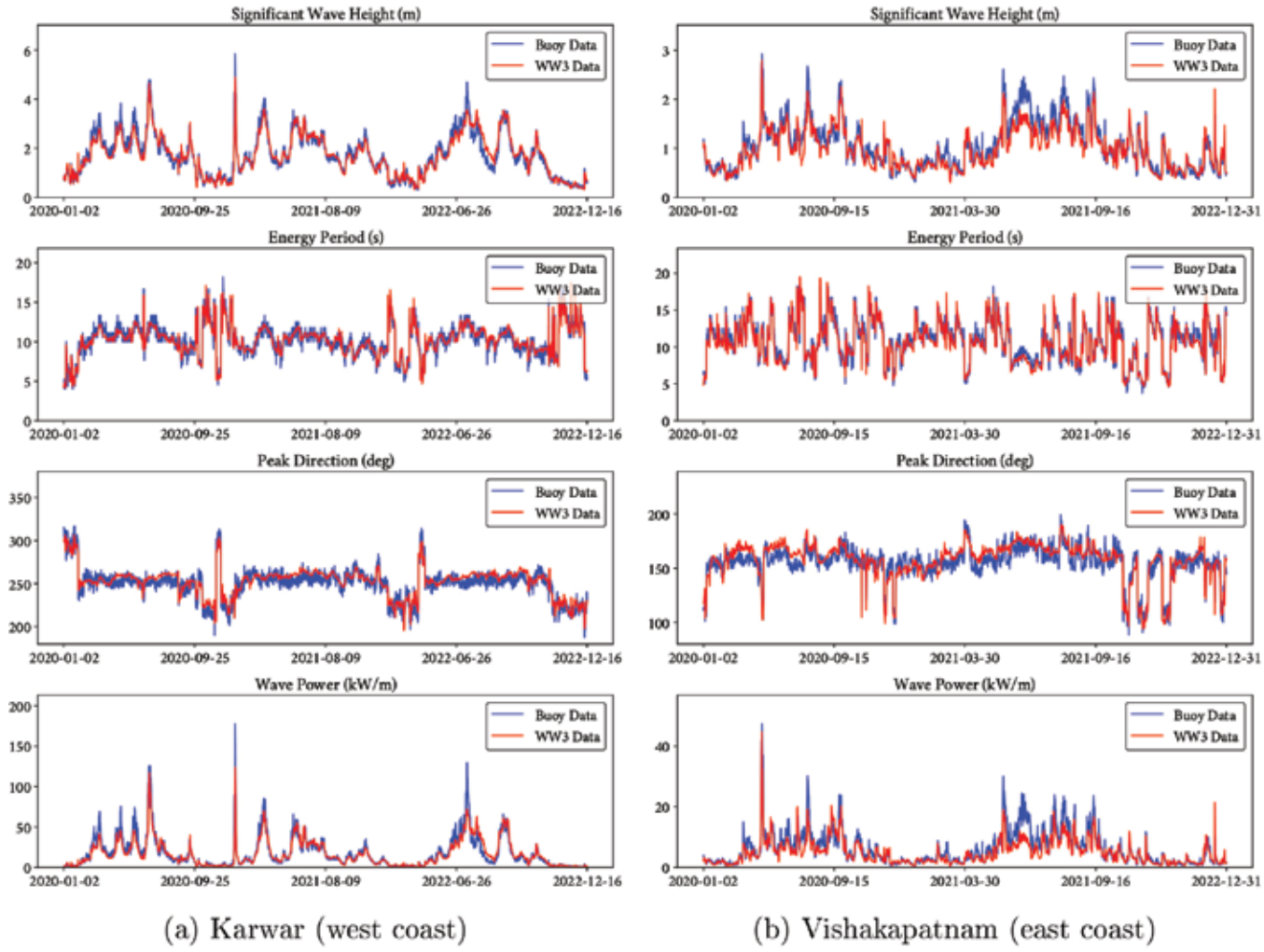


Figure 15: Validation of WW3 model using buoy data.

Table 1: Statistics of validation between buoy and model data.

Location	Parameters	Bias	RMSE	Correlation Coefficient	Scatter Index
Karwar	Significant Wave Height	-0.02	0.23	0.96	0.13
	Energy Period	-0.1	0.65	0.95	0.06
	Peak Direction	2.23	7.41	0.92	0.03
	Wave Power	-0.96	6.51	0.94	0.37
Visakhapatnam	Significant Wave Height	-0.08	0.20	0.93	0.19
	Energy Period	-0.21	0.54	0.99	0.05
	Peak Direction	2.11	8.13	0.90	0.05
	Wave Power	1.18	2.82	0.90	0.45

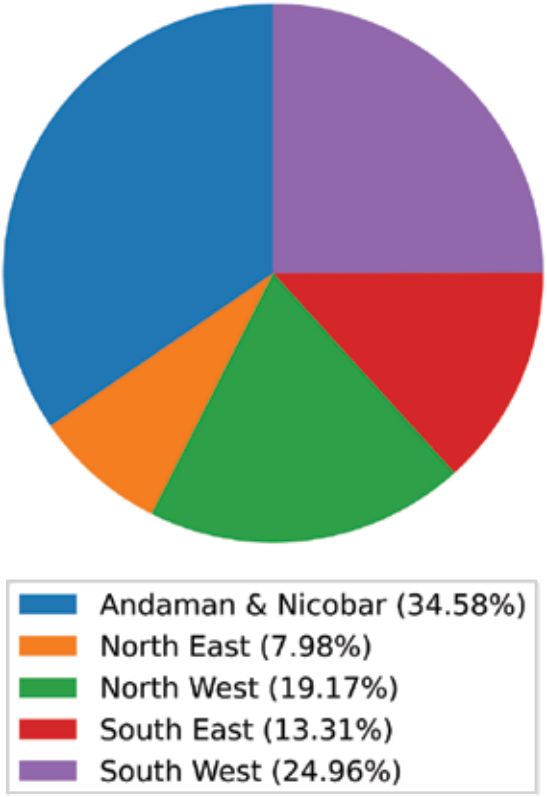


Figure 16: Percentage of annual integrated wave energy (>2 kW m^{-1} and <50 kW m^{-1}) available from five sectors.

Figure 16 shows the percentage share of available cumulative wave power density over an year across five sections in the Indian EEZ. While the Andaman & Nicobar Islands sector holds the maximum share of wave energy, along the Indian mainland, nearly 50% of the yearly cumulative wave energy comes from the combined North west and South west sector.

Figure 17 shows the annual wave power density as mean and cumulative along the Indian EEZ. It also has the representative plot of year-long availability marked by number of days where extractable energy inflow is present at a location in EEZ. In the Indian mainland, the north-western part of EEZ experiences the annual maximum, which is closely followed by the southern tip of India and north-eastern regions. In addition, the western off region of the Andaman and Nicobar Islands also experience the annual maximum. Figure 17 (c) shows the consistency of occurrences of wave power density (2–50 kW/m) along the Indian EEZ. Effective and economical means of energy harnessing requires a year-through flow of energy at the desired locations. Current technologies for Wave Energy Converters (WECs) are available maximum up to 150 meters of depth. Regions in the Indian EEZ like the southern tip of India, the north-eastern region of the mainland, the south-western region of Andaman & Nicobar Islands, and the north-western region of the mainland meet such requirements.

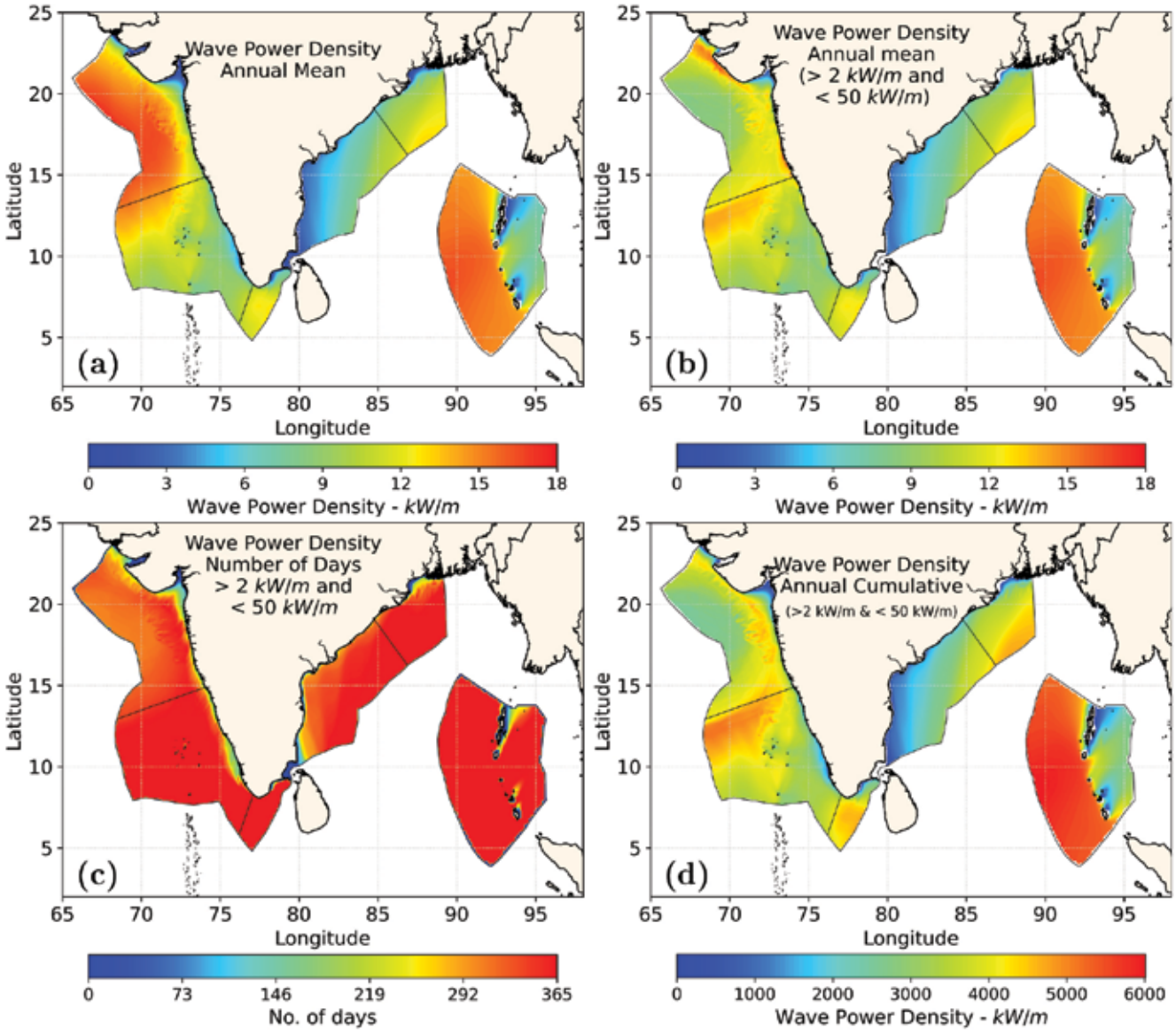


Figure 17: Estimated values of wave power density, P_{mod}, as annual mean (a), annual mean (>2 kW/m & < 50 kW/m) (b), annual consistency of P_{mod} in (> 2 kW/m & < 50 kW/m) (c), cumulative (d) along the Indian EEZ.

The unique, seasonally reversing monsoon system over the Indian Ocean adds considerable complexity to the region's wave dynamics, making it crucial to assess monthly wave power distribution across the entire Indian EEZ (as presented in Figure 18 and Figure 19). Given the significant seasonal variations in wave power density, a seasonal assessment provides the most valuable insights. The monthly mean of wave power along EEZ is grouped into the four boreal seasons namely, (i) winter (Dec., Jan., Feb.), (ii) spring (Mar., Apr., May), (iii) summer (Jun., Jul., Aug.), and fall (Sept., Oct., Nov.), and are presented in Figures 18 and 19. During fall, winter, and spring, the west coast of India experiences relatively low wave power density, typically below 20 kW/m across the region. However, from early May through late September, coinciding with the southwest monsoon, wave power density increases significantly, with levels exceeding 20 kW/m at most locations. Notably, during the summer peak, the northwest sector of EEZ has maximum wave power densities of up to 60 kW/m. Similar to the west coast, the east coast of India has low wave power density during fall, winter, and spring. In late spring, particularly in May, there is a noticeable increase in wave power density, with levels reaching 20–40 kW/m during the summer season. The region below the southern tip of the Indian mainland and the north-northeast sector stands out for receiving notably higher seasonal wave power densities. Specifically, the north-northwest sector, the southern tip of the Indian mainland, and the north-northeast sector are best suited for harnessing year-round wave power.

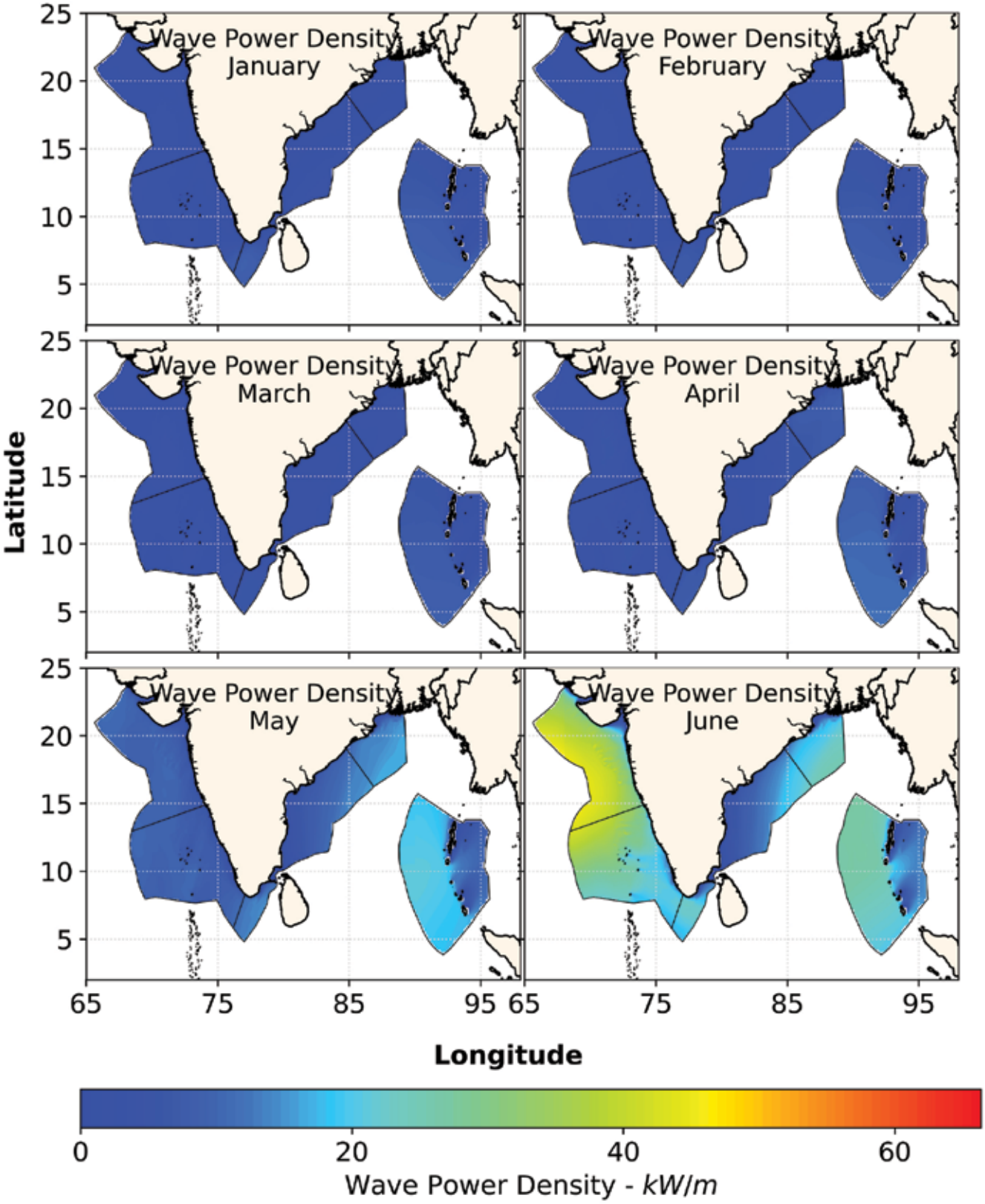


Figure 18: Monthly mean of wave power density along the Indian EEZ for the months of January – June.

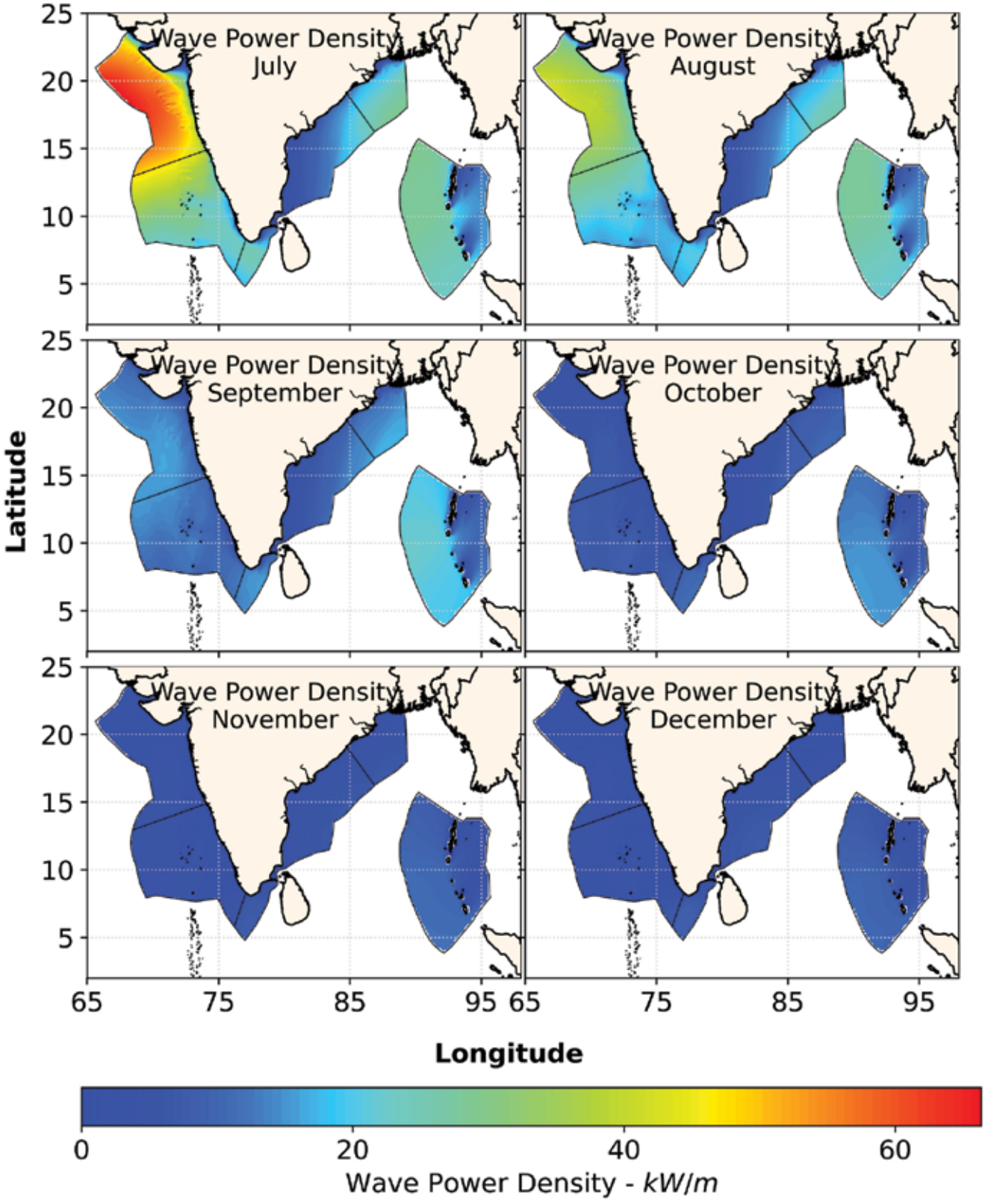


Figure 19: Monthly mean of wave power density along the Indian EEZ for the months of July – December.

One of the identified locations, the southern tip of the Indian mainland, follows our recommendation of year-long availability with high cumulative wave power density and has also been marked as a potential zone in many previous works such as [46]. Notably, it is the region where the Vizhinjam desalination plant (currently decommissioned) was powered solely by wave energy resources as a part of India's first-ever attempt to harness marine surface energy [44].

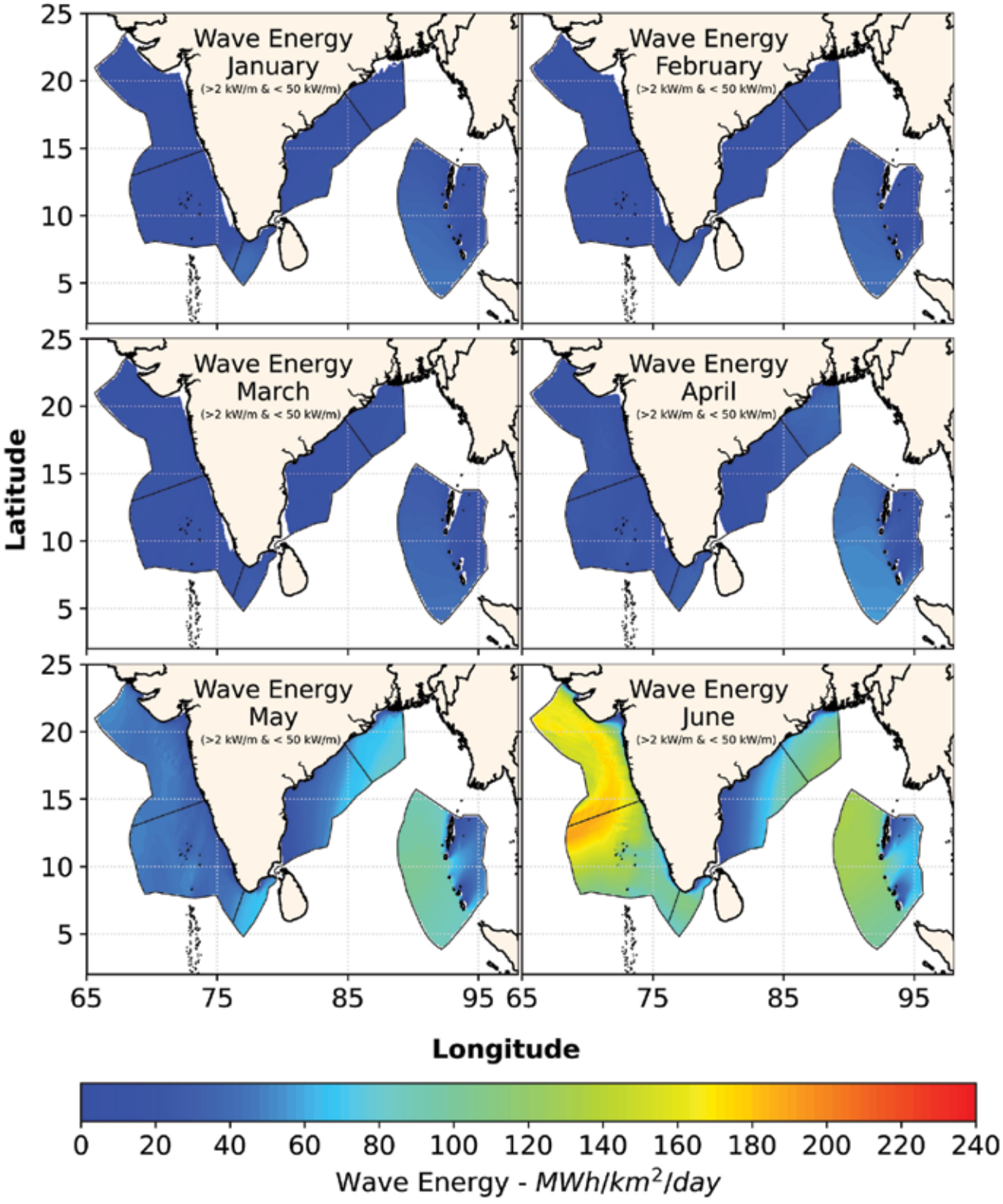


Figure 20: Monthly mean of wave energy along the Indian EEZ for the months of January – June.

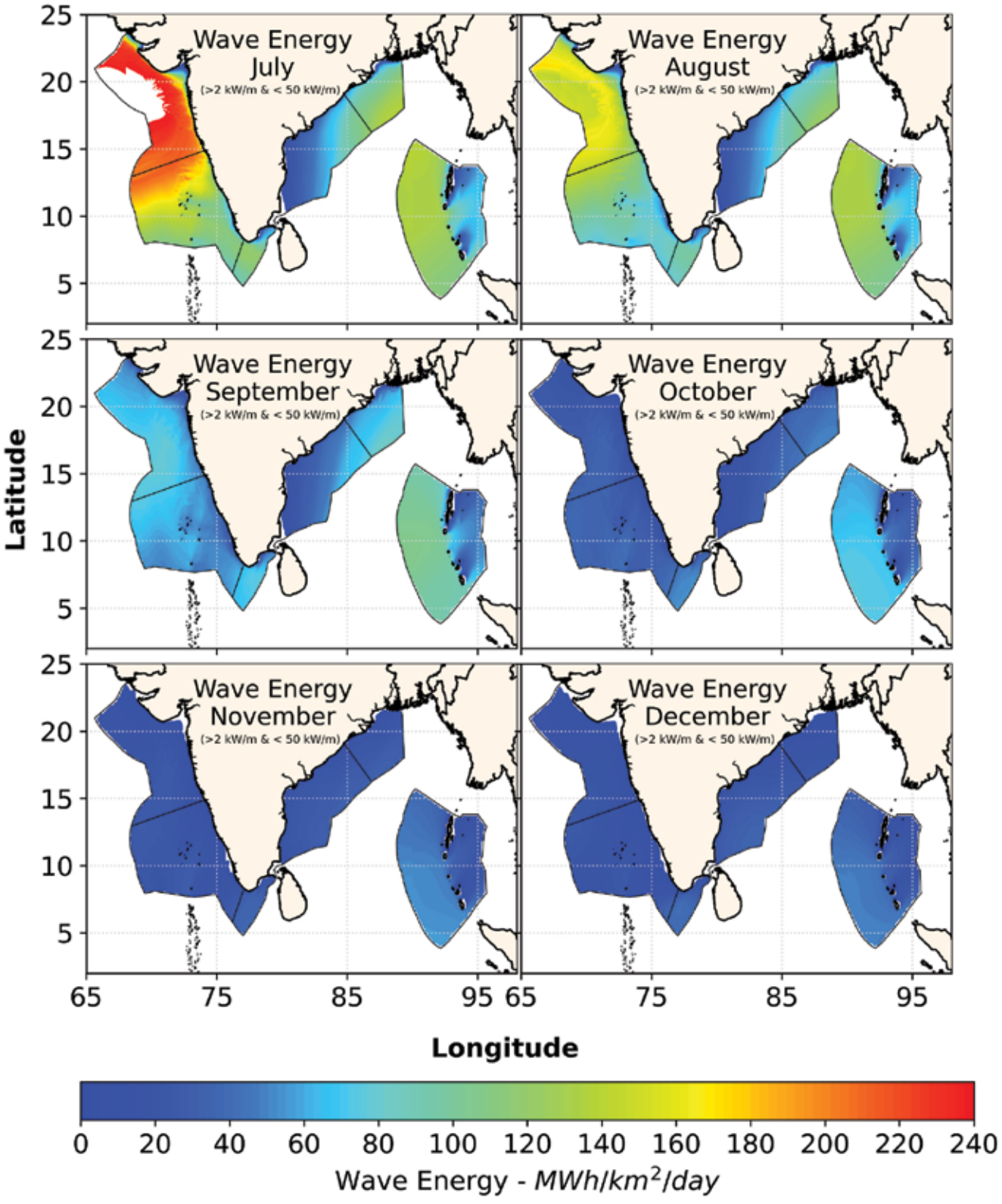


Figure 21: Monthly mean of wave energy along the Indian EEZ for the months of July – December.

5 Tidal Energy

Tides are generated due to the gravitational interaction of the sun, earth, and moon. The range between the high and low tides can sometimes range more than 12 m, creating significant potential energy. Tides can generate currents during flood and ebb phases, creating kinetic energy. Both these forms of energy can be harnessed using tidal energy technologies as renewable energy. Over the past several years, tidal energy extraction has gained prominence globally as a sustainable renewable energy source. However, global tidal energy extraction is yet evolving, with various countries actively contributing to the expansion of this renewable energy source. As technology advances and more projects come forward, tidal energy is expected to play a crucial role in the global energy mix.

Tidal energy extraction is a growing sector with several major players contributing to the global renewable energy landscape. The United Kingdom is a pioneer in tidal energy projects, with a substantial 10 gigawatts (GW) capacity.

Tidal range– refers to the vertical difference between high and low tide. Tidal range electricity generation methods primarily involve using tidal barrages and tidal lagoons.

Tidal current– refers to the horizontal movement of water. Tidal electricity generation methods include tidal stream systems and tidal turbines.

Tidal-range and tidal-current technologies contribute to diversifying marine renewable energy sources and can play a crucial role in achieving a cleaner and more sustainable energy future.

Though there has been increased interest in tidal energy exploitation over the past few decades, the tidal energy resources along the Indian coast are largely unexplored and exploited. The Gulf of Kutch, Gulf of Khambhat and in the northeastern Arabian Sea, the Northern part of the Bay of Bengal and Andaman coast show relatively large mean tidal ranges (4 m to 6 m), and so could be potential sites for tidal range and stream Energy exploitation.

There are two forms of tidal energy. Firstly, tidal-stream Energy exploits the kinetic energy of tidal currents that can convert the stream velocity of the currents into rotational torque. Secondly, the tidal range approach uses the potential energy from the water-level differences between two bodies of water over the rise and fall of the tide to create a sizeable water-level difference (Inter-tidal height) by which direct flow through turbines.

The present work aims to generate a monthly tidal Energy Atlas for Potential energy to estimate how much energy can be harnessed from the tides along the Indian coast.

5.1 Data and Methods

For the computation of tidal energy potential, tide heights and tide-induced currents have been calculated based on global tide constituents from the MIKE-21 model (12.5 km resolution) (M2, S2, K1, O1, N2, P1, K2 and Q1) of height and current to calculate Tidal energy at an hourly time scale for the entire Indian coast.

Computation:

The tidal height is calculated using [33] :

$$H_{tide} = \sum_{n=1}^{n} H_{ai} cos(\omega_i t + \psi_i)$$

where,
H_{tide} is the tidal height, H_{ai} and ψ are amplitude and phase of i^{th} harmonic frequency corresponding to ω_i

$Current\ Speed = \sqrt{u^2 + v^2}$

$Potential\ Energy(PE)[47] = \frac{1}{2}\rho g A R^2$

$Tidal\ Power\ (MW) = \frac{2\times\rho A g R^2}{8.92\times10^4} \times 10^{-6}$ where,
u and v are zonal and meridional components of tidal current, V is the current speed (ms^{-1}), ρ is the density of sea water, A is the area in m^2, g is the gravity and R is the tidal range.

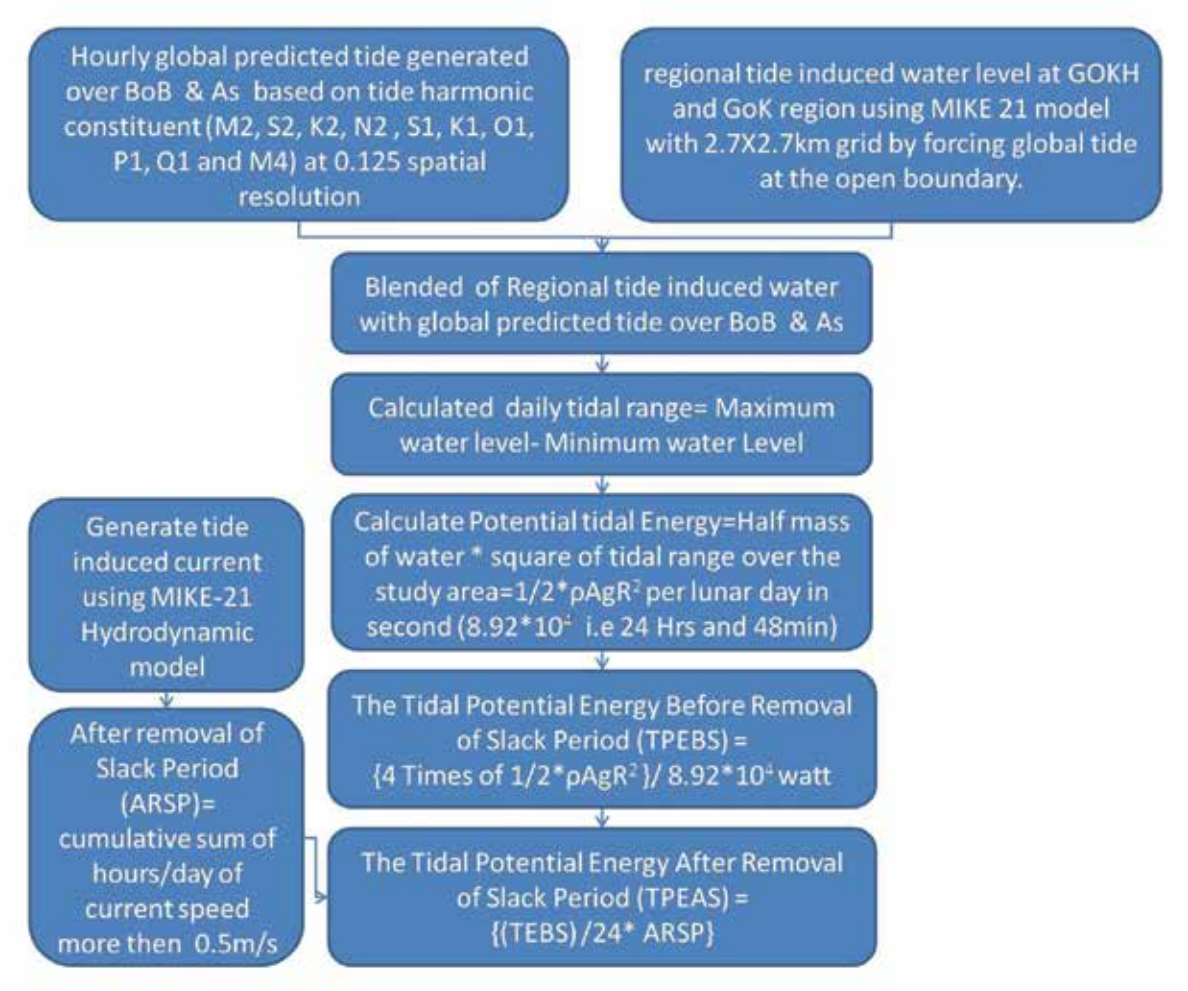


Figure 22: Methodology adopted for calculation of tidal potential energy.

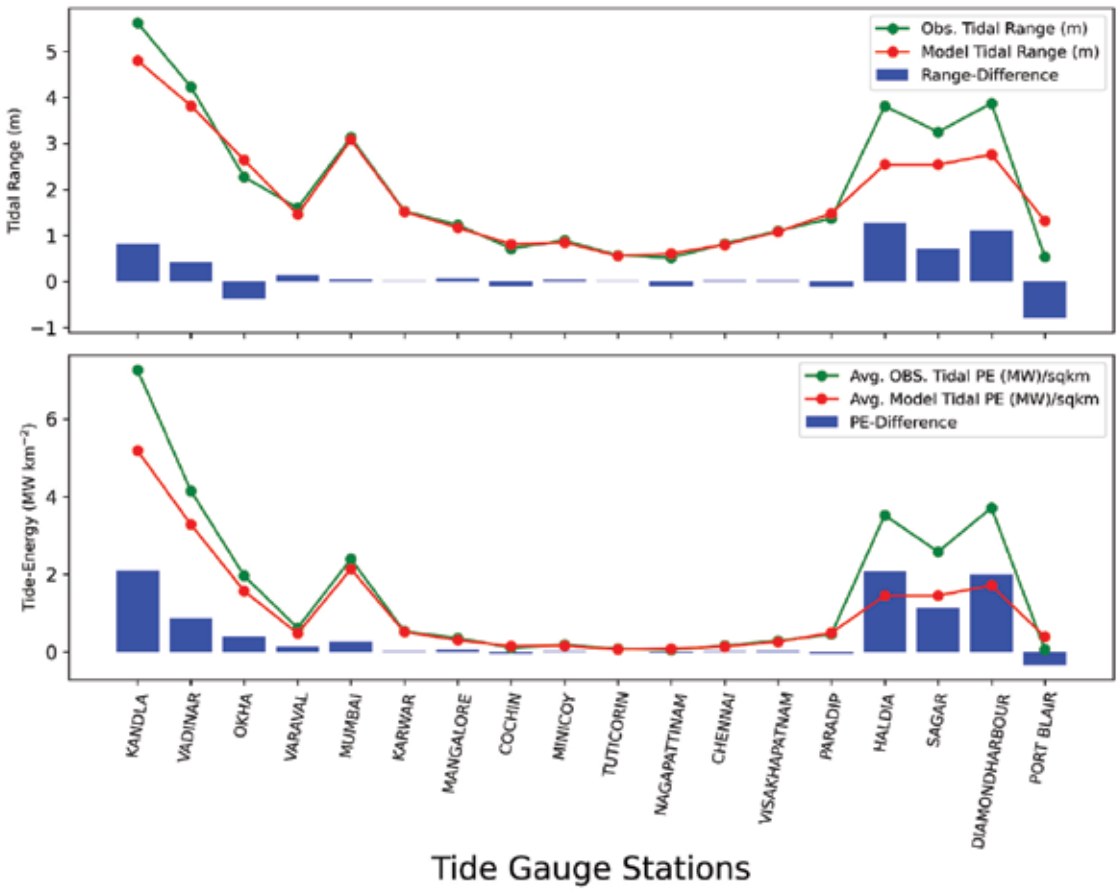


Figure 23: Comparison of simulated tidal ranges and potential energy against observed quantities and differences.

For the Gulf of Khambhat and Kutch (19^{0}N to 23.5^{0}N and 68^{0}E to 73.5^{0}E), we have set up MIKE-21 flow model with ≈2.5 km resolution with boundary forcing from global constituents as the low-resolution global model is not adequate to represent the tidal patterns within the Gulf. Tide-induced currents and tidal heights have been generated from the high-resolution model for the Gulf region and merged with the rest of the coast. These time series data have been used to extract the monthly tide potential energy averages. Further, frequencies of different ranges of energy levels have been estimated to identify the optimum potential of tide energy harnessing zones along the Indian coastal regions.

We have validated the tidal model using data available from tide-gauge stations along the Indian coast in terms of tidal ranges and potential energy (Figure 23). The comparison shows relatively higher differences for northern stations along India's east and west coasts, where the tidal ranges are high.

5.2 Results

From the Indian coastline, the Gulf of Kutch, Gulf of Khambhat, West Bengal coast and Andaman regions showed high potential for tidal energy with a range of ≈20 to 170 MWh km^{-2} during the study period. As tidal cycles are very regular, there is no significant variation among different months. We have estimated annual tidal range energy (Figure 24(a)) and subsequently removed slack period (when the tidal currents are less than 0.5 m/s) (Figure 24(b)) for the entire coastline of India. We have also estimated annual cumulative tidal energy after the removal of the slack period and presented in Figure 24(c). It is evident from the maps that the tidal energy is prominent along the Gujarat coast and, the Hooghly River in the northern parts of the Bay of Bengal. We have also estimated tidal energy for each month before and after slack period removal and presented in Figures 26 to 29.

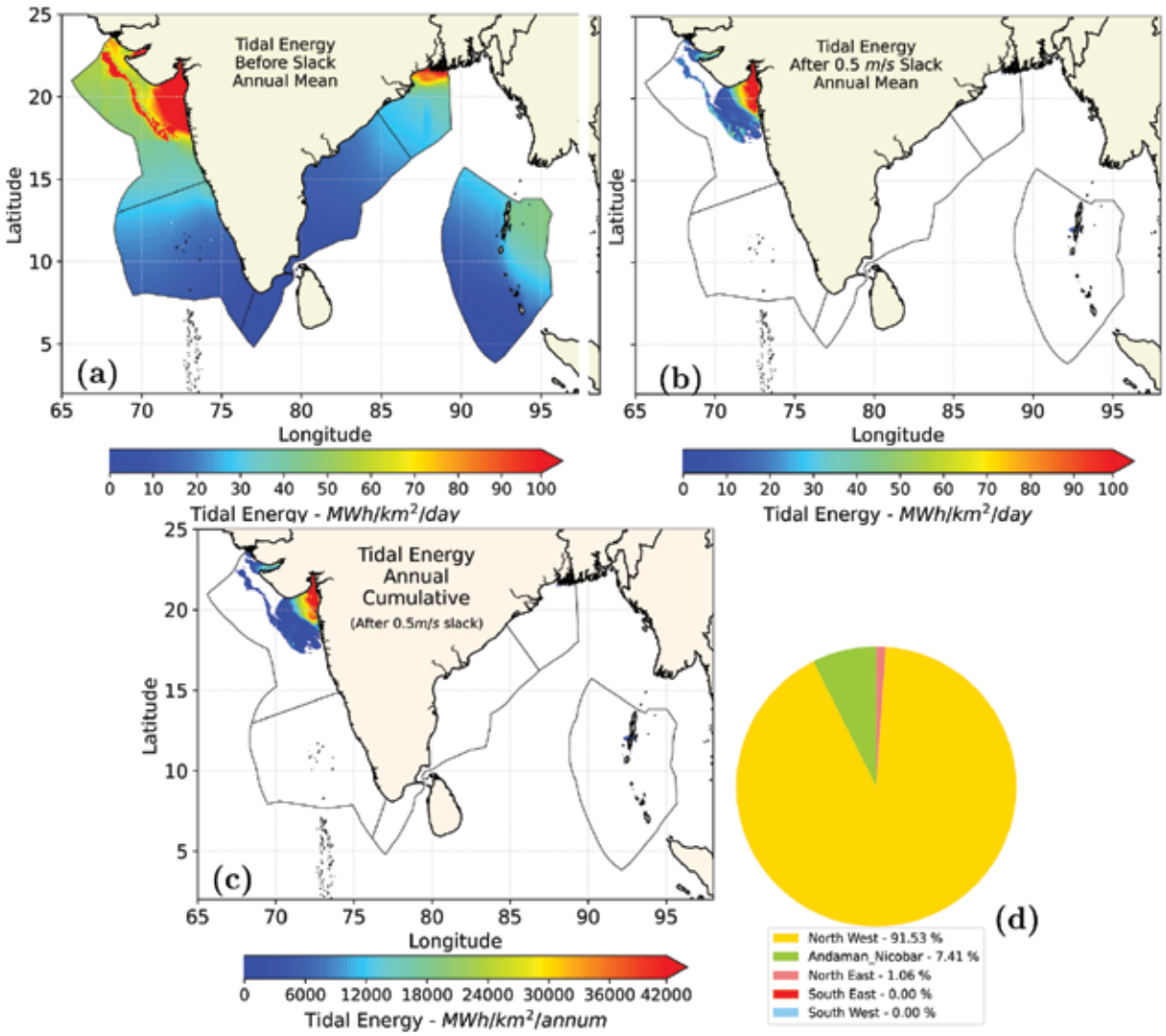


Figure 24: Estimated annual mean tidal energy before slack period removal (a), After slack period removal (b) Cumulative after slack period removal (c), from the Indian EEZ (c), Percentage of tidal energy available from different sectors (d).

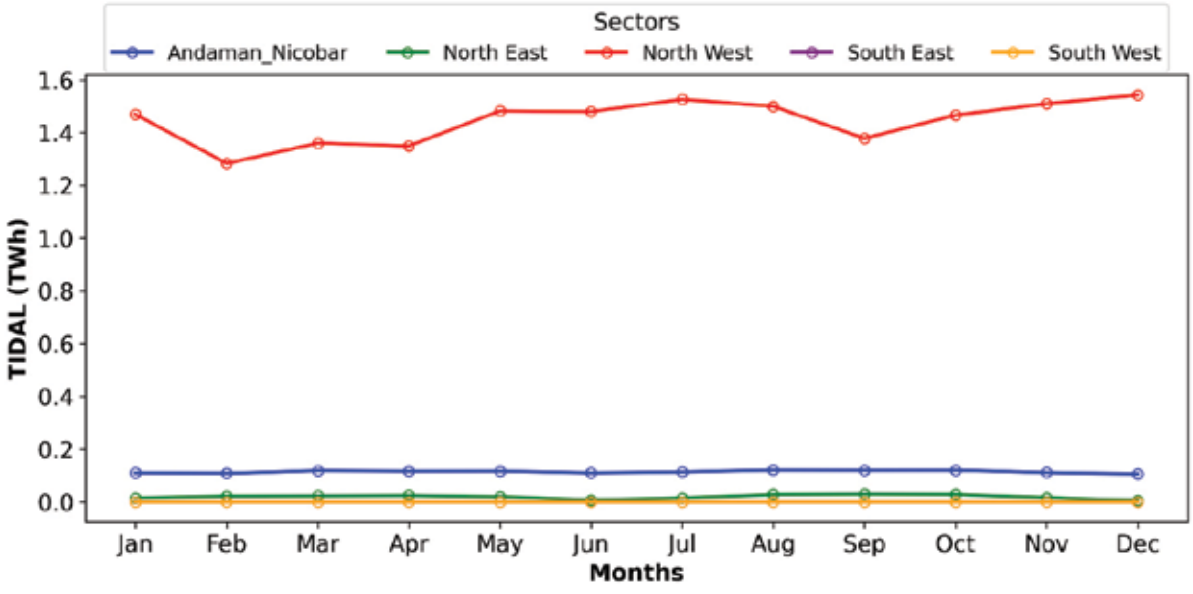


Figure 25: Monthly mean tidal energy from five sectors identified from Indian EEZ.

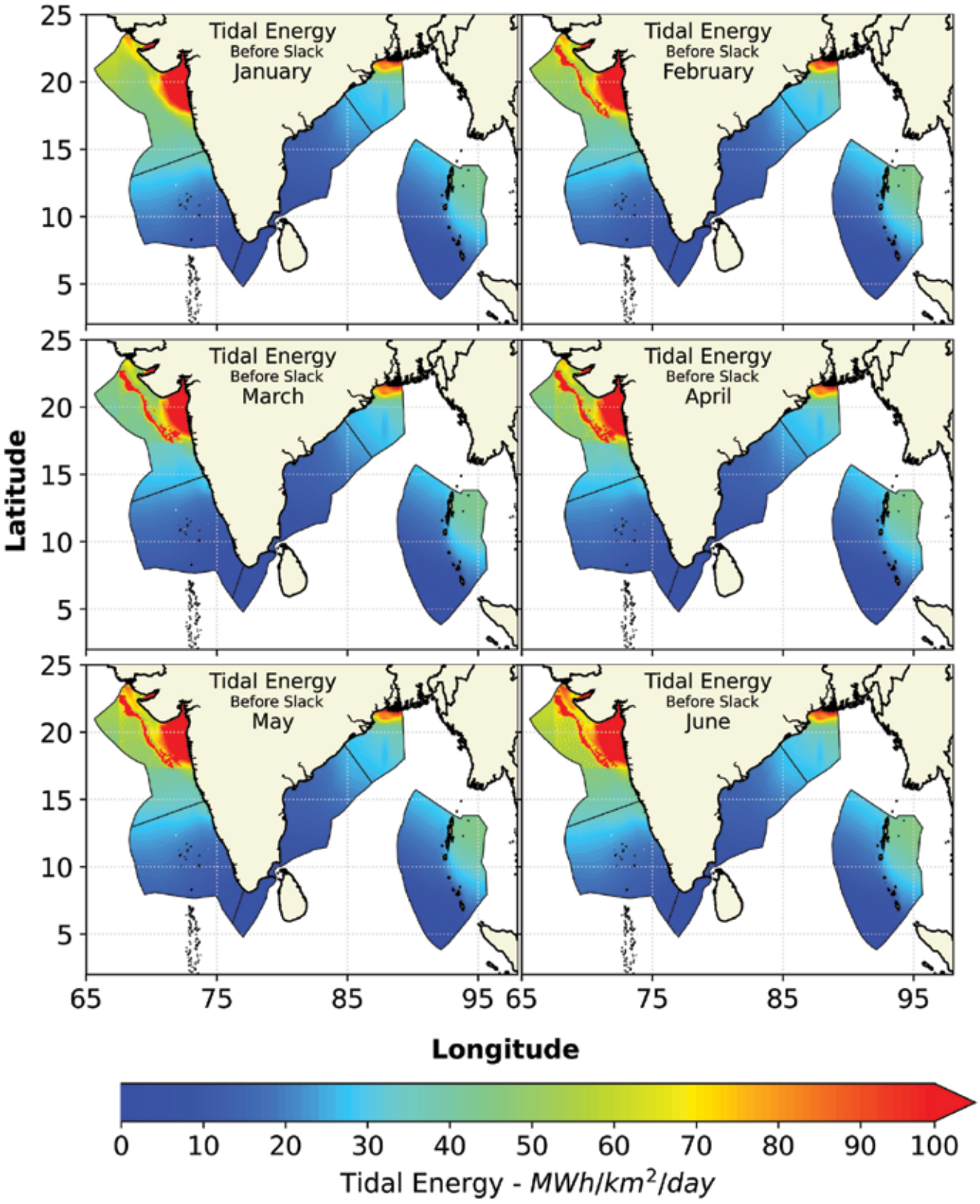


Figure 26: Estimated monthly mean tidal energy before slack period removal from the Indian EEZ (January – June).

Figures 25 to 27 show that maximum energy exists in Northwest sector followed by Andaman Nicobar and observed low tidal energy after slack period removal in other sectors. There is very less seasonality for tidal energy in all sectors.

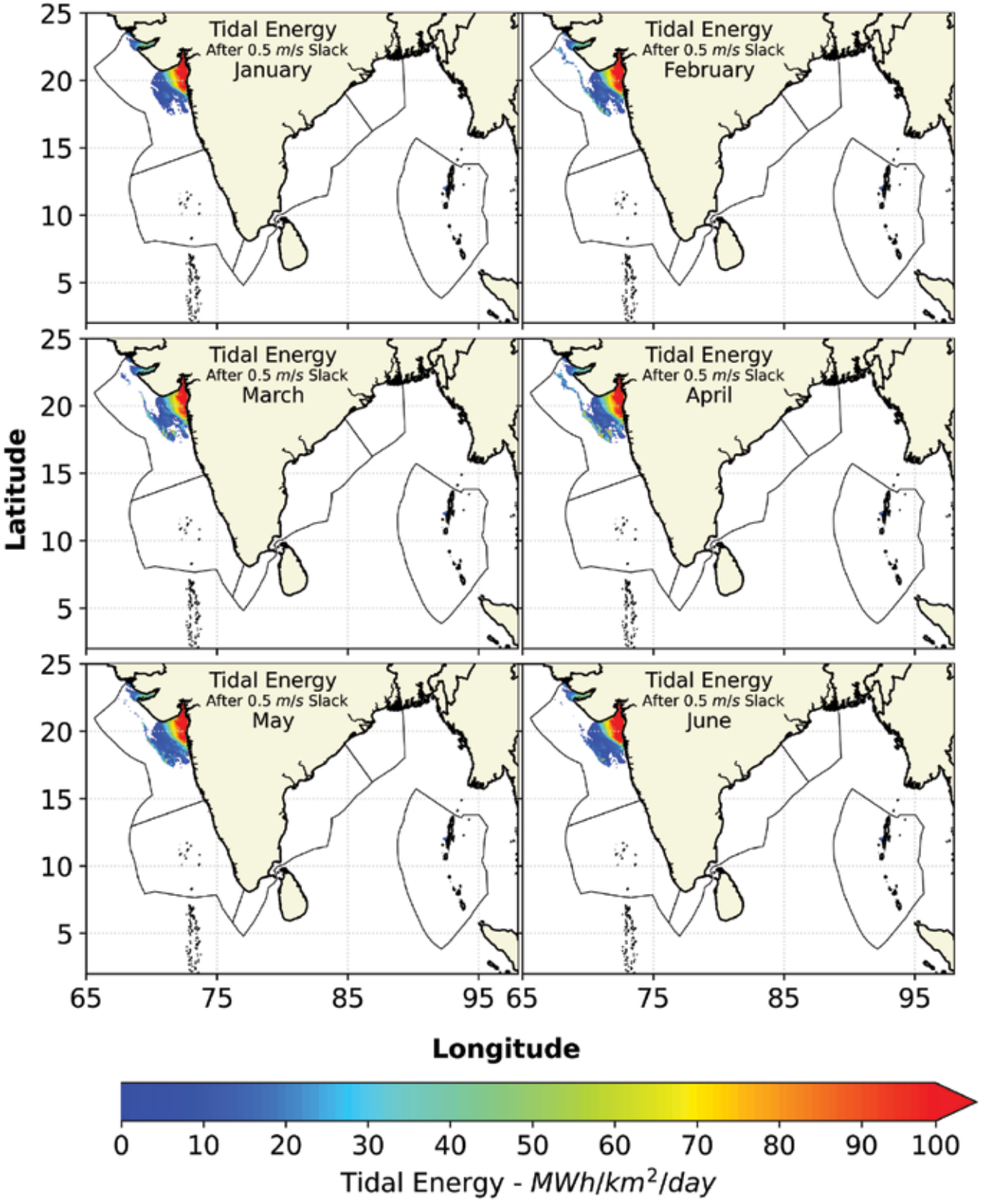


Figure 27: Estimated monthly mean tidal energy after slack period removal from the Indian EEZ (January – June).

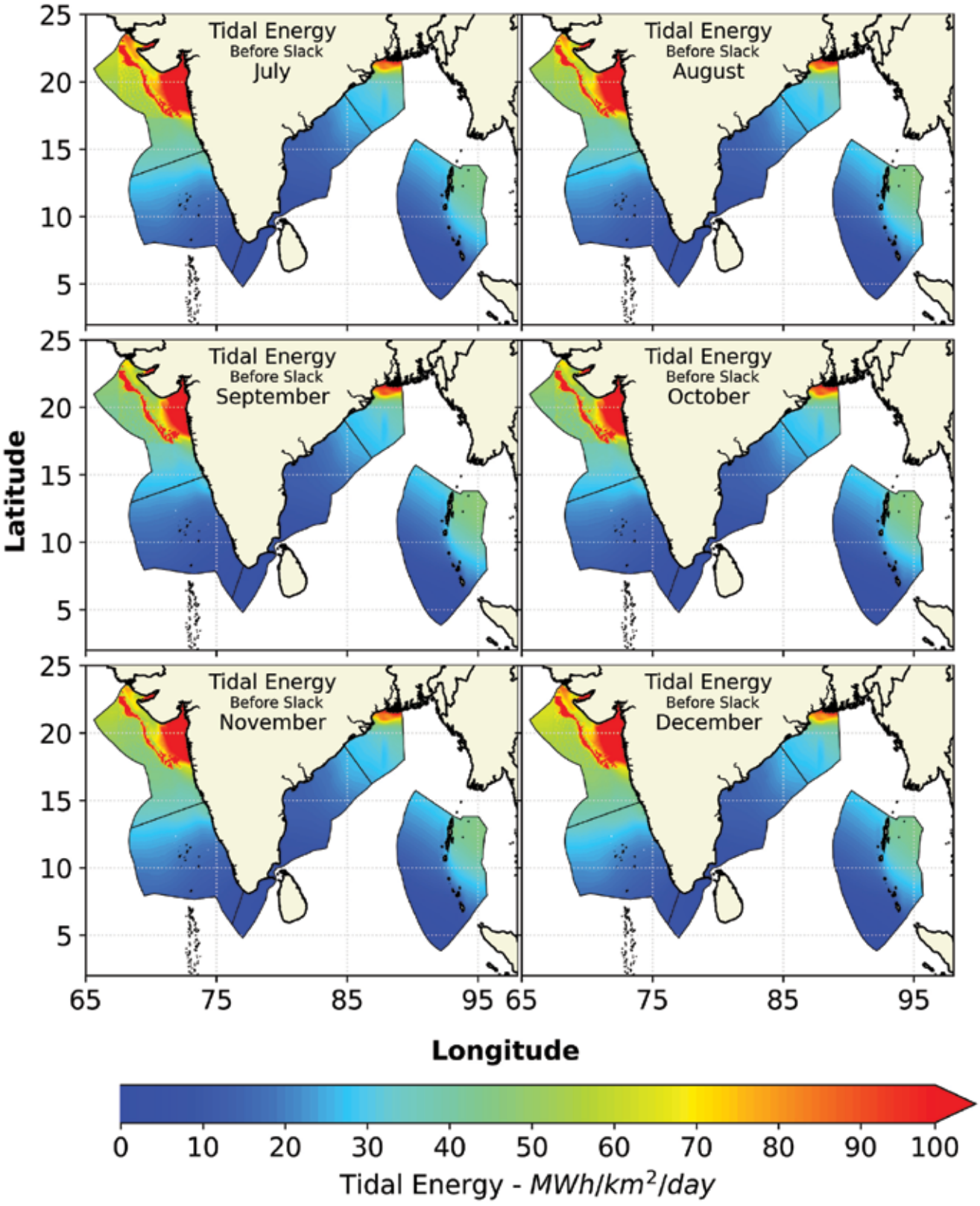


Figure 28: Estimated monthly mean tidal energy before slack period removal from the Indian EEZ (July – December).

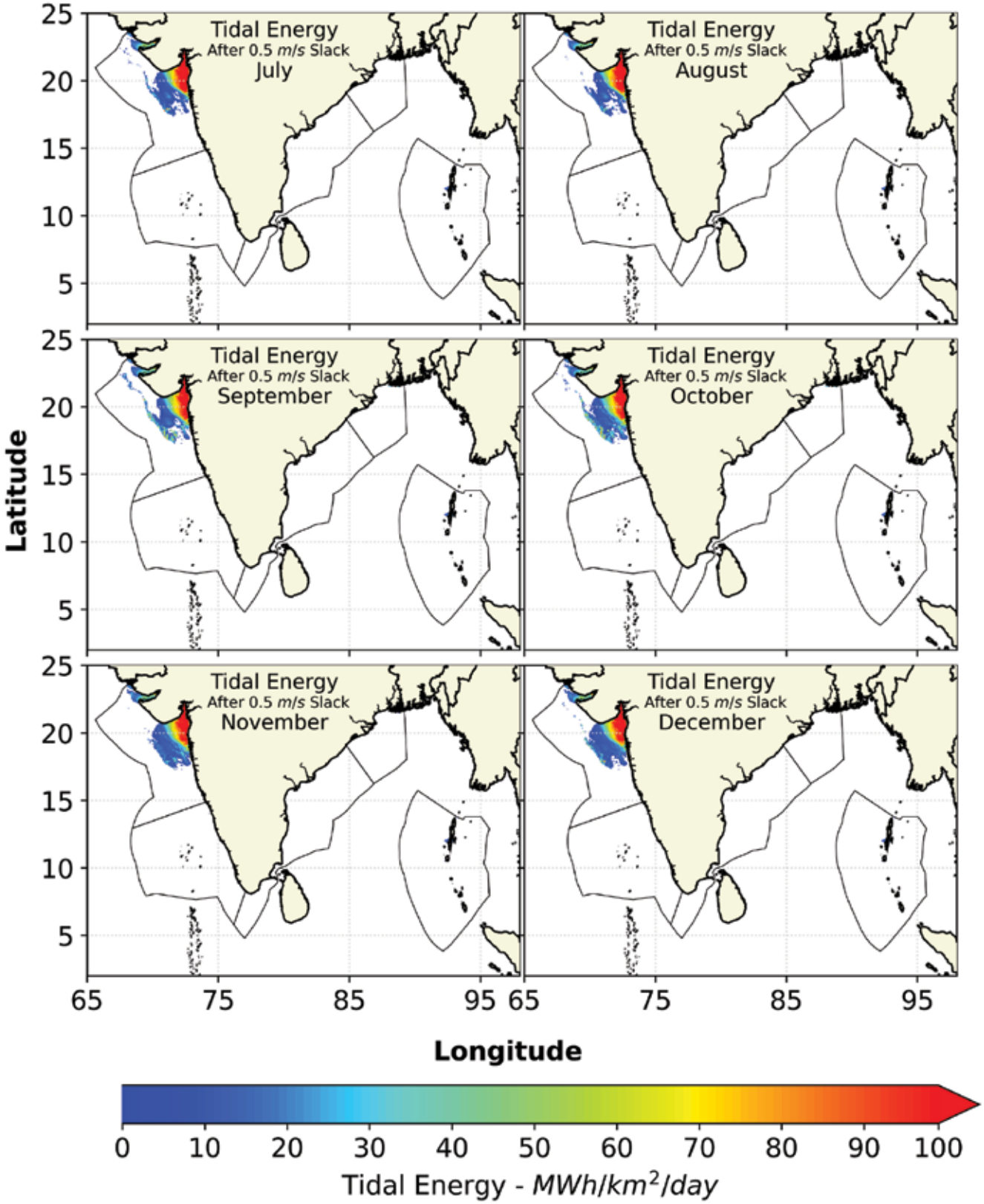


Figure 29: Estimated monthly mean tidal energy after slack period removal from the Indian EEZ (July – December).

6 Ocean Thermal Gradient Energy

Efforts to develop Ocean Thermal Gradient Energy technology started in the 1880s. In 1881, a French scientist, Jacques Arsene d'Arsonval, conceptualized tapping of the thermal gradient energy from the ocean. Later, in 1930, a student of d'Arsonval, Georges Claude, developed the first OTEC plant. Ocean Thermal Energy Conversion (OTEC) exploits the difference between cooler deep and warmer shallow or surface ocean waters to run a heat engine and produce useful work, usually in the form of electricity [13]. In tropical oceans, the thermal gradients between the surface to 1000 m depth with a gradient ≥ 20°C. The main technical challenge of OTEC is to generate significant amounts of power efficiently from slight temperature differences. It is still considered as an emerging technology.

Ocean thermal gradient energy holds the potential for sustainable electricity production, with various countries exploring this renewable resource. The global estimated potential of OTEC is one of the major ocean energy sources at 44,000 TWh per year [36]. Japan leads in utilizing ocean thermal energy conversion (OTEC) and contributes significantly to the global electricity production from ocean thermal gradients [6,28]. Plants rated at 100 kW have been successful in the Nauru island of Japan. The Republic of Korea recently developed a 1 MW plant in Kiribati in the Pacific Ocean. It is the largest and demonstrates OTEC's high potential in island applications. Island locations enable the use of the water flows for purposes other than energy generation, such as desalination, aquaculture and cooling. Top ten nations in the globe with access to thermal energy resources with their exclusive economic zones within 200 nautical miles include the United States, Indonesia, Brazil, Papua New Guinea, Japan, Philippines, Maldives, Madagascar, India and Mexico [30]. The United States actively engages in OTEC research and has an estimated potential of 4,100 TWh/yr from ocean thermal gradients [30]. Other countries, including India, the Maldives, and South Korea, are also making strides in harnessing ocean thermal energy [14,45,40]. These endeavours collectively highlight the increasing global interest and potential for ocean thermal gradient energy to diversify the renewable energy portfolio.

The most commonly used heat cycle for OTEC is the Rankine cycle, which uses a low-pressure turbine. Systems may be either closed-cycle or open-cycle. Closed-cycle engines use working fluids that are typically thought of as refrigerants, such as Ammonia or R-134a. Open-cycle engines use vapour from the seawater itself as the working fluid [42].

6.1 Data and Methods

We have used simulated temperature from INCOIS-HYCOM available at $\frac{1}{16}^{\circ} (\approx 7\ km)$. The average temperature from the top 20 meters and its difference from the temperature at 1000 meters is considered for computational purposes. We have considered the mass flow rate of deep seawater into the condenser of the power plant such that it can be replenished from the cold water brought in at deep sea by the abyssal circulation. The surface water is taken proportionally. The temperature between these is divided across the power plant based on the temperature ladder as suggested in [36].

Energy is then estimated based on the thermodynamic calculations of the Rankine Cycle, which runs on Ammonia as the working fluid. By default, losses for running the power plant, such as pumping losses, frictional losses, etc., are assumed to be at 40% of the estimated power production. The potential from Ocean Thermal Energy thus obtained is converted and presented in [MWh km^{-2} day^{-1}].

Computation:

Efficiency of Pump:

$$\eta_{pump} = \frac{v_{avg}(p_{exit} - p_{entry})}{h_{pump_{exit\ actual}} - h_{pump_{entry}}} = \frac{Isentropic\ pump\ work}{Actual\ pump\ work}$$

Efficiency of Turbine:

$$\eta_{turbine} = \frac{h_{turb_{entry}} - h_{turb_{exit\ actual}}}{h_{turb_{entry}} - h_{turb_{exit\ isentropic}}} = \frac{Actual\ turbine\ work}{Isentropic\ turbine\ work}$$

Entropy Change:

$$s_{after} - s_{before} = c_{p_{avg}} \ln \frac{T_{after}}{T_{before}}$$

$$Rankine\ Efficiency = \frac{W_{out_{net}}}{E_{in_{evaporator}}}$$

$$Carnot\ Efficiency = 1 - \frac{T_{L_{@1000m}}}{T_{H_{@avg20m}}}$$

where:

$W_{out_{net}}$: Net Work Output from Turbine (MW)
$E_{in_{evaporator}}$: Heat Added in Evaporator (MW)
T : Temperature (K)
p : Pressure (kPa)
v : Specific volume (m^3/kg)
h : Enthalpy (kJ/kg)
s : Entropy $(kJ/kg\ K)$
$c_{p_{avg}}$: Specific heat at const. pressure $(kJ/kg\ K)$

The Rankine cycle is the practical thermodynamic cycle on which the OTEC power plant works. Ammonia has been used as the working fluid for the OTEC power plant.

Assumptions made for the estimates:

Specific Heat of Sea Water $\Longrightarrow$ $c_p$sea water = 3.993 kJ kgK

Loss of pressure between evaporator exit and turbine entry $p_{loss} = 10kPa$

Turbine Efficiency $\Longrightarrow \eta_{turb} = 0.87 \approx 87\%$

Pump Efficiency $\Longrightarrow \eta_{pump} = 0.75 \approx 75\%$

Generator Efficiency $\Longrightarrow \eta_{generator} = 0.975 \approx 97.5\%$

6.2 Results

We have estimated annual (Figure 30(a)) and monthly means (Figures 32 and 33) of thermal gradient energy from the Indian EEZ and also deduced the number of days in an year when thermal gradient energy is extractable using present technology (Figure 30(c)) along with cumulative energy available for an year (Figure 30(b)). We have also computed spatial means of thermal gradient energy available from Indian EEZ under five different sectors, namely, Andaman Nicobar, Southwest, Southeast, Northwest and Northeast, in the decreasing order of thermal gradient energy (Figure 30(d)). Thermal gradient energy shows a minor seasonal bi-model distribution with a first peak from March to June and a second peak from September to November as evident from Figures 31 to 33.

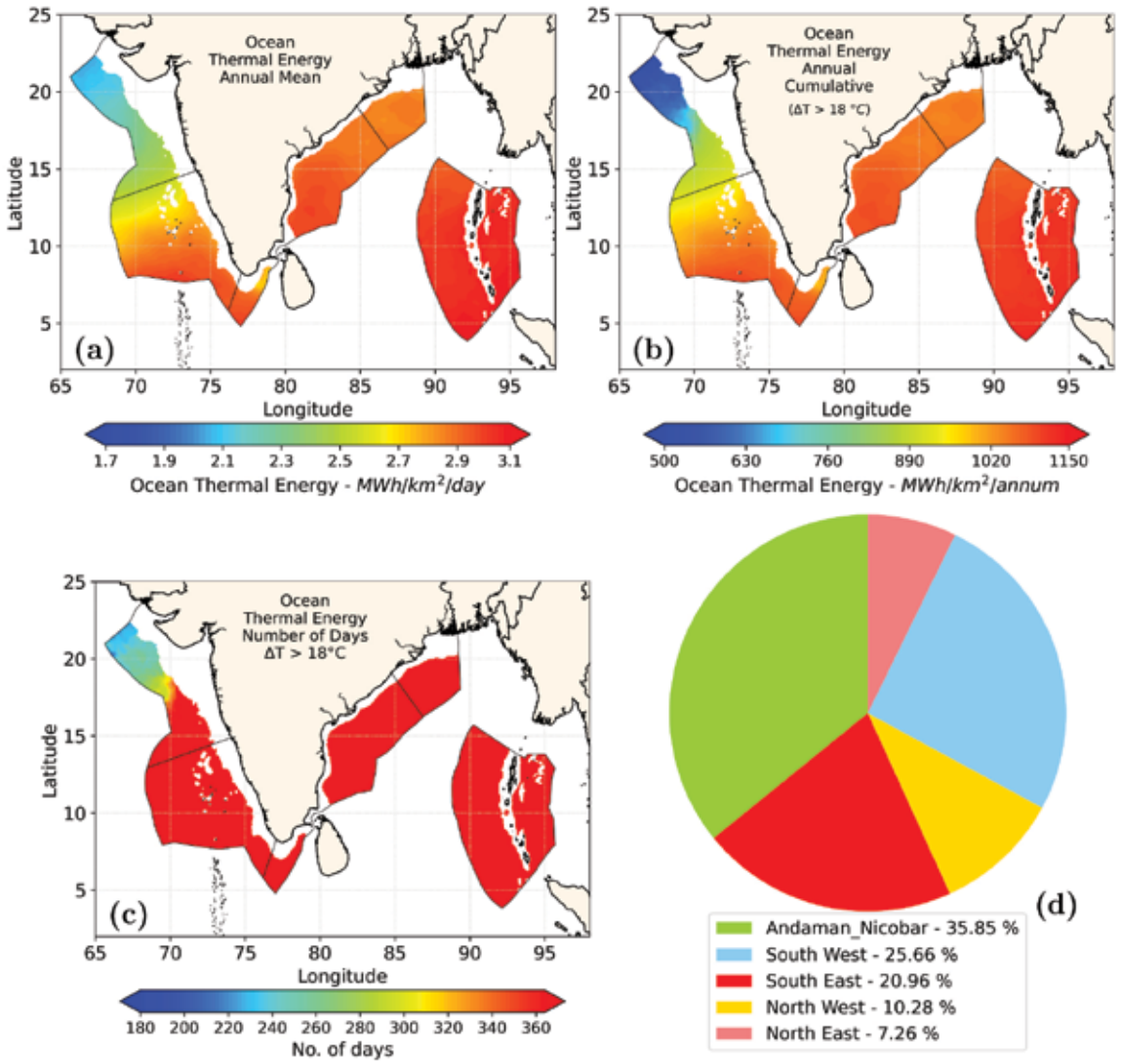


Figure 30: Estimated annual mean (a), Cumulative > 18^{0}C (b), Number of days above > 18^{0}C ocean thermal gradient energy from the Indian EEZ (c), Percentage of thermal gradient energy available from different sectors (d).

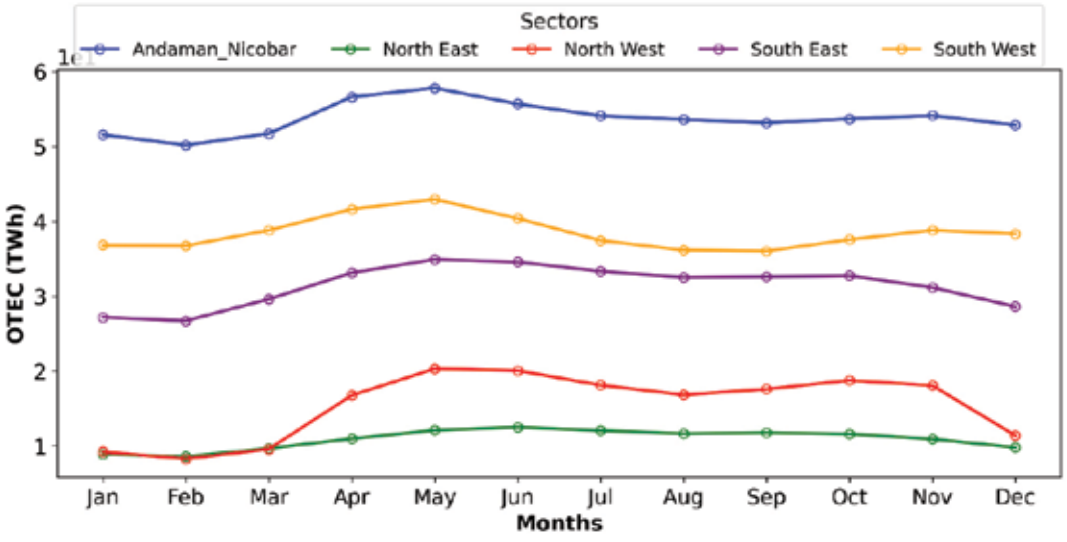


Figure 31: Monthly mean thermal gradient energy from five sectors identified from Indian EEZ.

As evident from Figures 31 to 33, ocean thermal gradient energy shows relatively lower seasonality compared to other energy forms, except for small amplification in April-May across sectors, and is minimum in the Northeast sector.

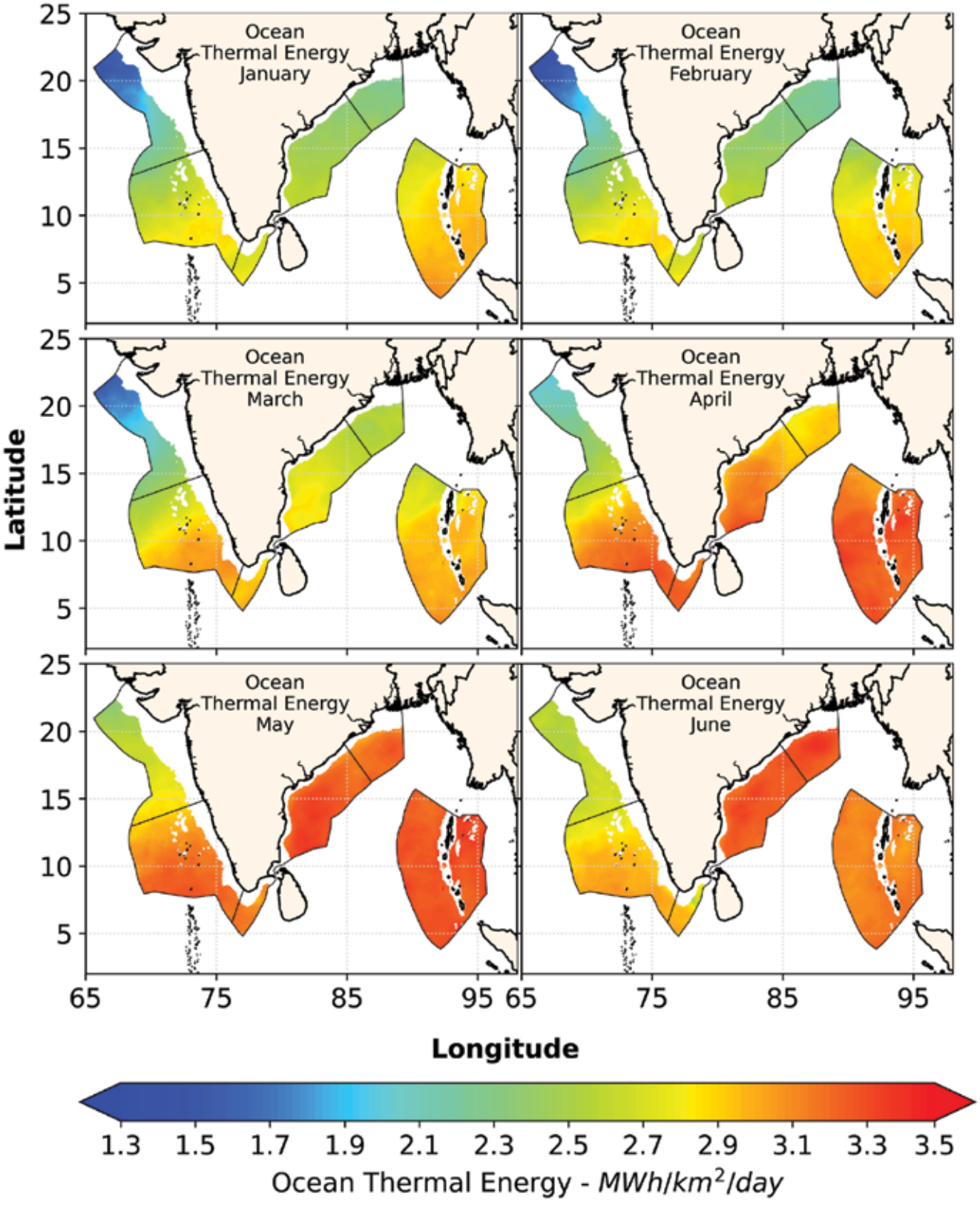


Figure 32: Estimated monthly mean ocean thermal gradient energy from the Indian EEZ (January – June).

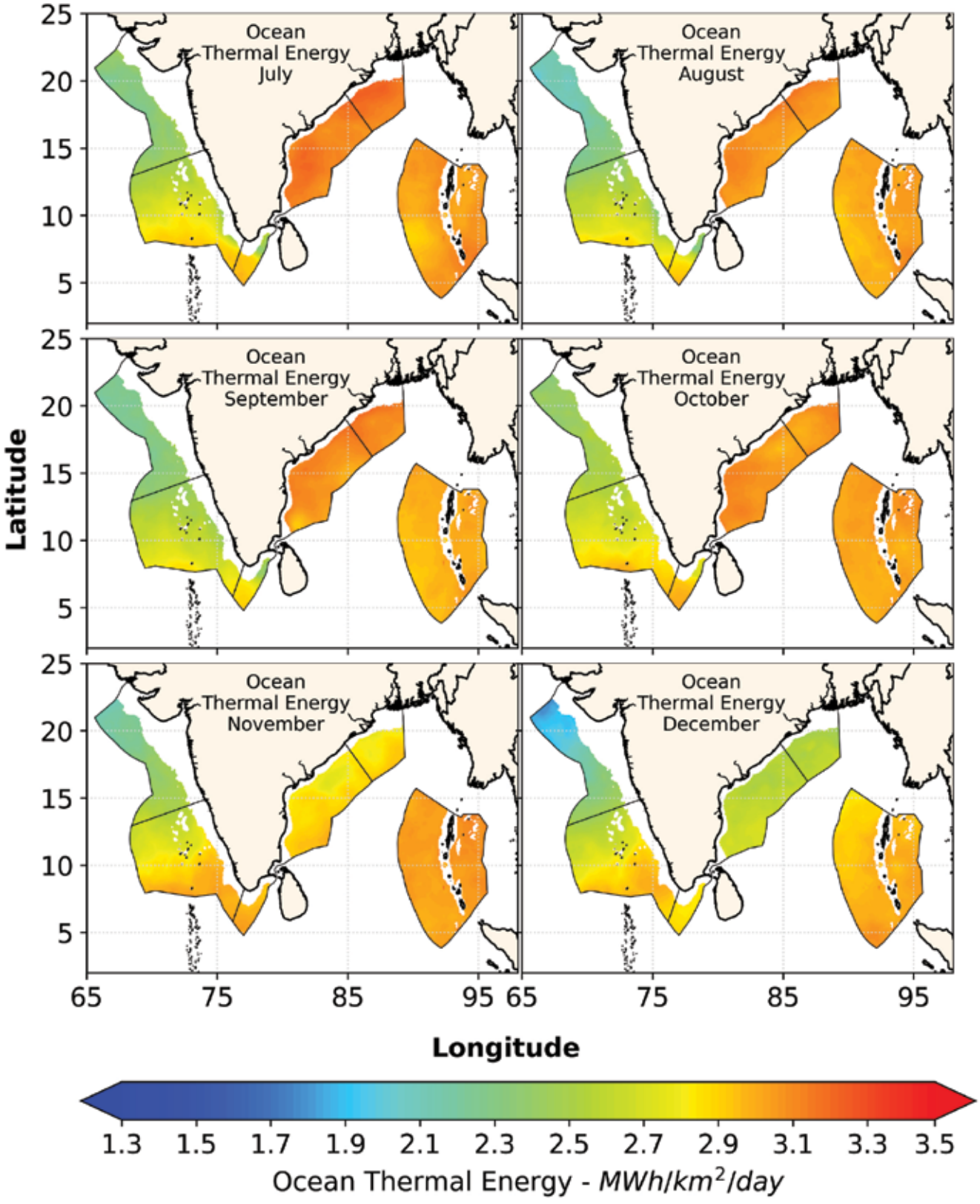


Figure 33: Estimated monthly mean thermal gradient energy from the Indian EEZ (July – December).

7 Salinity Gradient Energy

The first research on assessing the world's Salinity Gradient energy (SGE) resources near river mouths in the 1970s predicted that between 1.4 and 2.6 TW of theoretical SGE energy might be generated worldwide [25,49]. The theoretical potential has been measured in more recent studies to 0.23 TW [54], 3.13 TW [50], or 1.724 TW [26] (15,102 TWh/a, or 74% of the world's electricity consumption in 2011); only the most recent assessment took into account ocean salinity close to river mouths (from the World Ocean Database 2005), rather than global average values. Estimations of SGE resources on a regional and local scale have been made for Norway [27], the United States [22,37], China [17], Colombia [2], Australia [21], and the Canadian province of Quebec [5]. Salinity gradient energy has the potential to provide a sustainable and reliable source of electricity, contributing to the global shift towards clean and renewable energy sources [1]. The well-known techniques to generate energy from SGP are Pressure Retarded Osmosis (PRO) and Reversed Electrodialysis (RED). RED is the most common and efficient method. In a RED system, ion exchange membranes are arranged in a stack selectively permeable to ions while blocking others [12]. The pilot plant of SGP in the Netherlands are based on RED.

7.1 Data and Methods

For estimating SGP, we have used freshwater flow volume calculated from monthly river runoff data. For saltwater concentration, we used a model simulated salinity and validated using satellite-derived salinity for the north Indian Ocean. A theoretical mixing value of low and high-saline waters is computed initially to estimate the energy efficiency of the RED method. Gibbs free energy of mixing ΔG_{RED} for a pure monovalent salt and low concentration solution is calculated following [15,16].

The potential power generation from the salinity gradient can be estimated using the equation:

$$P = 2RT[\Phi_L C_L \ln \tfrac{C_L}{C_M} + \Phi_H C_H \ln \tfrac{C_H}{C_M}]$$

where:

$Power$: Theoretical Power from Salinity Gradient

R : Gas Constant $(Jmol^{-1}K^{-1})$

T : Temperature (K)

Φ_L^* : Discharge of River Water $(m^3\, s^{-1})$

Φ_L : $0.3\, \Phi_L^*$ (Tennant's method [52] for environmental flow)

C_L : Concentration of River Water $(mol\, m^{-3})$

Φ_H : Discharge taken from Sea Water $(m^3\, s^{-1})$

C_H : Concentration of Sea Water $(mol\, m^{-3})$

C_M : Concentration at Equilibrium after total mixing $(mol\, m^{-3})$

with

$C_M = \frac{\Phi_L C_L + \Phi_H C_H}{\Phi_L + \Phi_H}$

Assumptions made in the analysis:

Theoretical amount of energy extraction is equivalent to the difference of the Gibbs Free energy before and after mixing.

- Tennant's Method of 30% of river discharge for environment-friendly flow.
- Concentration of fresh water is assumed to be 0.13*PSU*.
- Major component of sea salts and river salts is taken as *NaCl*, (molar mass = $58.44\, \frac{kg}{kmol}$).

- Ratio of freshwater to seawater (in volume) for mixing is kept at 1:1
- Temperature of seawater and river water is the same at the river mouth.

We have used monthly river runoff from [11]. We have also used salinity data from global HYCOM and SMAP data for verification.

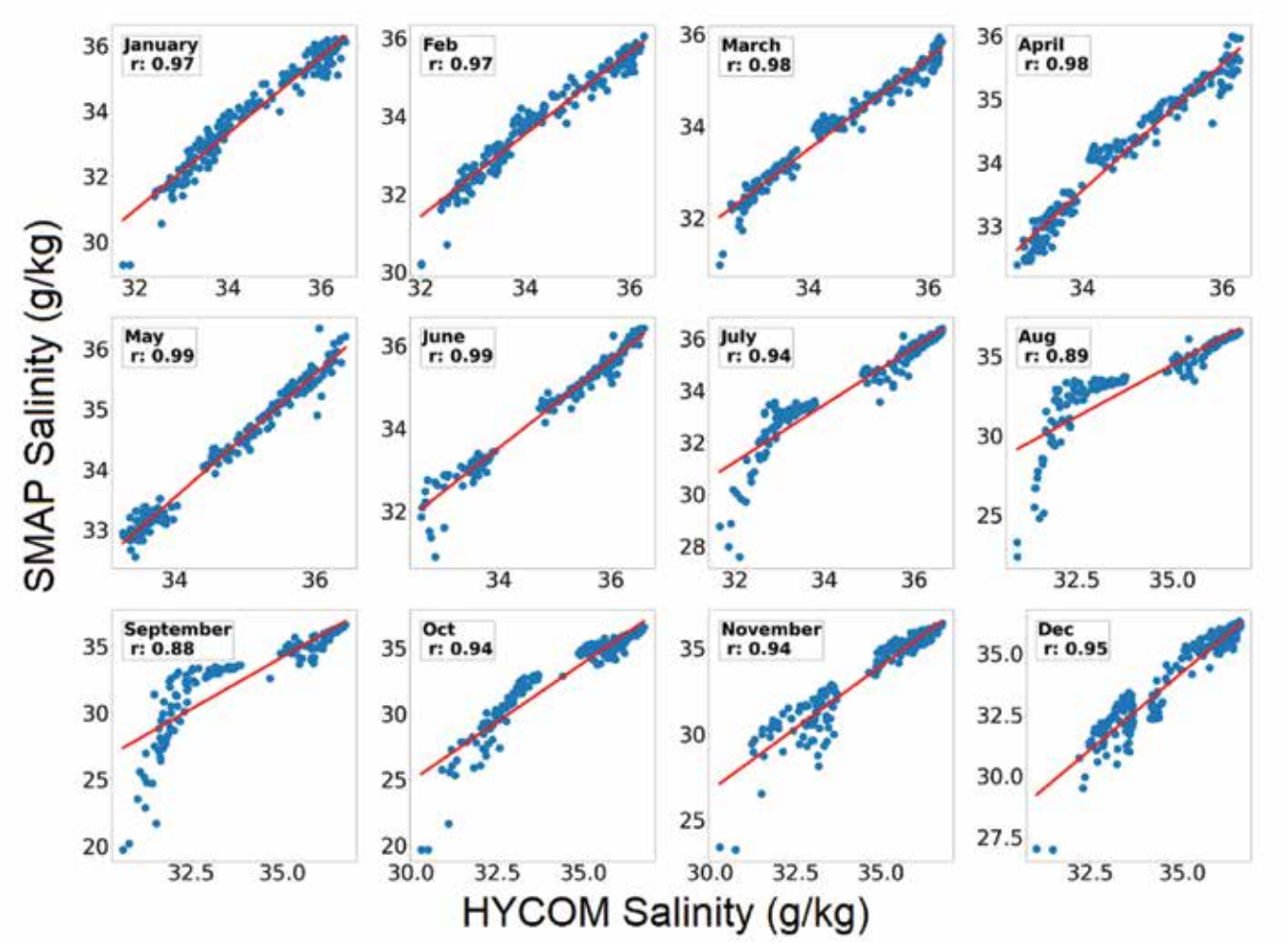


Figure 34: Monthly verification of HYCOM simulated salinity against the same from SMAP satellite.

7.2 Results

We have estimated salinity gradient energy following [10], which estimates salinity gradient energy for the Reverse Electro Dialysis (RED) method. In general, SGP plants are designed such that the residual river water after extraction does not fall below a critical value referred to as "environmental flow", which is the fraction of the river discharge required to satisfy the environmental demands of the river [1]. We have followed [52] and assumed 30% as the environmental flow.

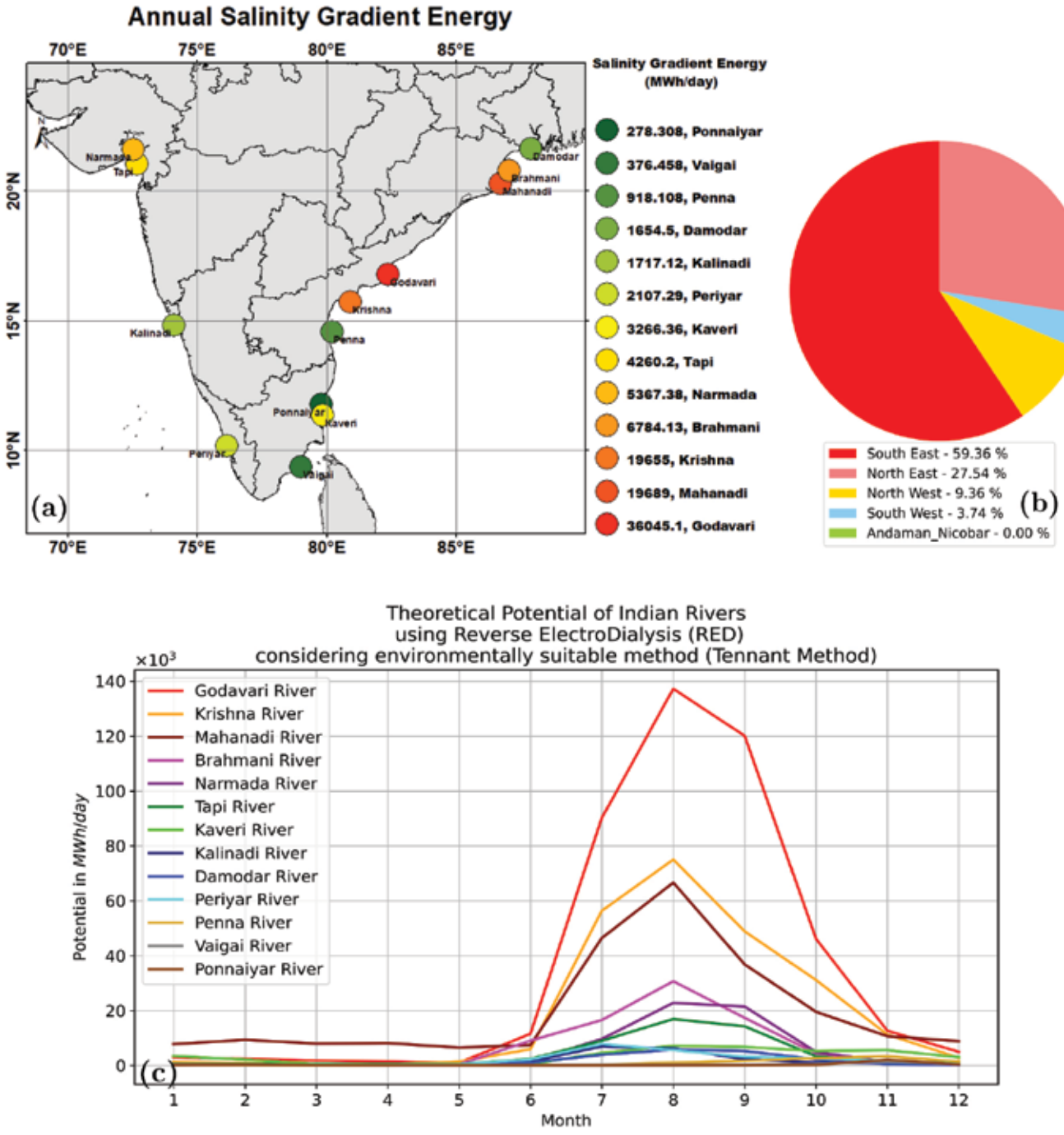


Figure 35: Theoretical Annual Salinity Gradient Energy (SGE) (a), Percentage of SGE available from different sectors (b), Monthly time series of SGE (MWh/day) estimated from 13 Indian Rivers (c).

The monthly SGE potential of 13 Indian rivers is estimated and presented in Figure 35. As evident from Figure 35, there is strong seasonality in the case of 6 out of 13 rivers, and they show increased SGE potential from June to November. Godavari, Krishna, Mahanadi, Narmada, Tapi, and Brahmani rivers offer significant seasonality compared to the rest. Except during the peak season of the six rivers, the SGE potential of all the rivers along the Indian coast is less.

Figures 36 and 37 show the spatial plots of the SGE potential of 13 rivers considered in this study with coloured circles. For most of the months, the Godavari, Krishna, Kaveri, Mahanadi, Brahmani, Narmada, and Tapi rivers showed relatively higher SGE potential than the rest.

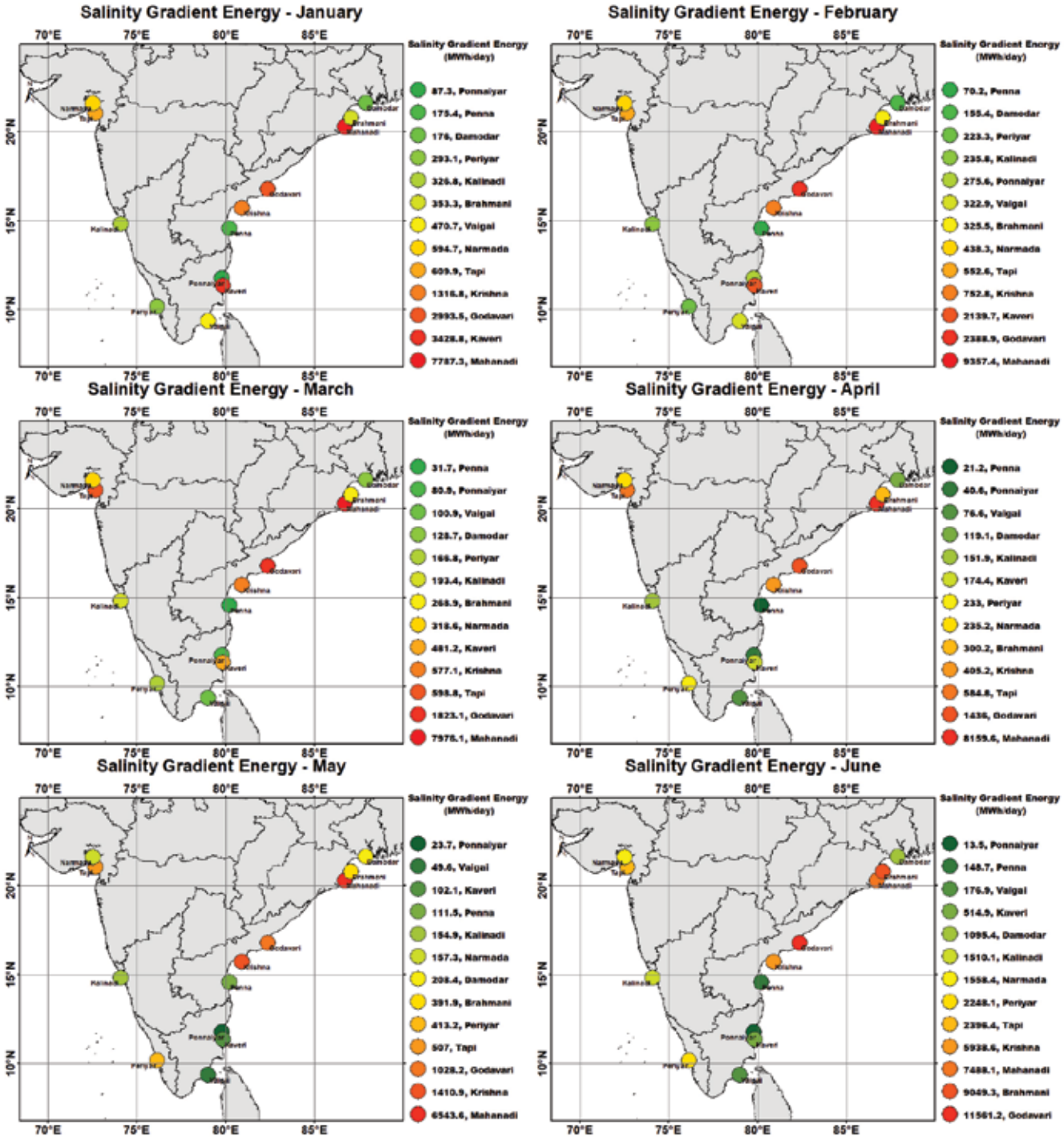


Figure 36: SGE potential of Indian rivers from January to June using river climatology prepared from [11] and INCOIS HYCOM salinity values for sea.

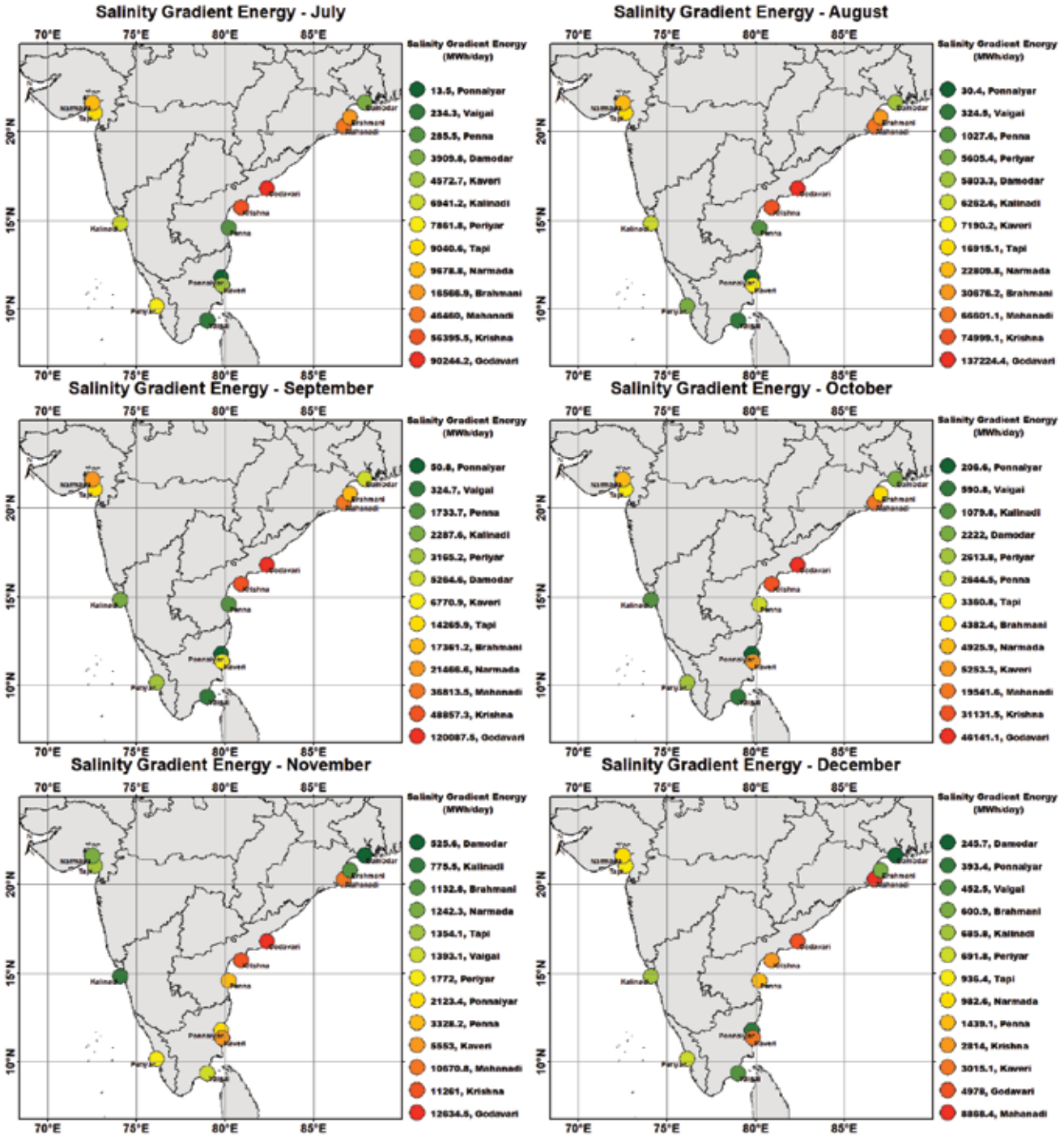


Figure 37: SGE potential of Indian rivers from July to December using river climatology prepared from [11] and INCOIS HYCOM salinity values for sea.

8 Ocean Currents: Energy Potential

Ocean currents are the continuous and consistent flow of ocean water. However, ocean currents vary significantly due to their driving forces, spatial locations, and temporal and spatial scales. The major driving forces for large-scale currents (0–1000km length-scale) include Earth's rotation (or Coriolis), gravity, wind stress, temperature and salinity differences (or density differences, to be exact). Besides these, mesoscale (0–100km length-scale) Ocean currents can also be driven by tides, river discharge, pressure gradients (generated by sea surface slope setup by coastal long waves), and bottom friction. Among these forcings, excluding Coriolis and gravity (which are constant in time), only astronomical tidal forcing is deterministic and thus allows for accurate forecasting [19].

The global estimate of power from ocean currents has been estimated to be 5,000 GW with power densities as high as 15kW/m^2. Current characteristics (current speed, direction, and depth) are to be analyzed to estimate power generation potential from ocean currents. As currents in the Indian Ocean (most of it being in Bay of Bengal and Arabian Sea) are relatively weak, the potential from ocean currents may not be significant with existing technology.

8.1 Data and Methods

An ocean current energy converter extracts and converts the mechanical kinetic energy in the current into a transmittable energy form. Various conversion devices are currently being proposed or are under active development, from a water turbine similar to a scaled down wind turbine, driving a generator via a gearbox, to an oscillating hydrofoil that drives a hydraulic motor. We have used ocean current simulations from INCOIS HYCOM available at ≈ 6.95 km from the year 2012 to 2016 for estimation of energy potential from currents.

The available in-stream power per unit area, or power density, is calculated using the equation below:

Computation:

$$\text{Power} = 0.5 \times \rho \times A \times V^3$$

where

ρ is the water density

A is the area swept by the turbine blades

V is the velocity of the ocean current.

Assumptions:

- Betz Criterion of 59.3% $\implies$ taking 40% efficient turbines $\implies$ $P_{t1} = 0.4P_{\text{turbine}}$
- Wake loss of 17% $\implies$ $P_{t2} = 0.83P_{t1}$
- Minimum velocity of current considered for the turbine to start producing power= 0.5 m/s
- Only pixels having a velocity greater than this were considered.

8.2 Results

We have estimated the energy potential of ocean currents for the Indian Exclusive Economic Zone (EEZ). We have fixed our depth of computation from the surface to 30 meters. An area of *1km* × *1km* has been considered to place one turbine of swept area equal to 400m^2 = $\implies$ ≈ Φ22.57m based on the method suggested by NREL. Appropriate wake loss has been considered. The turbines are assumed to be 40% efficient. The potential of currents estimated is presented by converting the units to *[MWh km^{-2} day^{-1}]*.

Ocean current energy potential is estimated using daily current data and is presented as annual average (Figure 38 (a)), annual cumulative currents energy (for speed >0.5 m/s)(Figure 38(b)), number of days ocean currents speed > 0.5 m/s(Figure 38 (c)), annual ocean currents power density (for speed >0.5 m/s)(Figure 38(d)). Percentage of ocean currents energy (for speed >0.5 m/s) available from different sectors(Figure 39). The monthly estimated ocean current energy is presented in Figures 40 and 41.

The maximum energy from ocean currents is evident from December to January along the east coast of India, followed by a slight amplification in April. Andaman EEZ has a second higher power density and shows two distinct highs during February and August. The northern part of the east coast has the third prominent power density from ocean currents, with a high during March. Though the power density from ocean currents is estimated along the Indian shores, the economic feasibility of extracting power from these currents depends on the technology available at a given time.

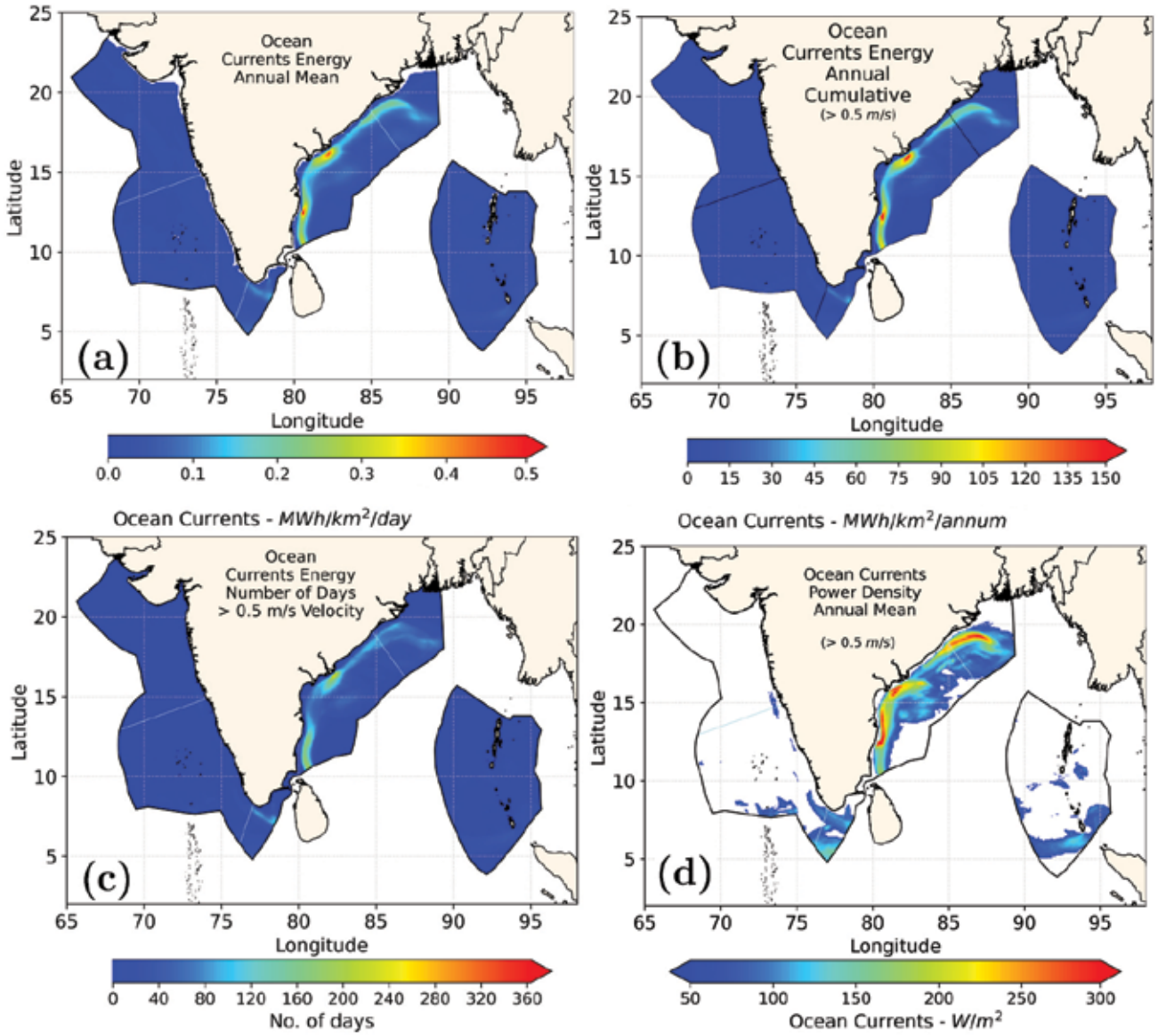


Figure 38: Estimated annual mean (a), Cumulative >0.5 m/s) (b), Number of days current speed > 0.5 m/s ocean current energy from the Indian EEZ (c), Annual ocean currents power density (current speed >0.5 m/s) (d).

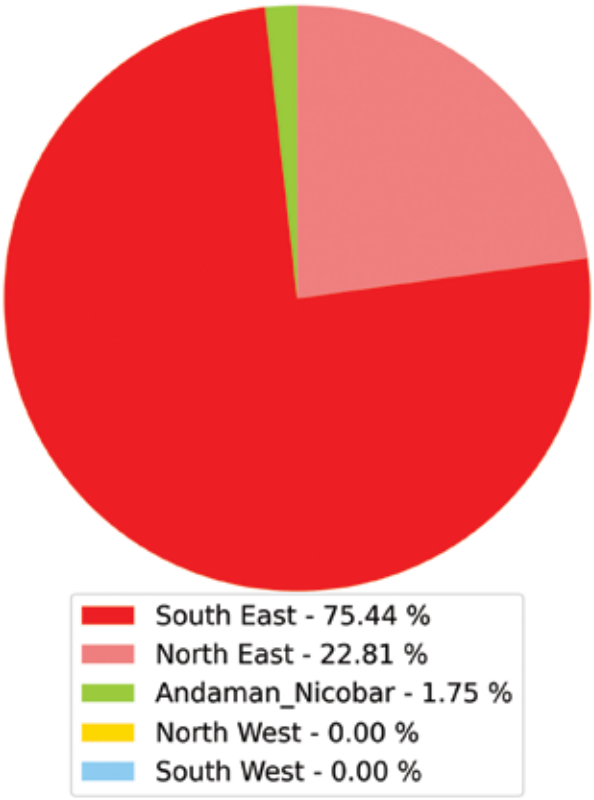


Figure 39: Percentage of ocean current energy (>0.5 m/s) available from different sectors.

Figure 39 shows the percentage of ocean current energy (current speed > 0.5 m/s) available from Northeast, Northwest, Southeast, Southwest and Andaman and Nicobar sectors.

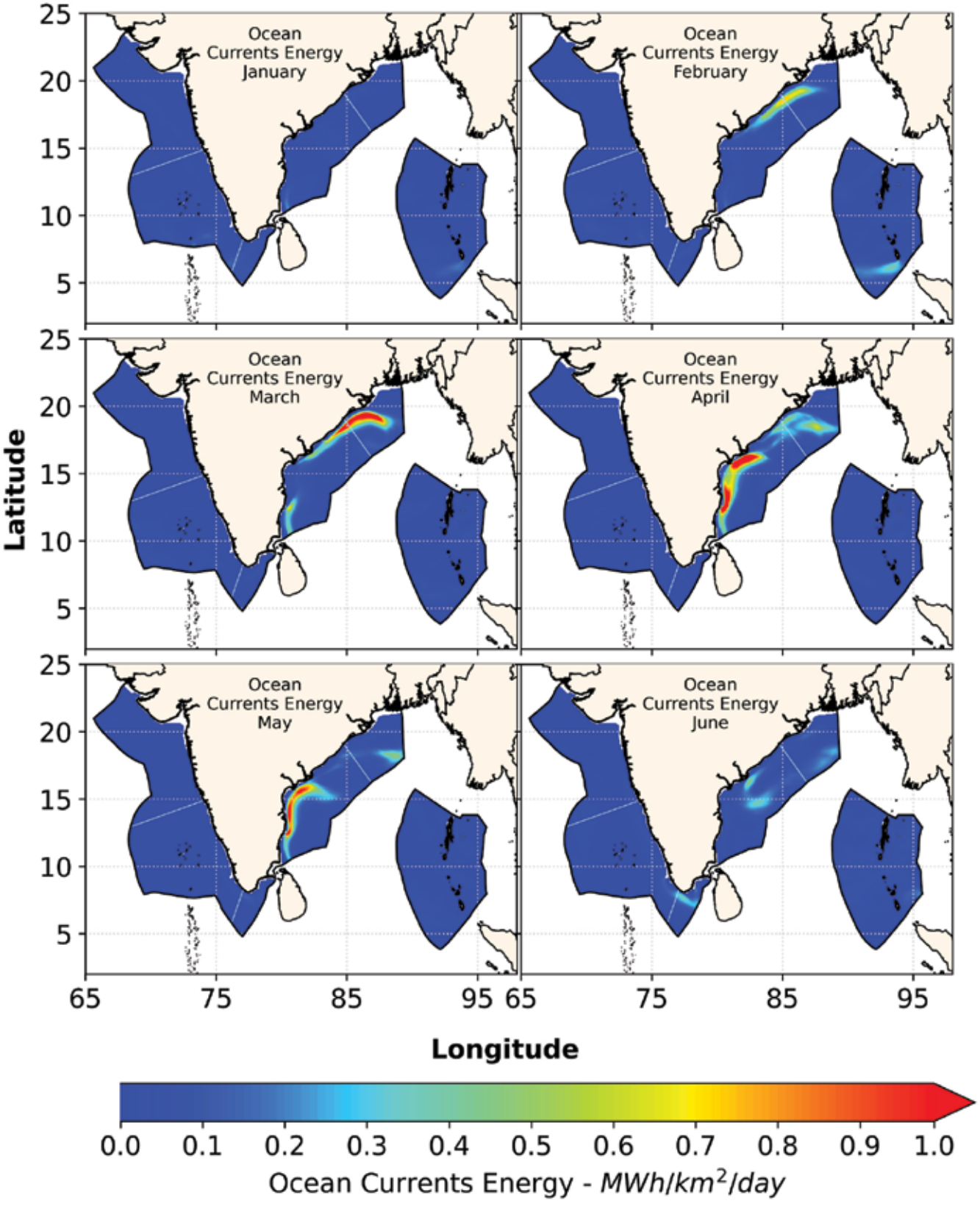


Figure 40: Estimated monthly mean ocean currents energy from the Indian EEZ (January – June).

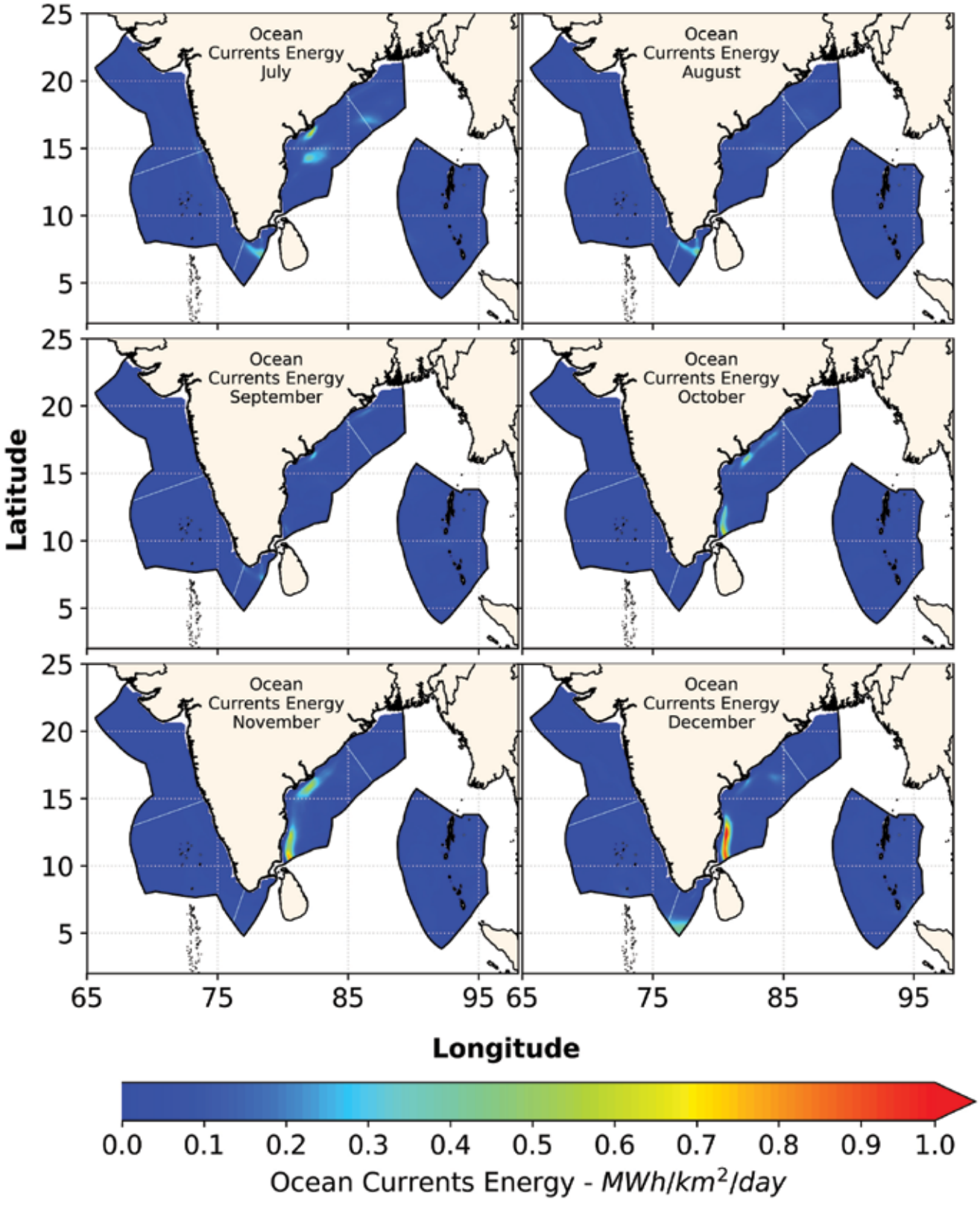


Figure 41: Estimated monthly mean ocean currents energy from the Indian EEZ (July – December).

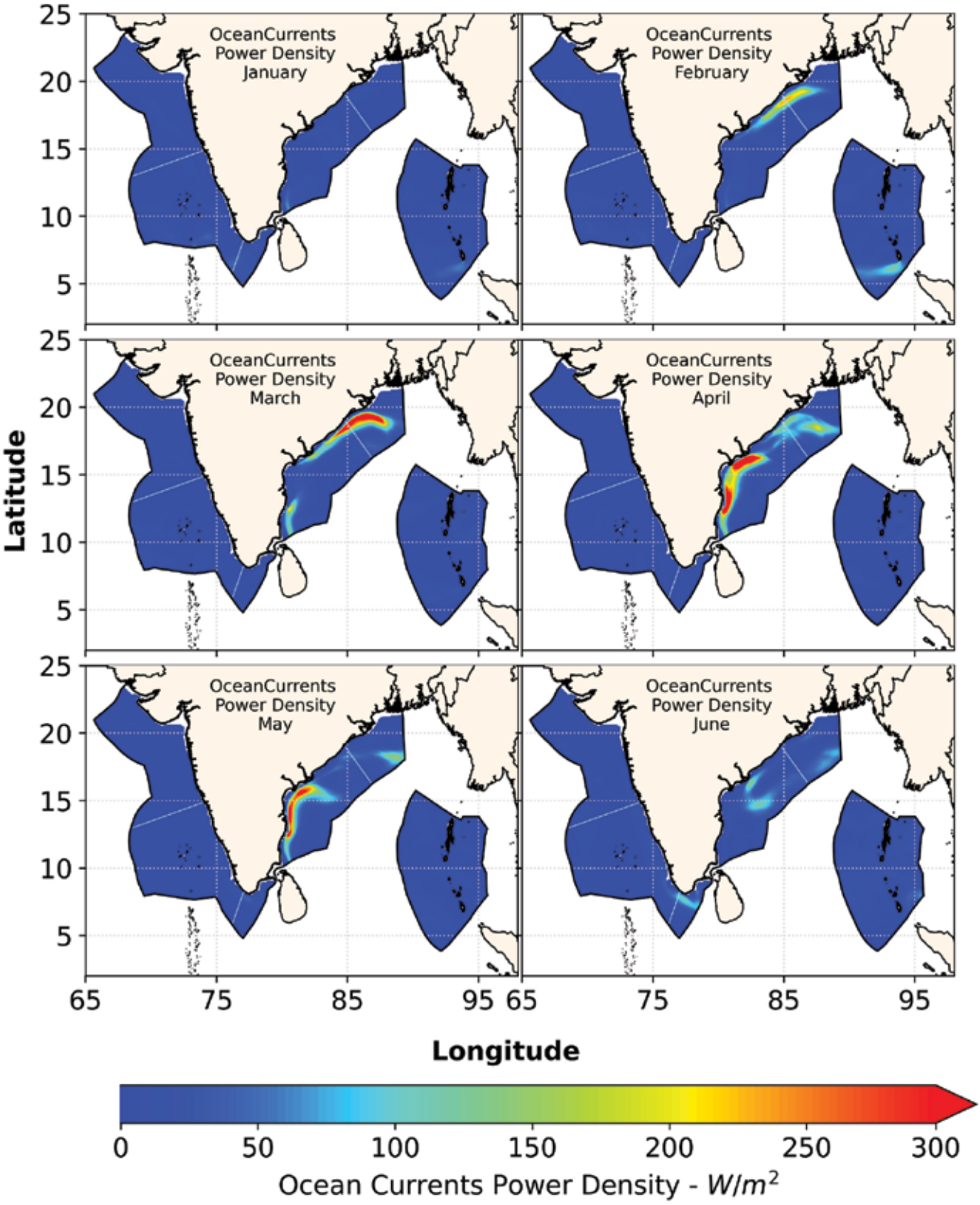


Figure 42: Estimated monthly mean ocean current power density from the Indian EEZ (January – June).

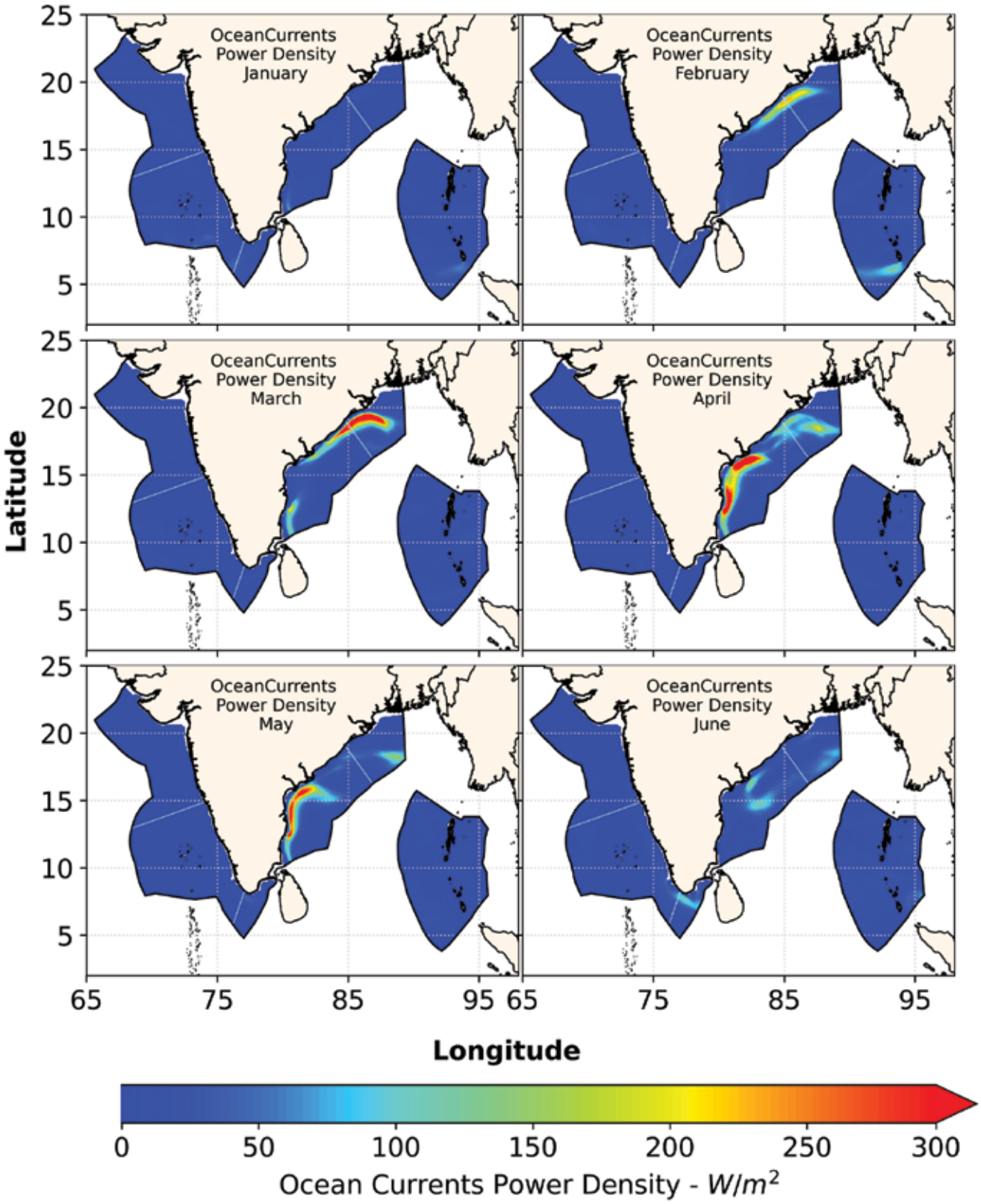


Figure 43: Estimated monthly mean ocean current power density from the Indian EEZ (July – December).

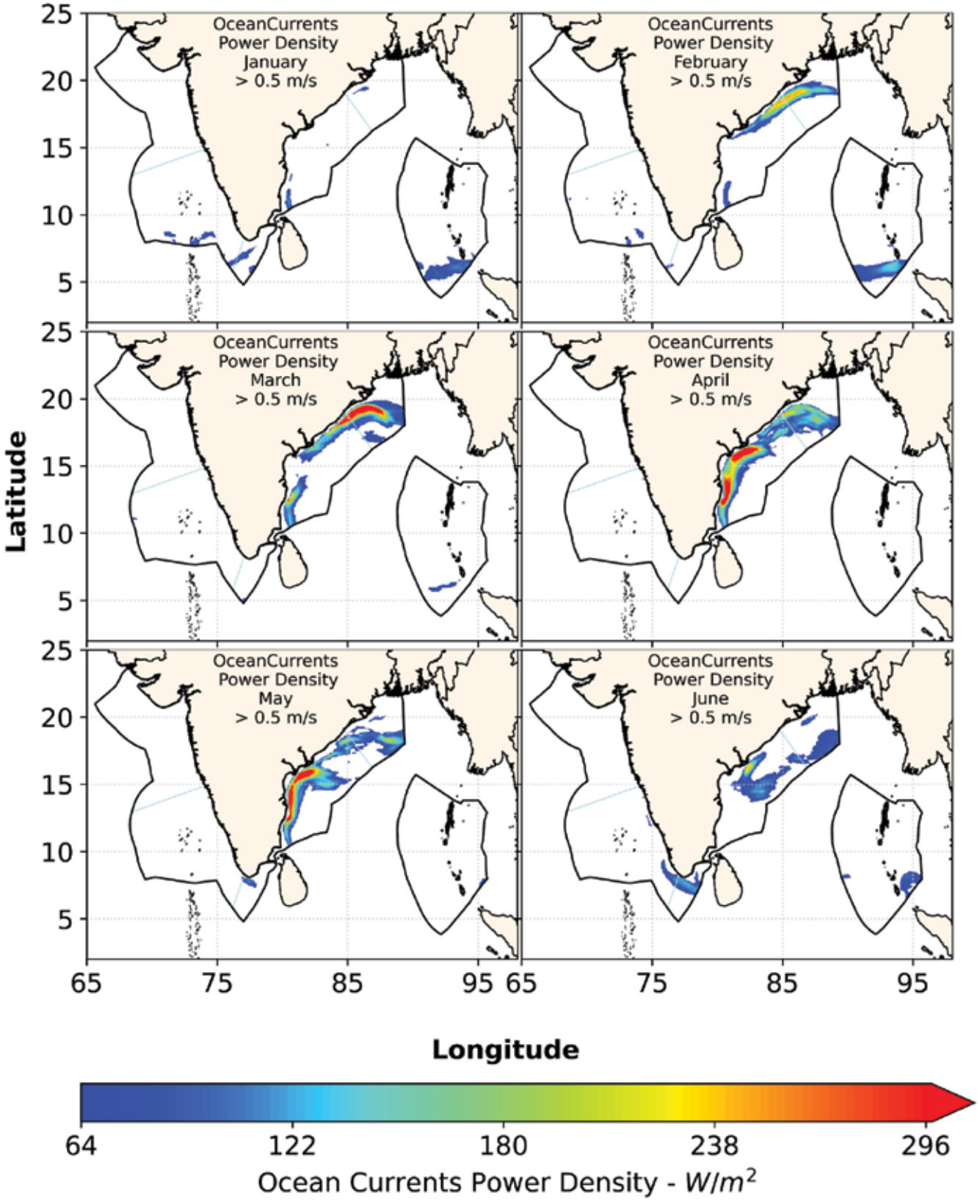


Figure 44: Estimated monthly mean ocean current power density (>0.5 ms^{-1}) from the Indian EEZ (January – June).

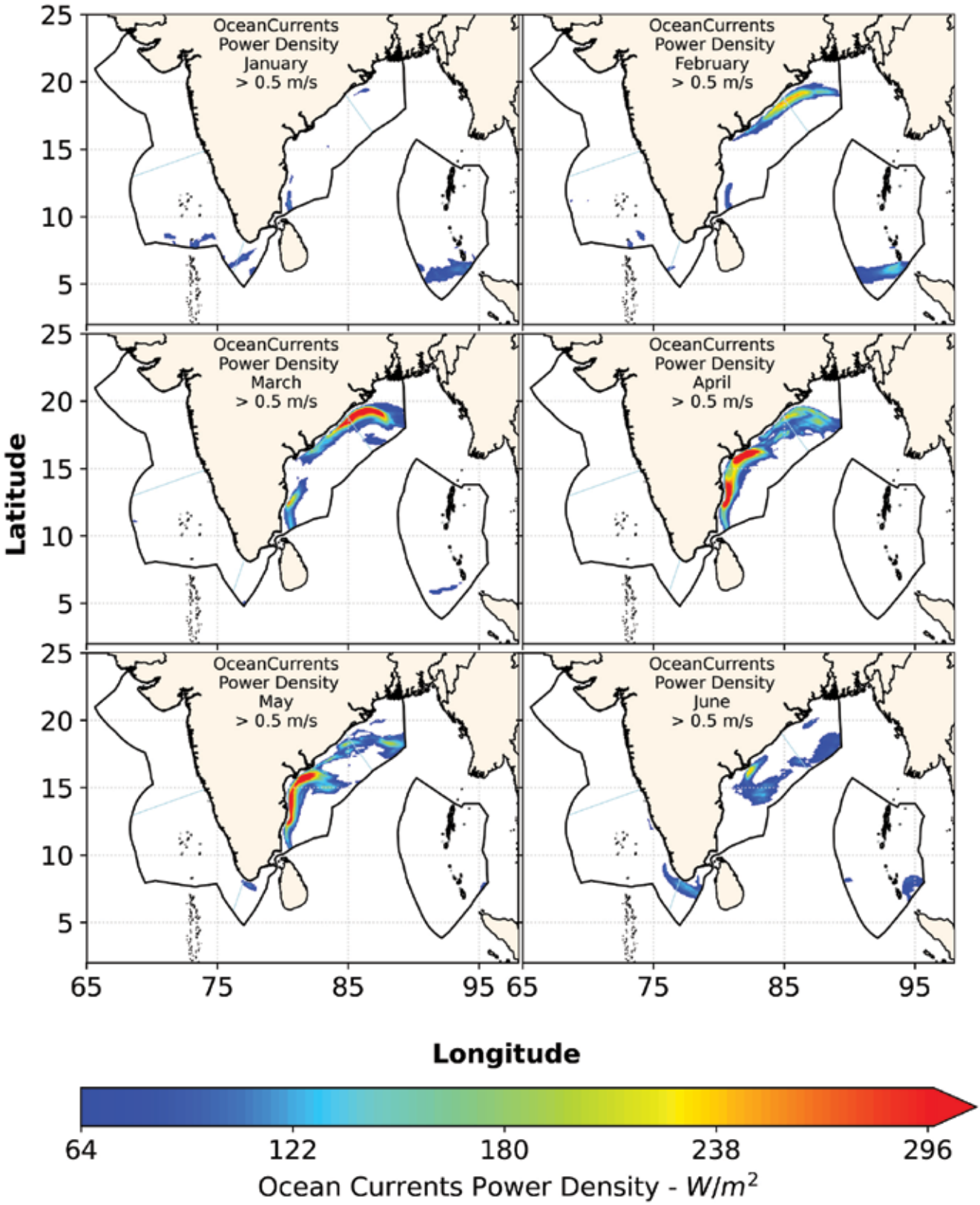


Figure 45: Estimated monthly mean ocean current power density (>0.5 ms^{-1}) from the Indian EEZ (July – December).

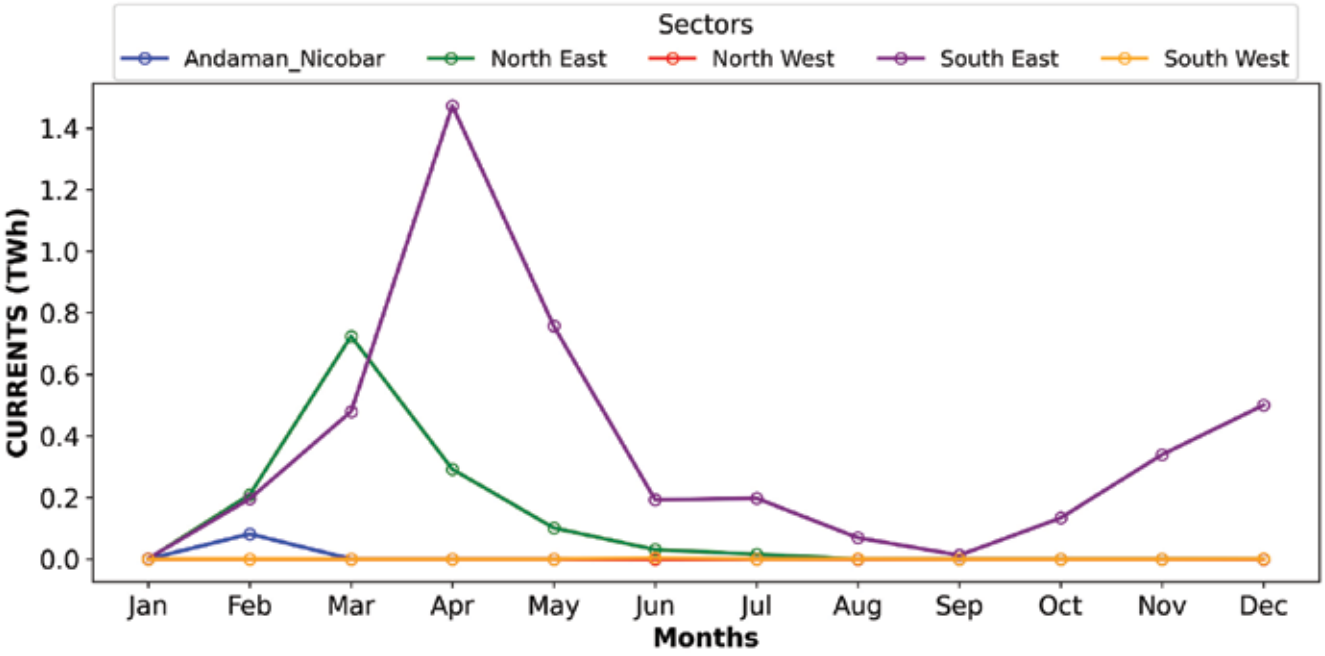


Figure 46: Monthly mean wave energy from five sectors identified from Indian EEZ.

There is an annual peak of current energy in the Indian EEZ from March to June as observed in Figures 39, 40 and 45. This annual maximum is more evident in the Southwest sector, followed by the Northeast sector and it is almost absent in Andaman Nicobar and Northwest sectors.

Currents Power Density is the standard units widely used by industries. However, for integration and to keep consistency with other energies, we have estimated current energy in Terra Watt Hours (TWh) and presented in this report Figures 39 and 40. Nevertheless, we have also computed current power density monthly maps without any threshold and with a threshold (>0.5 m s^{-1}) and are presented in Figures 41 to 44.

9 Integrated Energy from all Sources

Marine energy is one of the world's abundantly available forms of renewable energy. Global Energy Statistical Yearbook estimates that with efficient conversion systems, marine energy can contribute up to 20,000 to 80,000 TWh energy per year, which will be sufficient to meet the world's total electricity demand, which was 20,567 TWh in 2015, according to the yearbook. Though there is enormous potential for marine energy, there are several challenges in tapping the potential due to their intermittency, variability, high initial costs. Marine energy sources like wind, wave, and tidal energy are intermittent, making it difficult to ensure a stable power supply. Energy output can vary significantly according to weather conditions, tidal cycles, and seasonality.

Recently, there has been an increased interest in hybrid converters, which can combine multiple energy sources and reduce intermittency and variability, to address such challenges to a great extent. Hybrid converters are also preferred for increased energy outputs as they simultaneously harness energy from different sources. It can leverage maximum economic benefit for the initial infrastructural expenses in less time. By optimizing energy extraction and reducing losses, hybrid converters minimize the environmental impact of marine energy harvesting. Hybrid methods increase energy predictability and thus help in adjusting power generation accordingly. There are accelerated efforts towards wind-wave hybrids, solar-wave hybrids, and wind-solar-wave triple hybrids, which are designed to harness wind, solar, and wave energy. Those mentioned above innovative hybrid solutions can unlock the full potential of marine energy resources, reduce running costs, and contribute to a sustainable blue economy.

Thus, there is a strong imperative to estimate the integrated potential of marine met and hydro/hydrokinetic energy resources from the Indian EEZ. Apart from the printed version, INCOIS also prepared a WebGIS version of the marine energy estimates, which allows the end user to estimate integrated energy from seven different energy forms.

We have adopted the approach described below for each energy to compute integrated energy potential for the entire Indian coast line associated/aligned with each of the sector from marine energy resources [38] wave, tide, thermal and salinity gradients and ocean currents for every month and offshore energy above sea surface such as Wind [32,8,55] and Solar [32,8,55] presented in the tables below.

We used daily data in MWh/km^2/day for all energy forms except Salinity gradient for which only monthly river runoff data was available.

Hence, for estimating the integrated any energy of a sector per annum, we used the following approach:

- We multiplied the area of the pixel in km^2 to the value of the pixel in MWh km^{-2} day^{-1} v_i (MWh km^{-2}day^{-1})× Ai (km^{2}pixel^{-1}) to obtain, x_i in MWh pixel^{-1}day^{-1} for i^{th} pixel. Where v_i is the value of the i^{th} pixel in MWhkm^{-2}day^{-1} and Ai is the area of the i^{th} pixel in km^2.
- To find sum of all such values of x_i such that the i^{th} pixel falls in a particular sector, yj = Σx_i, where i^{th} pixel falls into a sector. This would give us (MWh sector^{-1} day^{-1}), where j is a sector.
- To integrate along time dimension, we added the values of y_j of all the days of a month or year to get the monthly integrated value or annual integrated value respectively.

  Integrated Potential of a Sector per annum = Σy_j values of 365 days. This would give us values in MWh sector^{-1} annum^{-1}.
- As the Integrated potential number is very large when expressed in (MWh sector^{-1} annum^{-1}), we divided it by 1,000,000 and expressed it in (TWh sector^{-1} annum^{-1}).

Except SGEP, every other energy has been brought into MWh km^{-2} day^{-1} for the ease of integration and also to be able to add them product wise. We also considered different thresholds as applicable in case of different energies. The methodology used for integration in case of Salinity gradient is provided below separately.

9.1 Methodology for Integrated Potential Estimation of Salinity Gradient Energy

In case of Andhra Pradesh sector.

It has 3 rivers within it. Godavari, Krishna, Penna.

Now,

For a certain month, based on RED and Tennant method,

Let the power potential of Godavari be = *2, 000MW*

Let the power potential of Krishna be = *1, 000MW*

Let the power potential of Penna be = *200MW*

Total power potential = *3, 200MW*

Energy of AP sector for 1 month = 3, 200$MW \times 720$ (No of hours in that month) = 2, 304, 000MWh = 2.304TWh

Similar way, energy potential for all other sectors and all months are calculated.

9.2 Integrated Annual & Monthly Marine Meteorological & Hydrological Energy estimates

We have segregated marine meteorological energy forms and marine hydrological energy forms and presented them separately as they are generally considered different by industries. We have added solar and wind energy estimates and prepared an integrated annual map (Figure 47) from the Indian EEZ under five sectors labelled as Northeast, Southeast, Northwest, Southwest and Andaman-Nicobar. As evident from Figure 47, the maximum marine meteorological potential exists in the Southwest, Southeast and Andaman Nicobar sectors, followed by the Northwest and the least energy is seen in the Northeast sector.

Similarly, we have added energy estimates from Wave, Tide, Ocean currents, and thermal and prepared an annual map of annually integrated marine hydrological energy presented in Figure 48. Marine hydrological energy is most prominent in Andaman Nicobar Islands, followed by the Southwest coast, Northwest and Northeast sectors. The Southeast sector has relatively lower integrated marine hydrological energy potential.

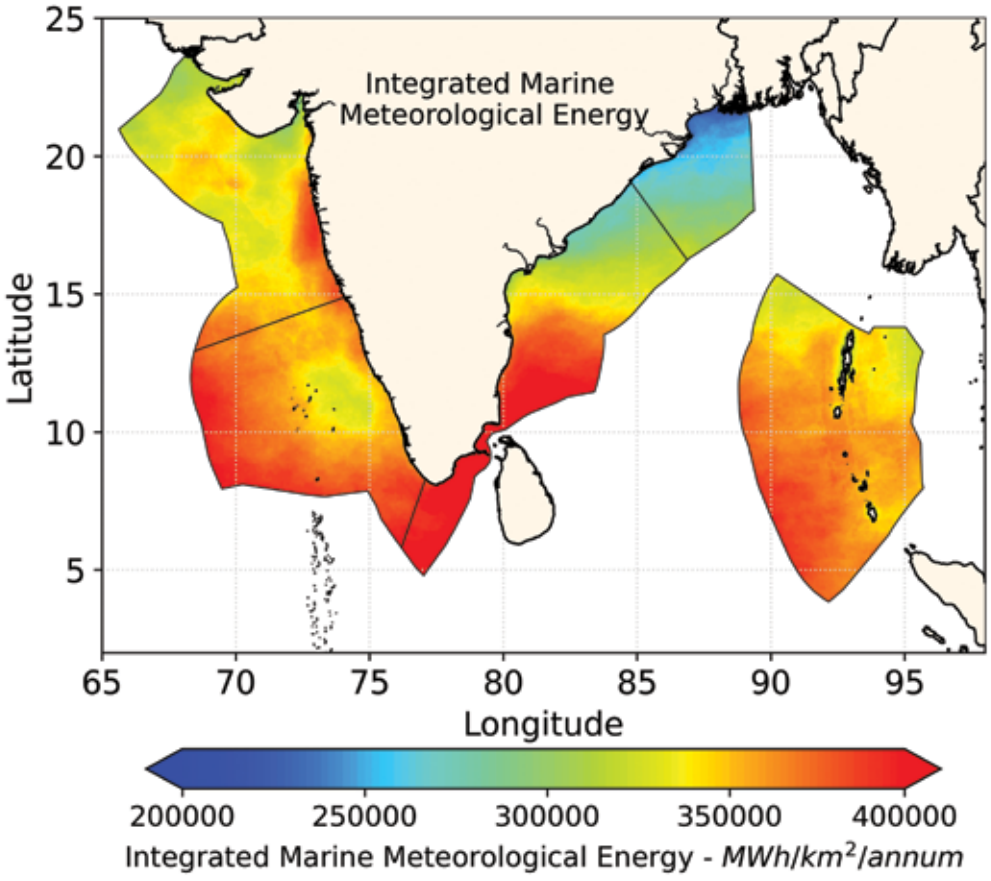


Figure 47: Annually integrated marine meteorological energy estimate from the Indian EEZ.

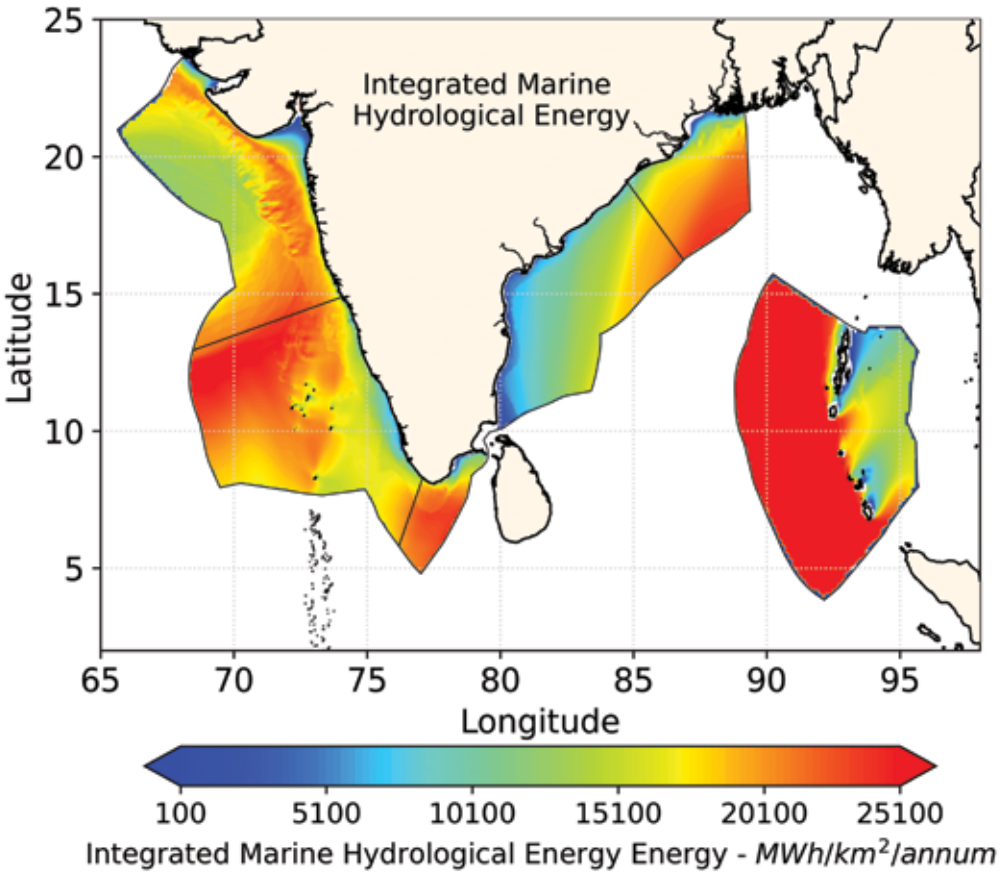


Figure 48: Annually integrated marine hydrological energy estimate from the Indian EEZ.

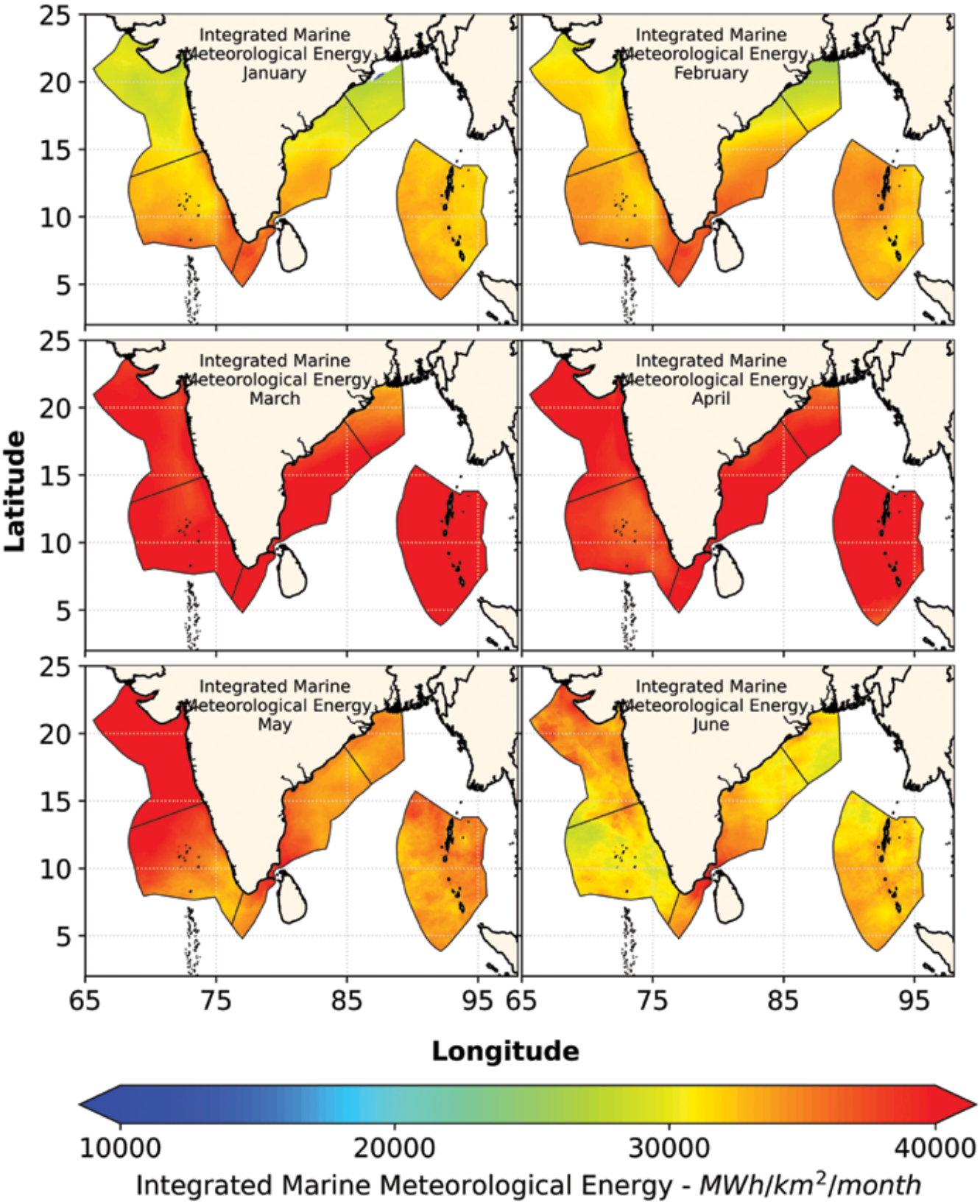


Figure 49: Monthly integrated meteorological energy estimates from the Indian EEZ (January – June).

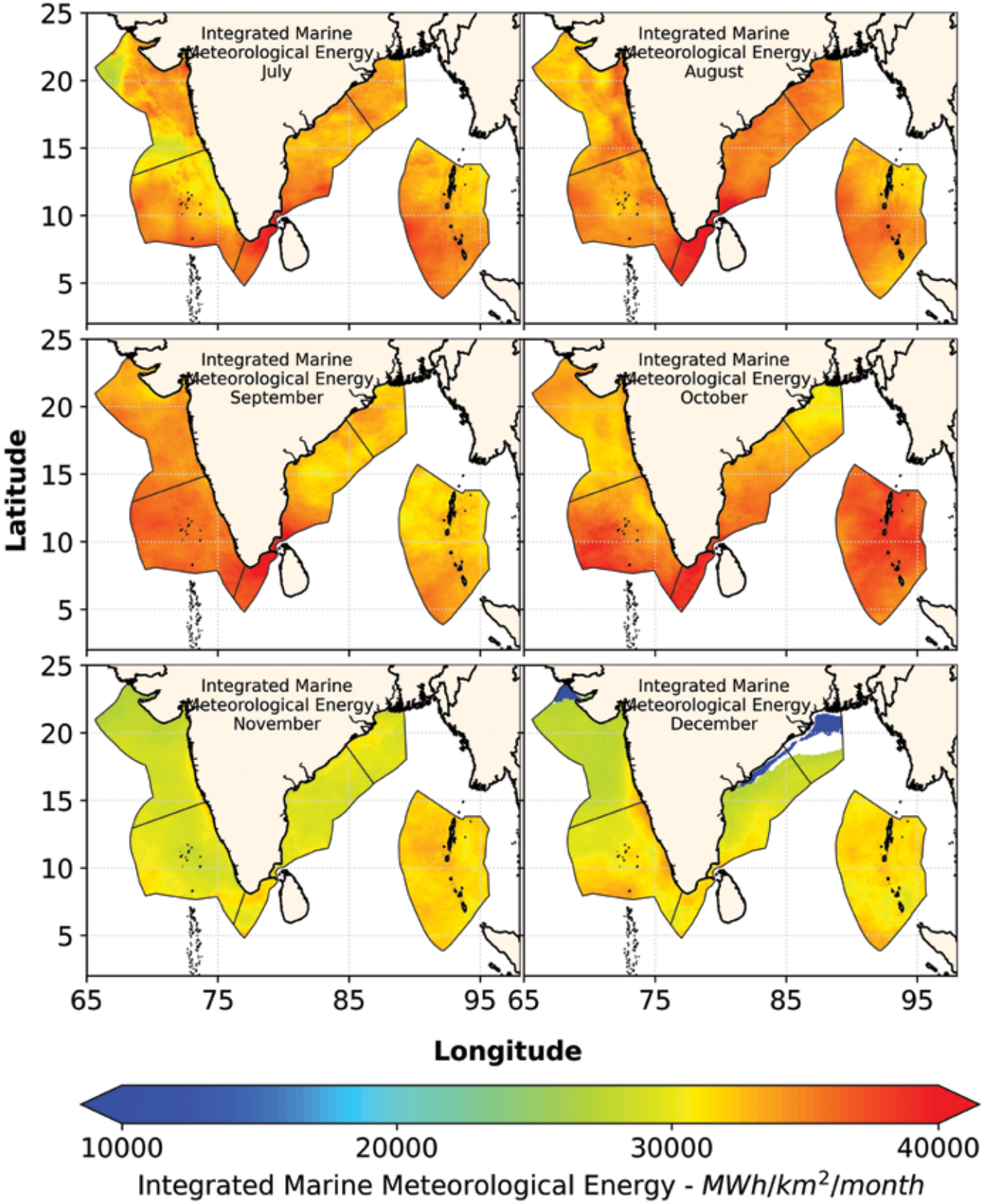


Figure 50: Monthly integrated meteorological energy estimates from the Indian EEZ (July – December).

The monthly integrated marine meteorological energy maps (Figures 49 and 50) show that the energy potential varies significantly among different months. The maximum potential is seen for March, April & May and the minimum is seen during November, December, January and February. During December, the northern part of

the Southeast and Northwest sectors and the eastern part of the Northeast sectors show minimal solar potential, and wind energy potential dominates the integrated meteorological energy.

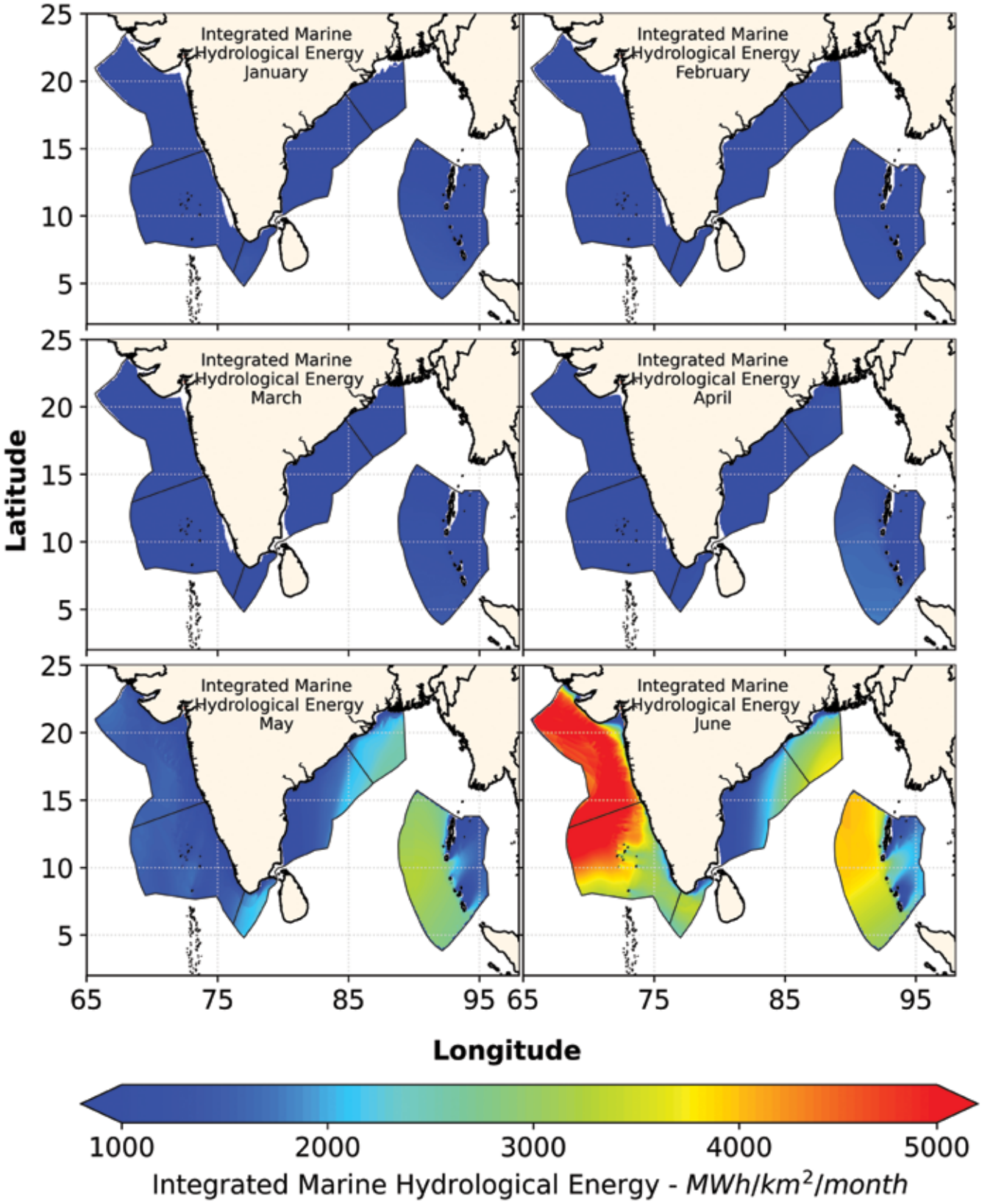


Figure 51: Monthly integrated hydrological energy estimates from the Indian EEZ (January – June).

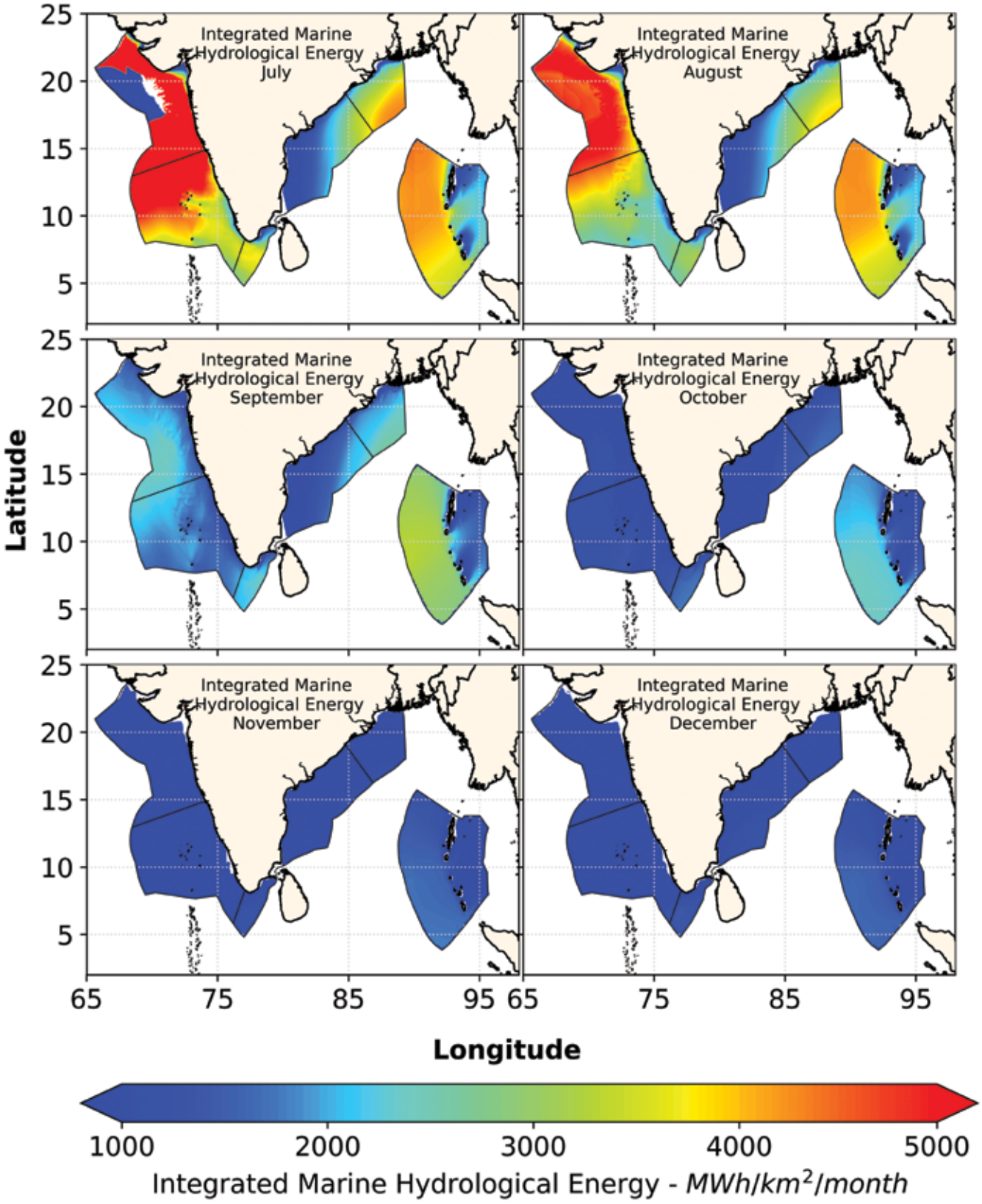


Figure 52: Monthly integrated hydrological energy estimates from the Indian EEZ (July – December).

In the case of monthly integrated Marine hydrological energy estimates (Figures 51 and 52), the maximum potential is seen during June, July and August months due to the dominance of Wave energy during the monsoonal season, which is complimentary to the marine meteorological energy forms which are dominated by Solar energy.

9.3 Sector wise marine Energy Estimates

We have estimated the sector-wise cumulative energy from marine meteorological fields Table 2 and marine hydro and hydro-kinetic energy forms Table 3. The values of wind energy in Table 2 is for the entire EEZ. However, the wind energy extraction can be carried out from ocean depth less 1300 m due to economical feasibility and other constrains as per Bureau of Ocean Energy Management. *(https : //www.nrel.gov/docs/fy22 osti/83650.pdf)*. Within 1300 meters depth from the India EEZ, the total wind energy potential from Indian EEZ comes down to 2376.51 TWh in place of 10372.03 without this constraint.

Sectors	Solar	Winds	Total
Andaman & Nicobar	270815.9	3201.34	274017.2
South East	171654.8	2371.76	174026.6
North West	185127.5	2323.94	187451.4
South West	221457.6	1681.34	223138.9
North East	64119.4	793.65	64913.1
TOTAL	**913175.1**	**10372.03**	**923547.1**

Table 2: Integrated marine met energy resources from the entire Indian EEZ without application of any limits.

Sectors	OTEC	SGEP	Currents	Wave	Tidal	Total
Andaman Nicobar	672	0	0.1	14406.1	1.4	15079.6
South East	384.8	22.2	4.3	5339.8	0	5751.1
North West	201.1	3.5	0	7728.7	17.3	7950.6
South West	490.1	1.4	0	10314	0	10805.5
North East	137.2	10.3	1.3	3146.1	0.2	3295.1
TOTAL	**1885.2**	**37.5**	**5.8**	**40934.7**	**18.9**	**42881.9**

Table 3: Integrated marine hydro & hydro-kinetic energy resources from the entire Indian EEZ without any thresholds.

In Table 3 of hydro and hydro-kinetic energy forms, the presented values of OTEC energy estimates are from depths more than 1000 m bathymetry to ensure sufficient thermal gradients. For the total current energy estimates, currents more than 0.5 m/s is only considered in present estimates in line with current technical feasibility. In case of waves, the estimates are carried out for values between $> 2kW/m$ *and* $< 50kW/m$ to meet the technical feasibility. For tides we have considered a slack period which consider only periods when tidal currents are above 0.5 m/s.

Contributions:

The following team of scientists from INCOIS worked towards preparing this report with motivation and guidance of Dr. M. Ravichandran, Secretary MoES and Dr. Srinivasa Kumar, Director INCOIS.

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