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Marine-Meteorological Atlas of Tropical Indian Ocean

by

Kameshwari N, TVS Uday Bhaskar, Suprit Kumar, E Pattabhi Rama Rao

Indian National Centre for Ocean Information Services (INCOIS)

(Earth System Science Organization (ESSO),Ministry of Earth Sciences (MoES))

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Author(s) [Last name, First name]:
Kameshwari N, TVS Uday Bhaskar, Suprit Kumar, E Pattabhi Rama Rao

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Abstract (150 words) :

This report discusses the preparation of climatology from the data which is from the ship observations obtained from the Indian Meteorological Department (IMD) and Naval Operations Data Processing and Analysis Centre (NODPAC). Processing of these datasets, extraction of surface meteorological variables and SST (Sea surface temperature), the quality control (QC) procedures followed are discussed. The individual records of International Comprehensive Ocean-Atmosphere Dataset (ICOADS) and those obtained from IMD are compared and the unique records from IMD data are extracted. The enhancement in ICOADS climatology after adding the unique records from IMD data and NODPAC is checked. ICOADS dataset has been found to be self robust, as there is no much significant improvement in the climatology even after adding new records . Frequency distribution of the ICOADS dataset alone and after adding new records showed no much difference. Spatial correlation between ICOADS monthly climatology fields before and after adding the new records, is greater than 0.9 at all grid points.

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ABSTRACT

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1 INTRODUCTION

The elements of our climate system are the atmosphere, hydrosphere, lithosphere, cryosphere, etc. Our understanding of the climate system stems from studying the processes in individual as well as their mutual interactions. The most important elements that affect the weather and climate are the atmosphere and oceans, and in particular ocean-atmosphere interaction processes. The heat energy supplied by the Sun, drives the convection both in atmosphere and oceans. Also, each one drives the other (air-sea interaction) by exchange of various interactive fluxes such as sensible heat, latent heat, momentum, etc. Oceans occupy 75% of the Earth's surface and there comes the significance to understand how oceans interact with the atmosphere. Having realized this there are worldwide efforts being made, to obtain as many observations of the ocean parameters and meteorological parameters over the oceans also known as marine meteorological parameters. However, vast areas of the oceans are still considered as the data sparse regions. To address this issue, numerous observational programs were designed and implemented over the years, such as ARGO (Array of Real-time Geostrophic Oceanography), IOGOOS (Indian Ocean Global Ocean Observing System), GOOS (Global Ocean Observing System), RAMA (Research moored array for African-Asian-Australian Monsoon Analysis), WOCE TOGA (World Ocean Circulation Experiment - Tropical Ocean and Global atmosphere), etc. All these programs use observational systems such moored buoys, drifting buoys, ships etc. One of the oldest method is the ship observations dating back to 1800s.

Measuring meteorological parameters and marine parameters across oceans facilitates the air-sea interaction research. Air-sea interactions form a part of any weather phenomenon be it a low pressure system or a hurricane or storm surge or upwelling in the sea or even general circulation in atmosphere and oceans. Numerous field experiments since 1950s were carried out exclusively for flux measurements, which are the key variables in the study of air-sea interaction. Wangara, Bomex (Barbados Oceanographic and Meteorological EXperiment 1969), BLX83 (Boundary Layer interaction eXperiment 1983), BOBMEX (Bay Of Bengal Monsoon EXperiment 1999), etc. are some of the field experiments over land and oceans. These experiments involve measurements of bulk variables namely Temperature (Dry bulb temperature-DBT), Moisture (Specific humidity-SPHUM), wind speed and direction (WS and WDIR), SST and sometimes direct measurements of surface fluxes. These field experiments and the results found are the backbone of the fundamentals in air-sea interaction study and they provide the datasets against which theories and models are tested. Several methods are found to calculate the surface fluxes when bulk variables are measured. As turbulence is the dominant process responsible for the flux exchange in the air-sea interaction process, these methods involve measurements of bulk variables either through fast-response sensors where the perturbations (or turbulence) are calculated or slow-response sensors where empirical parameterizations are used. However these field experiments are special programs dedicated to develop parameterization schemes and also to examine the developed theories and models. Also, they are conducted across specific category of terrain for example, flat land, hilly region, etc, and had covered very few oceanic regions. For the better understanding of the air-sea interaction processes, long term datasets with wide spatial density is necessary. The ship observations across all the basins would fulfill such criteria. The marine meteorological and ocean parameters measured onboard the ships can be used to calculate the fluxes and is a source of a huge dataset for understanding air-sea interaction processes across all the basins.

In the Indian ocean, air-sea interaction process is specifically more important. The North Indian ocean (NIO) is always considered unique in its characteristics both in marine meteorological and oceanic perspective. The monsoon reversal of winds, the number of rivers that discharge fresh water into the seas are some of the primary reasons behind the unique characteristic. As the atmosphere and ocean are always coupled, the air-sea interaction process are distinctly affected and in turn affect the weather phenomenon over NIO. The regular weather phenomenon across NIO are the tropical cyclones and the monsoon circulation (Indian summer monsoon-ISM). Several studies discussed the influence of air-sea interaction on ISM. (Chowdary *et al.* 2015, Goswami *et al.* 2016, etc.). Also, the influence of global teleconnections is opposed or enhanced by the local air-sea interaction event such as local convection, etc, (Chowdary *et al.* 2015). In addition to that, Indian ocean is considered as a data sparse region. Observation systems like, moored buoys, drifting buoys, ships, etc, and programs like BOBMEX, ARMEX (Arabian Sea Monsoon EXperiment), OMM (Ocean Mixing and Monsoon), etc. are carried out to obtain the data and also the understanding of the air-sea interaction processes. Any amount of data available from any reliable source is always beneficial. Owing to this fact, an attempt is made in this work to combine the ship observations obtained from IMD, NODPAC to the already existing collection of ship observations (ICOADS) within Indian ocean region (30E - 100E , 30S - 30N), with an aim of possible enhancement in the existing climatology.

Each of the marine meteorological and oceanic parameter is important. The air temperature and sea surface temperature difference defines the direction of sensible heat flux. The amount of moisture above the sea surface determines the intensity of latent heat flux. Winds blowing across the sea surface, transfer momentum to the water below causing waves and other dynamics. The accuracy of these independent parameters determine the accuracy of the calculated fluxes. This report elaborately discusses the QC of the ship observations.

Realizing such scientific and also the commercial value of meteorological information collected on ships, the meteorological organizations of many recruiting countries devised weather observation systems onboard the ships. The observations made onboard these ships were given to the meteorological organizations in return for forecasts and warning information at sea. This scheme came to be known as Voluntary observing ship (VOS) scheme. It is an international observing program with members nations of the World Meteorological Organization (WMO) that coordinates recruitment of ships for making weather observations and transmitting the same. There are different classes of ships under VOS scheme based on the extent of automation. The observing procedure onboard the ships is either fully automated or partially automated or done manually. Manual observations were more prominent during the earlier decades where the observations were recorded into logbook manually. The automated observing systems using Automatic Weather Stations (AWS) are replacing the traditional methods and have increased in number in the recent years. These ships with automated observing systems use electronic logbook software, for example, TurboWin, SEAS, etc. This software is set to send real-time observations at designated time intervals using onboard real-time communication system. It also saves a copy of it in a specific format in the ship's hard drive. The later is named as delayed mode observation (DMO). The observations used in this work are the DMO obtained from IMD, NODPAC and those used in the construction of ICOADS climatology. A climatology is prepared combining the above mentioned datasets..

ICOADS is the first climatology of marine-meteorological parameters utilizing mainly the ship observations (Slutz *et al.* 1985). ICOADS releases consists of the climatologies of individual parameters, some derived variables like difference between air temperature and sea surface temperature, etc, and pseudo fluxes .The individual records of ICOADS were used in several studies apart from construction of climatologies by daSilva *et al.* 1994, Woodruff *et al.* 2008, Fan *et al*. 2014, etc. Several authors formulated bias corrections of ship observations owing to the inaccuracies in observation methods (Kent *et al.* 1993a, 1993b, 1997, Josey *et al.* 1998). In this work, ship observations since 1960s is used. Individual records from ICOADS release 2.5 is one of the dataset used. As of now, the number of individual observations used in ICOADS are 261 million observations. These ship records are all available in a standard International Marine Meteorological Archive (IMMA) format. The strenuous endeavor of the ICOADS team to process such huge amounts of data and making it available is well recognized in the scientific community.

The second dataset is the ship records obtained from IMD which is spanning from 1961 to 2012. The format of the entire data except those records observed during the period 1961-1981 is according to International Marine Meteorological Tape (IMMT) format. In order to make use of this data, the formats of the data was studied and the records were carefully extracted into a usable form. It was quite laborious to extract the data as the format followed in some part of the data (of period 1961-1981) was one that could be managed with the limited resources available then. With the advancement of technology and recognition of the importance of collecting these data, significant changes were made with which collecting data, transmitting, extraction, etc, are now trouble-free. The third dataset used in this work is the records obtained from NODPAC, which are in standard GTS format spanning the period 2010-2012.

The description of all the datasets namely, IMDdata, ICOADS records, NODPAC records, their format are discussed in section 2. The format of the ship records of different datasets are different and the extraction process, complications faced during extraction are all discussed in section 3.1. Quality control check is one of the important step in making use of the accurate part of data. In this work, that QC procedure is applied which is simultaneously appropriate for checking both marine-meteorological data and the observing platform being a moving ship. The details are discussed in section 3.2 to 3.8. Meteorological parameters onboard ships are measured at different heights which are determined based on ship dimensions and other factors. Section 3.9 discusses about the ship metadata and the height correction procedure. The last step in the entire processing, is to prepare gridded fields of all the variables. Methodology used for gridding, number of records used in gridding are all detailed in section 3.10. Section 4 details about the variety of statistics reviewed to determine the enhancement and its possibility in ICOADS climatology after adding the new records. Section 5 discusses the conclusion and limitations faced in this work and the scope for future tasks. Owing to the inaccuracies in observing procedures, ship observations are to be bias corrected. Annexure I (section 6) discusses the bias correction of several variables and the step by step procedure to correct the same. However due to lack of sufficient metadata, bias corrections are not done to the data in this work.

2 OVERVIEW OF THE RAW DATA

The data mainly used in this work are the marine-meteorological observations made onboard VOS. The observations include a set of 59 lakh records obtained from IMD (henceforth referred to as "IMDdata"), the individual ship records that are used in building the ICOADS climatology, the gridded ICOADS climatology, the observations collected onboard Indian Navy ships (NODPAC dataset).

2.1 ICOADS

ICOADS data set is a collection of monthly statistical summaries across 1° x 1° (1960-2007) and 2° x 2° (1800-2007) globally analyzed fields and approximately 261 million individual observations from ships, buoys, sea stations, etc. The first release of ICOADS was in 1985 with 70 million individual observations, comprising observations recorded during the period 1854 to 1979. Gridded monthly statistical summaries were released in 1996. The latest version of ICOADS is Release 2.5 covering the time period from 1960 - 2012 (1° x 1°) and 1800 - 2012 (2° x 2°). In depth detailed description of ICOADS dataset can be referred from Woodruff *et al.* 2011.

In the current work, both the individual observations from ICOADS collection and 1° x 1° gridded monthly statistical summaries are used at three different levels. Both the non QCed ship records and QCed ship records are downloaded from CISL research data archive at " http://rda.ucar.edu/". The data downloaded was in IMMA format. The spatial density of ICOADS individual records is complete, across all the ocean basins. The gridded product is used in comparing with the final gridded field produced from IMDunique, NODPAC records and ICOADS-Qced records.

2.2 Ship records obtained from IMD

The raw ship records obtained from IMD were approximately 59 lakhs (hereafter referred as "IMDdata"). The records were of various byte sizes, namely 82, 126, 131, 151, 159. Here the byte size denotes the number of characters in each record. The IMDdata used in this work spanned the period 1961-2012. The variables present in the raw ship records from all byte sizes are given in table 2.1. Number of records available corresponding to each byte size is given in table 2.2 . The spatial coverage of the entire IMDdata is shown in figure 2.1 and the number of records yearwise is shown in figure 2.2 .

S. No	Variable name	S.No	Variable name
1	Air Pressure (SLP)	7	Swell wave parameters
2	Dry Bulb Temperature (DBT)	8	Weather and cloud conditions
3	Dew point Temperature (DPT)	9	Details of ship position
4	Sea surface Temperature (SST)	10	Time of observation
5	Wet bulb Temperature (WBT)	11	Details of the ship
6	Wind speed and direction (WS, WDIR)	12	Quality Control flags of all the parameters

Table 2.1 : Variables available in the IMD data

Record Size	Years Covered	Number Of Records
82 bytes	1961 - 1981	2349806
126 bytes	1982 - 1994	1706721
131 bytes	1982 - 2002	1106312
151 bytes	1990 - 2004	121526
159 bytes	1987 - 2012	692416

Table 2.2 : Number of records under each byte size

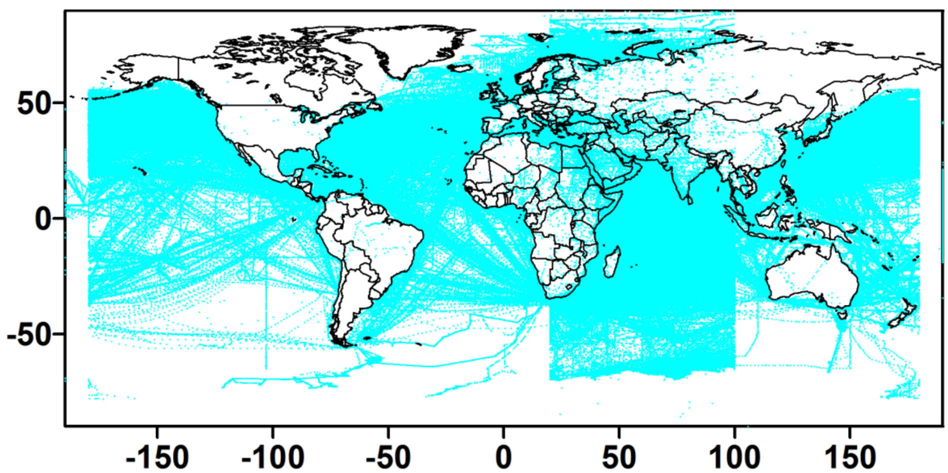

Figure 2.1 : Spatial coverage of the entire dataset obtained from IMD

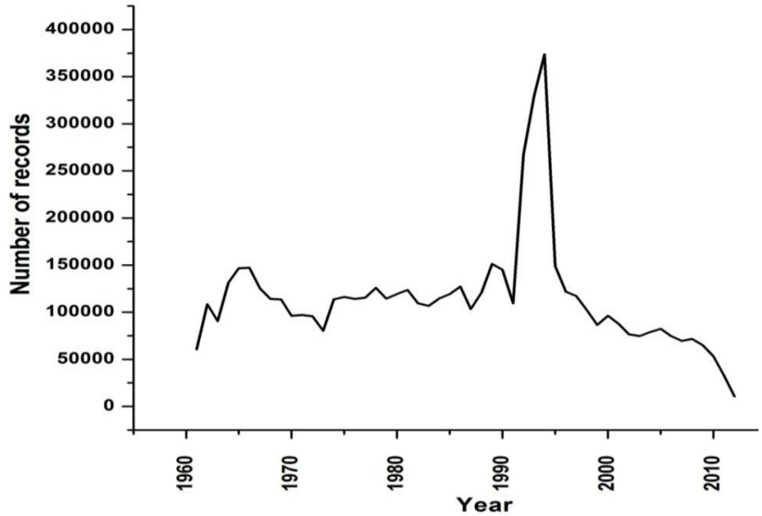

Figure 2.2 : Number of records (yearwise) in IMDdata

2.3 NODPAC

NODPAC data are basically observations made onboard Indian Navy ships. The NODPAC data is in GTS format and is concentrated in North Indian ocean. This data was spanning from 2010 to 2013. For the current work, data from 2010 to 2012 was only used.

3 METHODOLOGY

This section describes the methodology adopted in this work. Section 3.1 and 3.2 discusses the extraction of all the datasets into a useful form which is convenient for QC, which is the next step. Sections 3.3 to 3.8 discusses the QC check applied on the datasets. Section 3.9 discusses the height correction of DBT, WS, etc and about the metadata used for the same. Section 3.10 discusses about the gridding procedure adopted to grid the data.

3.1 Extraction of ICOADS records

As mentioned earlier, ICOADS-nonQCed and ICOADS-QCed ship records are the individual observations used in this work and the extraction of the same is discussed in this section. The ICOADS-nonQCed ship records are extracted in such a way that it is convenient to compare with the records of IMDdata. The order and number of fields in each yearly file that was compared was kept the same in both the datasets. The organizational data (year, month, date, hour, minutes, callsign, latitude, longitude) were the initial fields of each record, followed by the parameters namely, SLP (Sea Level Pressure), DBT, DPT (Dew Point Temperature), WBT (Wet Bulb Temperature), SST, WS, WDIR, WSINDIC (Wind Speed Indicator) and remaining variables. Also, the format of the numbers in each parameter field is stored in the same format of that of the IMDdata records.

The ICOADS-QCed ship records are extracted into separate variables. These records are extracted into that format which would match with the format of QCed records of IMDdata and NODPAC, as all the three datasets are combined before gridding.

3.2 Extraction of IMDdata and NODPAC records

As mentioned earlier, IMDdata records were in different byte sizes. The formats of the record under each byte size was slightly different. A separate '.FMT' file was provided for each byte size file. This file served as a manual and all the information about the variables i.e. the position value of each variable and the number of characters it occupied in the record, details like dimensional units of the parameters, the number of digits in the fractional part of the values, etc, are all clearly mentioned. The smaller byte size records had less information than the 159 byte size records (IMMT version IV). Wherever the variables that are present in 159 byte size records are missing in 82, 126, 131, 156 byte size records, a '/' was placed in order to make the record size equal to 159 bytes. The legends given in the .FMT file were almost similar to the IMMT layout. The 126, 131 byte size records layout were similar to IMMT version I layout and 151, 159 byte size records were similar to IMMT version IV layout. The 82 byte size records were very different from IMMT format and were the most difficult ones to extract.

Necessary changes were made to the 82, 126 byte size records so as to match the format of 159-records (IMMT version IV). Below mentioned are the salient ones:

1. Temperatures in some 82-byte size records and 126-byte size records were in Fahrenheit but in 131,151 and 159 - byte size records, temperatures were in Celsius. All the temperature values in Fahrenheit were converted into Celsius and the temperature indicator value is changed so as to match the format of 159-byte records. (Temperature indicator denotes the dimensional units of all the temperatures present in the record and also the fraction of the magnitude given).
2. In 82 and 126 byte size records, longitude was converted to 3-digits by eliminating the first digit. With the help of octant, the sign of the longitude value is determined. The three digit longitude value divided by 10 is the actual value if octant value is 0 or 5 or 3 or 8 else the actual longitude value will be the 3-digit value divided by 10 and added to 100.
3. All the negative temperatures were with an over punch of a character. Here punch refers to an extra character that is given above the record at its respective position. Such values were replaced with a binary digit as '0' or '1' to signify the sign of the temperature so as to follow the 159-records format.
4. Wind speeds in 159-byte size records were both in knots and m s^{-1}. Wind speeds in 82-byte size records were in knots. For the sake of simplification they are converted into m s^{-1} before placing into 159 size record.
5. Details of ice accretion, source of observation, observation platform, QC flags, rainfall and many other parameters were not present in 82-byte size records. Such parameters were given '/' value. Callsigns were absent in 82-byte size records. So, that was also given '/' value to denote a missing value.

Apart from the above modifications, there are several other critical issues during the extraction of IMDdata for further processing. Further processing includes QC check, height correction, and preparing gridded fields. Most of the difficulty was with 82 byte records. Following are the critical issues regarding the extraction of the data for 82, 126 bytes size records:

1. According to the details in .FMT file of the 82byte records, wind speed value in the record is supposed to be multiplied by a multiple of 10 to obtain the actual value of wind speed. Multiplying by 10 gave abnormally high values of wind speed resulting into rejection of those values in QC check. However it was found that the wind speed indicator was erroneous in a QC step which is discusses in section 3.3.
2. Also there was no ship call sign in the 82 byte records due to which time sequence QC checks (described in section 3.4) couldn't be performed.
3. There were some invalid characters like '-' , '}' , etc in the records. As these characters were not known i.e. their count and what invalid characters were present, all the characters except numbers, alphabets were replaced by '/'.
4. The 82 byte size records had two fields for humidity related temperatures. One field was computed dew point temperature or wet bulb temperature and the other was measured dew point temperature or wet bulb temperature. There were records where both the fields indicated the same temperature. For example, there were records with both computed and observed values of the same temperature parameter. The WBT and DPT were regarded as missing in records with such ambiguity.
5. The temperature indicator for some of the records was '4' which denotes that the value in the record corresponding to any temperature should be halved to get the actual temperature. Accordingly the temperature values present in the record were divided by two. However during the QC process, the temperature indicator in these records was found to be erroneous.(discussed in section 3.3)
6. In some records, few of the fields which should definitely consist of numerical digits had alphabets and other non-numerical characters. Such characters were replaced by '/'. And the value of such variables were considered as missing.

The NODPAC records were in standard GTS format. All the required variables along with their metadata were extracted. Also, all the different byte size records of IMD data were converted to a single format of that of 159-byte size record (IMMT version IV) and the files falling under each year are appended making the entire data into yearly files. The next step was to perform QC. The MQC

(Minimum Quality Control) program was used to perform the basic level of QC. For this, each yearly file was sorted based on callsign, month, date, hour and wherever there is no callsign the records got sorted based on date and time.

3.3 Quality Control - Comparison With ICOADS

Quality control (QC) is a necessary and essential step in processing any type of data corresponding to any domain. Adequate and sufficient QC checks have to be performed on the raw data, failing which would lead to rejection of good data points or inclusion of erroneous data points. Several steps of QC were performed on the IMDdata to ensure that, the correct data is retained while rejecting the outliers. Also as the IMDdata is basically ship observations, it was also compared with ICOADS data. This section discusses the procedure followed in comparing ICOADS and IMD data and how the unique records from IMD data are identified.

The following procedure was implemented for finding out the unique records in IMDdata with comparison to ICOADS-nonQCed records. The output after each step is named after the number of the level of QC. Here a point to be noted is IMDdata used for comparison was raw data which was not QCed. Firstly, both IMDdata and ICOADS-nonQCed records were sorted based on callsign, year, month, date, hour, minutes. As individual elements were compared, sufficient care was taken to keep the format of the elements same, in either records so that the actual values would be compared easily and difference in format wouldn't interfere the comparison.

1) **LEVEL - 1 :** Excess records which are reported multiple times have been removed from both ICOADS and IMDdata separately. Here multiple times refers to the cases where the entire record being repeated, i.e. each parameter value in either records is equal.

2) **LEVEL - 2 :** A hard-duplicate check methodology similar to that employed by Da Silva *et al.* 1994 was used. Five individual weather elements were compared as a set. They are WS, DBT, DPT, SST, SLP. Records with these five parameters being identical but with different organizational data, have been removed. The number of records before and after hard duplicate check in ICOADS-nonQCed and IMDdata is shown in figure 3.1 . It was observed that there is huge reduction in the number of records in ICOADS-nonQCed records in the latest years (2002 onwards) after this check. It was found that there are many records in these year-files where all the meteorological parameters were missing except with

some minor details of other variables and organizational data. As the missing value assigned would be the same, for example -999, etc, such records were considered as hard duplicates.

3) **LEVEL -3 :** After removing duplicates from ICOADS-nonQCed and IMDdata, duplicate check between ICOADS-nonQCed data and IMDdata was done for finding unique IMDdata. Wherever organizational data (year, month, date, hour, latitude, longitude) except the callsign was similar, such records have been considered as duplicate. Ship callsign wasn't compared because, there were many records without a callsign both in ICOADS-nonQCed data and IMDdata. The actual unique records of IMDdata from ICOADS (now onwards referred as "IMDunique" data) were extracted. Initially the duplicate records which were both in IMDdata and ICOADS-nonQCed data were identified and the corresponding duplicate records from ICOADS-nonQCed data were extracted. But some parameters in few of those records were missing. However those parameters were present in the corresponding duplicates records in IMDdata. These values were initially taken as unique data but later on, in view of better accuracy, they were kept aside and would be checked and included in the future work. Figure 3.2 shows the number of missing values in duplicate records corresponding to ICOADS records and actual unique records of each variable. Figure 3.3 shows the number of unique records yearwise. Figure 3.4 shows the data density plots of both missing values in duplicates (3.4 a, b, c, d, e) and actual unique data(3.4 f).

The common practice on board the ship is to convert the air pressure observed at the measurement height to sea level and then enter into the e-logbook. However some of the ships failed to practice the same(Kent *et al.* 1993). The pressure given in the IMD files was termed as "Air Pressure" without any reference to the height. Whereas the pressure given in ICOADS is termed as "Sea Level Pressure". After comparing the IMD records with the records of ICOADS, the pressure values in duplicate records between both the datasets matched exactly. This is how it has been confirmed that the air pressure values in IMD records were actually at sea level i.e., the air pressure measured has been reduced to the sea level from the measurement height. Similarly, while comparing IMDdata with the ICOADS data, it was observed that wind speeds given in 82 byte size records were actual values and need not be multiplied by 10 according to the manual. Also, based on the temperature indicator in few records of IMDdata, the temperature values were halved. But when such records were compared to those in ICOADS, latitude, longitude, time of observation, ship callsign, all meteorological values were exactly matching except for temperature. As the temperature value was different, such records in IMD data weren't recognized as duplicates. Also, these temperature values which were halved were found to give some misleading impression in polygon test (discussed in section 3.8) in the initial inspection of the data. This is how we recognized that, the temperature indicator given in the IMD record was actually erroneous. All such records were manually removed. In this way comparing our dataset with ICOADS has also helped in a way to perform a QC check.

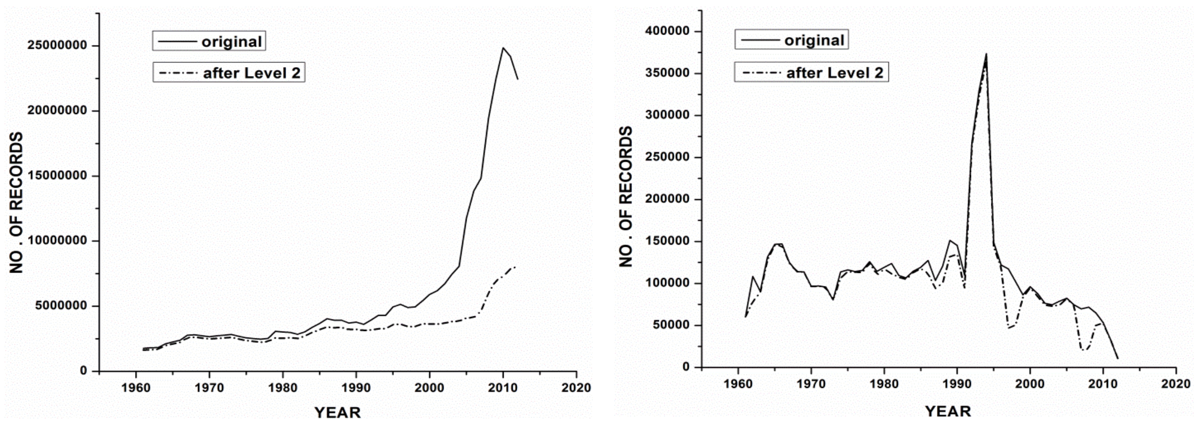

Figure 3.1 : No . of records in ICOADS (left) and IMDdata (right) before and after Level 2 QC

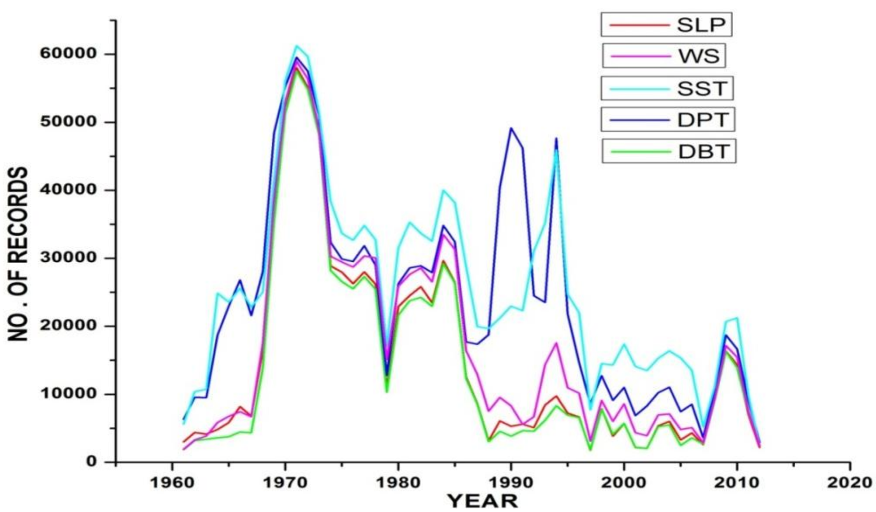

Figure 3.2 : Total no . of unique records including actual unique and missing values in duplicate records with ICOADS

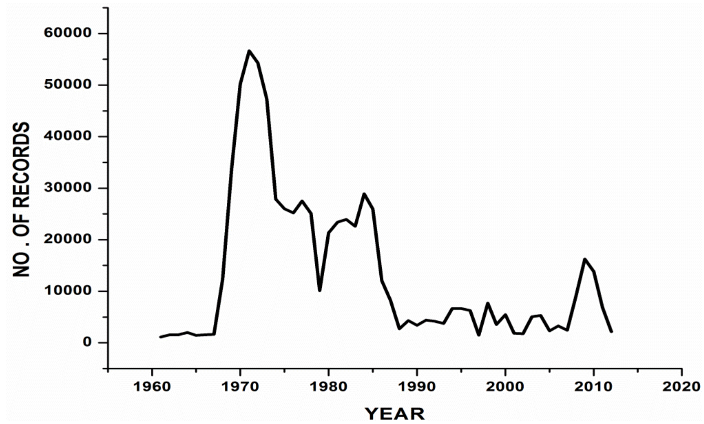

Figure 3.3 : No . of unique records yearwise

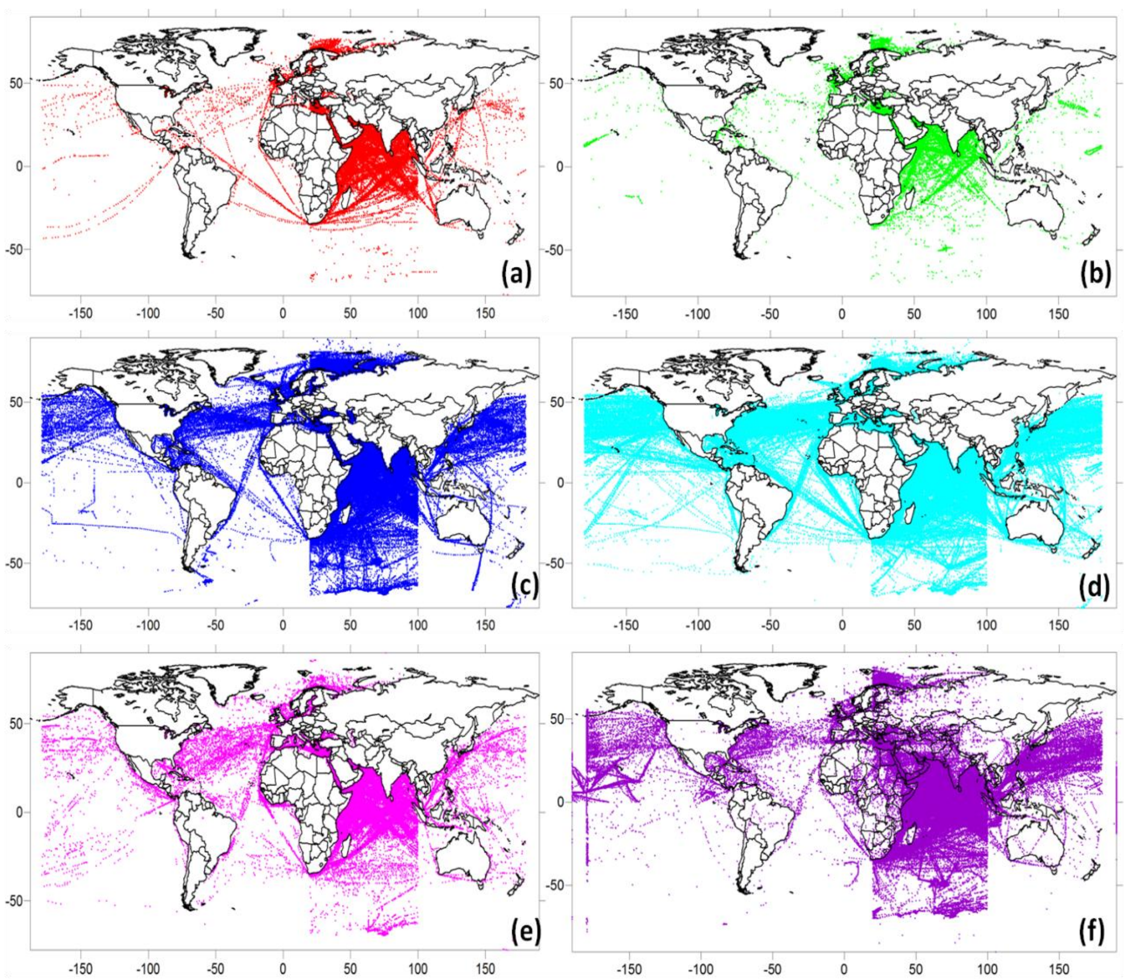

Figure 3.4 : (a, b, c, d, e) Data density of missing values in duplicate records in ICOADS but present in IMDdata. (f) is the data density of actual unique records. (a-SLP, b-DBT, c-DPT, d-SST, e-WS)

The total number of unique records are 7,03,994 which is 11.8 % of total data obtained from IMD i.e. IMDdata. Only this part of the data was further processed. As most of the data had already been utilized in ICOADS climatology, the aim was to see the enhancement in ICOADS climatology after adding the IMDunique records and NODPAC data. Another point to be noted is, there are no duplicate records between IMDdata and NODPAC data.

3.4 Minimum Quality Control (MQC)

As discussed earlier, QC is an important step in utilizing a dataset and to bring the best out of it. A QC check may consist of several steps which are apt for that particular dataset. Similarly meteorological parameters have a certain QC procedure. However the same QC procedure doesn't apply for the meteorological data collected from different platforms. Slight changes to the existing procedures have to be adopted and also additional checks may have to be included depending on the characteristics of the platform. This section and the following sections describe the QC procedure that is appropriate to check the meteorological data collected onboard the ships in detail.

The Global collecting centers (GCC) provided a software to process the observations from VOS within the Minimum quality control (MQC) guidelines set out by Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM). This MQC program is now available in WMO website in its 5th version. It is a fortran based code of around 3300 lines with a number of routines. In this work, as a first step of QC check , the same program with slight modifications was used in case of IMDdata records. In case of NODPAC data, the records were checked manually within the MQC guidelines.

Short description of MQC and the alterations made :

The MQC program available online is specifically written to check the records in IMMT format. As earlier mentioned, all the records have been converted to 159 byte size, which is similar to IMMT-4 format.

Salient points of MQC:

1. Position and time of observations together are called organizational data. If any of the organizational data is missing or any error is present, then that record is rejected.

2. When there is an ambiguity in temperature indicator, then all temperatures namely, DBT, DPT, WBT are given an 'inconsistent' QC flag. The QC flags used in MQC are described in table 3.1 . If temperature indicator is correct then DBT sign is checked and only when it is correct, further checks of remaining temperatures are made.
3. Range of DBT is -25 deg C to 40 deg C and DBT>WBT>DPT.
4. Air pressure must be within 930 hPa to 1050 hPa.
5. SST must be within -20 deg C to 37 deg C
6. The QC flag of ship position is checked based on quadrant, LAT and LON values.
7. QC flag of cloud amount, genus of low, medium, high clouds are checked.
8. Wind speeds must be less than 40 m s^{-1} or 80 knots.
9. Wave parameters (Height, period) are also checked.
10. Time sequence check
11. In IMMT format, each parameter has its own QC flag. (Table 3.1 details about the QC flags)

QC flags in MQC program :

The following table 3.1 gives the QC flags used in IMMT which are the same used in MQC also:

QC flag	Description of the QC flag
0	No Quality Control has been performed on this element
1	QC has been performed, element appears to be CORRECT
2	QC has been performed, element appears to be INCONSISTENT with other related elements
3	QC has been performed, element appears to be DOUBTFUL
4	QC has been performed, element appears to be ERRONEOUS
5	The value has been CHANGED as a result of QC
6	Flag set to "1" but the element was judged by MQCs to be either inconsistent, dubious, erroneous or missing
7	Flag set to "5" but the element was judged by MQCs to be either inconsistent, dubious, erroneous or missing
8	Reserved
9	Value of the element is MISSING

Table 3.1 : QC flags in IMMT records

A observation is rejected in the following cases:

1. Country code and callsign is either missing or invalid
2. Blanks in organizational data
3. Invalid FM-13 version of the records (A FM version is the format in which the ship observations are reported in real time)
4. Invalid character in record
5. Invalid year, month, date, hour
6. Missing or invalid latitude and longitude
7. In case of duplicate records
8. Invalid time or position change. (the 7th and 8th come under 'time sequence' check)

The above tasks are performed by several routines which are briefly explained in the following text.

Important routines in MQC:

1 . Routine METQC :

All the individual parameters in the record are first read into respective variables (variables declared in the program) and each variable is thoroughly checked.

- Flag values of variables like cloud height, visibility, total cloud amount, WDIR, WSINDIC, etc., are checked. Here, the flags refer to any character that denote the actual value of the variable.
- Variables like temperatures, SLP, WS are checked whether their actual values are within allowable range or not. Table 3.2 and 3.3 show the check for SLP and DBT respectively.

Air Pressure (P)	**QC Flag**
1000 hPa < P < 1050 hPa	Correct
930 hPa < P < 999.9 hPa	Correct
1050 hPa < P < 1070 hPa	Doubtful
870 hPa < P < 930 hPa	Doubtful
All other values	Error

Table 3.2 : Description of the QC flags assigned to Air pressure

Latitude	DBT	QC Flag
< 45	< -25 ^{o} C	Error
	> 40 ^{o} C	Doubtful
> 45	> 40 ^{o} C	Error
	< -25 ^{o} C	Doubtful
Latitude	**SST**	**QC Flag**
< 45	< -20 ^{o} C	Error
	> 37 ^{o} C	Doubtful
> 45	< -20 ^{o} C	Doubtful
	> 37 ^{o} C	Error

Table 3.3 : Description of the QC flags assigned to DBT

- Wind speeds must be less than 40 m/s or 80 knots. If either WS or WDIR is zero then QC flag of wind speed is given inconsistent.
- DPT and WBT are given QC flags only after DBT and DBT sign have passed the QC. If DBT is found to be correct then the remaining temperatures are tested for consistency and then given QC flags.

  - DBT < WBT (both DBT , WBT Qced as Inconsistent)

  - DBT < DPT (both DBT , DPT Qced as Inconsistent)

  - WBT < DPT (both WBT , DPT Qced as Inconsistent)
- Consistency check is made between cloud parameters also. For example, if total cloud amount is missing but there are values given to genus of low or medium or high clouds, then an inconsistent flag is given in the QC flag.
- Present weather is checked for its flag value. It is also checked against latitude. This is needed because, the weather pattern mentioned must be feasible to that latitude.
- Primary and secondary wave period and height are checked

2 . Routine INIFULLNESS:

This routine checks whether the fields are complete in information. SLP, DBT, DPT, WBT, amount of pressure tendency, amount of precipitation, SST, present weather, visibility, WDIR, WS are checked for their completeness. Leading spaces are ignored. If any element is found to be incomplete then it is further not checked.

3 . Routine TSCHECK (Time Sequence Check):

- This routine checks whether records reported from each ship are in accurate temporal and spatial sequence. The difference in time and distance between two subsequent observations reported from the ship and the average speed of the ship are used to determine the accuracy of time and geographical position reported in the record.
- The rate of change of latitude must be less than 0.7 deg/hr
- The rate of change of longitude must be according to the values in the table 3.4 shown below. This value is latitude dependent because, distance between longitude is not uniform across all the latitudes.

  In order to check the NODPAC data for time sequence check, a separate fortran routine was written following the MQC guidelines.

Latitude	Change
0 – 39.9	< 0.7 ^{o} / hr
40 – 49.9	< 1.0 ^{o} / hr
50 – 59.9	< 1.4 ^{o} / hr
60 – 69.9	< 2.0 ^{o} / hr
70 -79.9	<2.7 ^{o} / hr

Table 3.4 : Rate of change of longitude at different latitudes

Alterations:

The IMDdata had many records in which several variables were either missing or were erroneous. Many records had no callsign, proper FM version, etc. The online MQC program is written in such a way that the records with above mentioned deficiencies would be rejected. But the organizational data and values of Marine or meteorological parameters in those records might actually be right. Hence necessary changes were made as discussed in the table 3.5, inorder to retain such records irrespective of the missing non Marine or non meteorological parameters.

MQC	Alteration
Accepted country codes were based on ISO alpha-2 list	Check of valid country code was skipped. As there were records with numerical country codes which is not part of ISO alpha-2 list..
If any of the important meteorological element was missing, the record was rejected	Such records were retained
Thorough check of the callsign was present	Such robustness is reduced as for many records, the callsign wasn't there.

Table 3.5 : Alteration made to the online MQC program before using it on IMDdata

This QC level is **Level-4**. After MQC check was done, all the individual variables namely, SLP, DBT, SPHUM, SST, WS, whose quality flag was set to one, were extracted into ".csv" files. The following variables along with their corresponding metadata were extracted and the total number of fields were 27. After this, all the QC check were carried separately for each variable.

3.5 Quality Control - Removing Records With Missing Values

A copy of IMDunique records after MQC check were taken and all the records with missing values of sea level pressure are removed. Similarly, from another copy of IMDunique data, records with missing values of wind speed, sea surface temperature are removed. In case of air temperature, the records with missing values of air temperature are removed from the wind speed files which have undergone the entire QC check. This was done to ensure that the wind speed values used for height correction of DBT must have passed QC check. The same files are used further for both air temperature and dew point temperature. Similar procedure was adopted for NODPAC data also.

3.6 Quality Control - Removing Land Points

Etopo 5-min file was used to mask data on the land. The latitude, longitude values in IMDunique records have a precision upto one decimal point. So, values in IMDunique records and

Etopo5min data were compared upto one decimal point without rounding off the etopo lat-lon values. The elevation of the location in each record is extracted from etopo file based on nearest lat-lon position present in it. Later, all the records with position whose elevation is greater than 0 were removed as those positions correspond to land.

3.7 Quality Control - STDEV Trimming

At this stage, all the IMDunique records which are yearly are made monthly. Monthly files were taken for STDEV trimming (**Level-6**) inorder to preserve the seasonal variability within the data. The procedure followed in statistical trimming is similar to that used in ICOADS with few changes. Data falling within a 3 degree box around each grid point are arranged in ascending order and divided into sextuples. σ1, σ5 are the difference between the median of the first and fifth sextuple and median (g) of the third sextuple respectively. g is the median of the third sextuple. σ1, σ5 are multiplied by a factor of 3.5 in order to avoid rejection of good data. Rest of the procedure was similar to that done in ICOADS (Slutz *et . al* 1985). The below figure 3.5 shows how outliers(black circles) have been removed in statistical trimming. Figure 3.6 shows the flowcharts of processing of each variable. Table 3.6 shows the number of records before and after each level of QC.

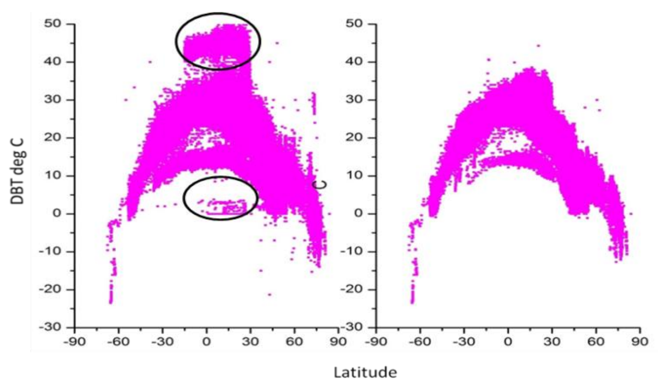

Figure 3.5 : Outliers eliminated after stdev trimming (black ellipses)

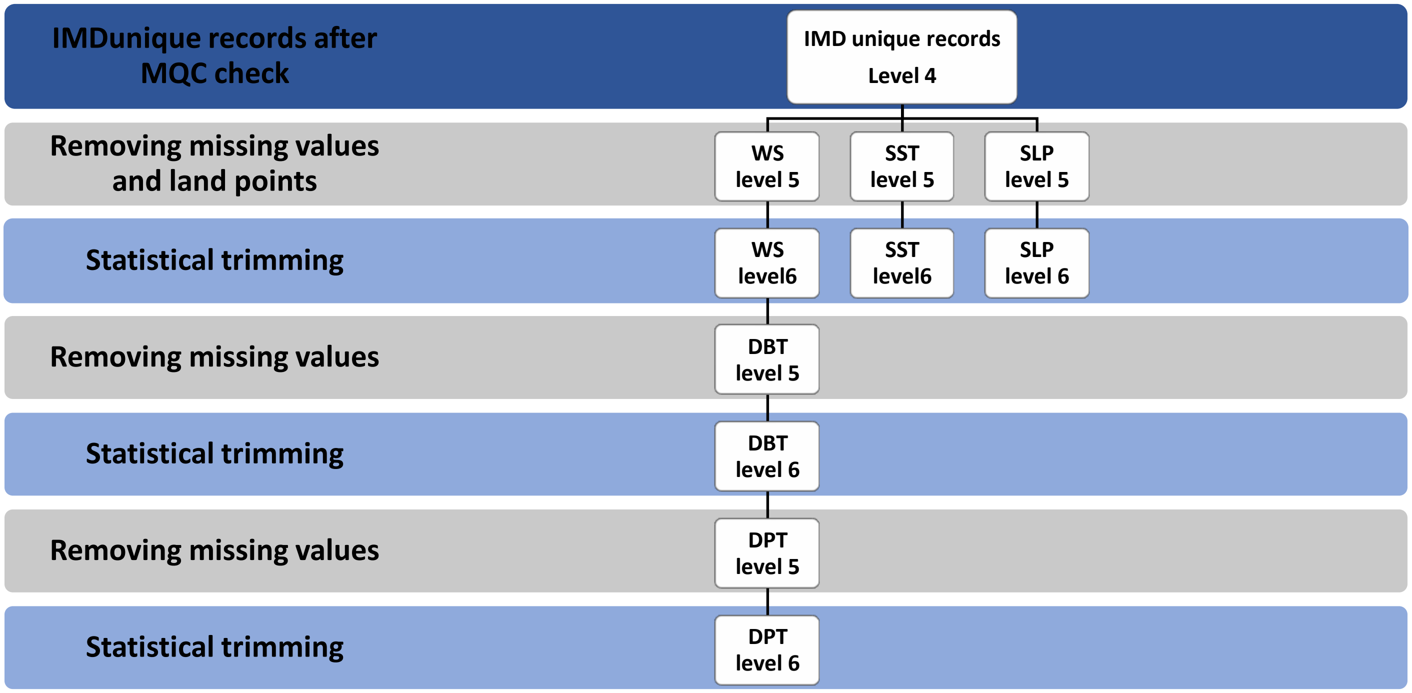

Figure 3.6 : Flowcharts of QC for each variable

Table 1.6 shows the number of records before and after each level of QC.

Data	No of records after MQC check	Removing records with missing value and land points	STDEV	% lost
IMDunique - SLP	7,03,994	6,85,905	6,71,576	4.6
IMDunique -DBT	7,03,994	5,61,158	5,31,762	25
IMDunique - DPT	7,03,994	4,58,081	4,26,414	40
IMDunique - SST	7,03,994	4,25,199	3,78,809	47
IMDunique - WS	7,03,994	6,22,630	5,66,204	12.5
NODPAC - SLP	9,258	9,242	8,537	0.7
NODPAC - DBT	9,258	8,185 -> 8,085	6,875	25
NODPAC - DPT	9,258	6,875	5,615	40
NODPAC - SST	9,258	6,703	6,023	34
NODPAC - WS	9,258	9,258	8,185	11

3.8 Quality Control - Visual Inspection

This QC check (**Level-7)** primarily identifies those data points which are peculiar from the rest of the points observed in similar conditions. Such data points may sometimes fulfill range test, may lie in the permissible limits of standard deviation. However, they sometimes become the cause of noise in carrying out objective analysis. Visual inspection was carried out to remove such data and is described in detail in this subsection. In this QC check each parameter is plotted against its latitude where it was observed, this is a method proposed by Uday Bhaskar *et al.* (2016). This method describes that any parameter plotted against latitude or longitude follows a pattern. Mathematically a polygon could be built across such pattern (Murali Krishna *et al.* (2016)). All the data points falling outside the polygon are rejected as they are considered as outliers. In this work, a polygon isn't used but all the isolated points which are very few in number and fall far apart from the rest of the cluster were considered as outliers. Each variable value in the record is plotted against the latitude value where the observation is made. Figure 3.7 shows a sample of polygon based QC. As, this is the last step of QC, there were very few number of points removed. The red circles around the points are the isolated points which are removed. Figure 3.8 shows sea level pressure and wind speed versus the latitude. It can be noted from the above plot in figure 3.8, that a lobe coming out from the polygon, starting from June and retrieving back in September. These are the points belonging to the low pressure systems that form in Bay of Bengal (BoB) during monsoon season and few of them belong to those over Red sea and Persian gulf under Inter tropical convergence zone (ITCZ). Similarly the peak protruding out from the polygon during monsoon in the wind speed (below plot in figure 3.8), corresponds to the increase in wind speed magnitude during monsoon time. This shows that even the unique part left from the IMDdata is having very good signal due to its good spatial and considerable temporal density.

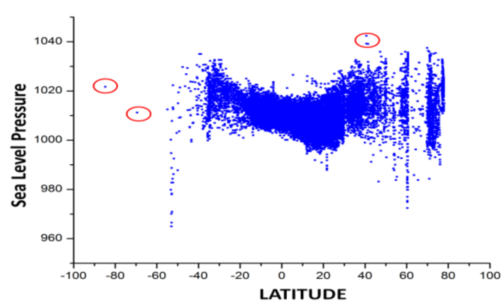

Figure 3.7 : Polygon QC (black ellipses around the points denote isolated points, which were removed)

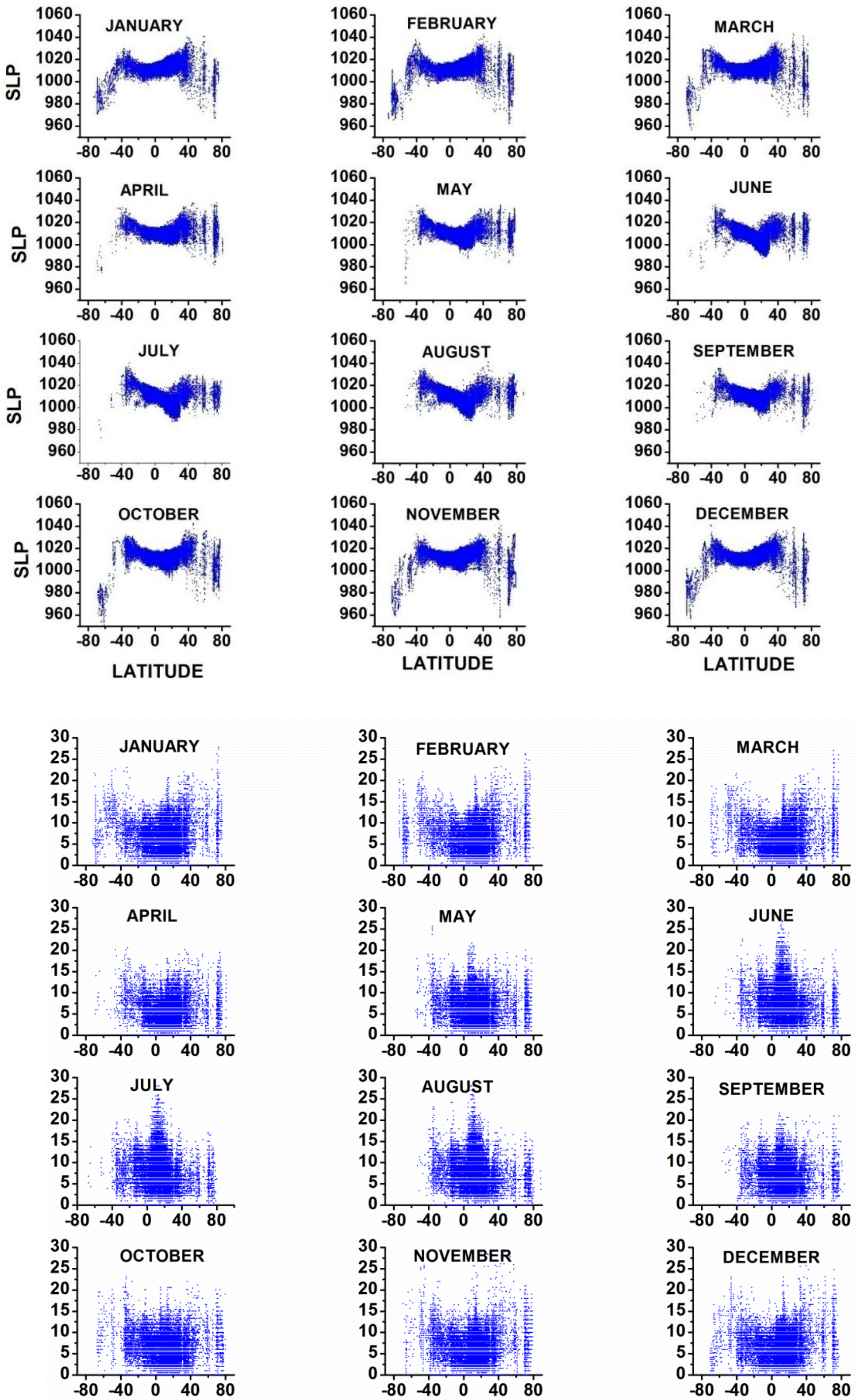

Figure 3.8 : Sea level pressure (above) and Wind speed (below) versus latitude for all months

3.9 Metadata Extraction And Height Correction

The properties of climate variables not only vary spatially but also in vertical. Thus height of measurement matters in determining the actual surface value of a parameter as it doesn't remain the same. The height of measurement varies with each ship, depending on the type and size of the ship, etc. Also the observation procedures followed to measure various parameters vary among different ships. The procedures depend on the type of ship, the background knowledge possessed by the ship personnel, the ship recruiting country, the observation facilities available, etc. The details of the measurement procedures, details of the ship, namely metadata are listed in WMO PUB No 47 document which is published every year. The recruiting countries submitted the details of ship, dimensions, measurement facilities available, measurement procedures followed corresponding to each ship callsign to the WMO and are published in this document. They were submitted yearly upto 2009 and from then, metadata were submitted quarterly. In this work, the type of VOS ship, platform type, kind of vessel, ship dimensions, height at which wind speed, air temperature, DPT are measured, the method of measurement, etc., are the metadata used.

3.9.1 Metadata Extraction

The source of the metadata files corresponding to the years 1961 to 2012 are given in table 3.7 .

Year	File / Folder
1961 - 1972	http://icoads.noaa.gov/metadata/wmo47/cdmp_1955-72/
1973 - 1994	http://icoads.noaa.gov/metadata/wmo47/kent_1973-94/WMO47/
1995 - 1998	http://icoads.noaa.gov/metadata/wmo47/wmo_annual/
1999 - 2007	https://www.wmo.int/pages/prog/www/ois/pub47/pub47-home.htm
2007 - 2008	https://www.wmo.int/pages/prog/www/ois/pub47/pub47-home.htm (Version - 3)
2008 - 2012	https://www.wmo.int/pages/prog/www/ois/pub47/pub47-home.htm (Version - 4)

Table 3.7 Source web links for the metadata used

All the callsigns, year, month of each record in the IMDdata were extracted. Month was also needed because the metadata in the latest years was published quarterly. The callsign in the record was searched in the metadata file of the corresponding year of observation. When it is matched, the corresponding metadata namely, 'type of VOS ship', 'Kind of vessel', 'height of thermometer', 'platform height,' exposure of hygrometer', 'SST measurement indicator', 'depth of SST measurement', 'height of anemometer' were extracted. If a call sign wasn't found in the current year metadata file then two previous year files are checked and then the next year file is checked. This is similar to the method followed by Josey *et al.* 1998. In this way metadata for IMDdata records were extracted and saved yearwise. Then each callsign in the IMDunique data is searched in these saved files and when found all the fields were appended at the end of the record. After appending the metadata the total number of fields in IMDunique ".csv" files summed upto 35.

Figure 3.9 is the number of records in the IMDdata for which the metadata could be obtained from WMO 47 document. Metadata was extracted for the data spanning from 1982 to 2012, as there were no callsigns for the earlier data i.e. 1961 to 1981. For the data from 1961-1981 in IMDdata the height of thermometers and anemometer were taken to be at 18 m and 20 m based on the discussion in Josey *et a.l* (1998). Metadata of NODPAC was obtained through personal communication. The metadata of ICOADS records was downloaded along with the actual data itself from CISL research data archive. Figure 3.10 shows the spatial density of the records where some metadata about the type of ship were available which were used to obtain the height of measurement which is discussed in the subsequent sections.

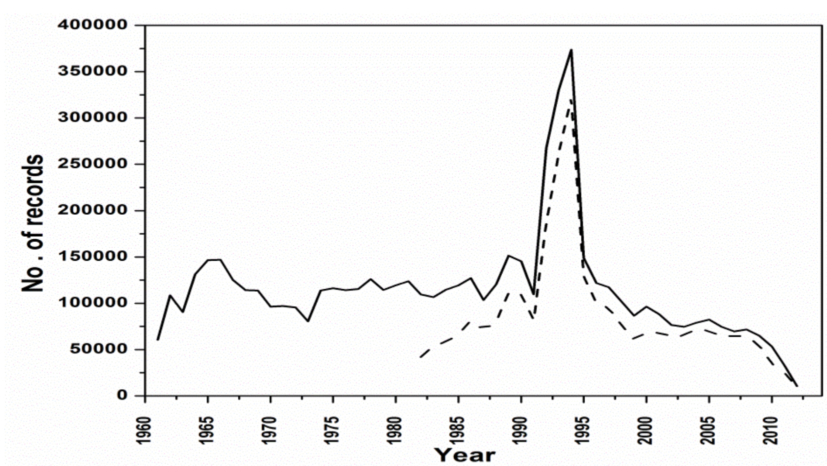

Figure 3.9 : Raw IMDdata (solid), no . of matched callsigns from WMO 47 (dashed)

Having extracted the above details, wind speeds, dry bulb temperatures, specific humidity were corrected to 10 m height following Large and Pond (1981). Detailed procedure is explained in section 3.9.2 under respective parameter.

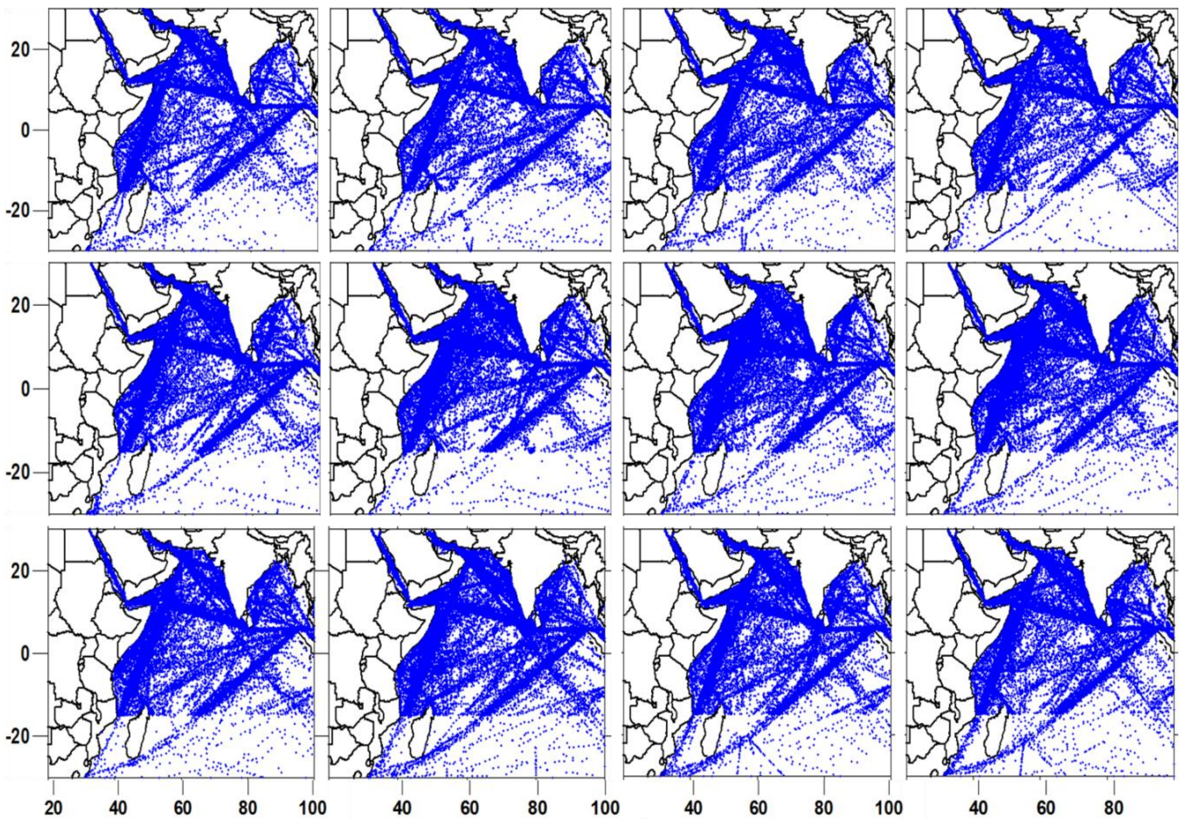

Figure 3.10 : Spatial density of availability of "kind of vessel" metadata for IMD unique records. "Kind of vessel" was used to determine anemometer measurement height and platform height. (Twelve plots correspond to the twelve months)

3.9.2 Height Correction

Wind Speed

ICOADS and IMDunique data consisted wind speeds measured by both anemometer and visually estimated through Beaufort scale equivalent. Thomas *et al.* 2004 and Lindau 1995 discussed that the Beaufort scale gives wind speeds under neutral conditions at 10 m height directly. Kent and Taylor 1996 mentioned that the Beaufort estimates aren't to be corrected to 10 m height under stability conditions. As many number of records have visually estimated wind speeds(shown in figure 3.11), the anemometer wind speeds are also corrected to 10m height under neutral stability conditions. Also, wherever wind speed indicator is missing in the record, the corresponding wind speed value was assumed to be a Beaufort estimate (Josey *et al*. 1998). As wind speed values from ICOADS and IMDunique records are corrected under neutral condition to 10 m height, the wind speed values from NODPAC data are also corrected under similar conditions.

The wind speed onboard Indian navy ships was measured only by anemometers which are fixed at a height around 15 to 20 m. So, a constant height of 17.5 m was chosen for the wind speed values from the NODPAC records. The anemometer heights for the winds in IMDunique data is taken from the WMO metadata and in the case of ICOADS records the metadata is obtained along with meteorological parameters. If direct anemometer height was mentioned then the same value was used or else with the help of the metadata regarding the type of VOS ship and vessel type, the corresponding information about height is noted from the table given by Kent *et al.* 2006. The anemometer height is then taken as height of measurement of wind speed. The table 3 of Kent *et al.* 2006 provides ship length, platform height, anemometer height and difference between platform height and anemometer height. If none of the direct measurement height or the metadata regarding the ship type were present then a default value of 20 m is taken as in Josey *et al.* 1998.

The number of anemometer measured and Beaufort estimated wind speeds in the records (monthwise) is shown in figure 3.11 .

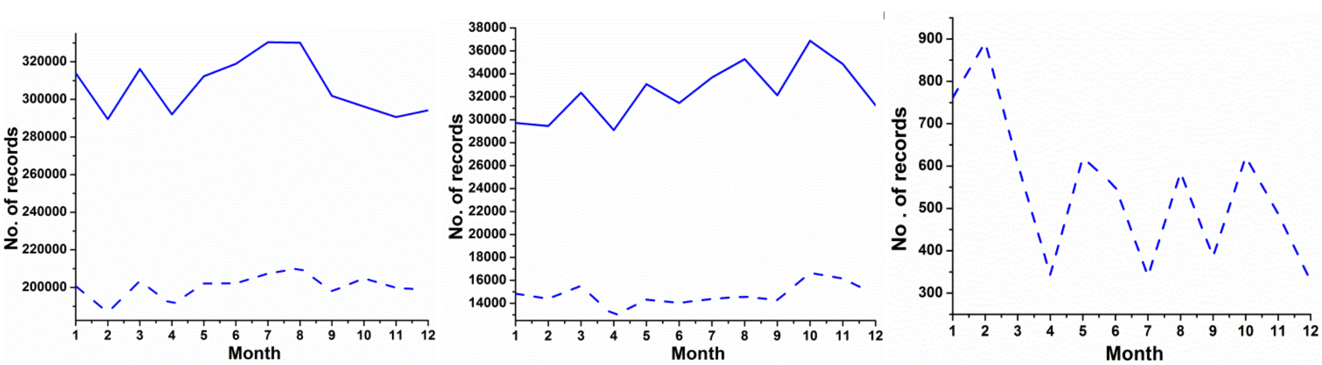

Figure 3.11 : Number of records that are estimated using Beaufort scale and measured by anemometer. Left: ICOADS data, Middle : IMD unique data, Right: NODPAC data. (solid-Beaufort estimates, dashed-anemometer measured)

Air Temperature

For correcting air temperature under stability conditions, SLP, SST, WS, SPHUM are all required. Thus the records with SLP, SST and WS missing are not height corrected. However, wherever DPT alone is missing, SPHUM is calculated assuming 80% relative humidity.

Height of temperature measurement onboard Indian navy ships was at around 10 to 15 m. So, a constant height of 12.5 m was taken. The measurement height for IMD data is extracted from the WMO metadata and in the case of ICOADS records the metadata is obtained along with meteorological parameters. A similar procedure to that of wind speed was followed. If the direct value of temperature measurement height was present, then the same was used or else, platform height was taken from the table given in the work by Kent *et al.* 2006. Here in case of DBT measurement height, platform height plus 1 m was taken as the height of measurement of temperature following the discussion in Thomas *et al.* 2004**.** If the height of measurement couldn't be retrieved by the above mentioned methods then a default value of 18 m is taken. The height of DPT measurement is same as that of DBT.

The first step in DBT-height correction was to bring the wind speed measurement to DBT measurement height. This was done assuming neutral stability similar to the one used to convert wind speeds to 10m height but here the final wind speed would be at a height of DBT measurement. Teten's formula from Buck (1981) was used to calculate vapor pressure at saturation and then specific humidity is calculated from vapor pressure and sea level pressure. Wherever DPT was missing a default value of 80 % was taken for relative humidity and the specific humidity is calculated from it. Then the rest of the procedure involving loop iteration against stability value was adopted from Da Silva *et al.* 1994. Wherever DPT is present only those records were taken to calculate specific humidity values and correcting the same to 10 m height.

From figure 3.4f, it can be observed that, the concentration of data is high in Indian ocean. The data density of NODPAC records is also highly concentrated in the North Indian ocean. As the aim of the work is to see the enhancement in the existing ICOADS climatology after adding the records from IMDunique and NODPAC, the climatology is restricted to 30E - 120E and 30S - 30N. The records of ICOADS-QCed, IMDunique, NODPAC are all combined month wise and separately for each variable namely, SLP, DBT, SPHUM, SST, WS. All of these records have undergone QC and DBT, SPHUM, WS values are corrected to 10 m height. The next step is to objectively analyze the data to prepare monthly climatology of the above mentioned variables.

3.10 Objective Analysis

After all the levels of QC, gridding is done to produce monthly climatologies of DBT, SST, SPHUM, SLP, WS, UWIND (zonal wind component), VWIND (meridional wind component), using surfer software. Median filtering was used as the gridding method, where all the values at a grid point are arranged either in increasing or decreasing order and the median value is selected as the grid point value. This gridding method was chosen, as the median value would be the best representation of the climatology as discussed in Helber *et al.* (2009). Then blanking is done using a blank file to mask all the land points, if any. Note that in the gridding procedure, there may be data points which would appear on land. A surfer blank file has a series of headers. Each header has a number of proceeding data points and a blanking flag number. If the flag is '1' then blanking is done inside the boundary and if it is '0' then blanking is done outside the boundary. Gridding is done at 1-degree resolution in the Indian ocean region (30S - 30N, 30E - 100E) as IMDunique data and NODPAC records were mostly concentrated in this region.

Following subsections discusses the number of records from each of the dataset i.e. ICOADS-QCed, IMDunique and NODPAC used in gridding under each variable. To observe the enhancement, the gridded fields are compared with ICOADS gridded climatology. The ICOADS 1-degree standard climatology with monthly third sextuple statistic was used for comparison.

3.10.1 Sea level pressure

The total number of records for sea level pressure from IMD unique data and NODPAC data were 5,81,500. And those from ICOADS are 1,08,21,943. The monthly count of the records used in gridding are given in table 3.8.

3.10.2 Wind speed

The total number of records for wind speed from IMD unique data and NODPAC data were 2,83,621. The number of ICOADS records that are used for gridding were 61,32,840. Those records with incomplete information about wind speed are rejected. Only those records which had clear information about the method of observation and dimensional units were extracted. The monthly count of the records used in gridding are given in table 3.8 . In case of wind speed, gridding is done for u, v components and scalar wind speed separately.

3.10.3 Dry bulb temperature

The DBT records which are used for gridding are height corrected. As it can be noted that for height correction under stability conditions, certain other parameters are also required, like, SLP, WS, etc. So, the records which are to be height corrected would need all the above parameters to be present. Because of this, the count of the records used for gridding has reduced. The number of records for dry bulb temperature from IMDunique data and NODPAC were 3,31,688 and of specific humidity are 2,39,492 which are less when compared to other variables. In case of ICOADS, these are 42,50,113 in number for DBT and 37,06,544 for specific humidity. The monthly count of the records used in gridding are given in table 3.8.

3.10.4 Sea surface temperature

The number of records for sea surface temperature from IMD unique data and NODPAC data were 3,33,622. And those from ICOADS are 1,17,13,529. The monthly count of the records used in gridding is given in table 3.8 .

	Sea Level Pressure			Wind Speed			Dry bulb temperature		
Month	ICOADS	IMDunique	NODPAC	ICOADS	IMDuniqu	NODPAC	ICOADS	IMDuniqu	NODPAC
1	910125	46147	809	517414	22095	761	222558	26188	621
2	835408	44526	1094	479297	20899	892	378934	24780	632
3	936225	49134	756	523220	22871	605	223389	26923	386
4	906233	43215	431	486708	19398	343	198407	22878	356
5	938230	48297	717	518372	24343	620	412290	28416	378
6	905117	44499	640	523174	22468	551	410691	26696	387
7	928821	47286	384	540825	24338	340	420874	28740	238
8	927440	49921	668	544797	25484	585	423048	30240	312
9	851312	47501	490	503269	22983	386	390249	27558	241
10	882563	54399	746	504722	25733	622	392037	30239	389
11	883122	52528	562	494670	24193	487	387243	28439	312
12	917347	46342	408	496372	22296	328	390393	26125	214
Total	10821943	573795	7705	6132840	277101	6520	4250113	327222	4466

	Specific Humiidty			Sea Surface Temperature		
Month	ICOADS	IMDunique	NODPAC	ICOADS	IMDunique	NODPAC
1	195411	19751	529	964993	26261	1152
2	329771	19192	587	882978	24450	1821
3	195986	20735	320	999938	27702	1097
4	173507	17732	268	969948	24168	514
5	359560	19838	185	1007521	28560	785
6	357307	18627	184	983988	24167	722
7	368538	19257	136	1019055	26132	516
8	370227	20618	244	1004669	27829	688
9	341594	19560	208	928933	25965	811
10	341716	21621	301	973593	31293	927
11	337195	20690	216	976020	29951	678
12	335732	18553	140	1001893	26864	569
Total	3706544	236174	3318	11713529	323342	10280

Table 3.8 : No . of records that are used in gridding for all the five variables

4 RESULTS AND DISCUSSIONS

4.1 Comparison with ICOADS climatology

In this section, we evaluate the new climatology by comparing with the existing ICOADS climatology. Though there is 11 % unique data (≈ 7,00,000 records), but after QC, the numbers have come down to approximately 80% (≈ 5,00,000 records) for SLP and approximately 45% (≈ 3,00,000 records) for remaining variables. **It is observed that there is no significant improvement in ICOADS climatology even after adding these new records**. Our attempt is to build a new climatology by adding new data to ICOADS available data. We expect the new product to improve climatological representations as compared to the existing ICOADS climatology. However, since the two climatologies look similar, we have done some statistical analyses to investigate further. Next few sections describe the same.

Frequency distribution of the ICOADS data with and without adding IMDunique and NODPAC data and spatial correlation between the same are explored to ascertain the cause of lack of improvement. ICOADS is a collection of enormous amount of data with spatial data density which is completely full across all the ocean basins. As there are no gaps, any amount of data added would only blend into the existing data unless until when the new data is carrying a new signal. In such cases there would be a new peak arising in a data distribution plot which is not witnessed in case of any variable of any month. Also, the spatial correlation between the ICOADS dataset with and without adding the new datasets is almost 0.9 and more, at every grid point. This establishes the self-robustness of the ICOADS climatology. Following sections 4.2, 4.3 and 4.4 discusses the frequency distribution, spatial correlation and bias between ICOADS data with and without adding the IMDunique and NODPAC datasets.

4.2 Frequency Distribution

The frequency distribution plots of various variables for which the climatology has been prepared by adding the IMD and NODPAC data to ICOADS data, are shown in figures from 4.1 to 4.7 . It can be observed that there is basically no much difference between the distributions after adding the new data. In the distribution plots of the combined data , there are slight increments in the existing bars of ICOADS records because of the addition of new records.

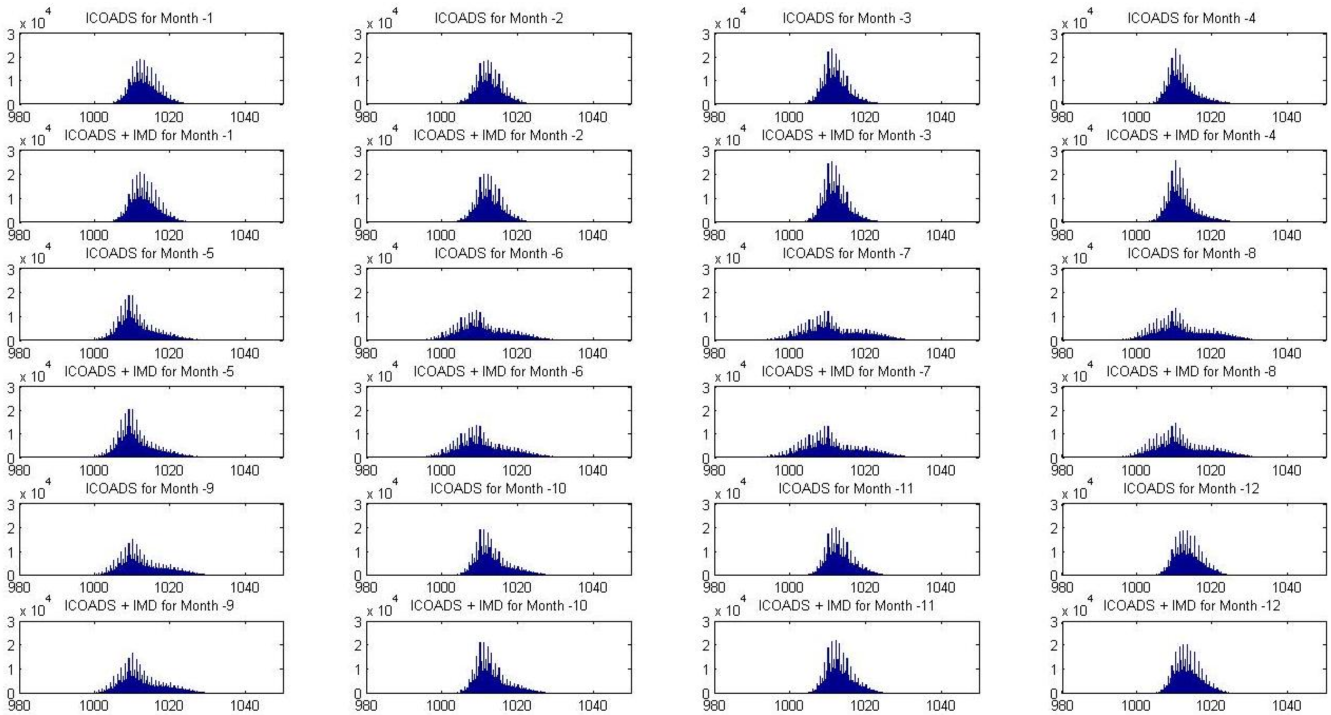

Figure 4.1 : Comparison between frequency distribution of ICOADS data with and without adding IMDunique and NODPAC data for sea level pressure

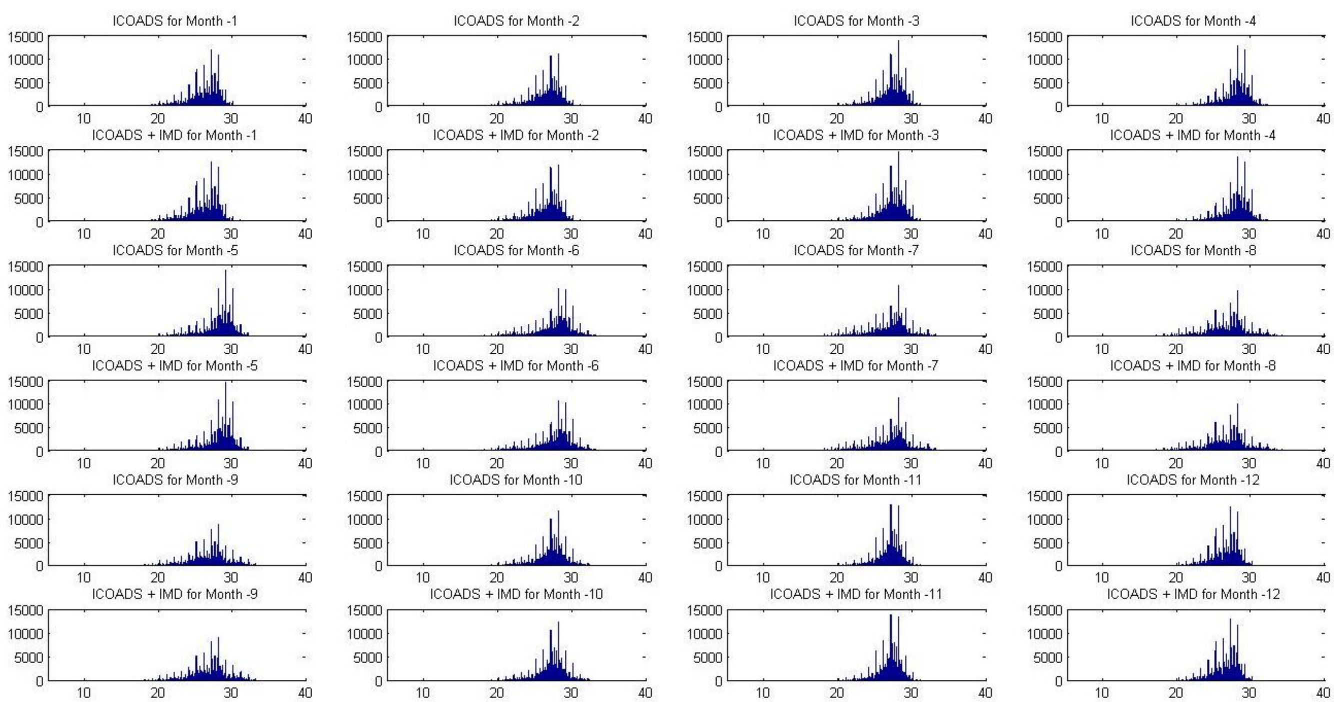

Figure 4.2 : Comparison between frequency distribution of ICOADS data with and without adding IMDunique and NODPAC data for air temperature

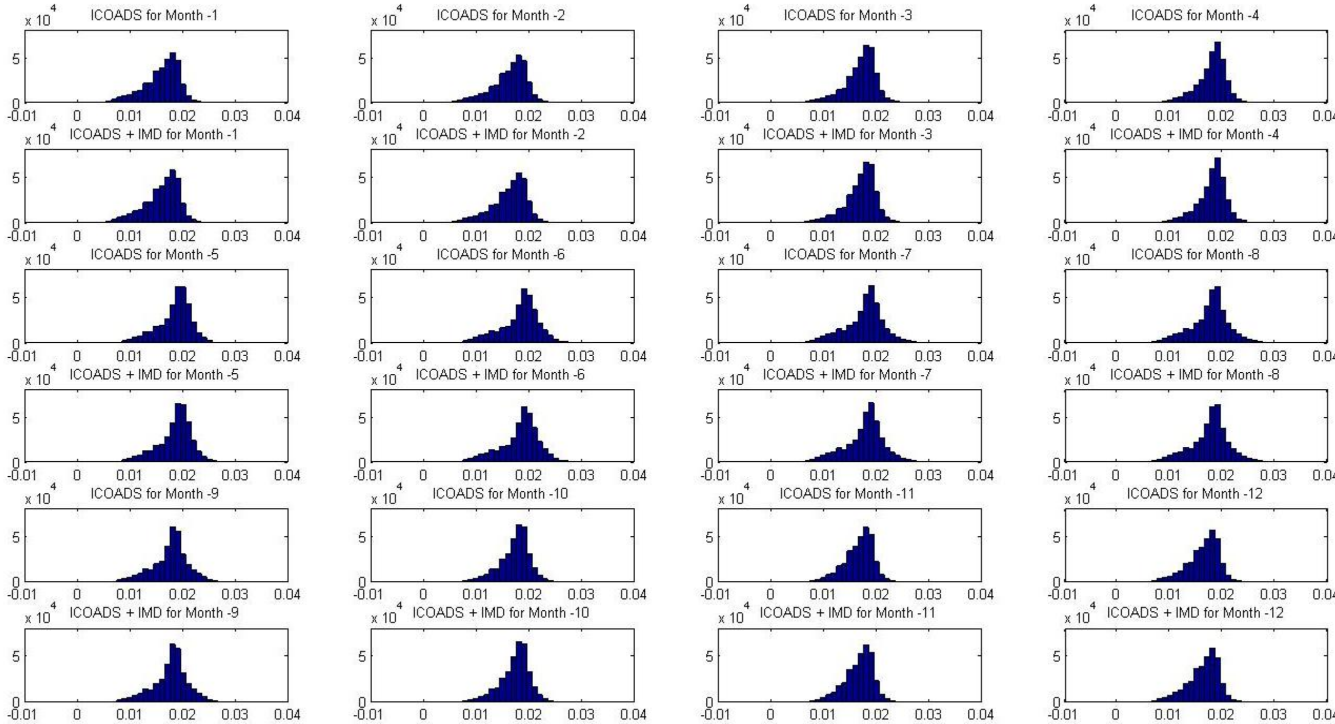

Figure 4.3 : Comparison between frequency distribution of ICOADS data with and without adding IMDunique and NODPAC data for specific humidity

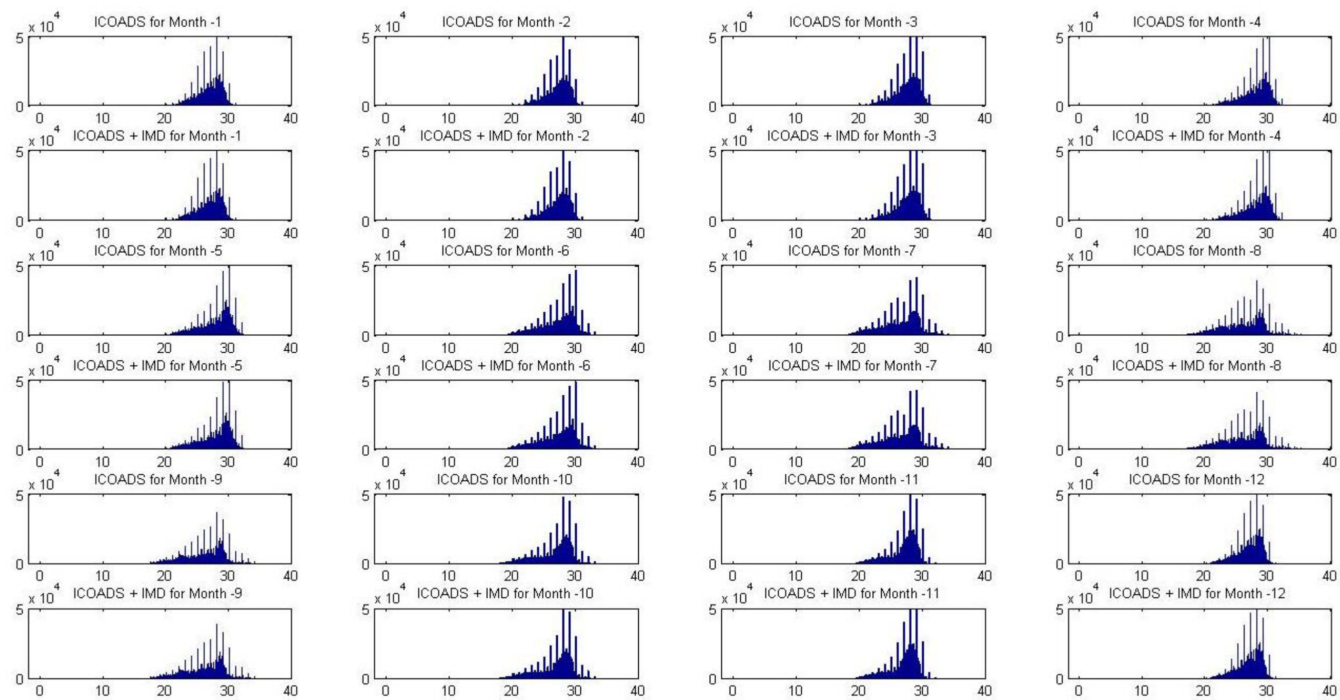

Figure 4.4 : Comparison between frequency distribution of ICOADS data with and without adding IMDunique and NODPAC data for sea surface temperature

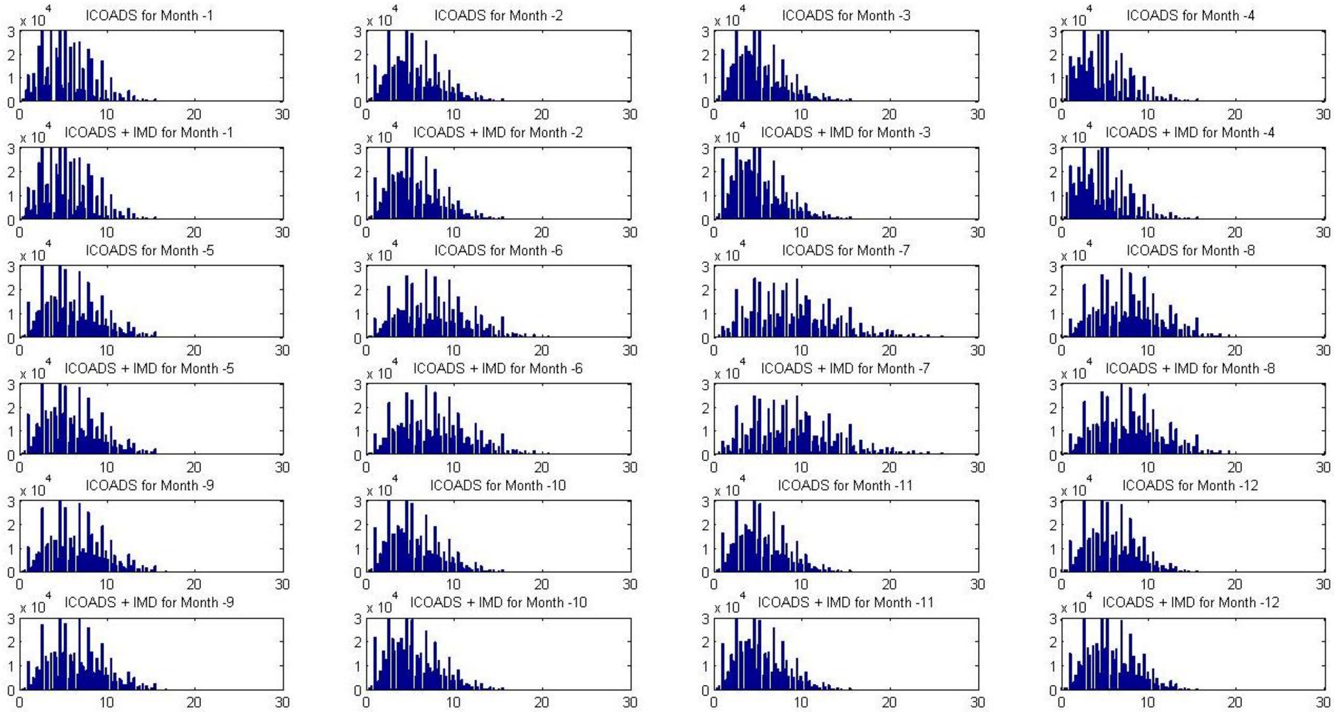

Figure 4.5 : Comparison between frequency distribution of ICOADS data with and without adding IMDunique and NODPAC data for scalar wind speed

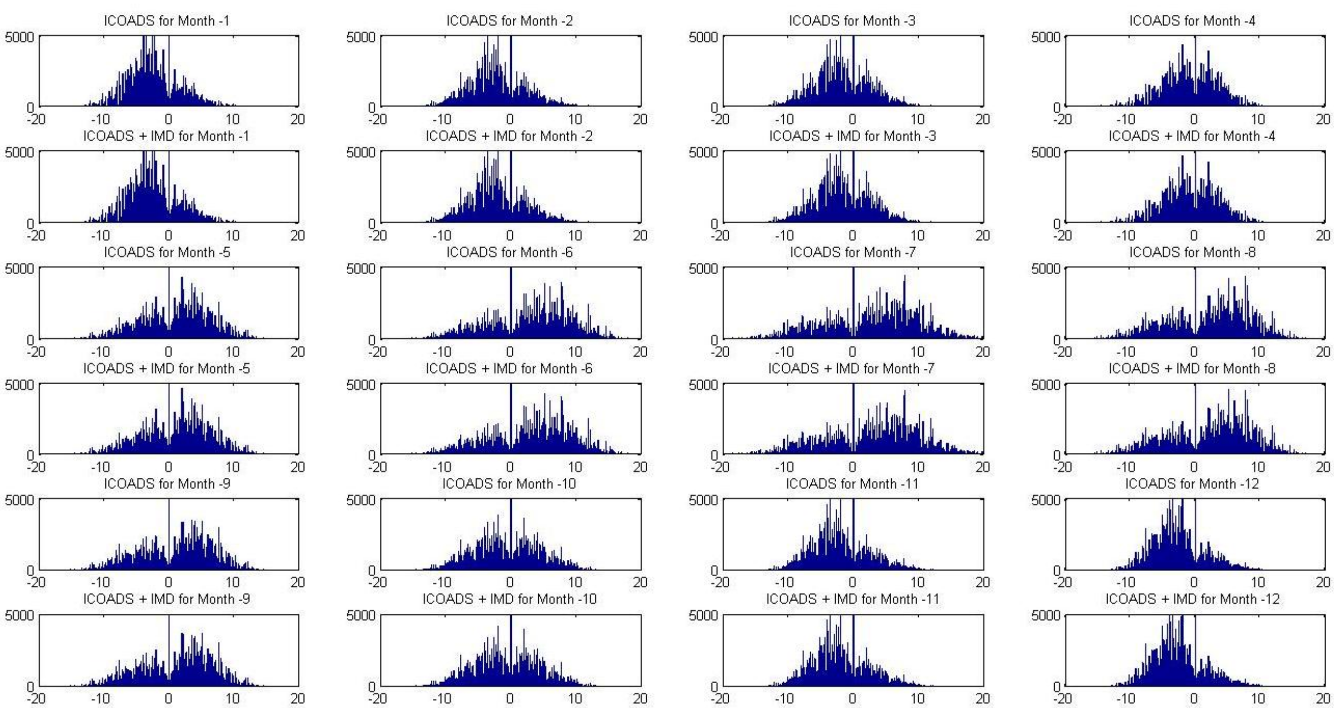

Figure 4.6 : Comparison between frequency distribution of ICOADS data with and without adding IMDunique and NODPAC data for zonal wind

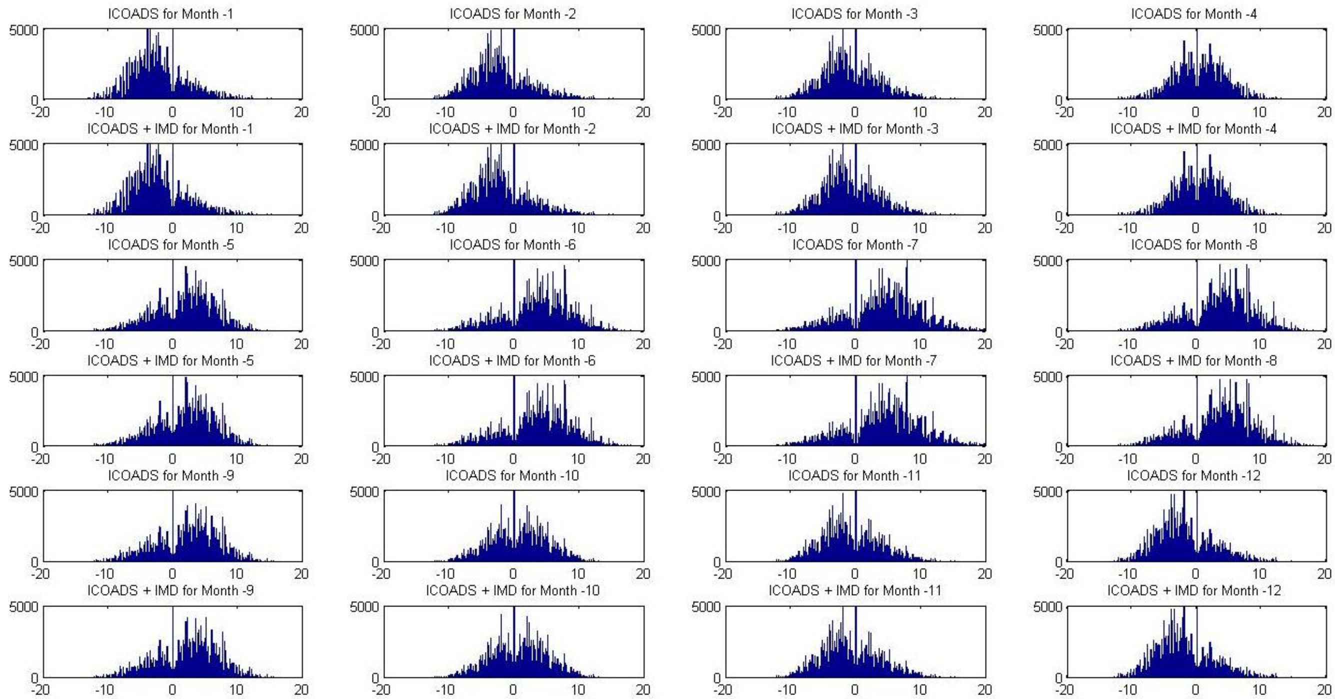

Figure 4.7 : Comparison between frequency distribution of ICOADS data with and without adding IMDunique and NODPAC data for meridional wind

4.3 Spatial Correlation

Figure 4.8 show the spatial correlation between ICOADS data and ICOADS+IMDunique+NODPAC data. It was observed that they were correlated very well at almost all the grid points.

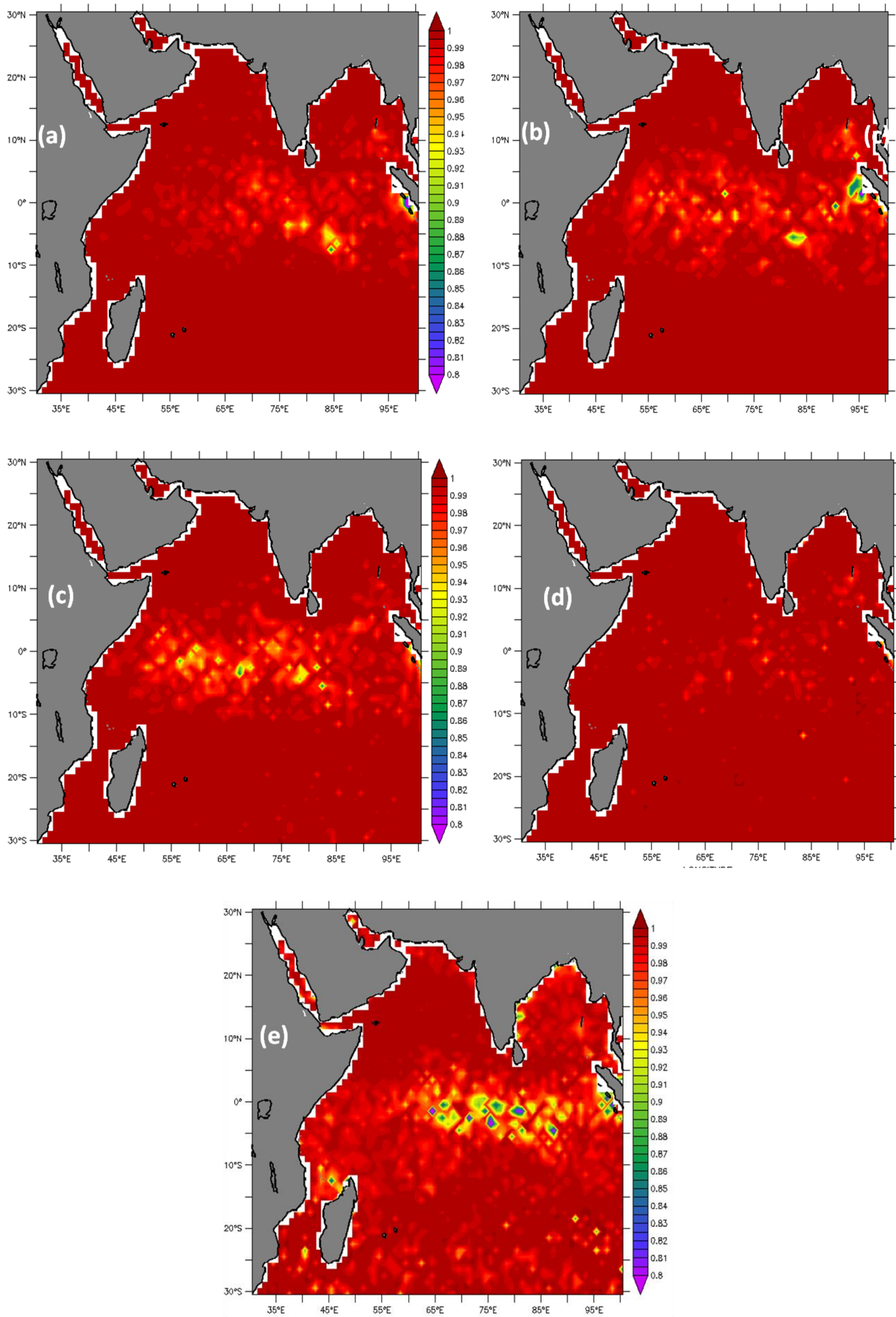

Figure 4.8 : Spatial correlation between ICOADS climatology before and after adding new records of all the five variables (a) DBT (b) SPHUM (c) SLP (d) SST (e) WS

4.4 Bias

Bias is calculated across spatial domain between the ICOADS data before and after adding the IMDunique and NODPAC data. The spatial plots of bias are given in figures 4.9 to 4.11 . Following formulae is used to calculate bias.

$$Bias = \sum (ICOADS_i - (ICOADS + new\ data)_i)$$

where *i* is the number of the month, so I = 1 to 12

Σ is the summation across all the months

$ICOADS_i$ is the grid value from ICOADS gridded field of *i* th month.

$(ICOADS + new\ data)_i$ is the grid value from ICOADS+IMDunique+NODPAC gridded field of *i* th month

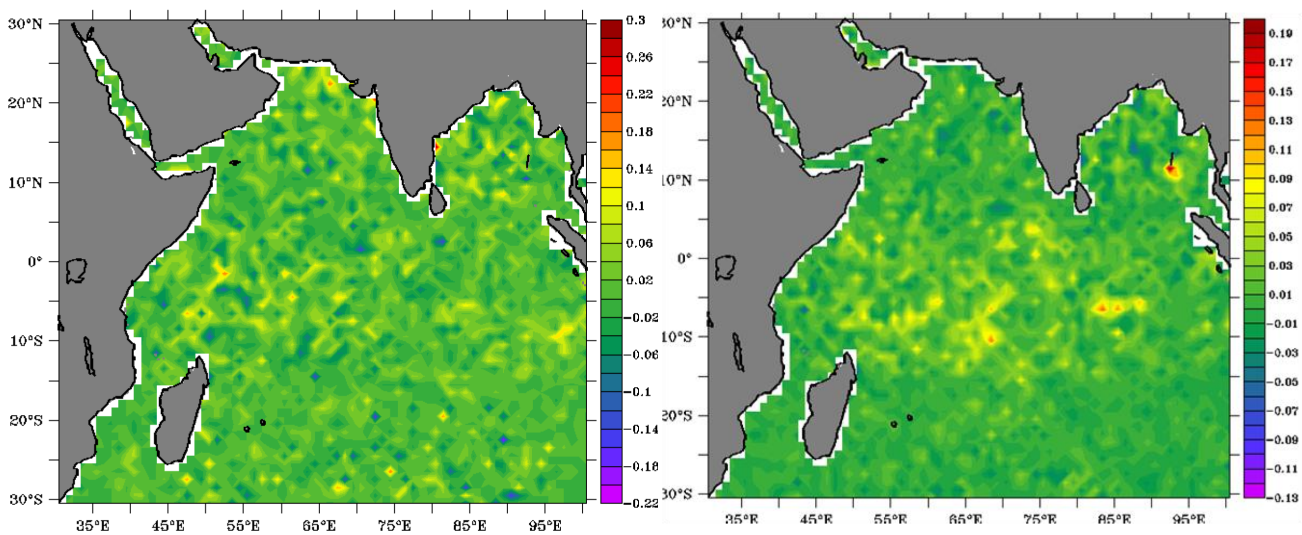

Figure 4.9 : Bias in Sea level pressure (hPa) and dry bulb temperature (deg Celsius)

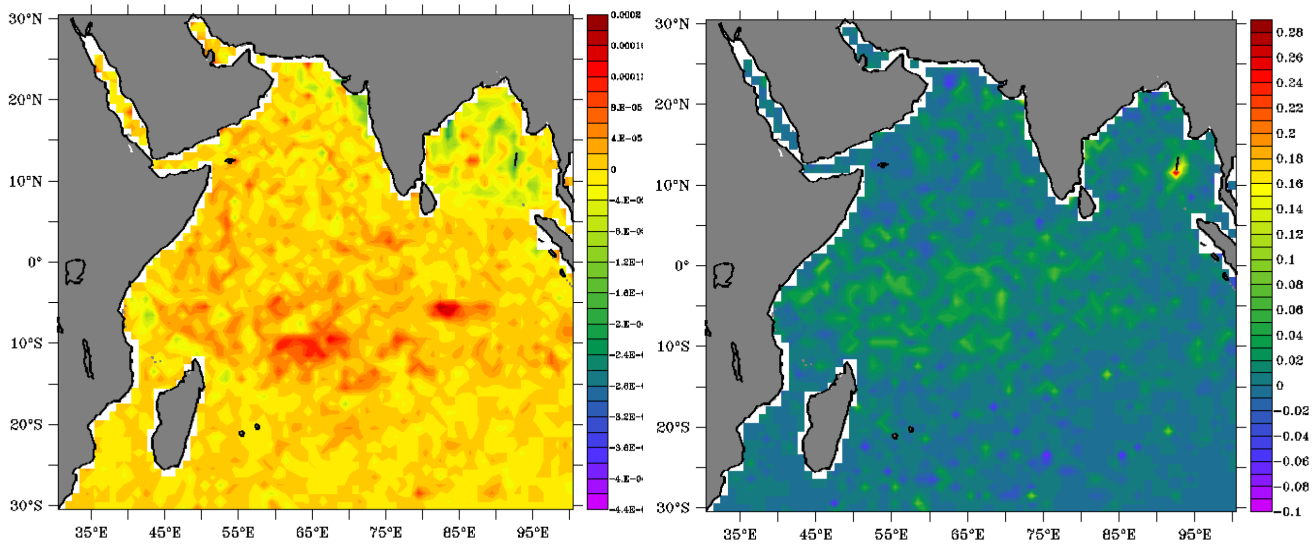

Figure 4.10 : Bias in Specific humidity (g / kg) and Sea surface temperature (deg Celsius)

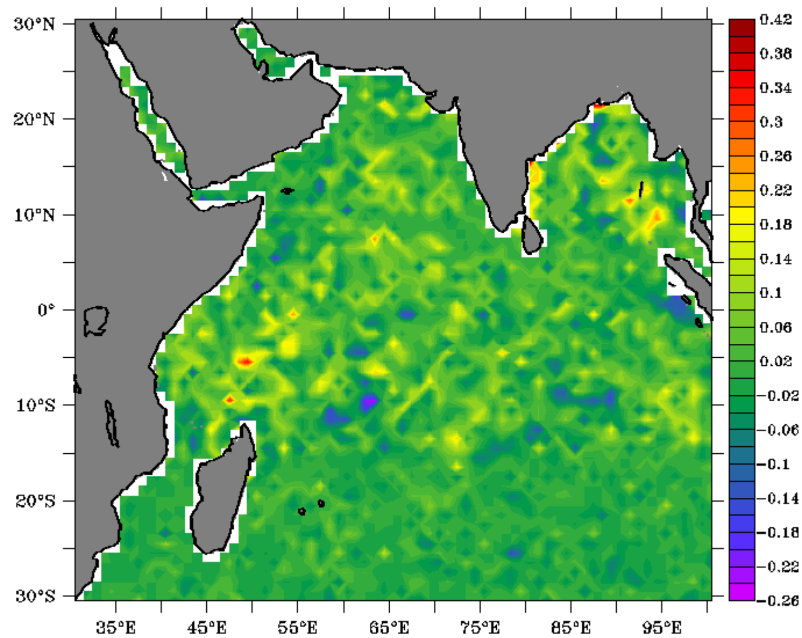

Figure 4.11 : Bias in Wind speed (m/s)

5 CONCLUSION AND FUTURE SCOPE

Ship observations are one of the oldest and reliable observational component for collecting marine-meteorological data. The collection in ICOADS dataset is huge and will always be the best choice for studying meteorological parameters across oceans and also few of the ocean parameters. In simple words, these ship records are a boon to study air-sea interaction processes. Adding any number of records to this dataset makes it more robust.

We have made an attempt to make use of the new ship records obtained from IMD data and NODPAC data. Even though there is no significant improvement, the addition of new data into existing climatologies is always beneficial and it is hoped that this attempt will essentially be useful to the user community.

Nevertheless, addition of new records (IMDunique and NODPAC) into ICOADS individual year-monthly climatologies is expected to show a considerable improvement. This task has already been initiated. Also, preparing a decadal climatology with the latest years wherever there is substantiate data records with complete information of all parameters and their metadata is another task that would be taken up.

5.1 Limitations Of The Dataset

In this work, ship records obtained from IMD are compared with the existing ICOADS ship records and the unique data records are extracted. This unique data along with NODPAC data are added to the ICOADS ship records and a new climatology is derived. Statistically there is no much significant difference between the ICOADS monthly climatology before and after adding the new records.

While checking ICOADS and IMD data records, in the hard duplicate check, all of the hard duplicates are eliminated without referring to which record could actually be the right one. Also, wherever the height of measurement of meteorological parameters are absent and couldn't be fetched from other sources as discussed in section 4, default values of 18m , 20m (according to Josey *et al.* 1999) were taken as wind speed and DBT measurement height without reference to ship or platform type. This is because, there is no metadata information available and in addition to that there are no callsigns for many records . This would definitely introduce certain amount of error.

Bias corrections appropriate to the data available are formulated but are not applied for a number of reasons. One reason is that, the absence of values of some parameters in the record. For example, inorder to correct for bias in DBT, RWS is needed. For calculating RWS, ship speed and direction are required. But in many records, these values are absent. Also, there are many records with missing callsigns. Without a callsign, the ship metadata cannot be extracted from WMO PUB 47 document. However, preparation of climatologies over a decade or so, with the latest years can be attempted. Because, in the latest year records, all the data in the records are present and metadata is also definitely available.

6 Annexure - I BIAS CORRECTIONS

It has been recognized that the observations made onboard the ships are subjected to both systematic and random errors. Errors in the observations can be due to faulty working of the instrument, improper calibration, errors while entering the value into the log sheet, transmission error, errors due to improper measurement method, etc. The magnitude of the errors vary depending on the source. Some of them may be small but may become a cause behind erroneous results, for example, forming a trend(Cardone *et al.* 1990) or systematic biases in flux estimation (Kent *et al.* 1992). Some of the errors are inherent in the data and sometimes may even cancel out when huge number of observations are taken as in case of random errors. Whereas random errors are difficult to point out and correct, the systematic errors are often easily recognised and hence corrected. It has been recognized that measurement methods could cause biases in ship observations. In a project titled VSOP-NA (Voluntary Observing Ships Special Observing Project for the North Atlantic), the effect of different instrumentation and observing practices on the ship data was established(Kent *et al.* 1992). Thus the biases due to measurement techniques are to be corrected. The following bias corrections were worked on:

1. Biases in Beaufort estimates of wind speeds due to inaccurate Beaufort scale
2. Biases in air temperature due to the heat given off by the ship body
3. Biases in DPT when measured in unventilated screens or improperly wetted wicks.
4. Biases in SST when measured through a thermometer placed in engine-cooling system.

The bias correction of wind speed has been taken up as a separate whole task. The previous authors who tried to derive a correction for correcting the Beaufort estimates couldn't come with a globalized correction which would be valid for wind speeds measured across all ocean basins. An attempt has been made to derive a new correction which would be valid for Indian ocean exclusively.

6.1 Correction of Dry bulb temperature

On ships DBT is measured by screened thermometers or hand held thermometers. As mentioned earlier, the value measured by any method was found to be effected by the ship body heat and also on relative wind speed. This is based on the discussion by Kent *et al.* 1993. He compared the observations with a model output. He found that air temperature sensor, ship dimensions didn't affect the difference between the observations and model output. The difference between observations and model output was dependent on incoming solar radiation and relative wind speed. The difference increased with increasing incoming solar radiation. However RWS played equally important role in carrying the heat away from the ship body. Increasing RWS has been observed to decrease the difference. In case of night time observations, the difference tended to be more negative with increase in RWS. Kent devised a formula to correct this difference. This difference or the error is directly proportional to incoming solar radiation except due to the effect of RWS. The correction is as follows,

$$\delta T = (2.7 * 10^{-3}) * SW - (3.2 * 10^{-5}) * RWS$$

where δT is the temperature correction

SW is the incoming short wave radiation

RWS is the relative wind speed

RWS is calculated from true wind speed, wind direction and ship speed and direction during three hours preceding the time of observation. Ship speed and ship direction are given in IMD data at 97th and 98th position in 159 IMMT format and in case of ICOADS data, both of them are downloaded along with other data from CISL data archive. In case of NODPAC data, these two elements are present in first group in second section ('$222D_sV_s$'). Ship direction is the direction in which the ship is heading but the wind direction reported is the direction from which it is blowing, so it has been ensured to correct either of them to match with each other. Wherever the ship speed and direction are absent, correction cannot be done. Sometimes, in IMMT format, a position for RWS is directly provided in the record but in maximum number of records, it is blank and further based on the discussion of Kent *et al.* 1993, the reported RWS weren't reliable.

SW is calculated using Okta model given by Dobson and Smith 1988.

$$T = \frac{Q}{(1-\propto)\, Q_o \, sin\theta} \qquad \text{Equation 1}$$

where *Q* is the incoming solar radiation

T is transmission factor

Q_o is the mean solar flux being 1368 W/m^2

$\propto$ is the albedo of the sea surface

θ is the solar elevation angle

$$T = A_i + B_i * sin\theta \qquad \text{Equation 2}$$

where A_i, B_i are coefficients based on cloud cover

Dobson and Smith calculated solar elevation angle using a computer routine from Davies (1981). But we couldn't get that literature, so we used the formulation similar to that followed by da Silva *et al.* 1994 to calculate solar insolation. It is basically based on the equations from Smithsonian Meteorological tables (List 1958). In his report, Da Silva has clearly explained how to use the equations in calculation of solar elevation angle.

Firstly, based on the total cloud amount, A_i, B_i are found out from Okta model. The cloud amounts and the corresponding values of , A_i, B_i are given in the following table 6.1 .

Cloud category	A_i	B_i
0	0.400	0.386
1	0.517	0.317
2	0.474	0.381
3	0.421	0.413
4	0.380	0.468
5	0.350	0.457
6	0.304	0.438
7	0.230	0.384
8	0.106	0.285
9	0.134	0.295

Table 6.1 : Coefficients A,B based on cloud category given by Okta model

Basically, okta model was adapted from Lumb's model (Dobson and Smith 1988) . In this model, solar radiation can be calculated for each observation on hourly basis. Equation 2 is actually a Lumb's regression formula fitted between atmospheric transmission factor and solar elevation angle under nine cloud categories. These categories are based on both cloud type and cloud amount under each of those cloud type. But in ship records, cloud amount of all cloud types is given as a single value and not under each cloud type separately. Thus Dobson and Smith again fitted the QCed data corresponding to cloud oktas and derived the coefficients shown in the above table. Because of the inherent r.m.s. error in the data used for fitting, it was suggested to use the model coefficients by averaging the cloud amount over several observations. Averaging over a day gives a r.m.s error upto 28-31 W/m^2. and averaging over a month further reduces the r.m.s. error to 7-8 W/m^2. With hourly observations of cloud amounts the r.m.s. error would remain at 80 W/m^2. Kent suggested to use a non linear model (Dobson and Smith 1988) which includes diffuse radiation term for cloud oktas less than six and to use the linear okta model described above for cloud covers greater than or equal to six. In case of non linear model, the cloud level and cloud type are required to determine the coefficients. This information is available in IMMT records in 47, 48, 49th positions. But due to lack of consistent availability of information of cloud categories and their geneses in case of each cloud type (here being the low, medium, high clouds), we followed what has been discussed in Josey *et al.* 1998. Josey *et al.* used the okta model for each observation i.e. on hourly basis for all levels of cloud cover.

After obtaining A_i, B_i values the Julian day number is calculated. The subsequent steps involved in the calculations of solar elevation angle are detailed in the flow chart. Albedo is taken from a table given in Payne 1972. The table gives the albedo value based on the solar elevation angle and transmission factor. The nearest value of the former mentioned parameters are searched and corresponding albedo value is taken. After calculating solar elevation angle, it is substituted in equation 2 and in turn T is substituted in equation 1 to obtain 'Q'. Finally 'Q' which is solar insolation is substituted to get DBT measurement error. Figure 6.1 describes the procedure for DBT correction at a glance.

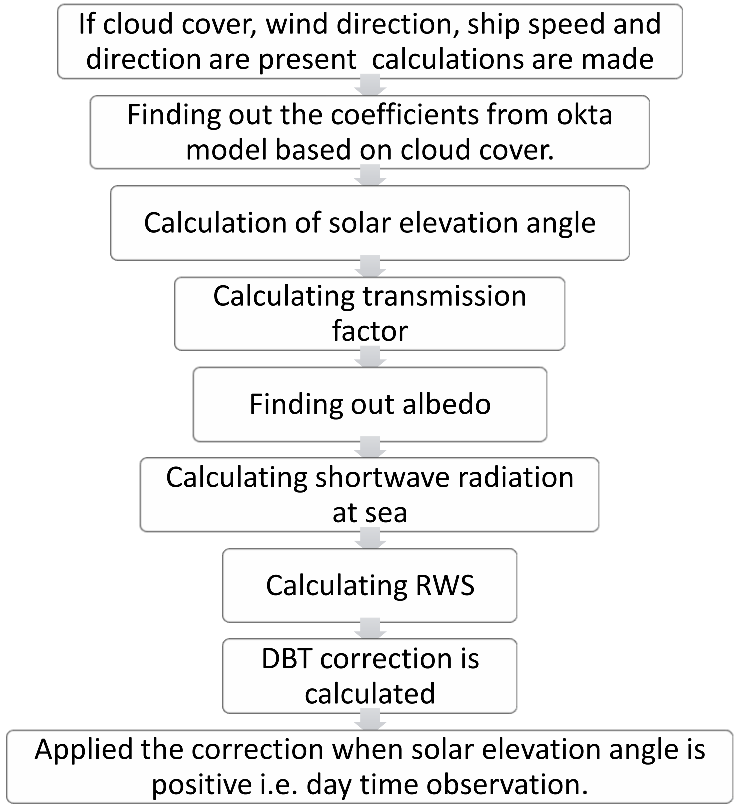

Figure 6.1 : Flow chart of procedure followed in dry bulb temperature correction

6.2 Correcting Sea surface temperature

Several methods are in use for measuring SST such as bucket thermometer, engine intake, hull contact sensor, etc. The SST bias correction was also a part of the work done by Kent *et al.* 1992. The difference between the model SST values and observations from bucket thermometers and hull contact sensors were less, i.e. they are in good agreement. Whereas, the observations made in engine intake system were consistently warmer. The error was due to the increase in temperature of water after absorbing heat from the engine because here, water is a coolant. And the observation is taken at a later stage. Also, the increase in temperature is more in case of larger ships, suggesting more distance between the point of intake and point of observation. The warm bias was found to be around 0.3^0 Celsius. Josey *et al.* applied a correction of -0.35^0 Celsius. Similar bias correction is applied to all SST values which are measured in engine cooling system. The method of observation is found from the value at 54th position in IMMT format. For those observations where method of observation is not present, it is taken from WMO metadata that has been appended to the IMD data, when available (discussed in subsection 4.1) . Wherever the measurement technique was absent, the percentage of number of ships measuring SST through engine intake is found and then multiplied by -0.35^0 Celsius. Two factors were thus derived. First factor -0.19^0 Celsius for the data within 1961-1981 and the second factor -0.24^0 Celsius for the data within period from 1982 to 2012. These factors were applied for correction wherever there is no information about method of observation. The factors were found separately because as earlier mentioned, there were no callsigns for the data during the period 1961-1981.

6.3 Correcting Dew point temperature

Humidity is usually measured by wet bulb depression. The wet bulb thermometer is either placed in the same screen or psychrometer with the dry bulb thermometer that is used for air temperature measurement. Kent *et al.* 1992, discussed that the difference of dew point temperatures of model output and ship observations were found to be more dependent on the instrument method. The most reliable values were those measured by the psychrometer. Observations measured by the screened instrument were generally warmer than the model values up to 1.5^0 Celsius. The measurement error is due to improper ventilation in the screen or a contaminated or imperfectly wetted wick. As a result, there is less moisture that gets carried away from the wick, so there will be less cooling effect and hence reduced wet bulb depression and hence increased dew point temperature. Josey *et al.* 1998 discussed the correction as follows and it is a negative correction,

Corrected DPT = 1.029 *Uncorrected DPT - 1.080

The above correction is applied when method of observation of DPT obtained from WMO metadata is "Unventilated screen". Wherever the information about method of observation is not available, a procedure similar to that followed in case of SST is followed. Two factors based on the percentage of number of ships using unventilated screen were derived and multiplied to the correction. The factors derived were 0.26 for data within 1961-1981 and 0.34 within 1982-2012. These factors are derived based on the IMD records.

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25. WMO metadata for data between 1995 to 1998 :

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26. WMO metadata for data between 1999 to 2007 :

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27. WMO metadata for data between 2007 to 2008 :

https://www.wmo.int/pages/prog/www/ois/pub47/pub47-home.htm (Version - 3)

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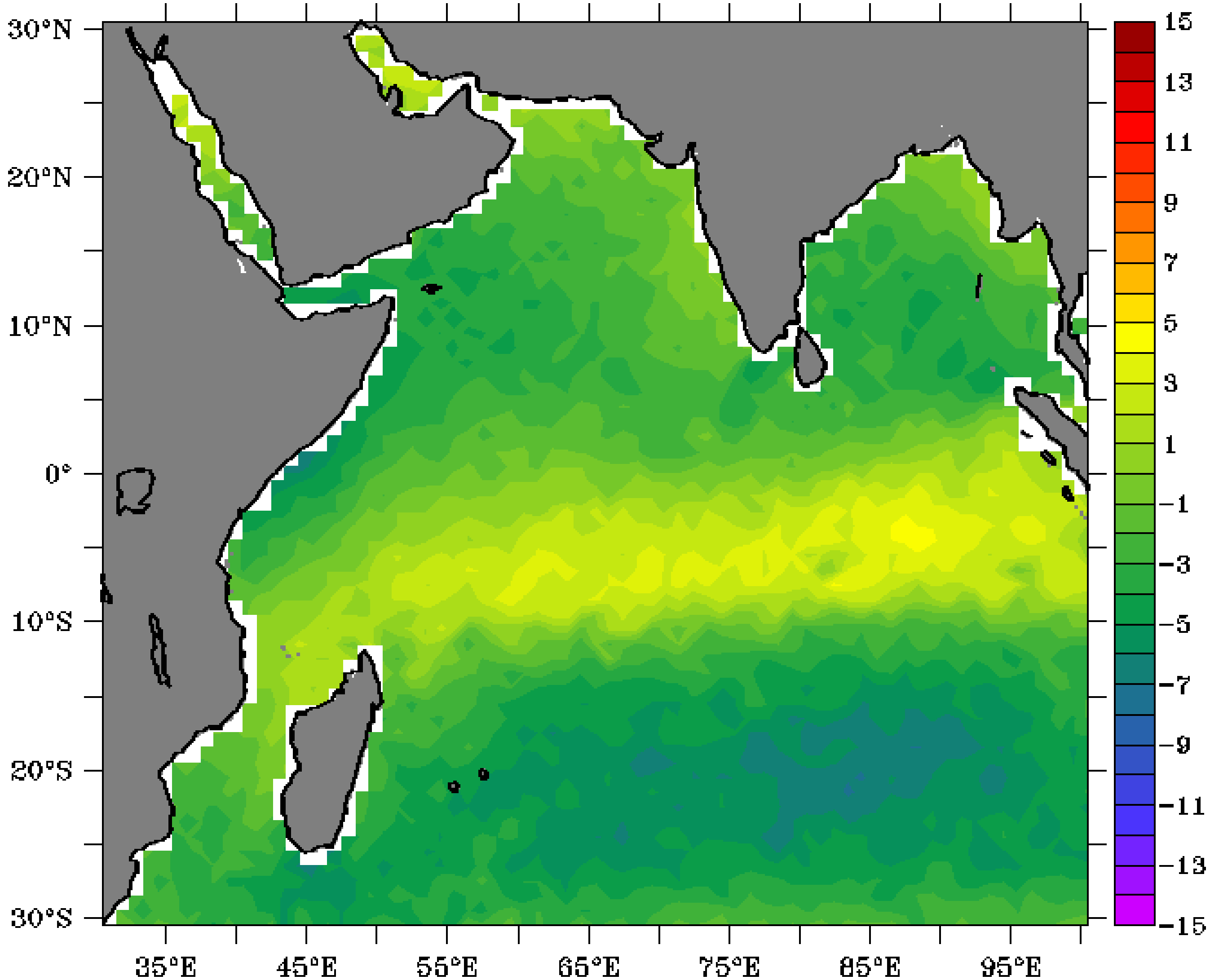
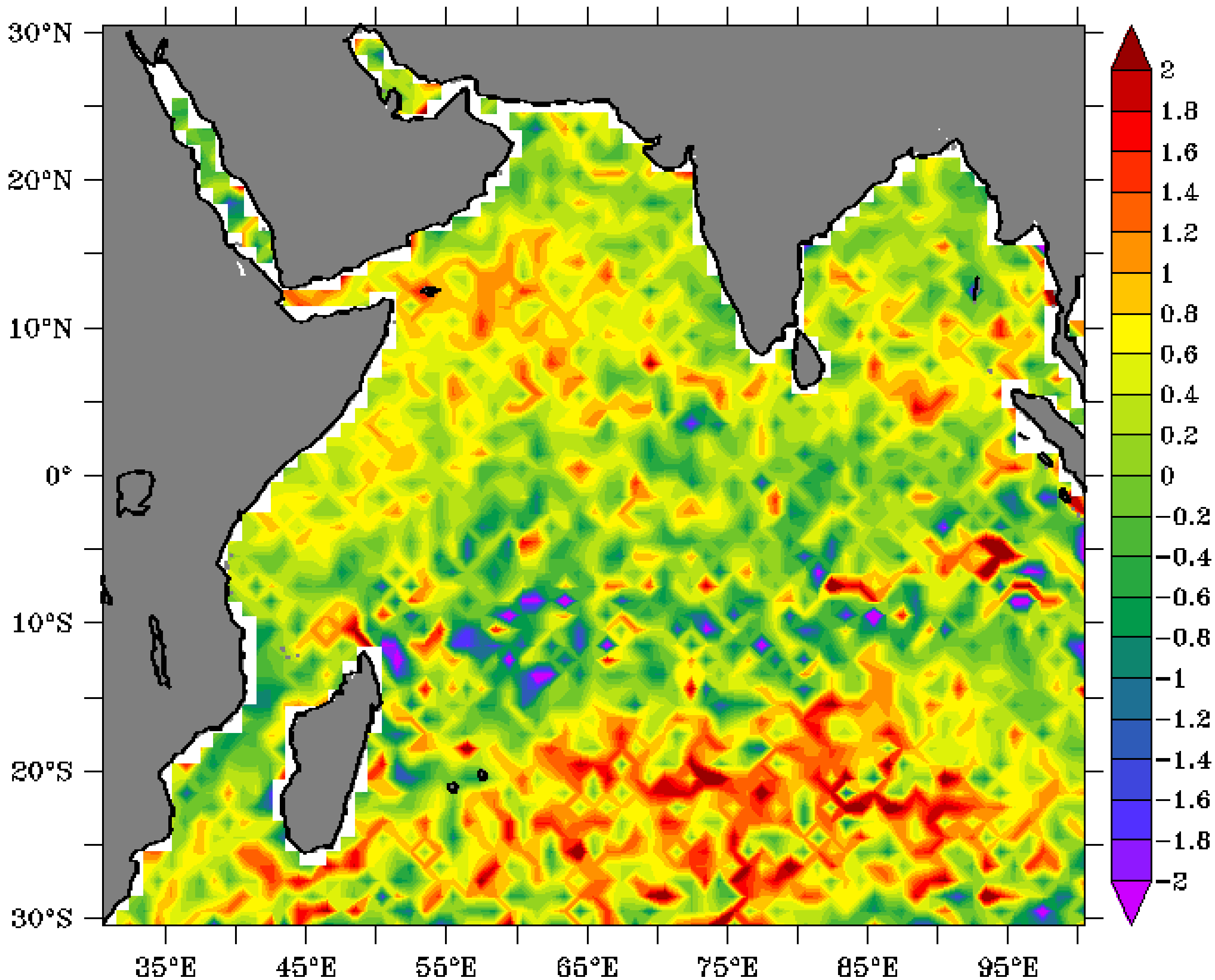
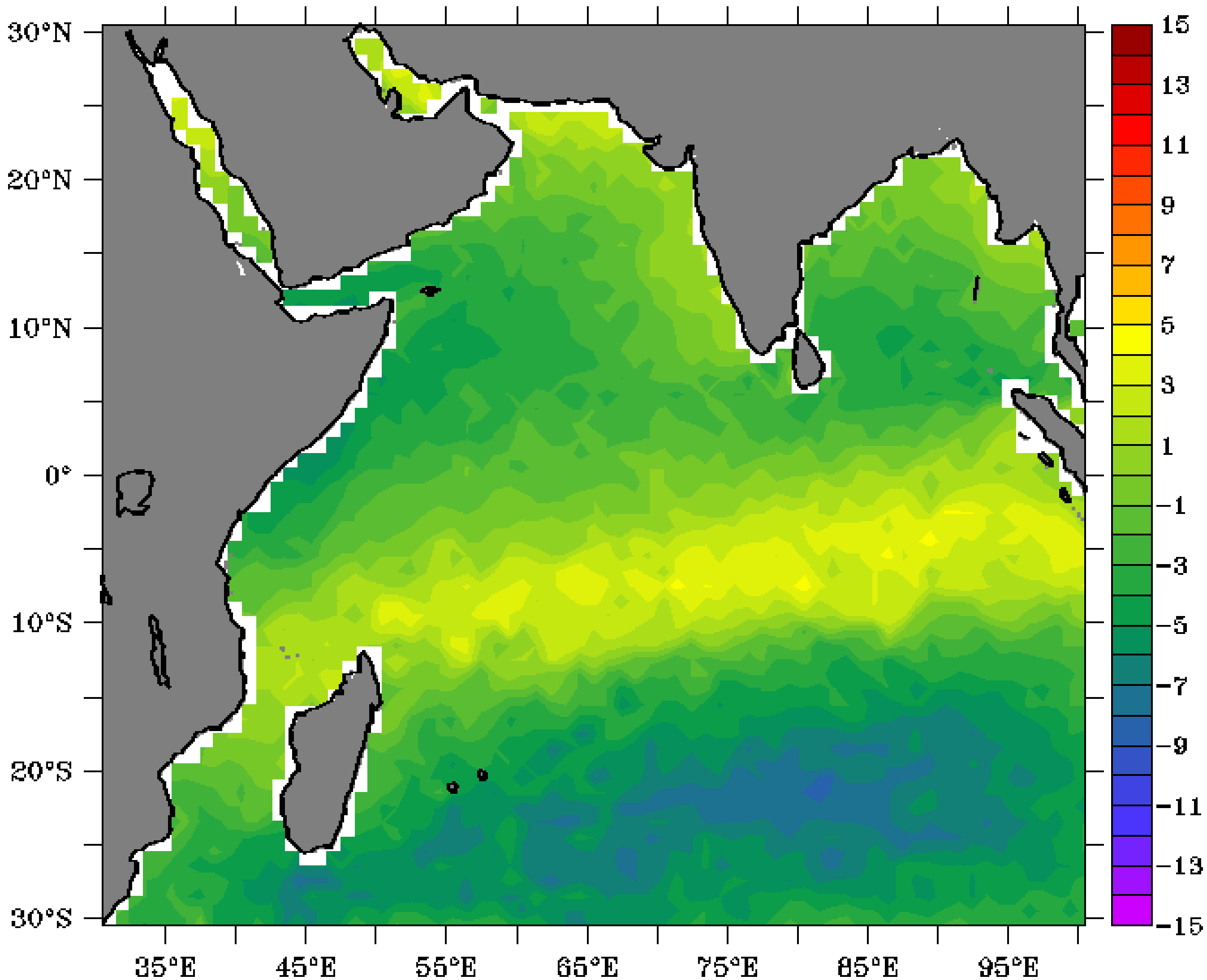


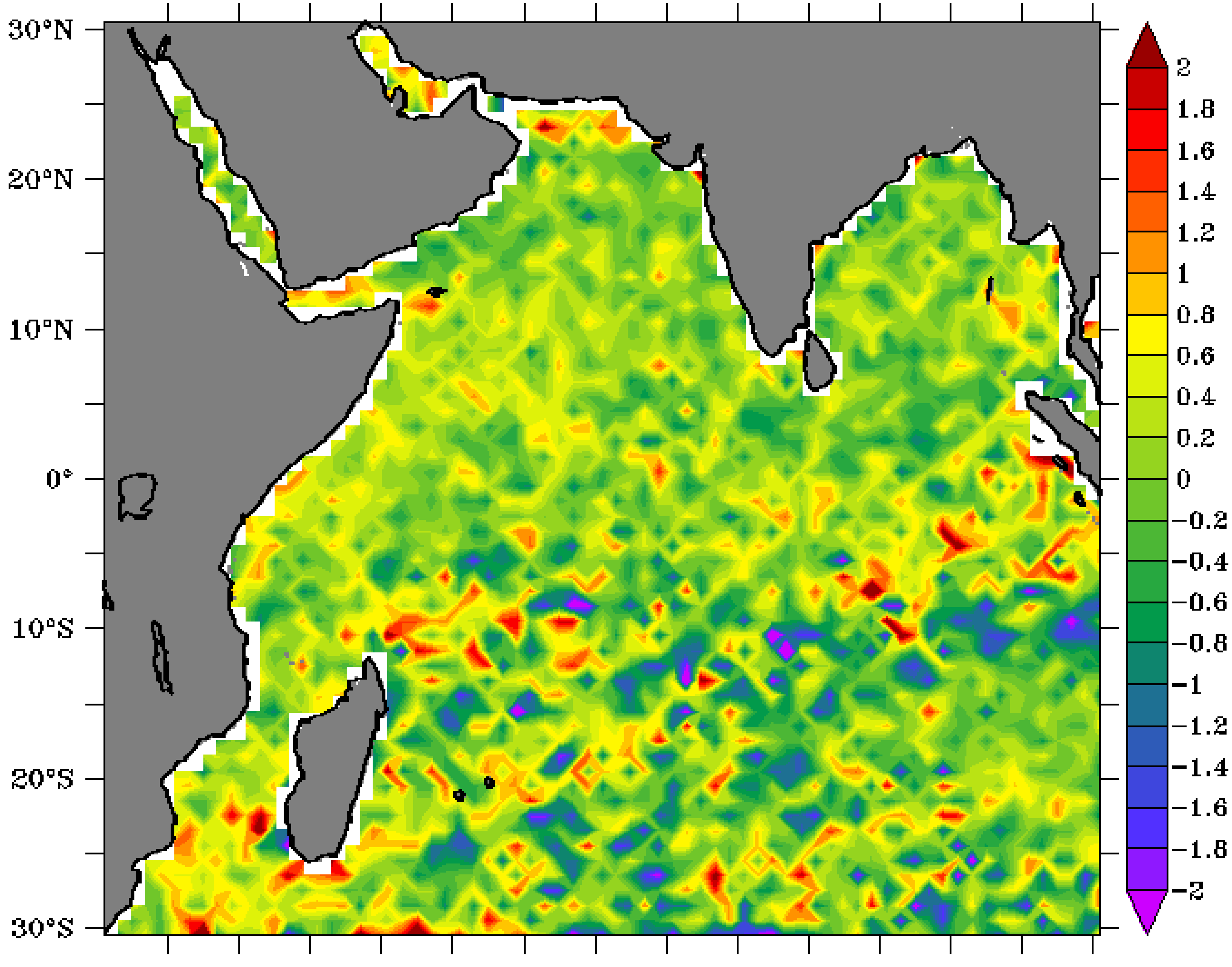
Zonal wind speed (m/s) JANUARY


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

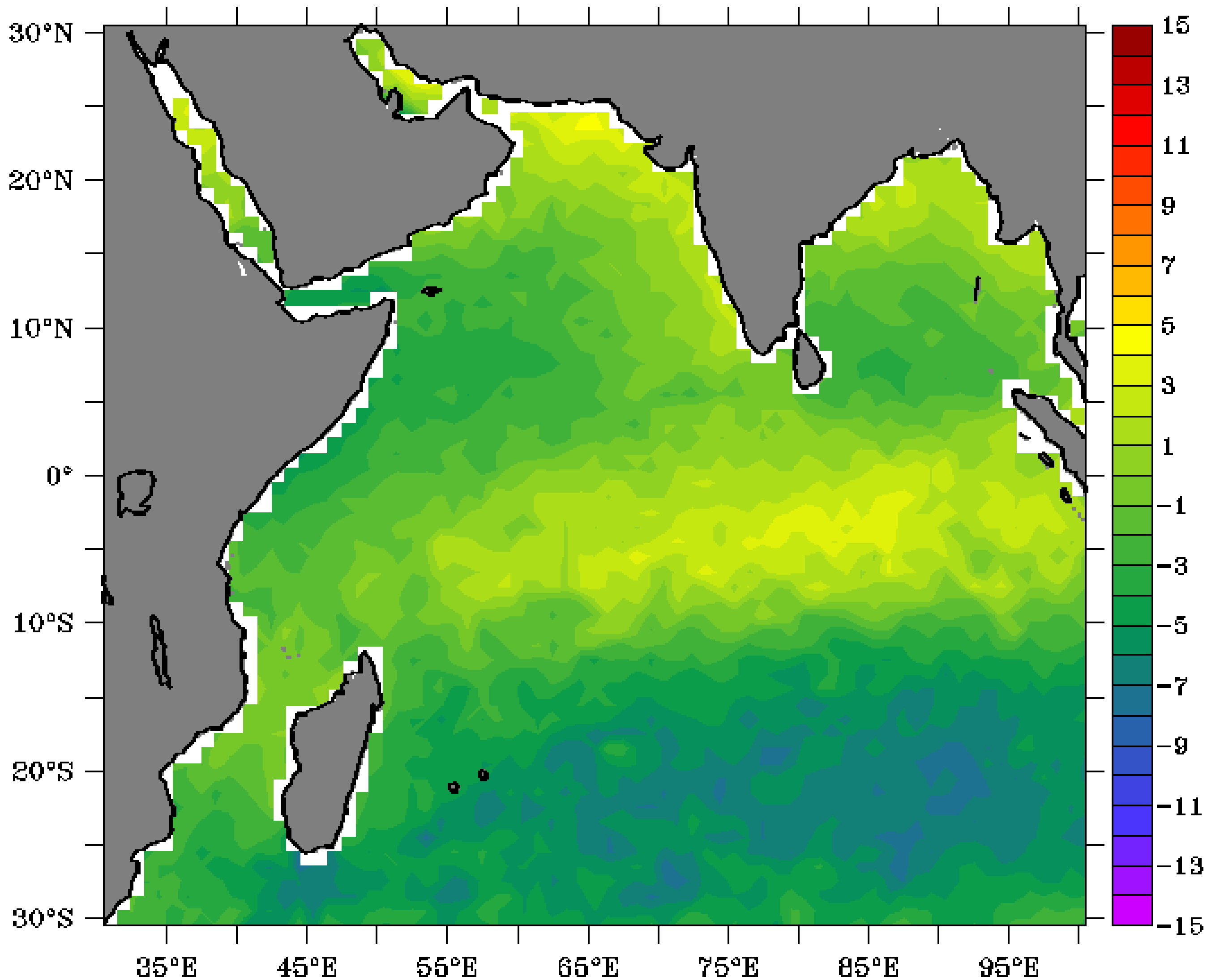
Anomaly (m/s)



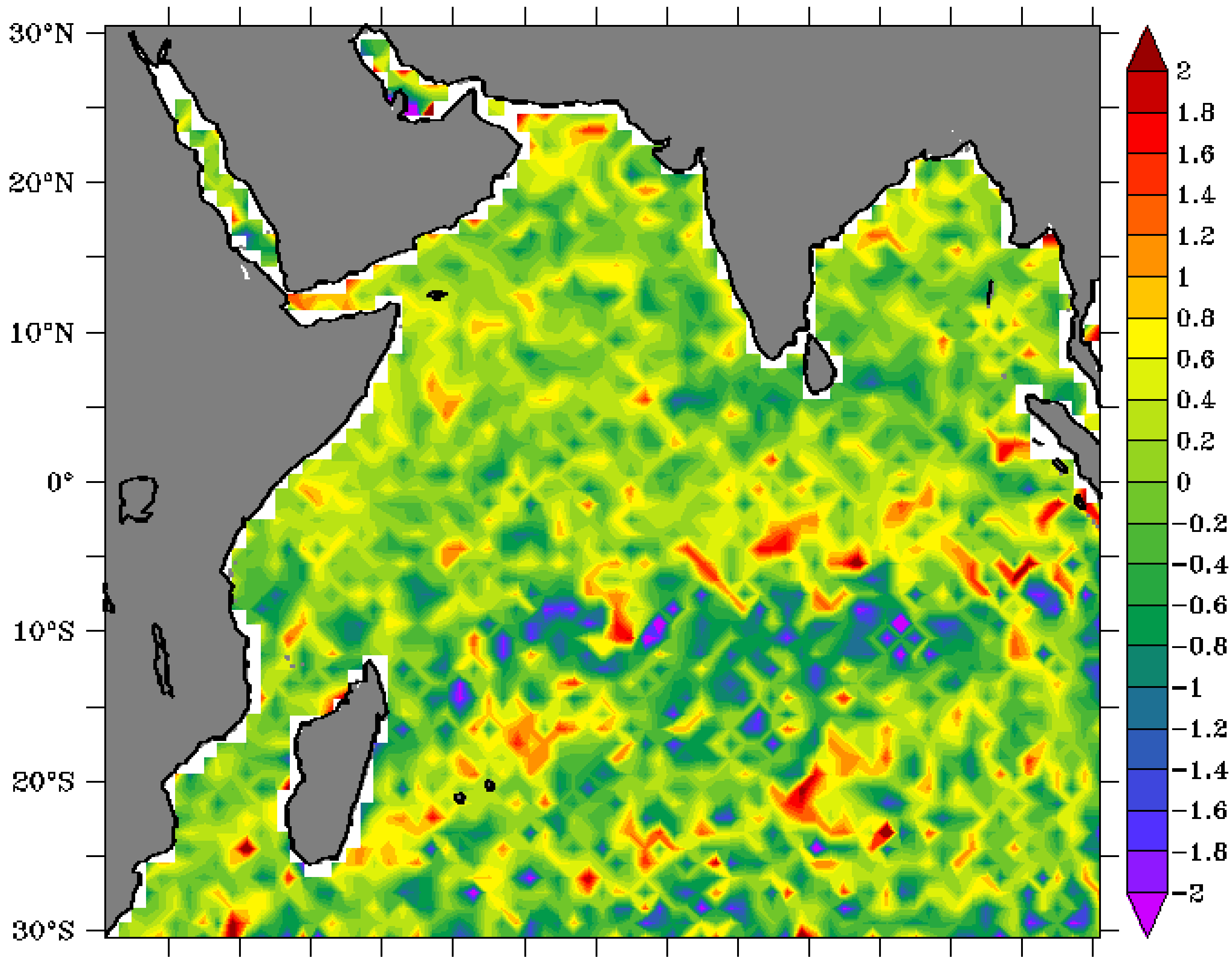
Zonal wind speed (m/s) FEBRUARY


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

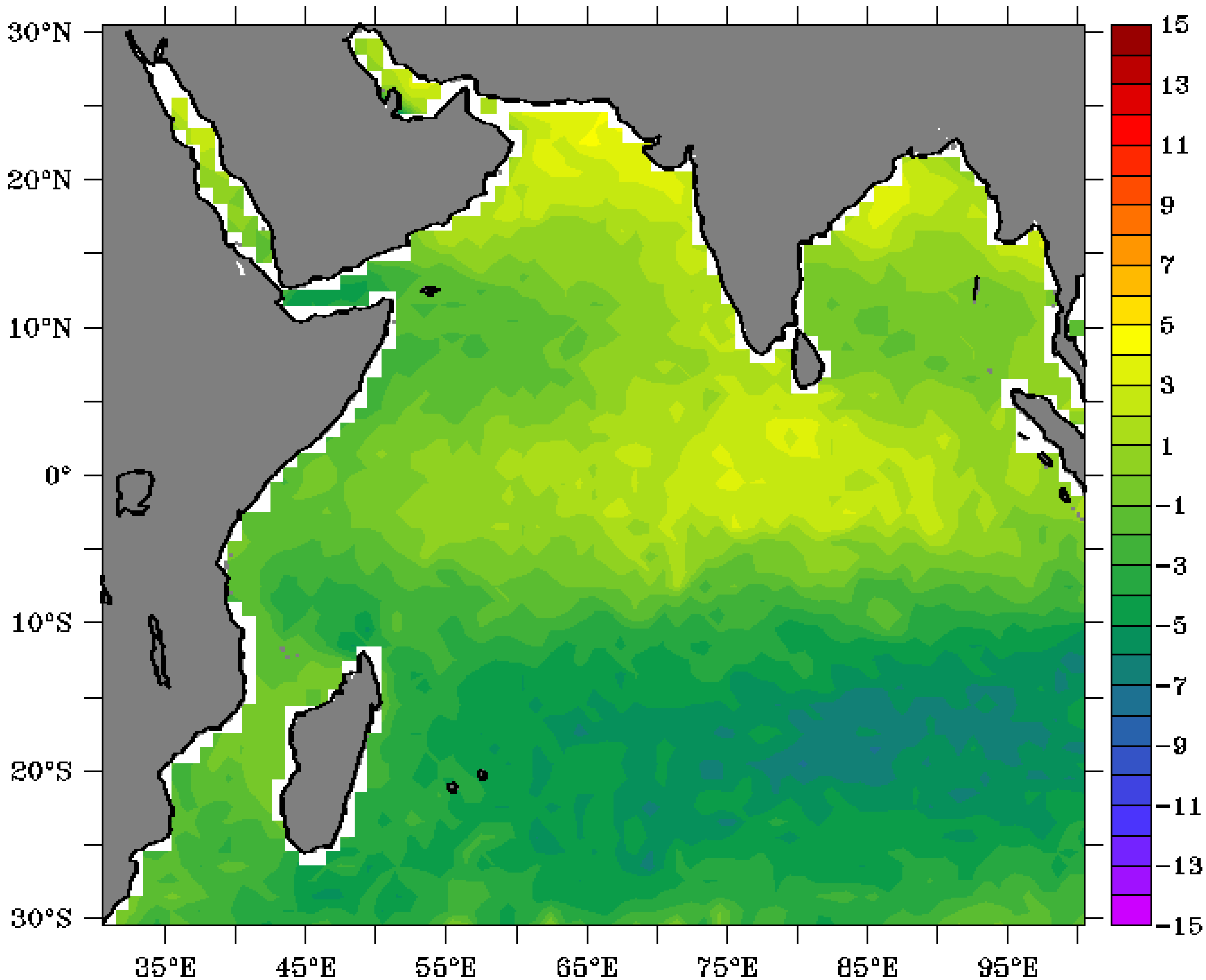
Anomaly (m/s)



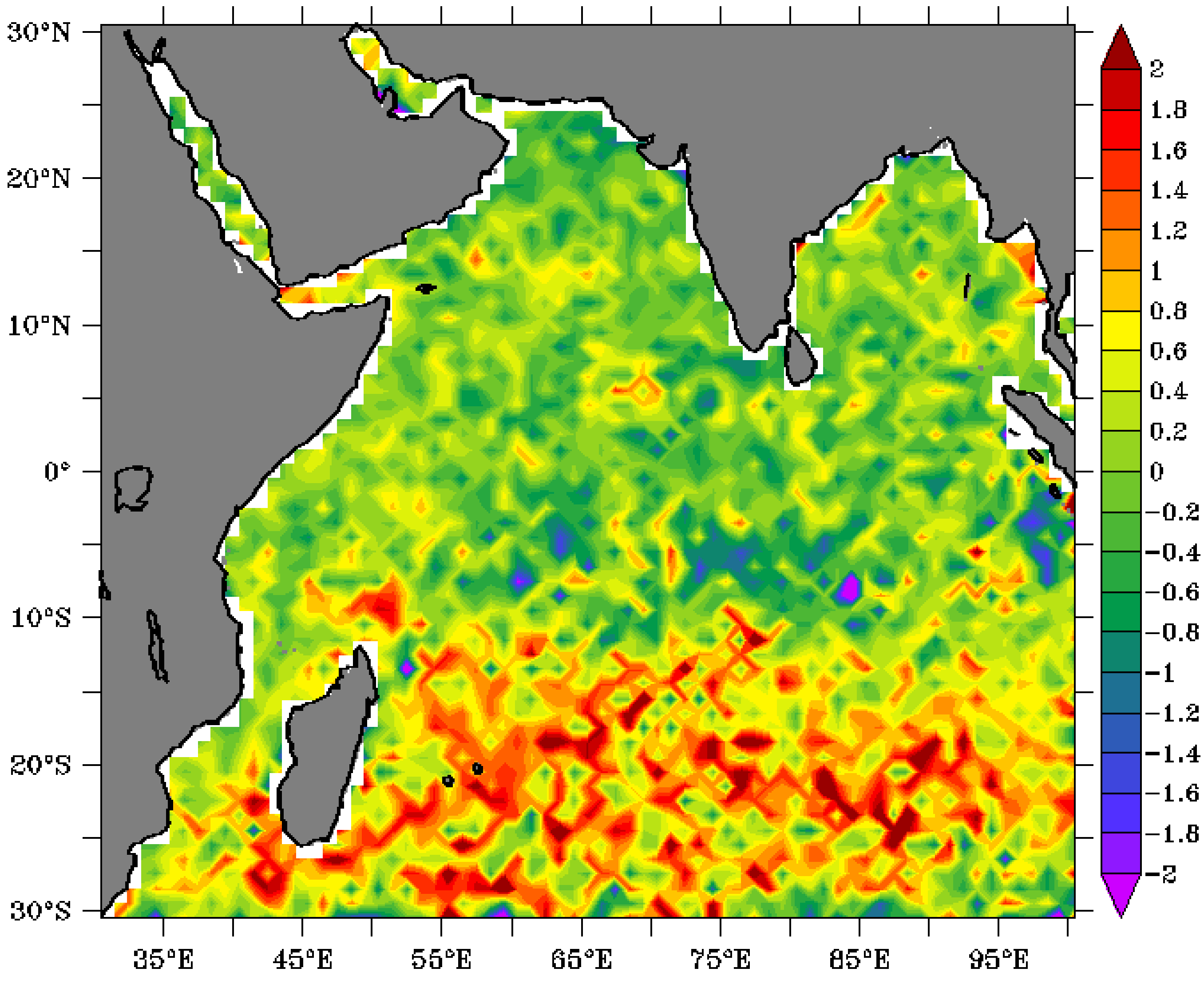
Zonal wind speed (m/s) MARCH


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Zonal wind speed (m/s) APRIL


30°N
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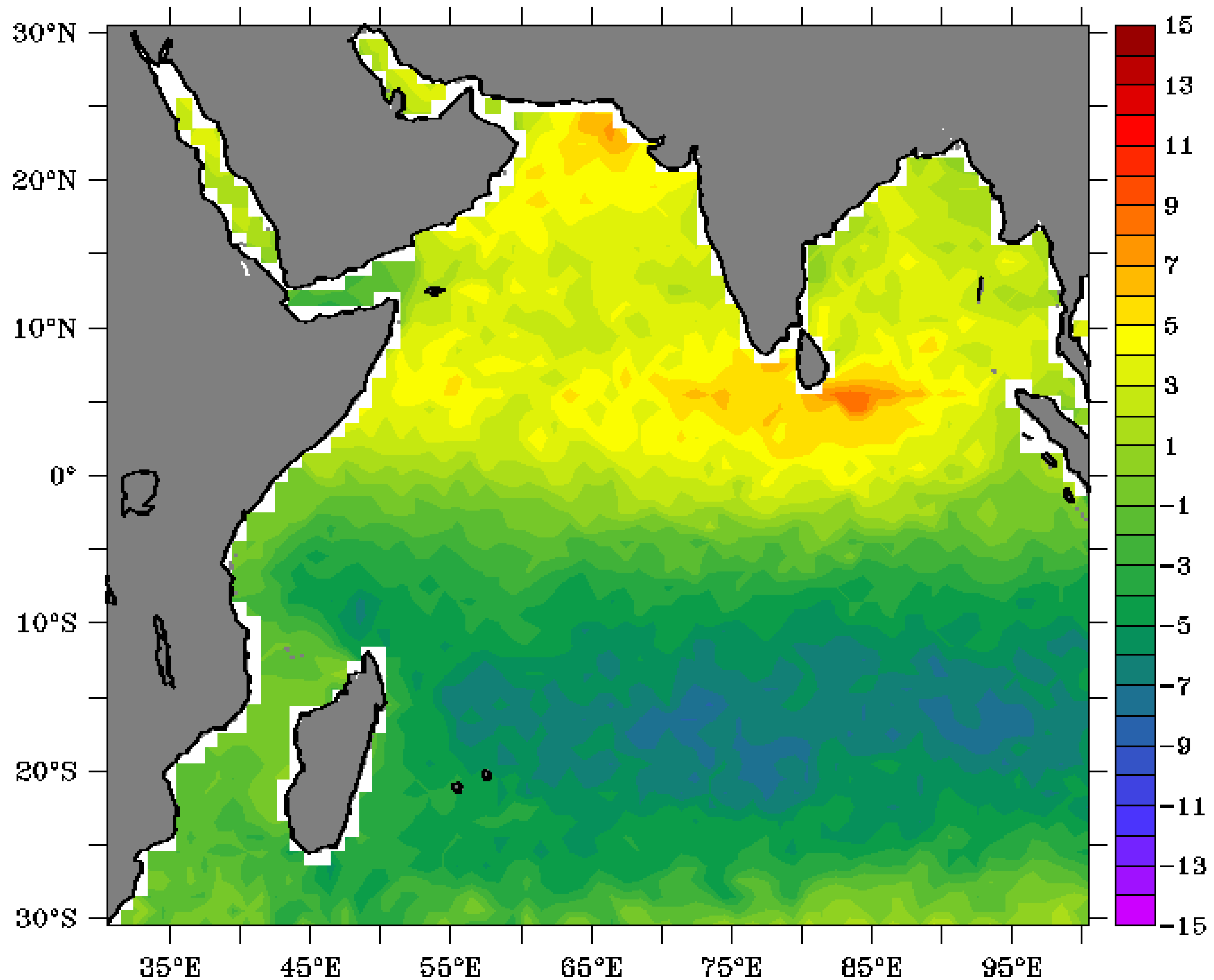
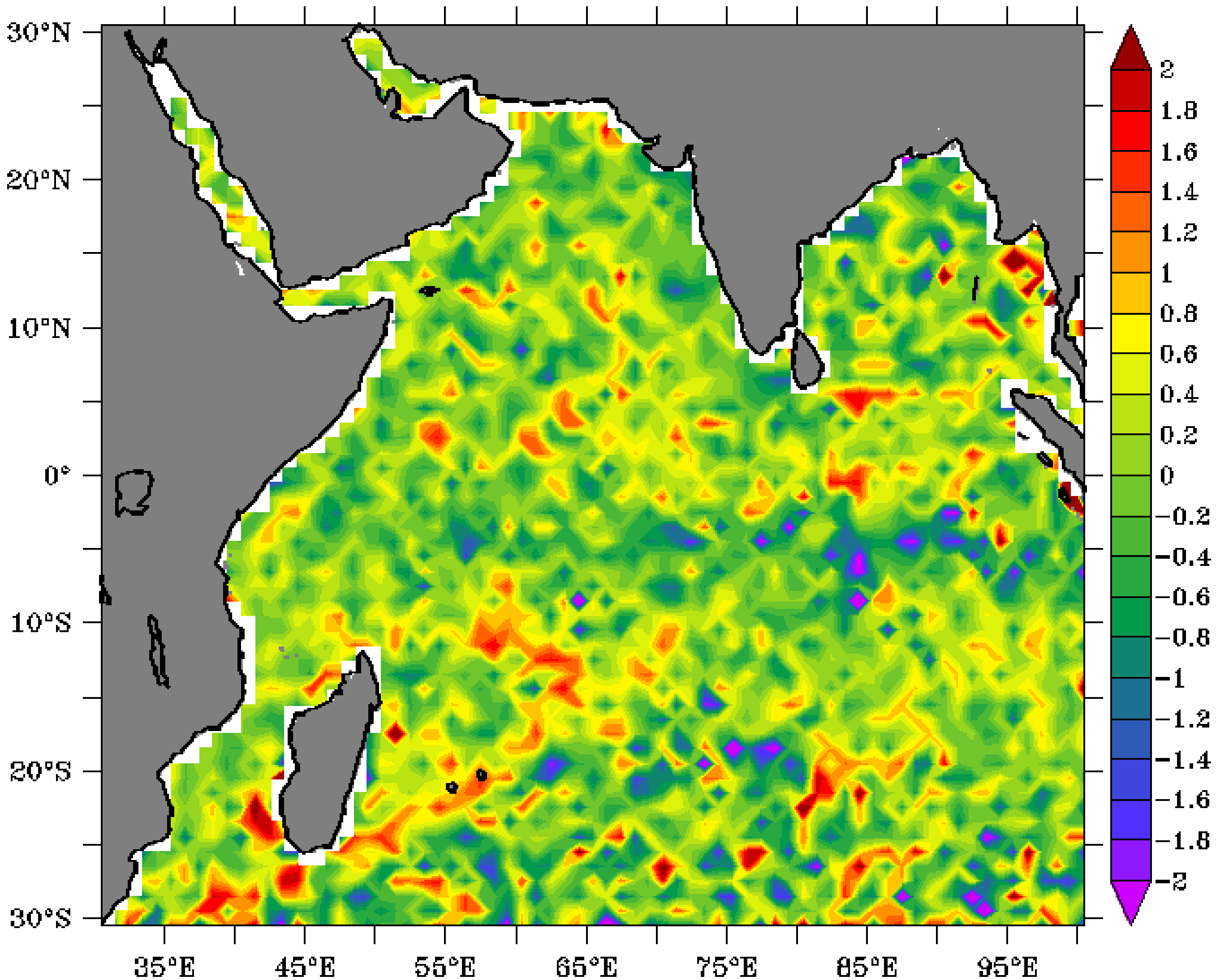
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2

Anomaly (m/s)



Zonal wind speed (m/s) MAY


30°N
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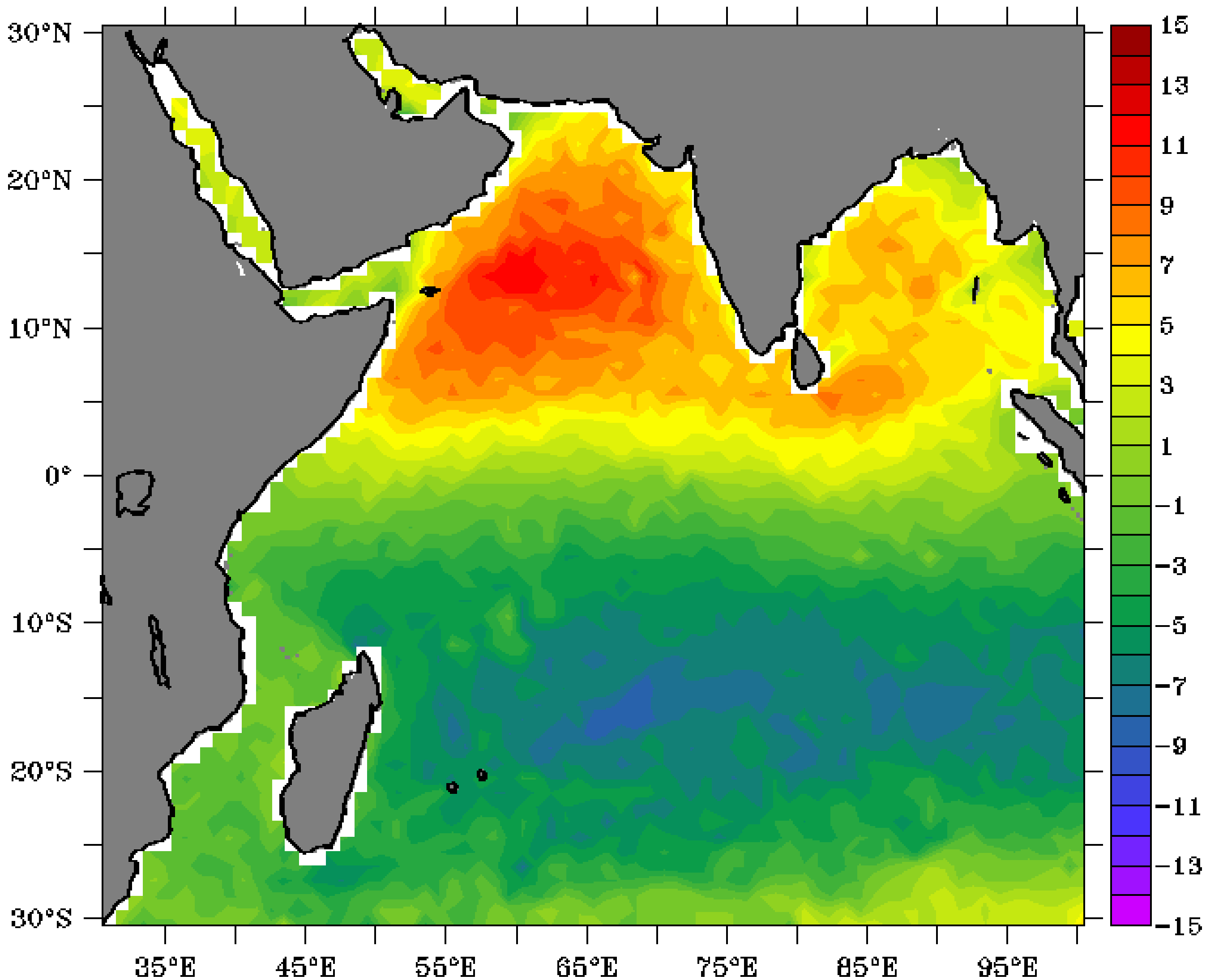
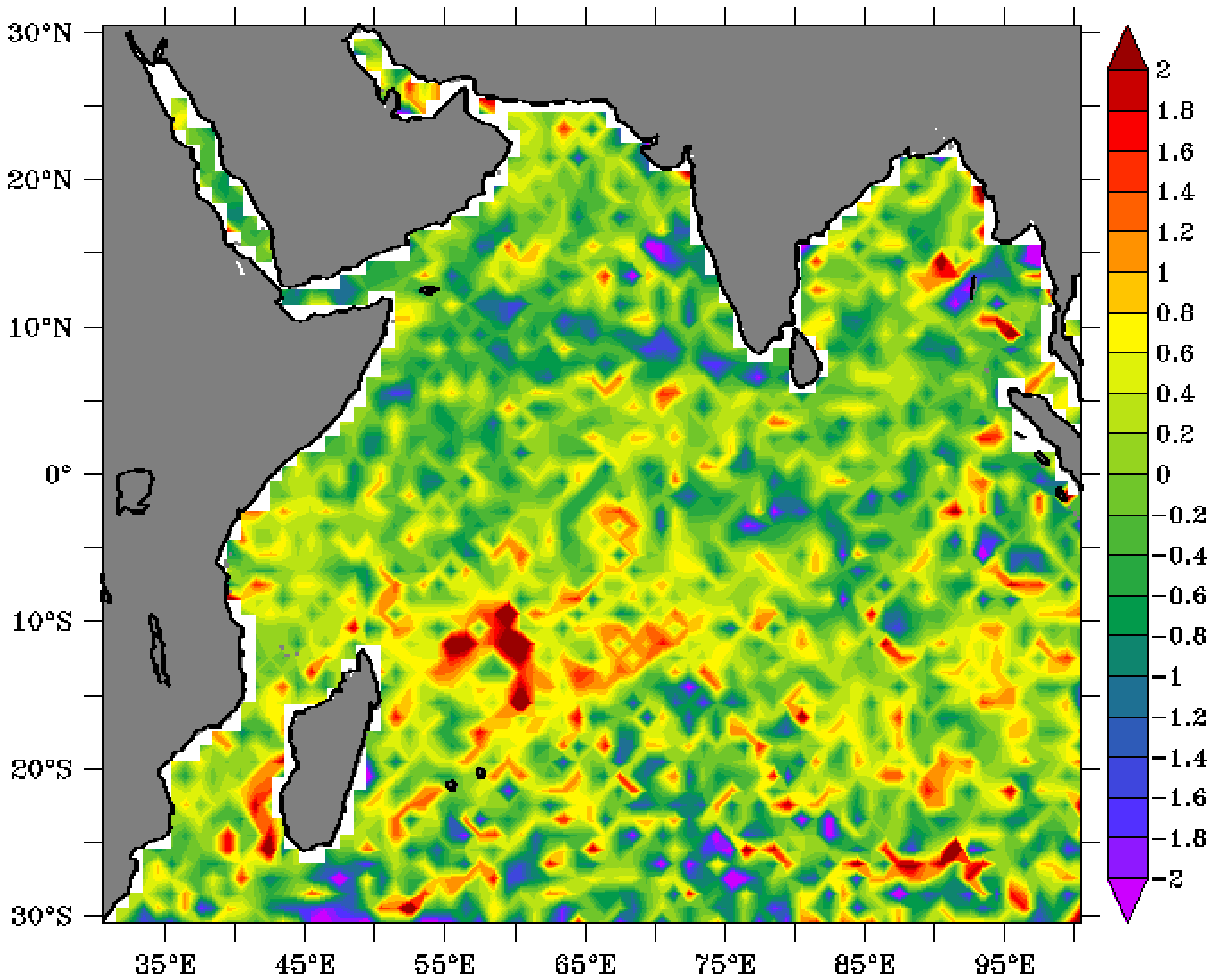
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Zonal wind speed (m/s) JUNE


30°N
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20°S
30°S
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45°E
55°E
65°E
75°E
85°E
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2
1.8
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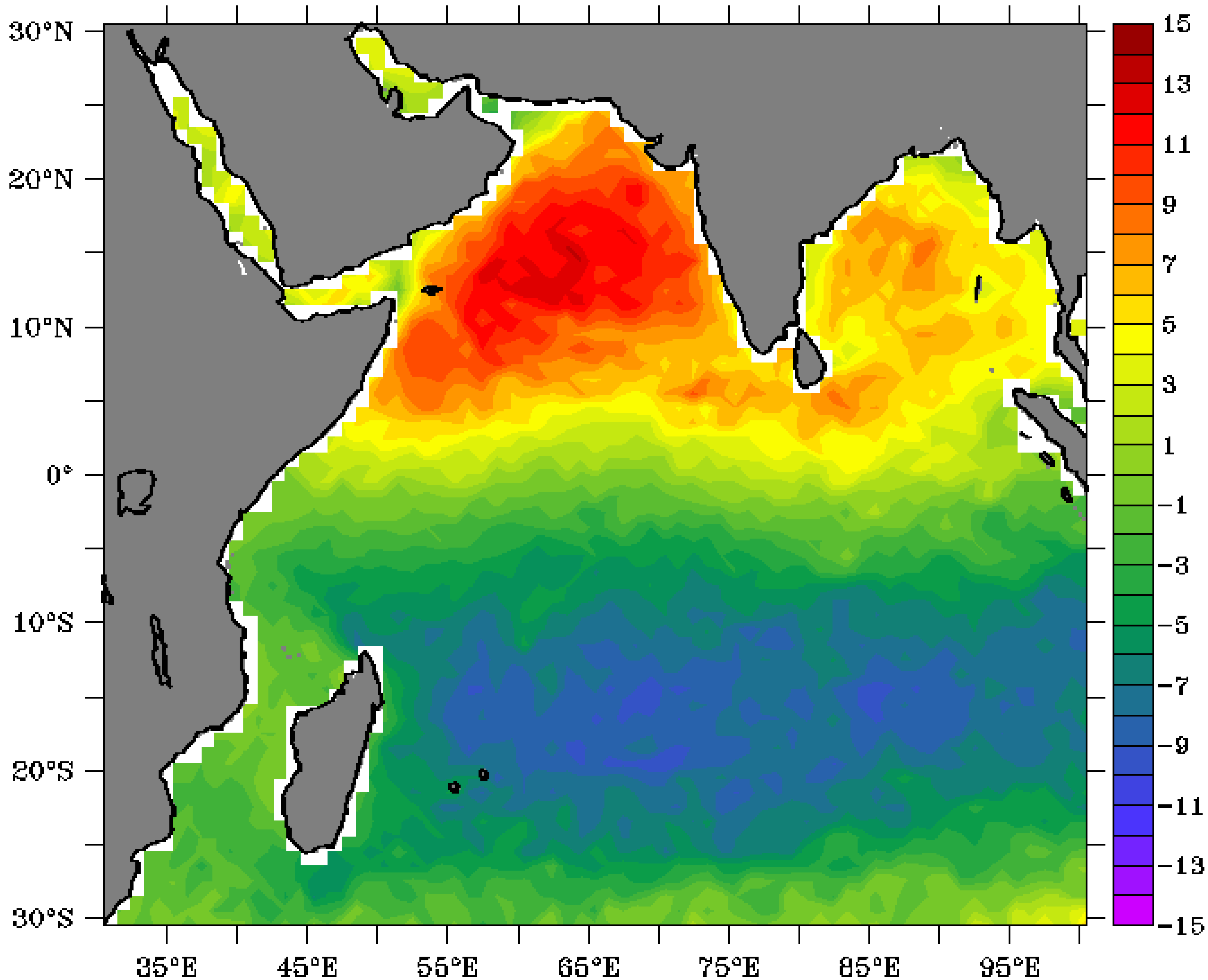
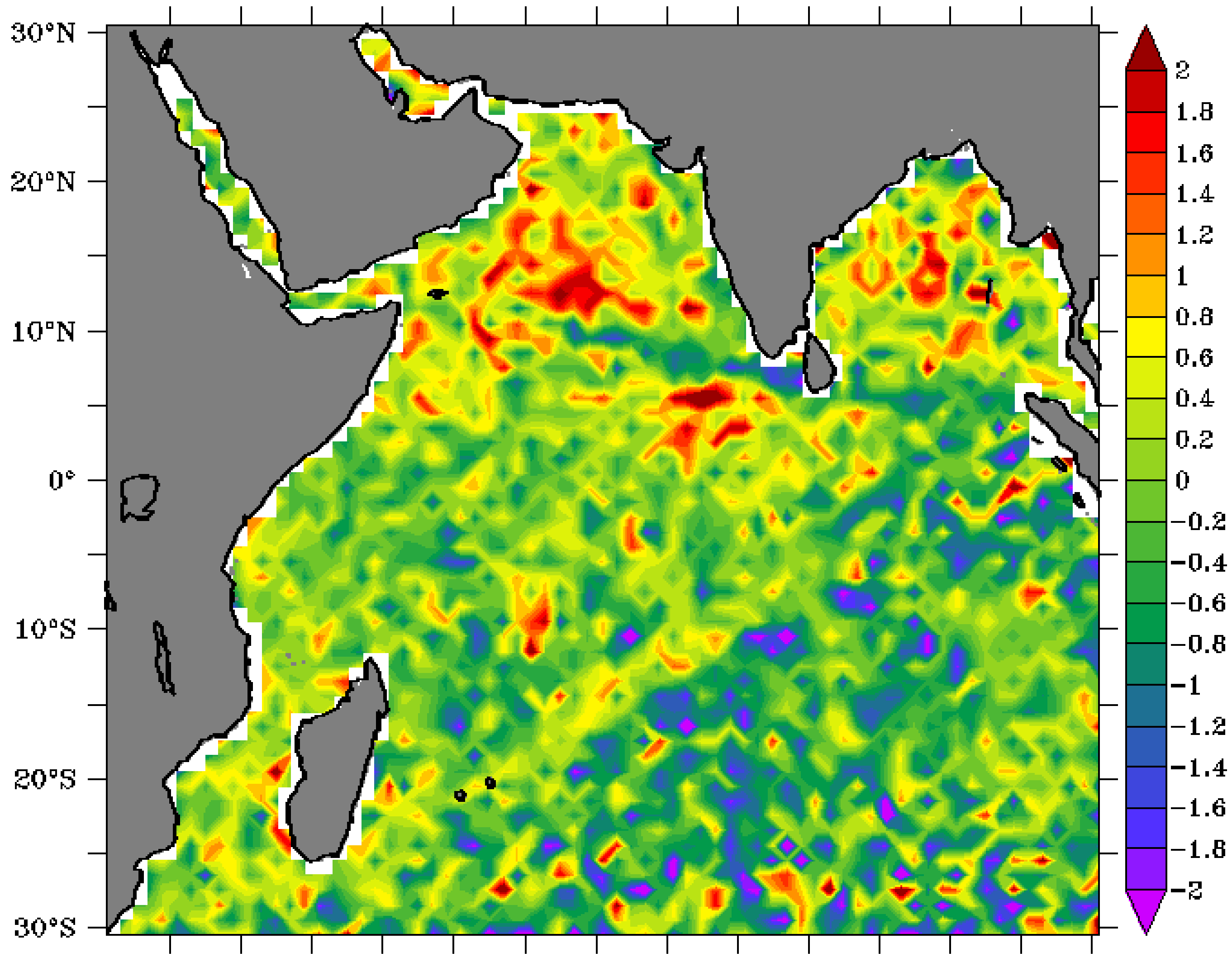
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Zonal wind speed (m/s) JULY


30°N
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20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
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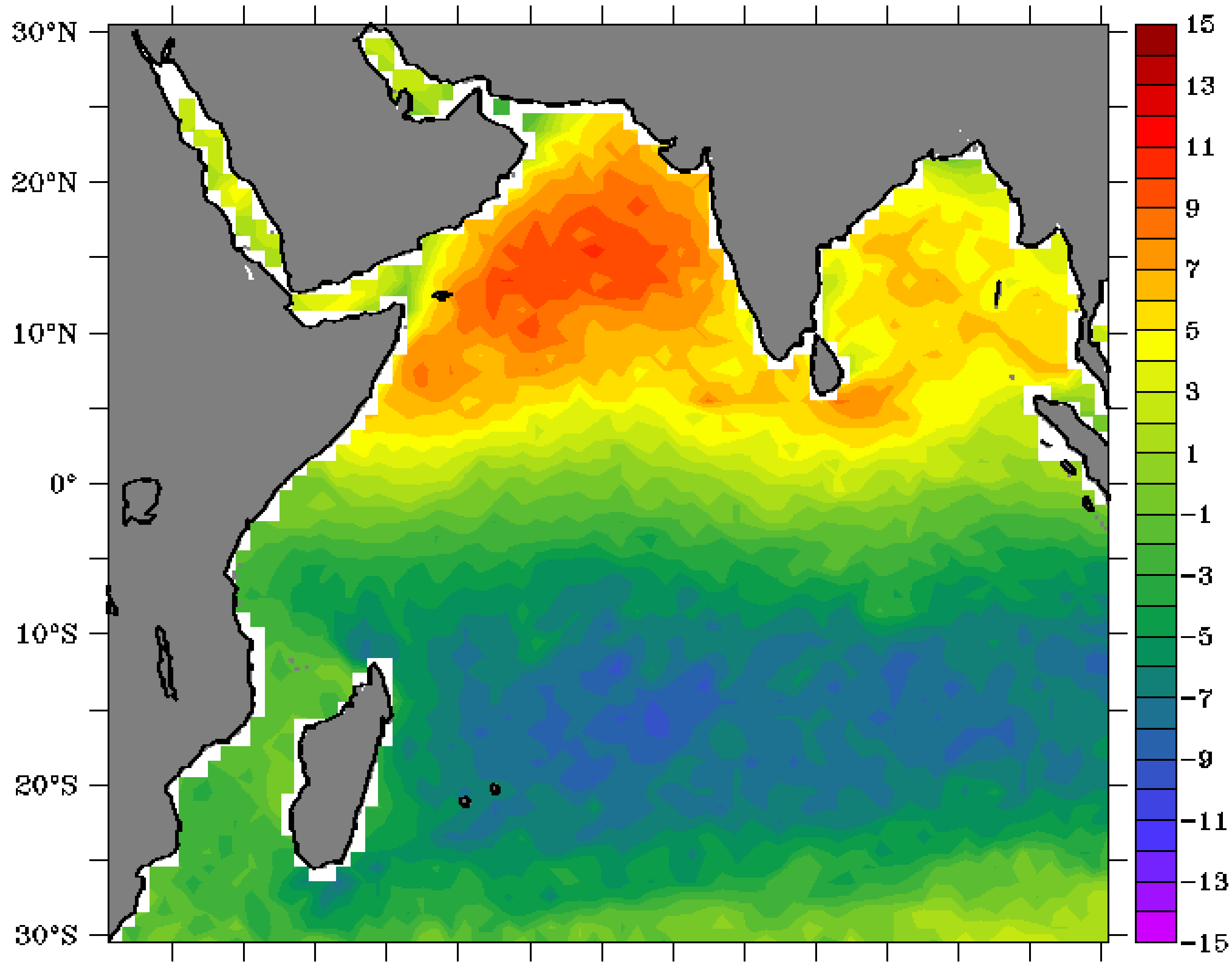
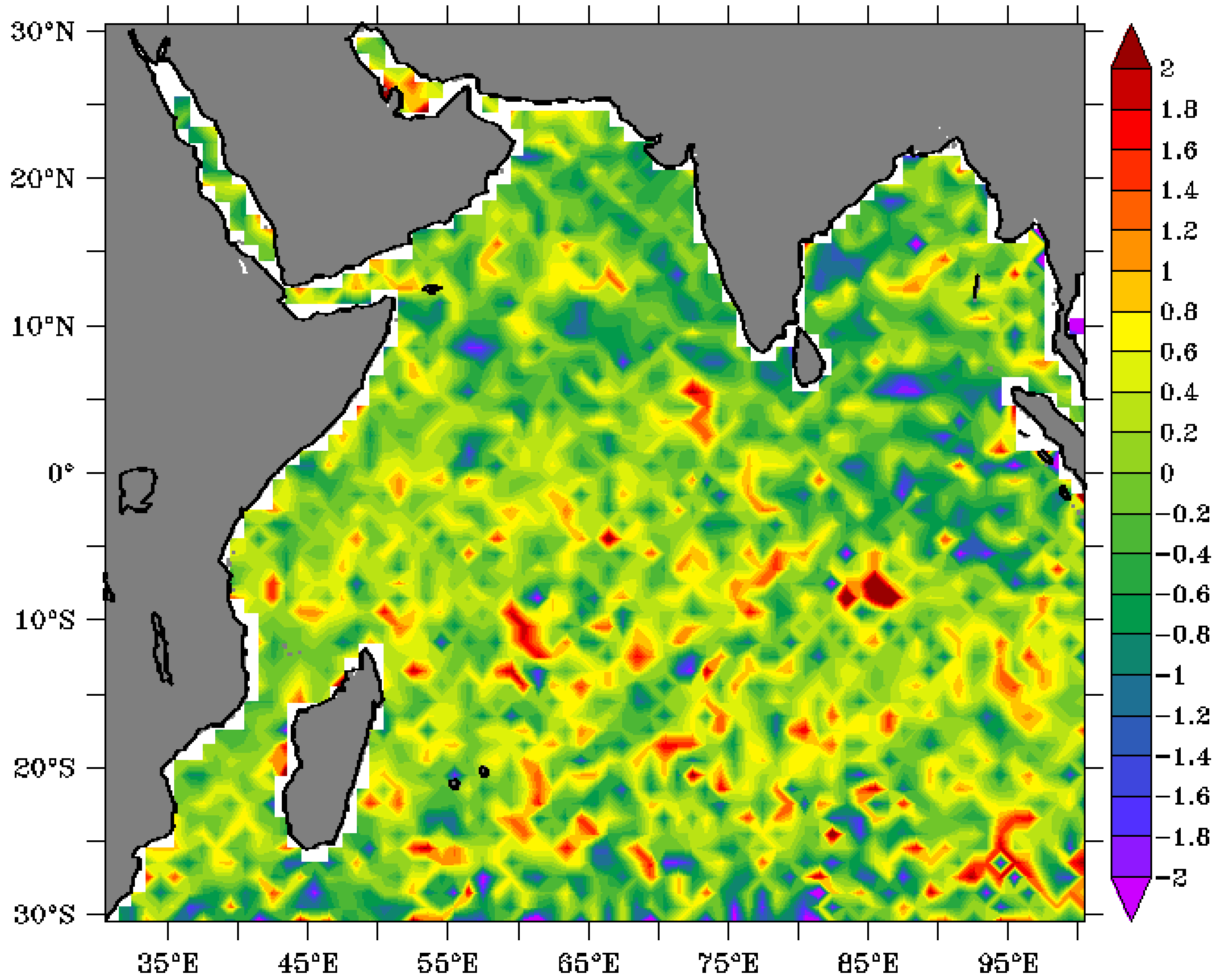
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Zonal wind speed (m/s)   AUGUST


30°N
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20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
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1.8
1.6
1.4
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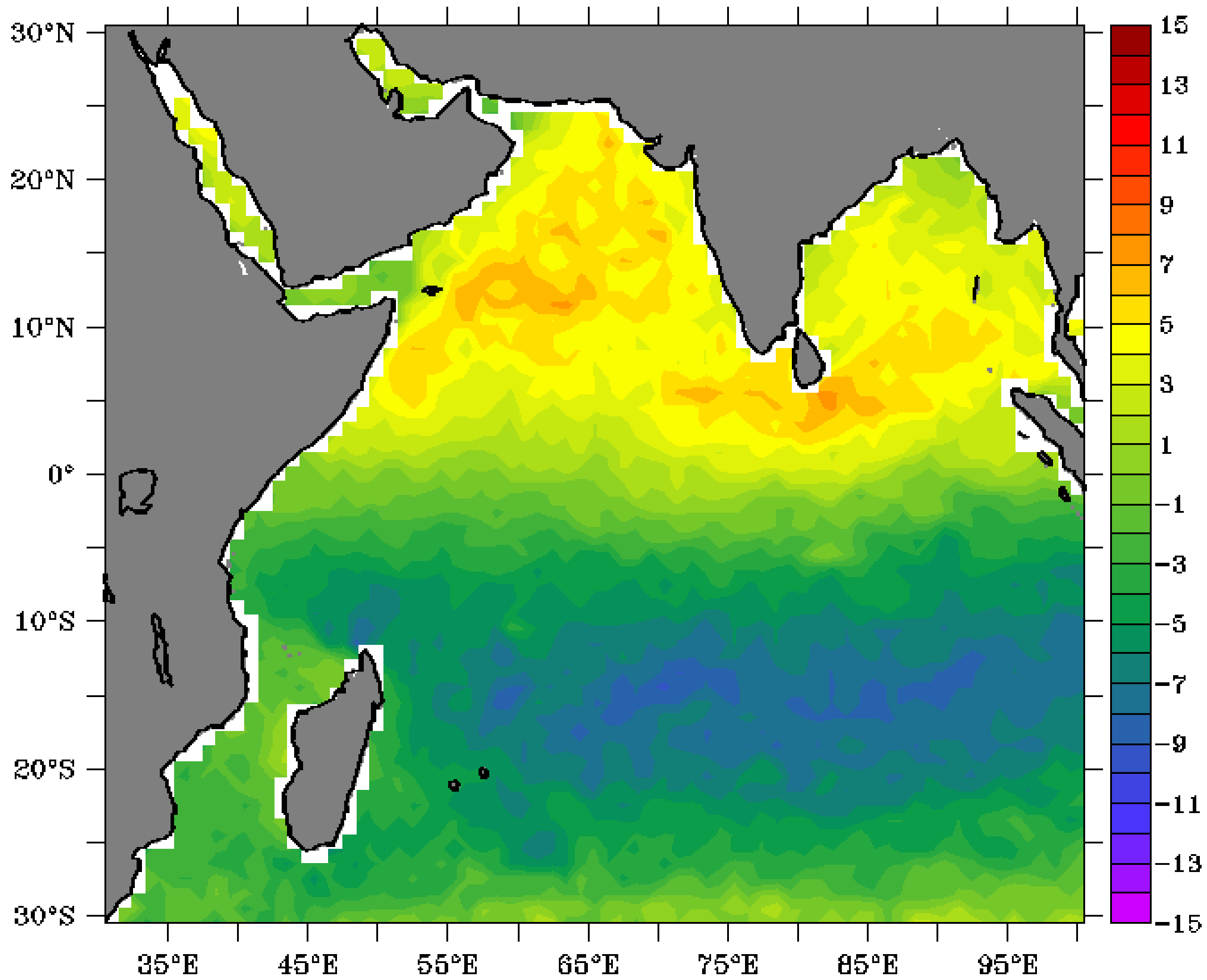
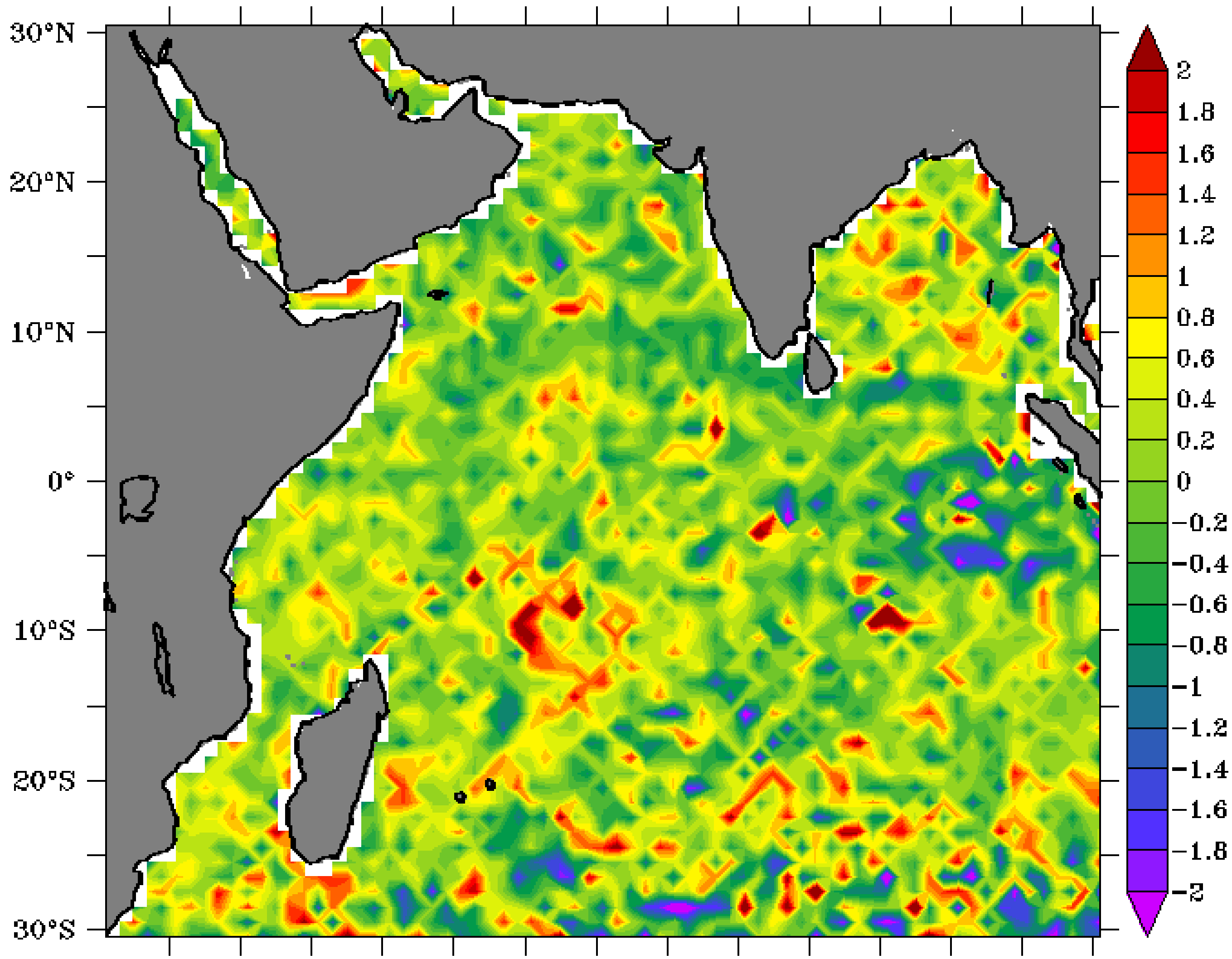
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Zonal wind speed (m/s) SEPTEMBER


30°N
20°N
10°N
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20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
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1.4
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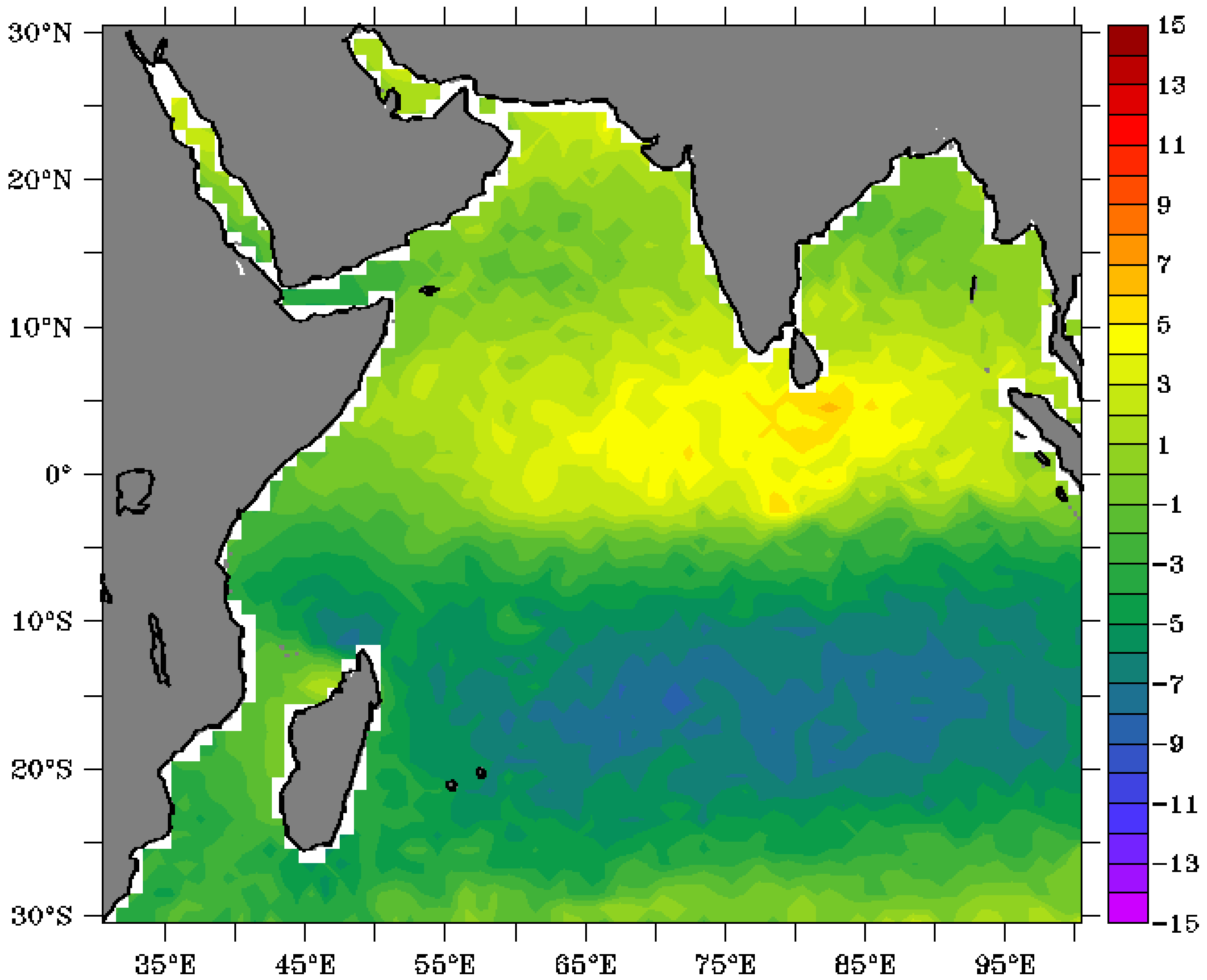
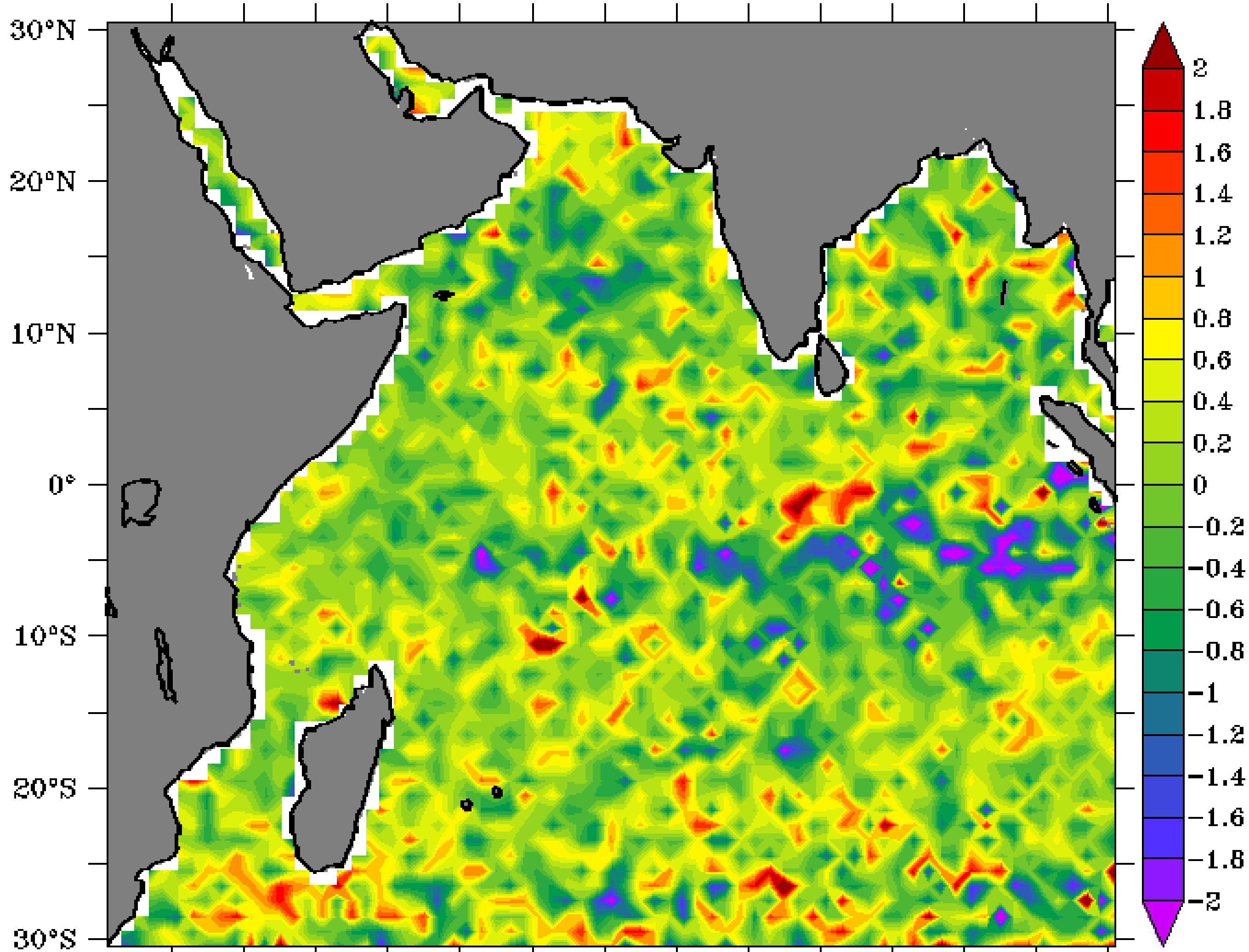
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Zonal wind speed (m/s)   OCTOBER


30°N
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−0.2
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−0.8
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−1.2
−1.4
−1.6
−1.8
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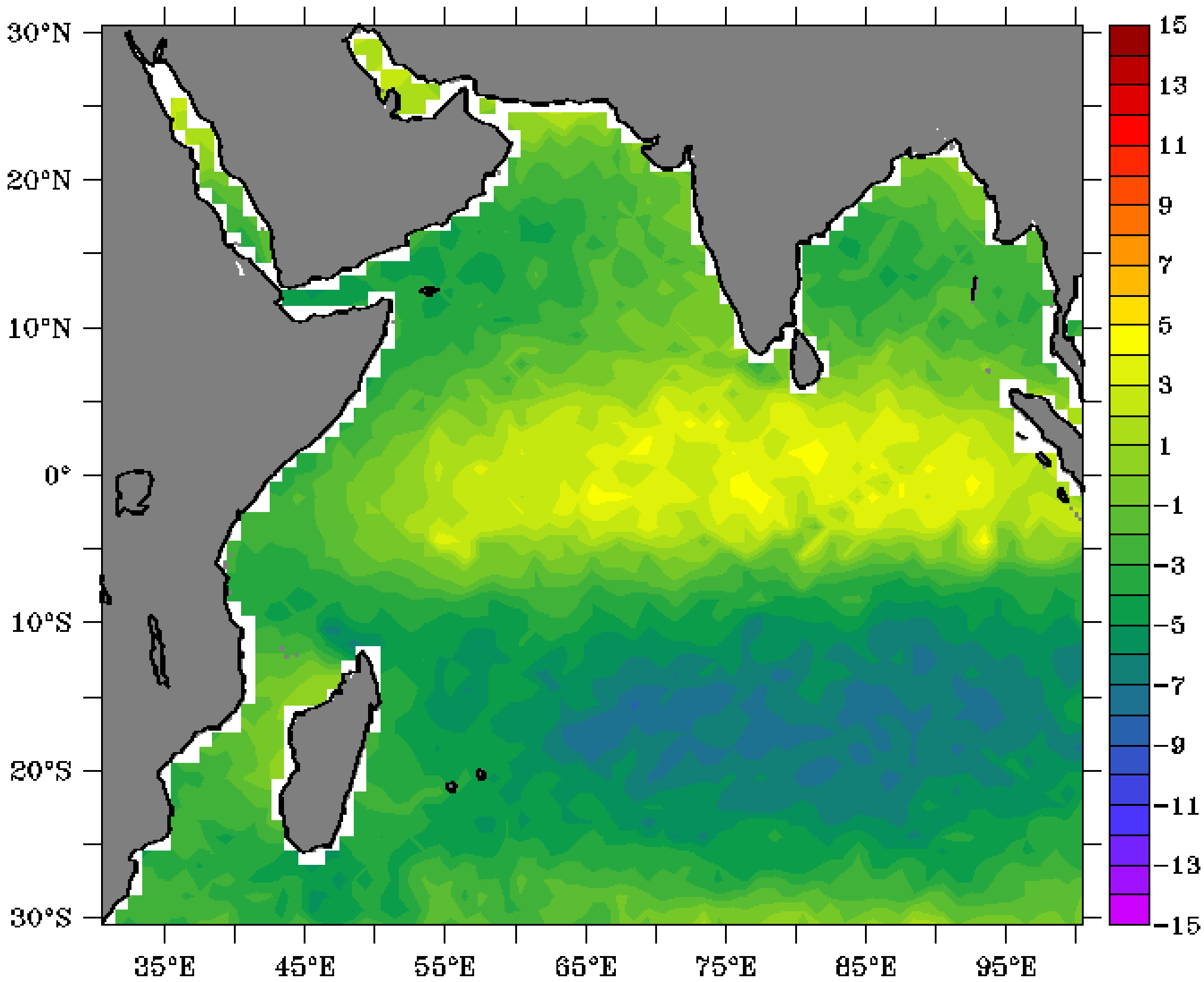
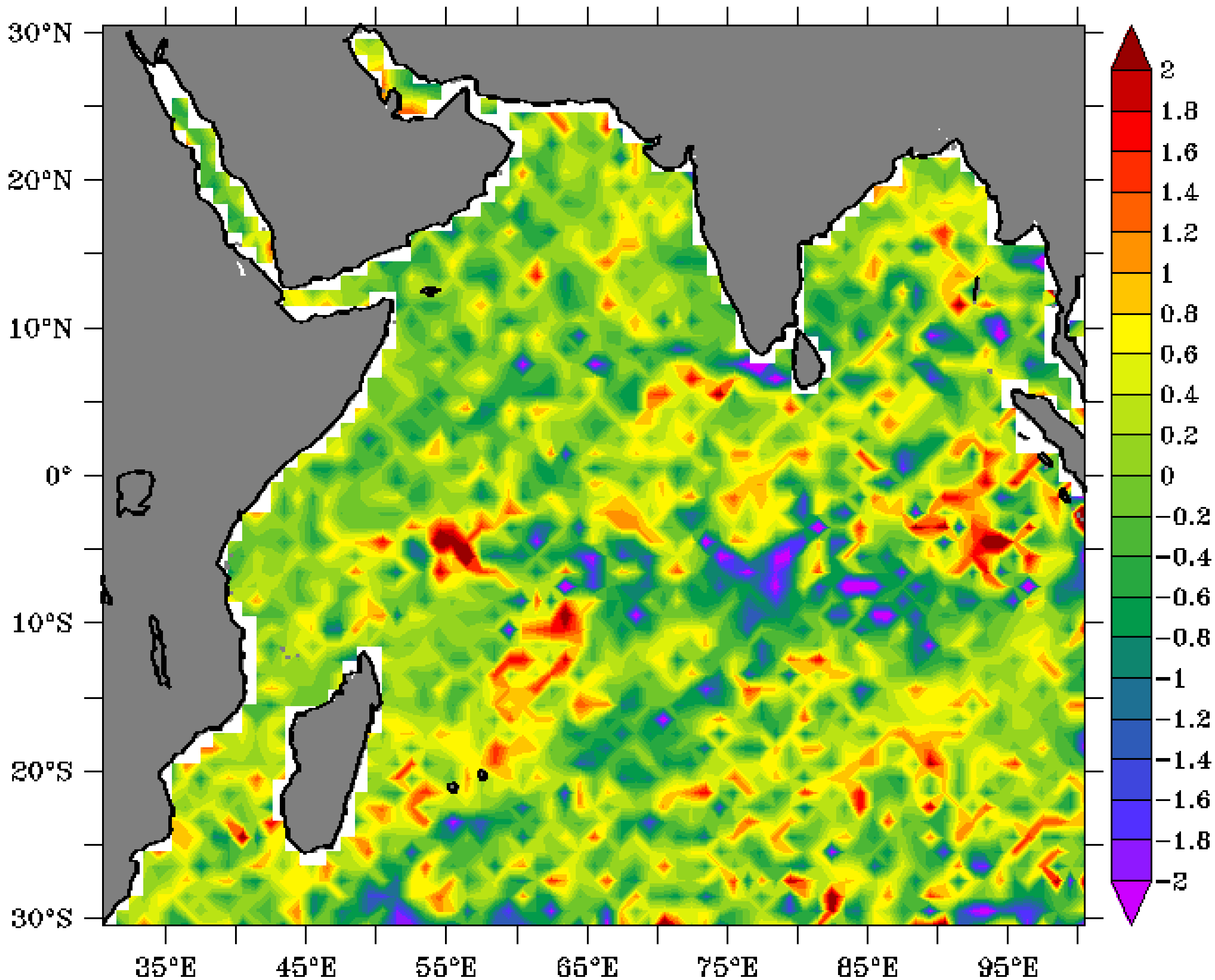
Anomaly (m/s)



Zonal wind speed (m/s)   NOVEMBER


30°N
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−0.2
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−1.2
−1.4
−1.6
−1.8
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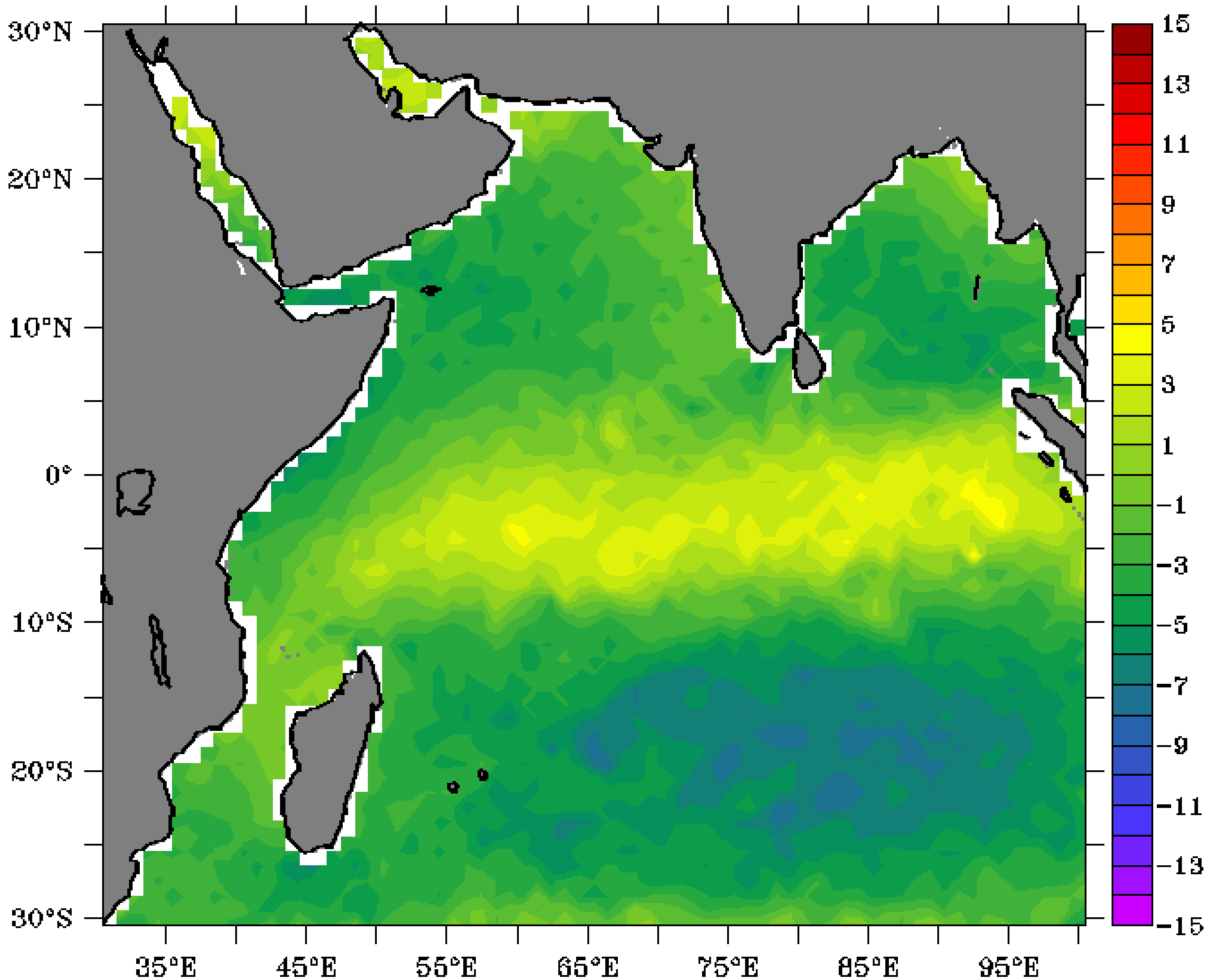
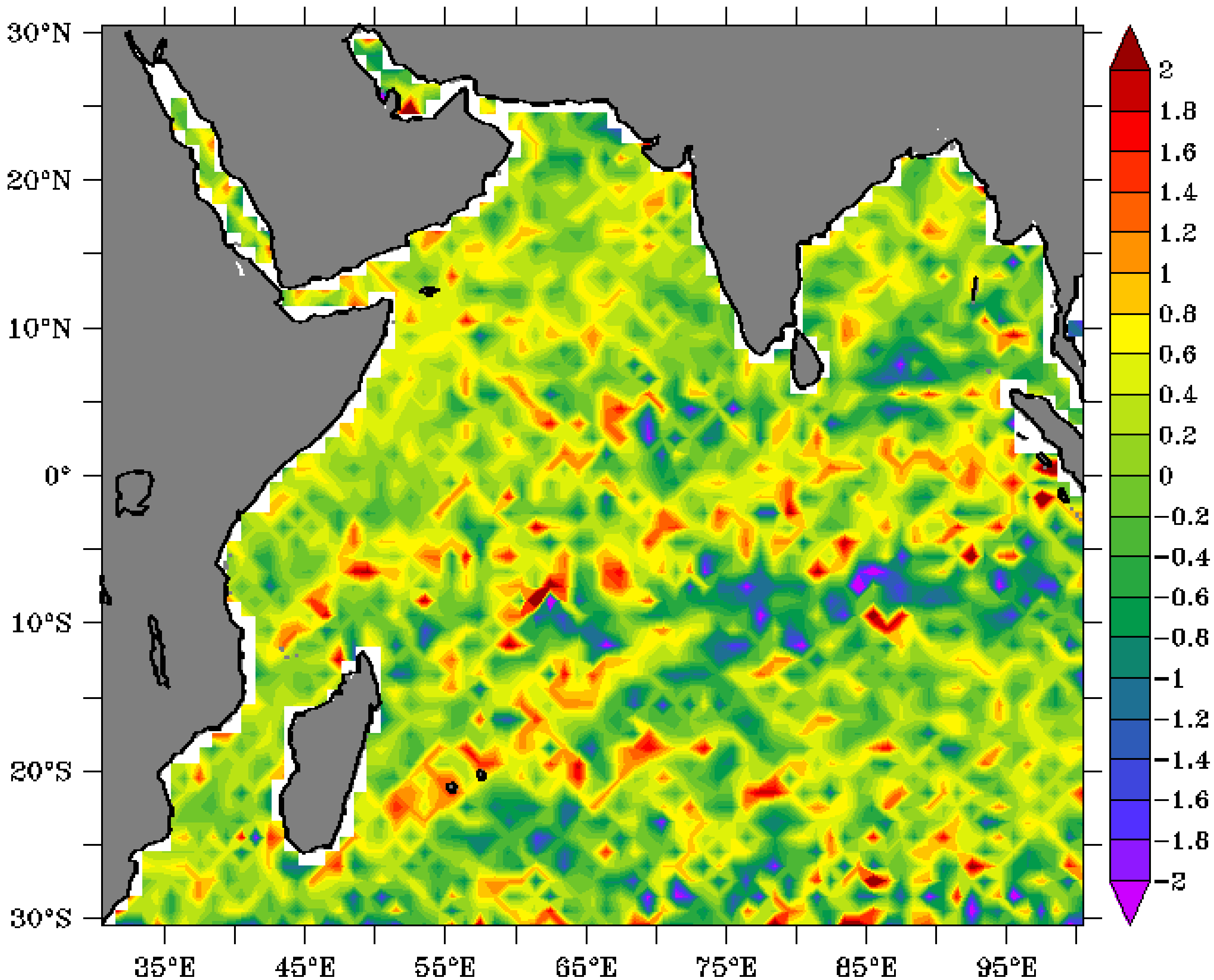
Anomaly (m/s)



Zonal wind speed (m/s)   DECEMBER


30°N
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−1.4
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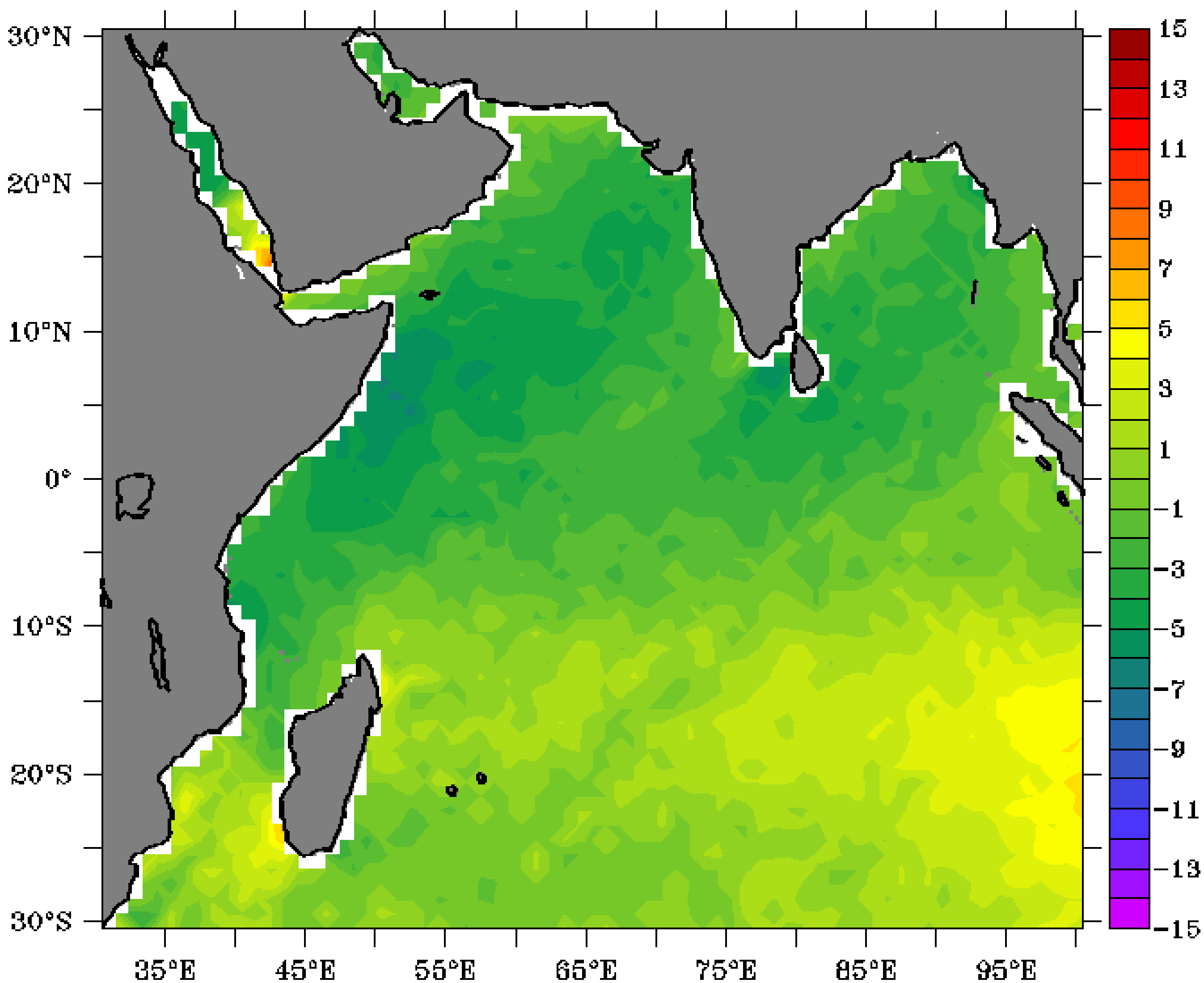
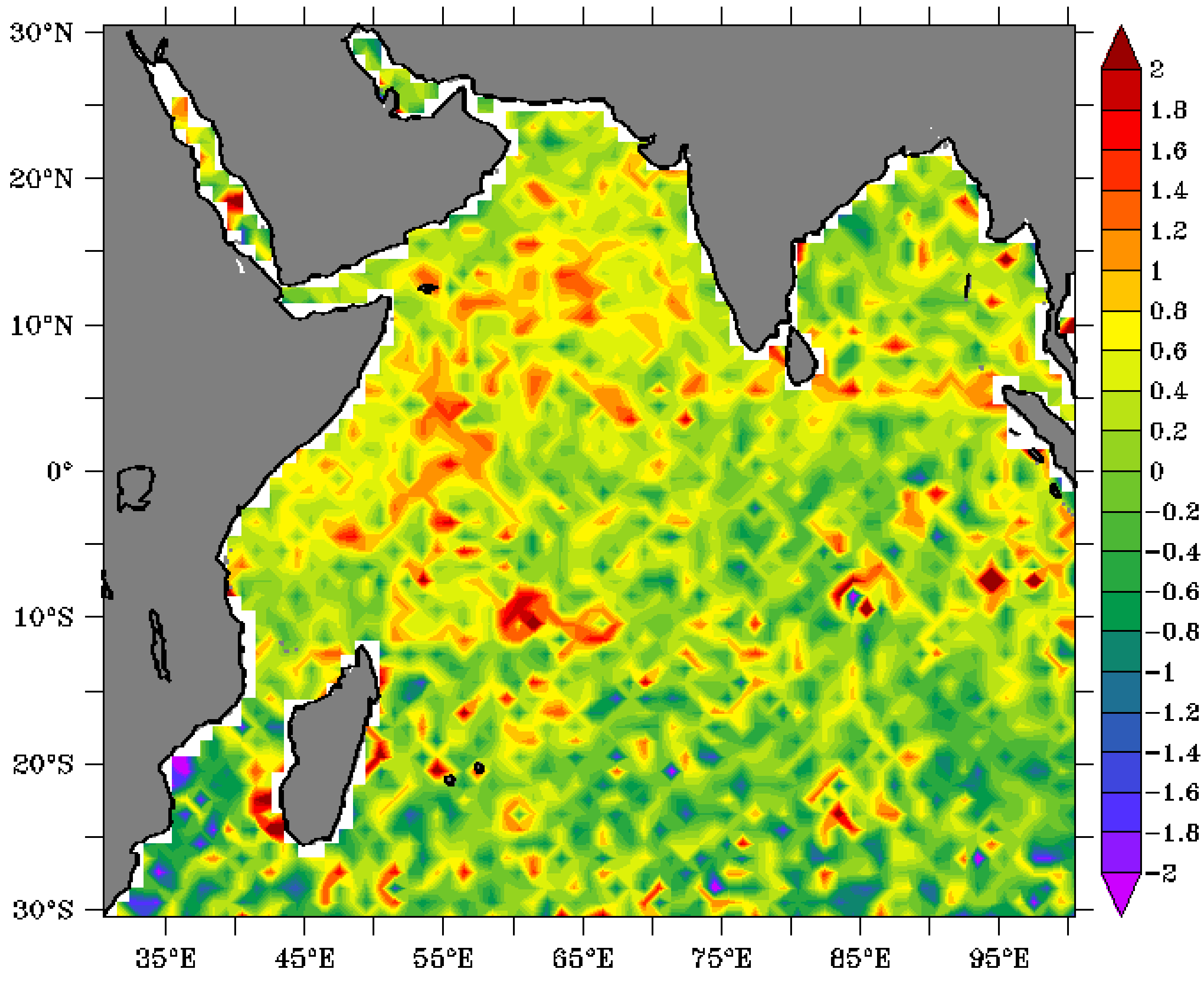
Anomaly (m/s)



Meridional wind speed (m/s) JANUARY



30°N
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−1.4
−1.6
−1.8
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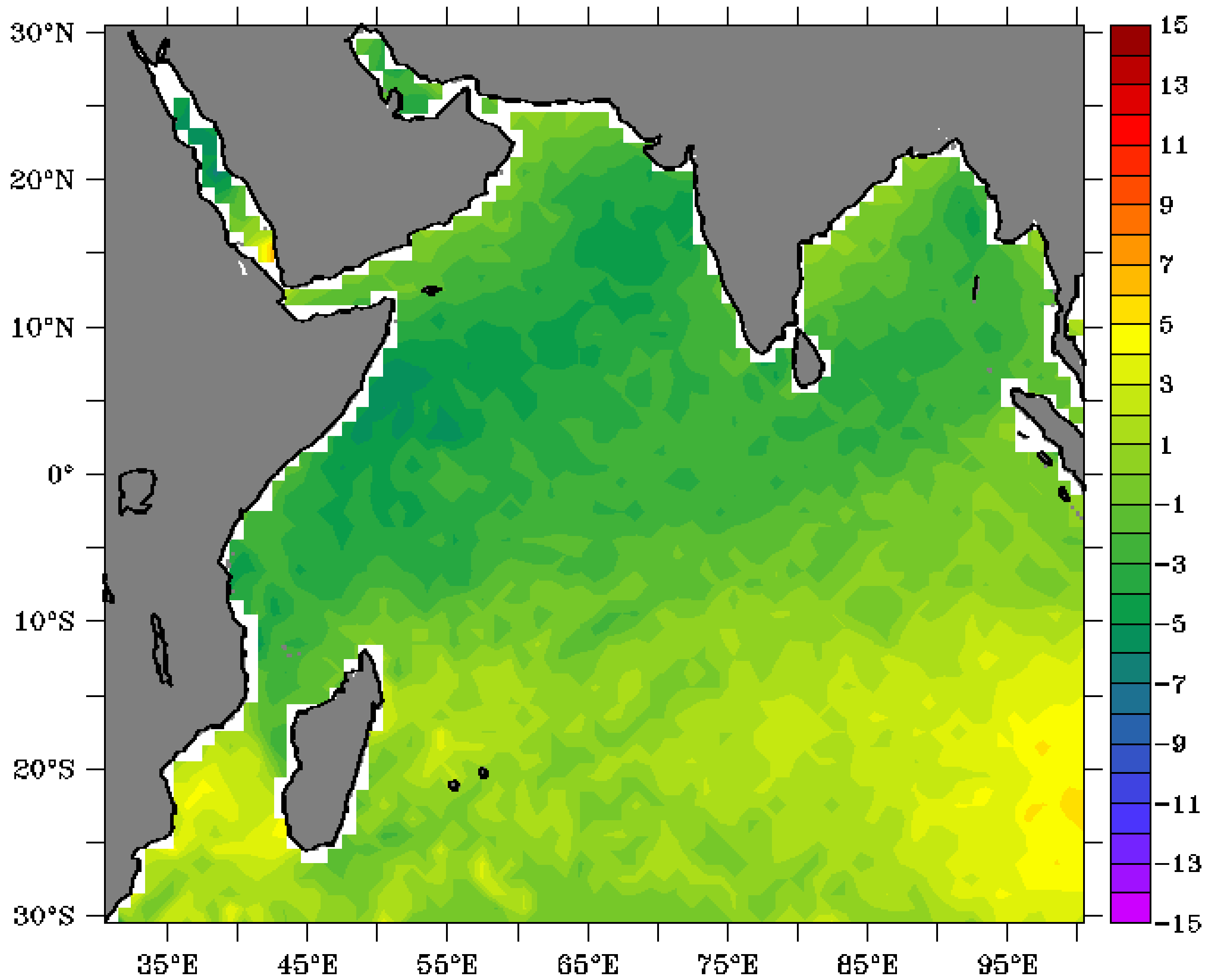
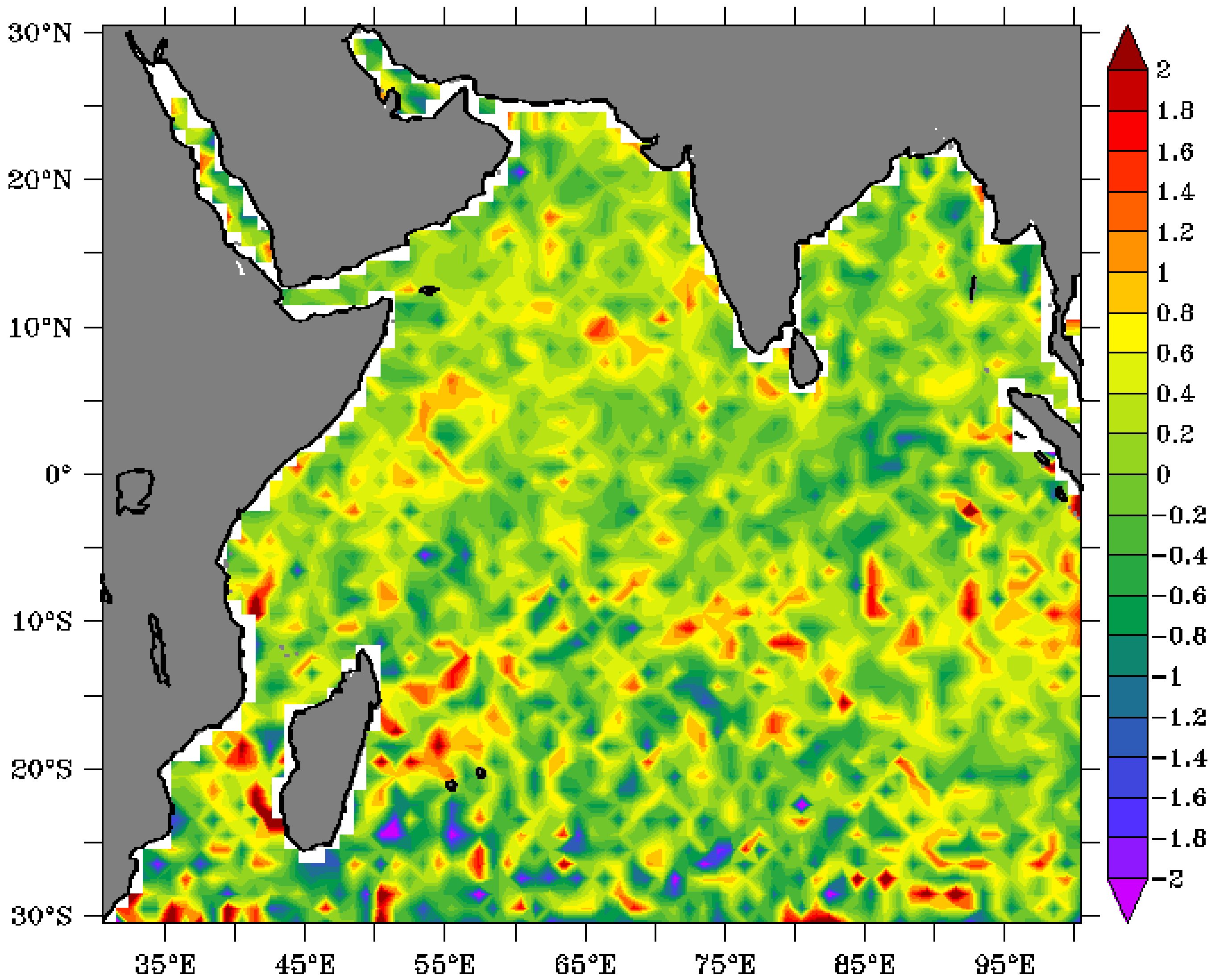
Anomaly (m/s)



Meridional wind speed (m/s) FEBRUARY


30°N
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55°E
65°E
75°E
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−0.8
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−1.2
−1.4
−1.6
−1.8
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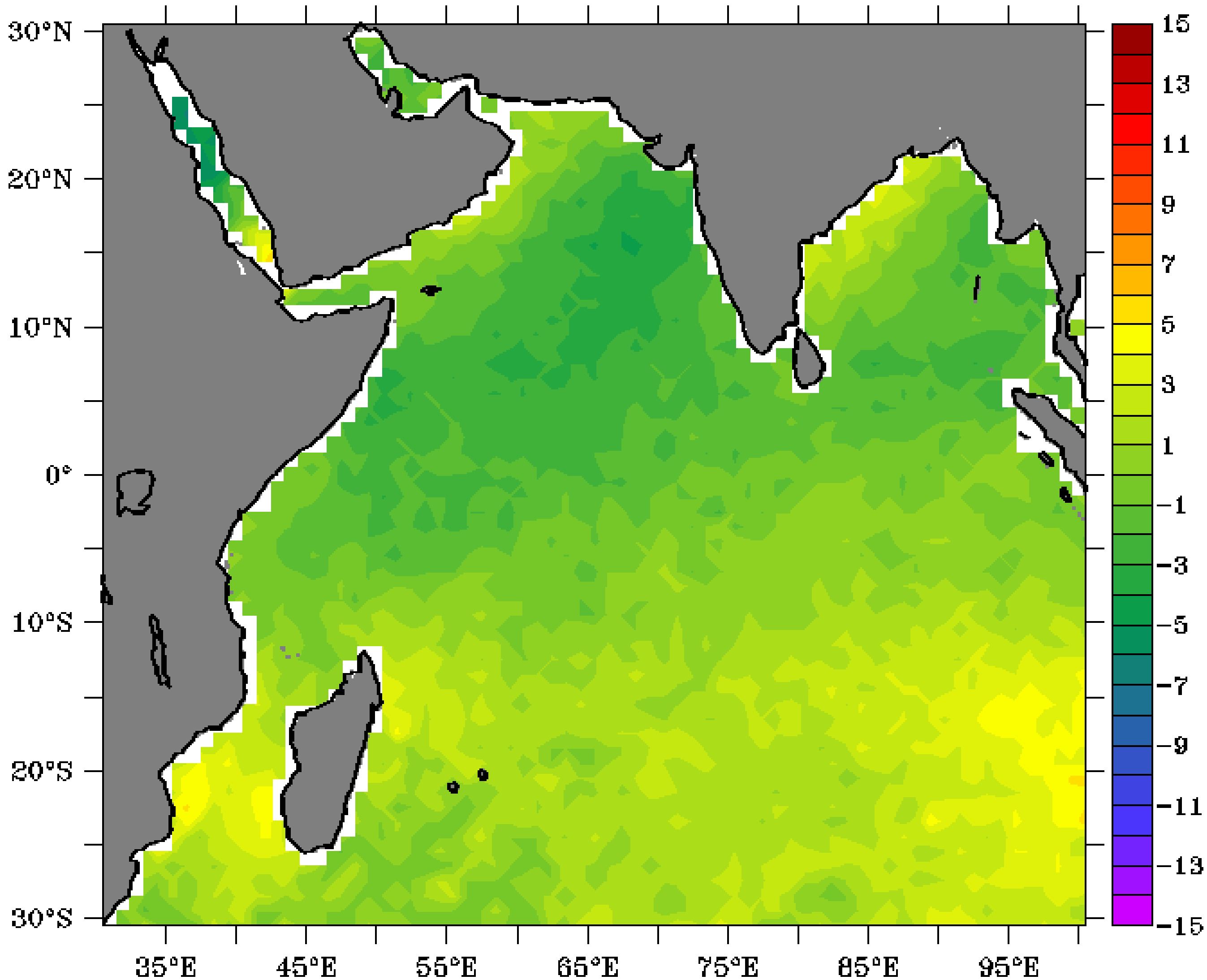
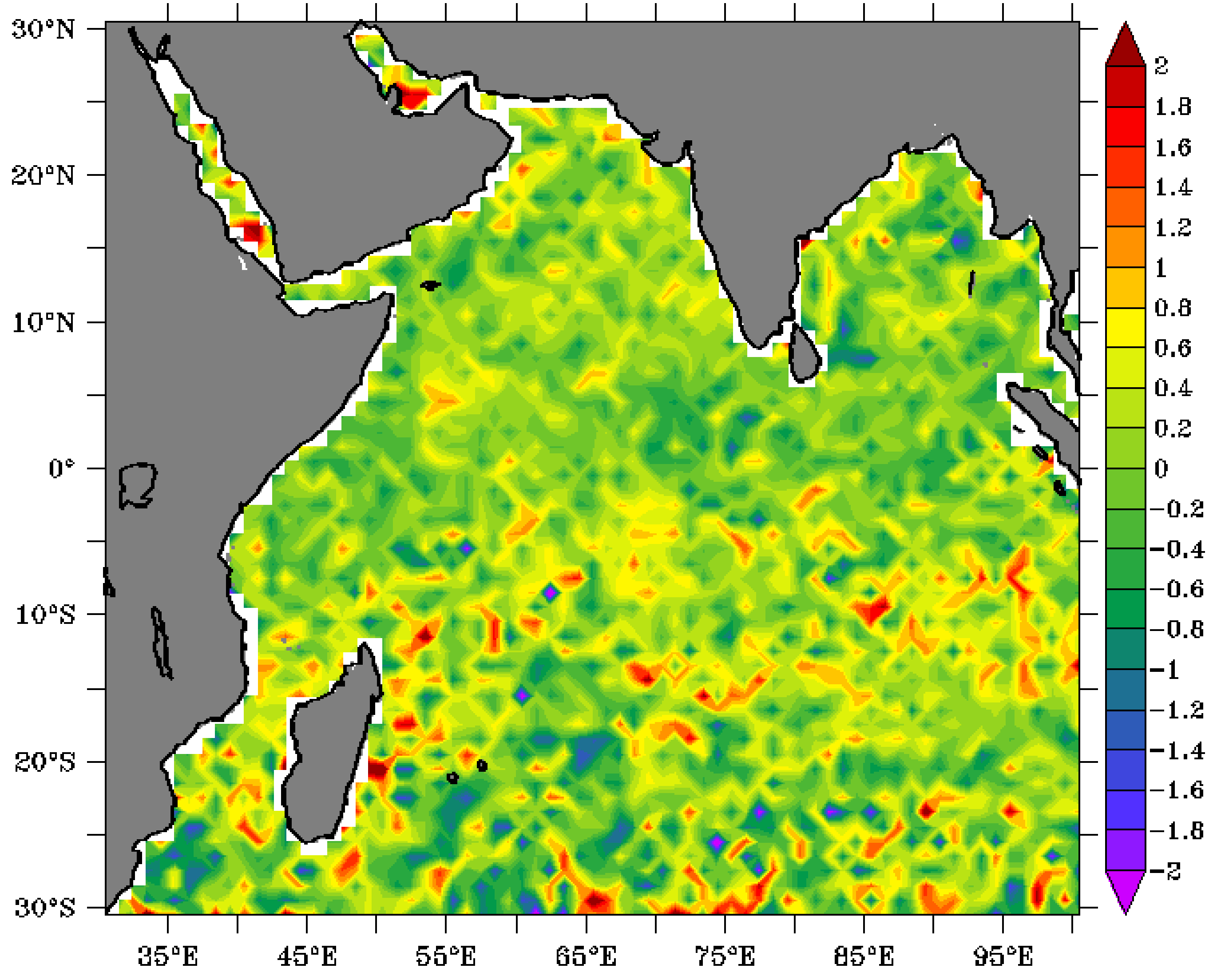
Anomaly (m/s)



Meridional wind speed (m/s) MARCH



30°N
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65°E
75°E
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−1.8
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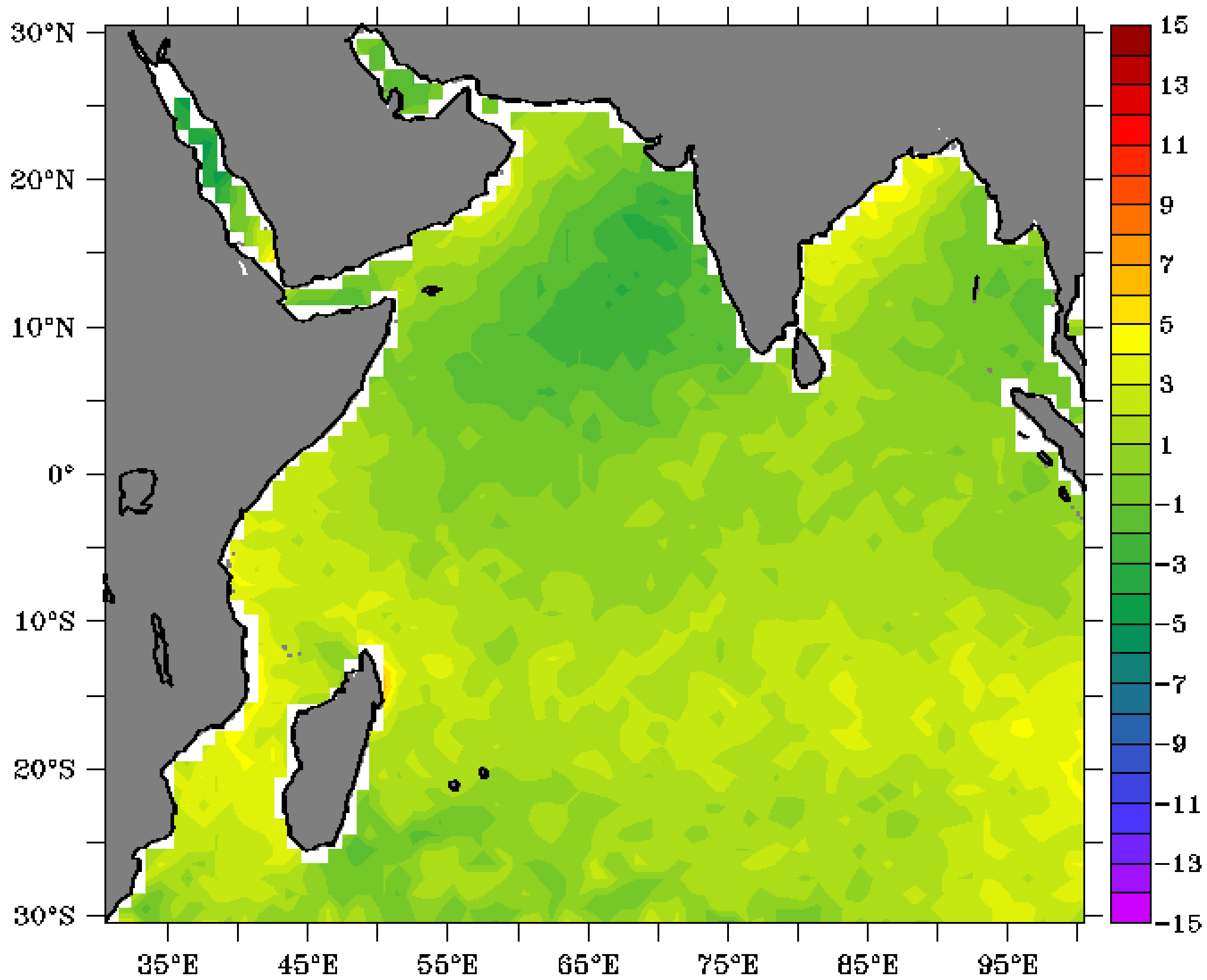
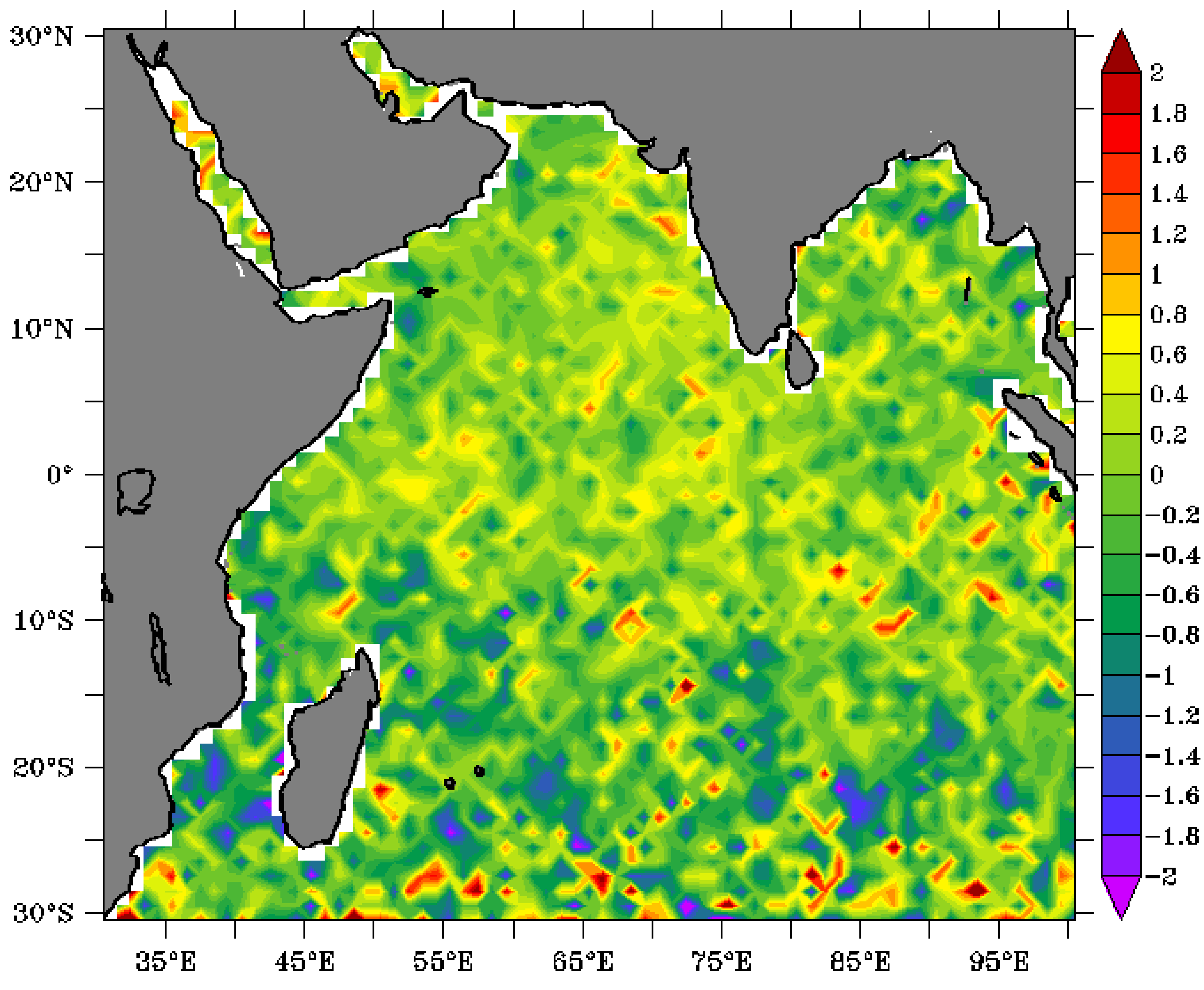
Anomaly (m/s)



Meridional wind speed (m/s) APRIL


30°N
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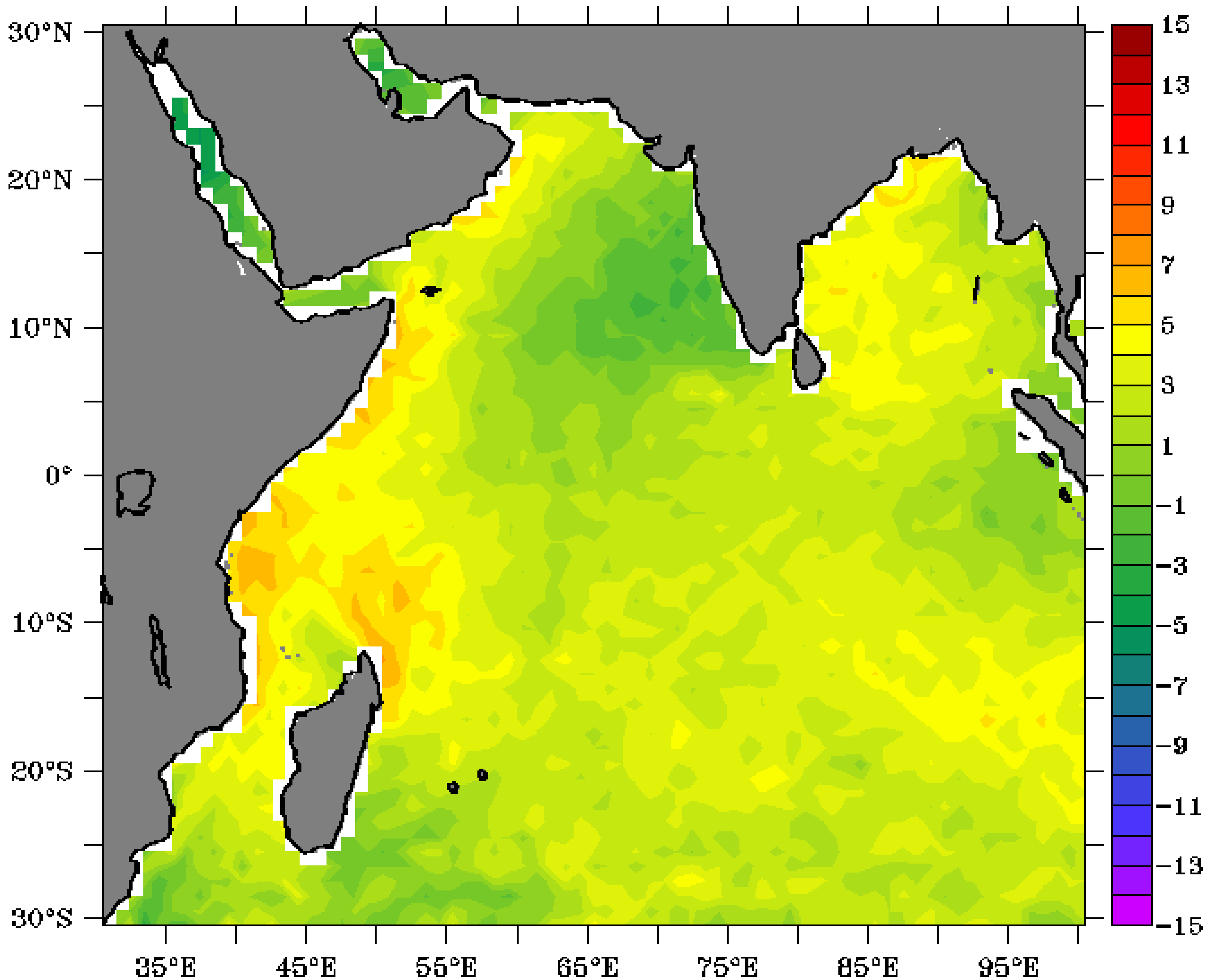
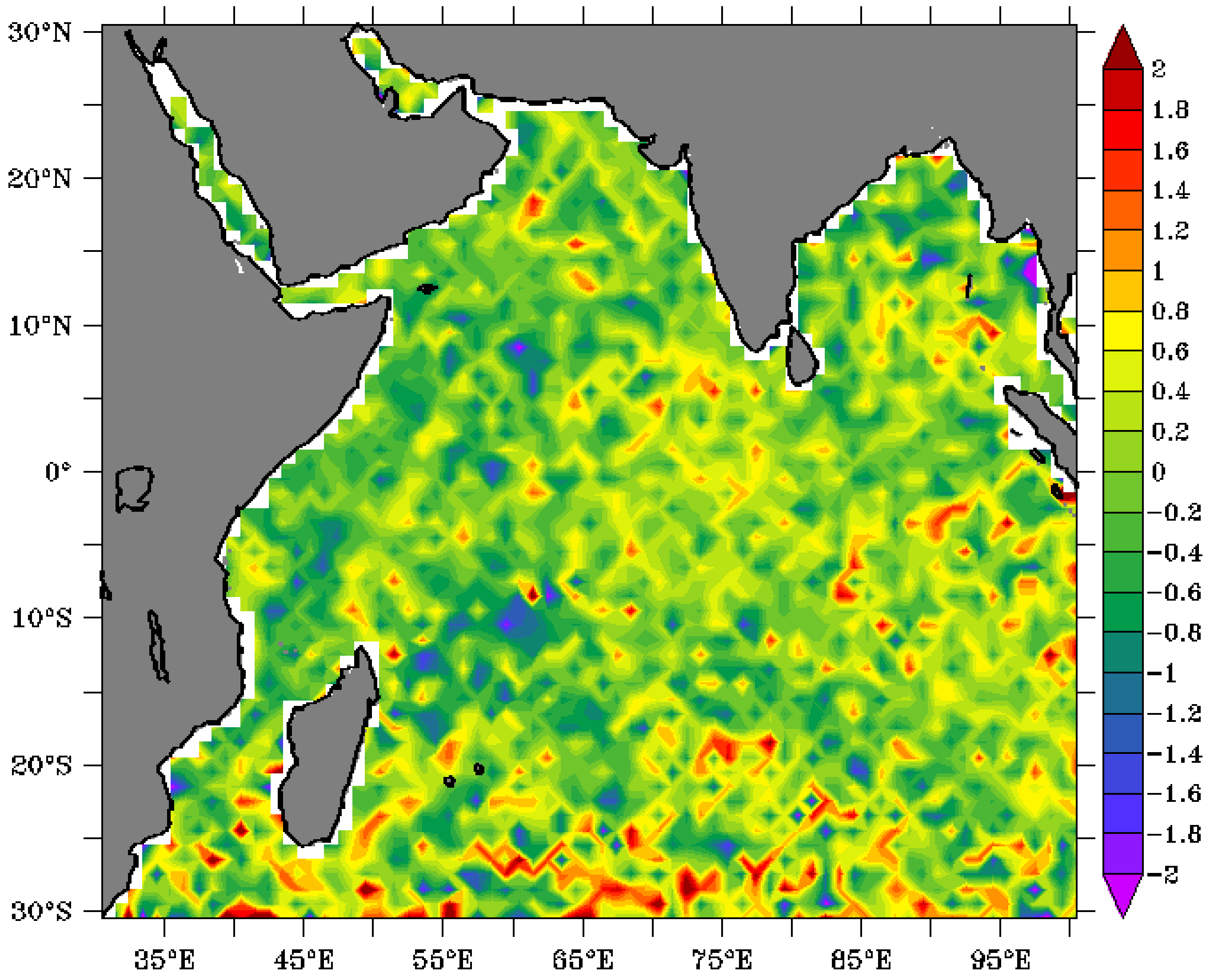
Anomaly (m/s)



Meridional wind speed (m/s) MAY


30°N
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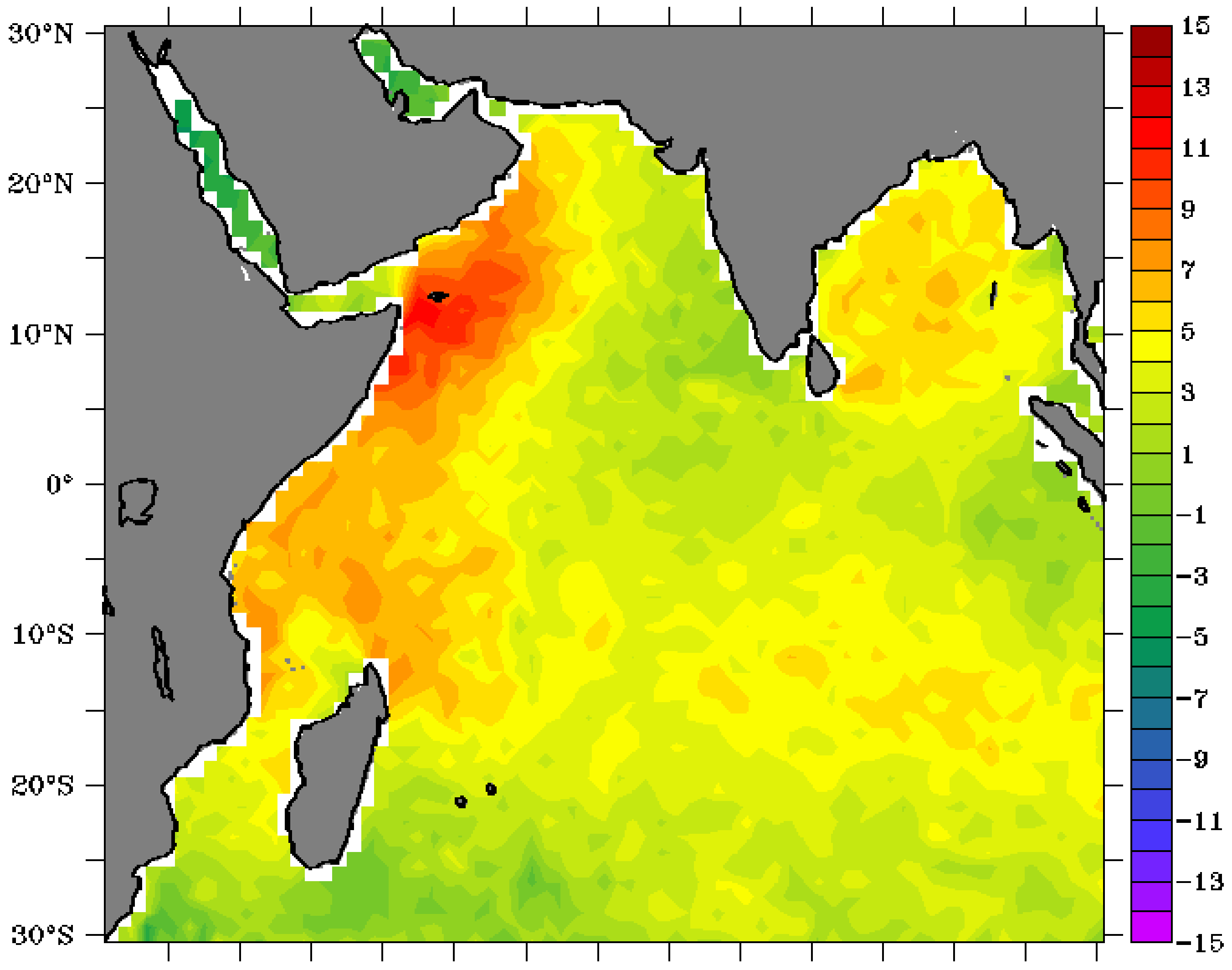
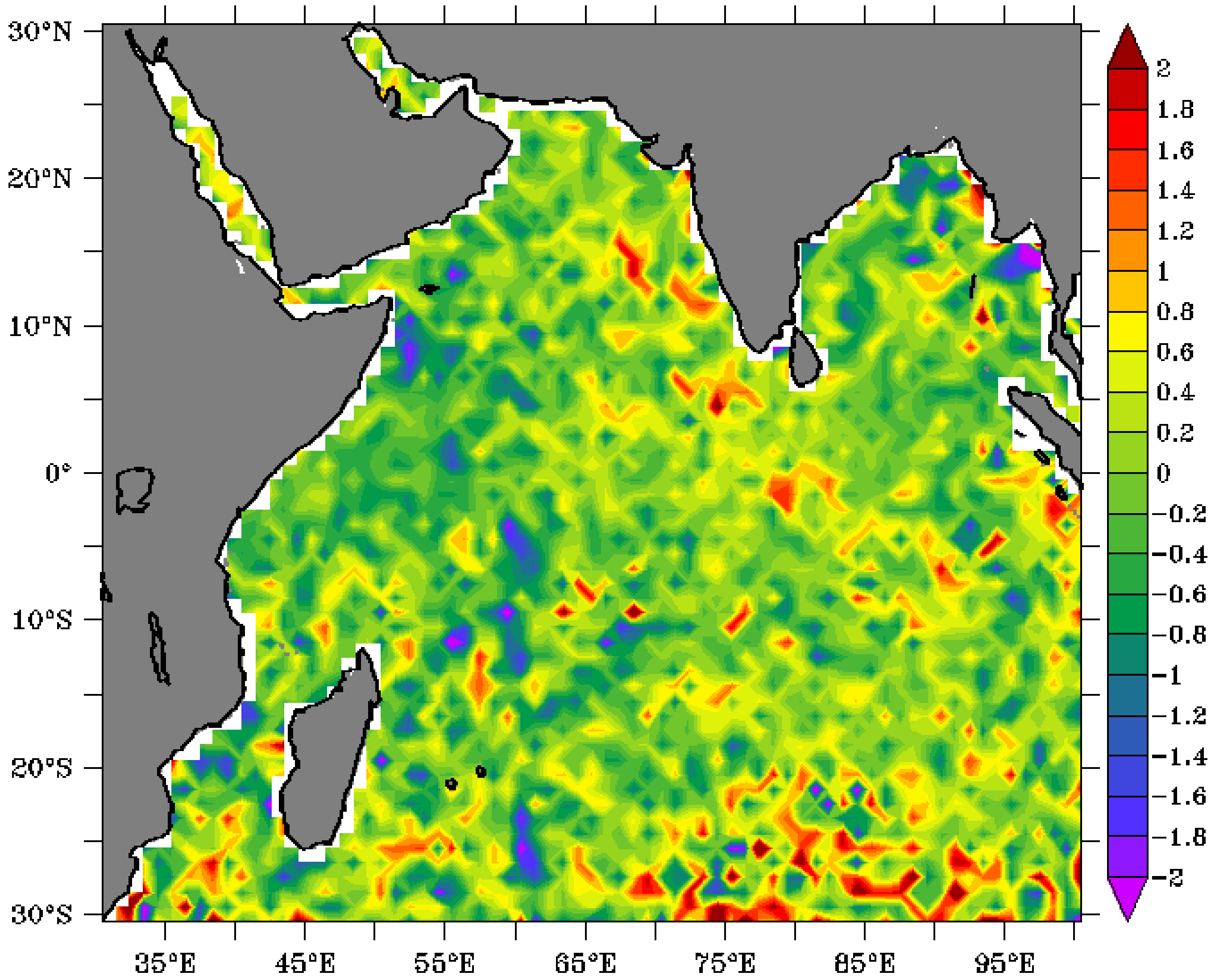
Anomaly (m/s)



Meridional wind speed (m/s) JUNE


30°N
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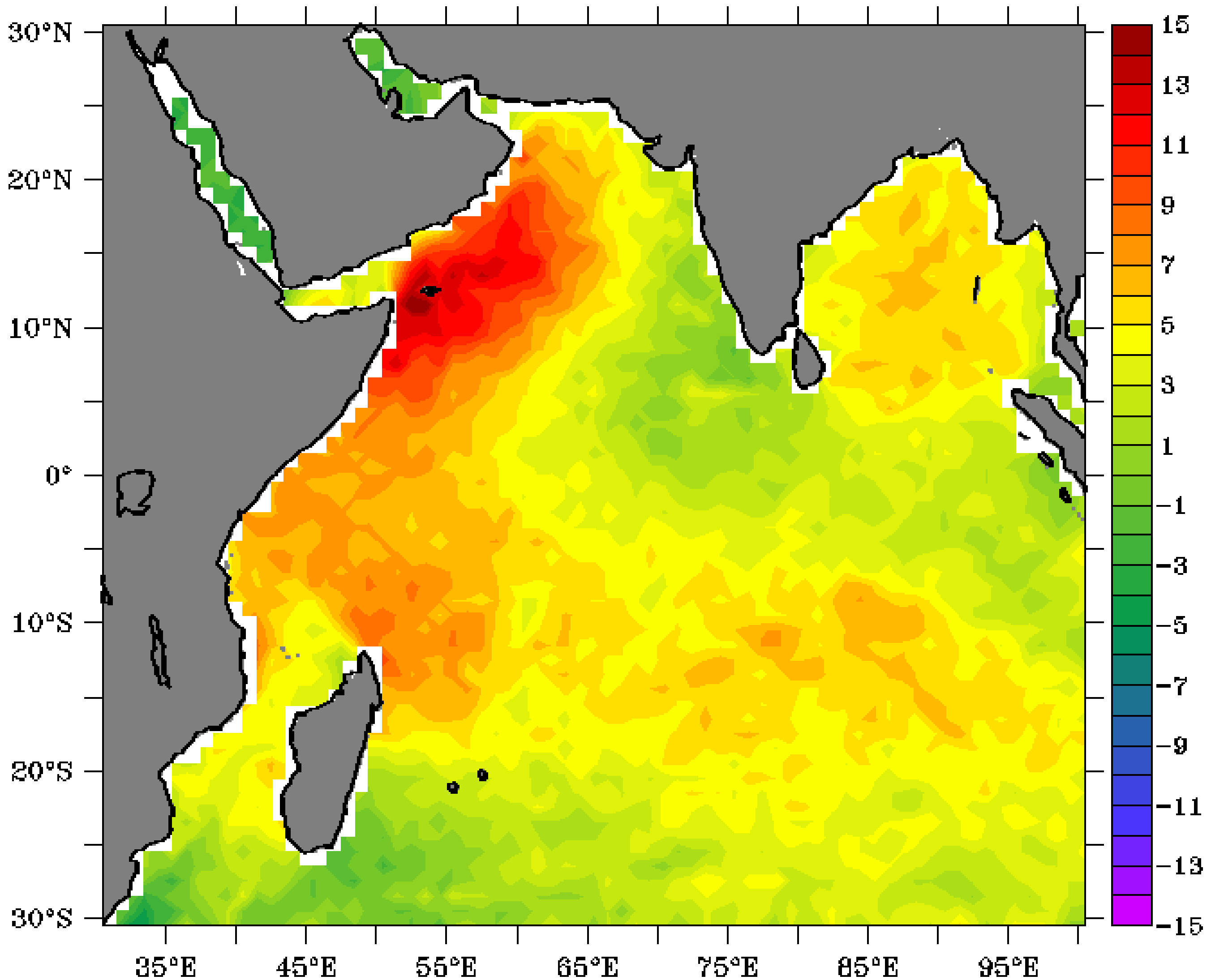
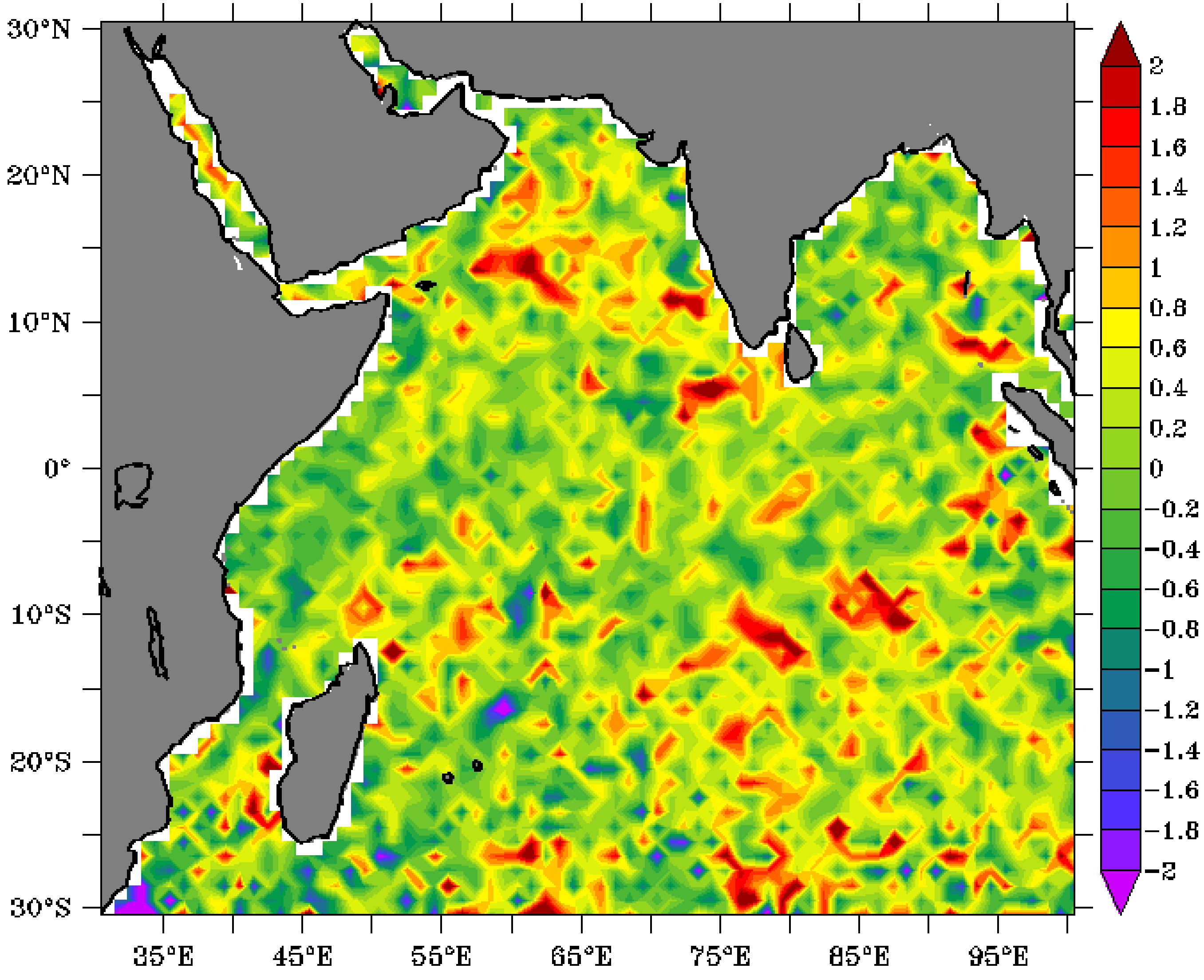
Anomaly (m/s)



Meridional wind speed (m/s) JULY


30°N
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-1.6
-1.8
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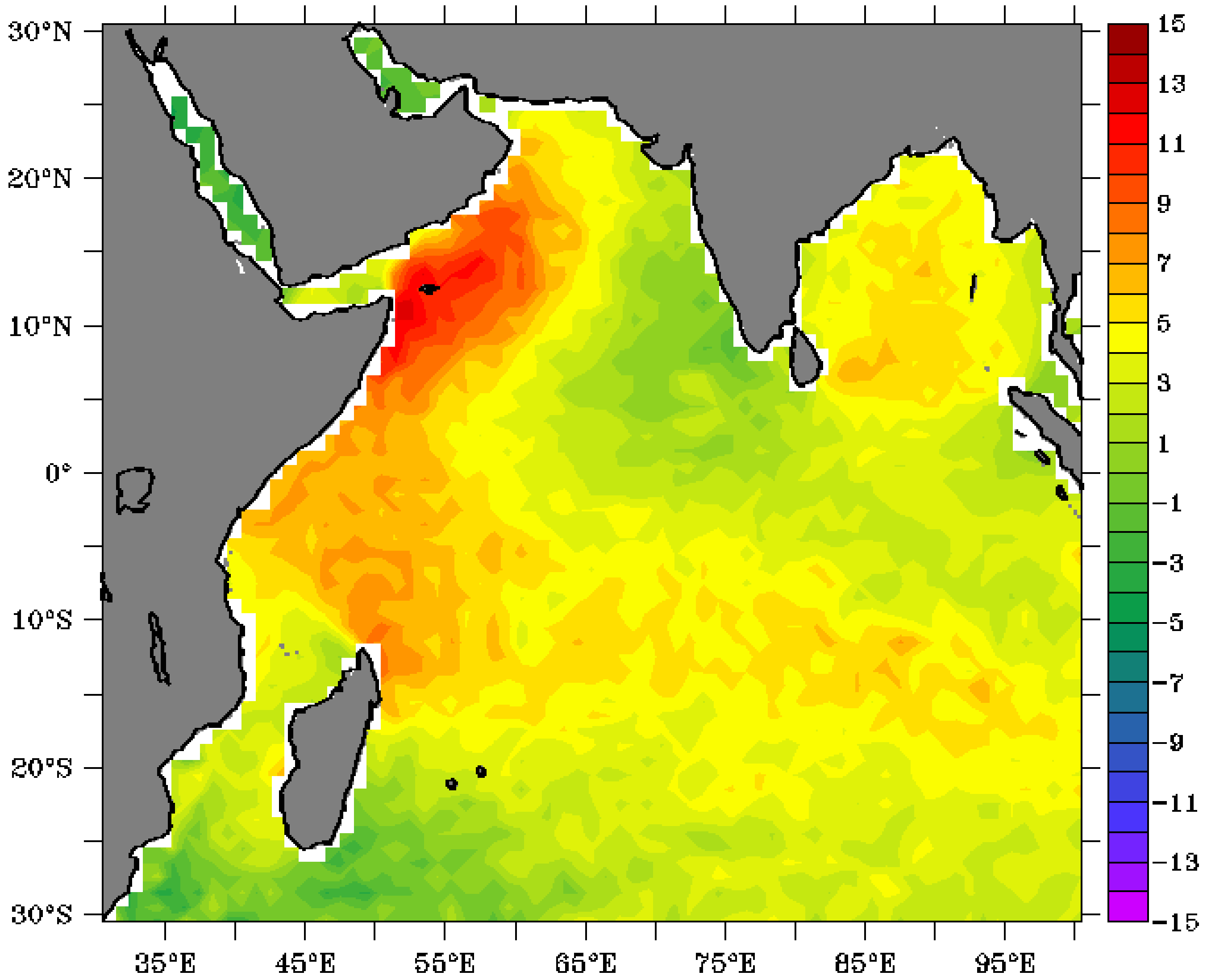
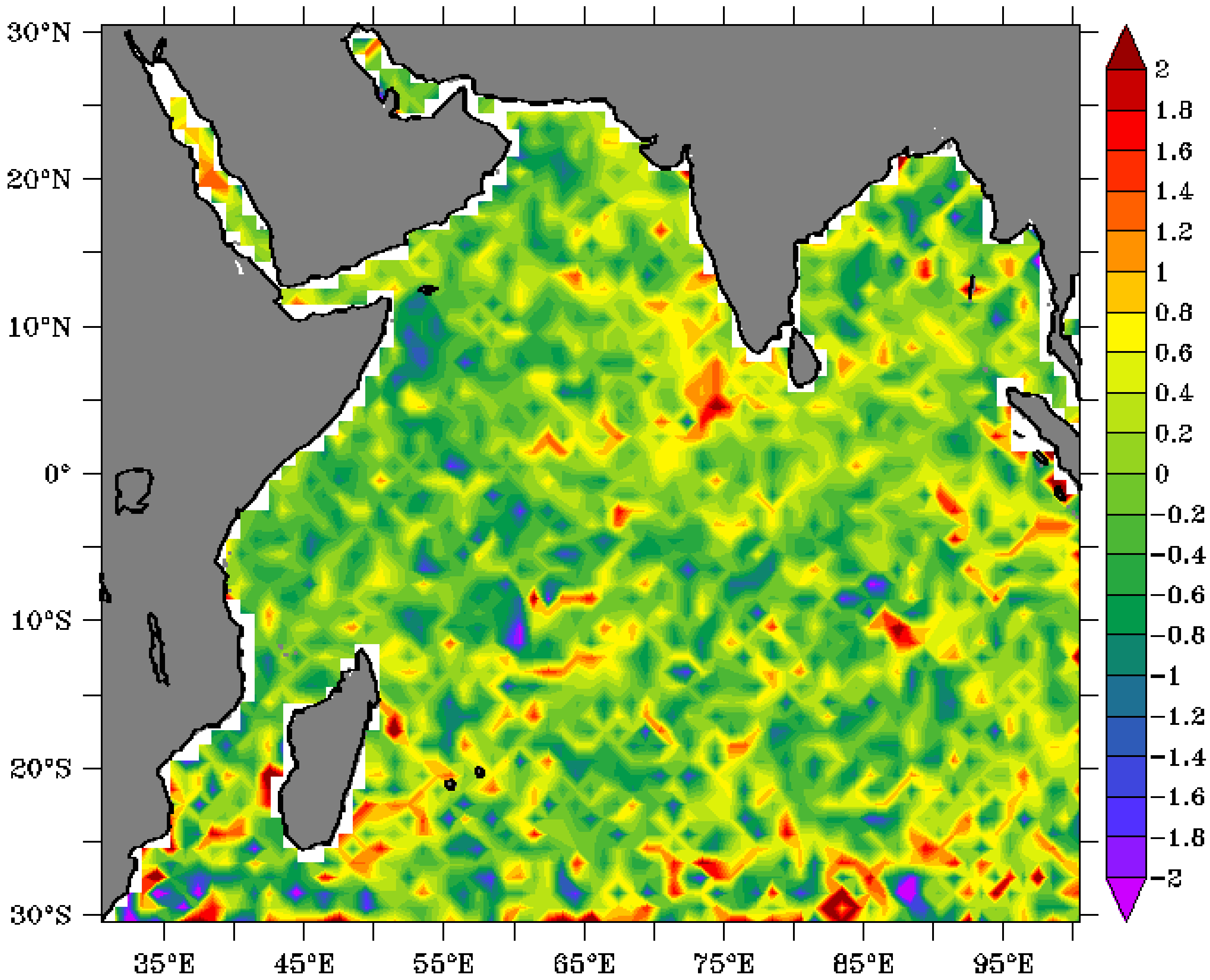
Anomaly (m/s)



Meridional wind speed (m/s)   AUGUST


30°N
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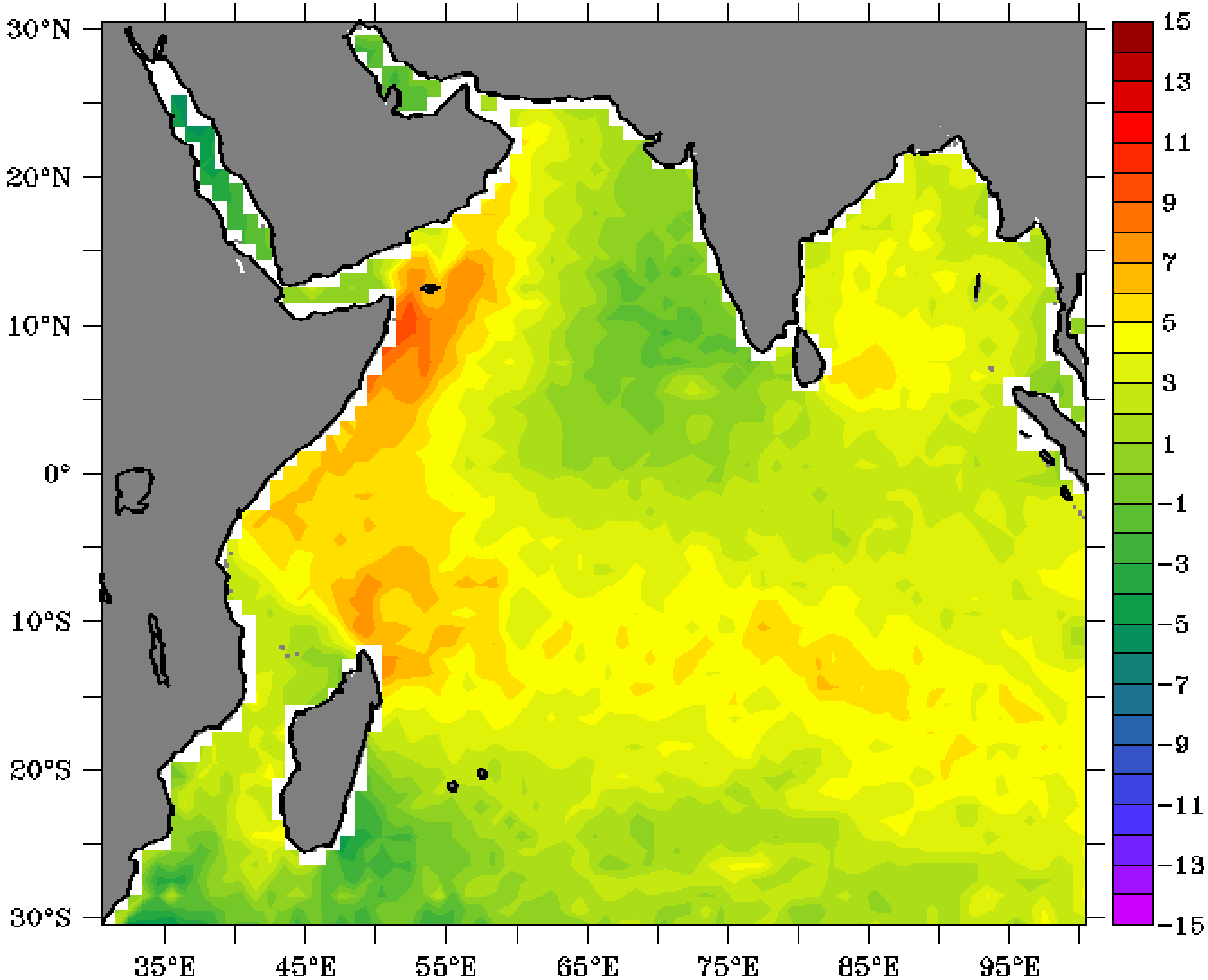
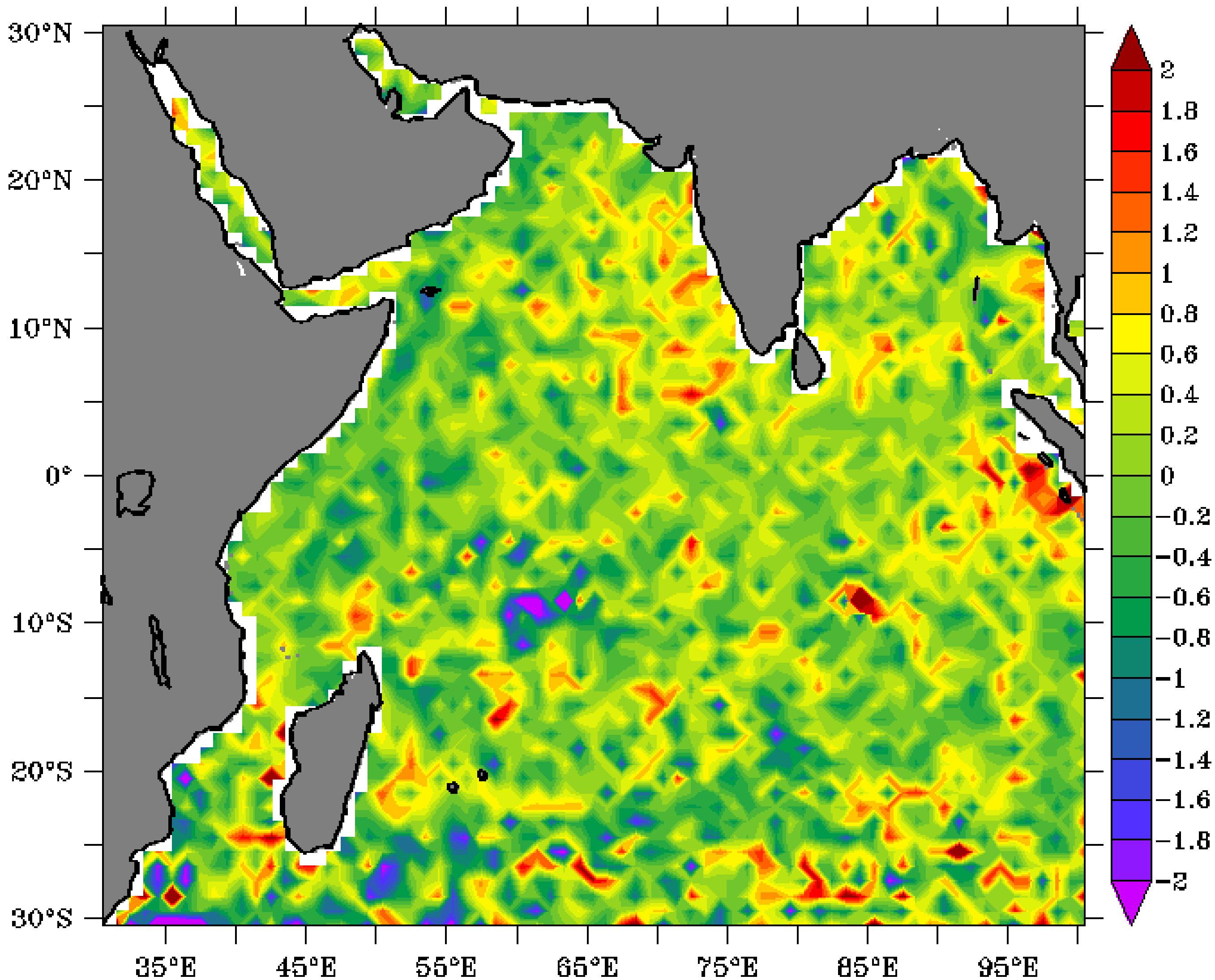
Anomaly (m/s)



Meridional wind speed (m/s) SEPTEMBER



30°N
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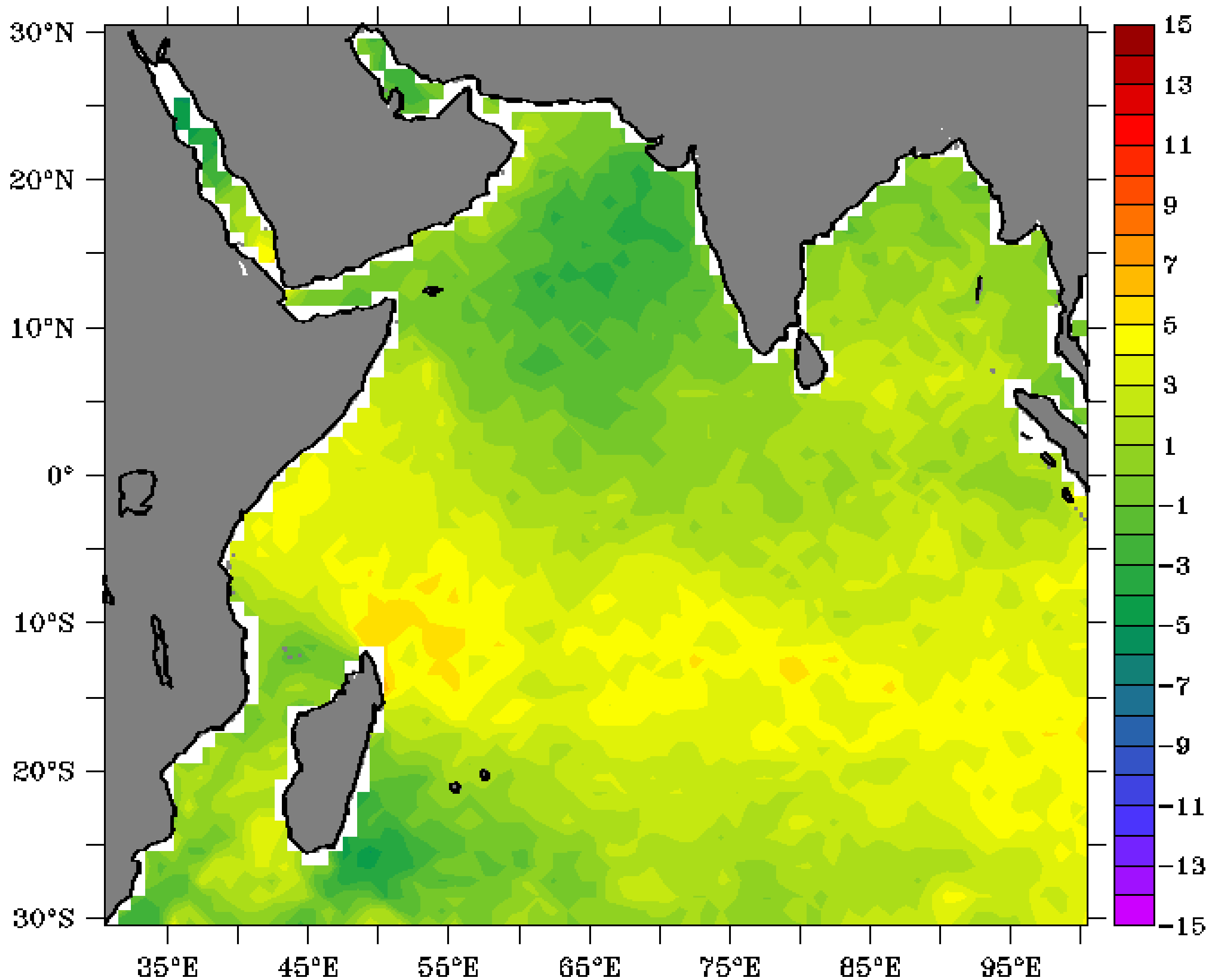
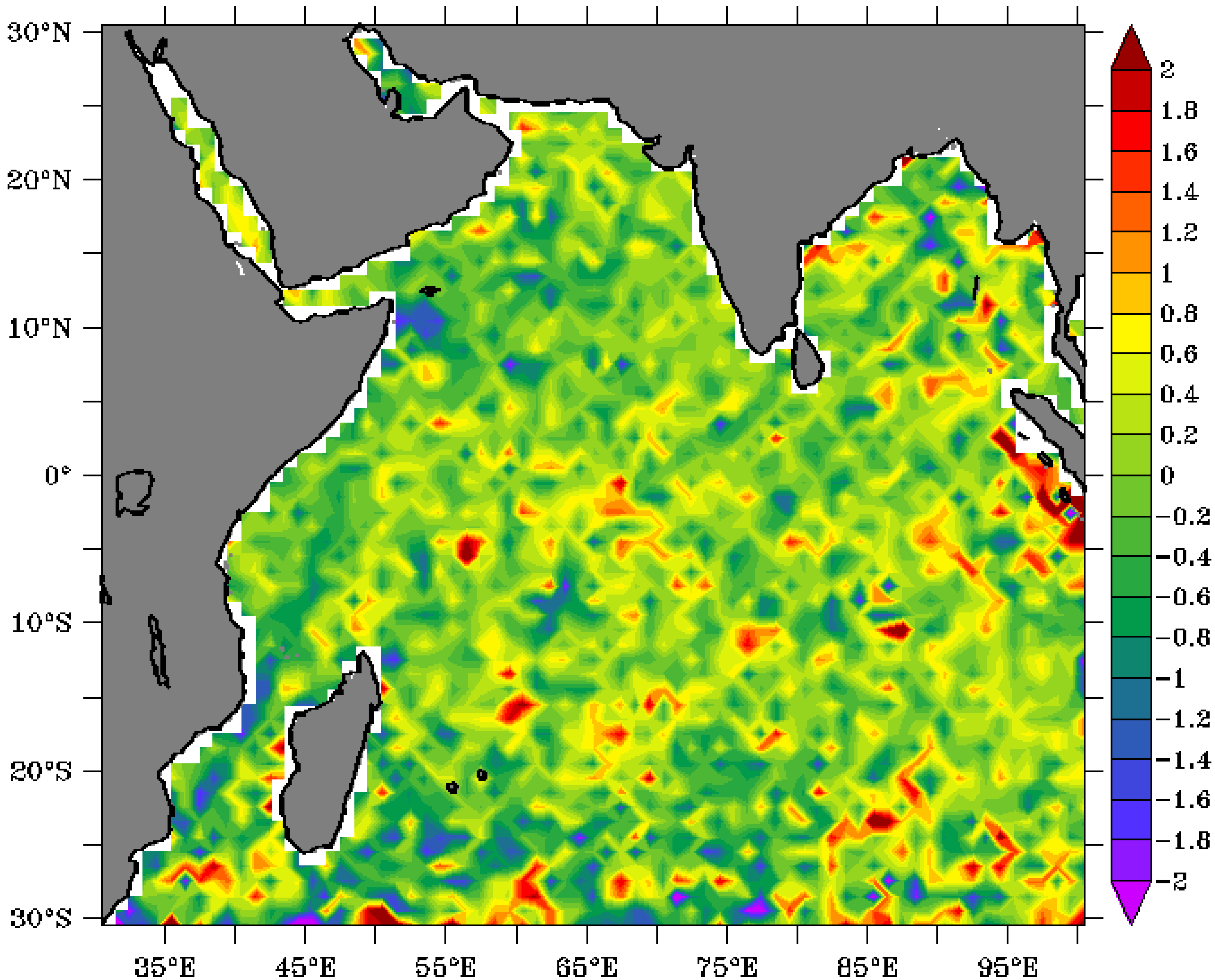
Anomaly (m/s)



Meridional wind speed (m/s)   OCTOBER


30°N
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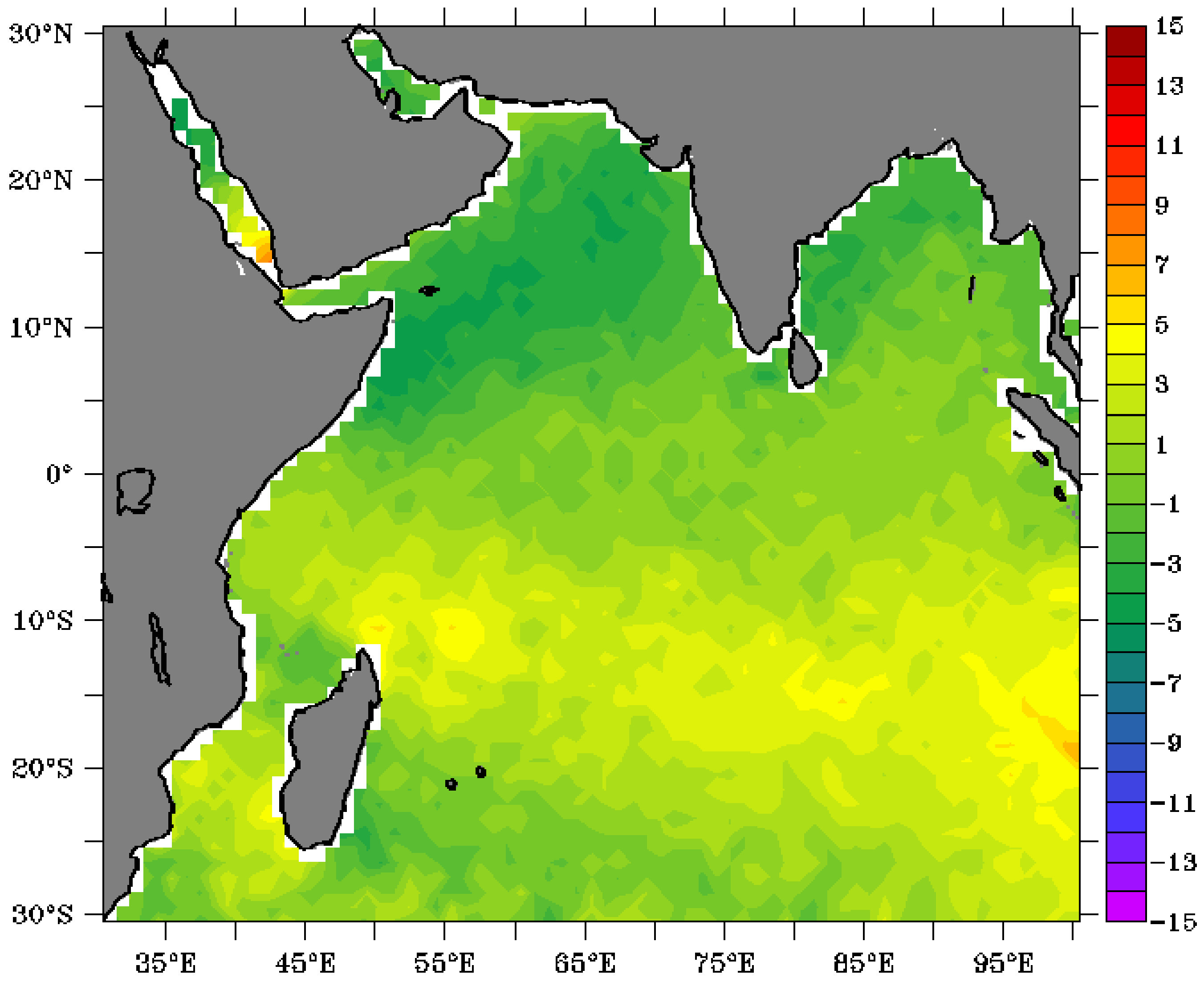
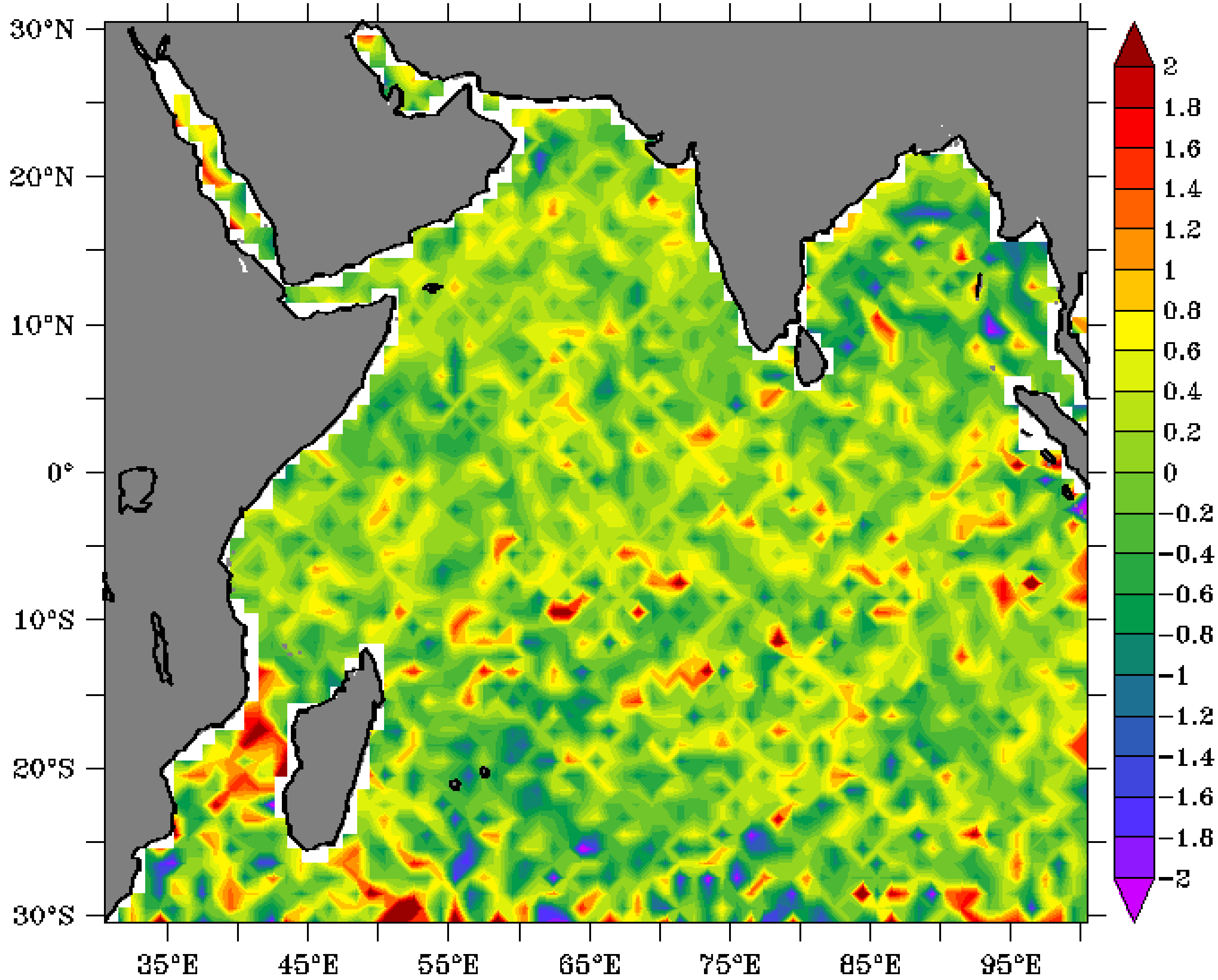
Anomaly (m/s)



Meridional wind speed (m/s) NOVEMBER


30°N
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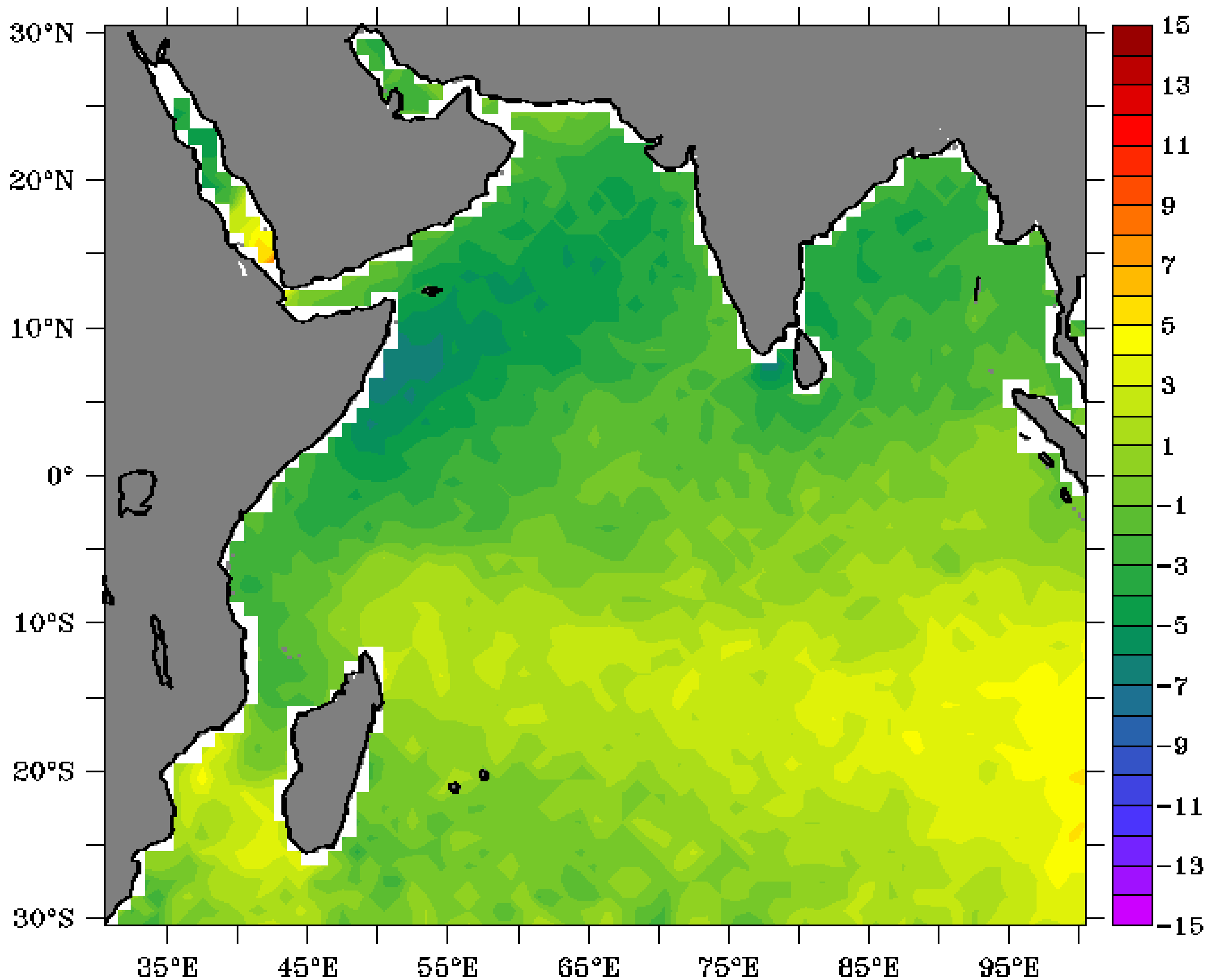
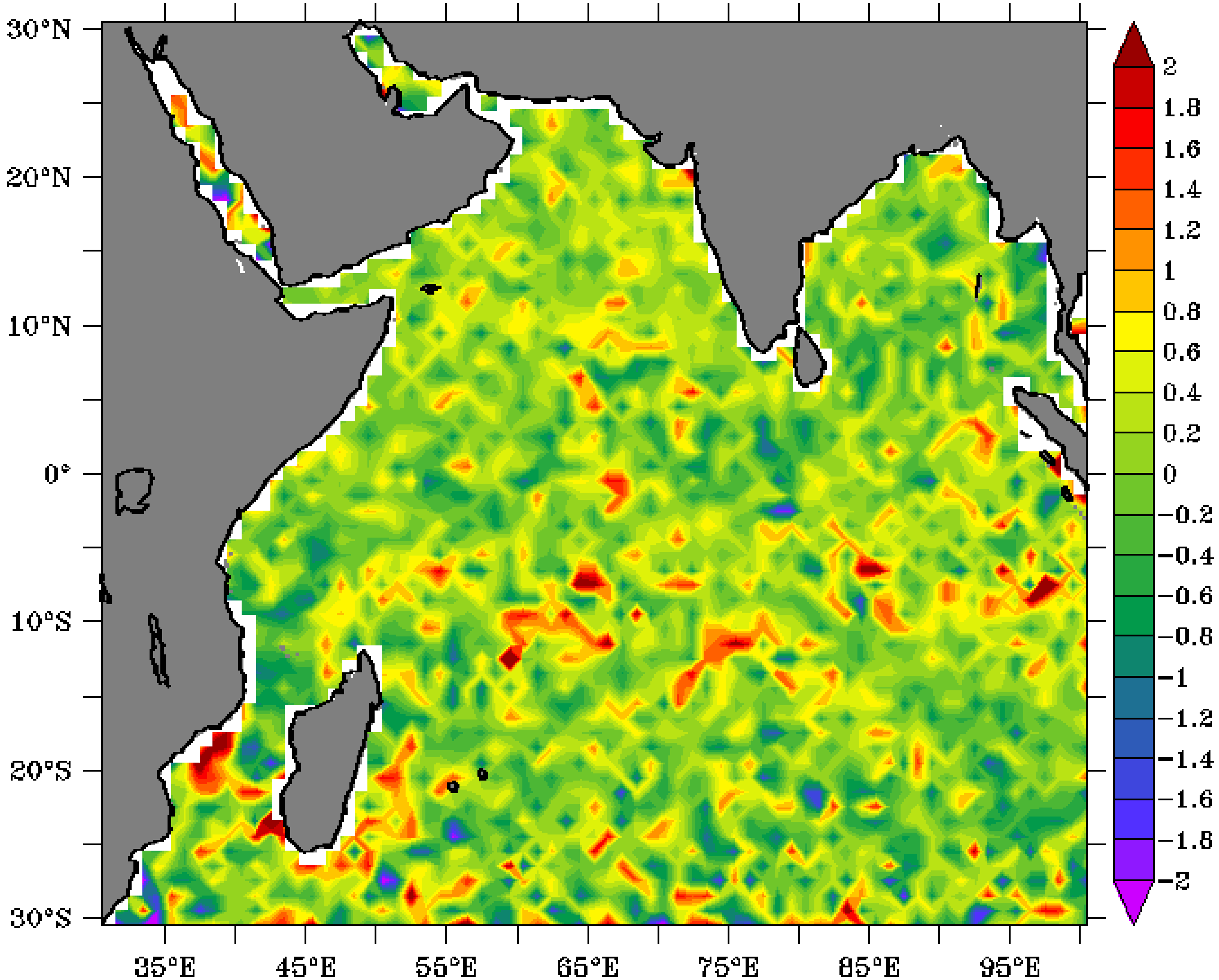
−2

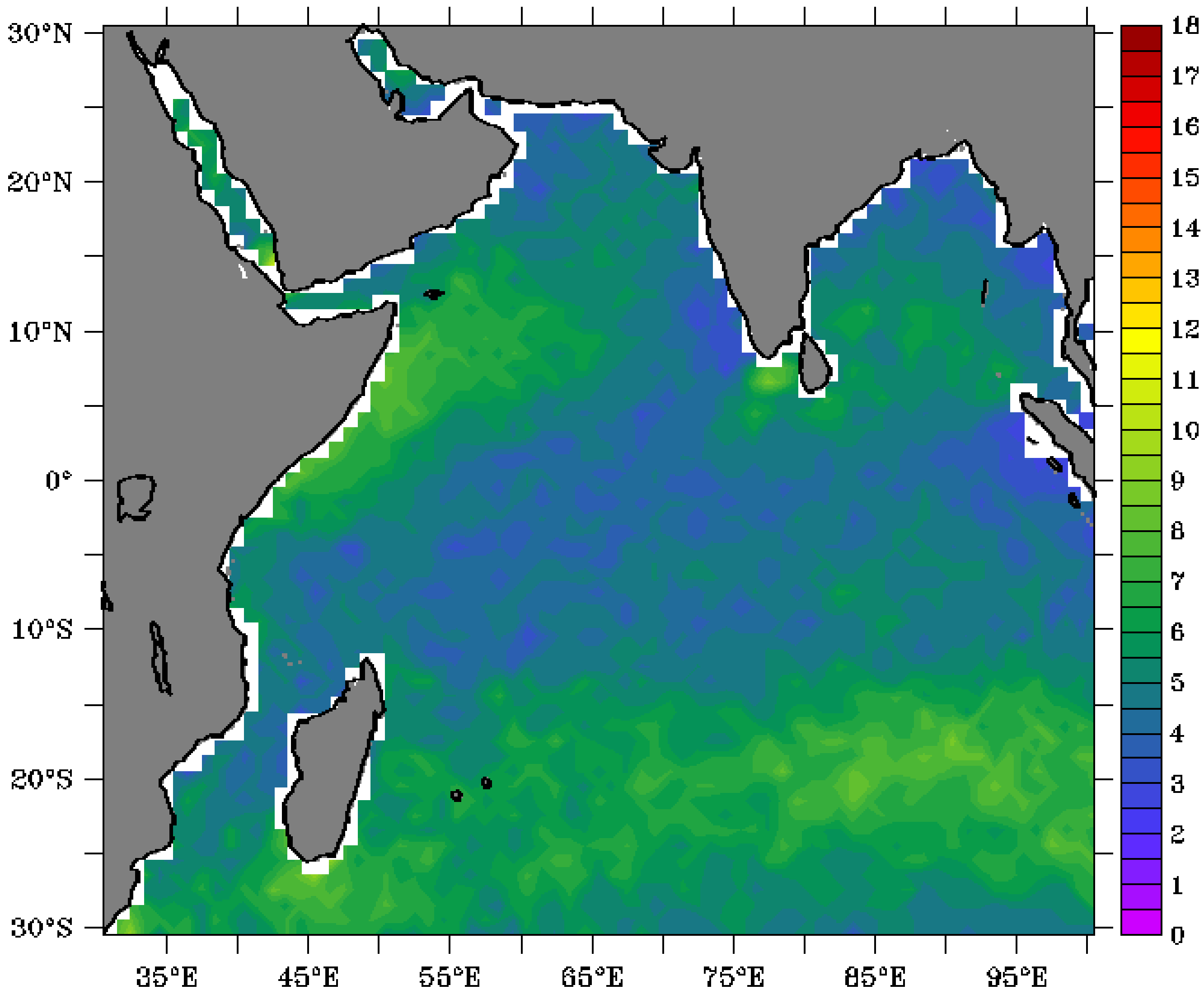
Anomaly (m/s)



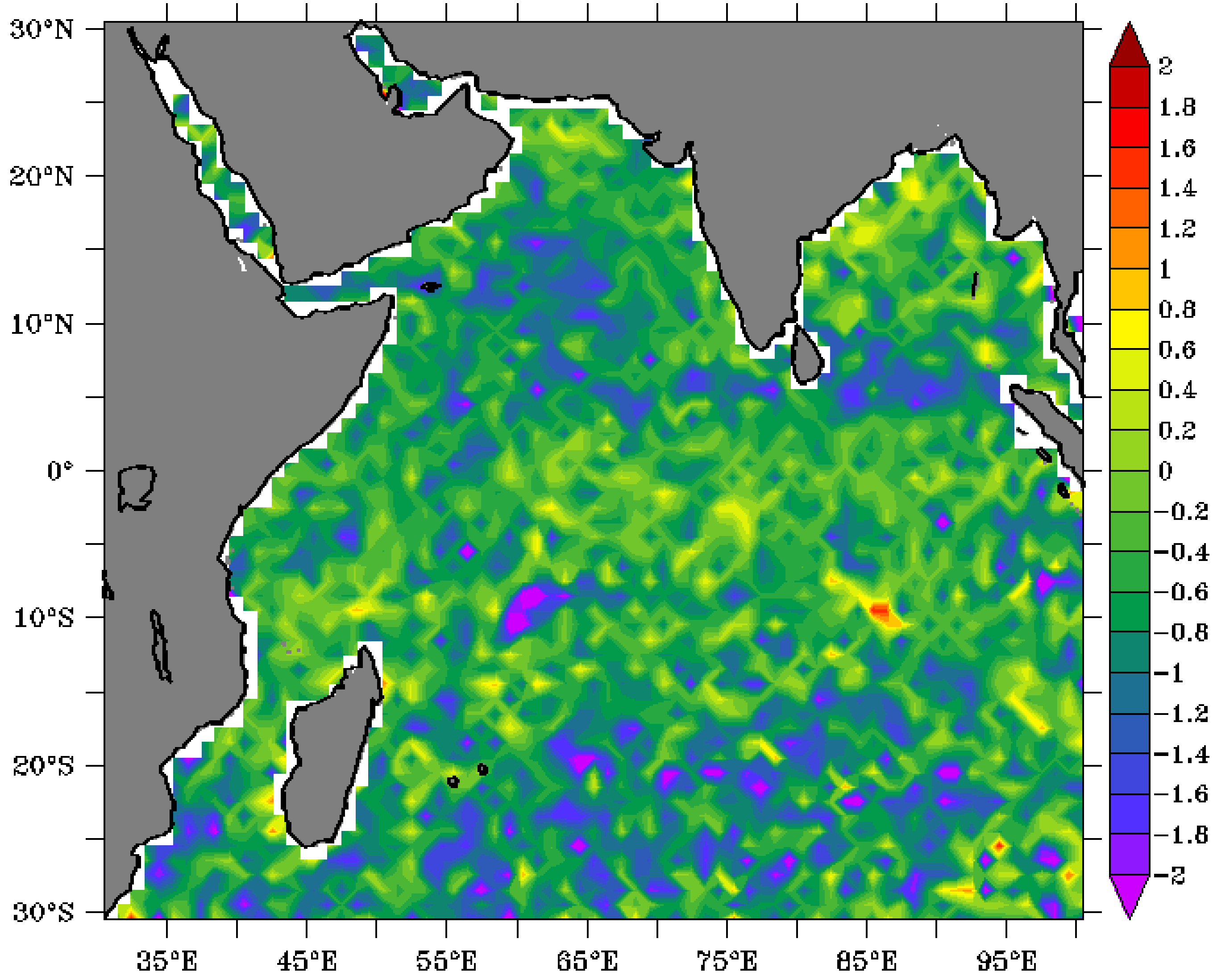
Meridional wind speed (m/s)   DECEMBER


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

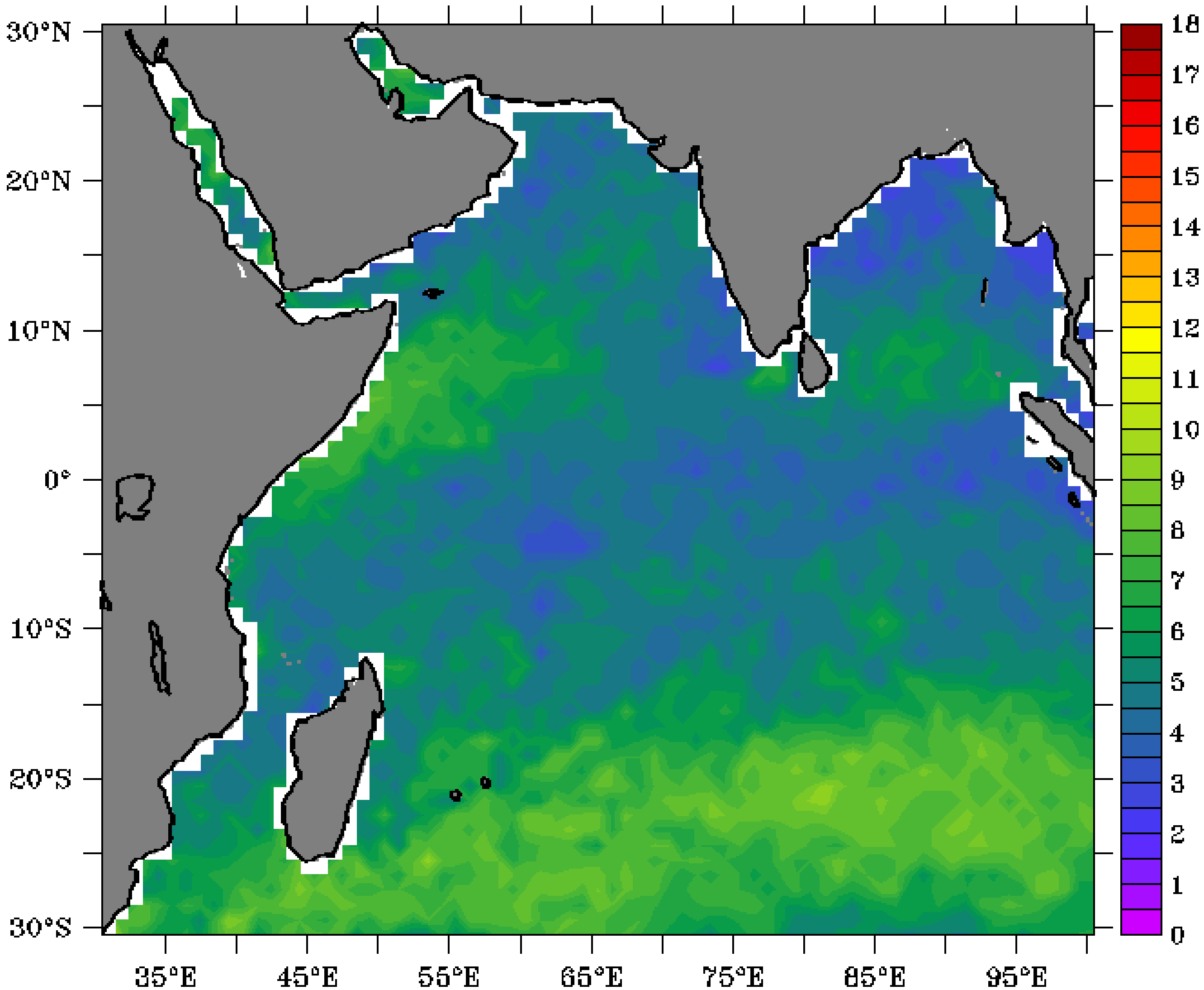
Anomaly (m/s)



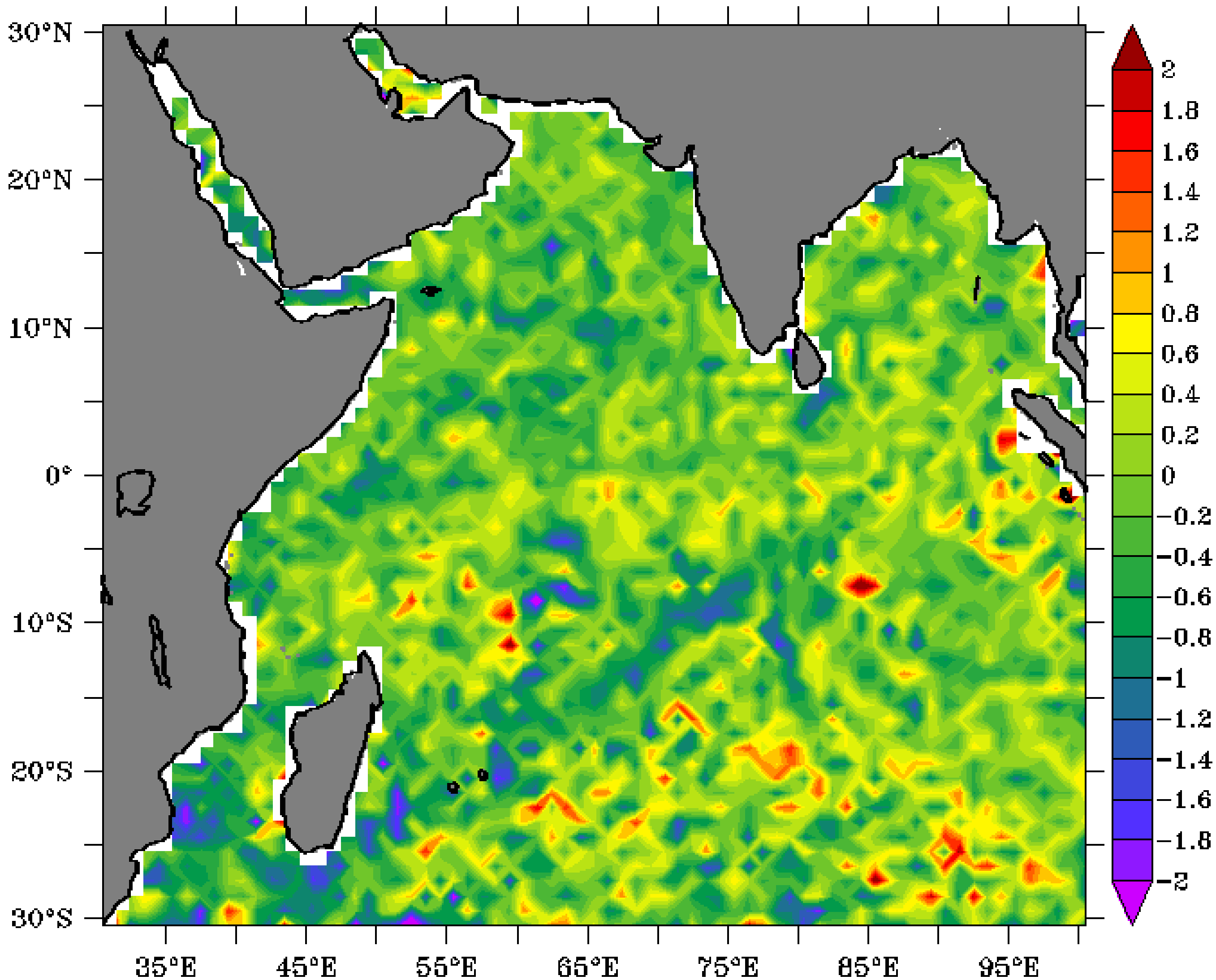
Wind speed(m/s) JANUARY


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Wind speed(m/s) FEBRUARY


30°N
20°N
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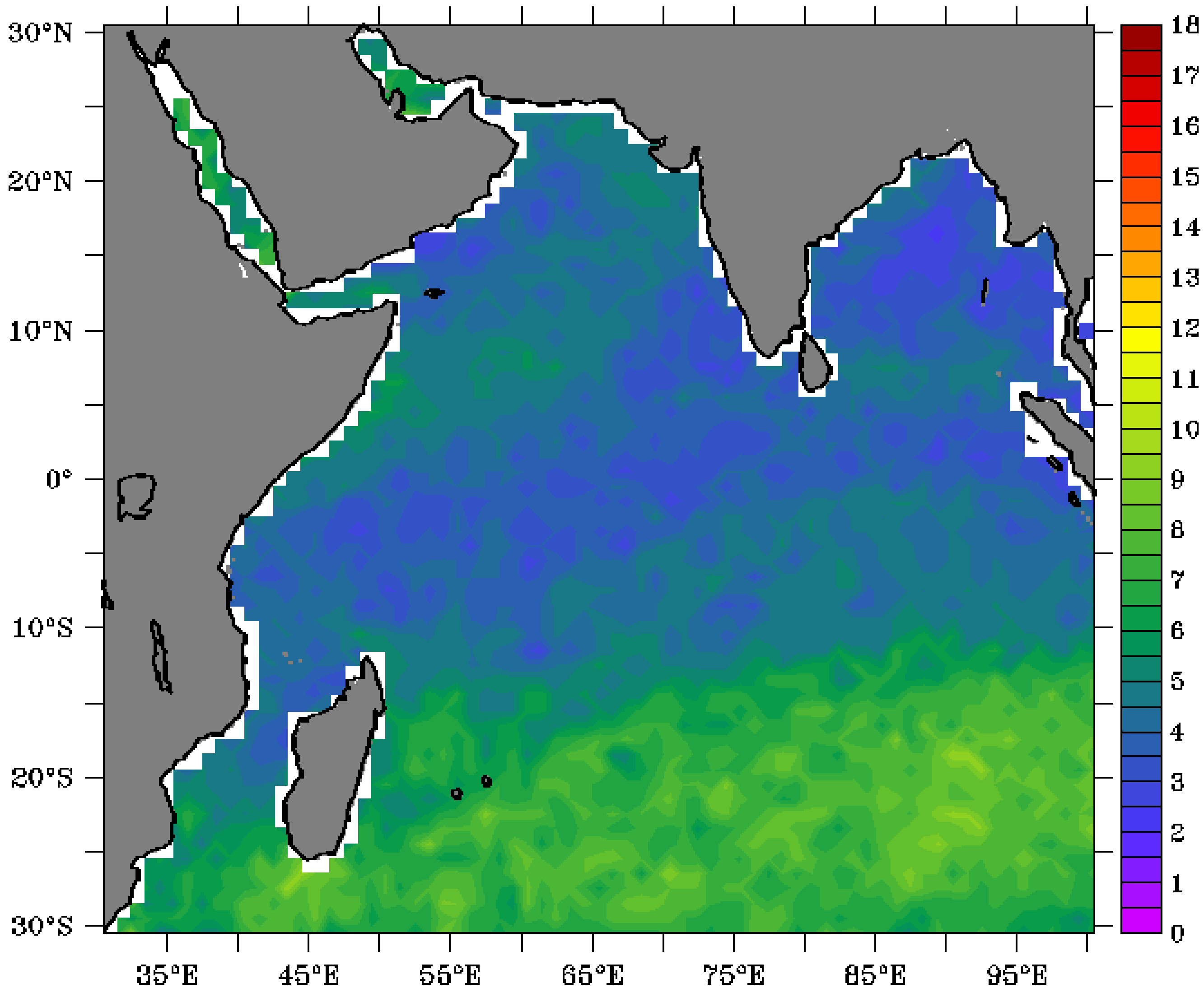
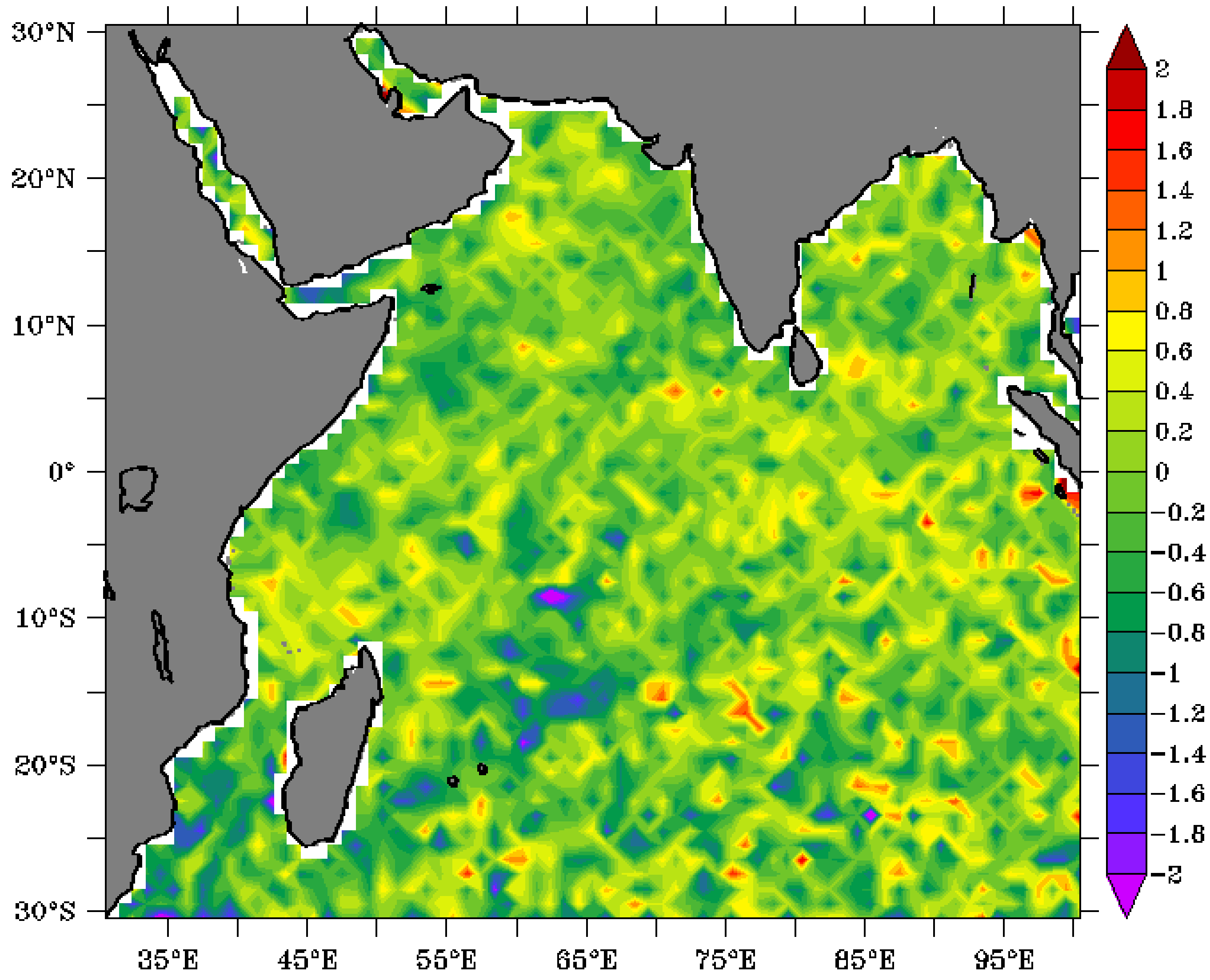
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

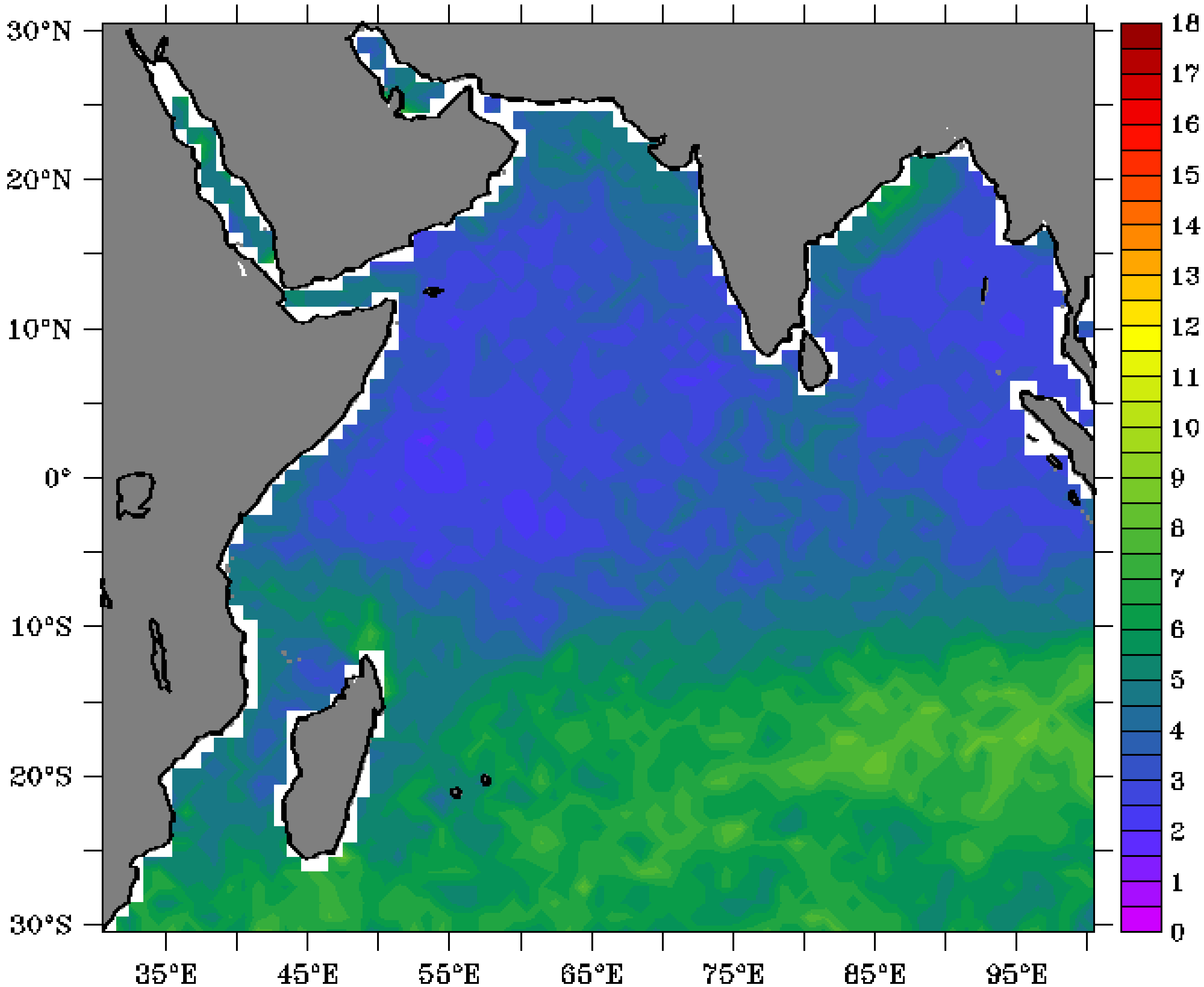
Anomaly (m/s)



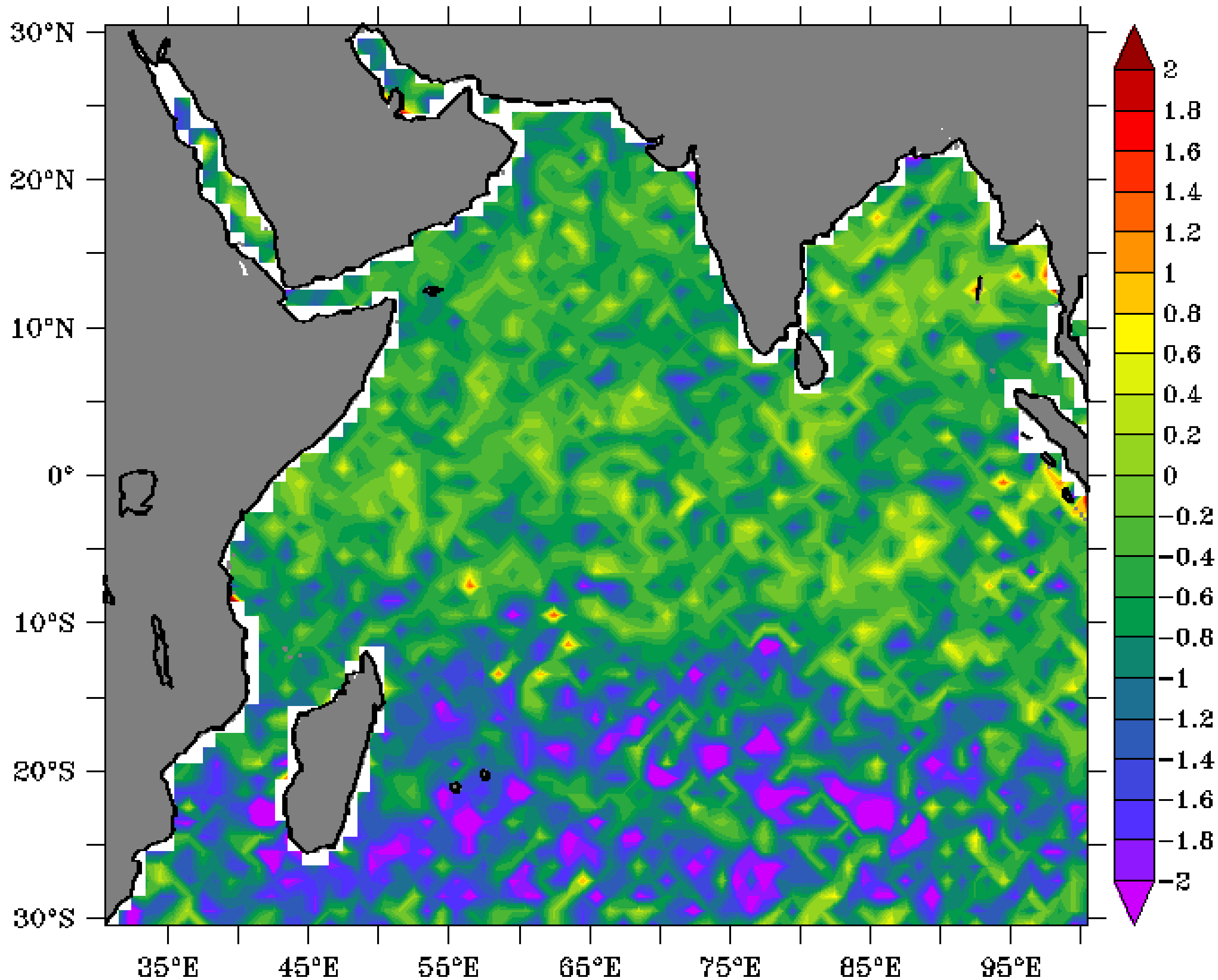
Wind speed(m/s) MARCH


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Wind speed(m/s) APRIL


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
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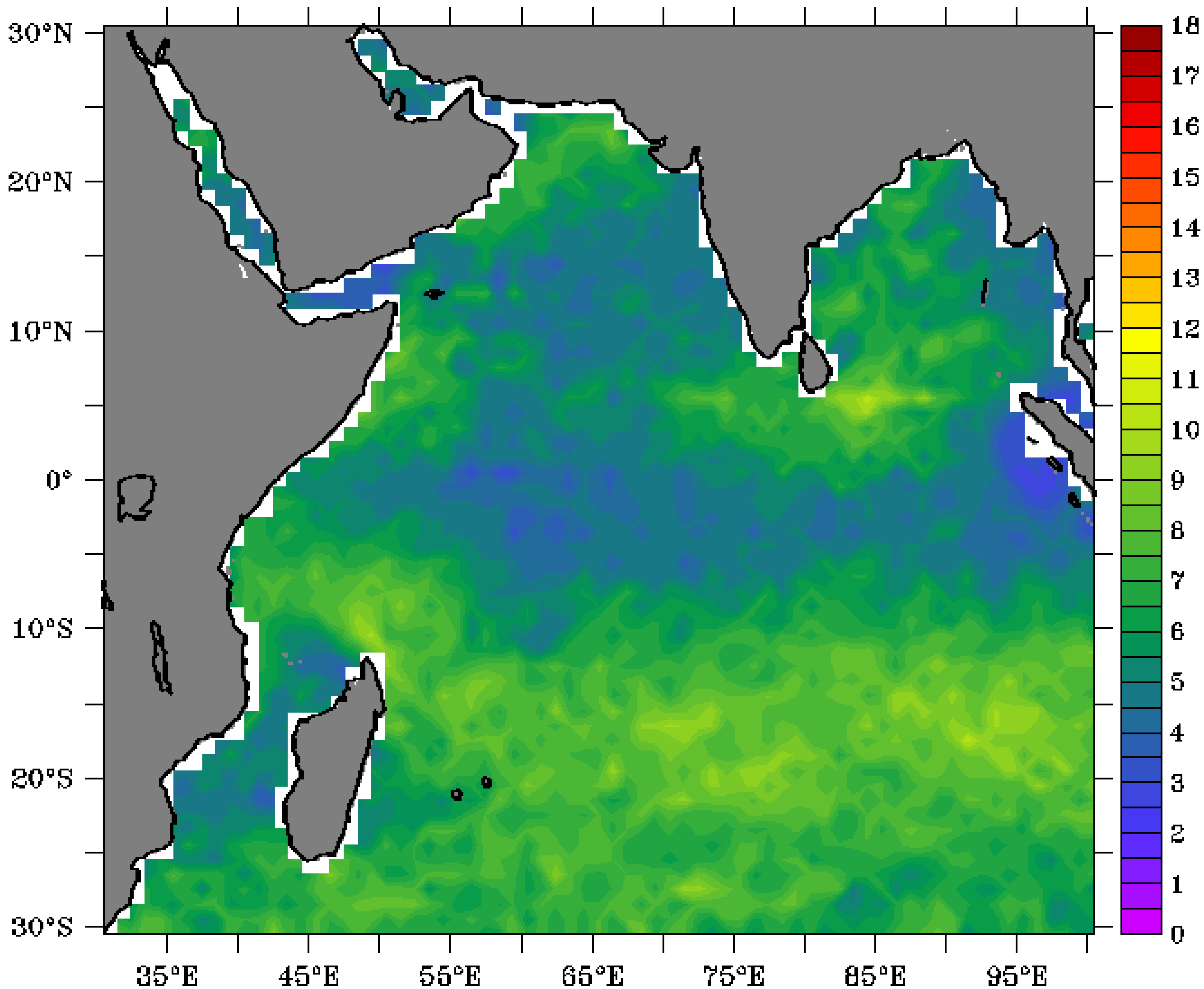
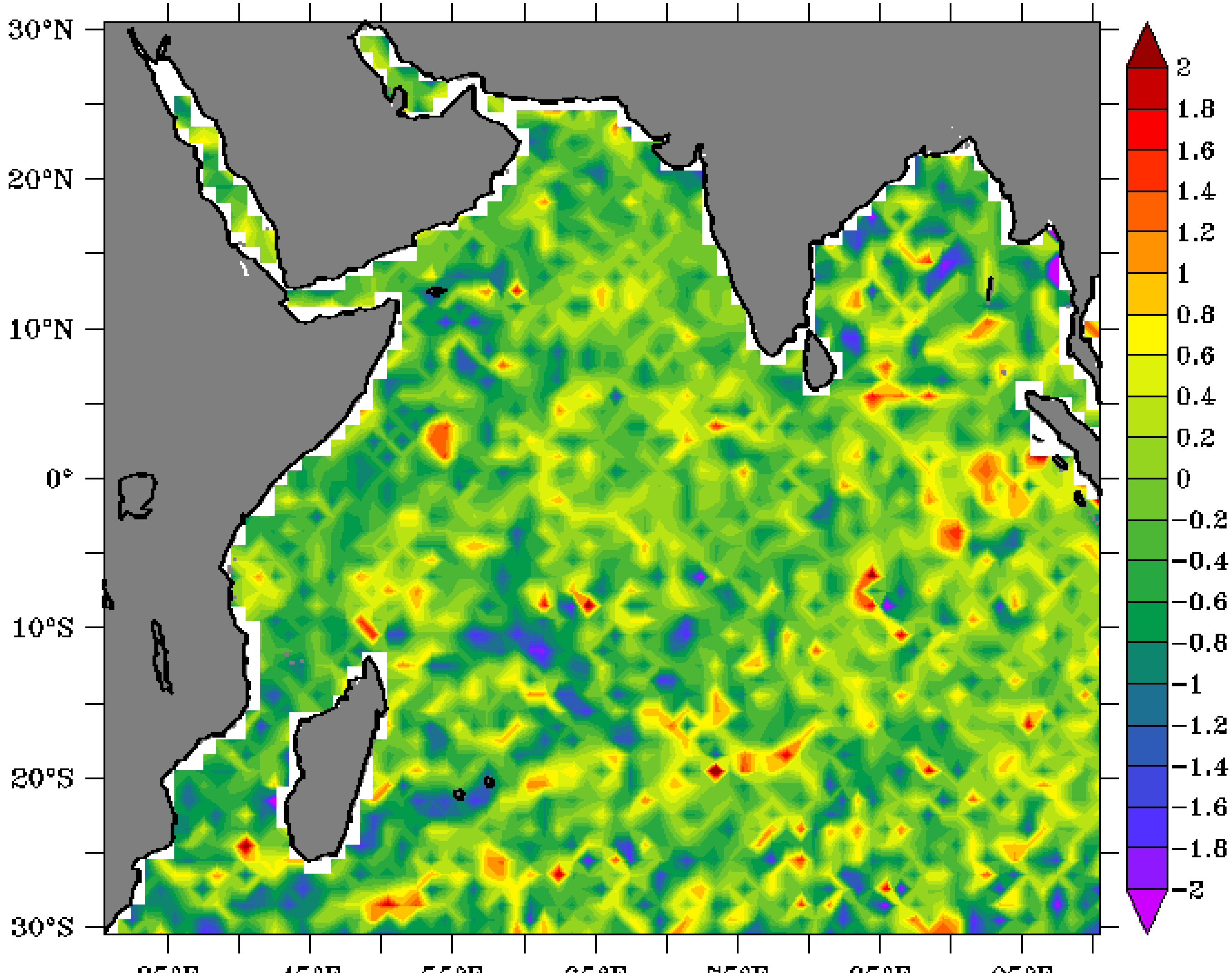
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)

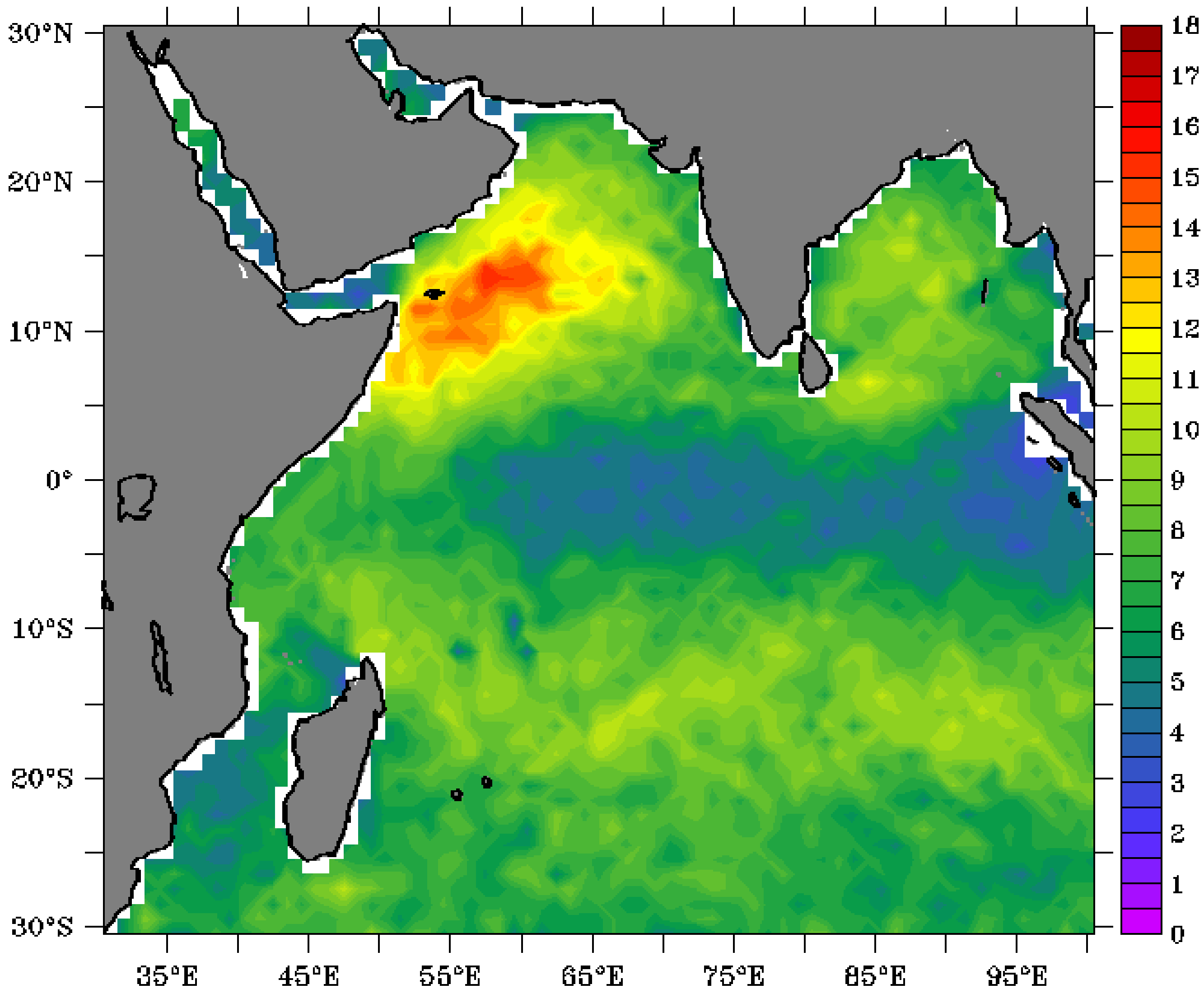
0



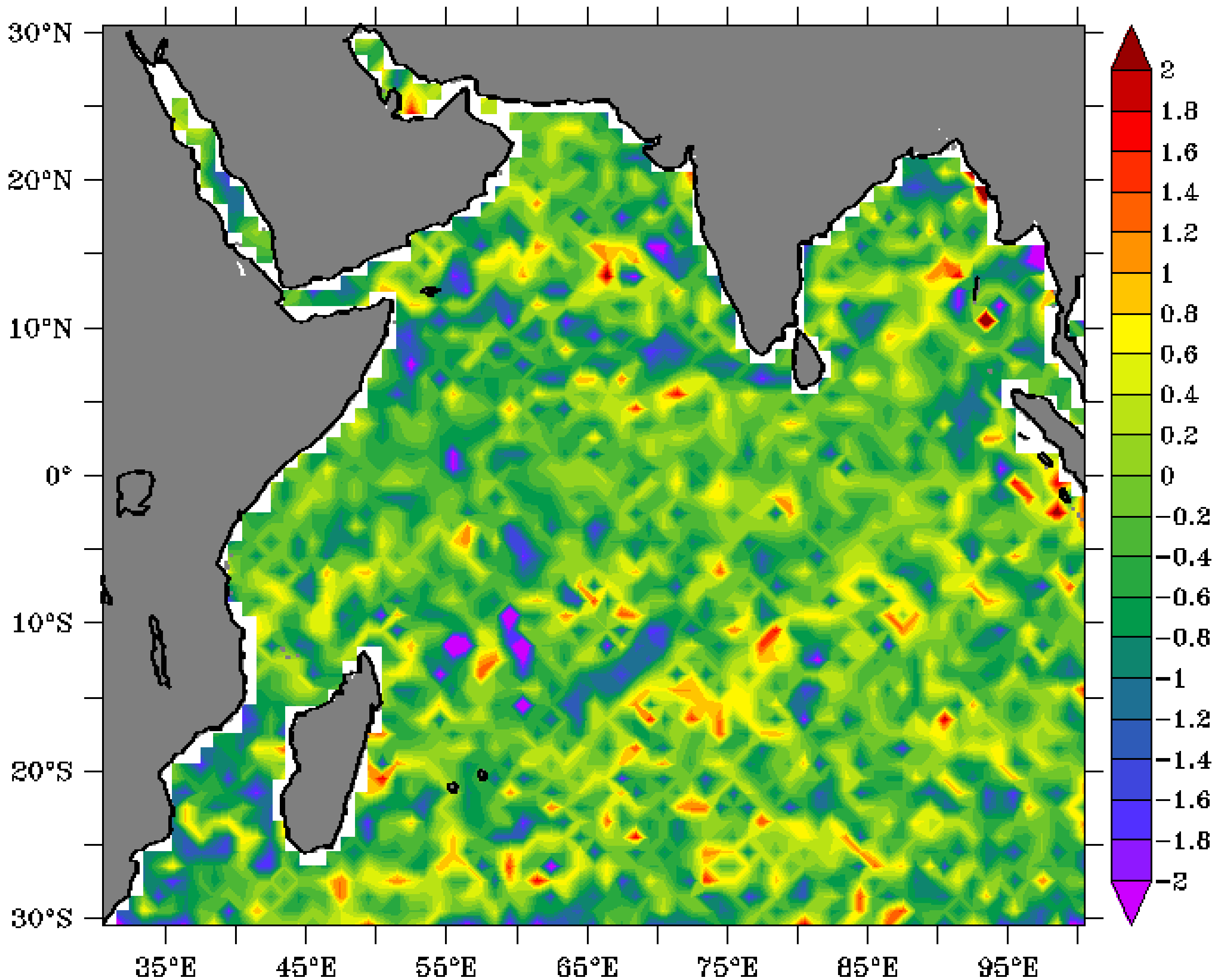
Wind speed(m/s) MAY


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Wind speed(m/s) JUNE


30°N
20°N
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20°S
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35°E
45°E
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65°E
75°E
85°E
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2
1.8
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1
0.8
0.6
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0.2
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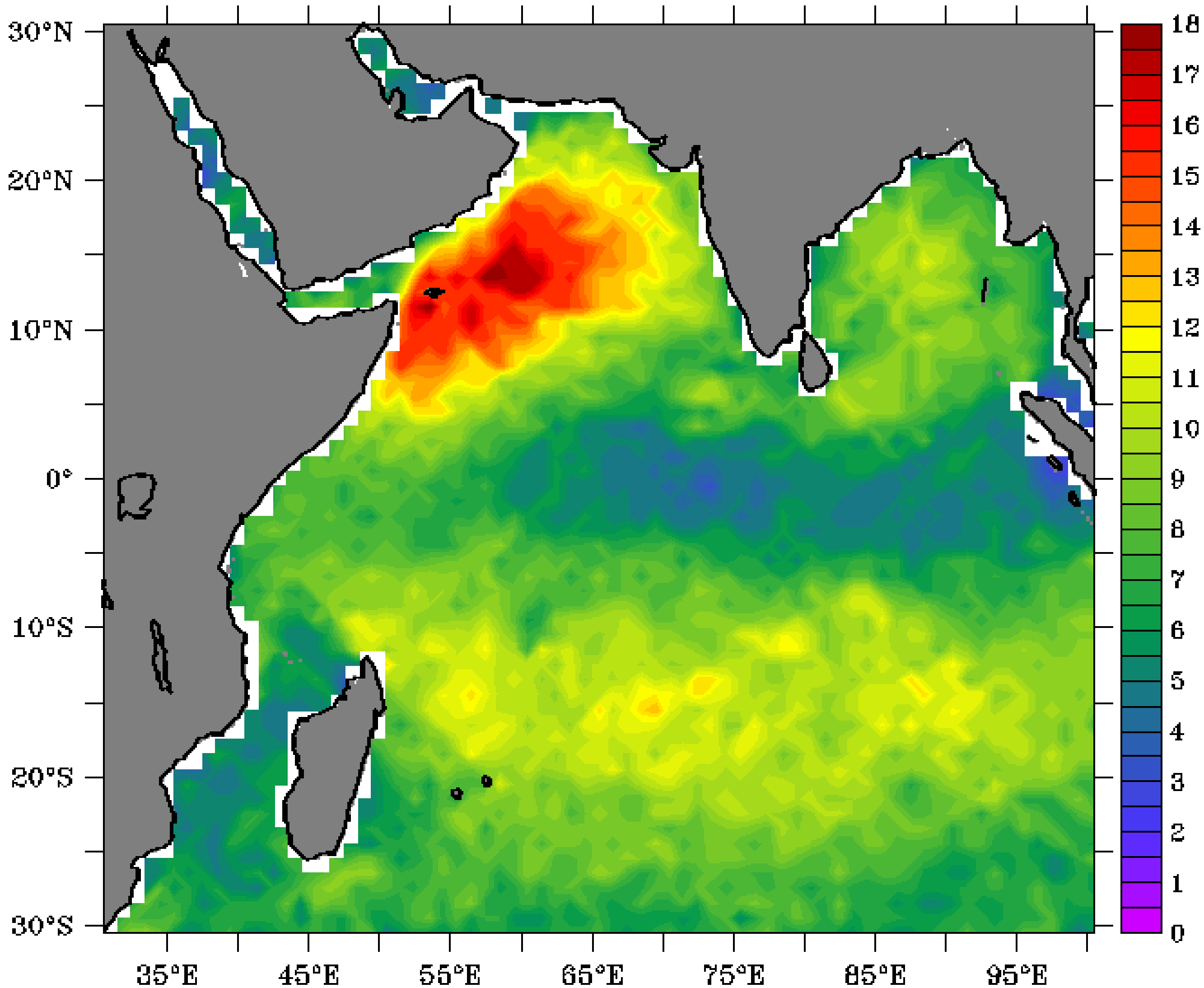
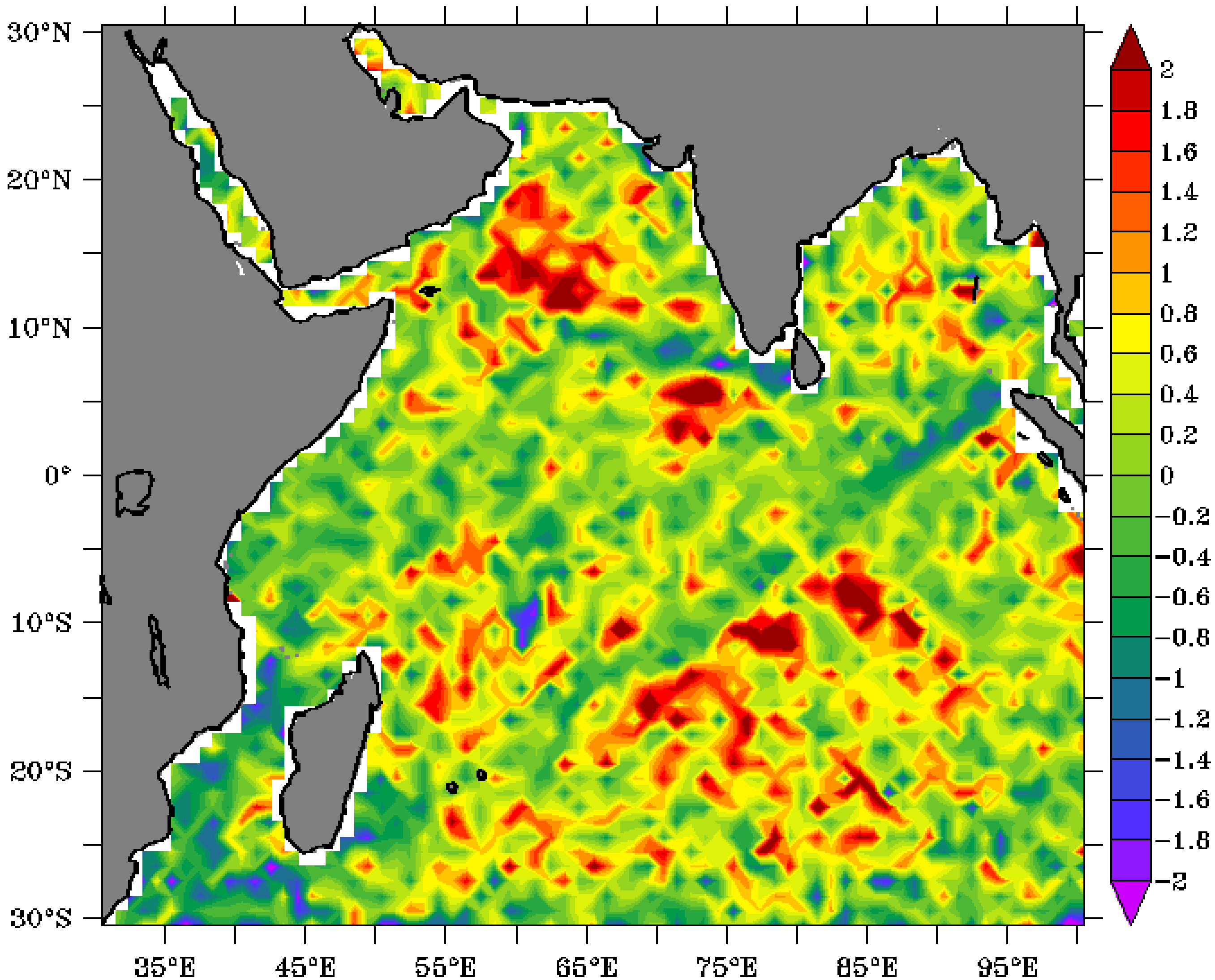
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2

Anomaly (m/s)



Wind speed(m/s) JULY


30°N
20°N
10°N
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10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
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1.6
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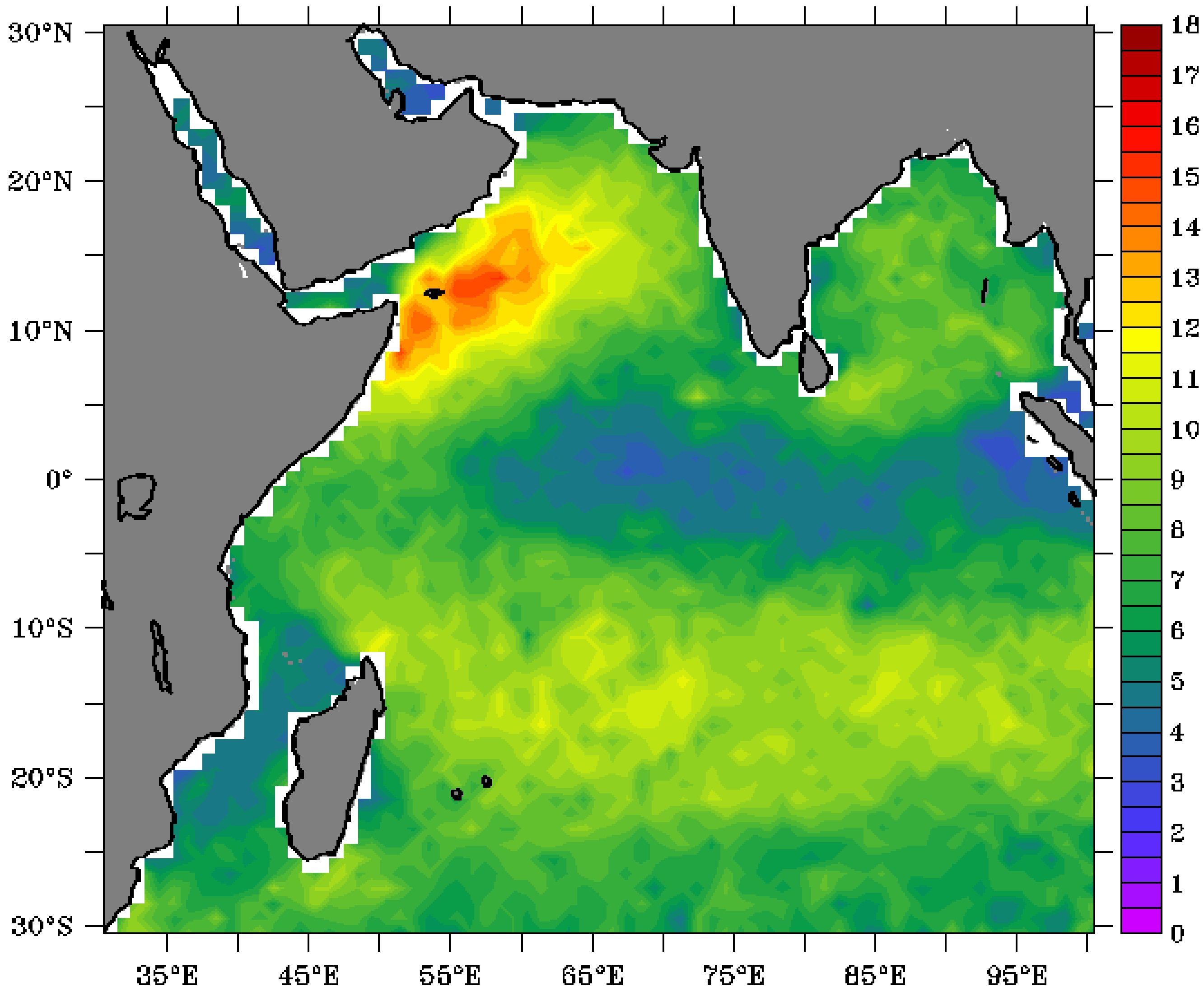
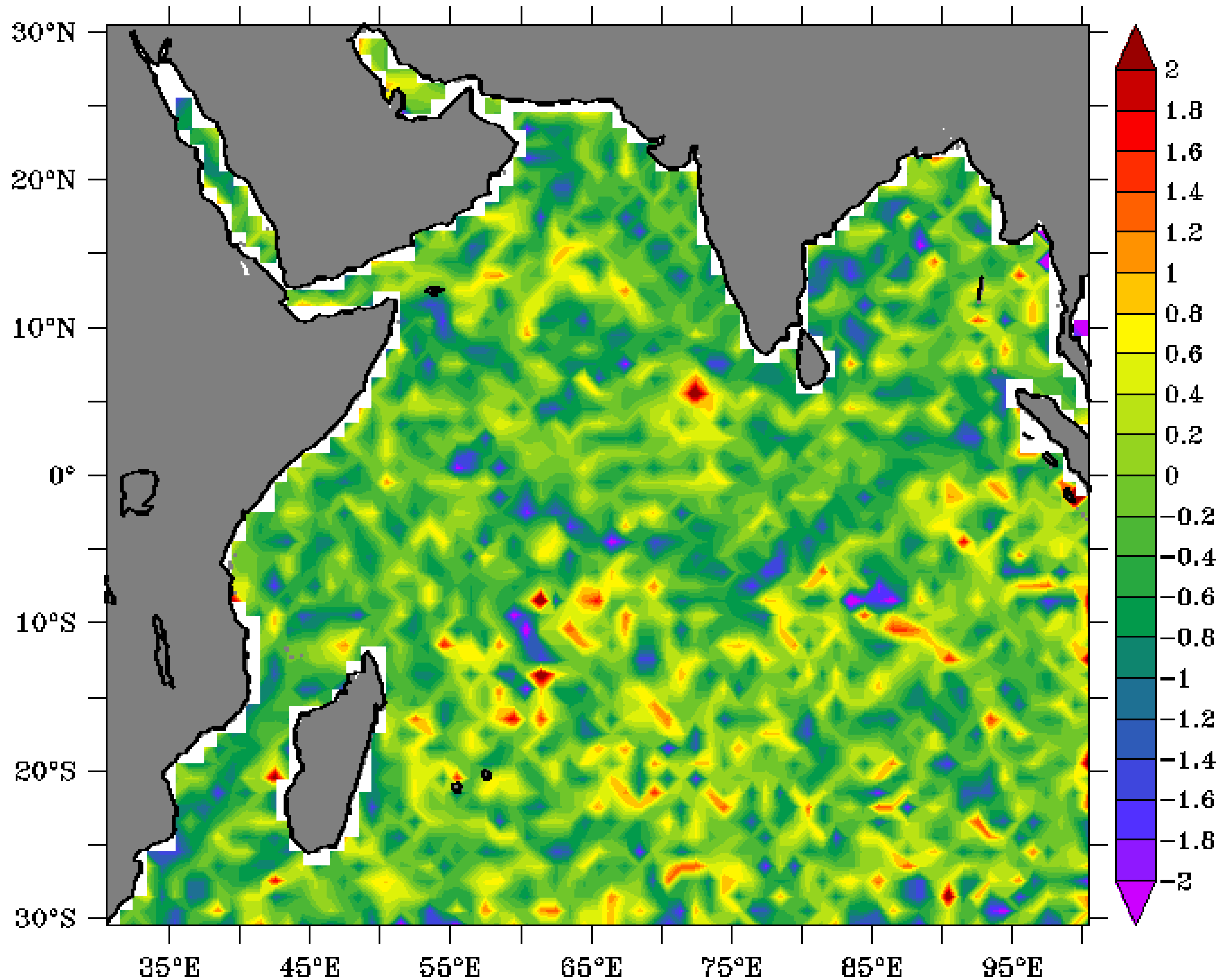
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Wind speed(m/s) AUGUST


30°N
20°N
10°N
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10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
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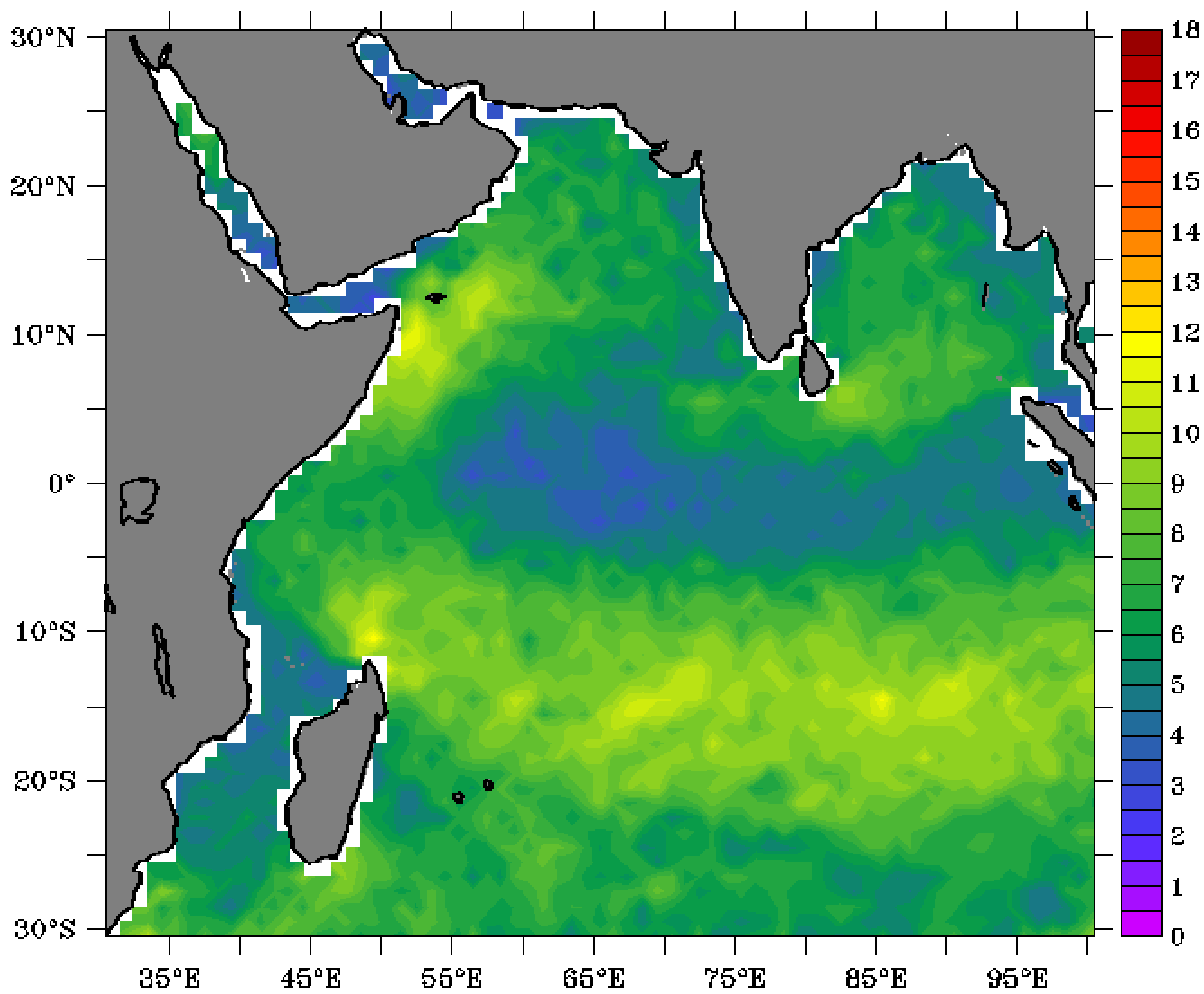
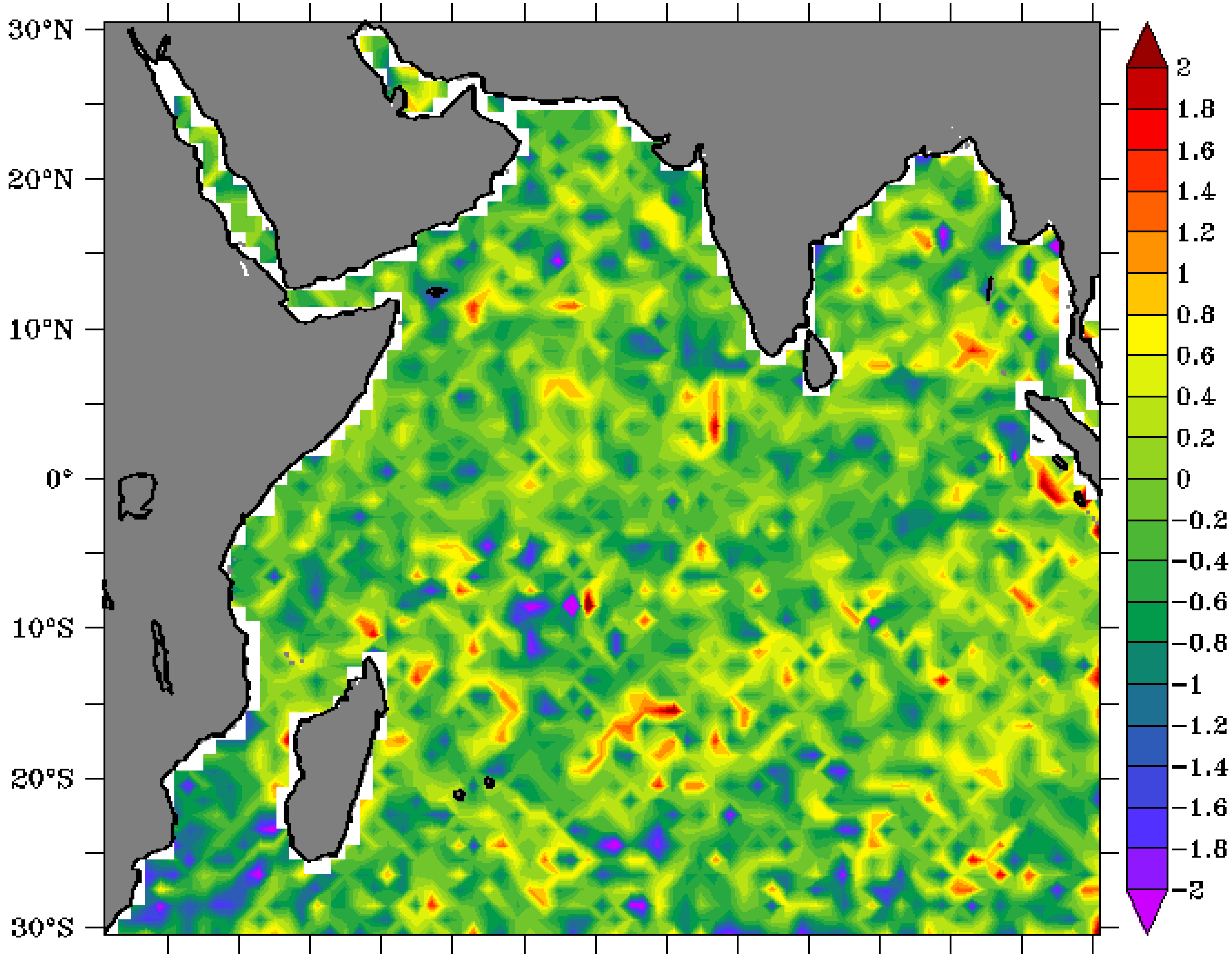
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2

Anomaly (m/s)



Wind speed(m/s) SEPTEMBER


30°N
20°N
10°N
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20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
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1
0.8
0.6
0.4
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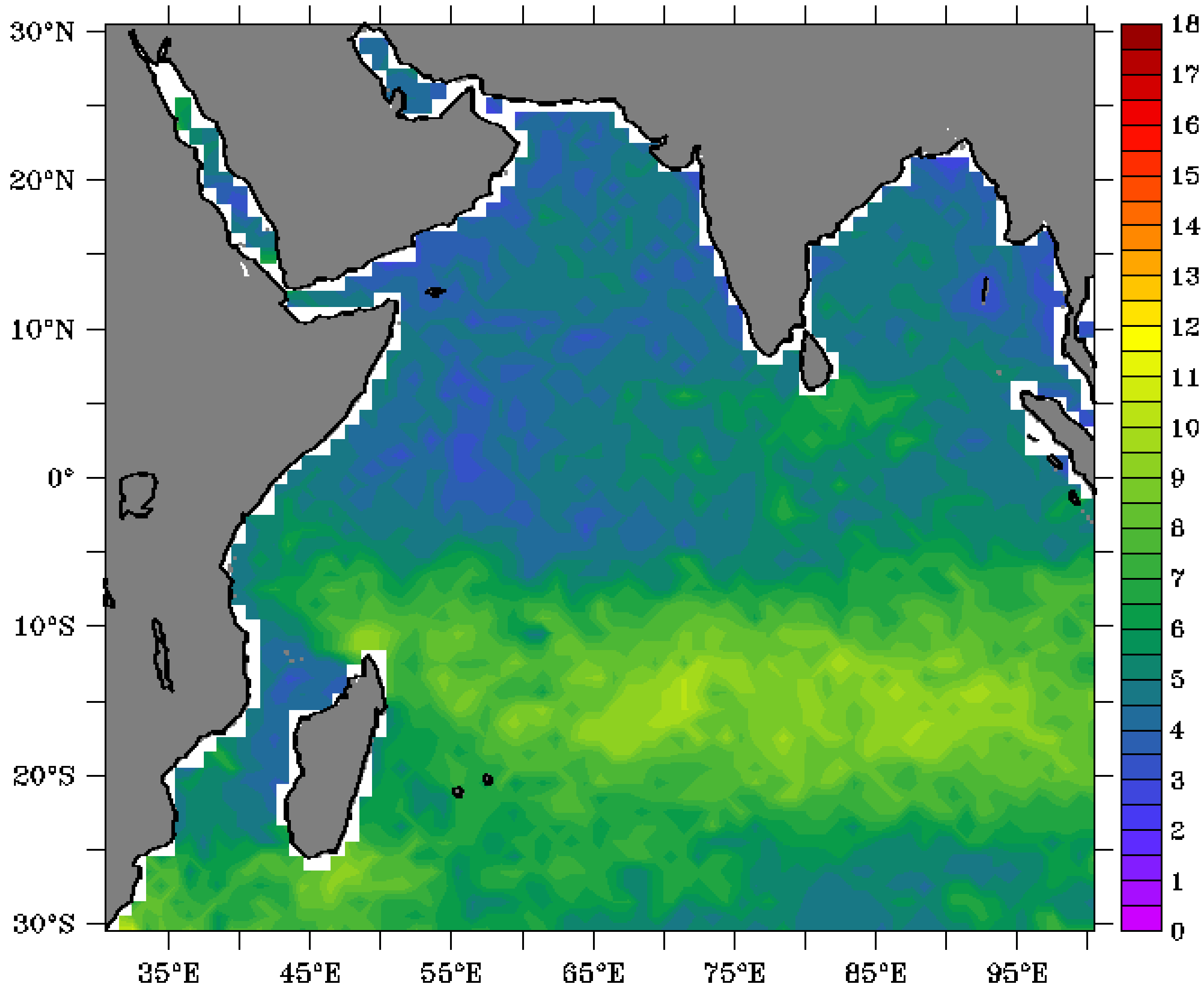
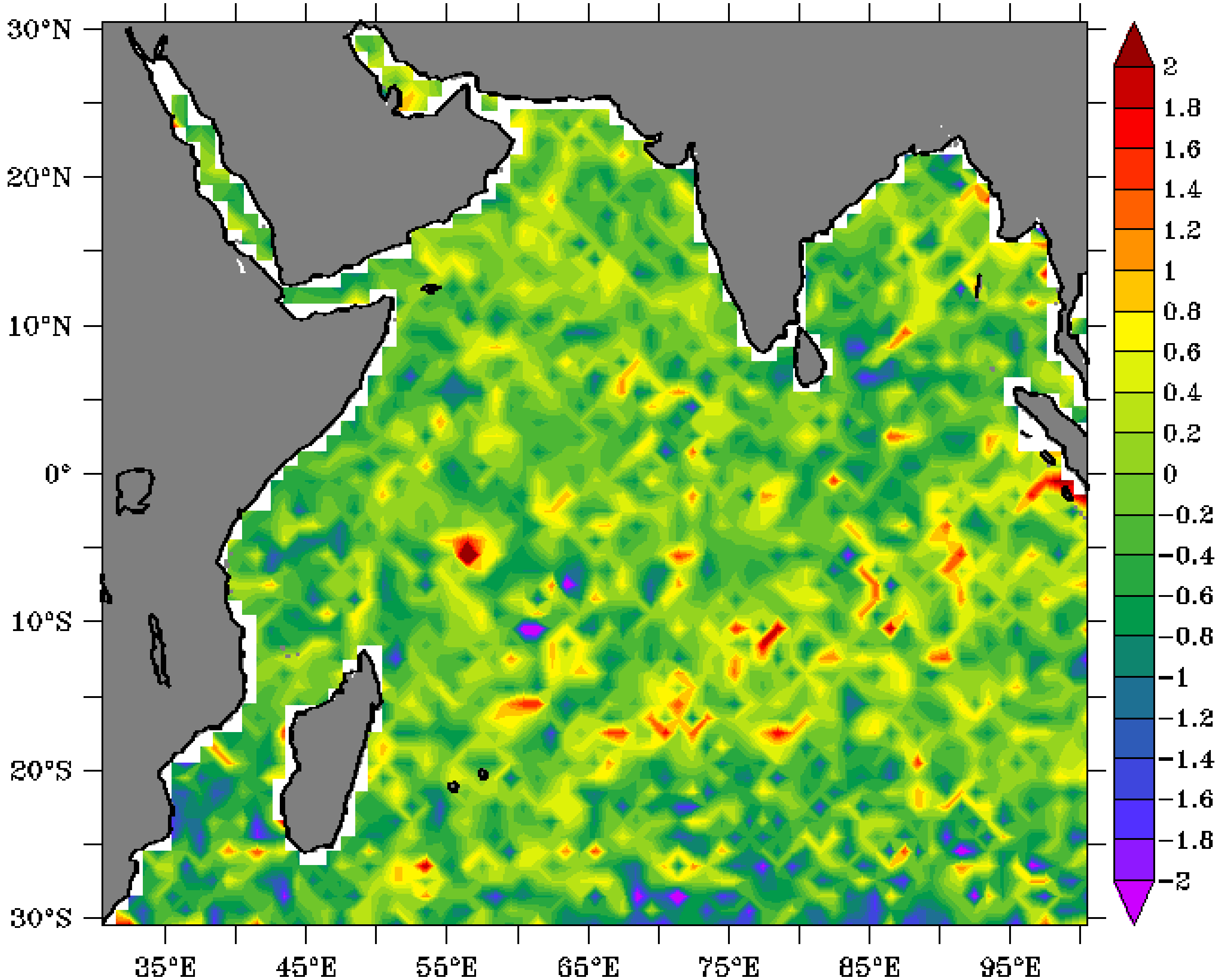
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Wind speed(m/s) OCTOBER


30°N
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10°N
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20°S
30°S
35°E
45°E
55°E
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75°E
85°E
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1
0.8
0.6
0.4
0.2
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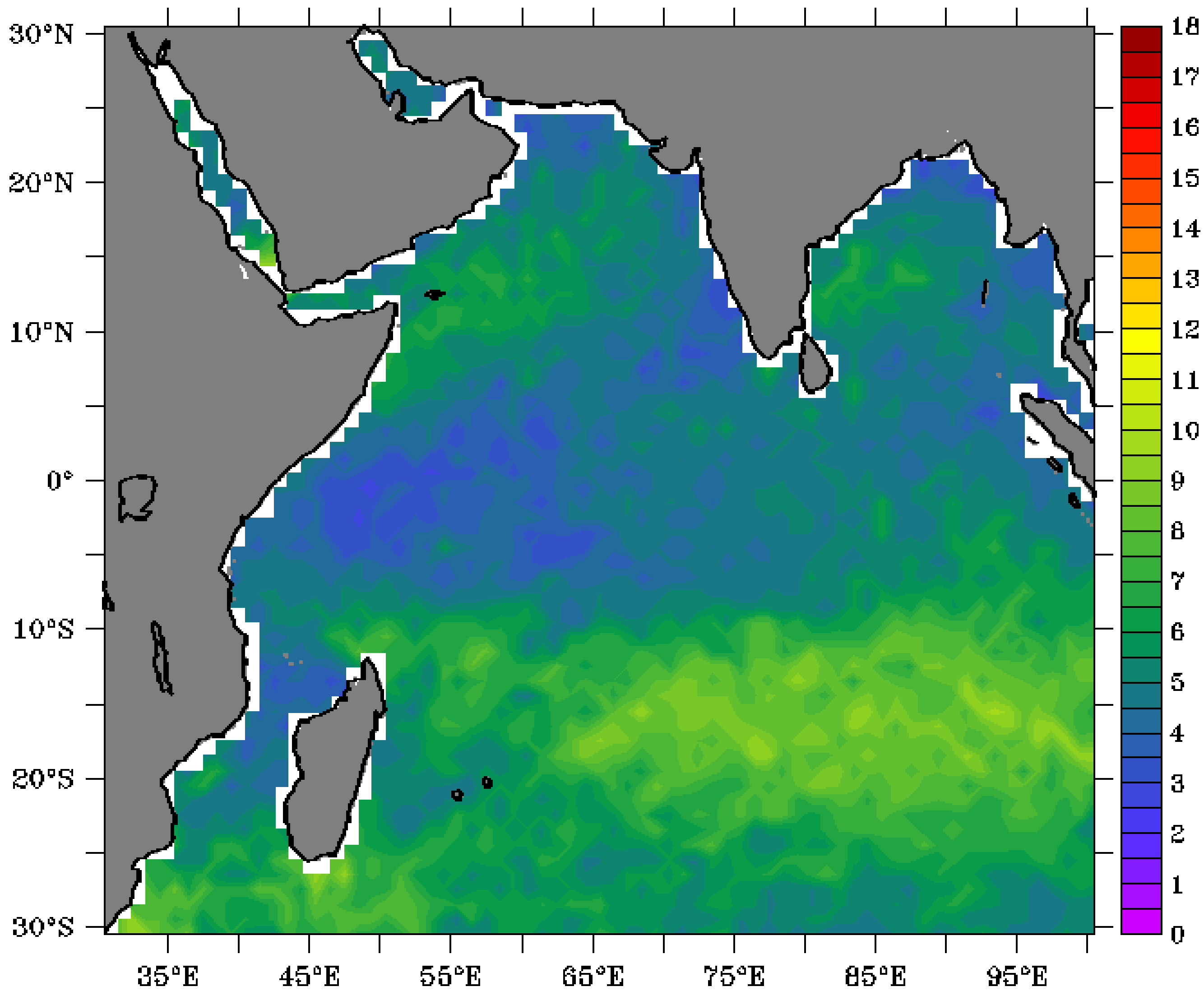
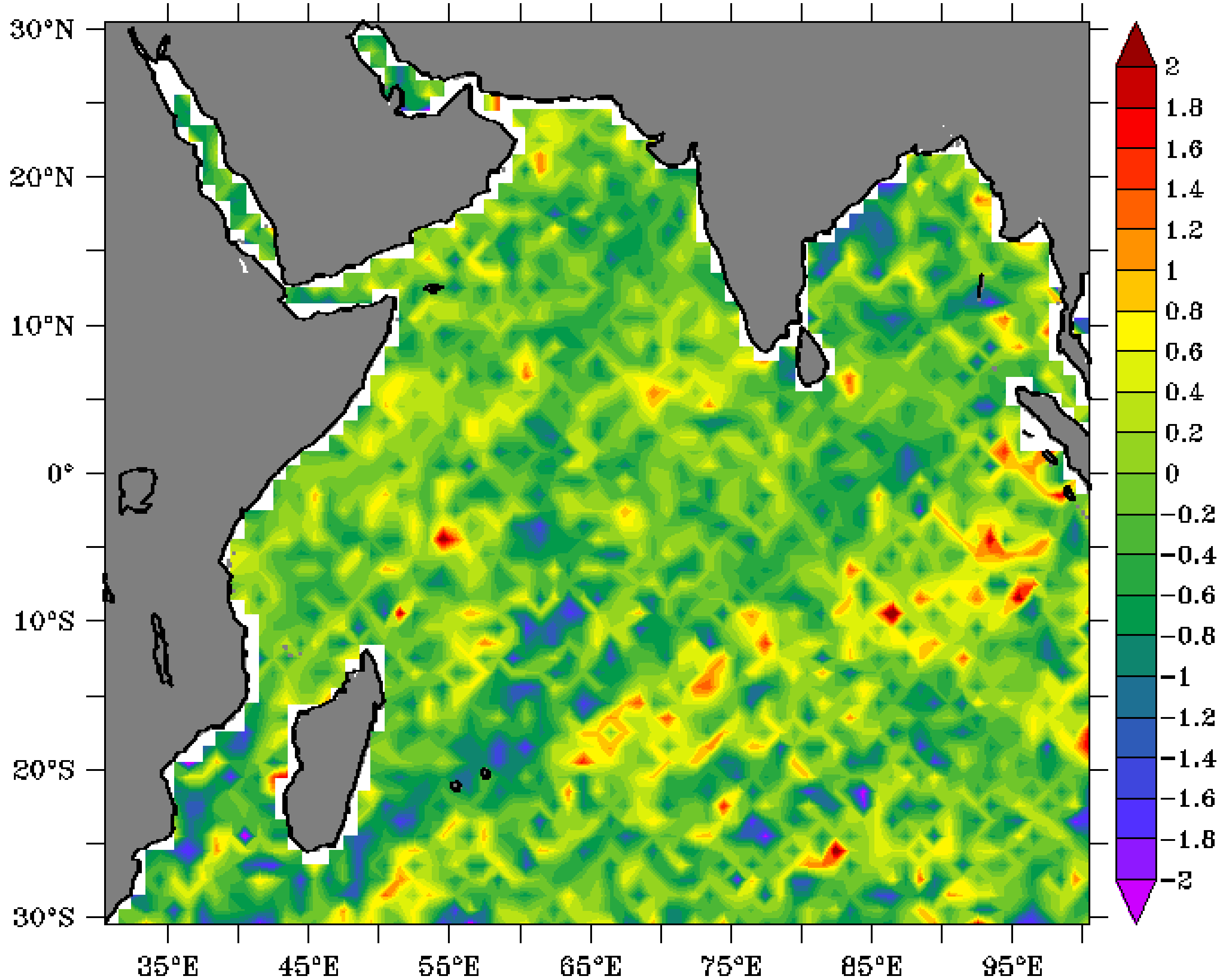
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2

Anomaly (m/s)



Wind speed(m/s) NOVEMBER


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
1.8
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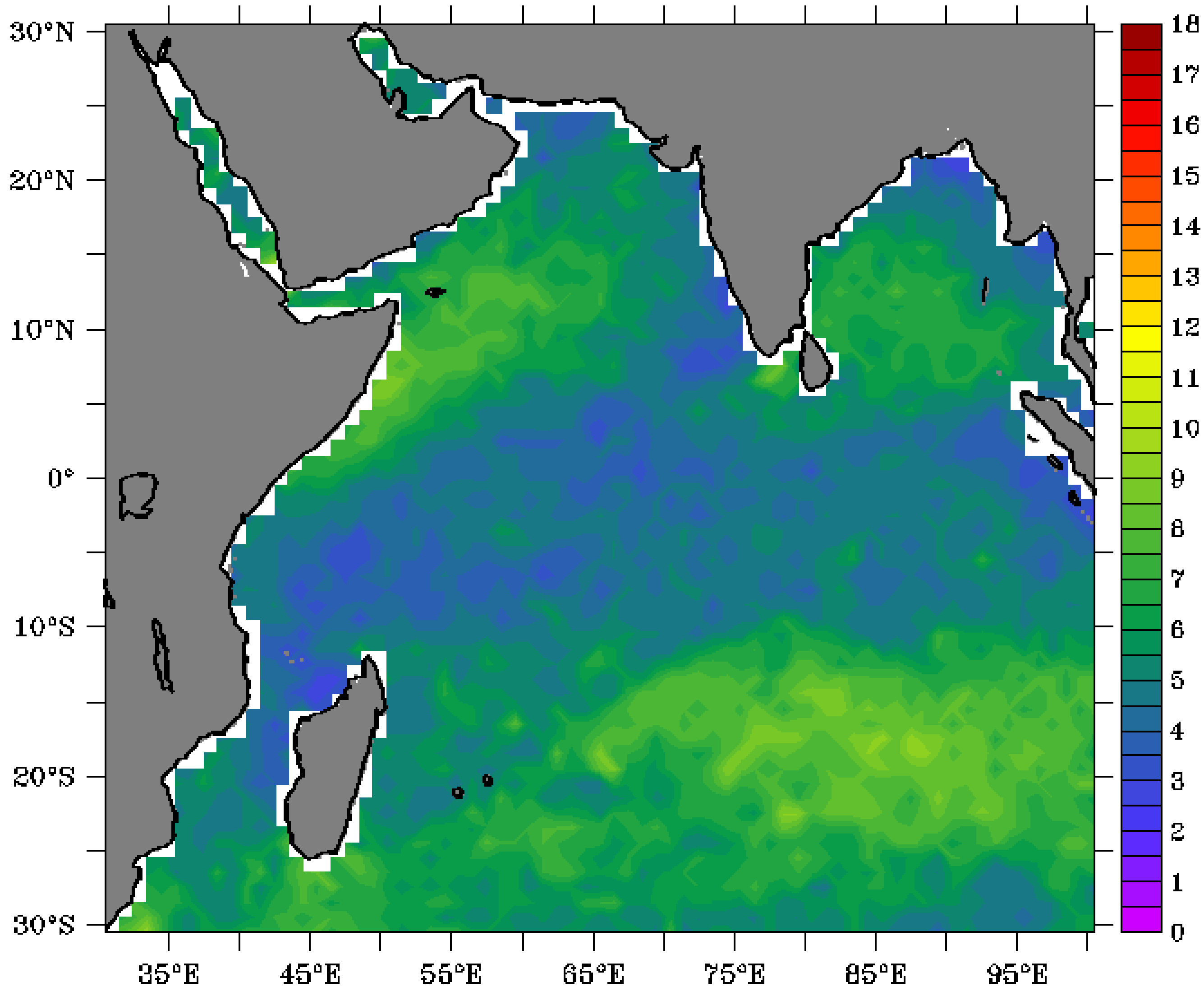
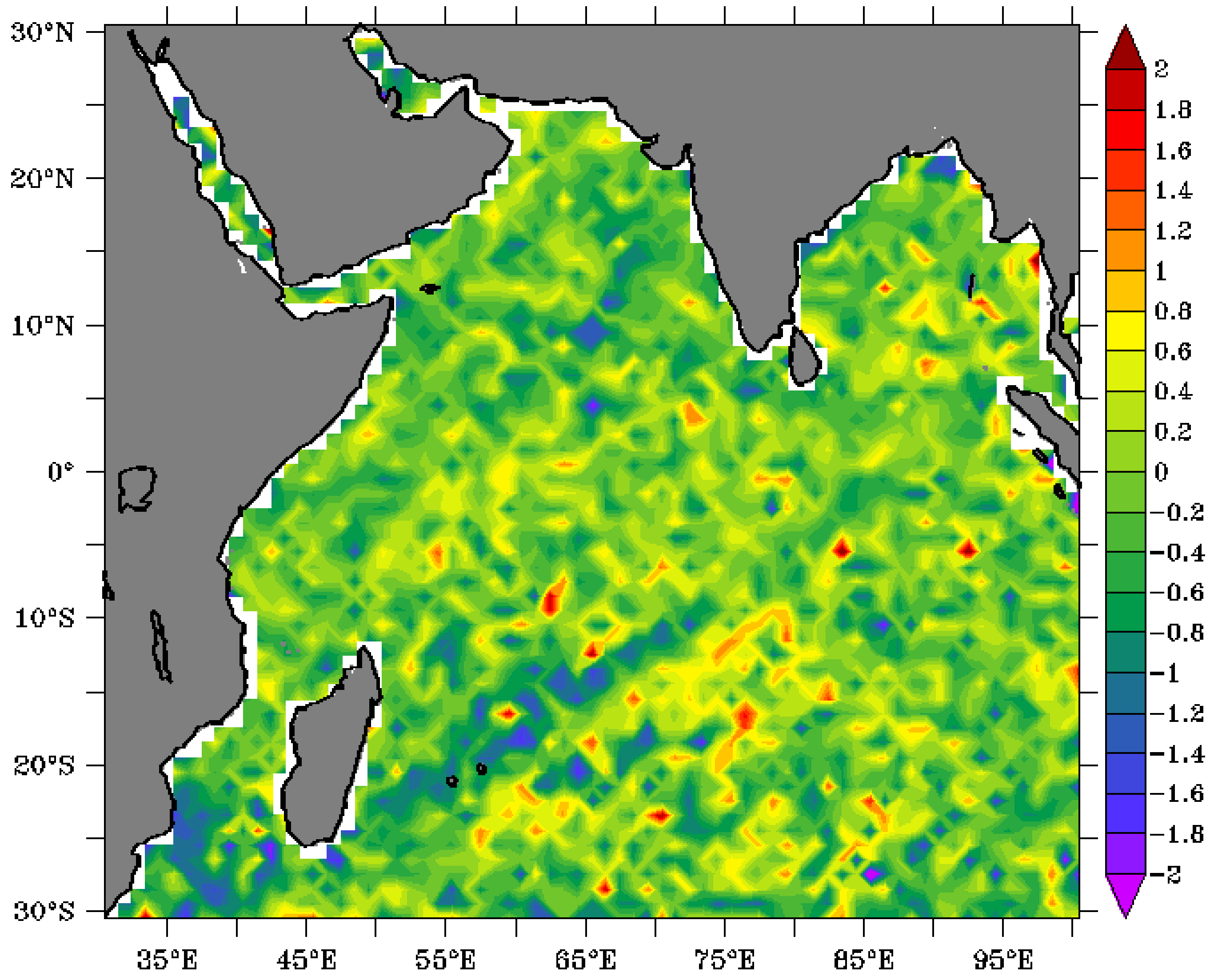
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (m/s)



Wind speed(m/s) DECEMBER



30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
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1.8
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−1.2
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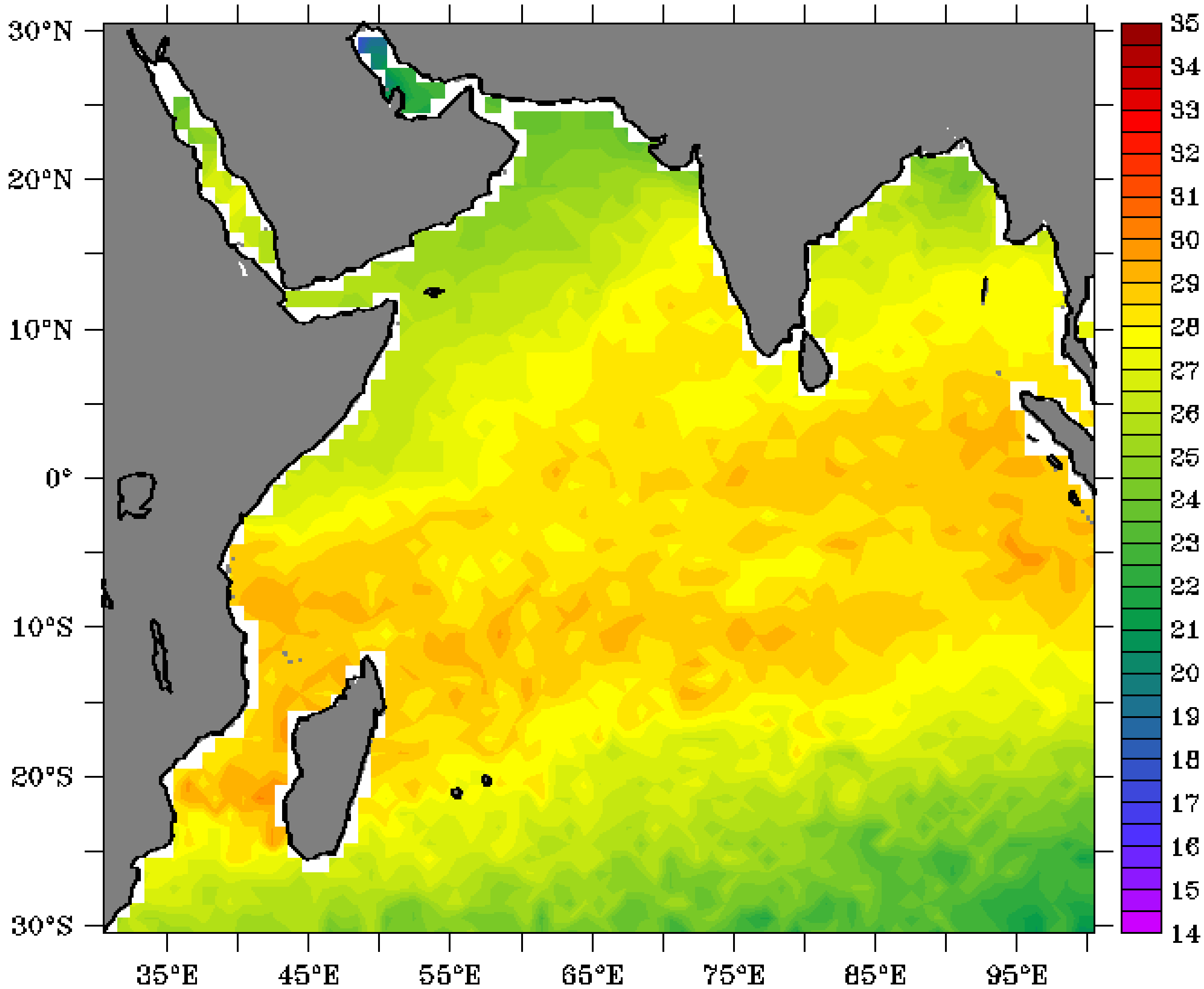
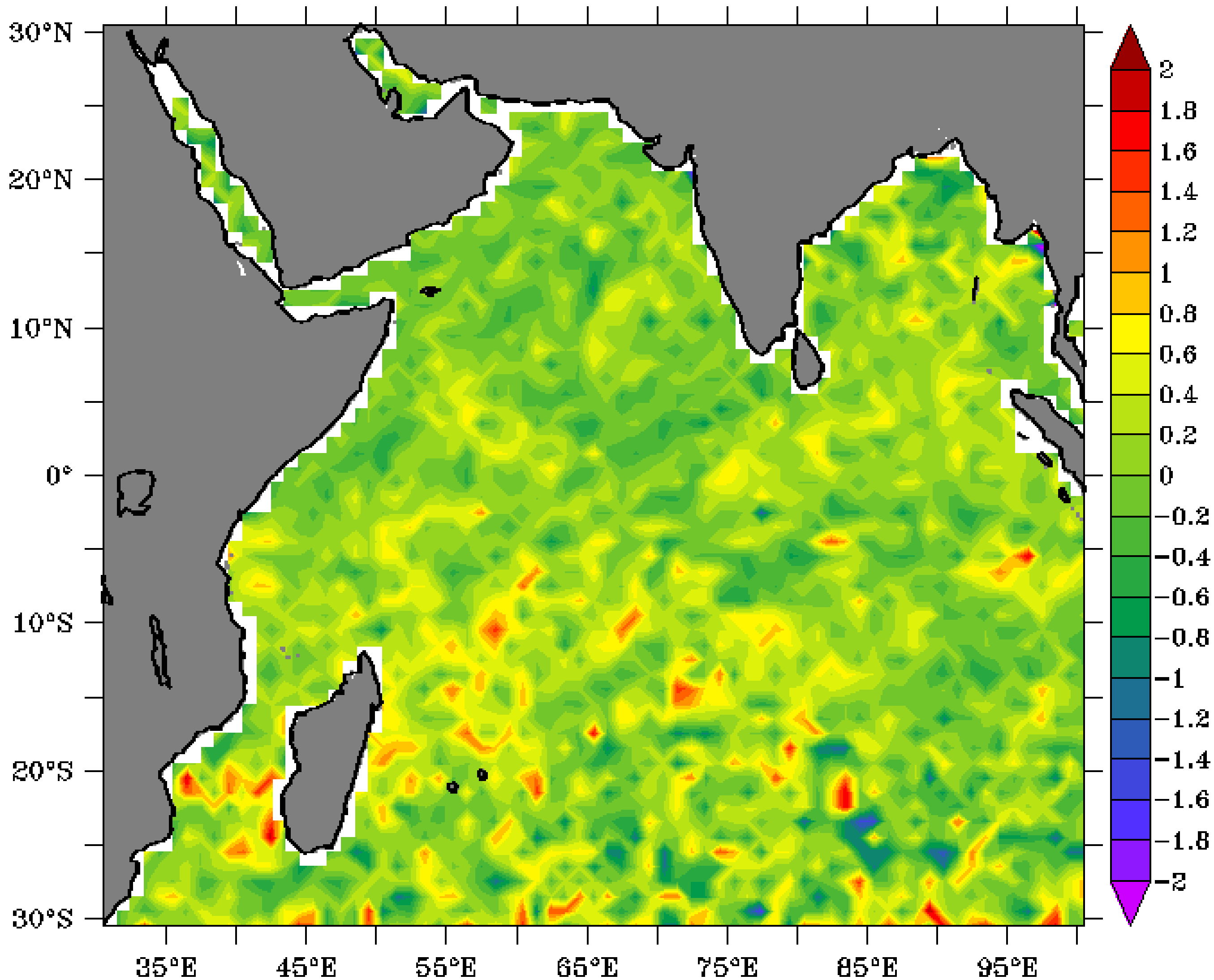
−1.6
−1.8
−2

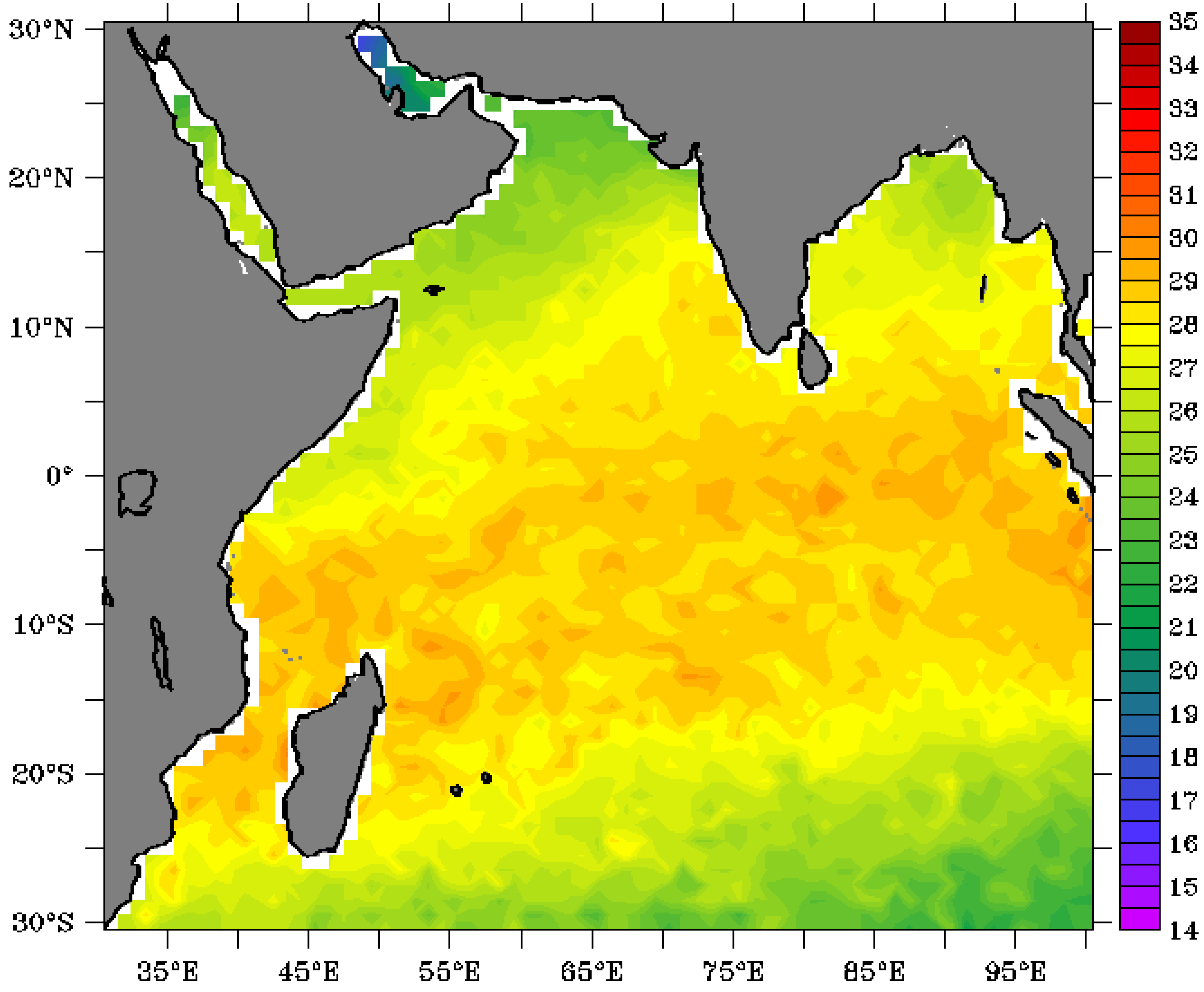
Anomaly (m/s)



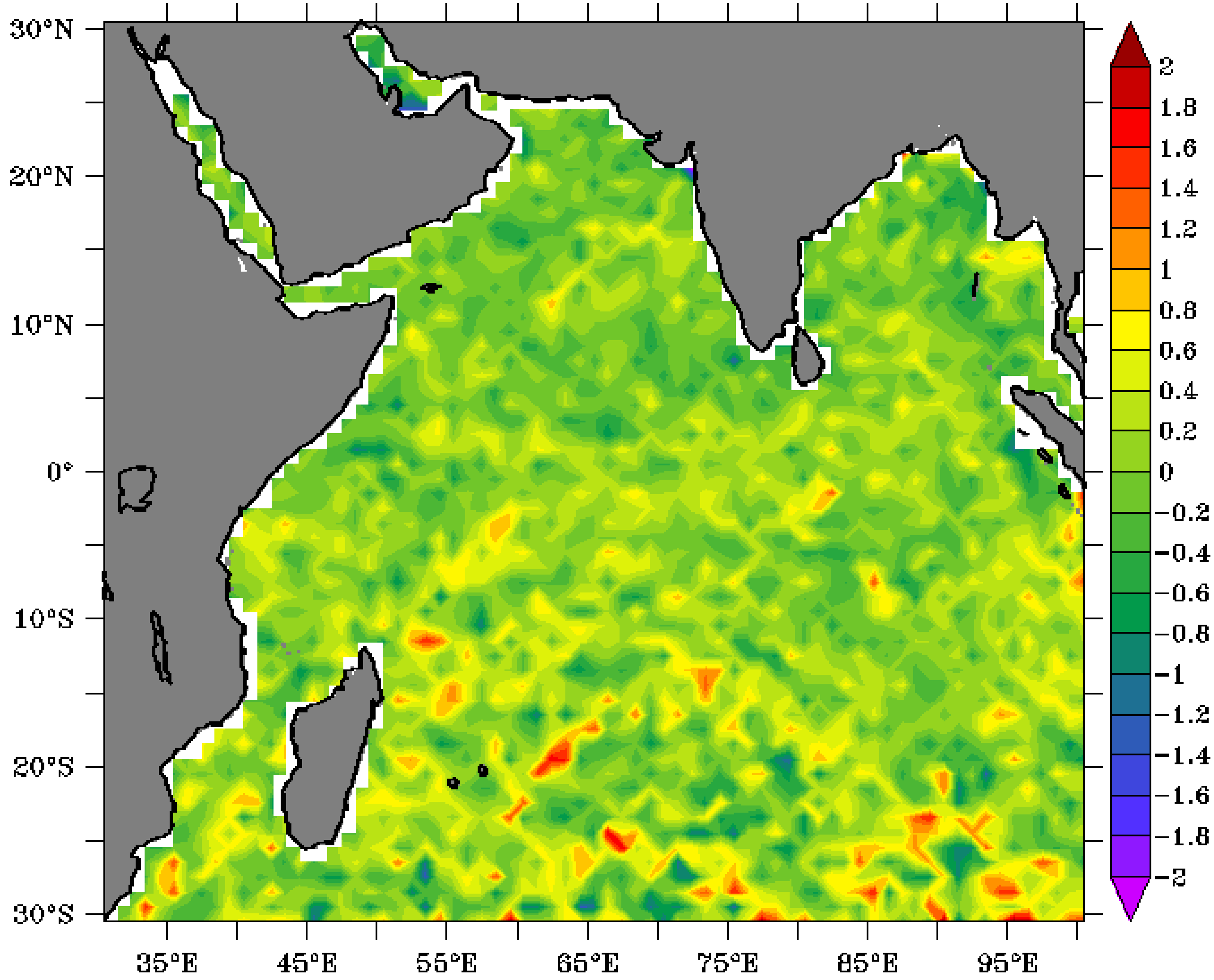
Sea surface temperature (deg Celsius) JANUARY



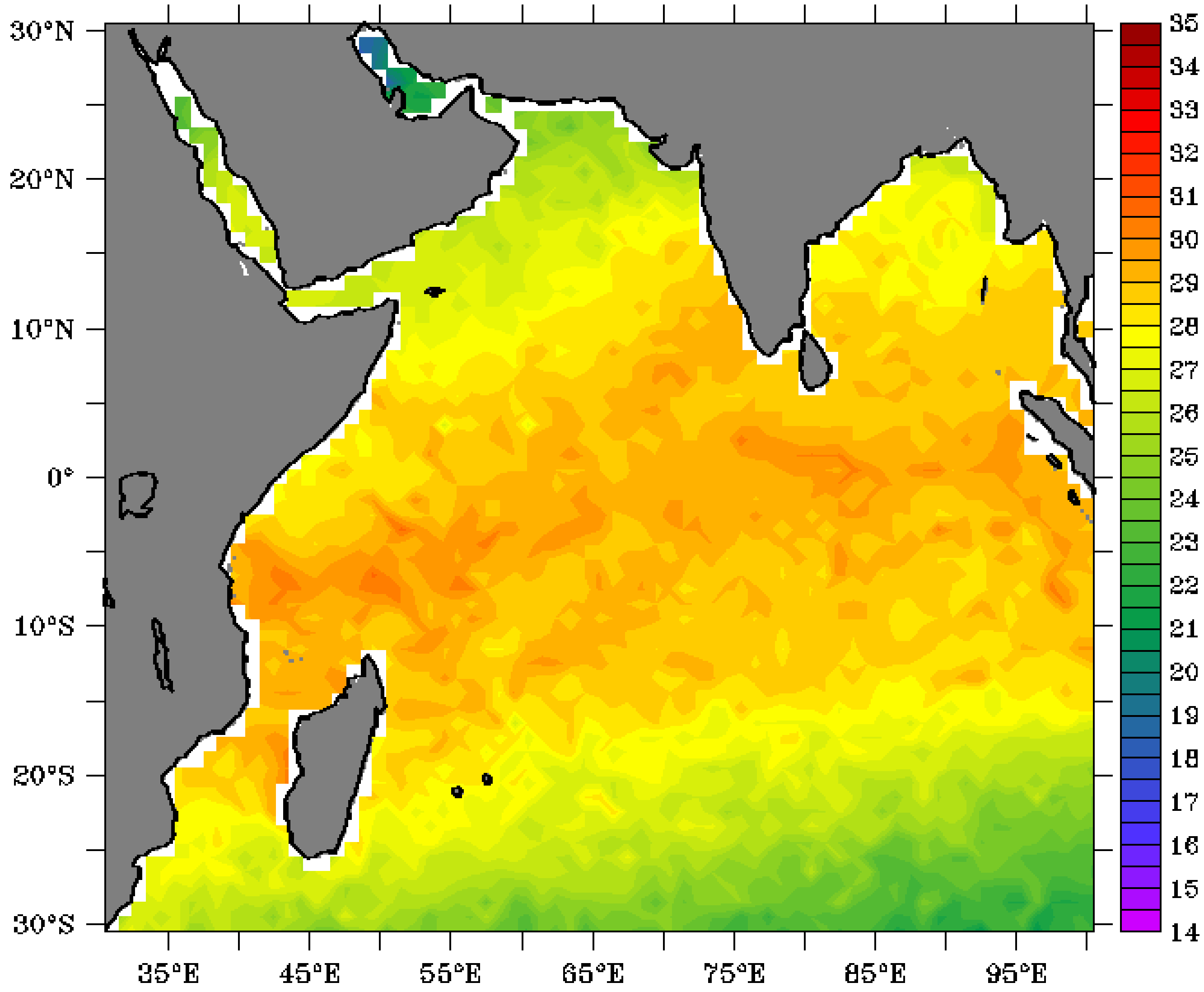
Anomaly (deg Celsius)



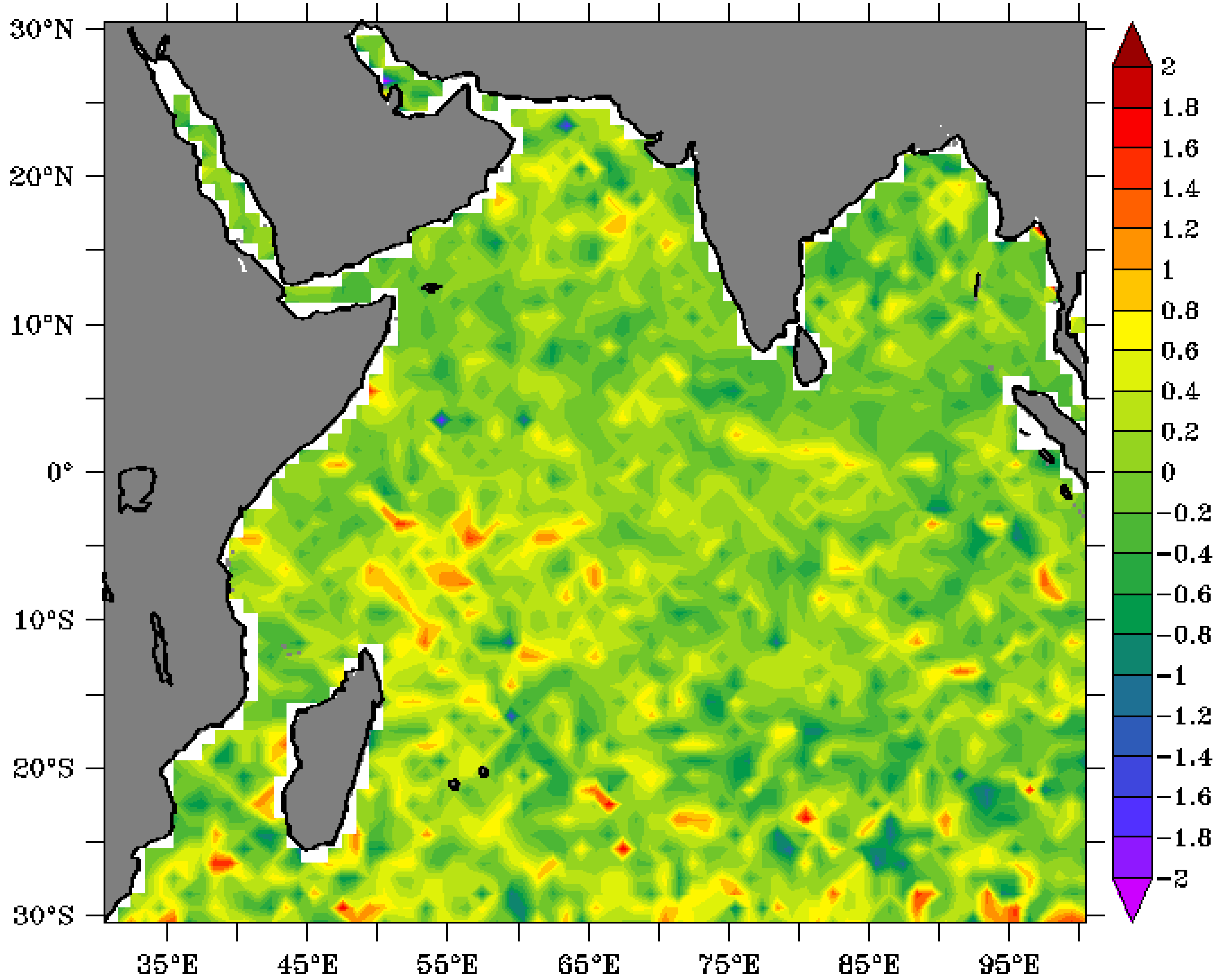
Sea surface temperature (deg Celsius) FEBRUARY



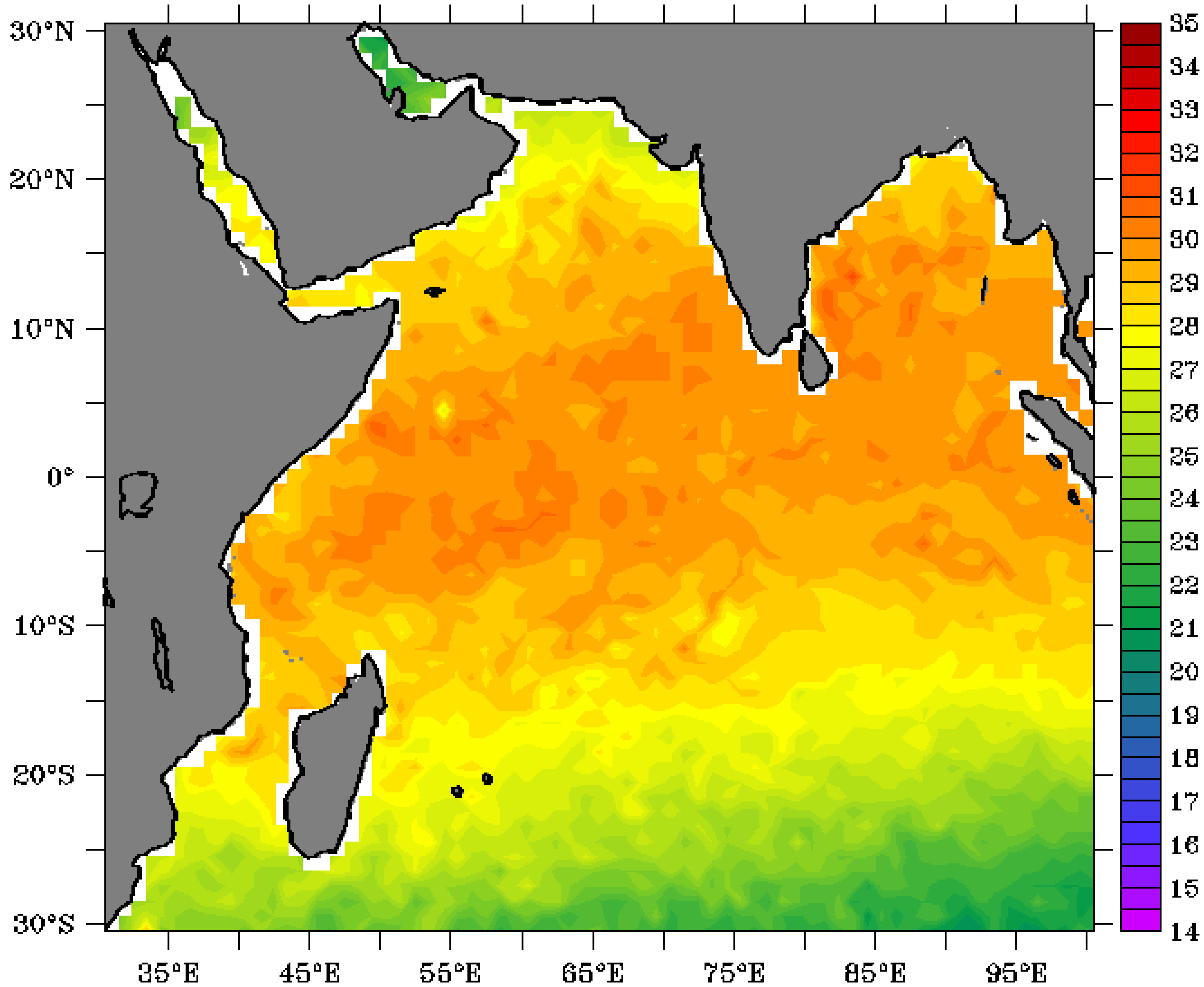
Anomaly (deg Celsius)



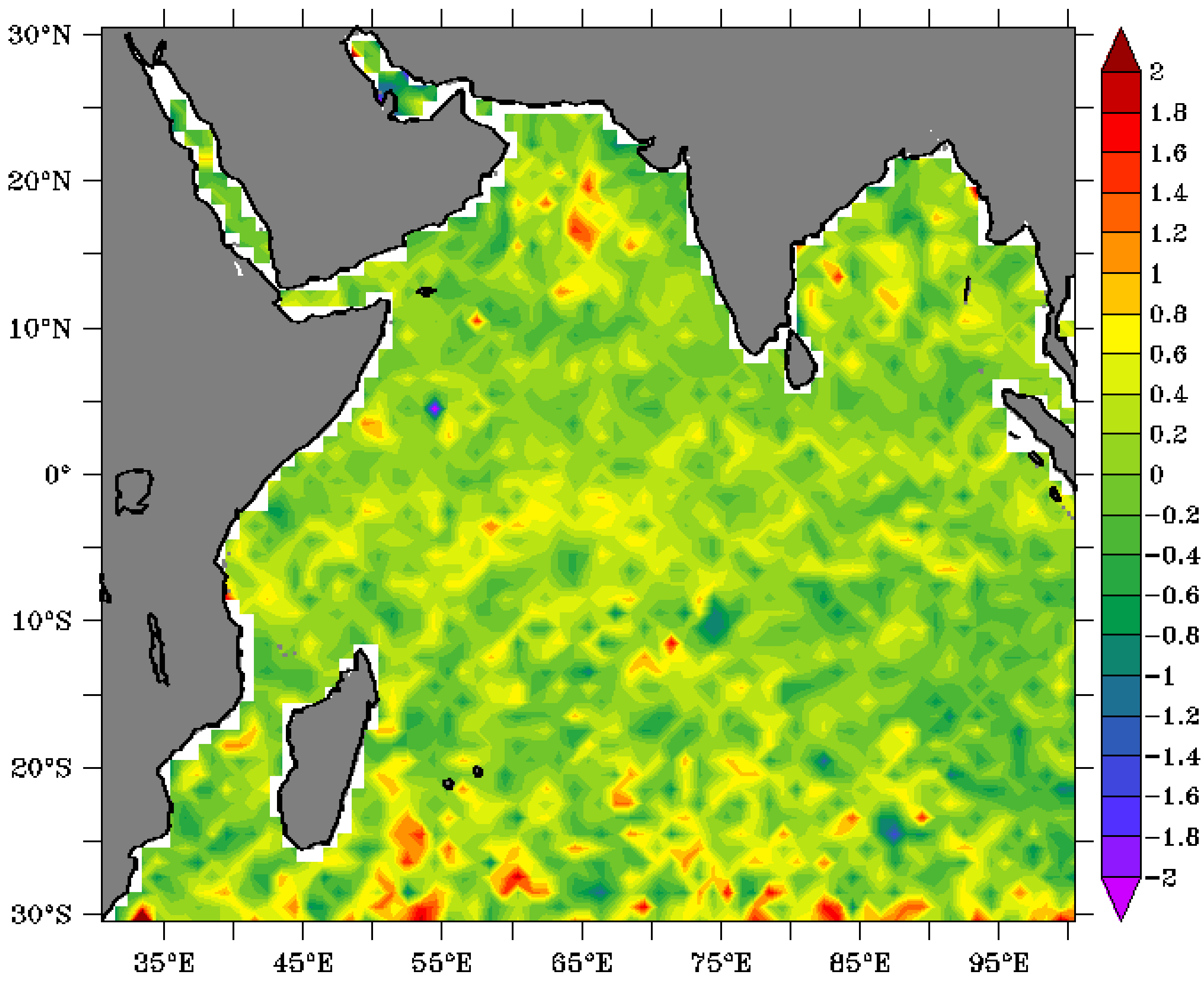
Sea surface temperature (deg Celsius) MARCH



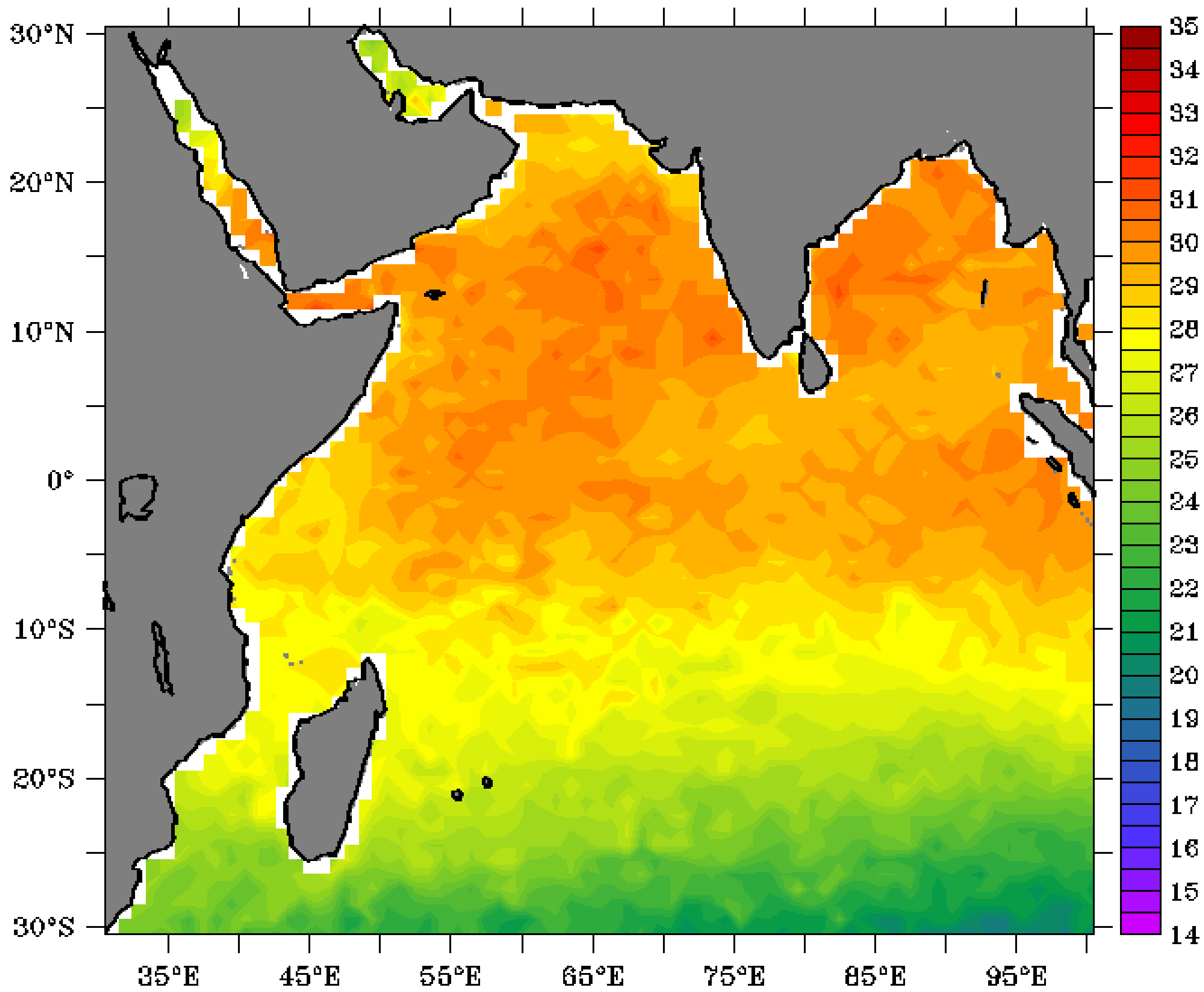
Anomaly (deg Celsius)



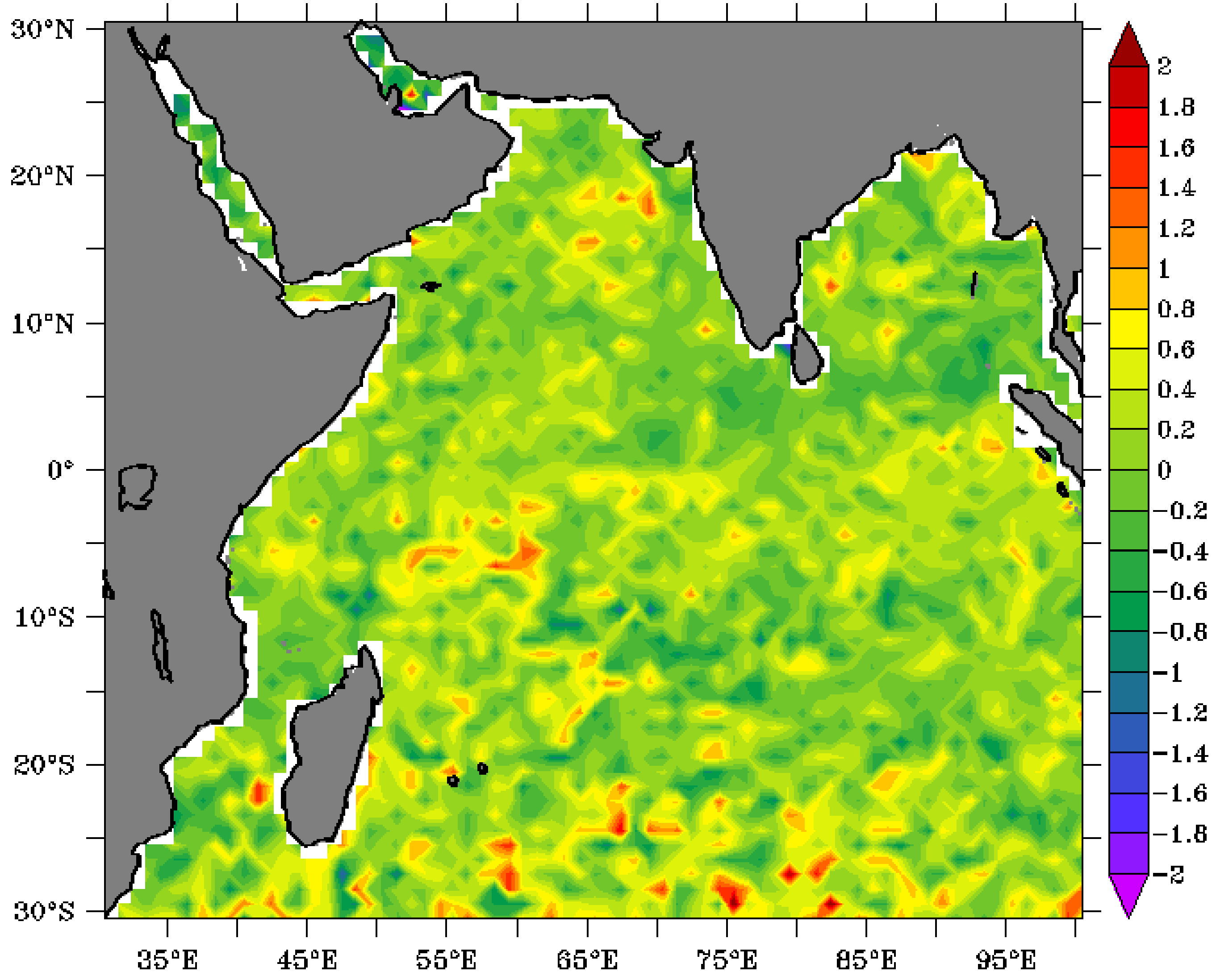
Sea surface temperature (deg Celsius) APRIL



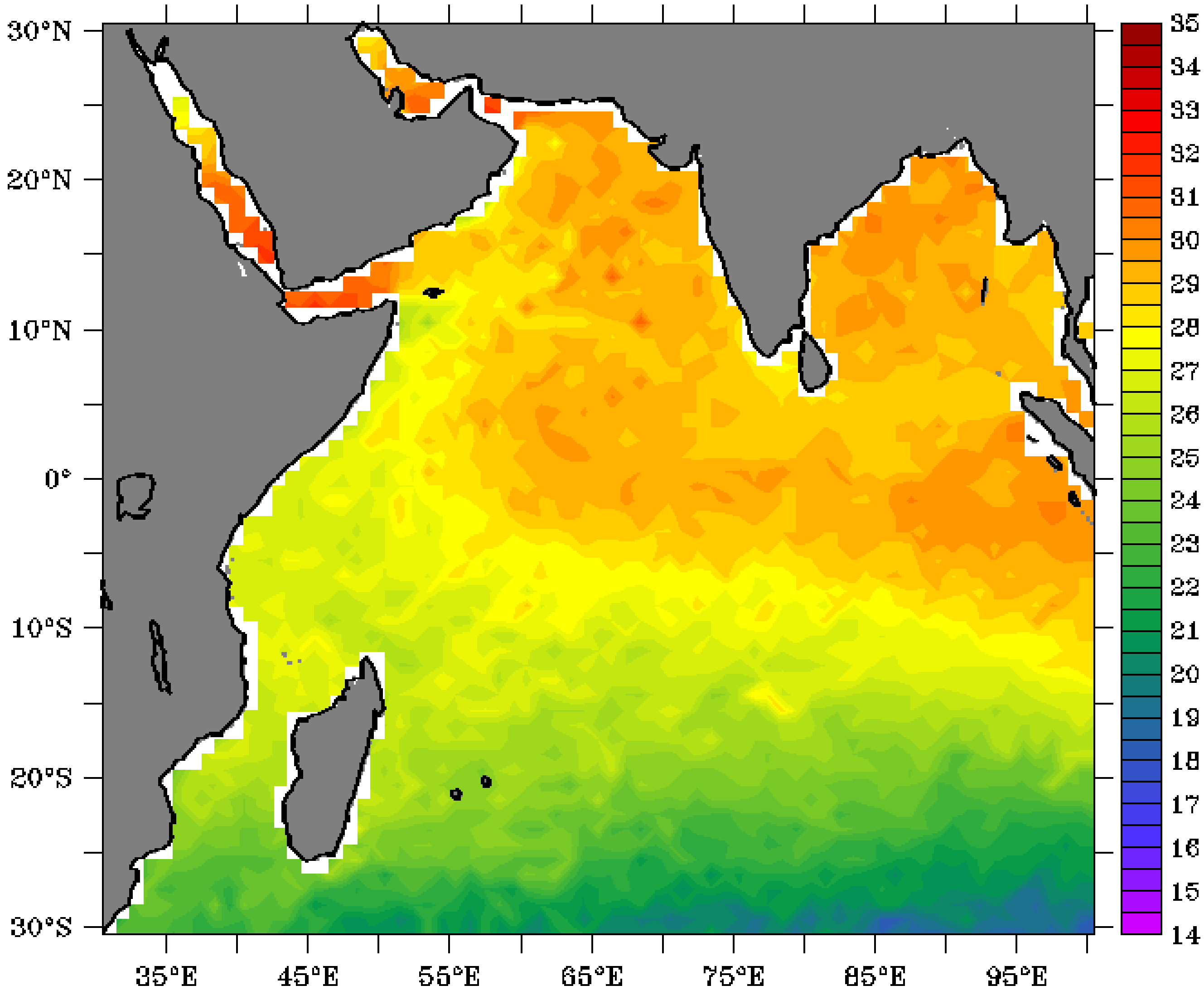
Anomaly (deg Celsius)



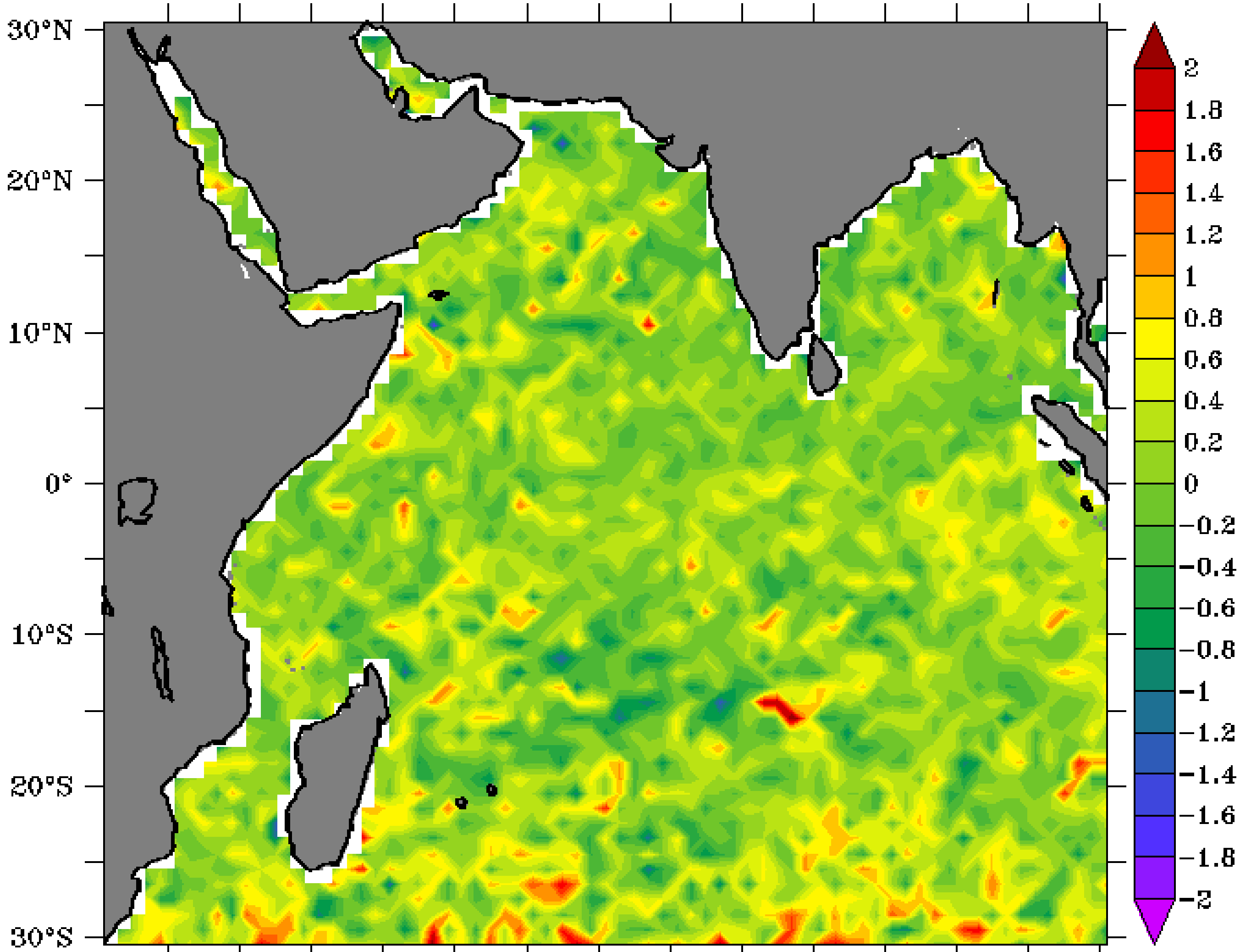
Sea surface temperature (deg Celsius) MAY



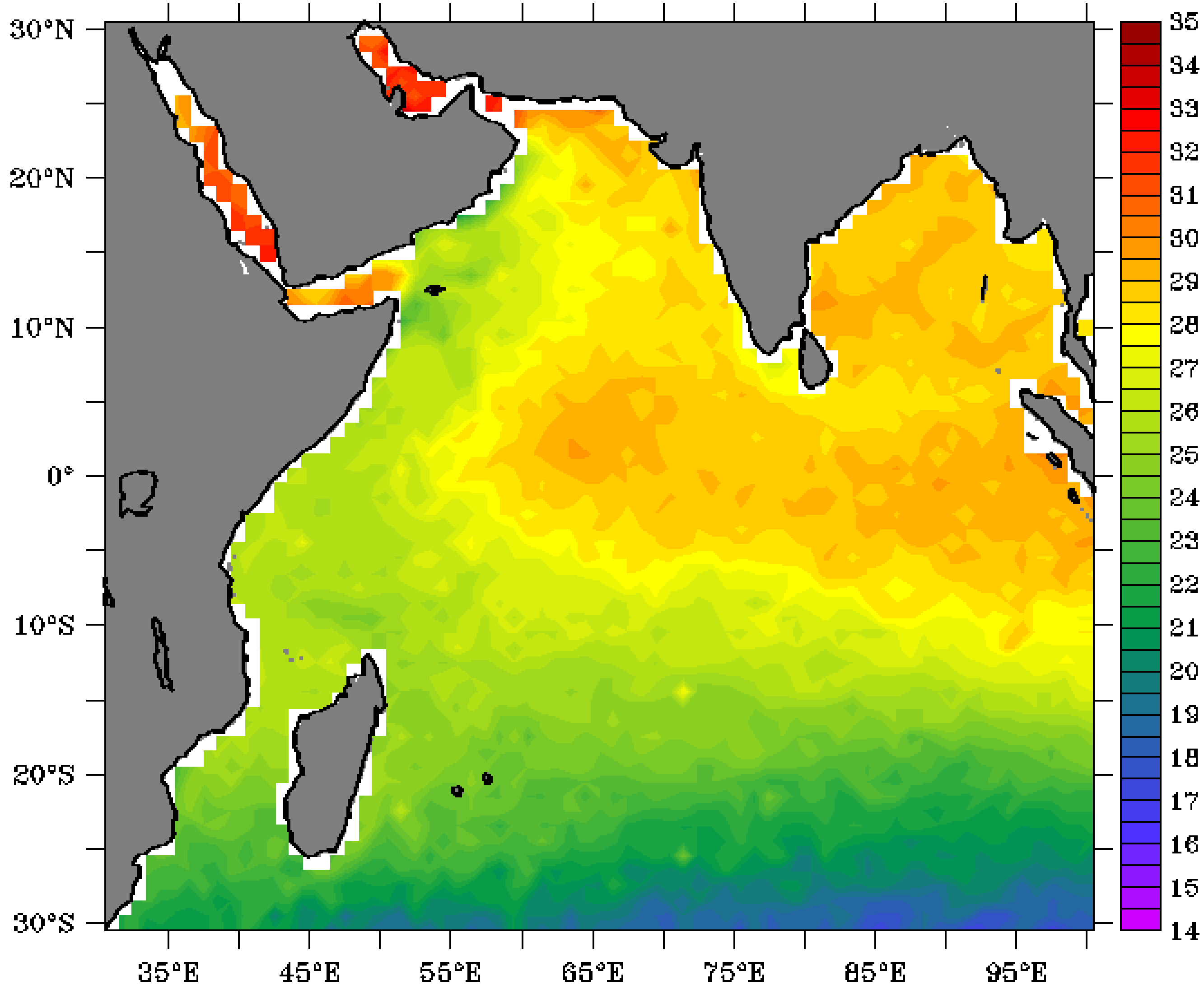
Anomaly (deg Celsius)



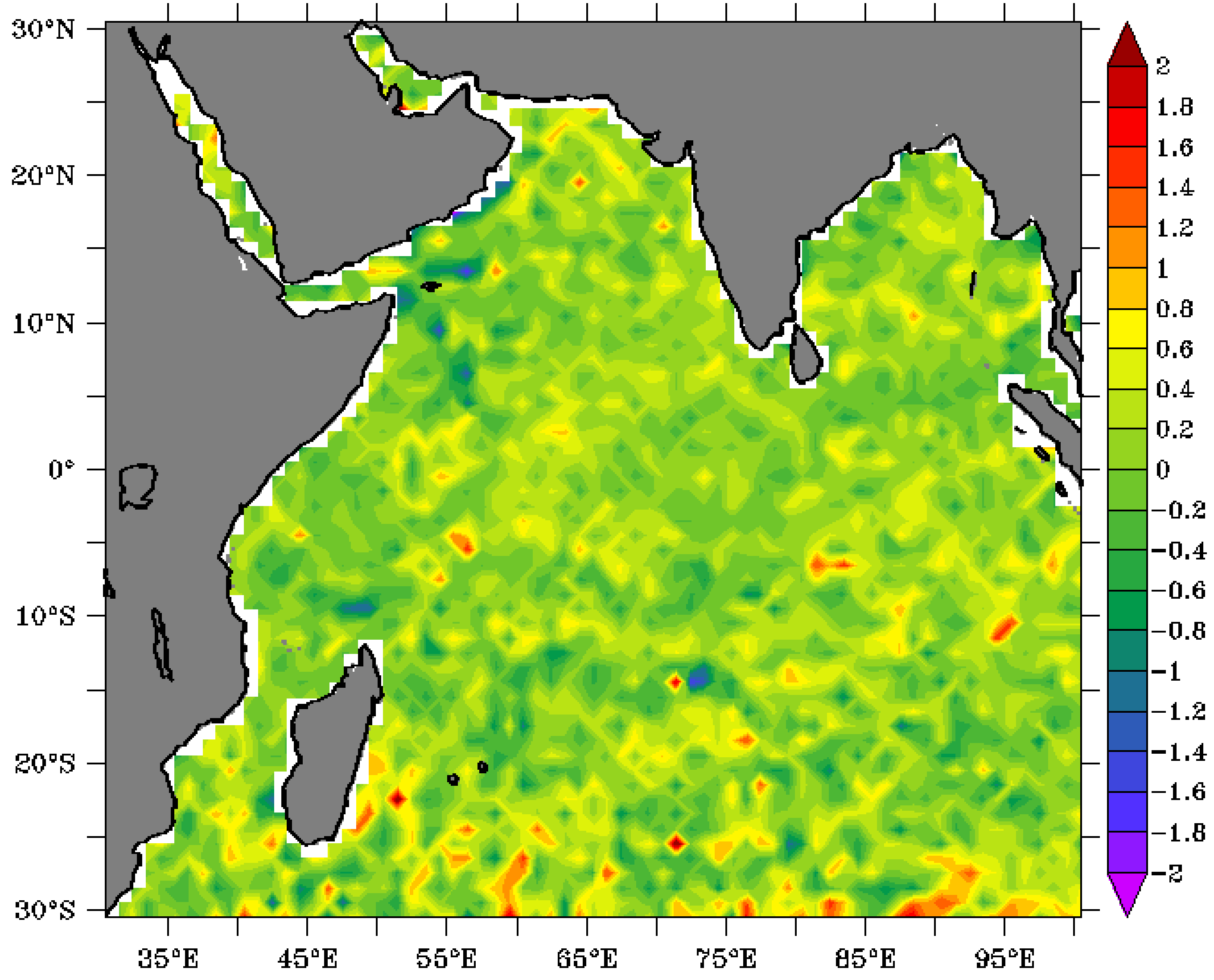
Sea surface temperature (deg Celsius) JUNE



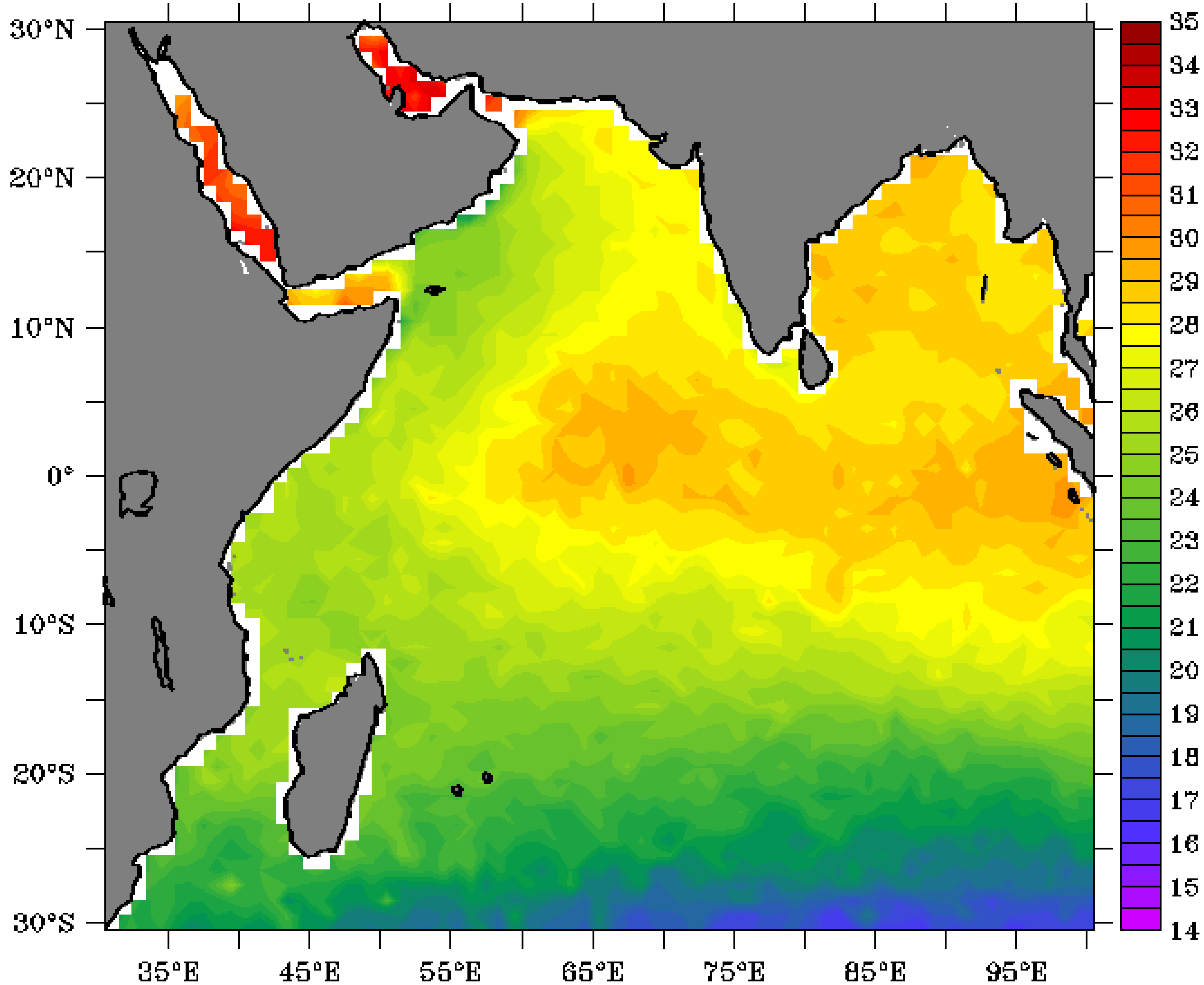
Anomaly (deg Celsius)



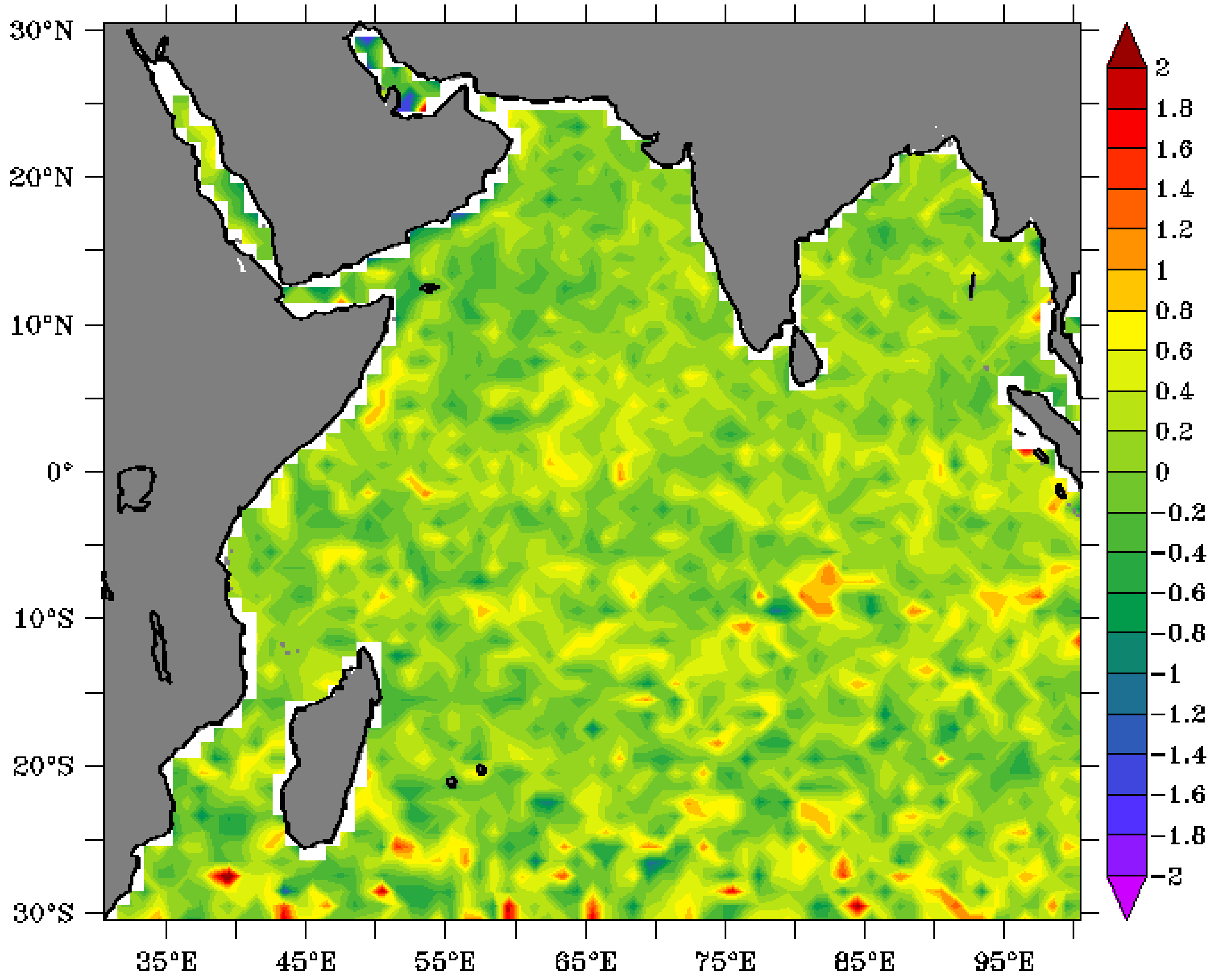
Sea surface temperature (deg Celsius) JULY



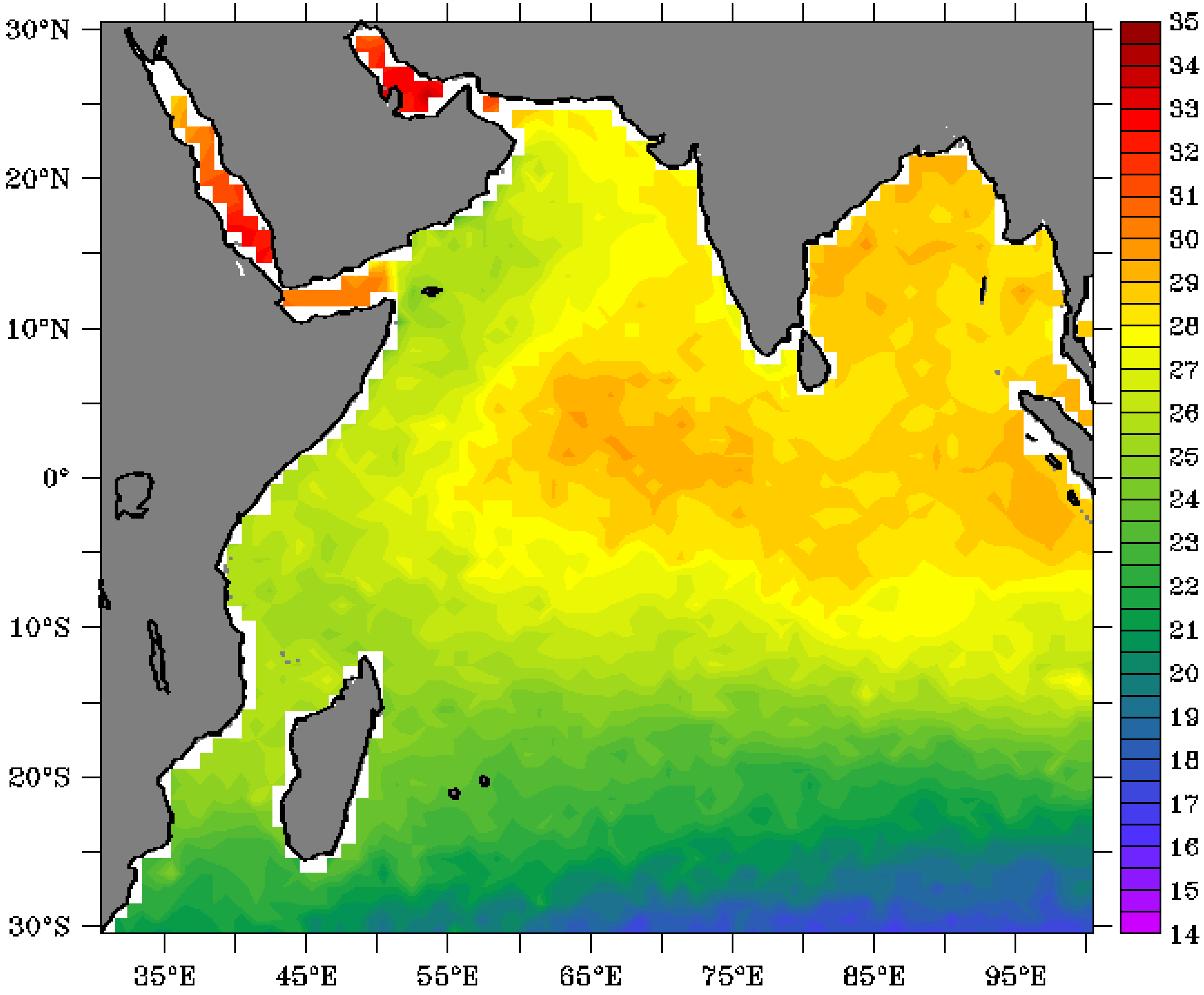
Anomaly (deg Celsius)



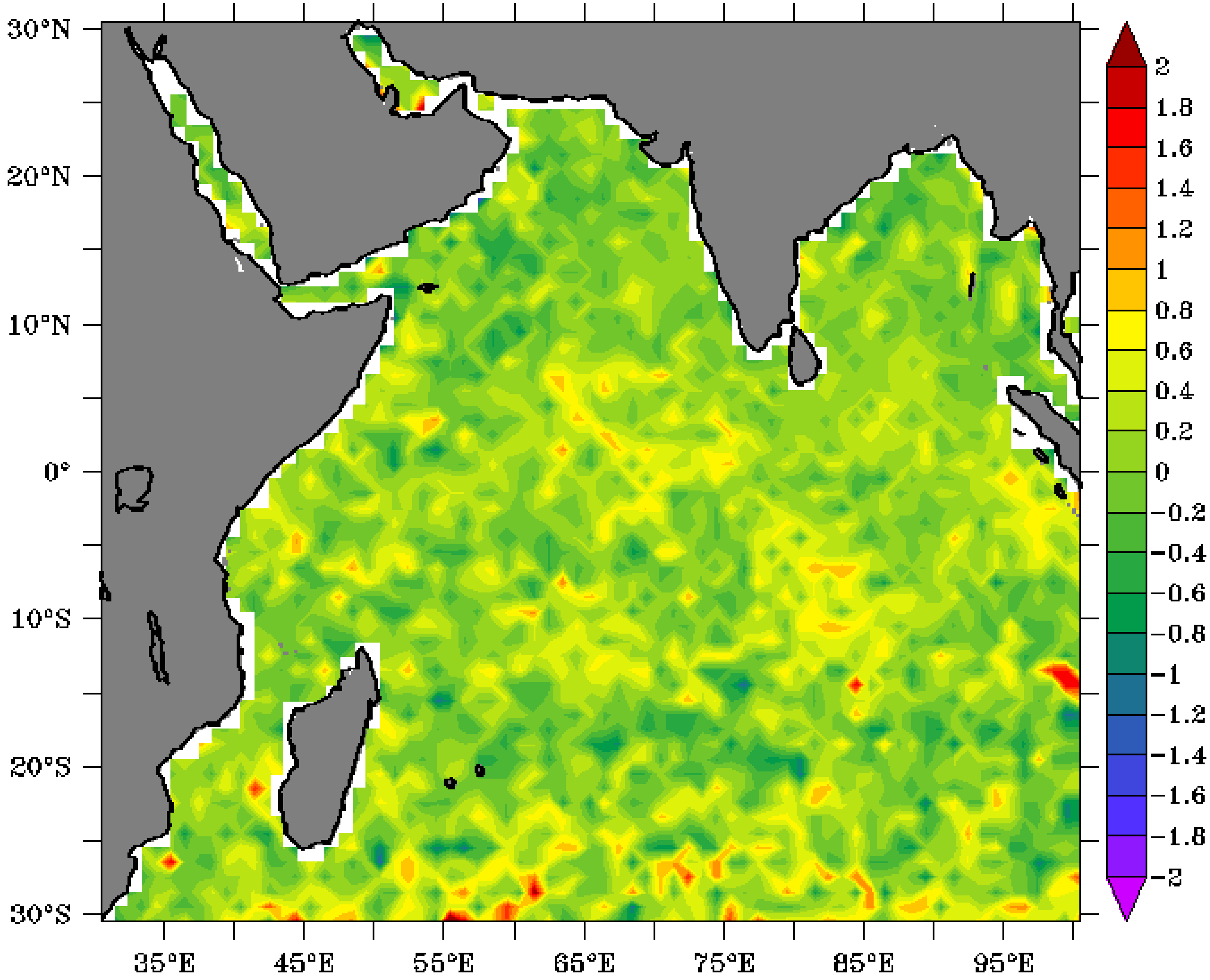
Sea surface temperature (deg Celsius) AUGUST



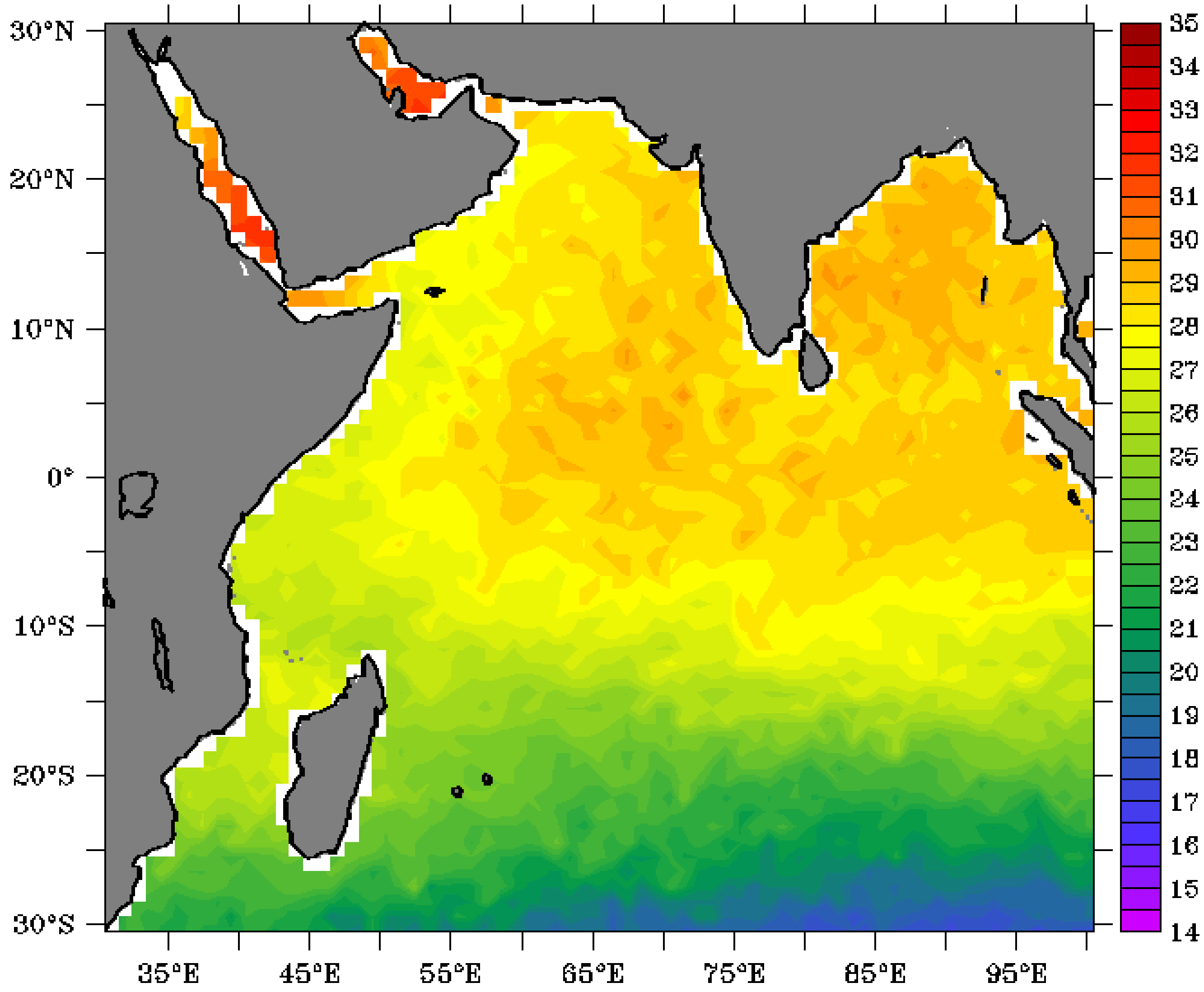
Anomaly (deg Celsius)



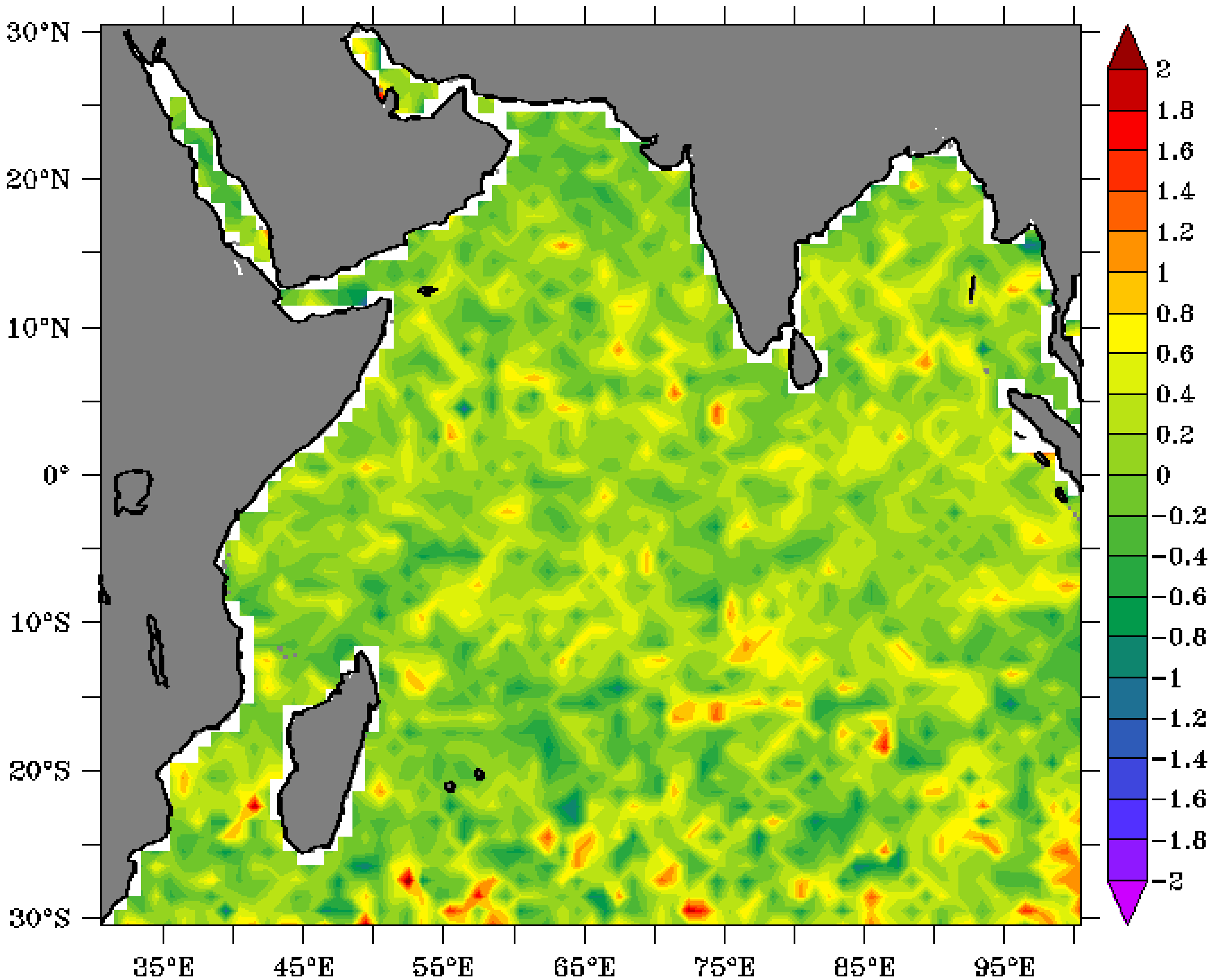
Sea surface temperature (deg Celsius)   SEPTEMBER



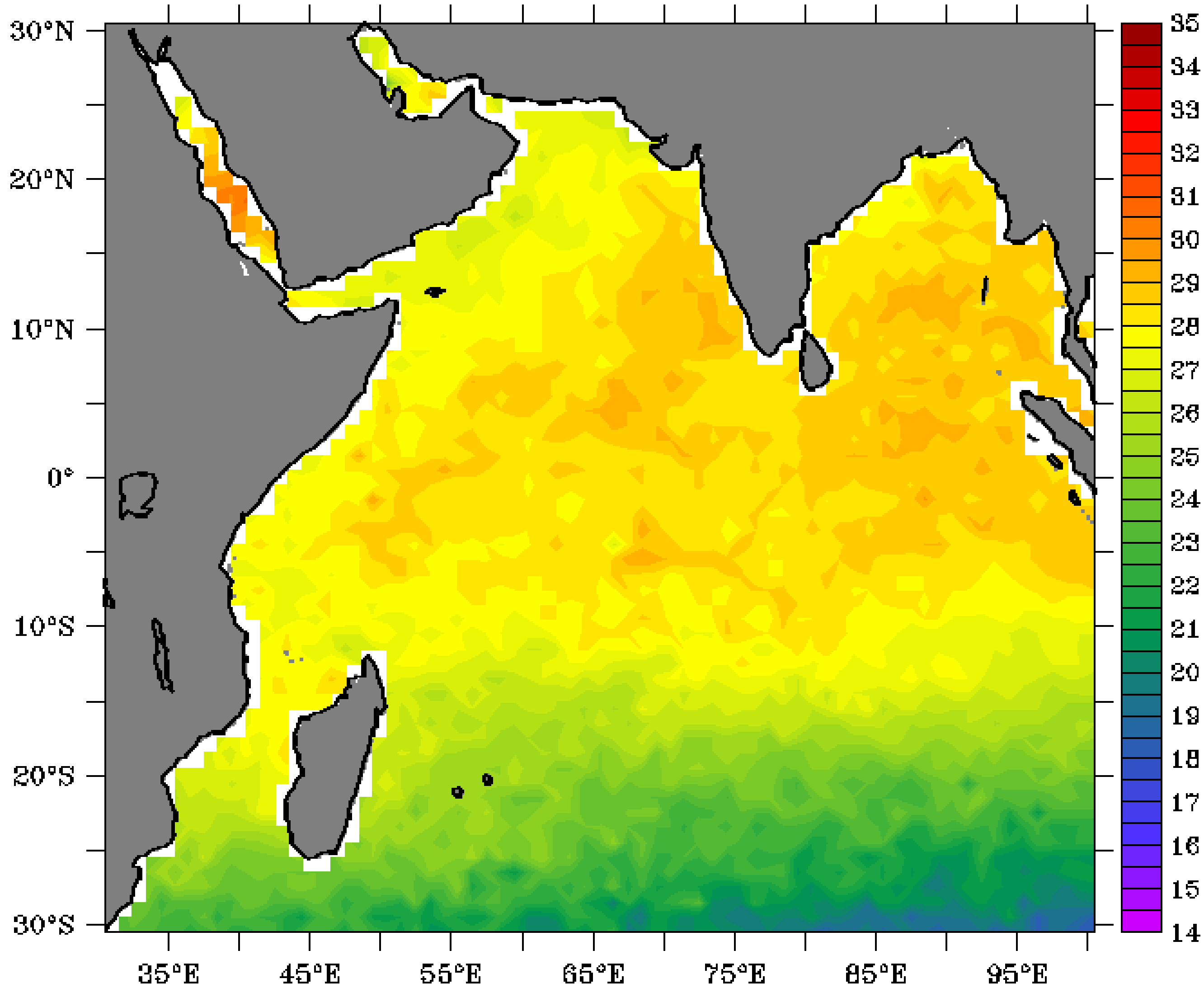
Anomaly (deg Celsius)



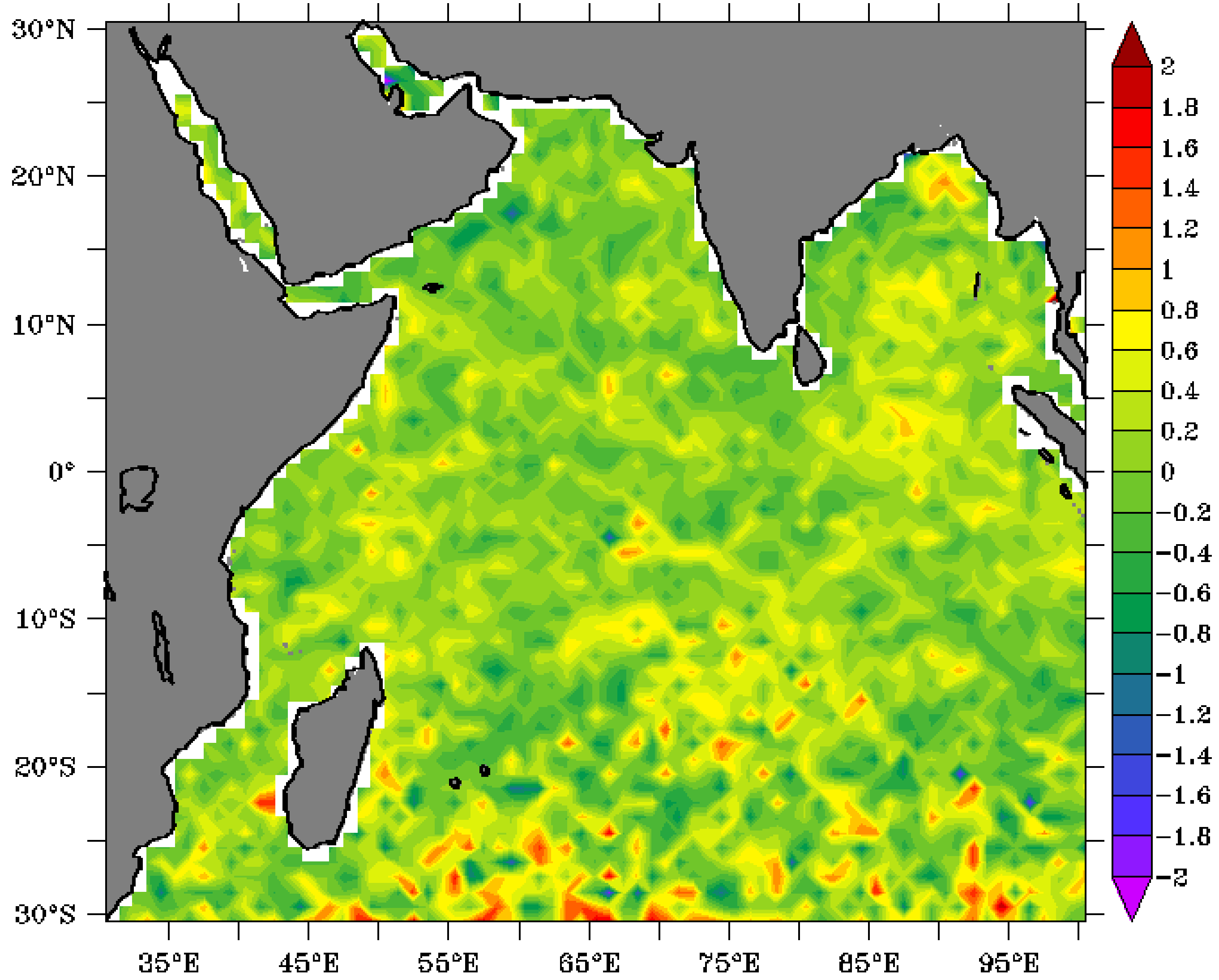
Sea surface temperature (deg Celsius)   OCTOBER



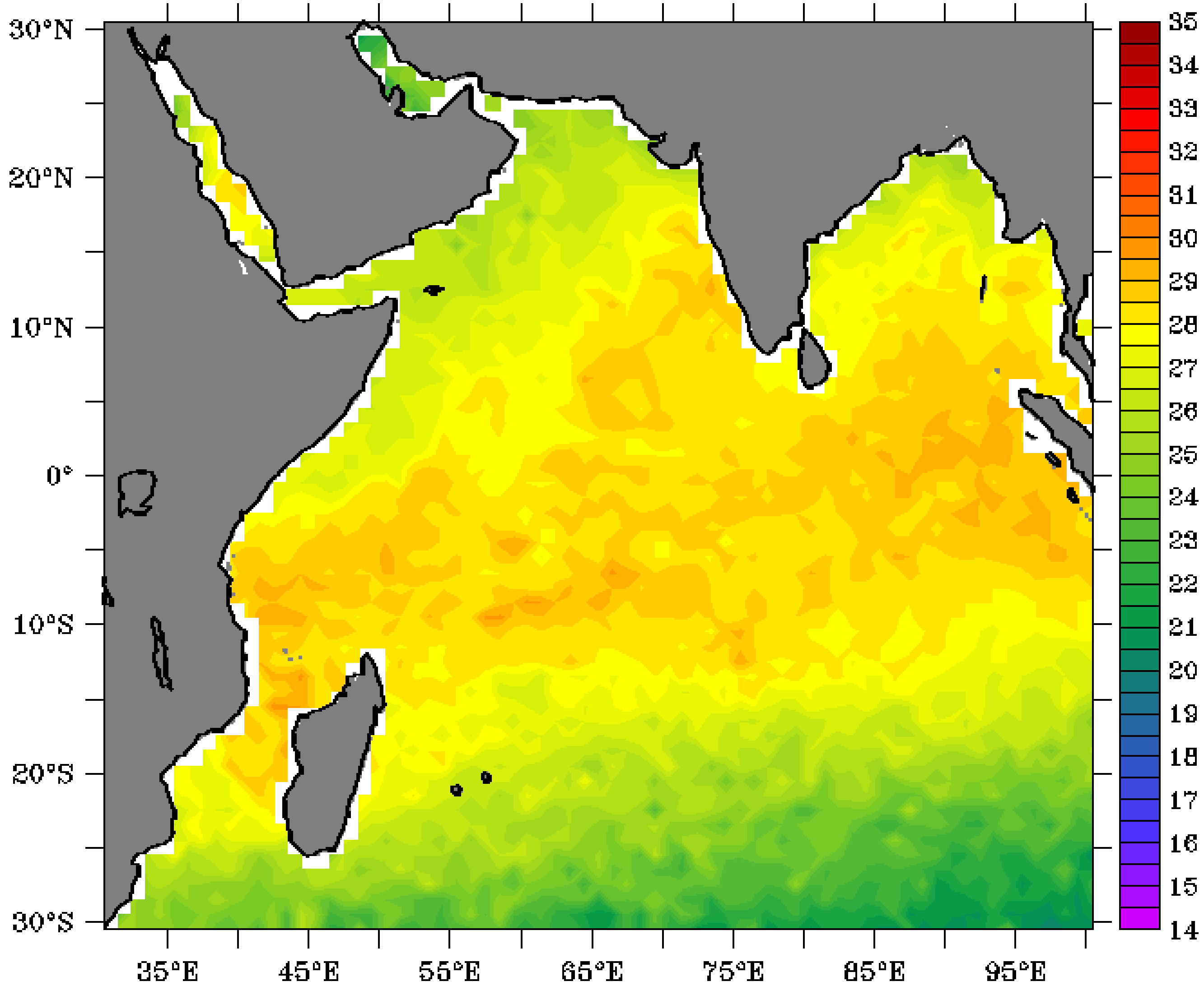
Anomaly (deg Celsius)



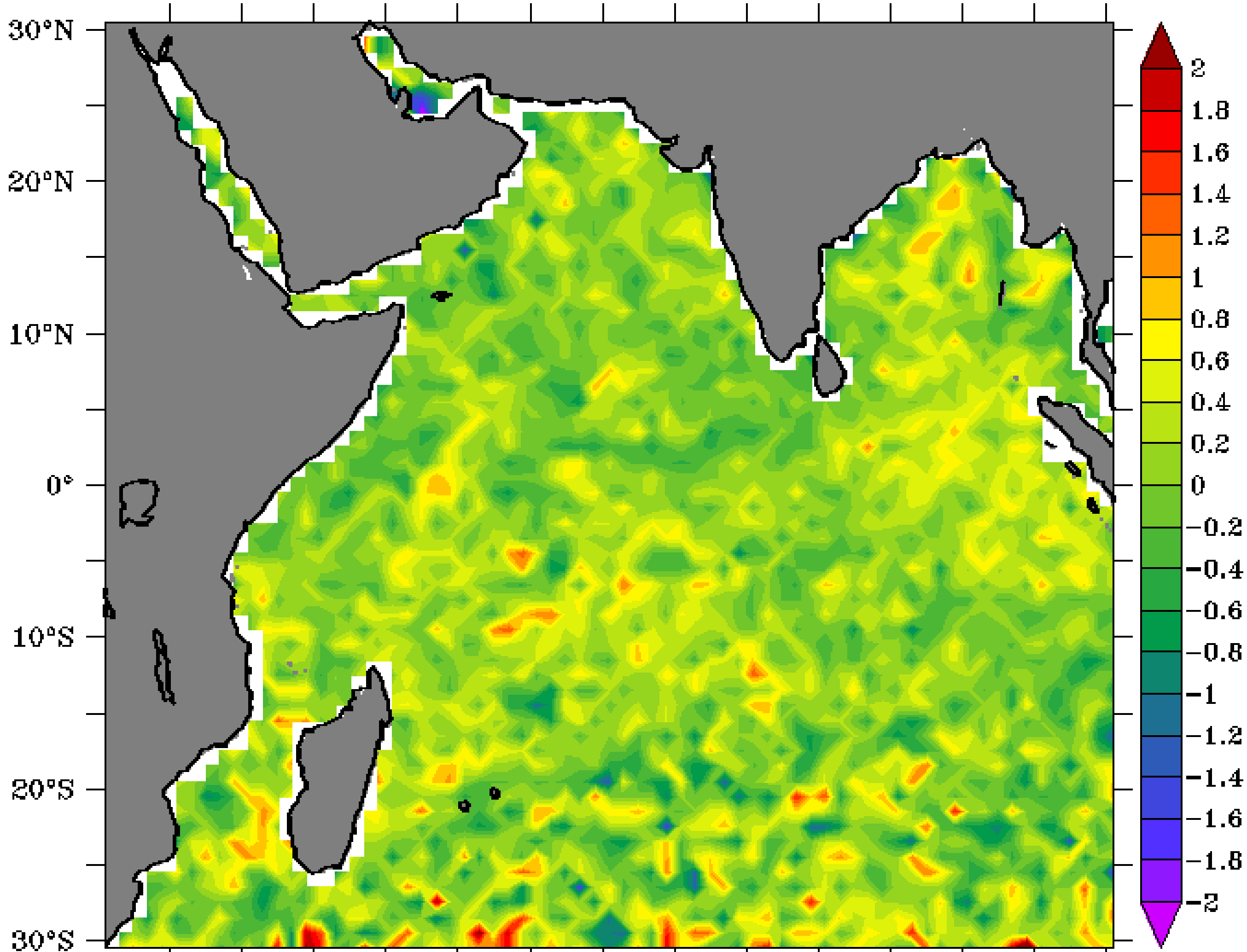
Sea surface temperature (deg Celsius) NOVEMBER



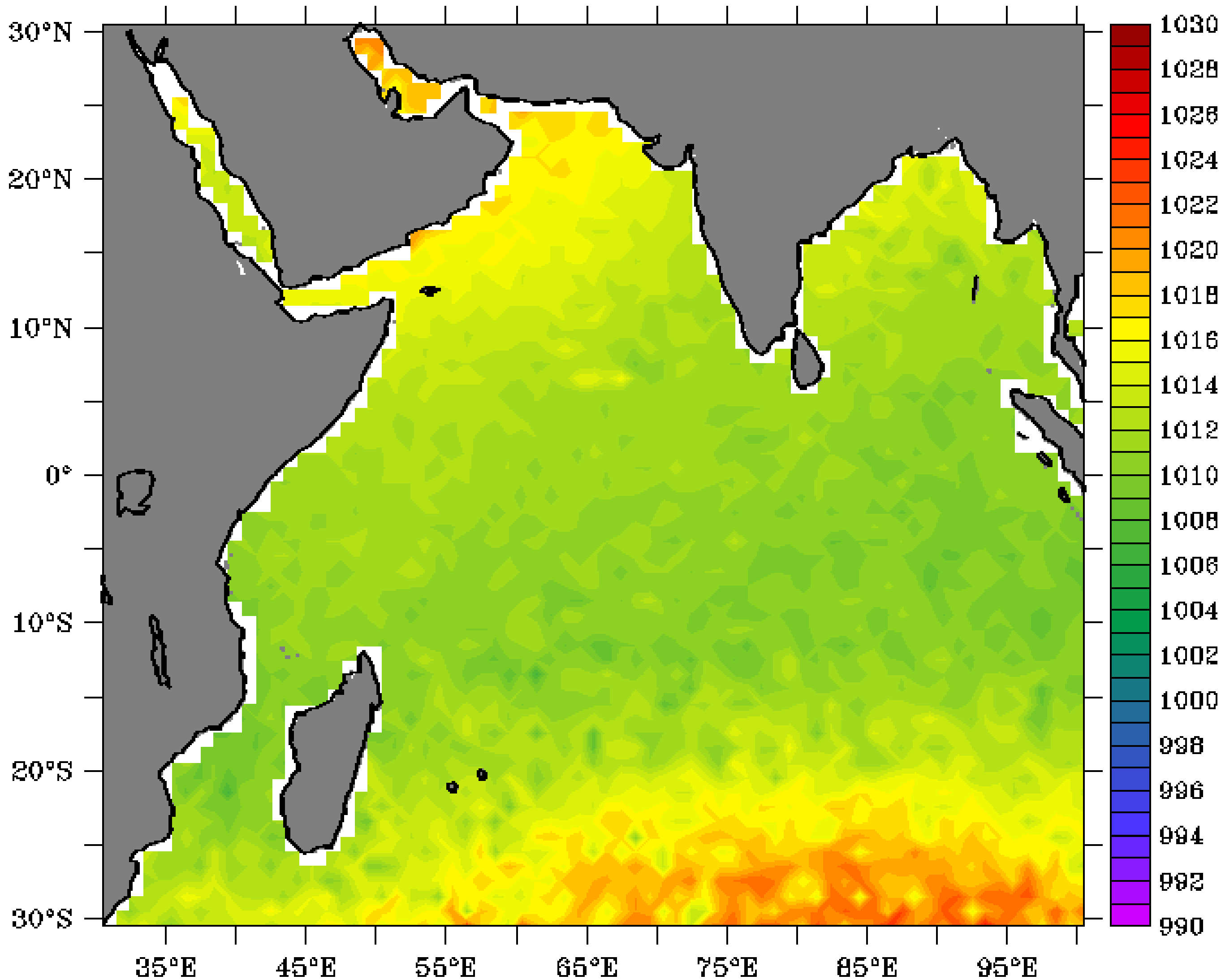
Anomaly (deg Celsius)



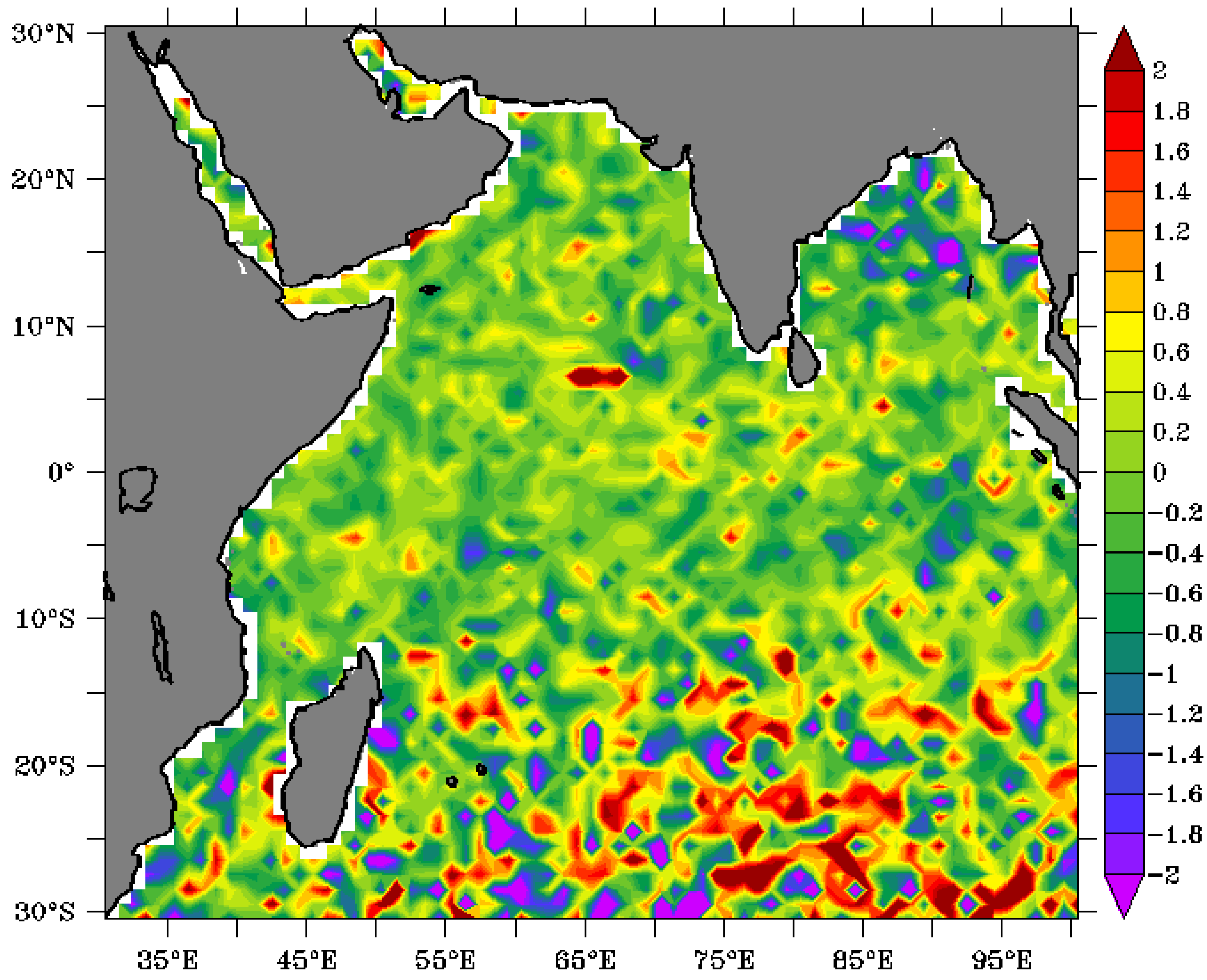
Sea surface temperature (deg Celsius) DECEMBER



Anomaly (deg Celsius)



Sea level pressure (hPa) JANUARY


30°N
20°N
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30°S
35°E
45°E
55°E
65°E
75°E
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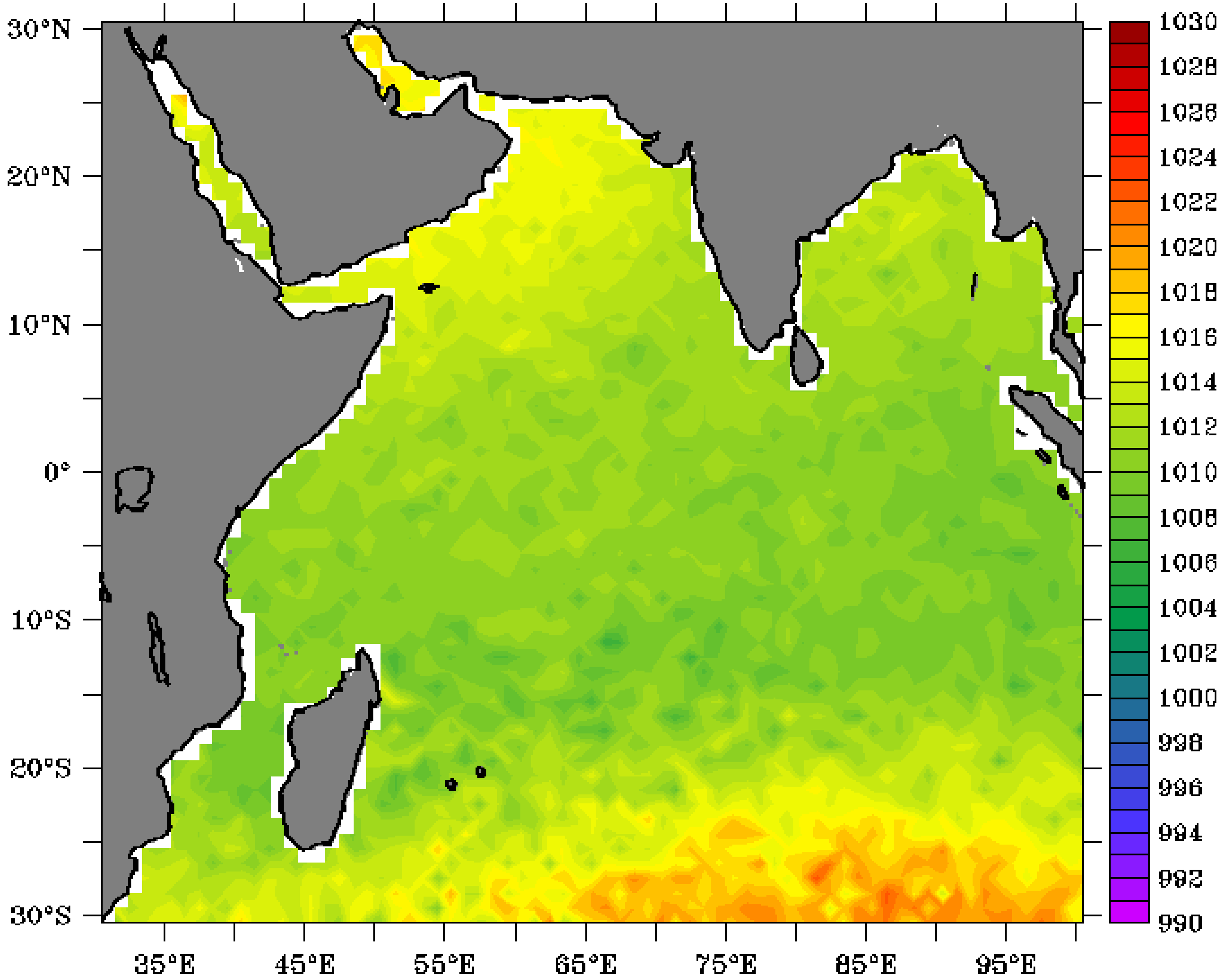
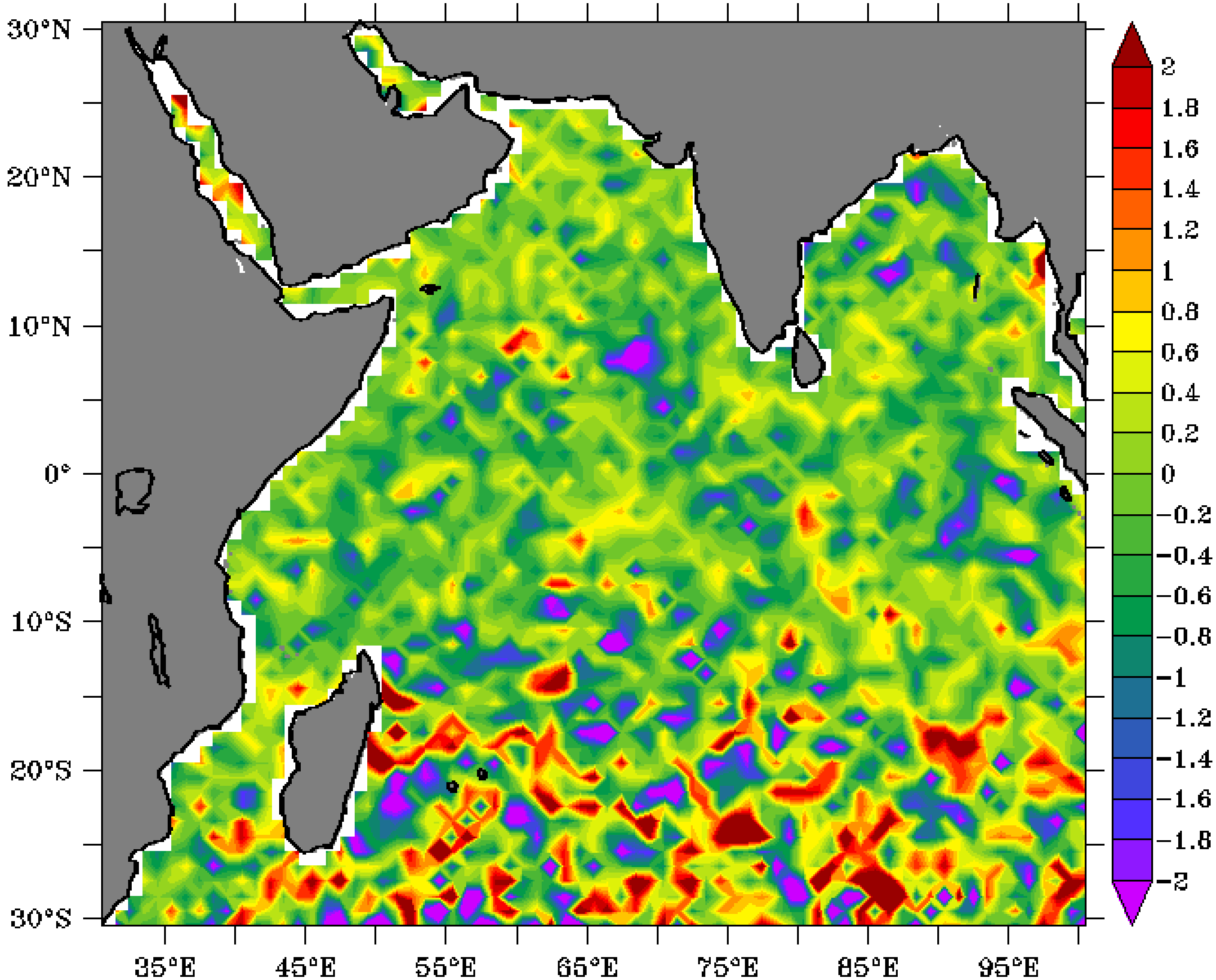
95°E
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (hPa)



Sea level pressure (hPa) FEBRUARY



30°N
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20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
2
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1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
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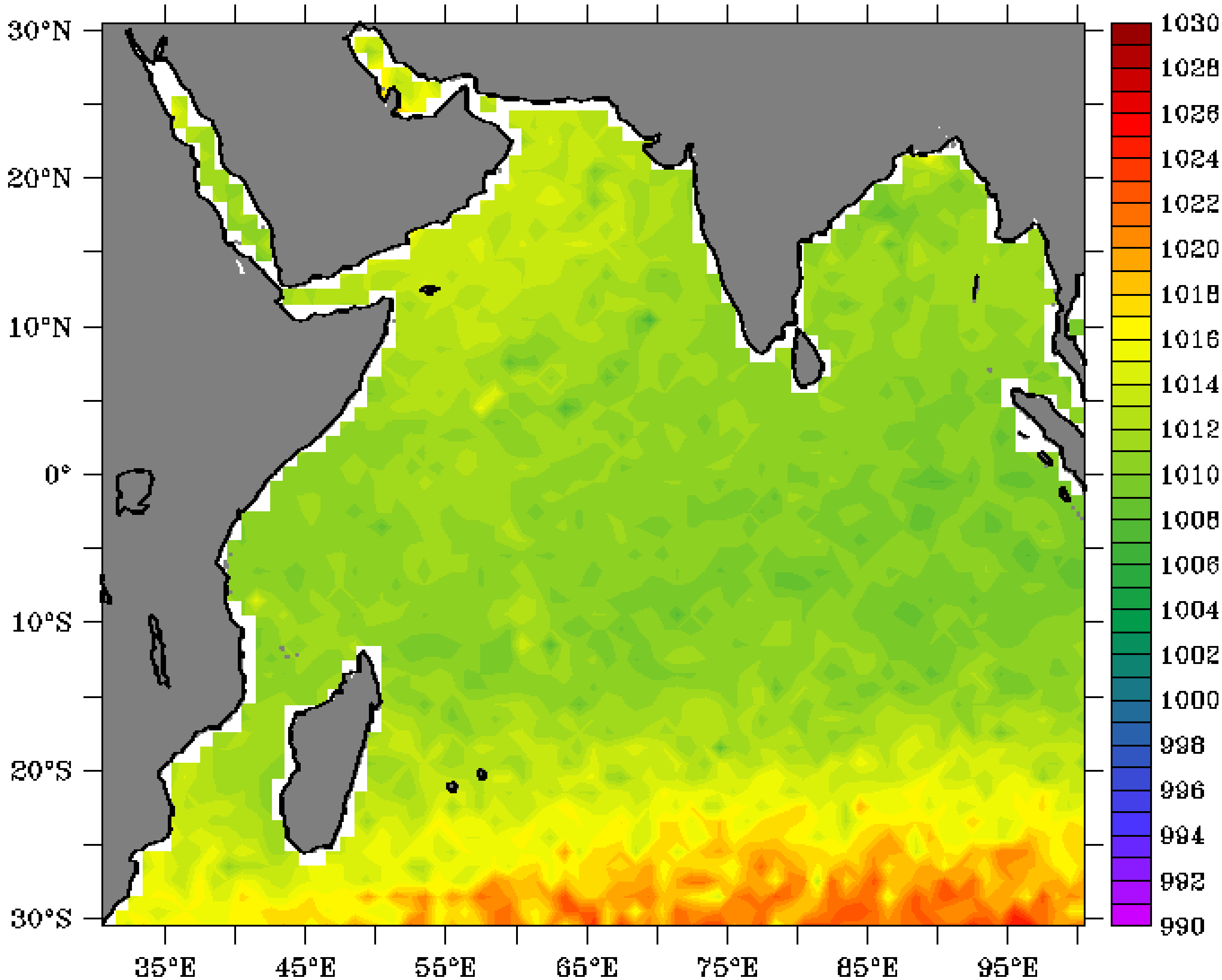
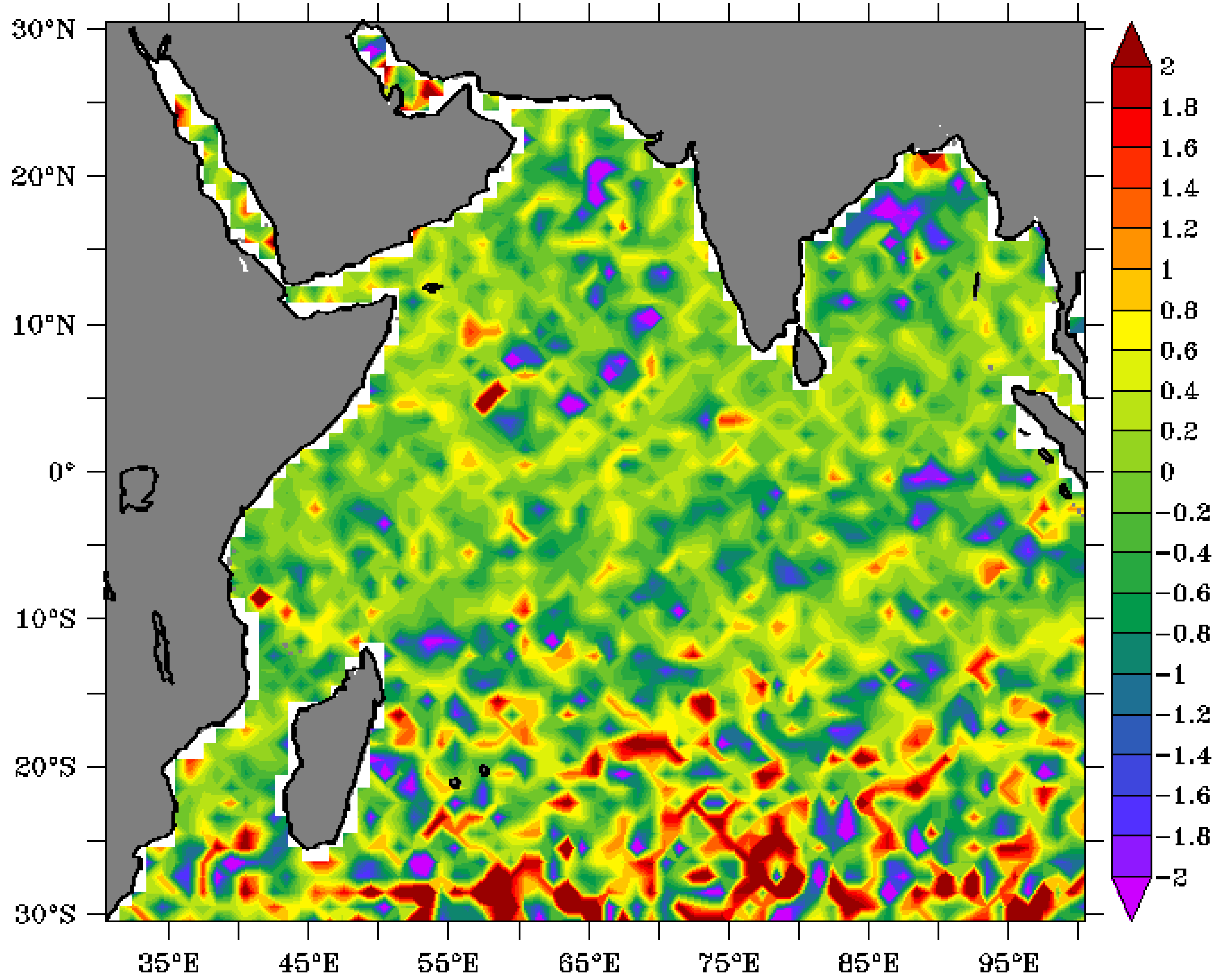
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (hPa)



Sea level pressure (hPa) MARCH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1
0.8
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0.2
0
−0.2
−0.4
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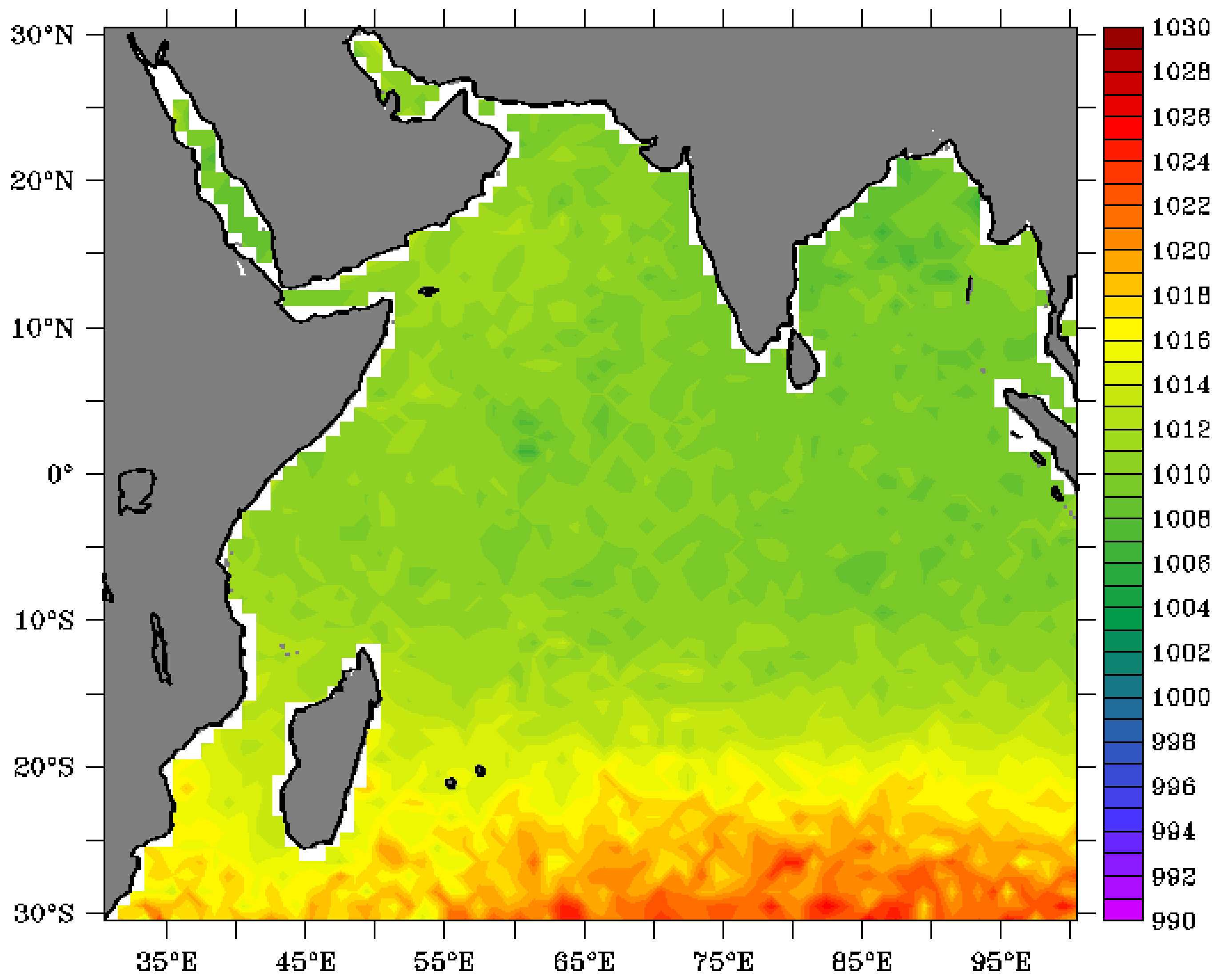
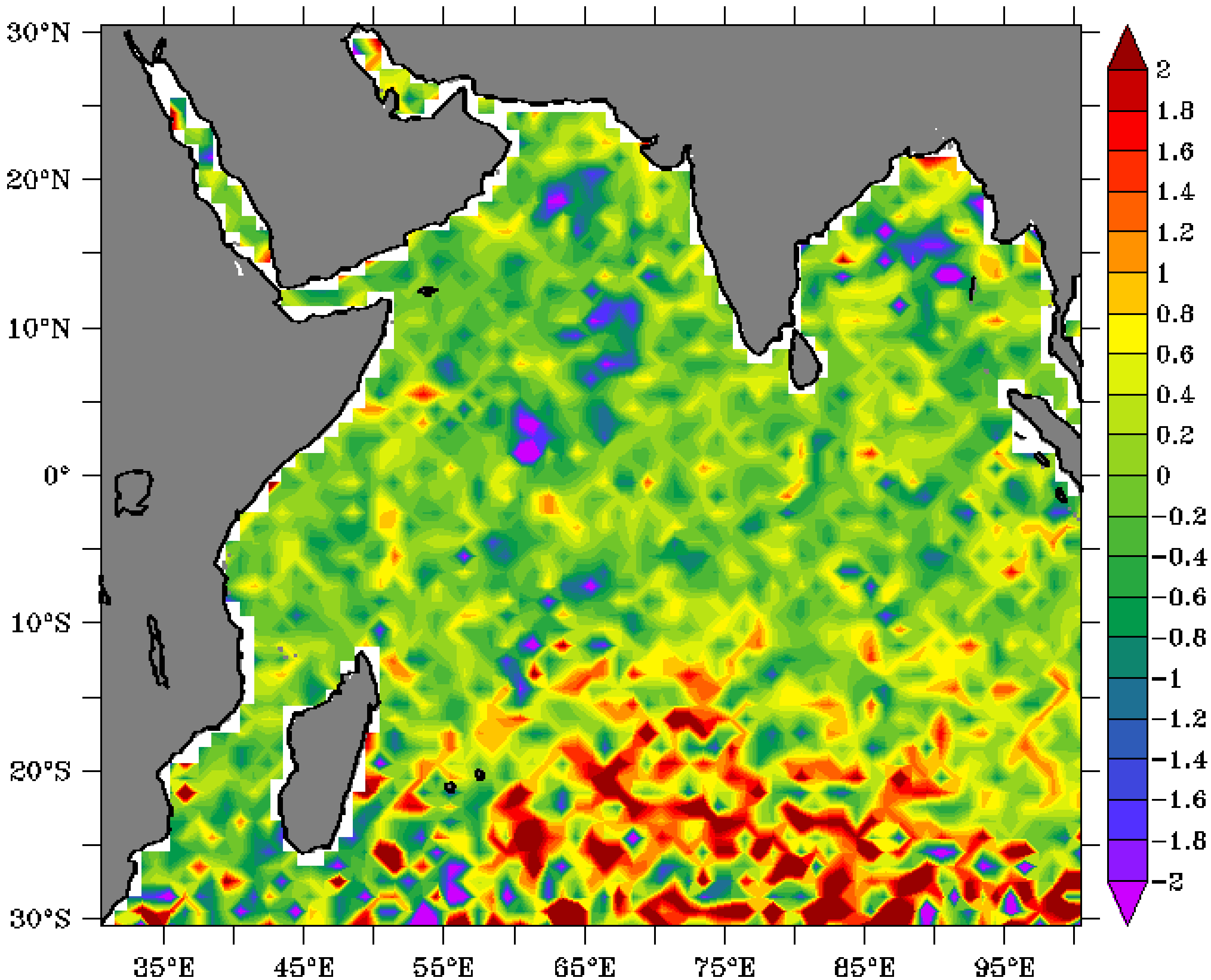
−0.8
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (hPa)



Sea level pressure (hPa) APRIL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0.8
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−0.2
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−0.8
−1
−1.2
−1.4
−1.6
−1.8
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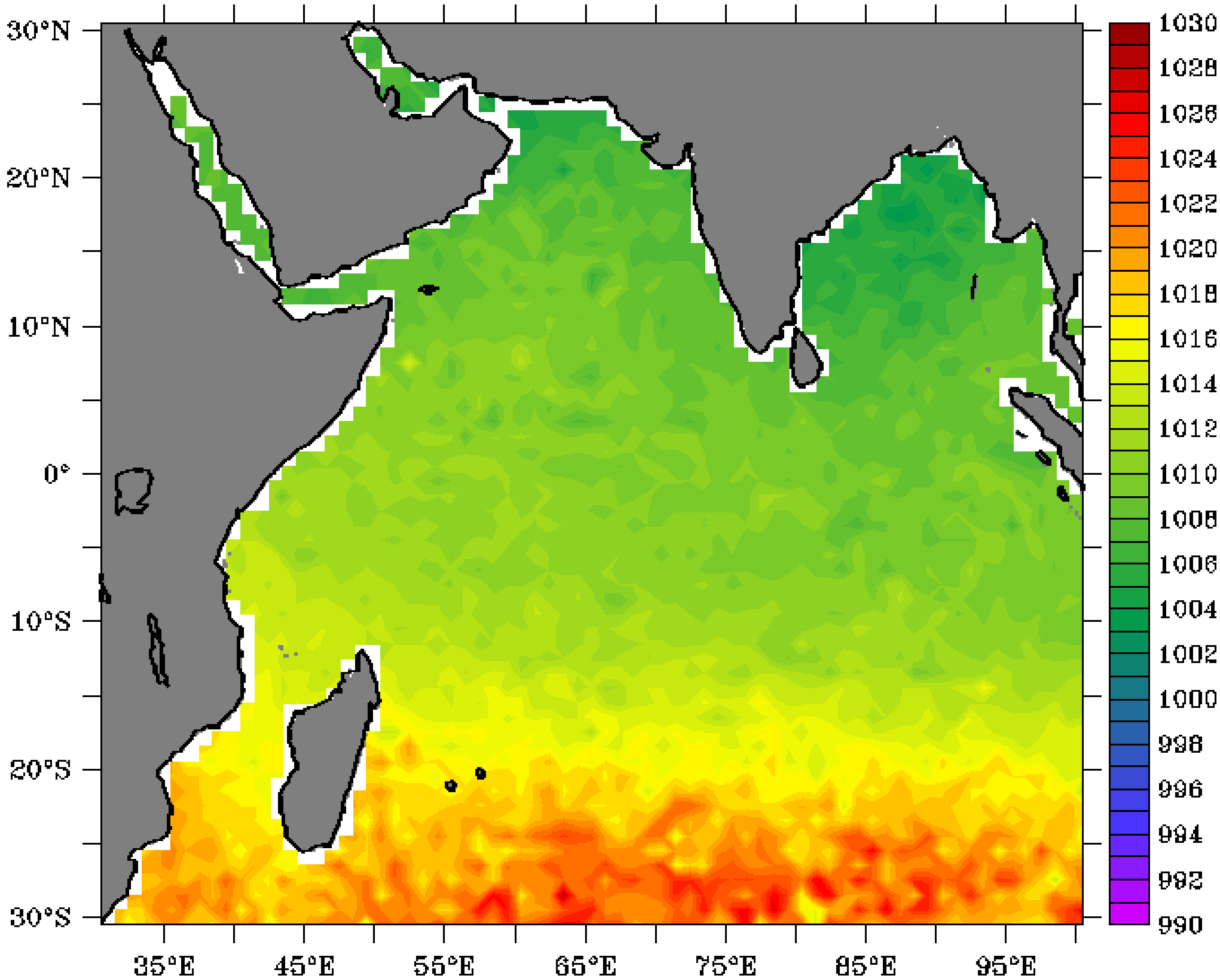
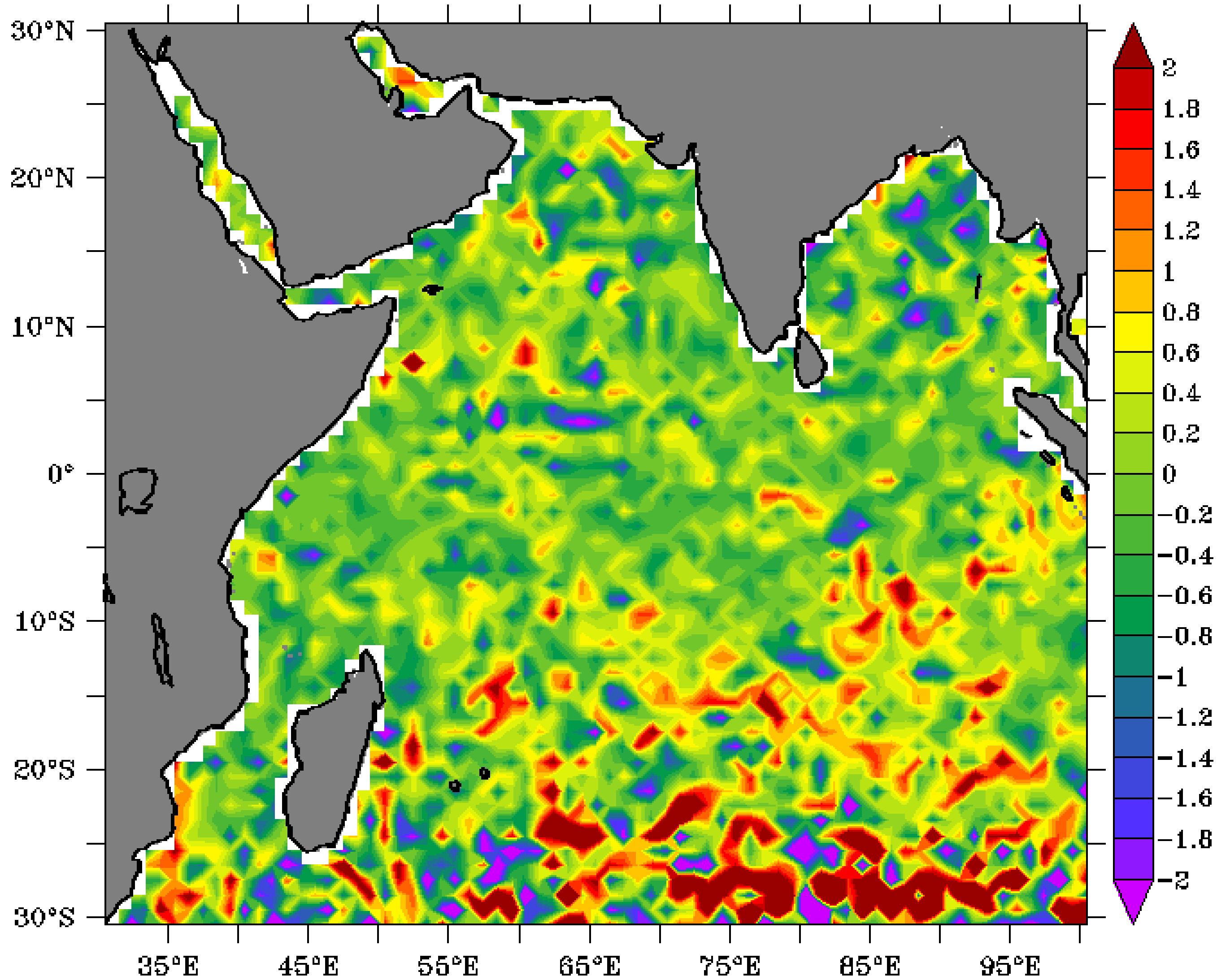
Anomaly (hPa)



Sea level pressure (hPa) MAY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65°E
75°E
85°E
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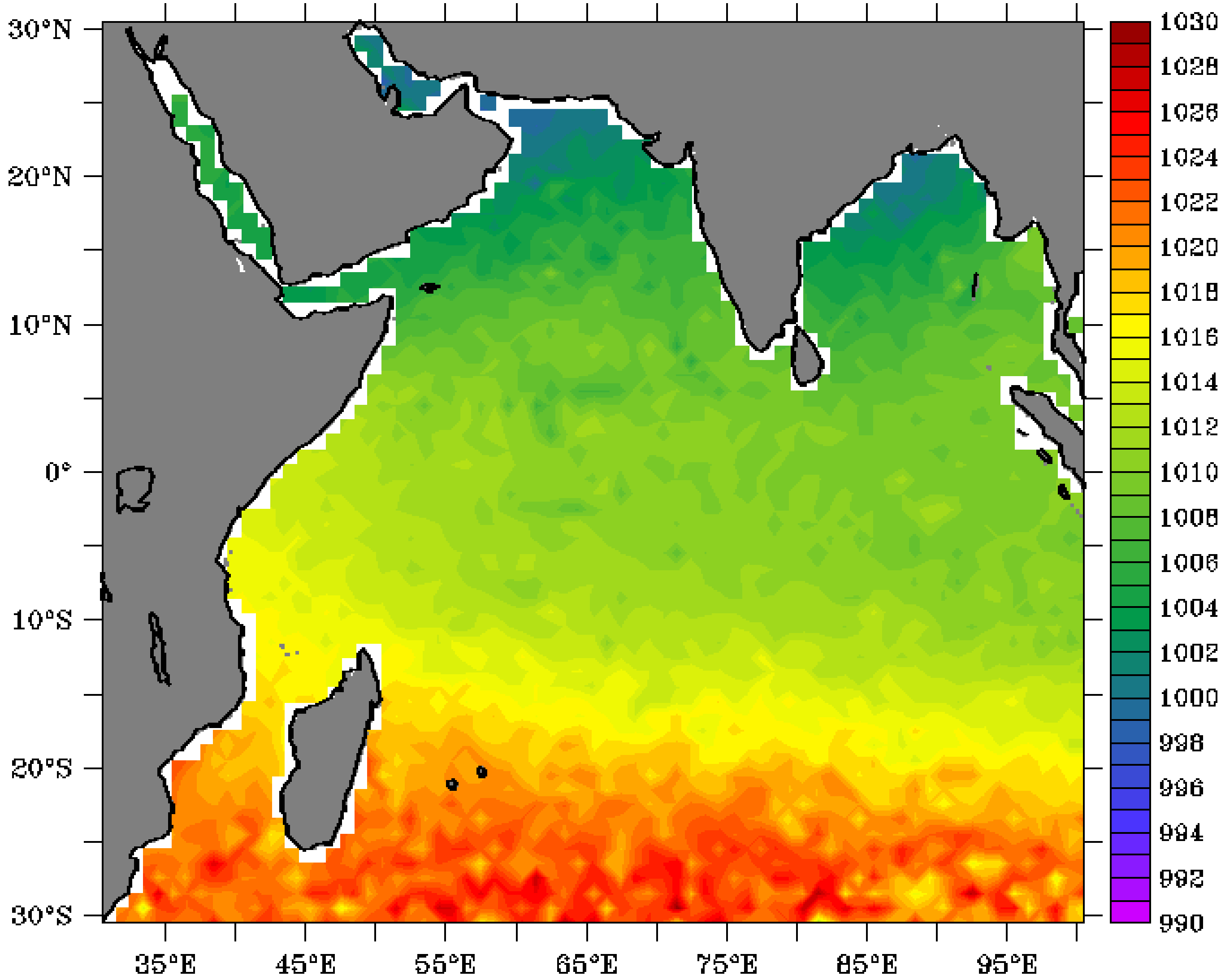
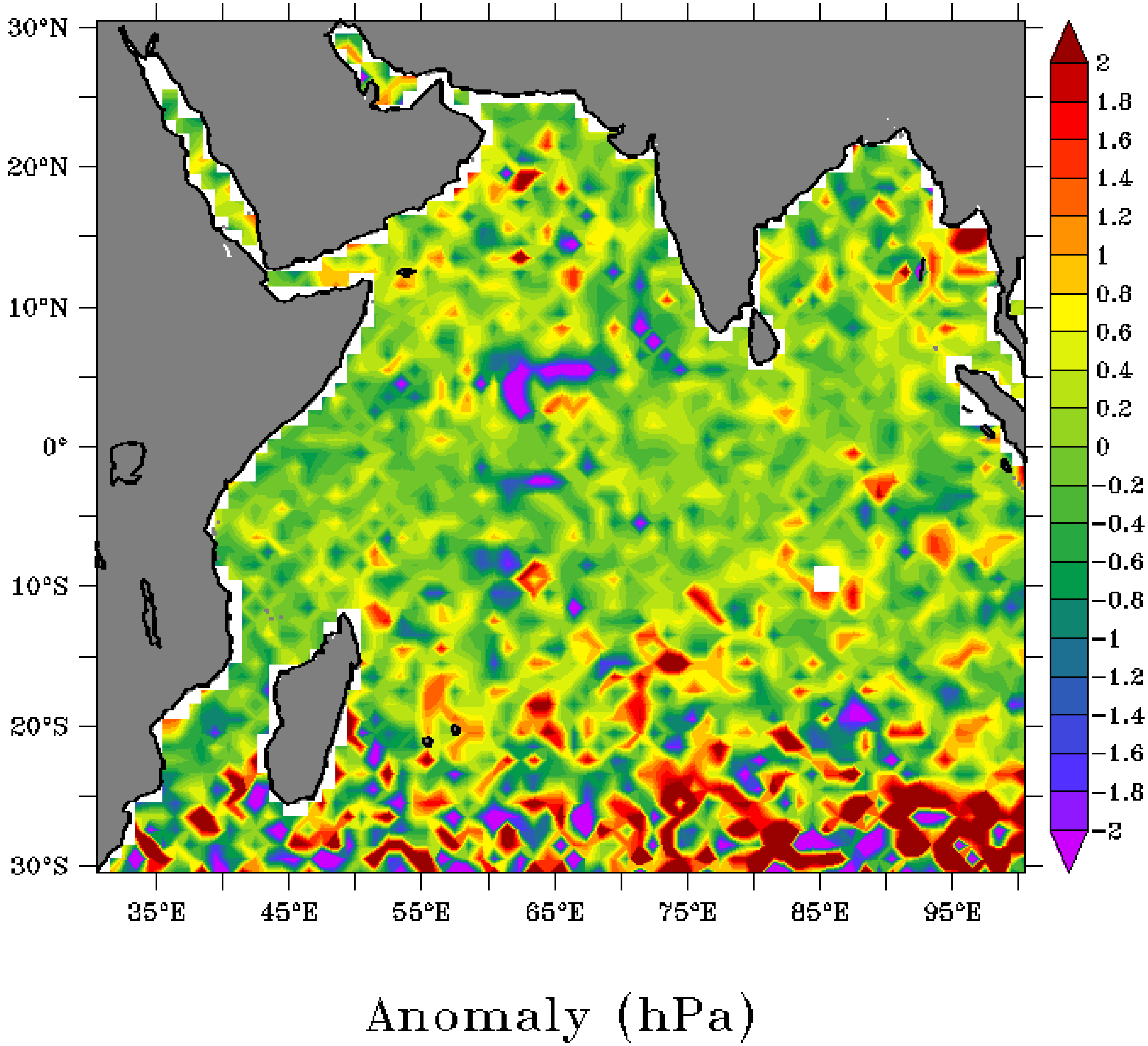
−1
−1.2
−1.4
−1.6
−1.8
−2

Anomaly (hPa)



Sea level pressure (hPa) JUNE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−1.4
−1.6
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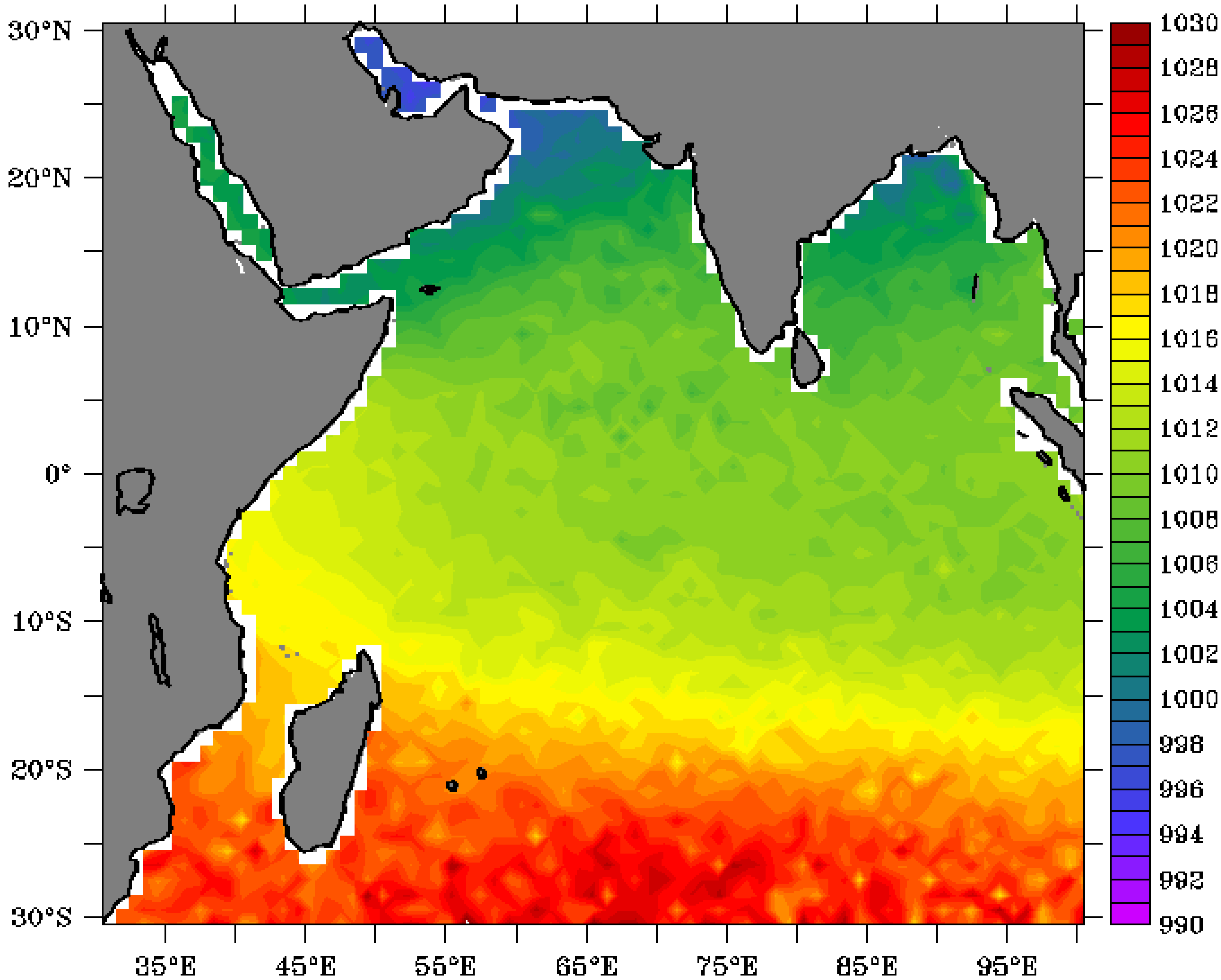
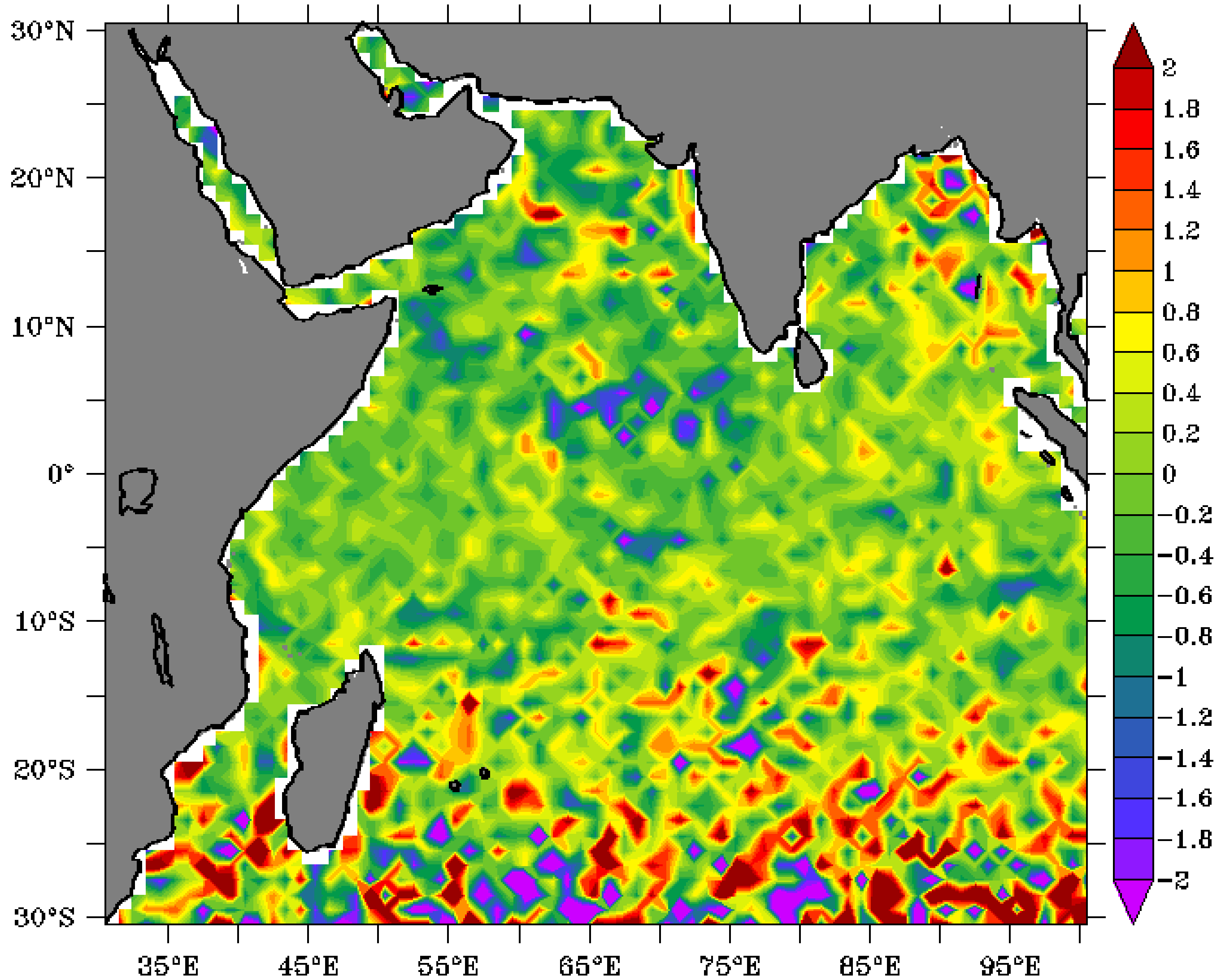
Anomaly (hPa)



Sea level pressure (hPa) JULY


30°N
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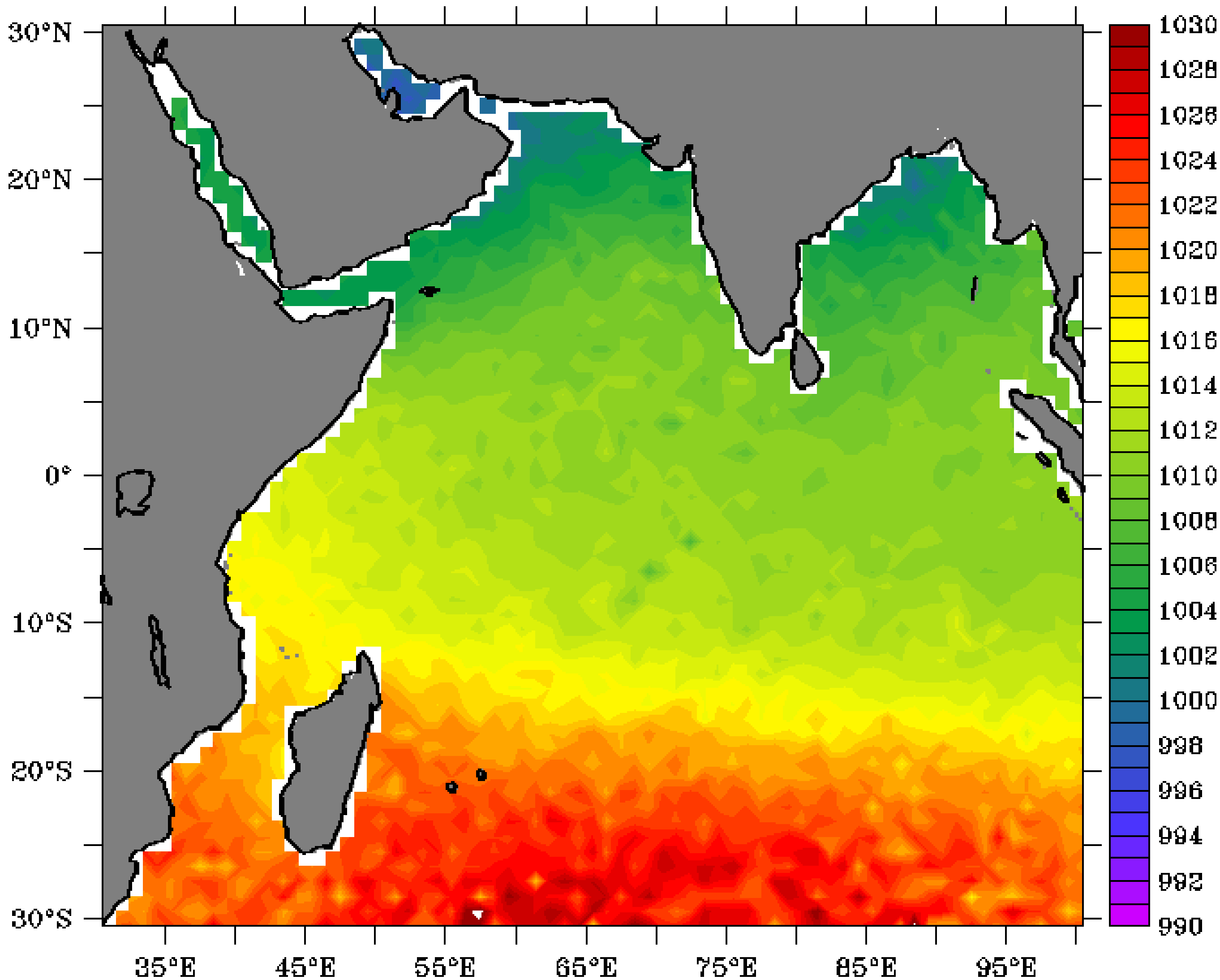
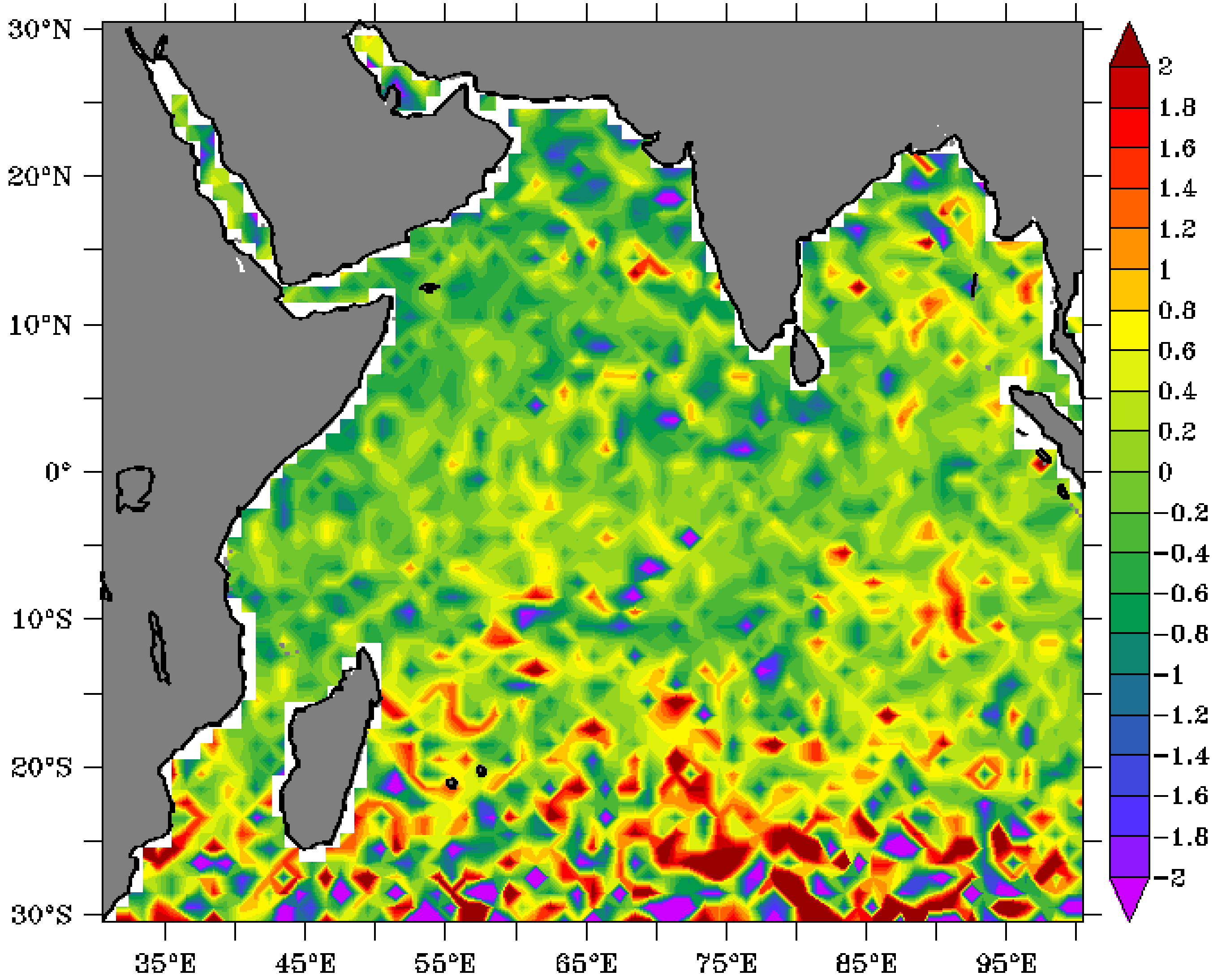
Anomaly (hPa)



Sea level pressure (hPa)   AUGUST



30°N
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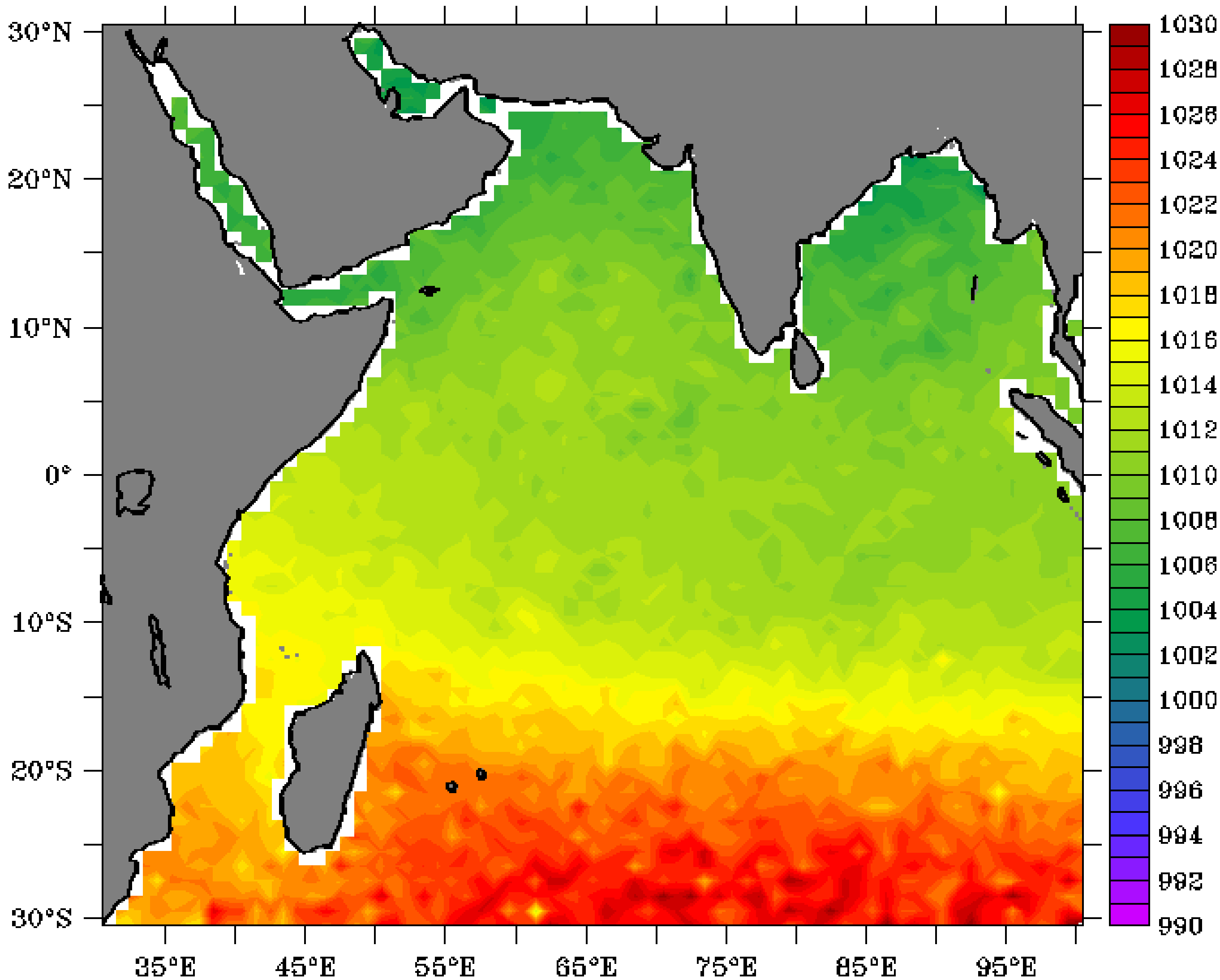
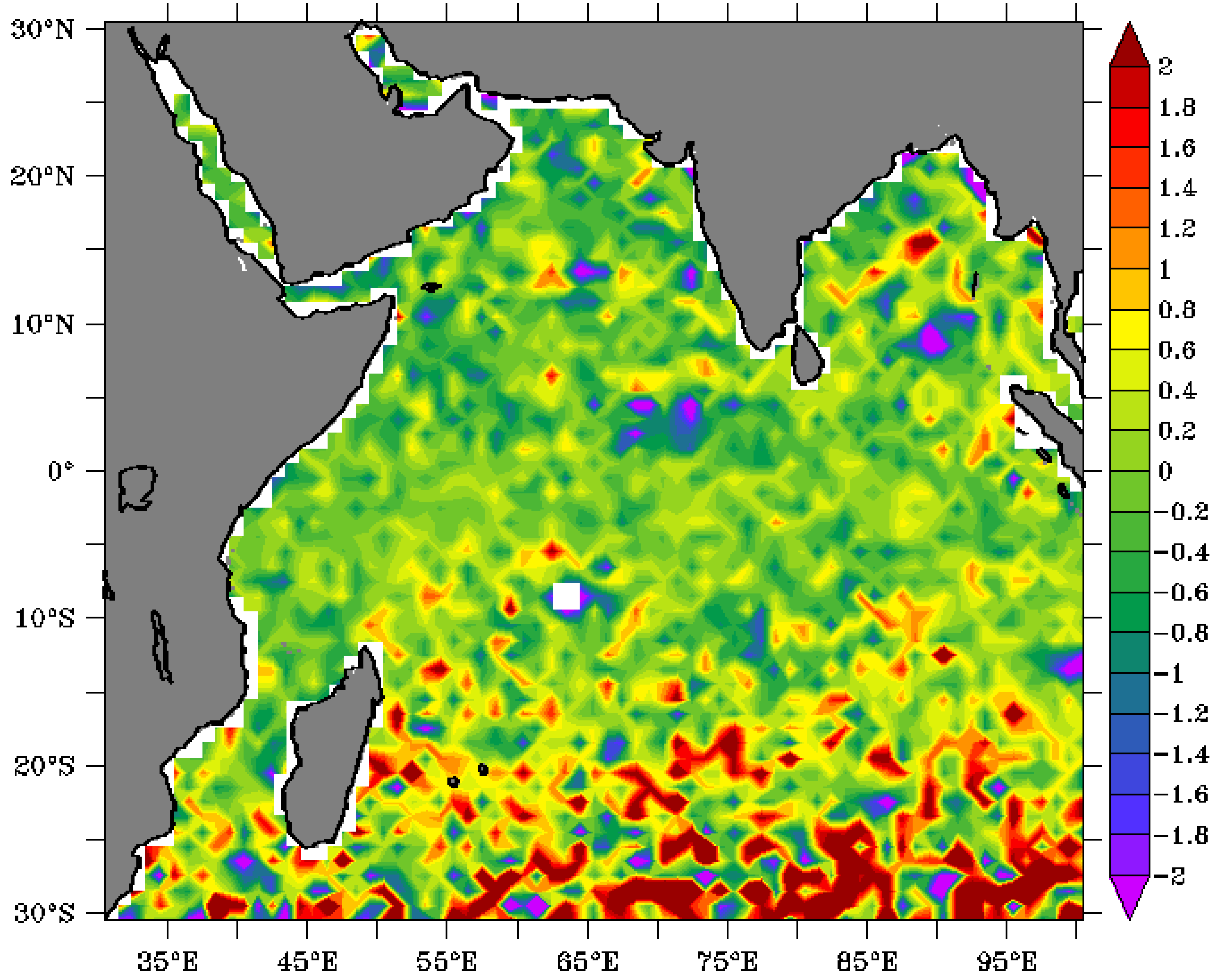
Anomaly (hPa)



Sea level pressure (hPa) SEPTEMBER


30°N
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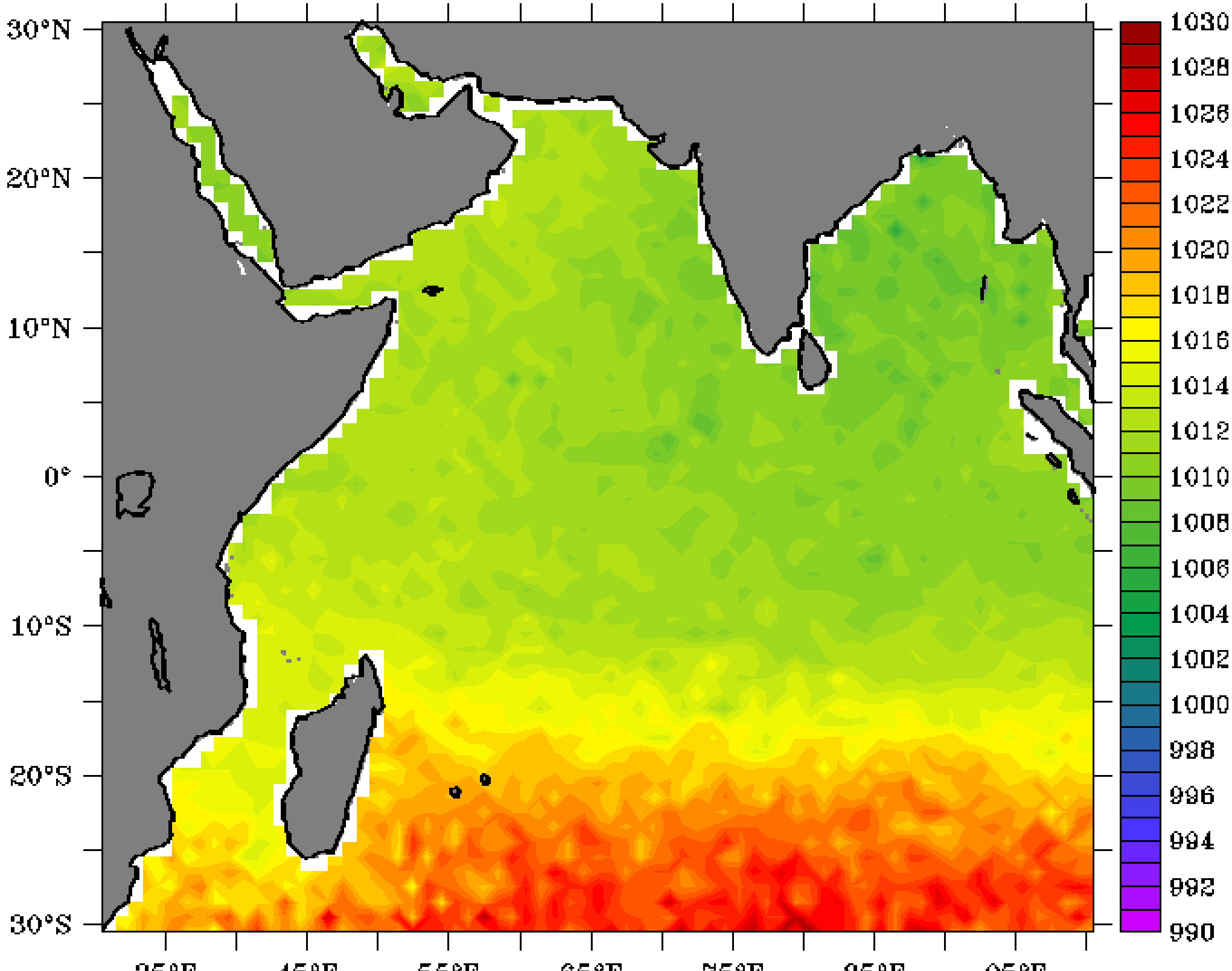
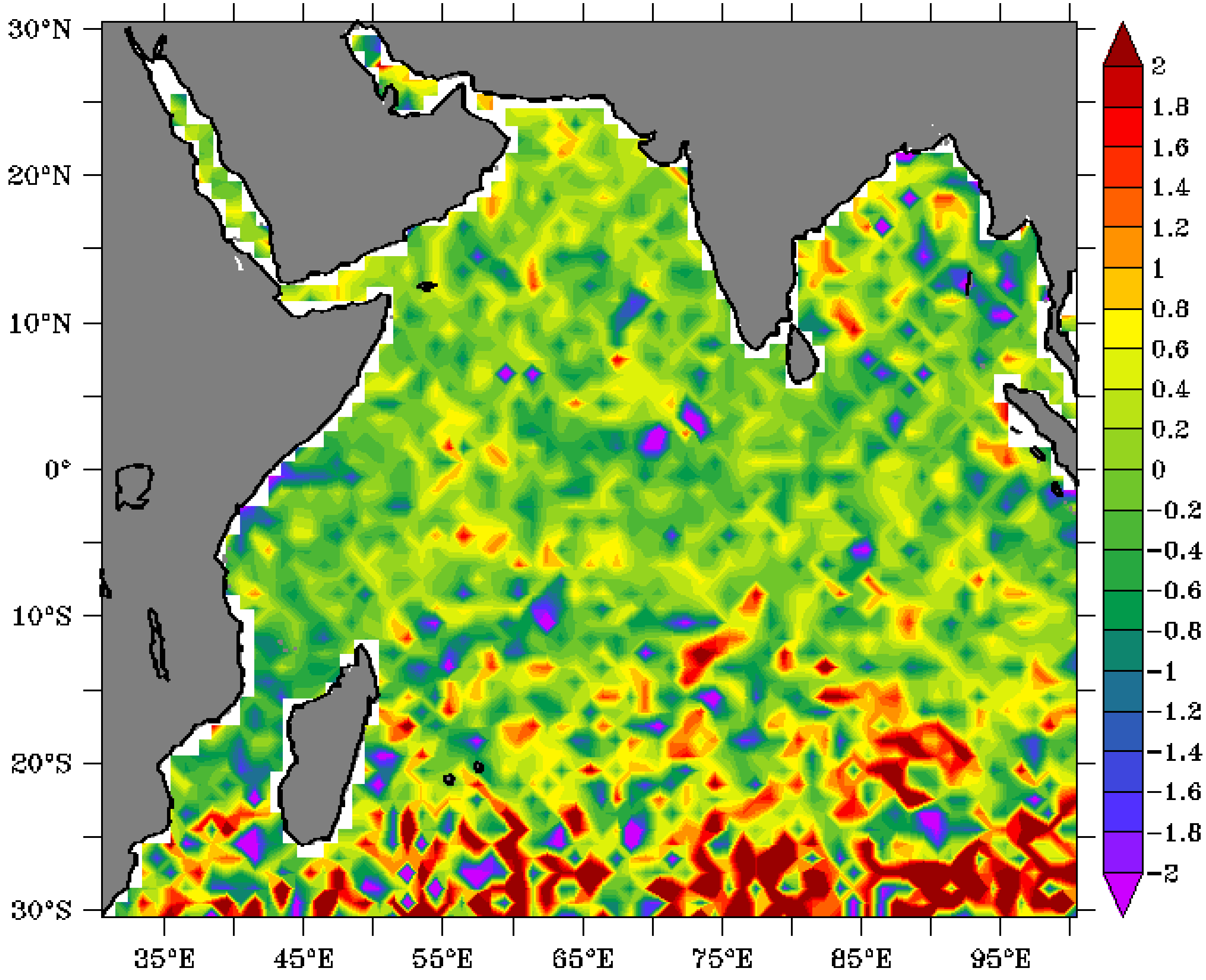
Anomaly (hPa)



Sea level pressure (hPa)   OCTOBER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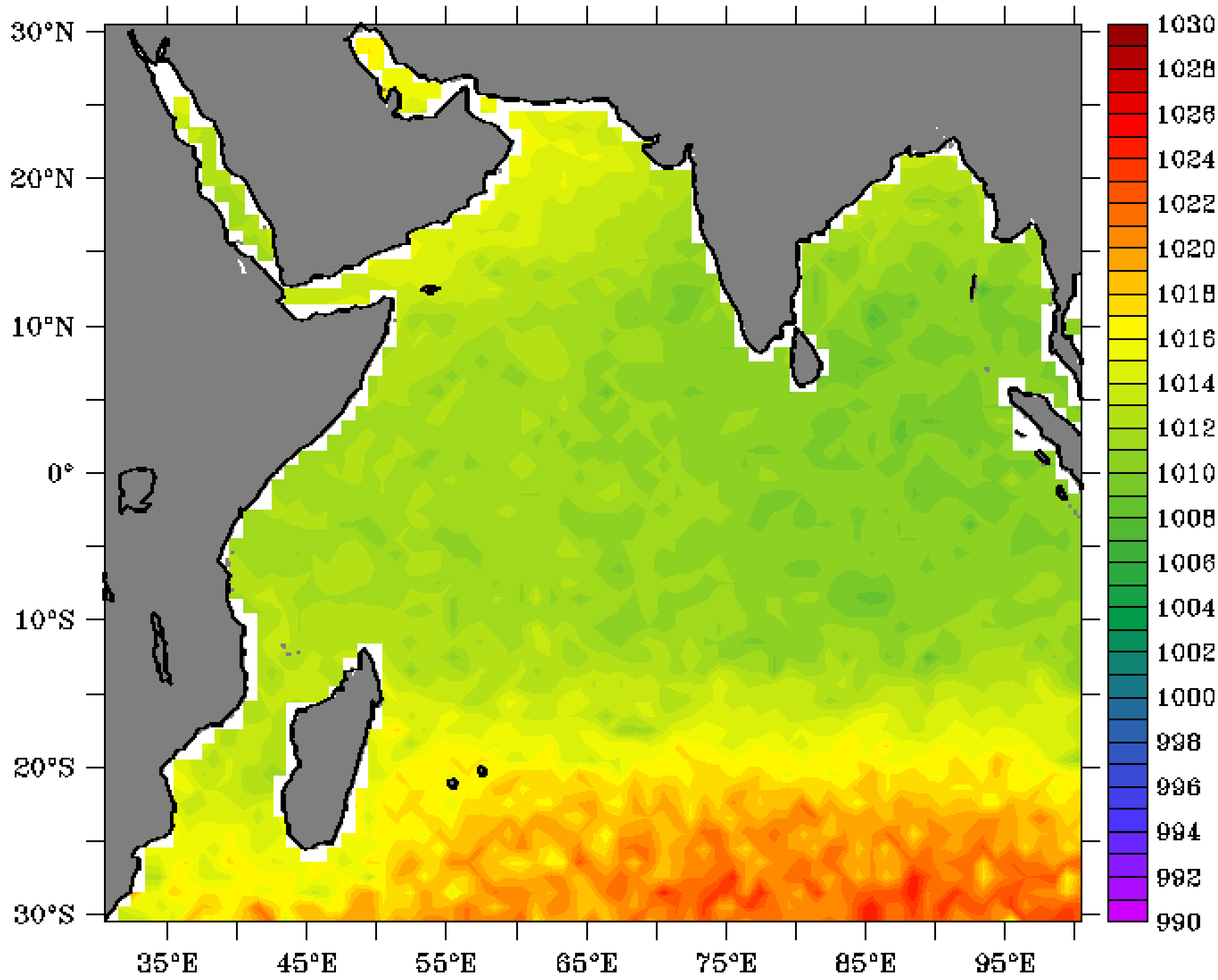
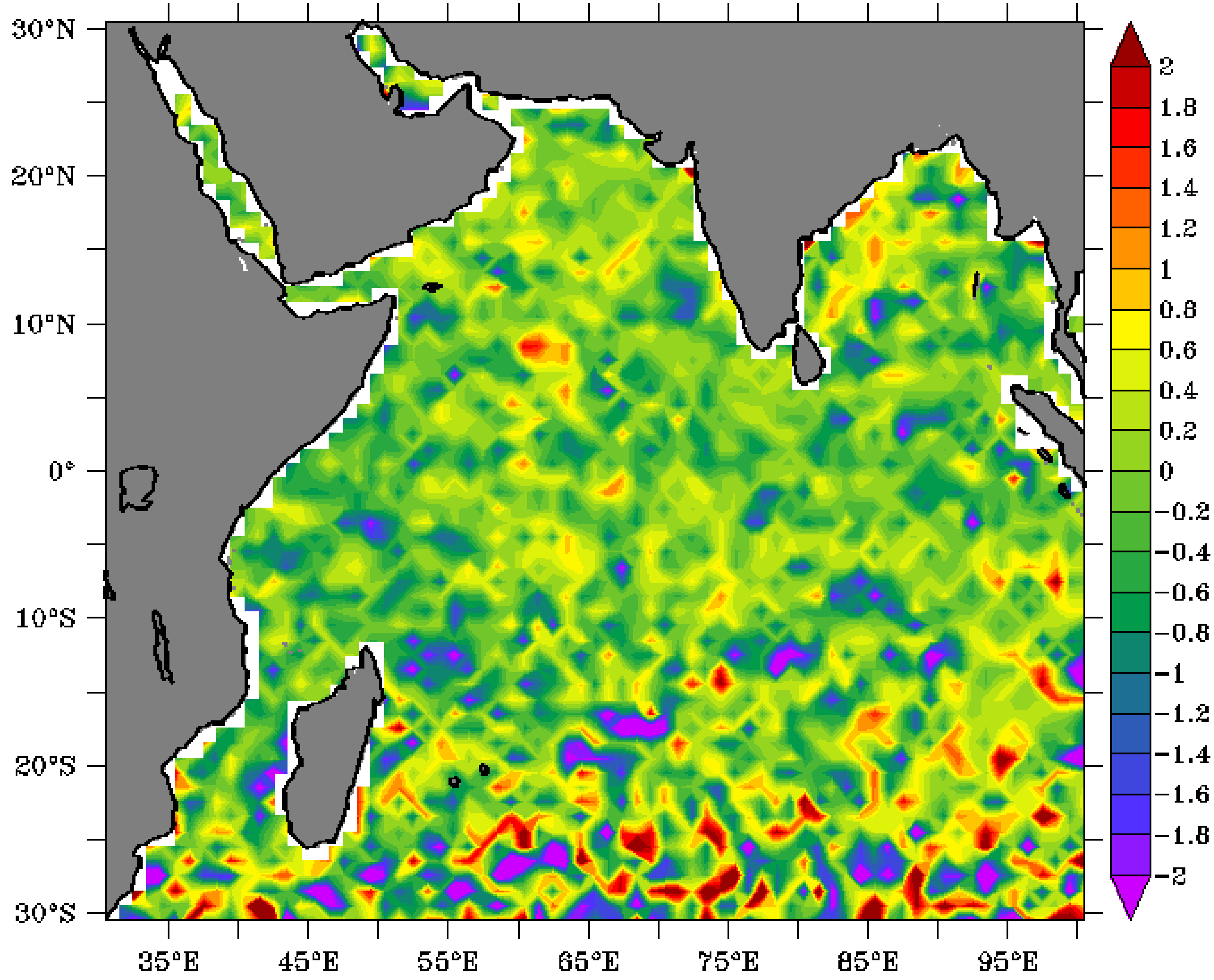
Anomaly (hPa)



Sea level pressure (hPa)   NOVEMBER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-1.4
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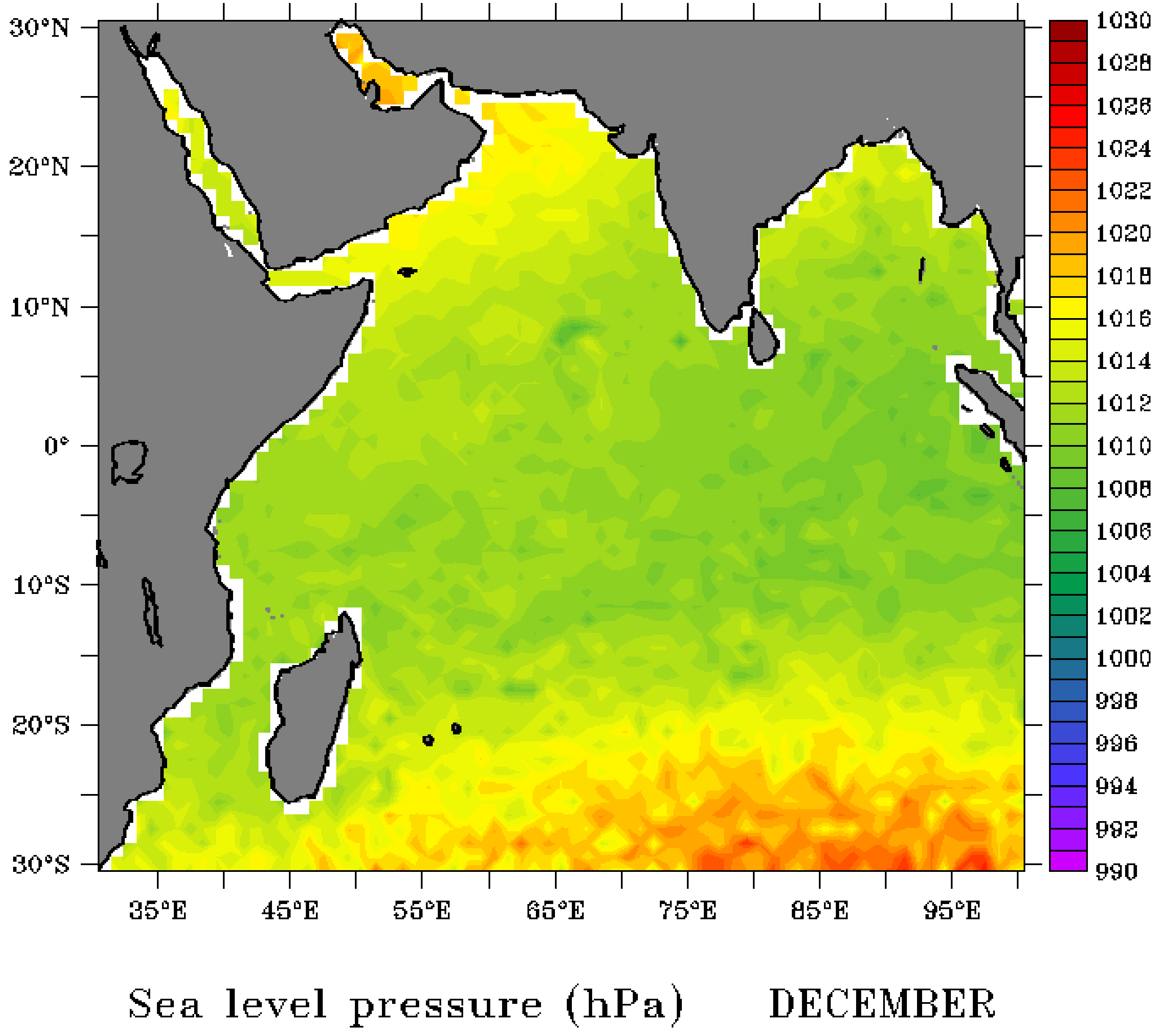
Anomaly (hPa)


30°N
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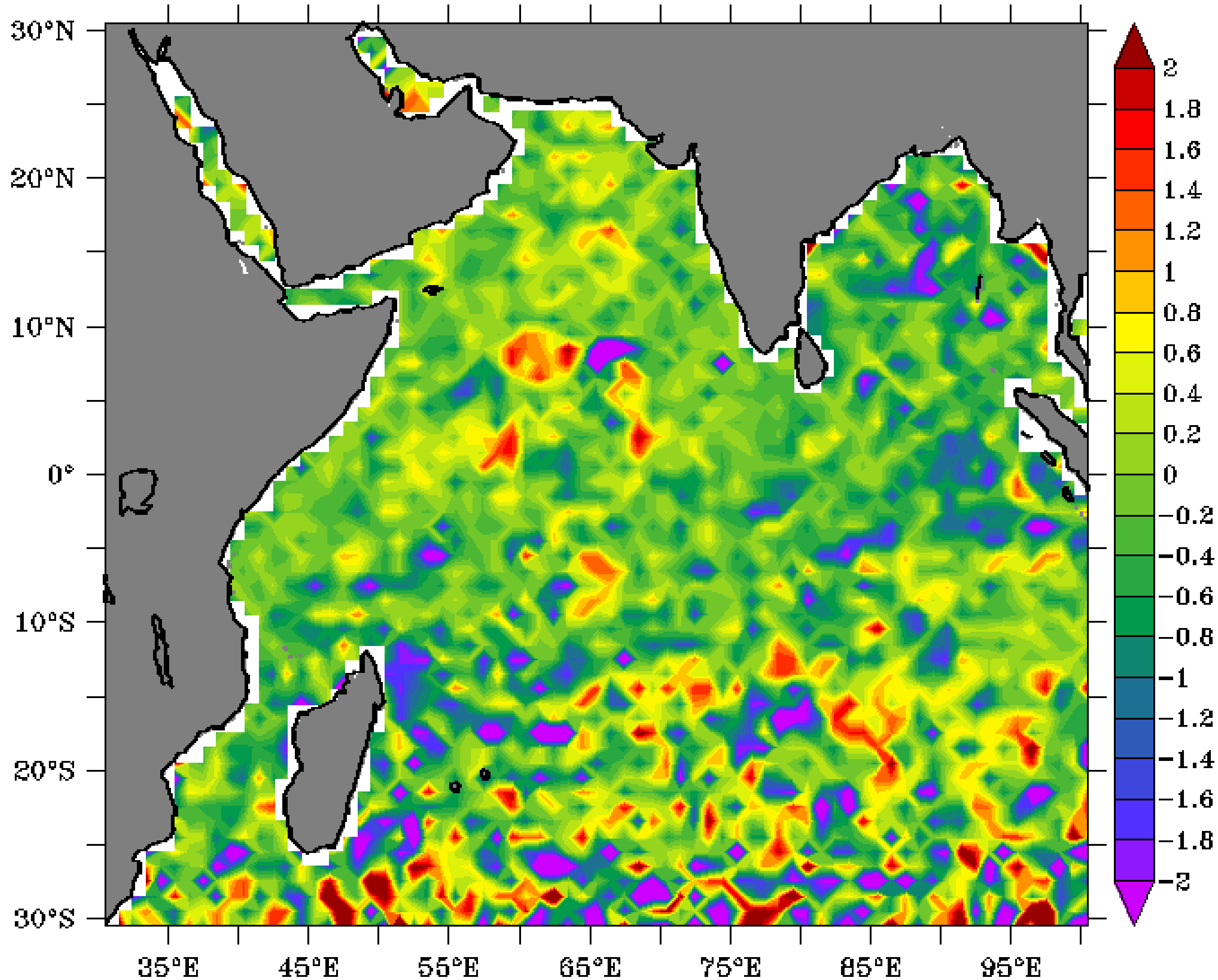
1030
1028
1026
1024
1022
1020
1018
1016
1014
1012
1010
1008
1006
1004
1002
1000
998
996
994
992
990
Sea level pressure (hPa) DECEMBER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−1.2
−1.4
−1.6
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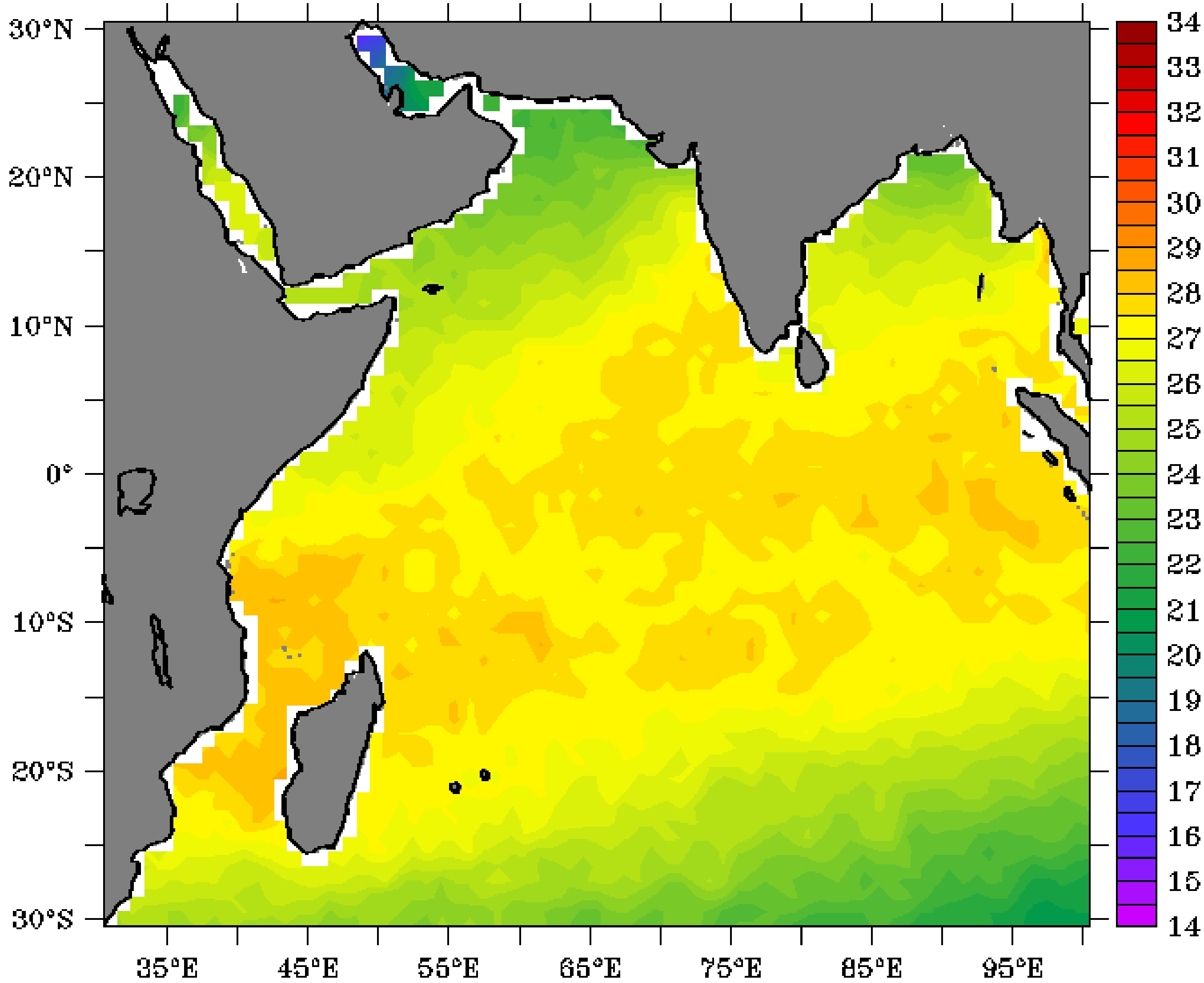
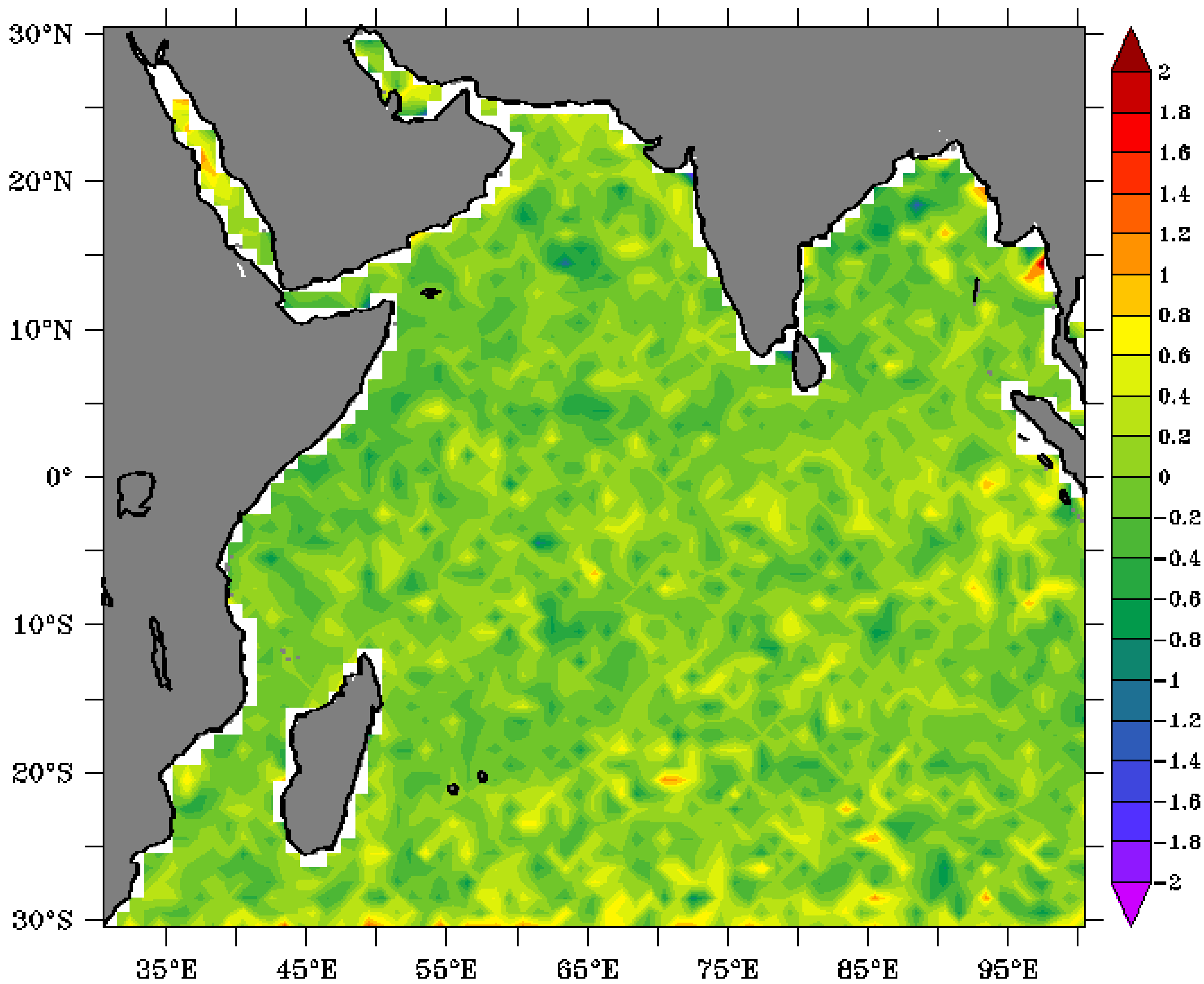
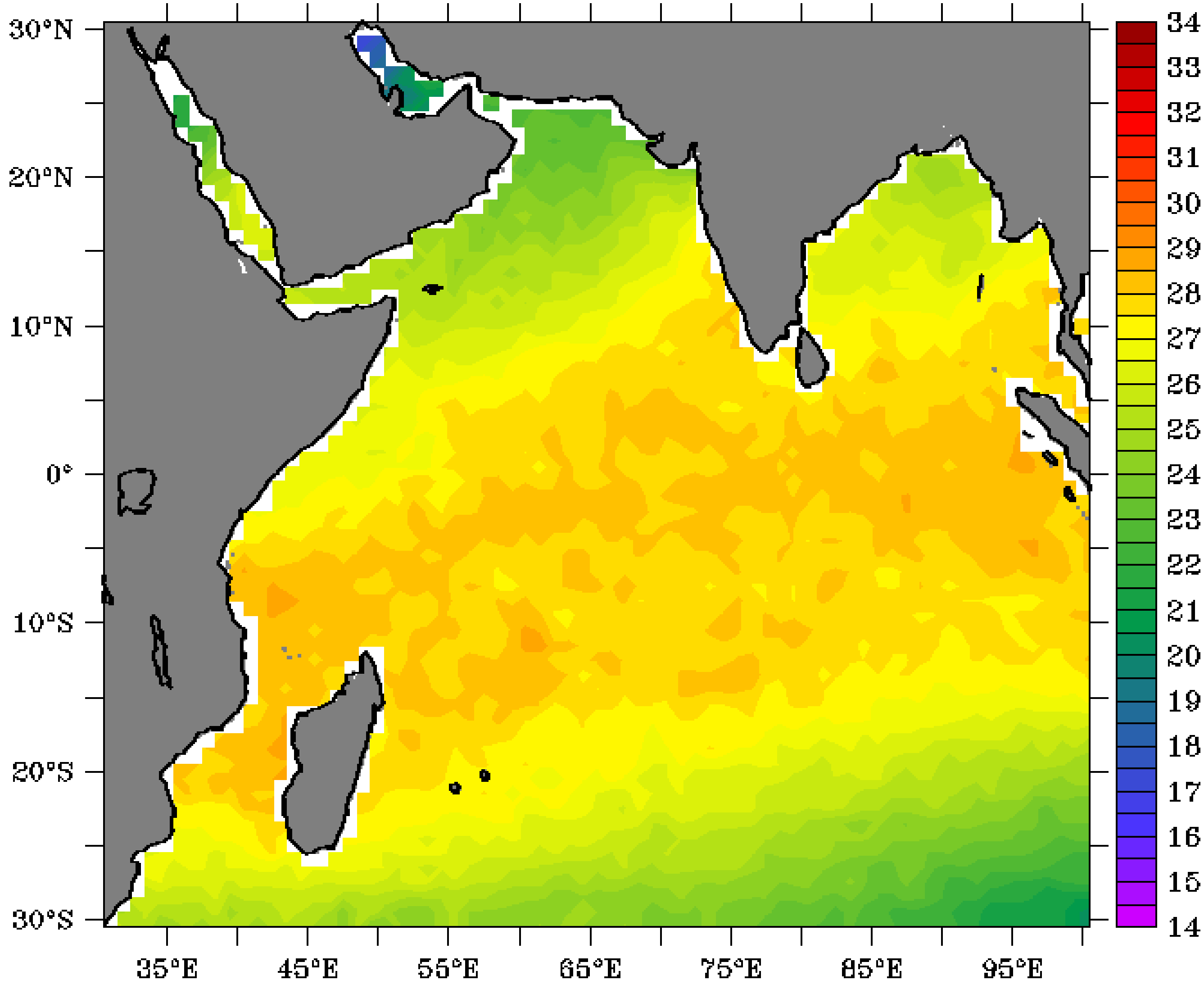
Anomaly (hPa)



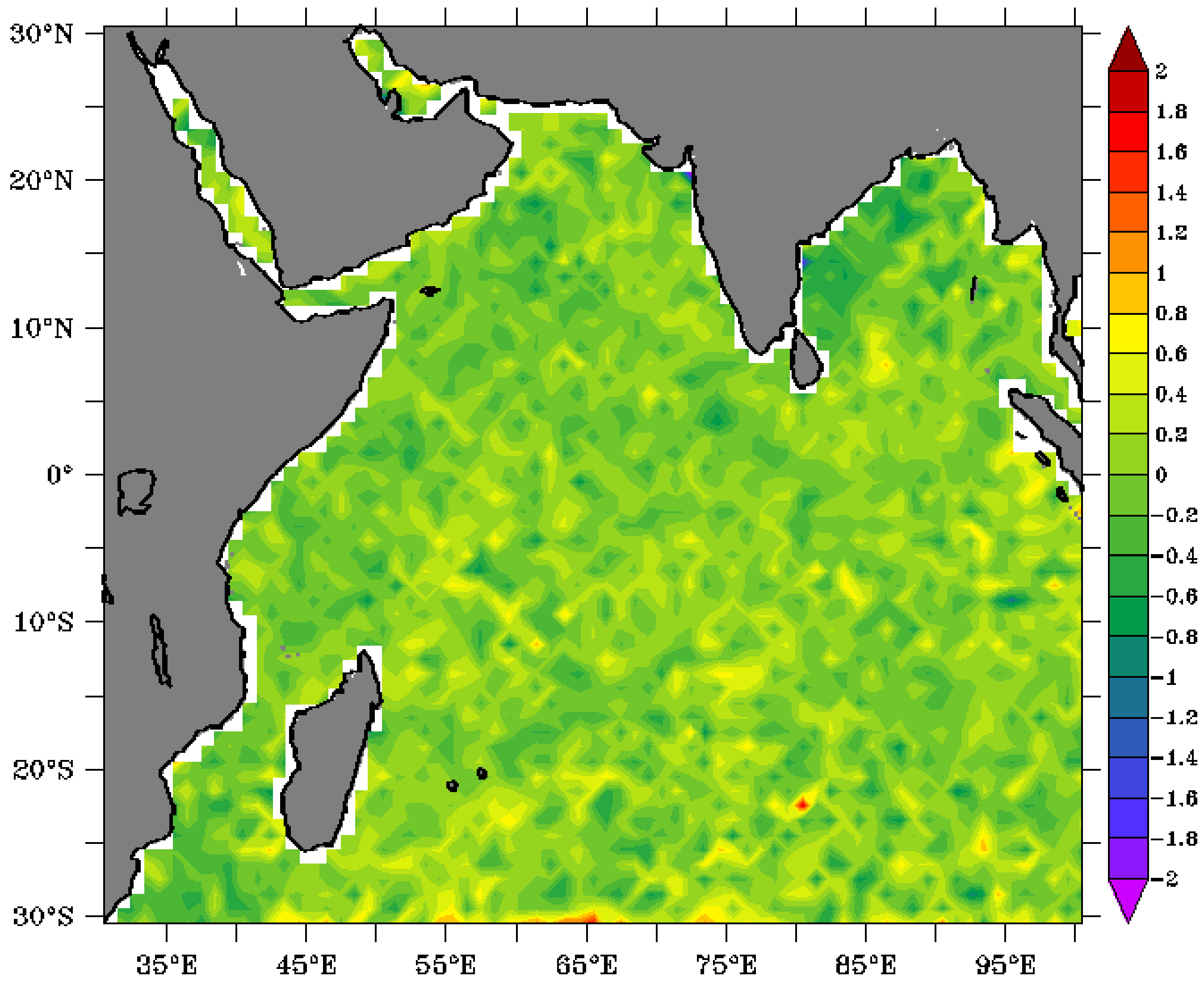
Air temperature (deg Celsius) JANUARY



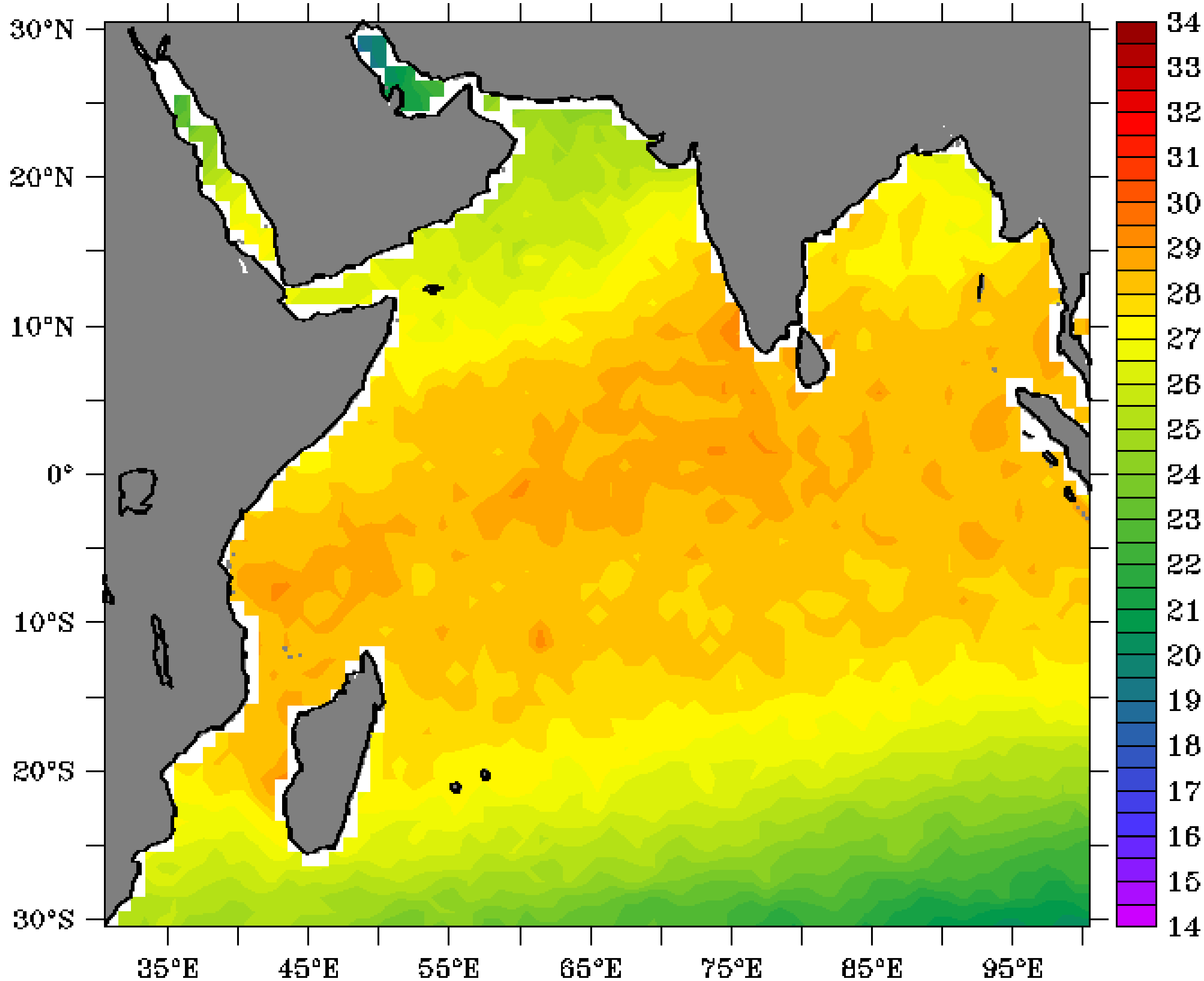
Anomaly (deg Celsius)



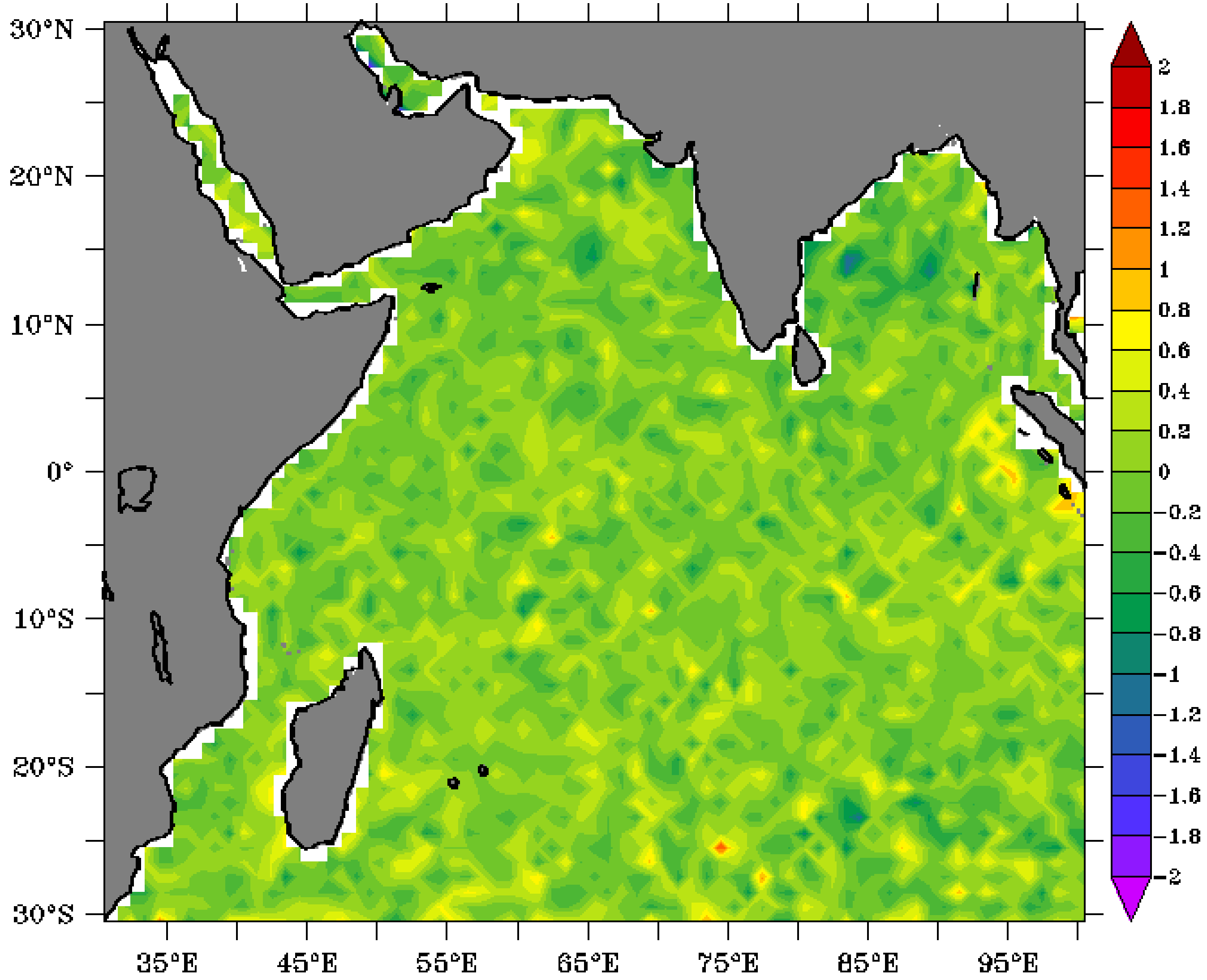
Air Temperature (deg Celsius) FEBRUARY



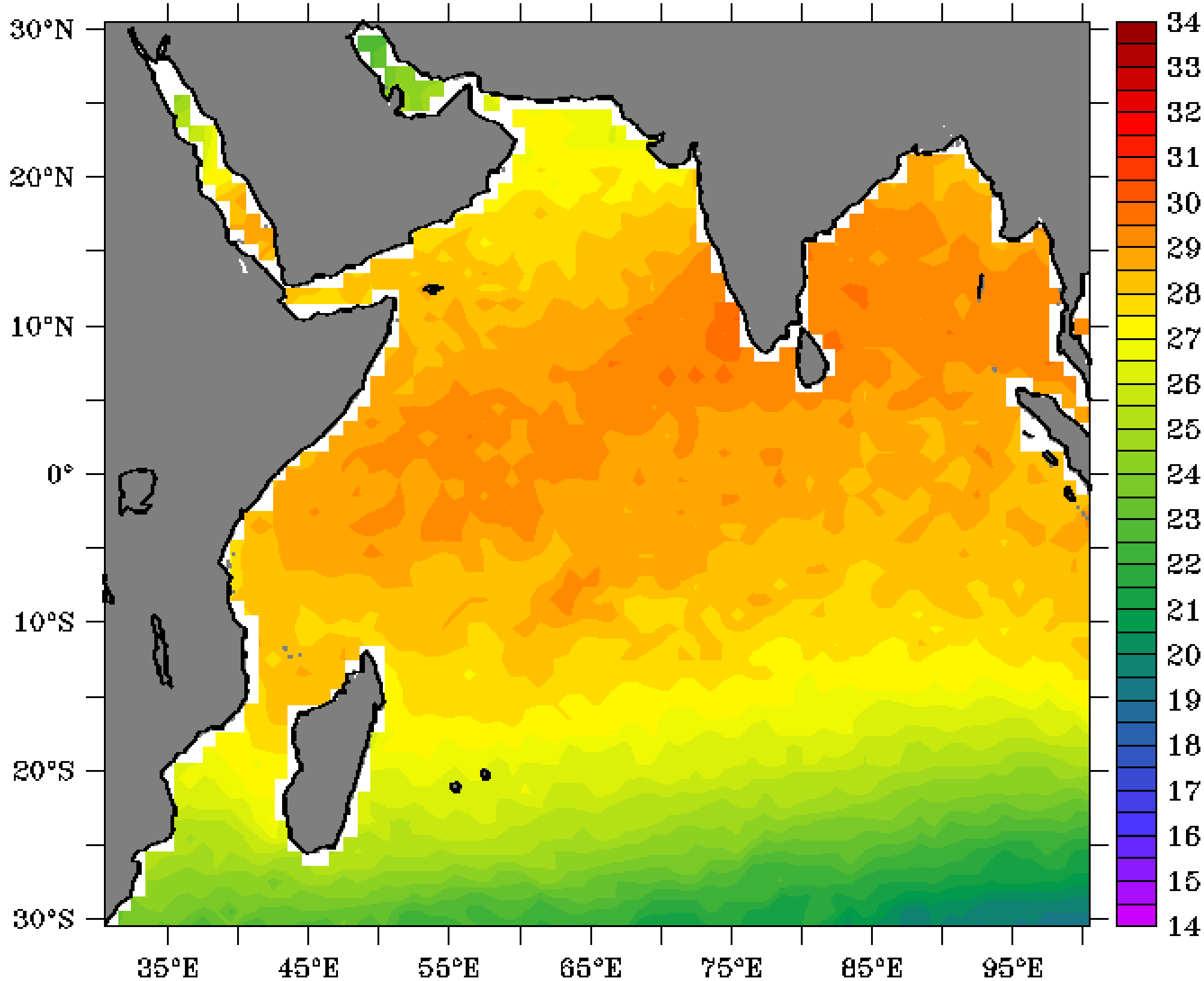
Anomaly (deg Celsius)



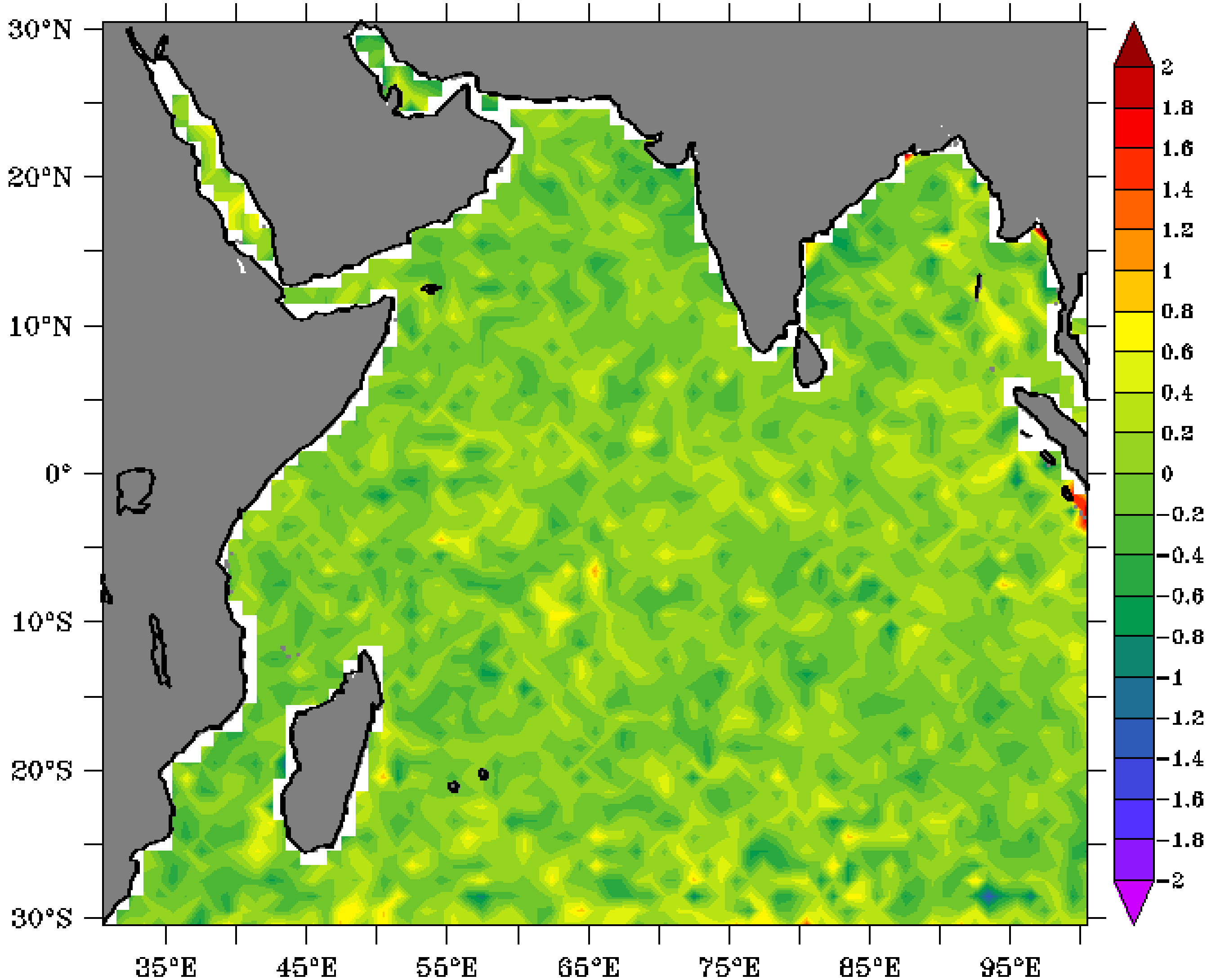
Air Temperature (deg Celsius) MARCH



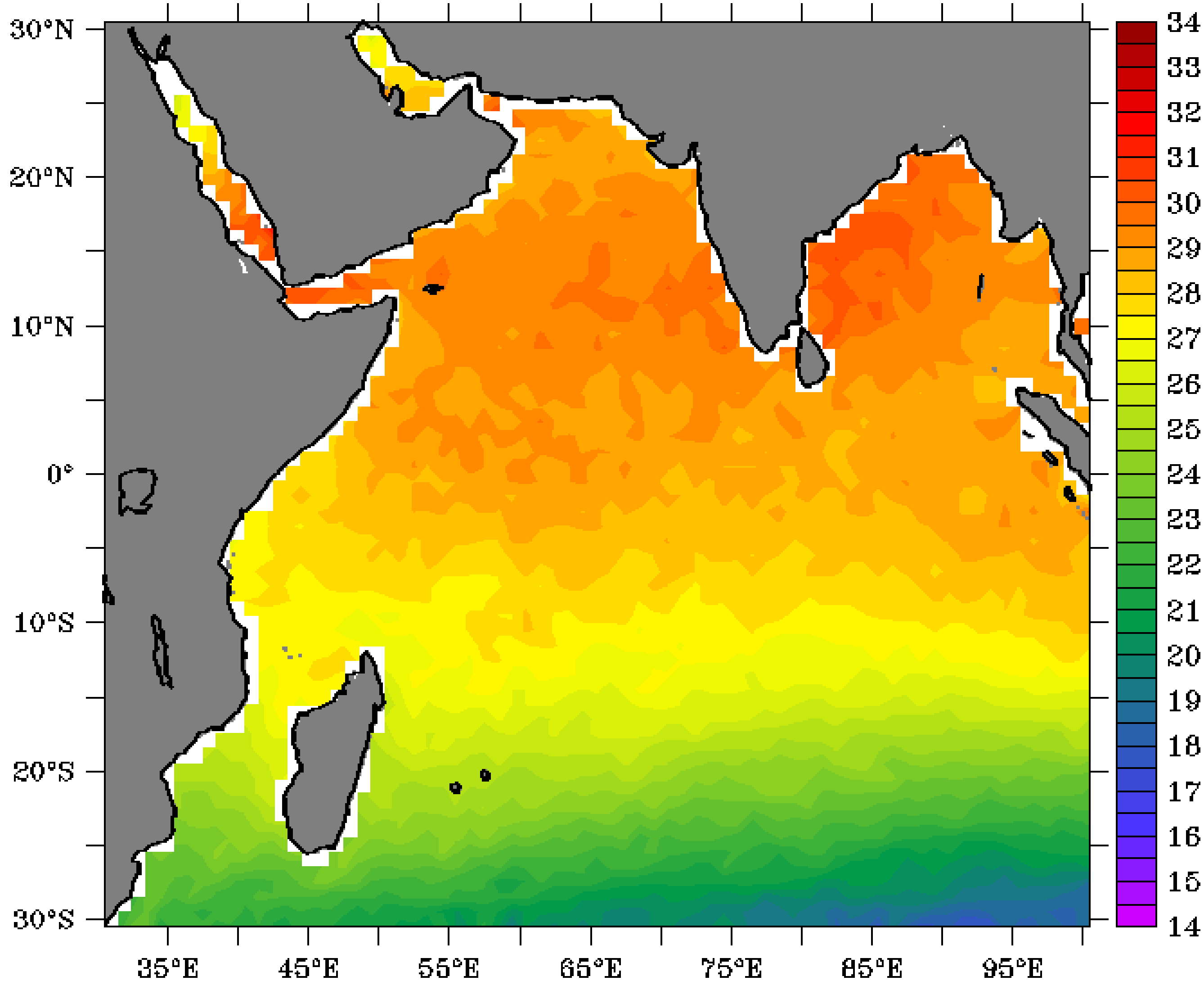
Anomaly (deg Celsius)



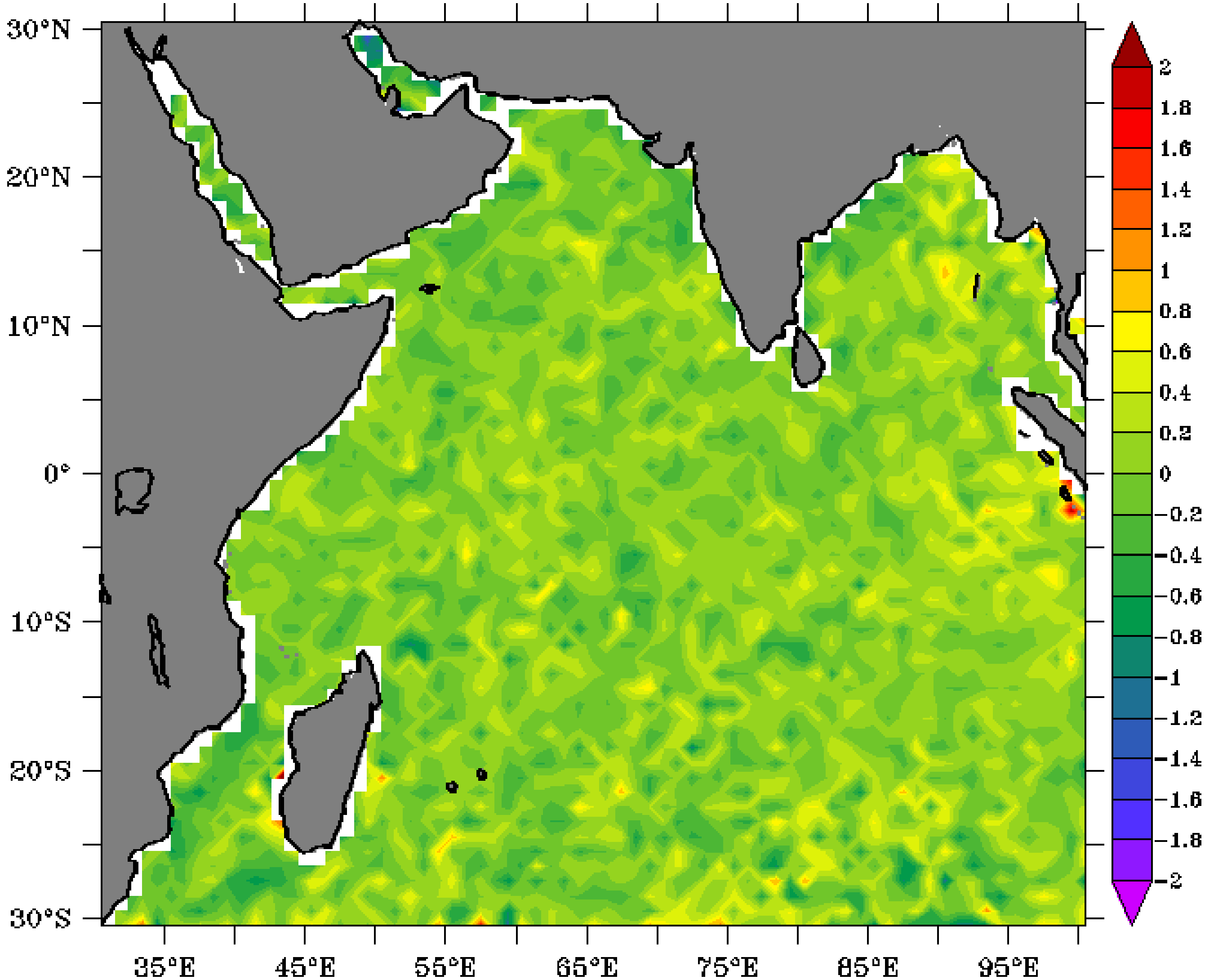
Air Temperature (deg Celsius) APRIL



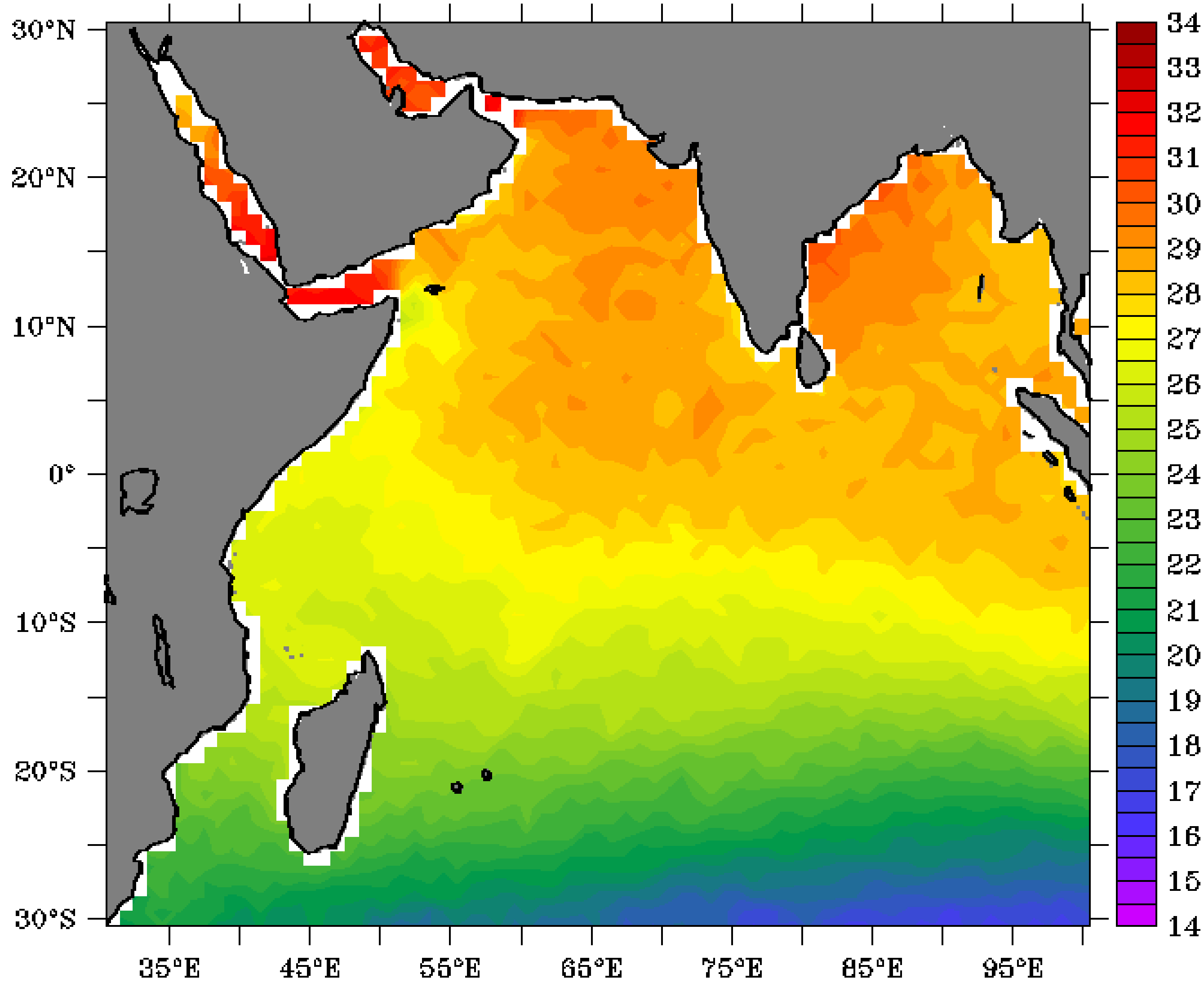
Anomaly (deg Celsius)



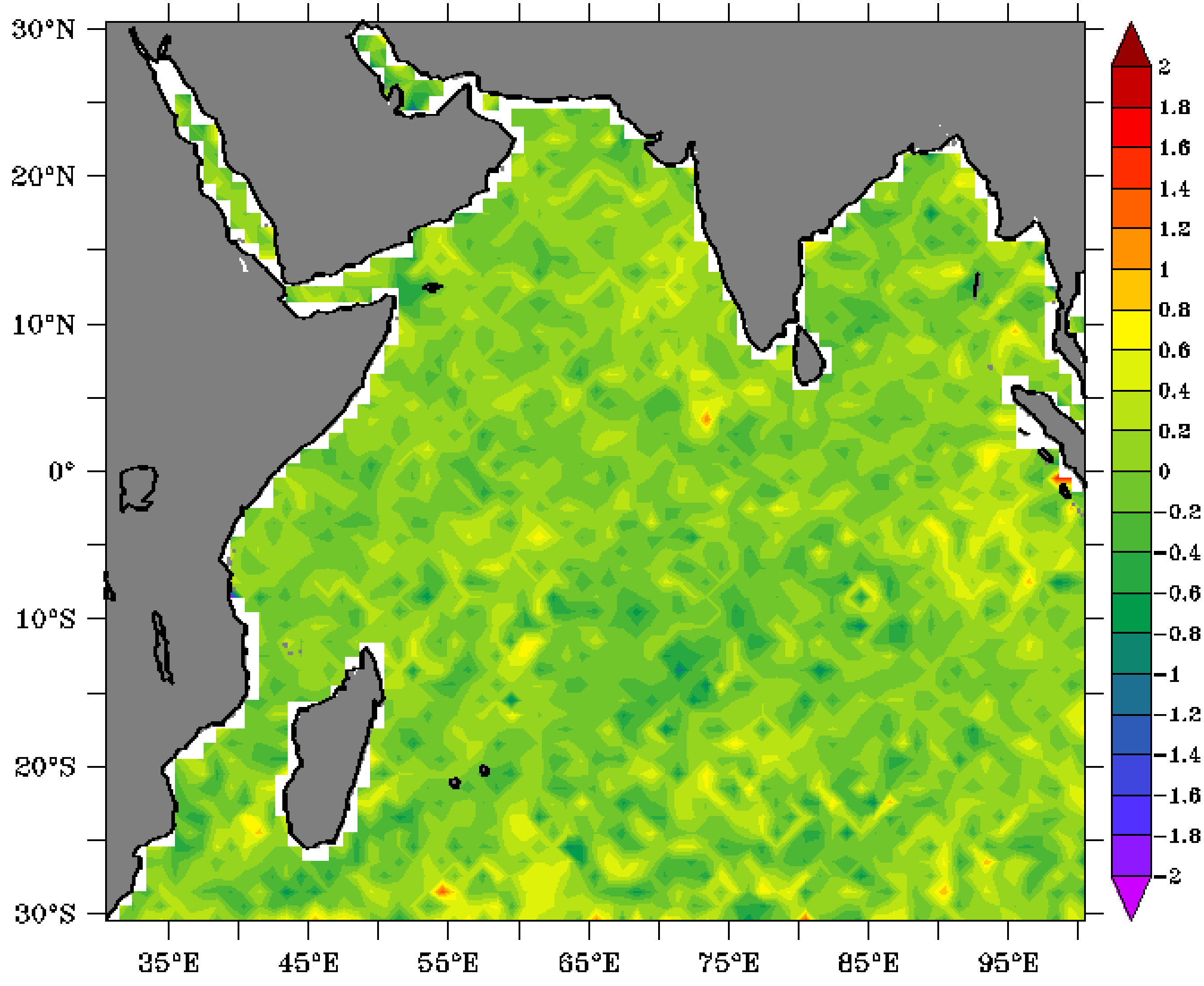
Air Temperature (deg Celsius) MAY



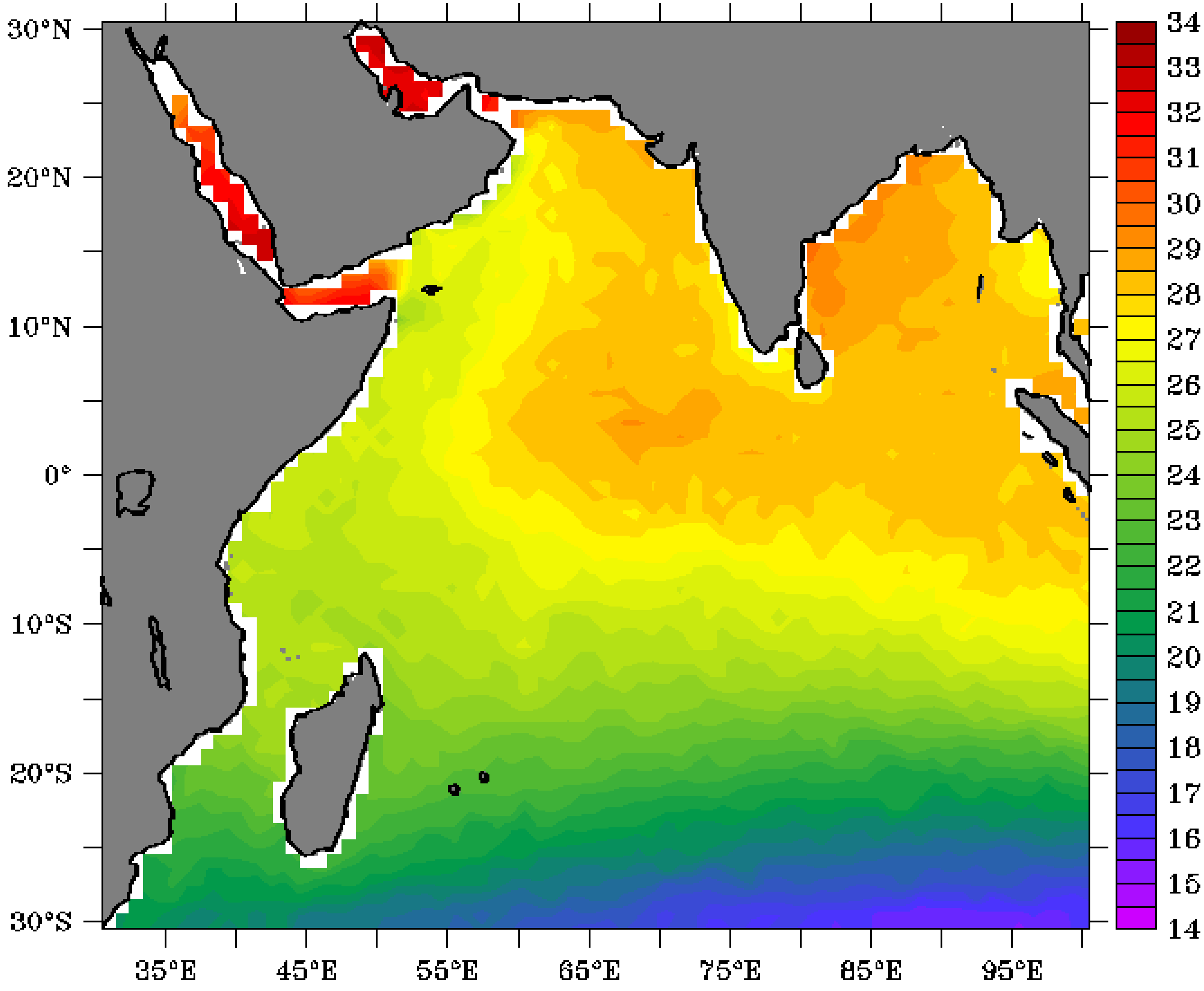
Anomaly (deg Celsius)



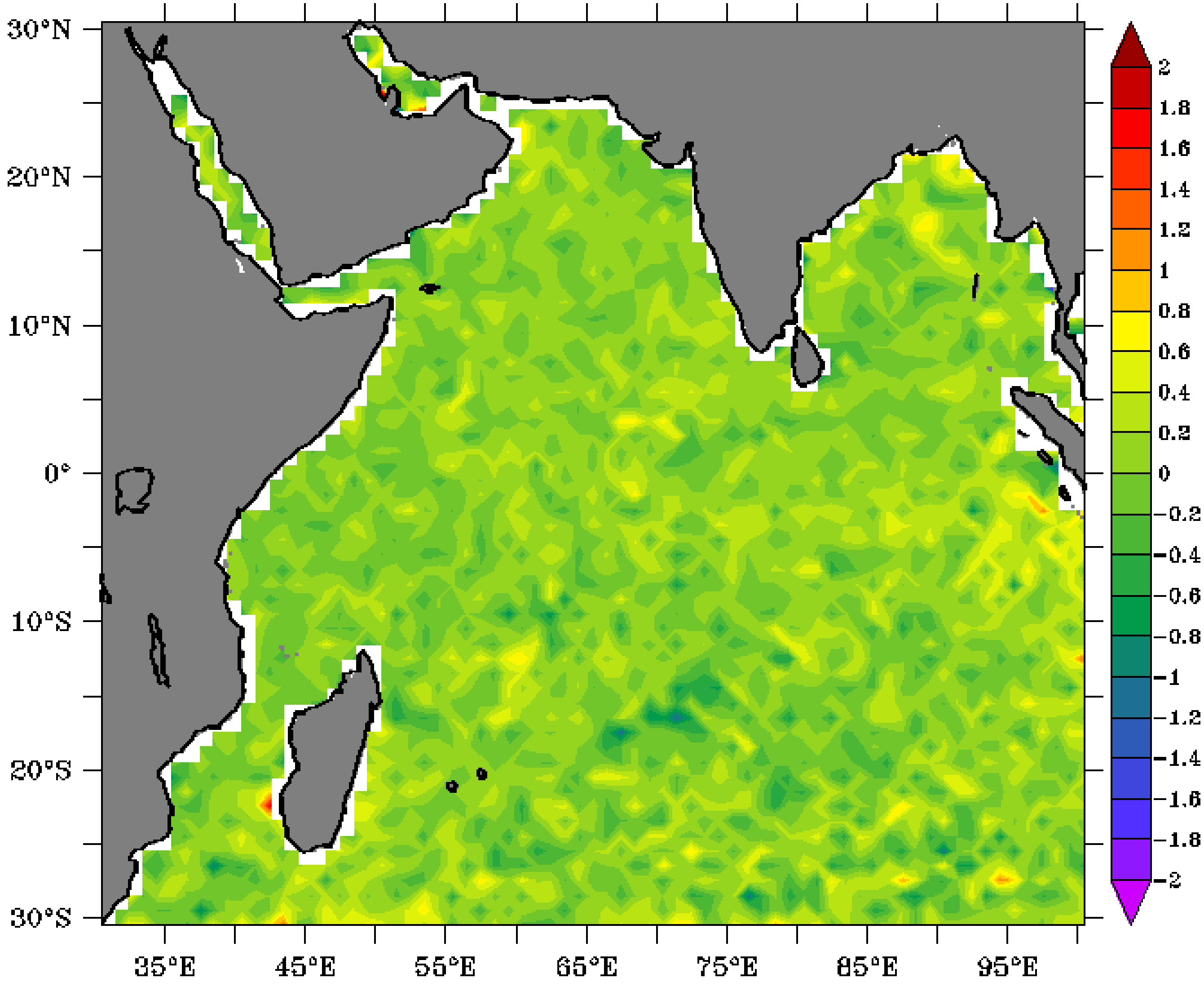
Air Temperature (deg Celsius) JUNE



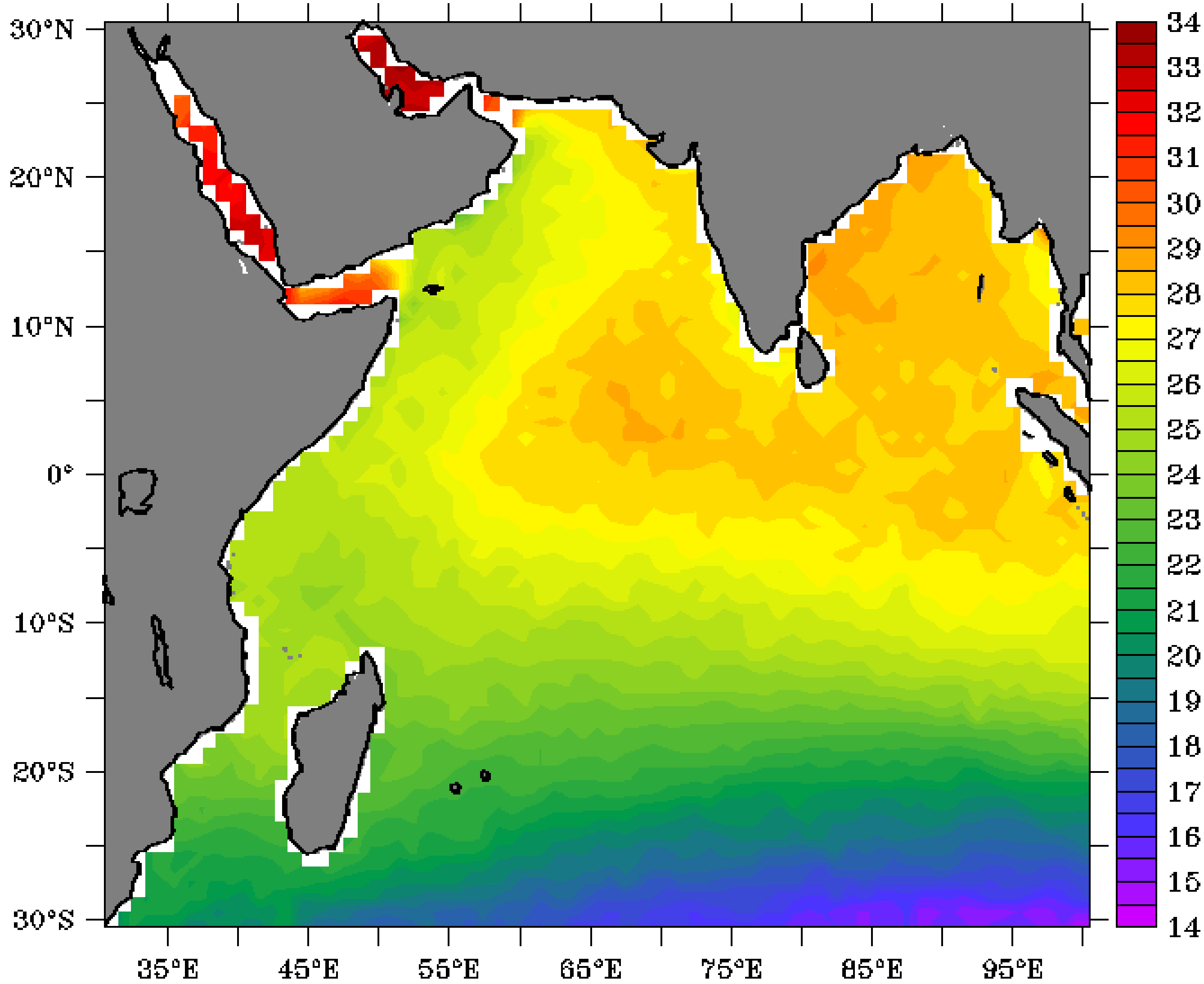
Anomaly (deg Celsius)



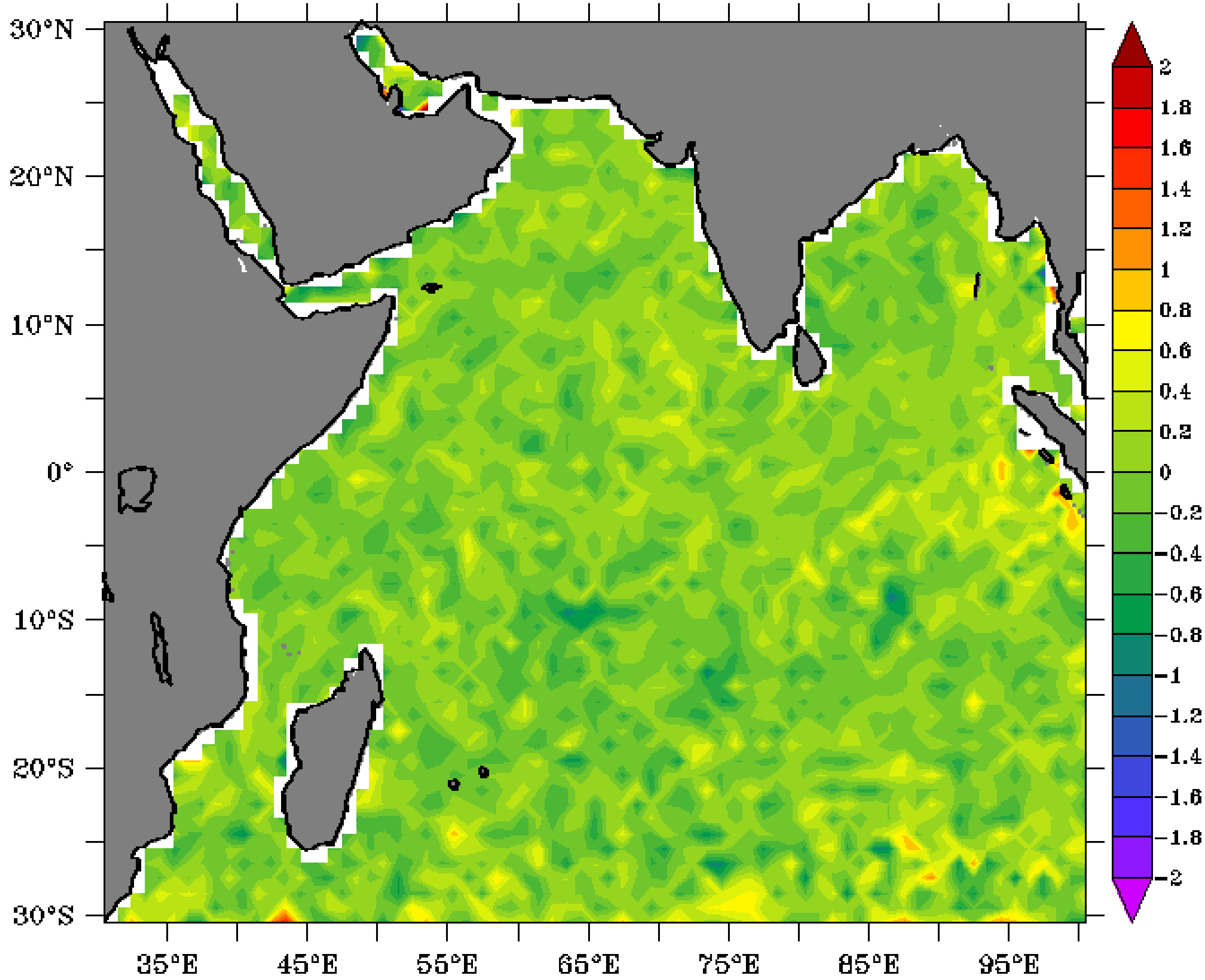
Air Temperature (deg Celsius) JULY



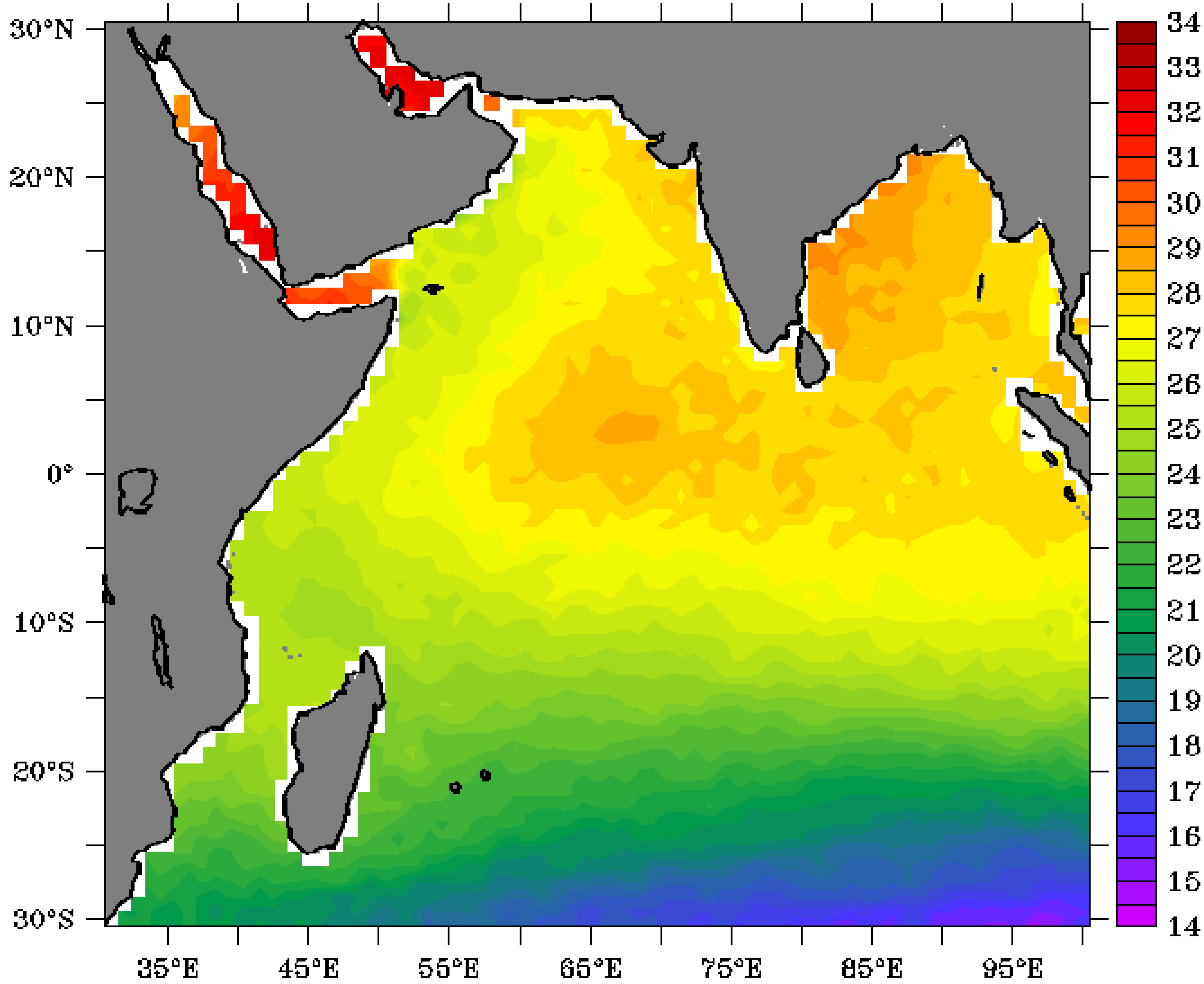
Anomaly (deg Celsius)



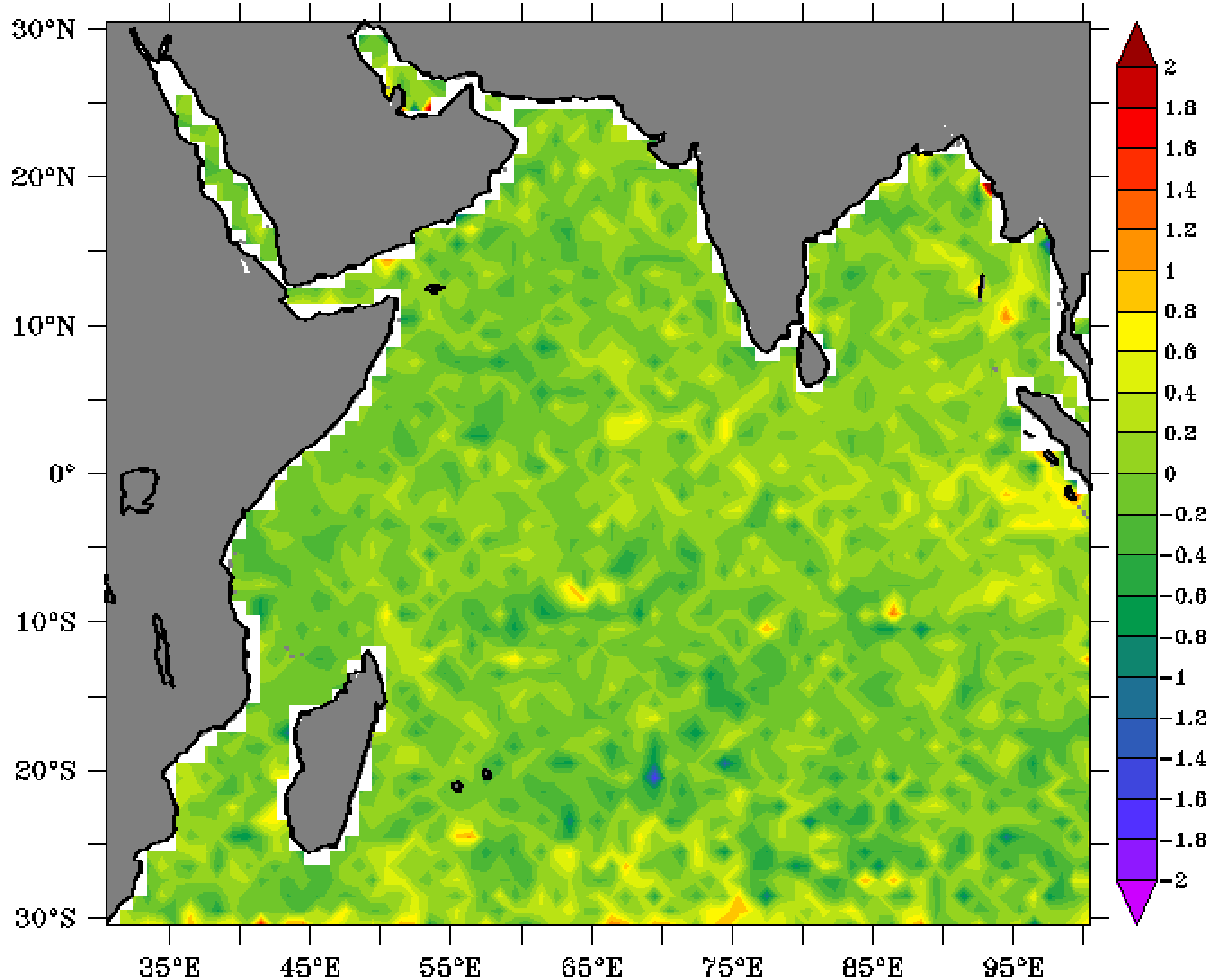
Air Temperature (deg Celsius) AUGUST



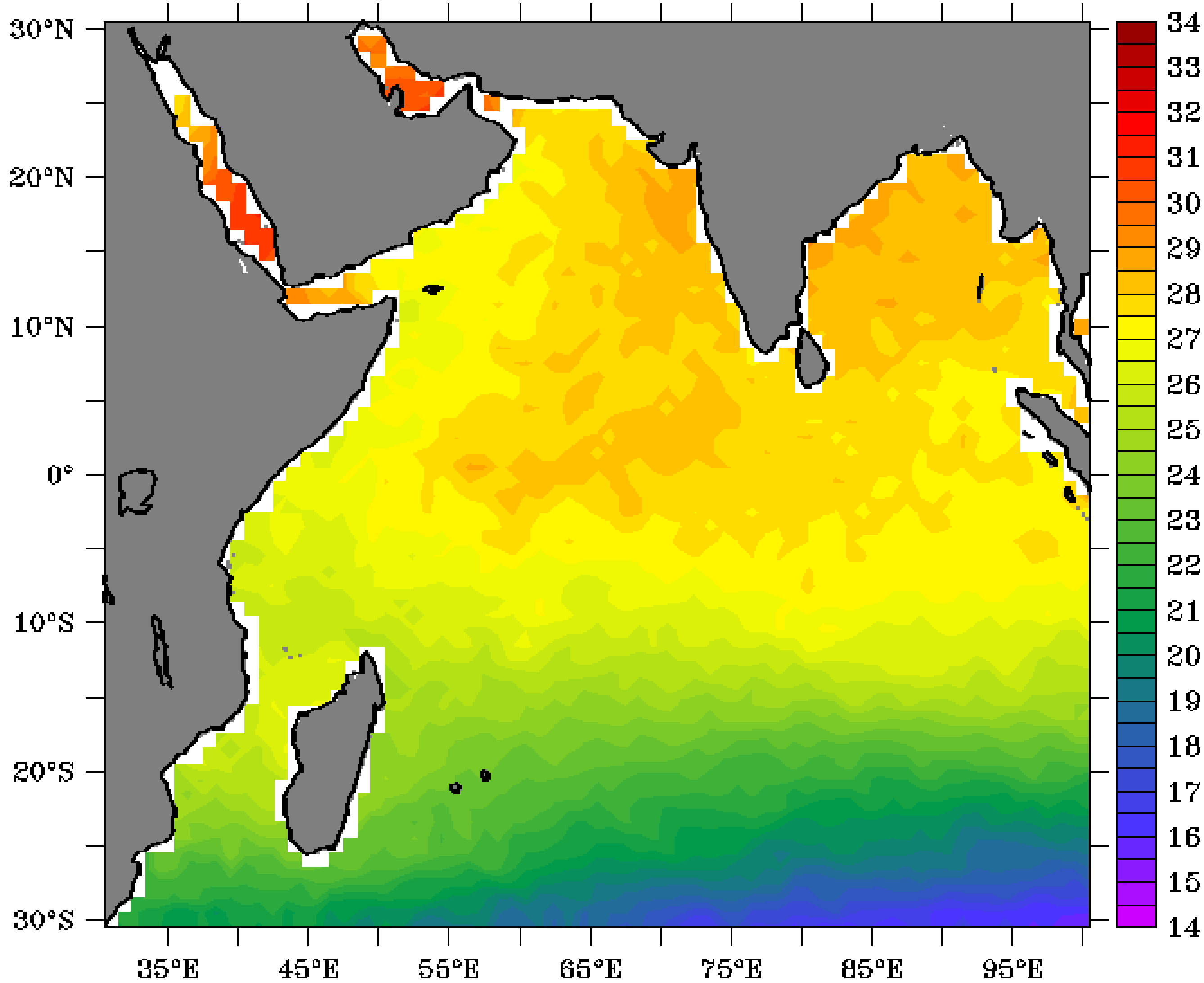
Anomaly (deg Celsius)



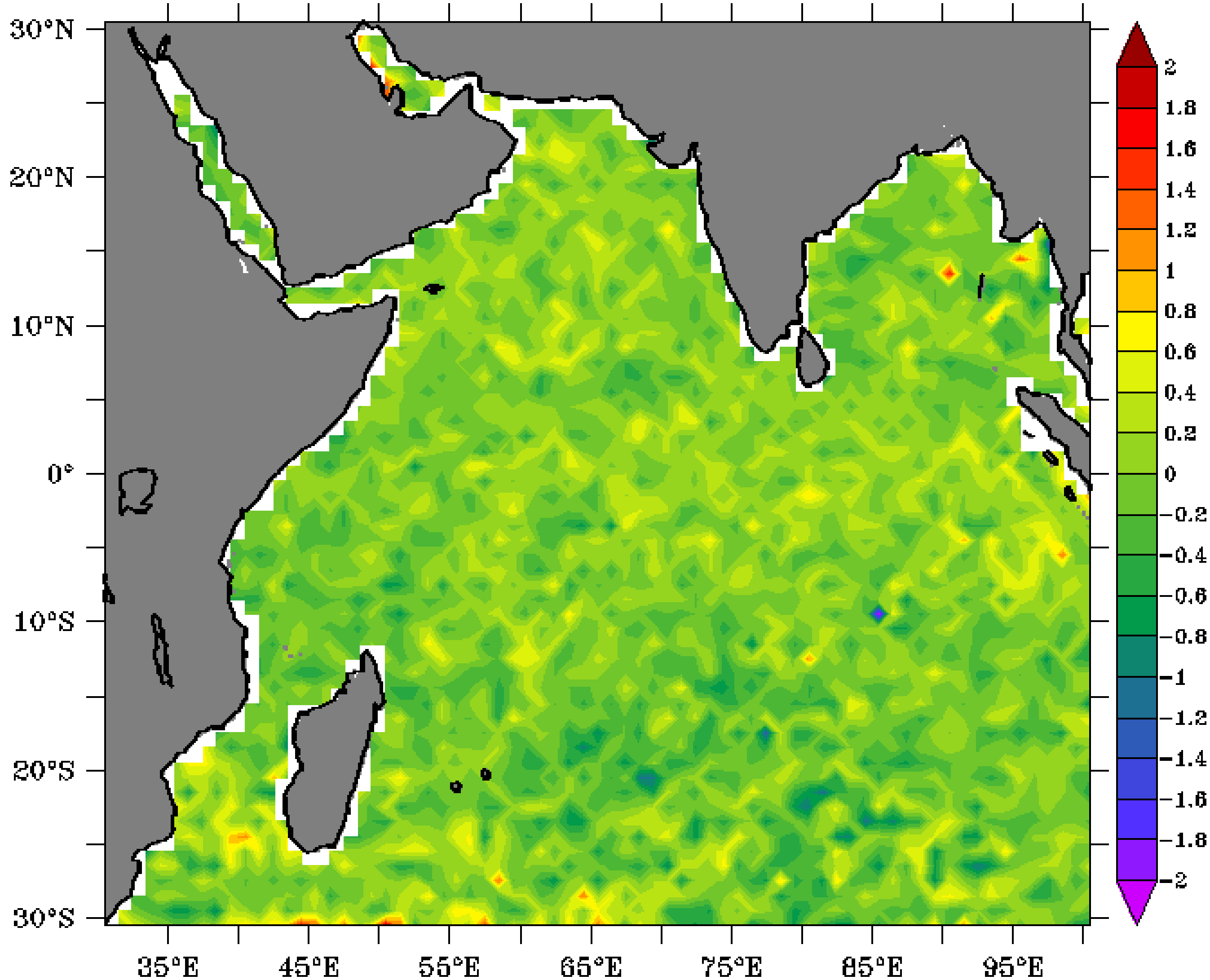
Air Temperature (deg Celsius)   SEPTEMBER



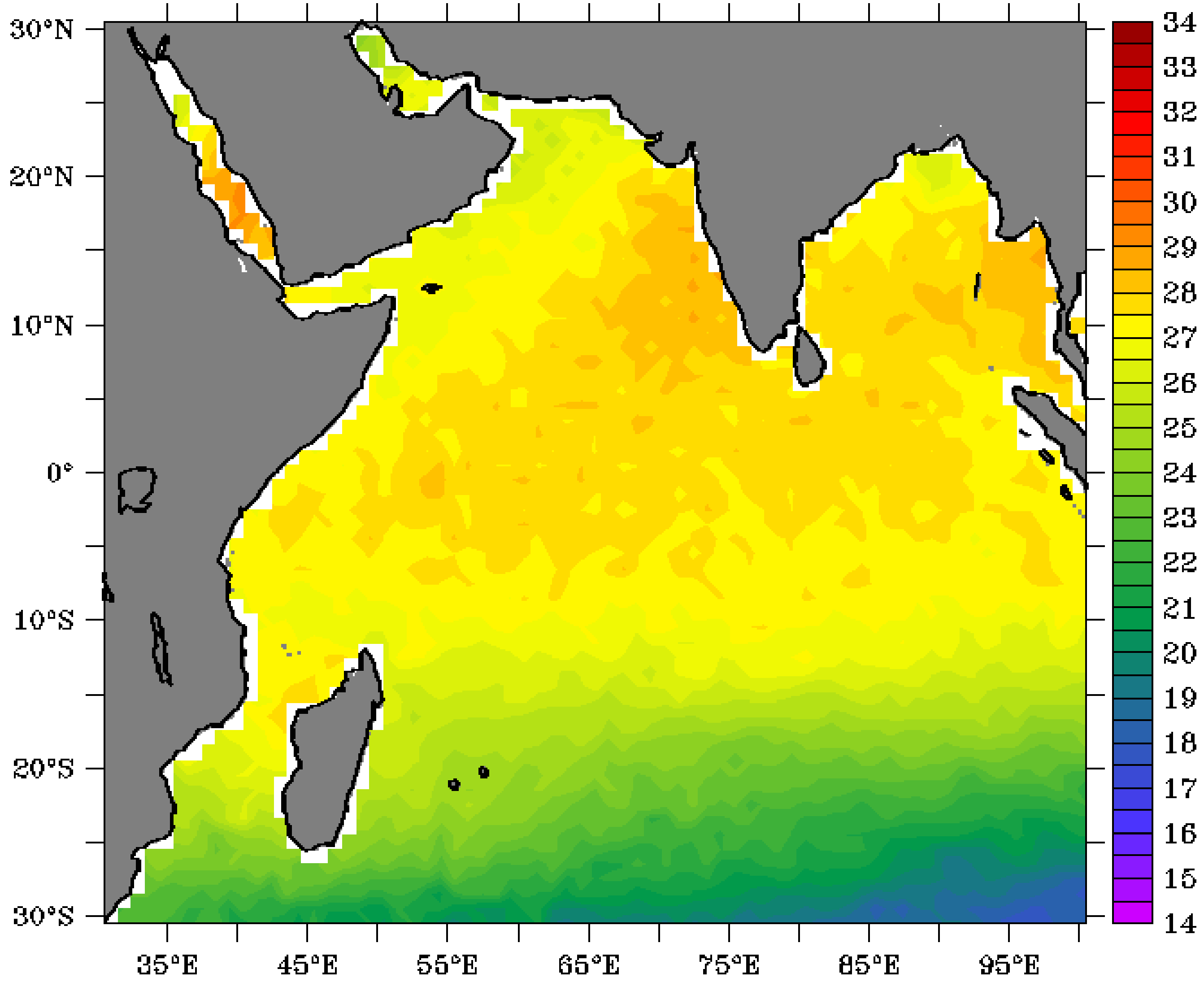
Anomaly (deg Celsius)



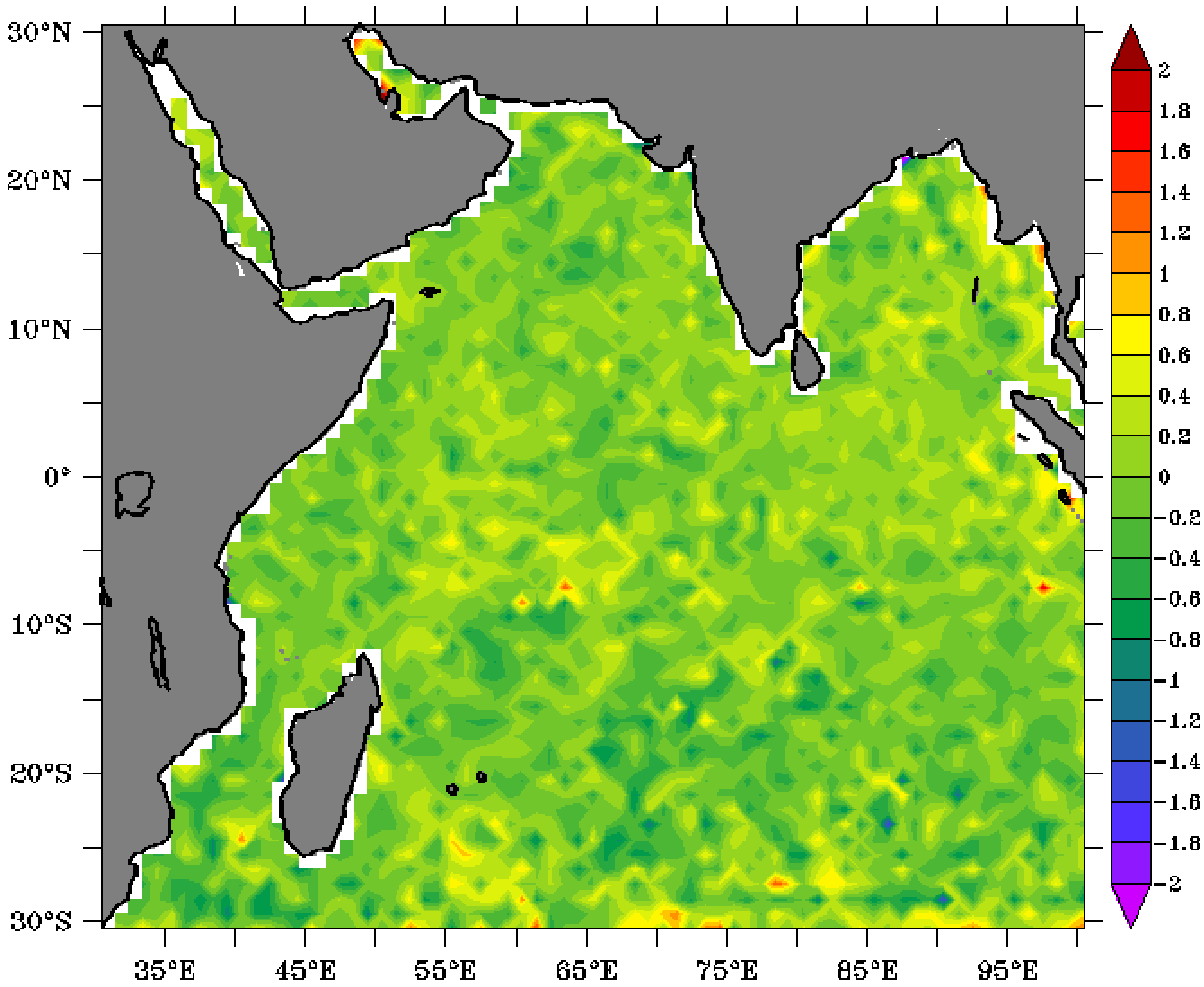
Air Temperature (deg Celsius) OCTOBER



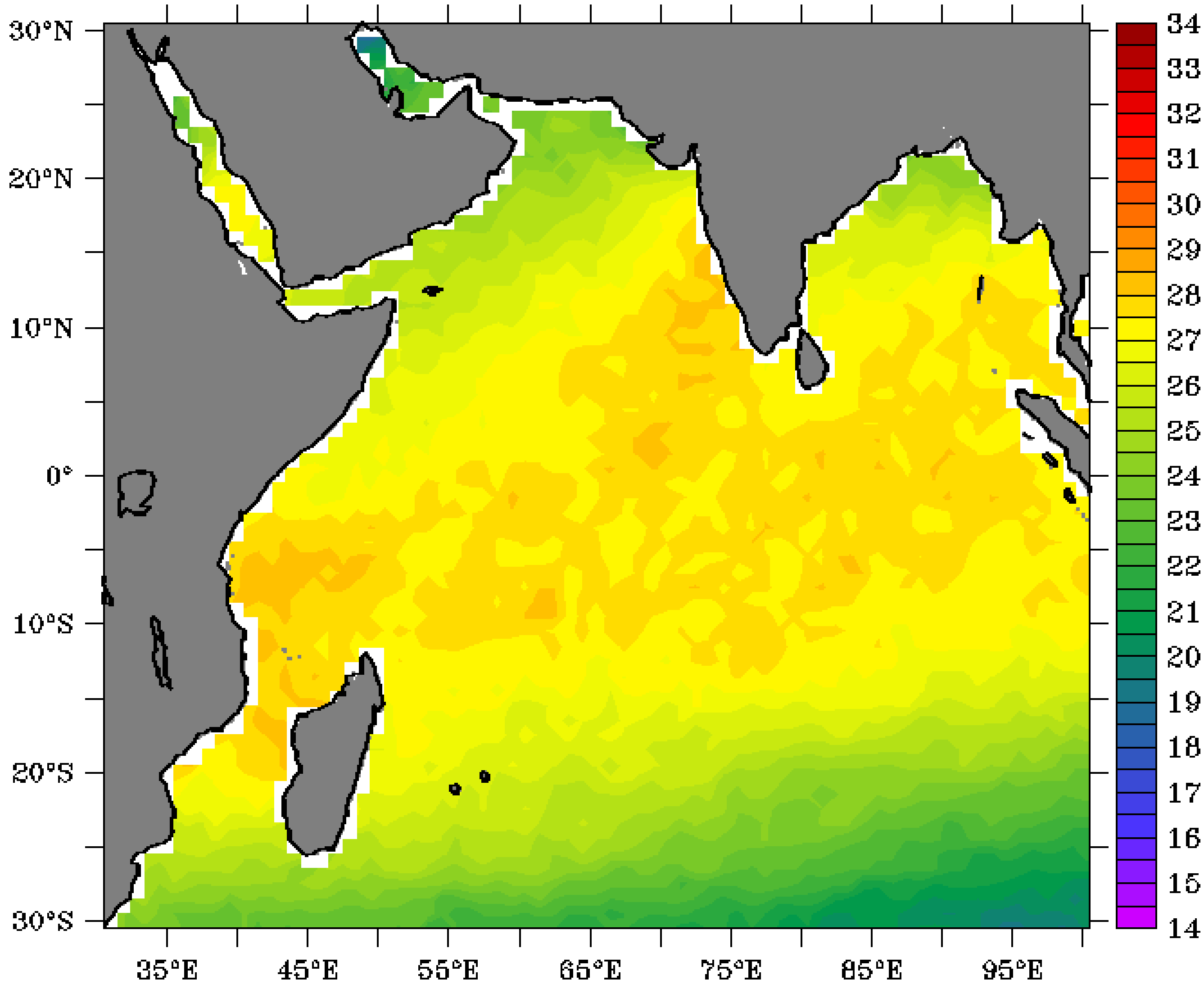
Anomaly (deg Celsius)



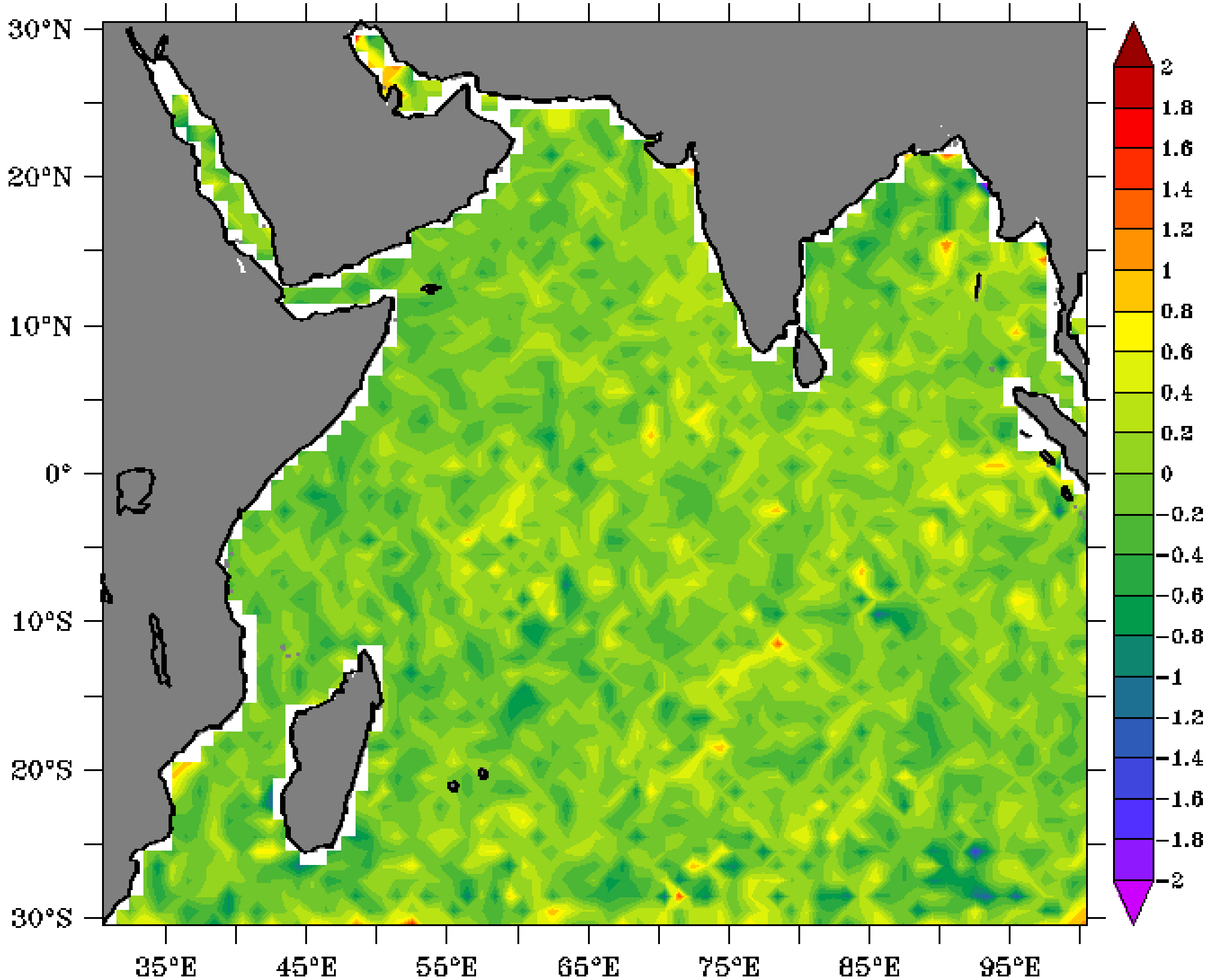
Air Temperature (deg Celsius)   NOVEMBER



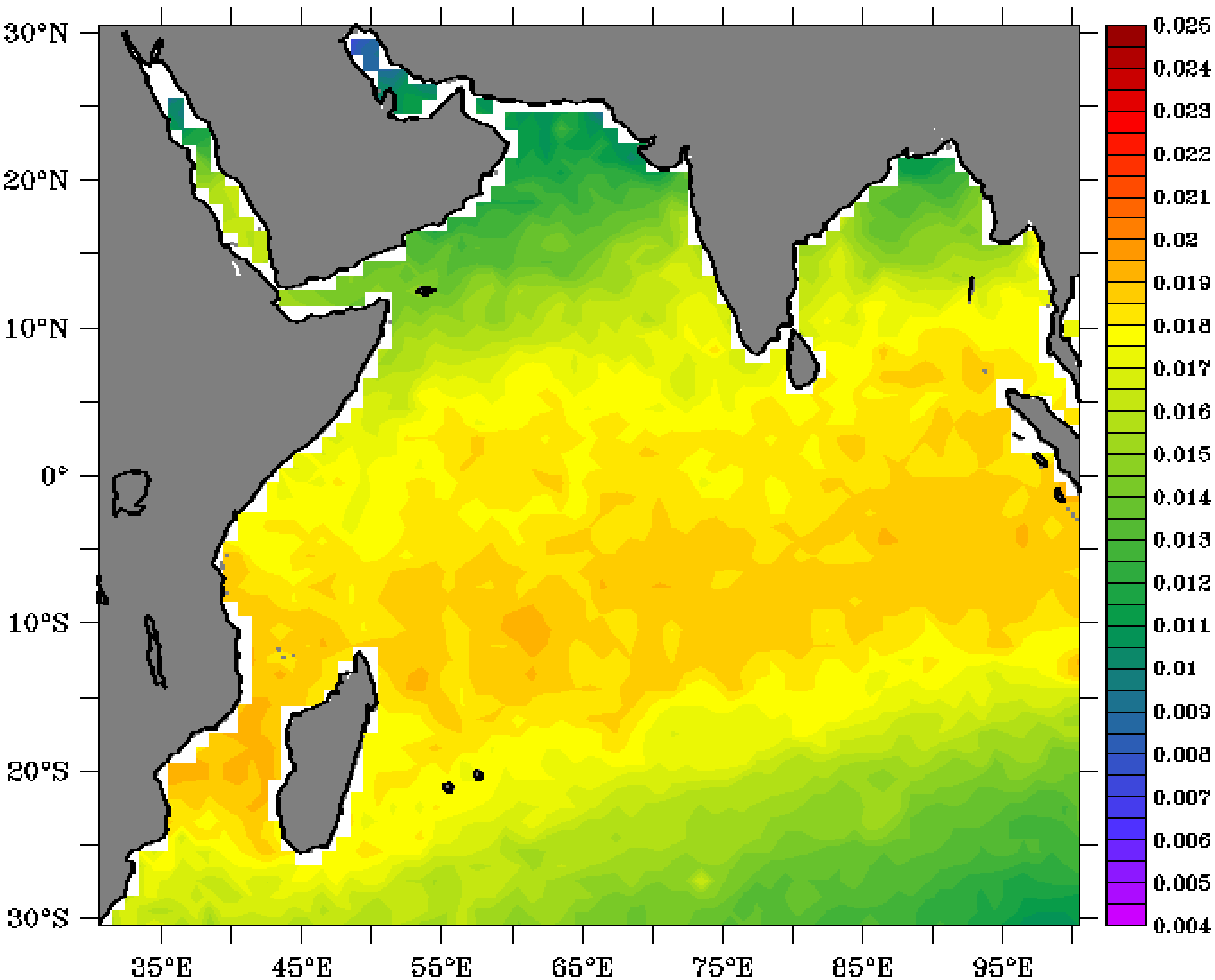
Anomaly (deg Celsius)



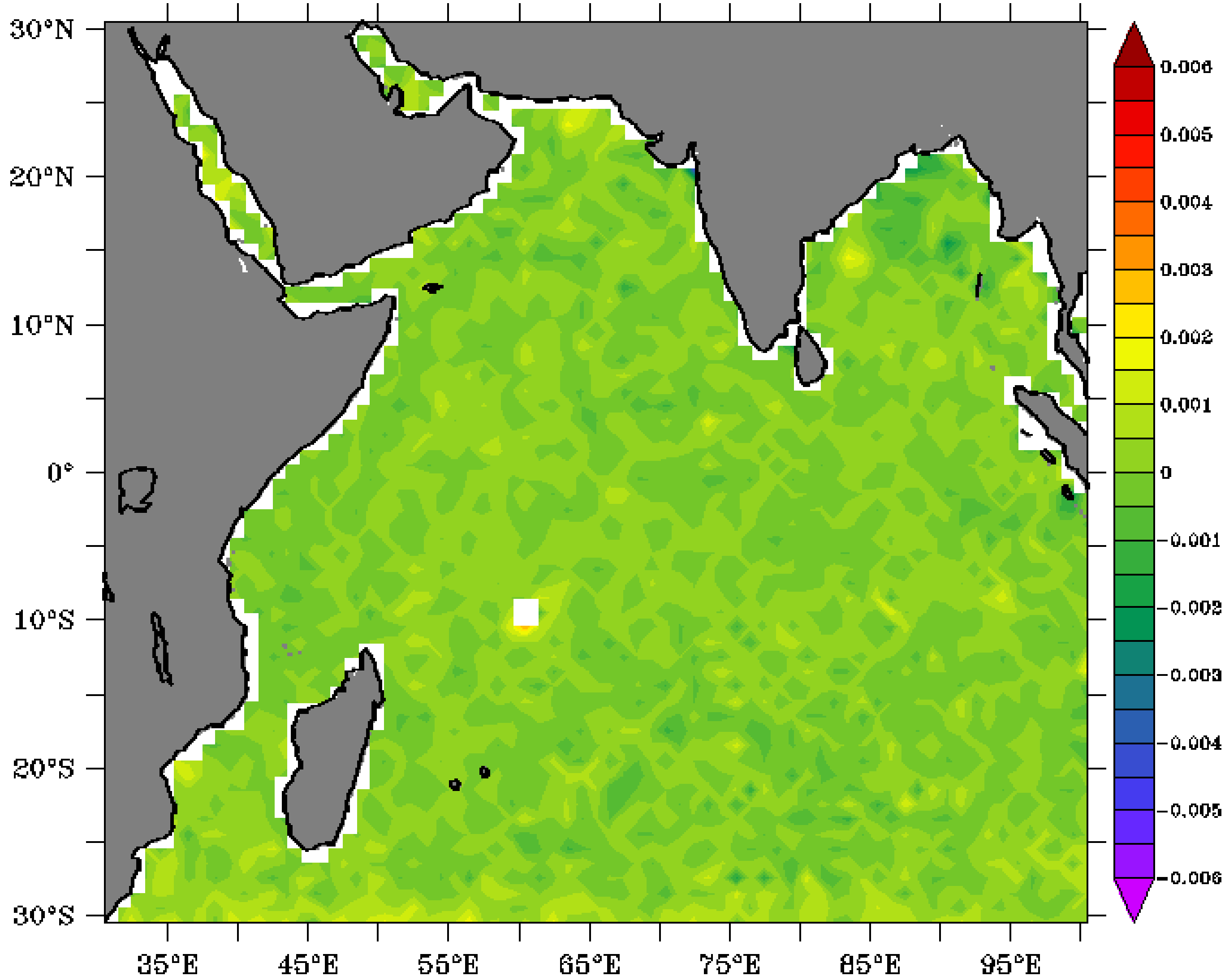
Air Temperature (deg Celsius) DECEMBER



Anomaly (deg Celsius)



Specific Humidity (g/g) JANUARY


30°N
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20°S
30°S
35°E
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55°E
65°E
75°E
85°E
95°E
0.006
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0.004
0.003
0.002
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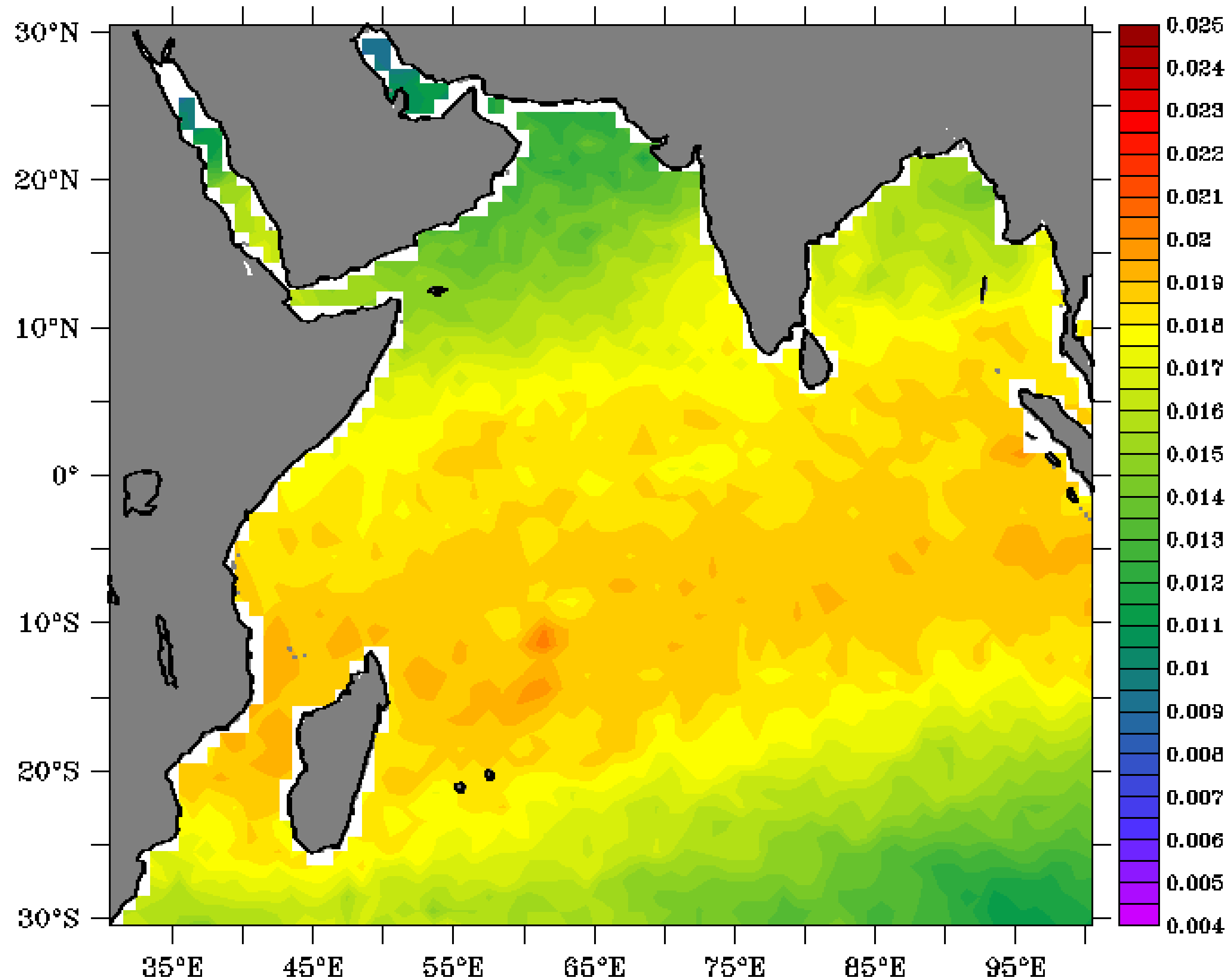
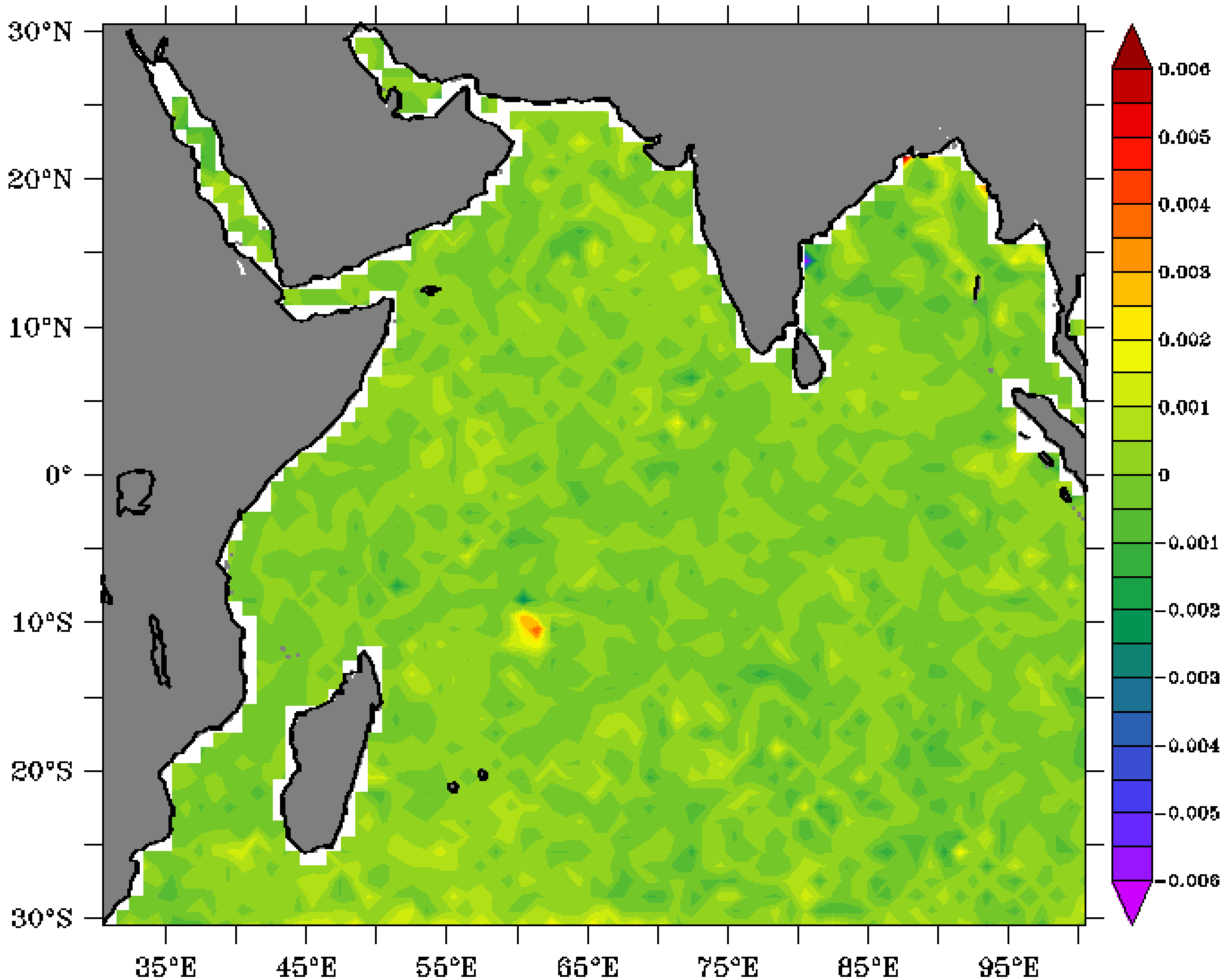
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

Anomaly (g/g)

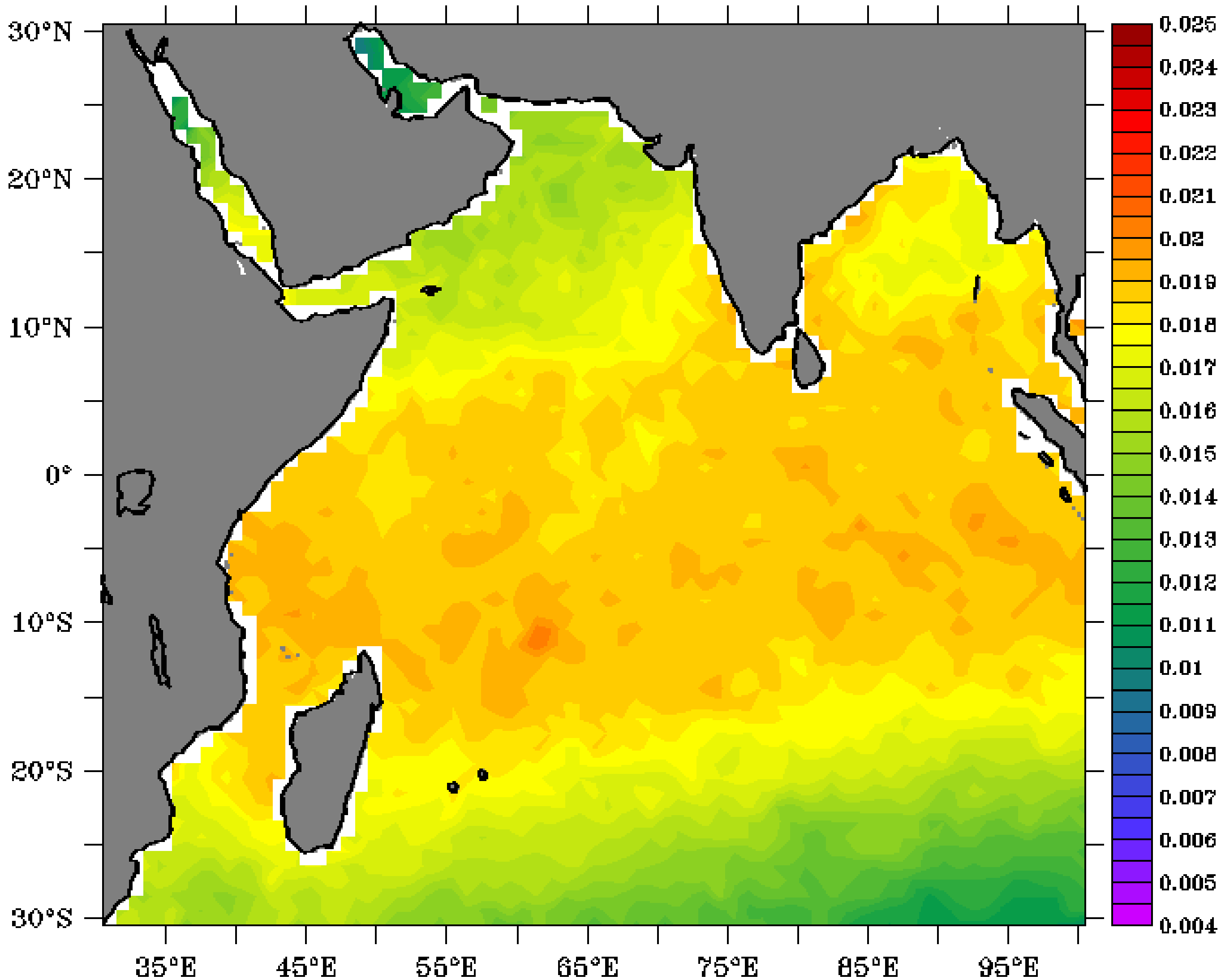


Specific Humidity (g/g) FEBRUARY

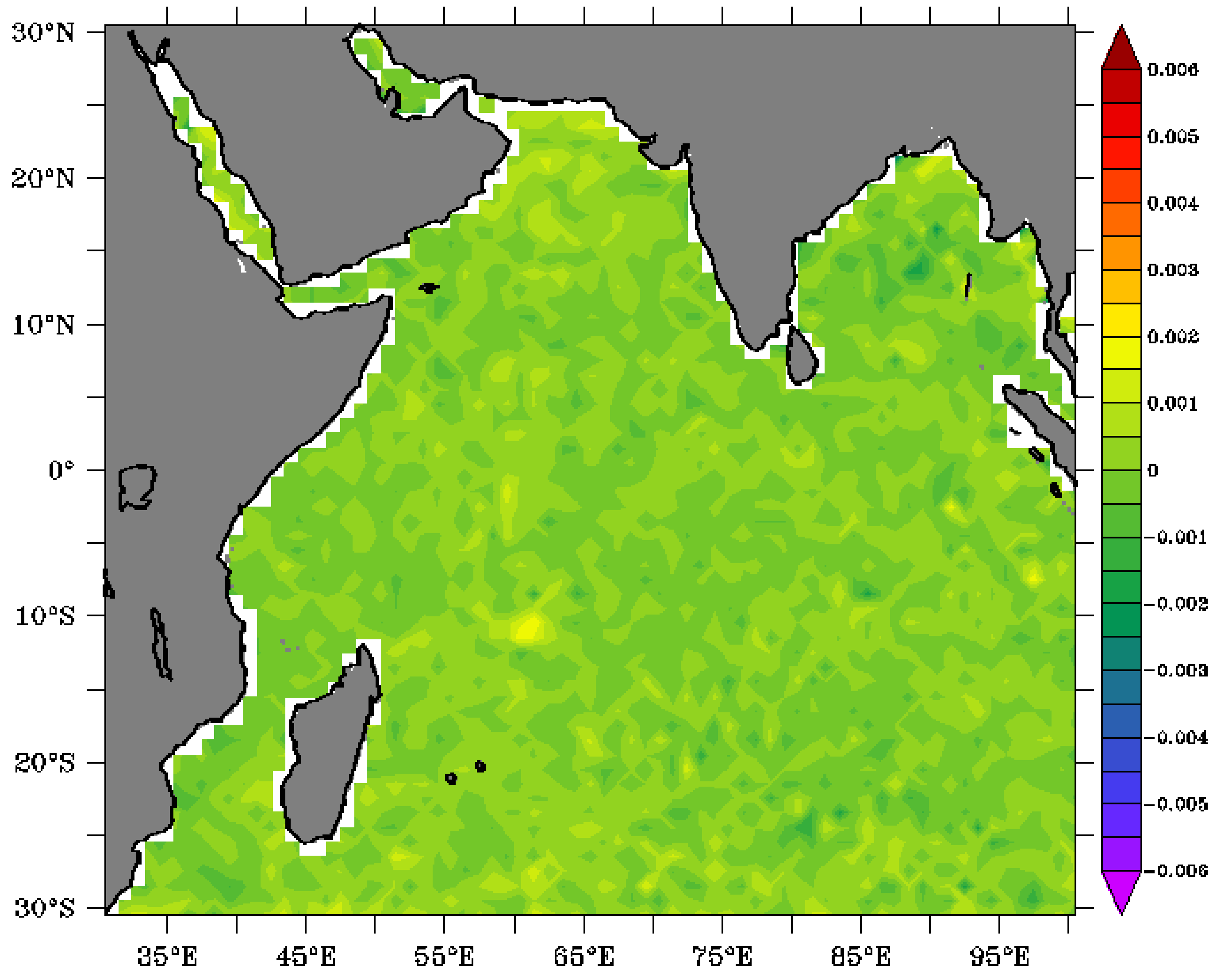


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

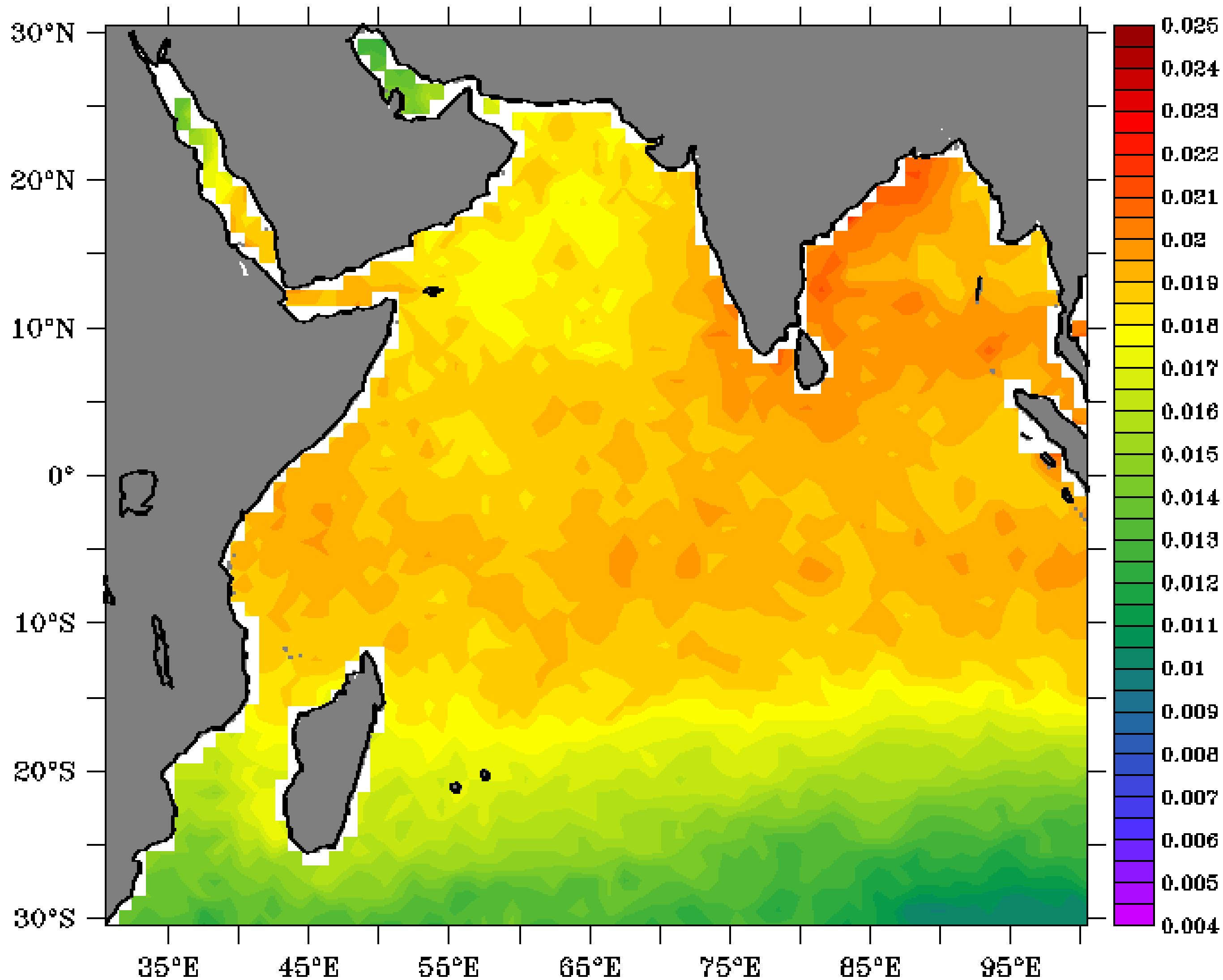
Anomaly (g/g)



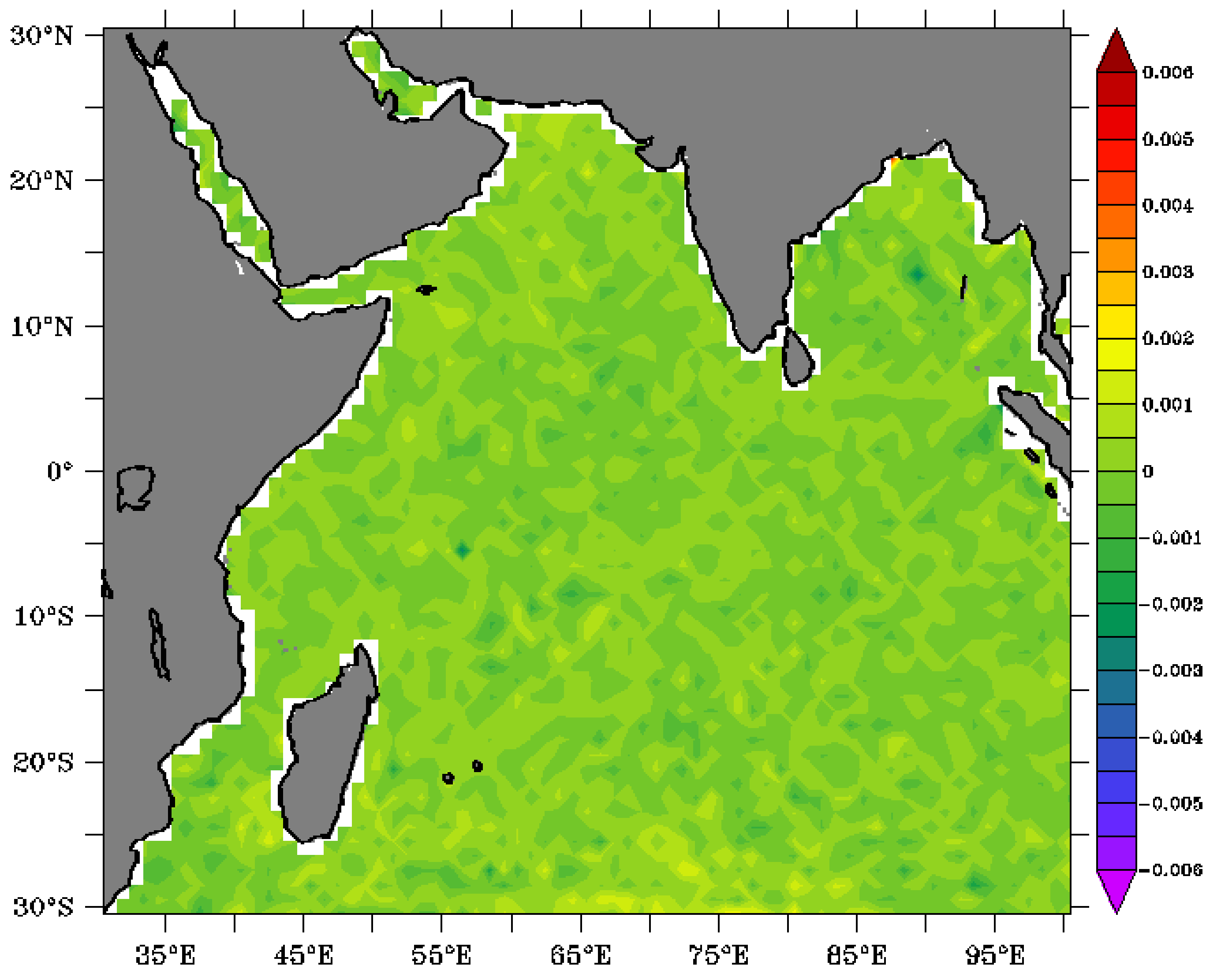
Specific Humidity (g/g) MARCH


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

Anomaly (g/g)

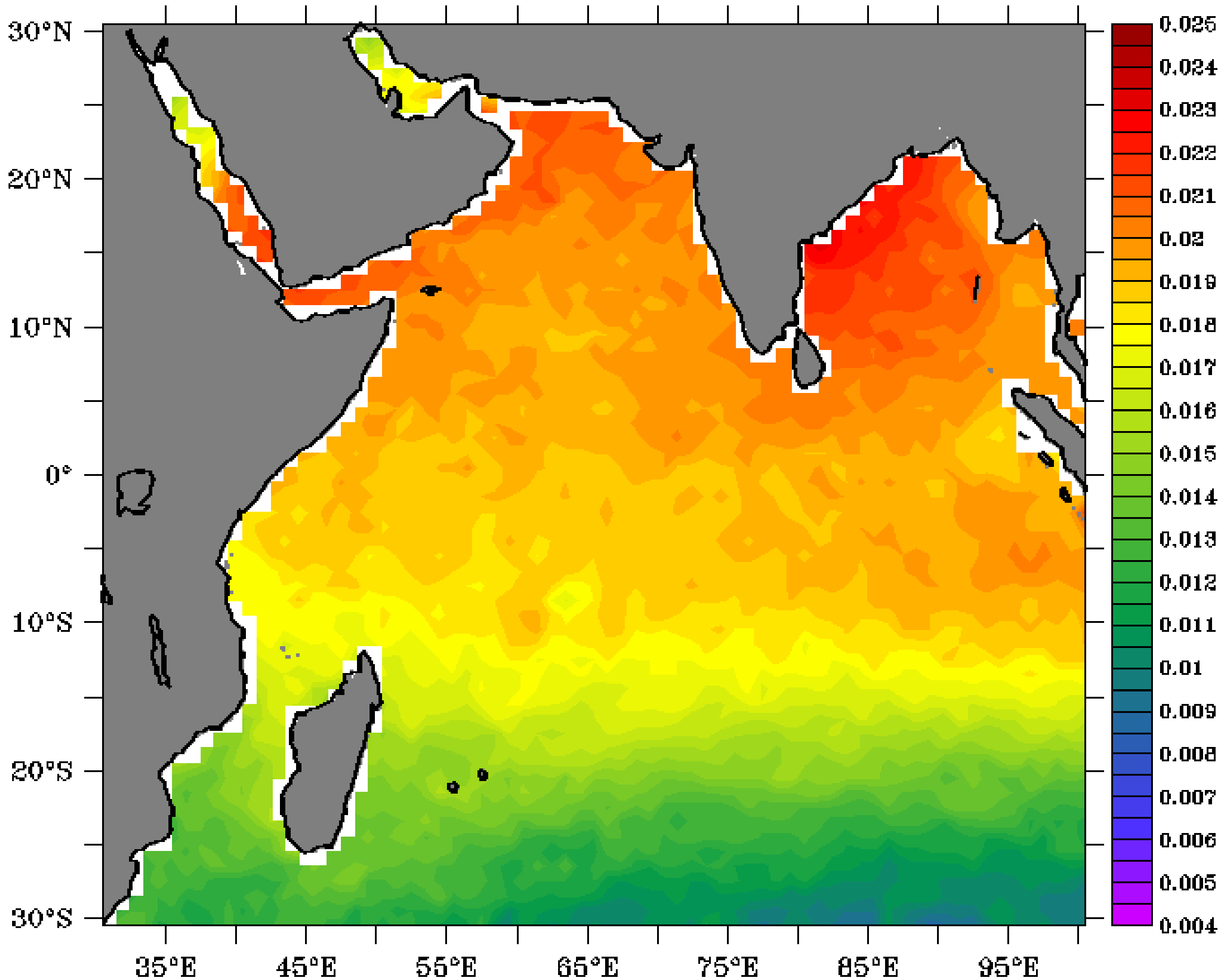


Specific Humidity (g/g) APRIL

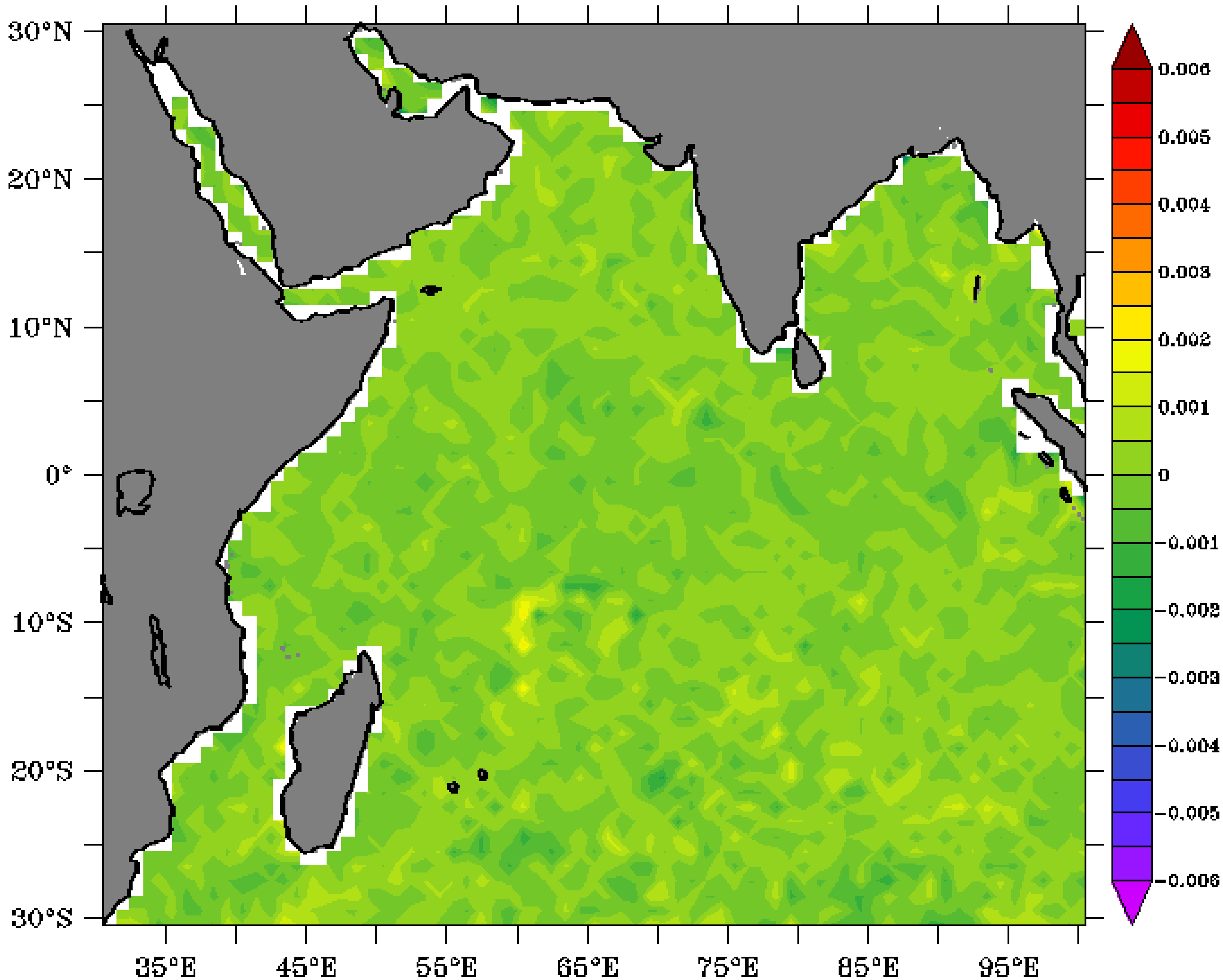

30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

Anomaly (g/g)

0

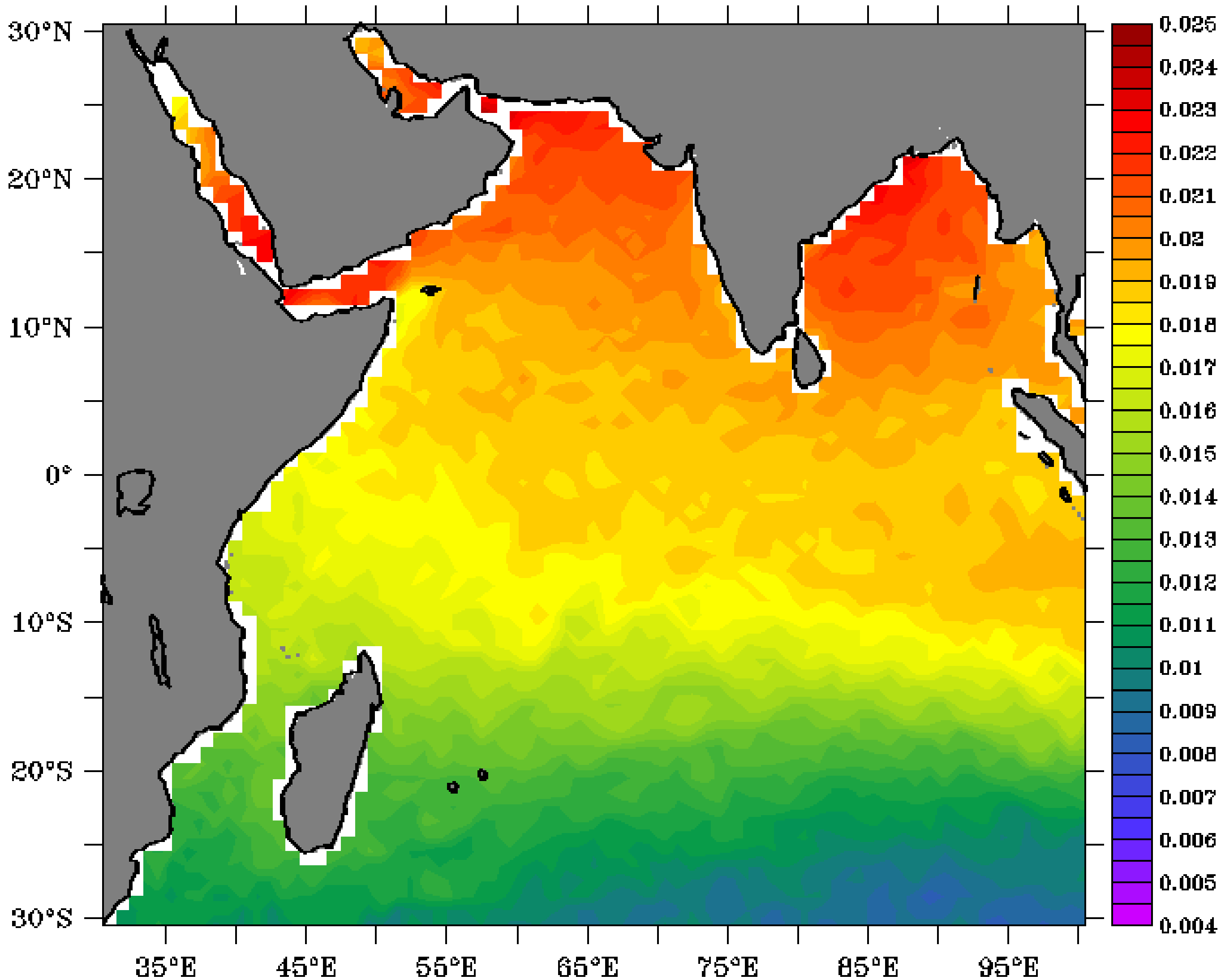


Specific Humidity (g/g) MAY

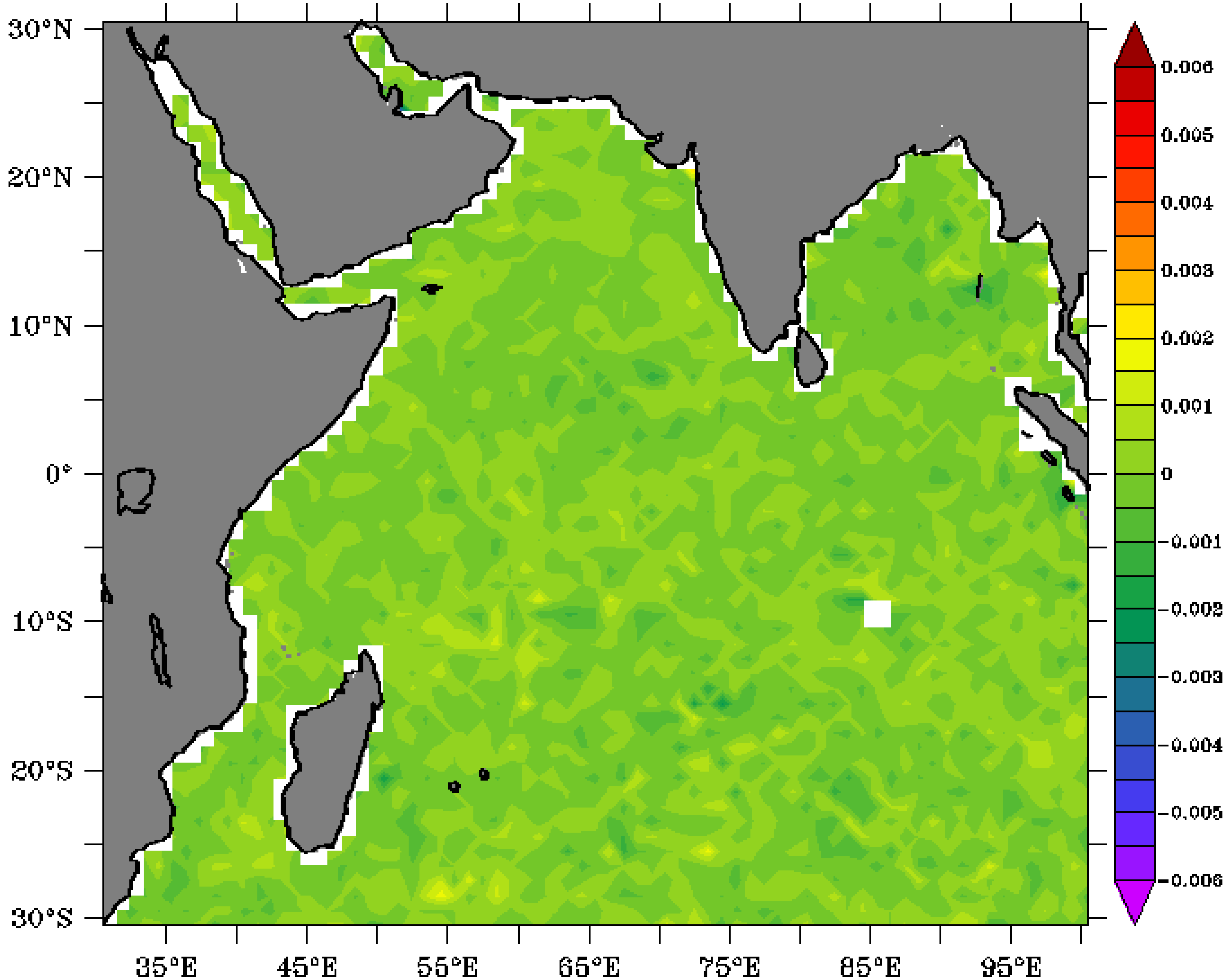


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

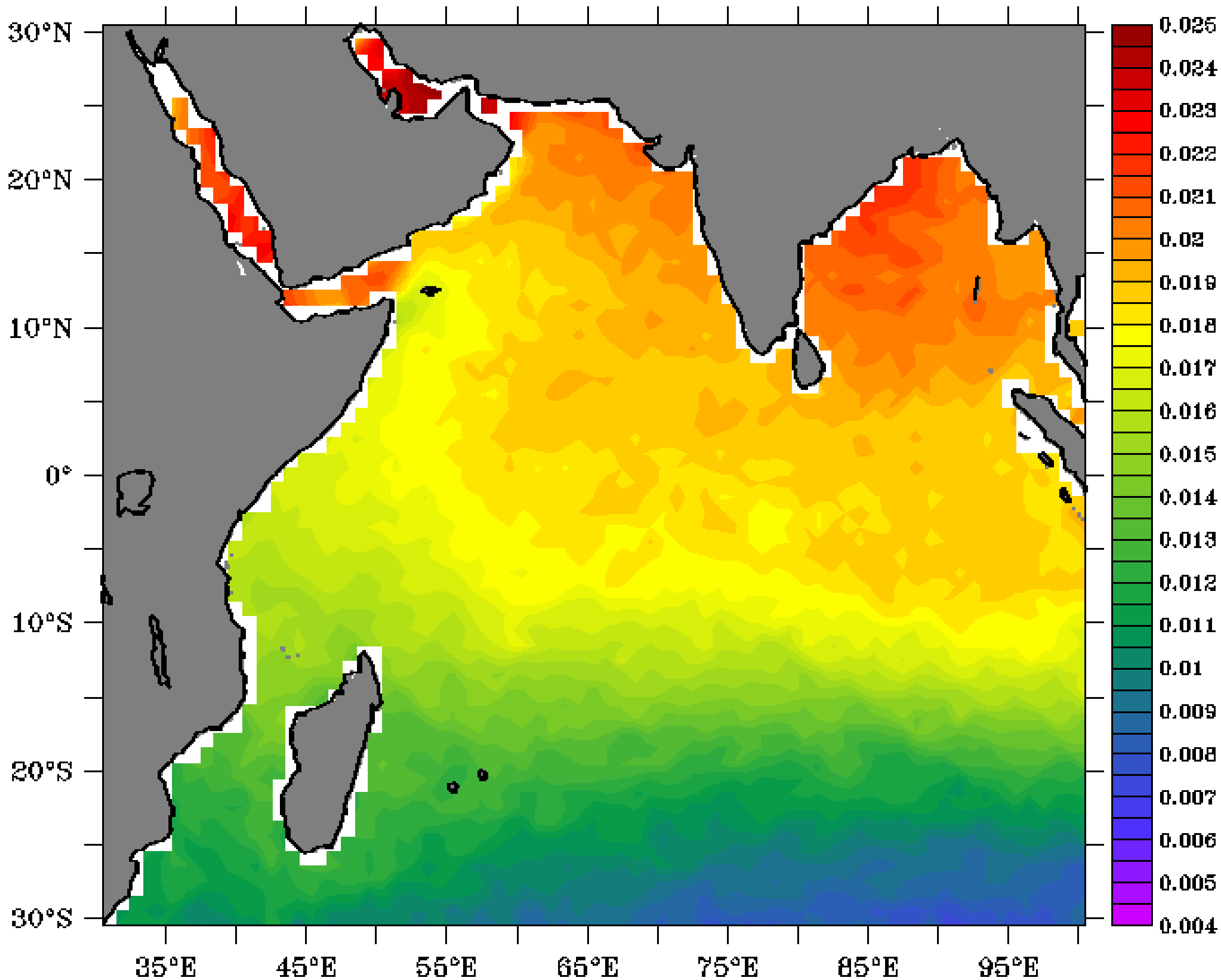
Anomaly (g/g)



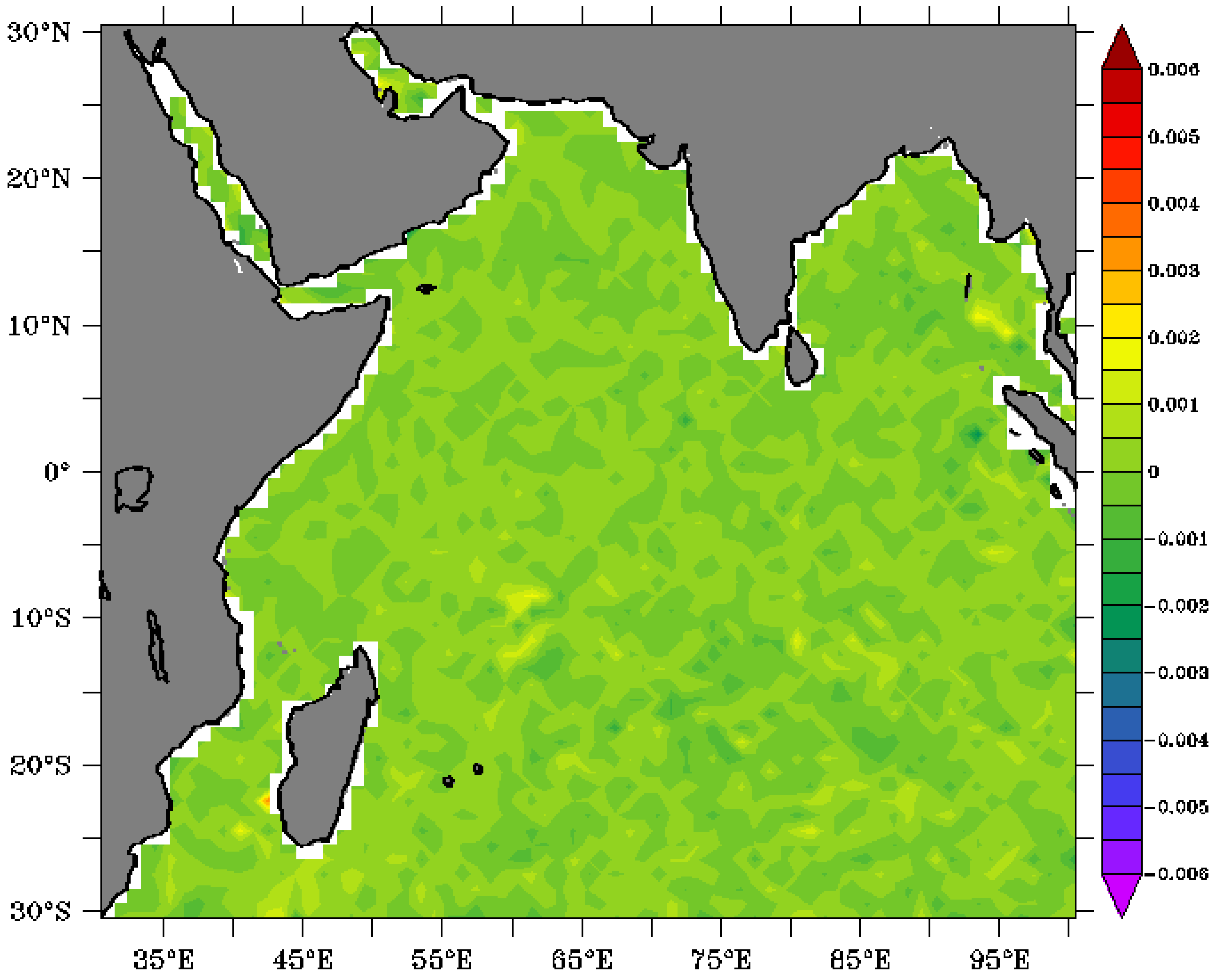
Specific Humidity (g/g) JUNE


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

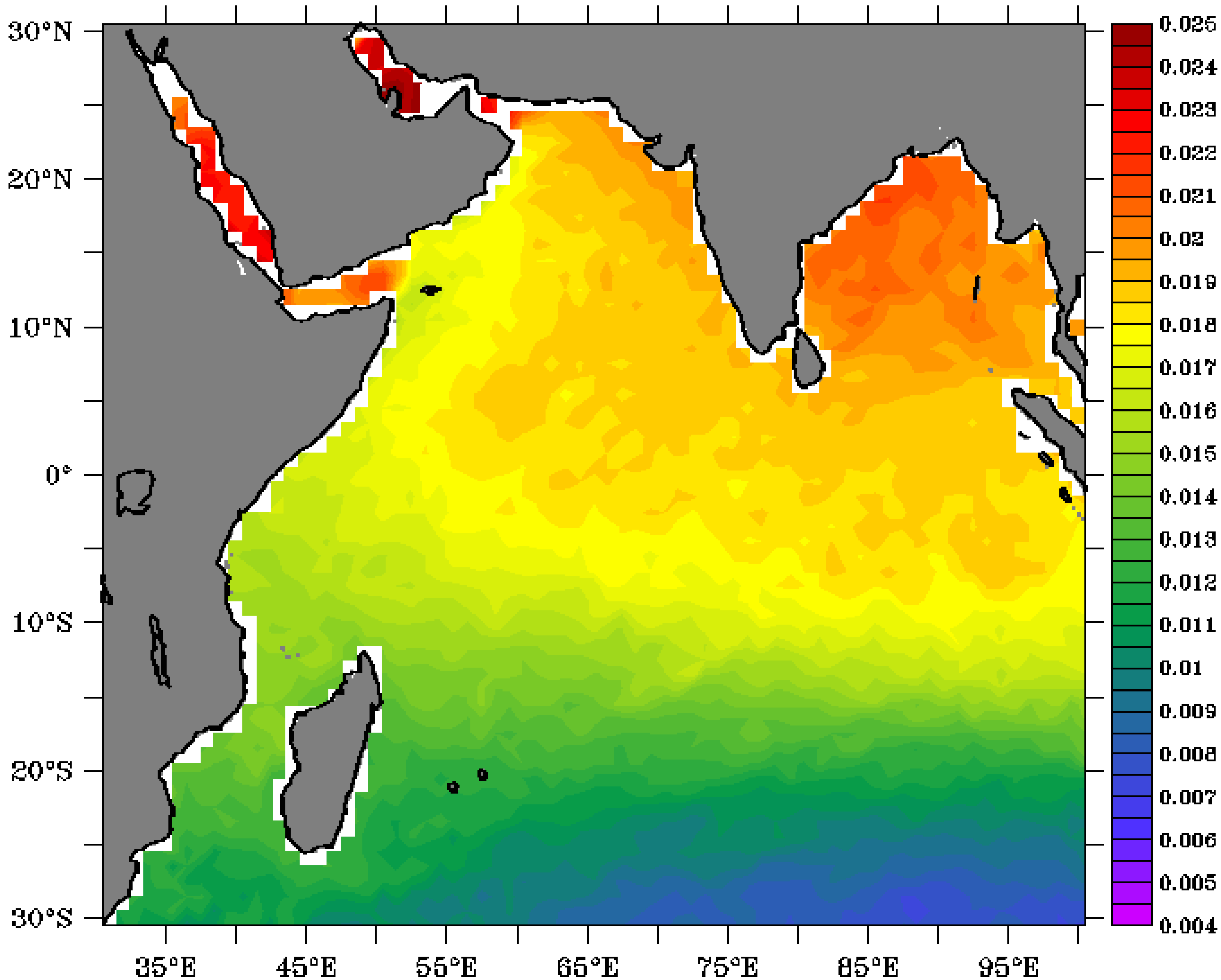
Anomaly (g/g)



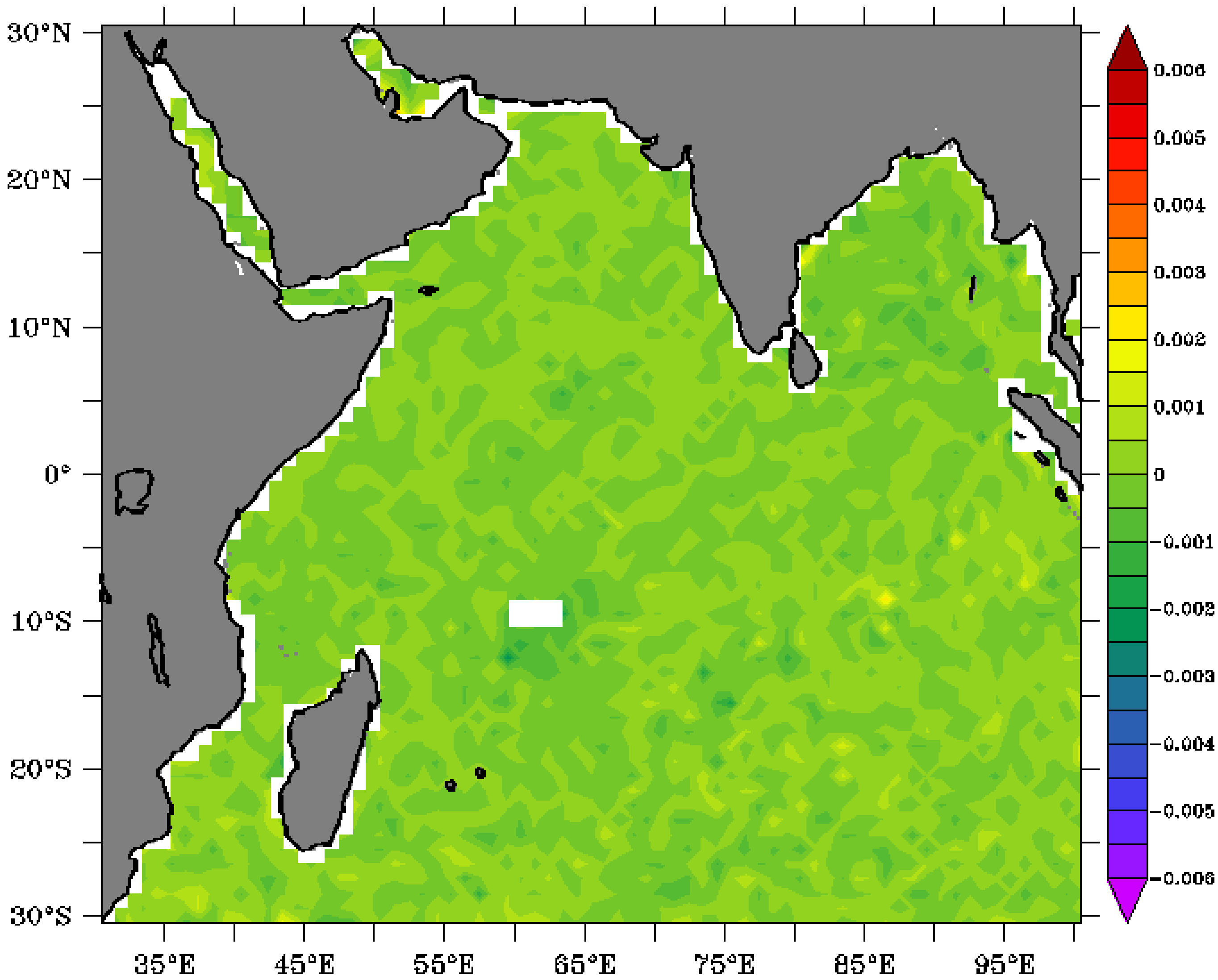
Specific Humidity (g/g) JULY


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

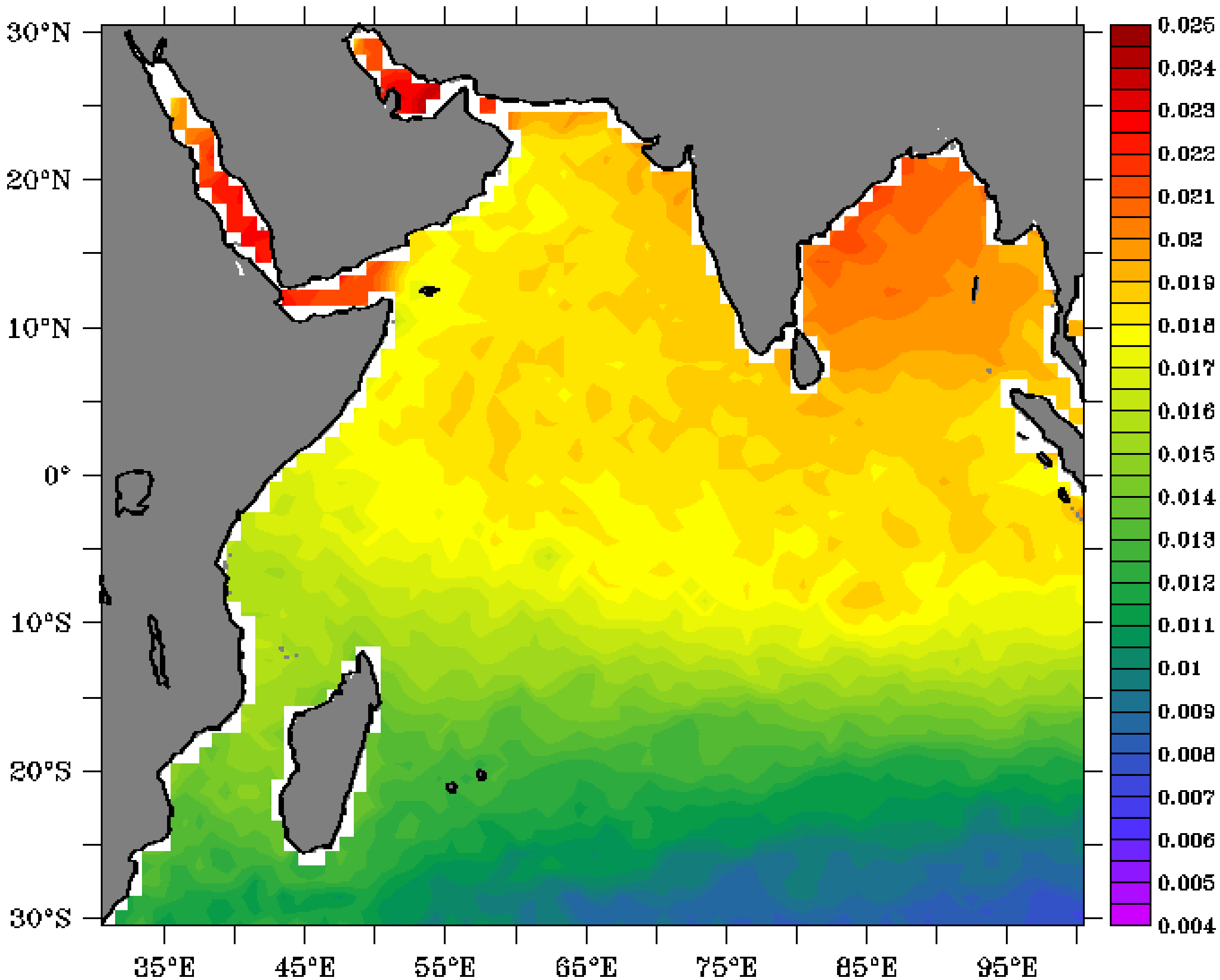
Anomaly (g/g)



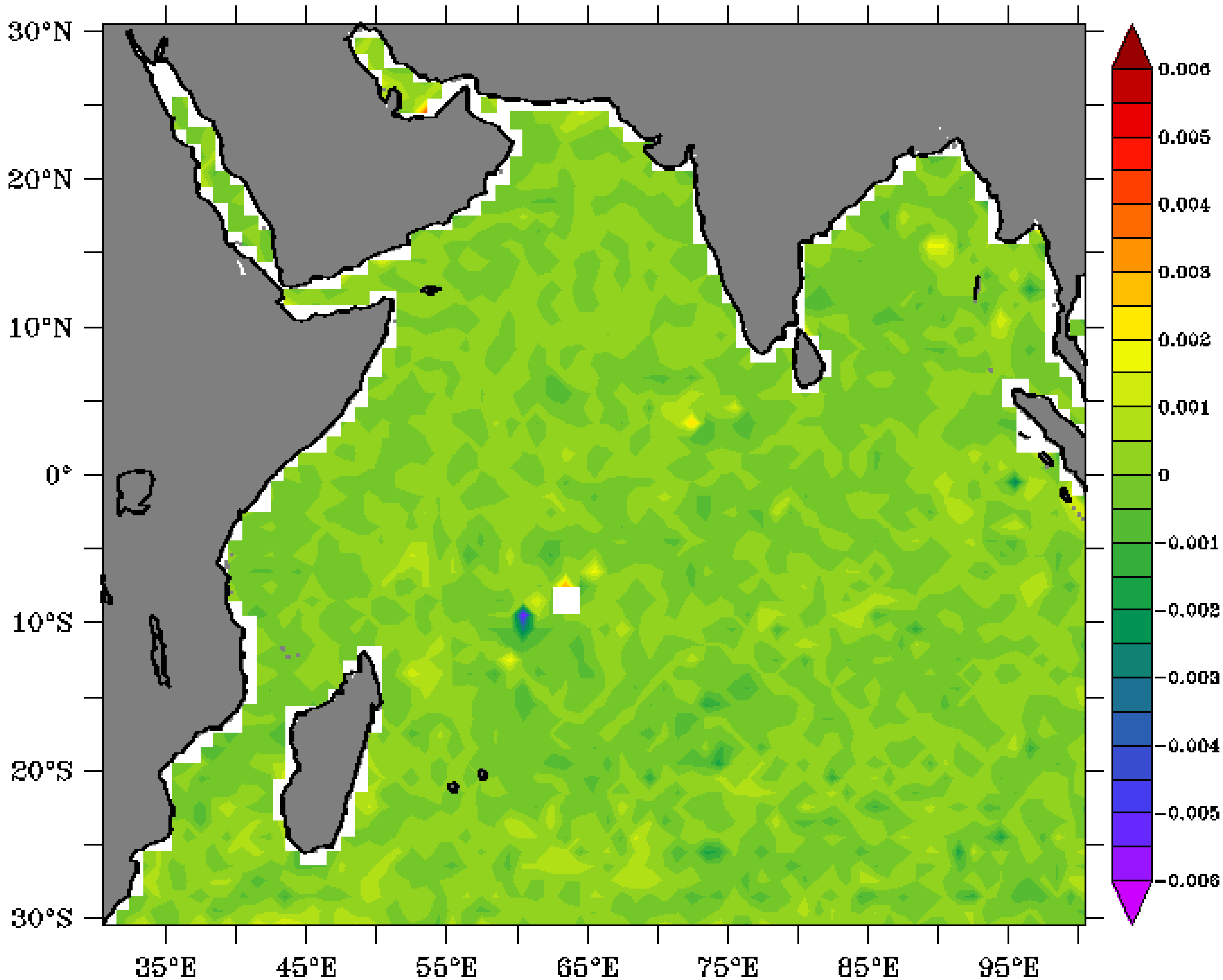
Specific Humidity (g/g) AUGUST


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

Anomaly (g/g)

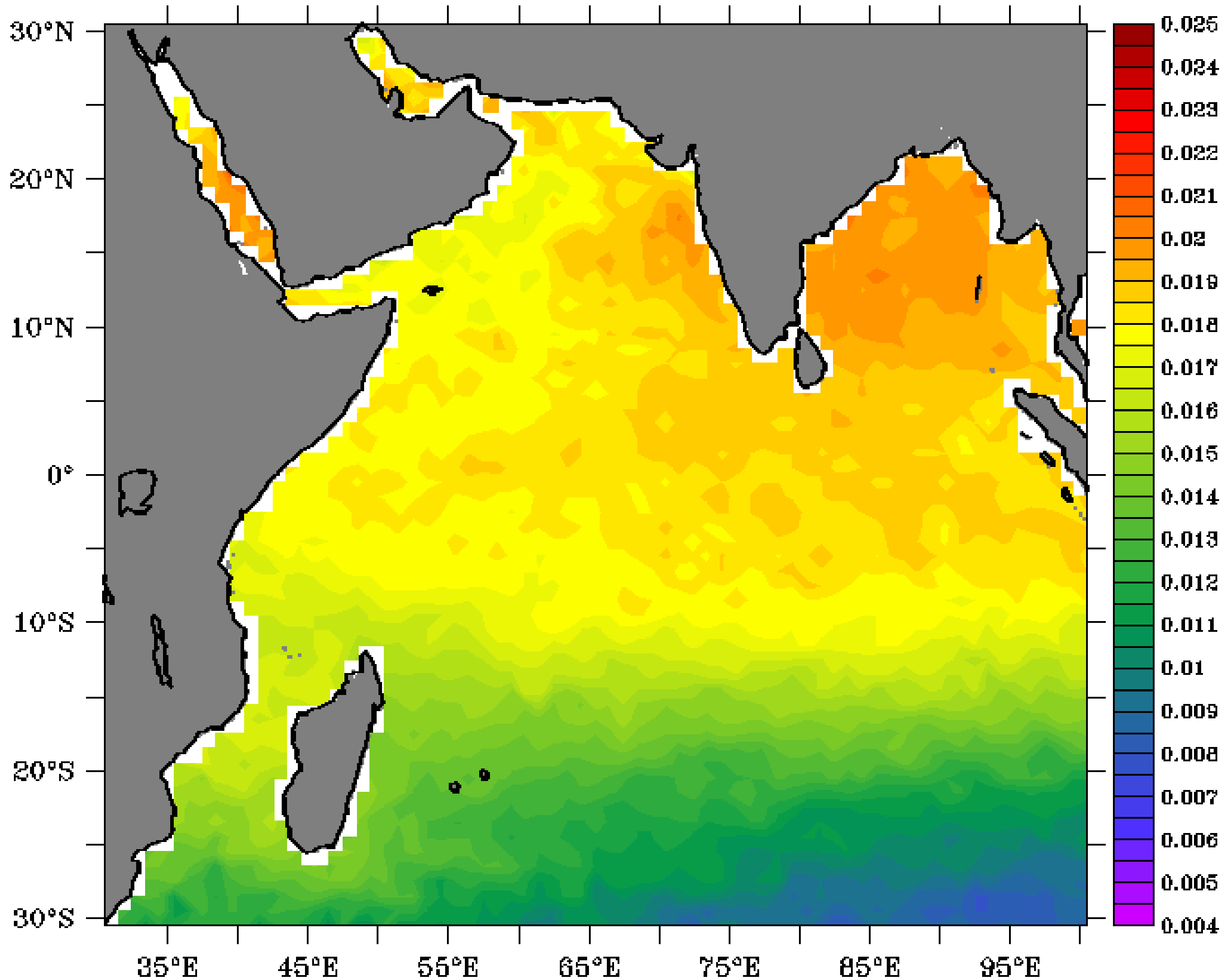


Specific Humidity (g/g) SEPTEMBER

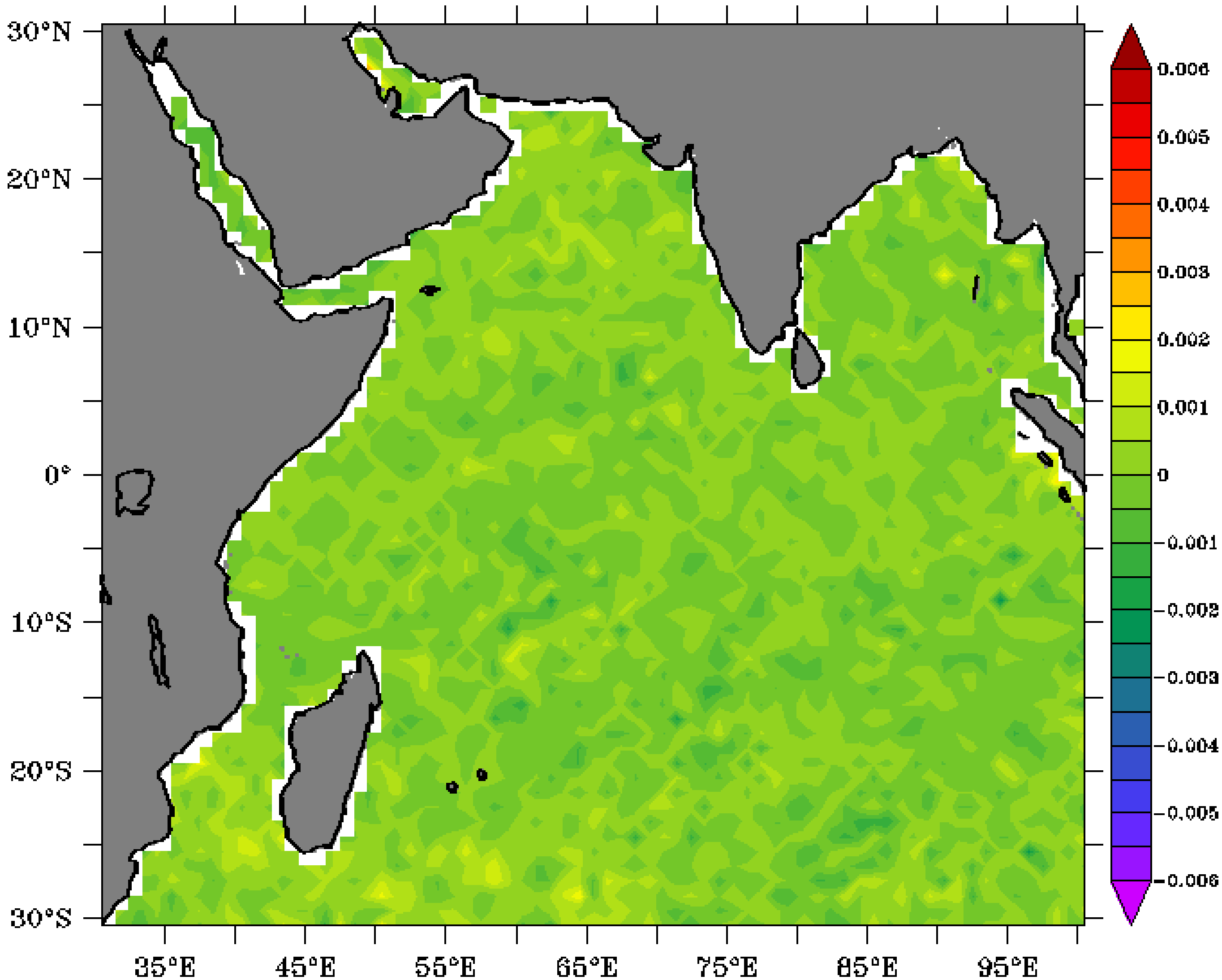


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

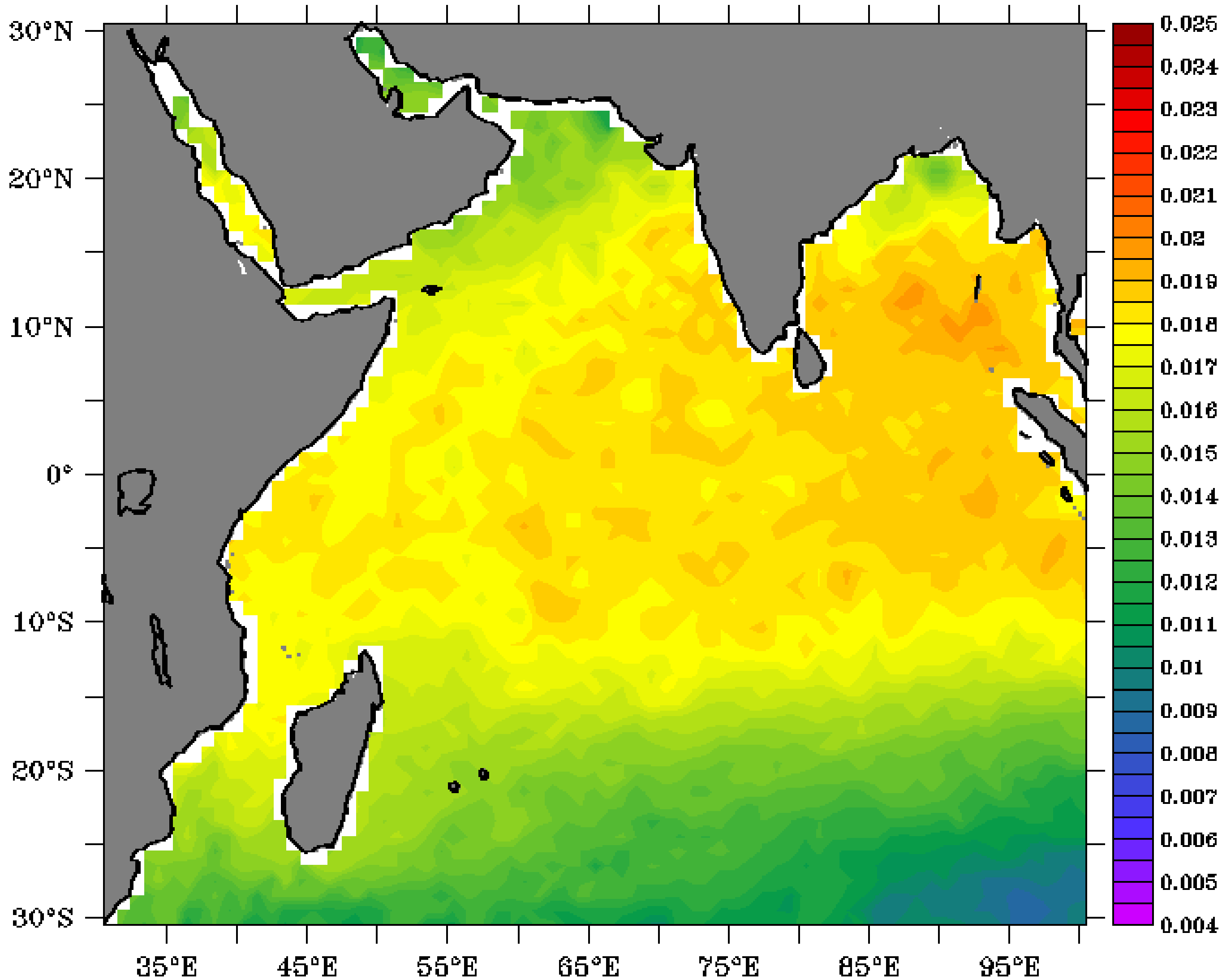
Anomaly (g/g)



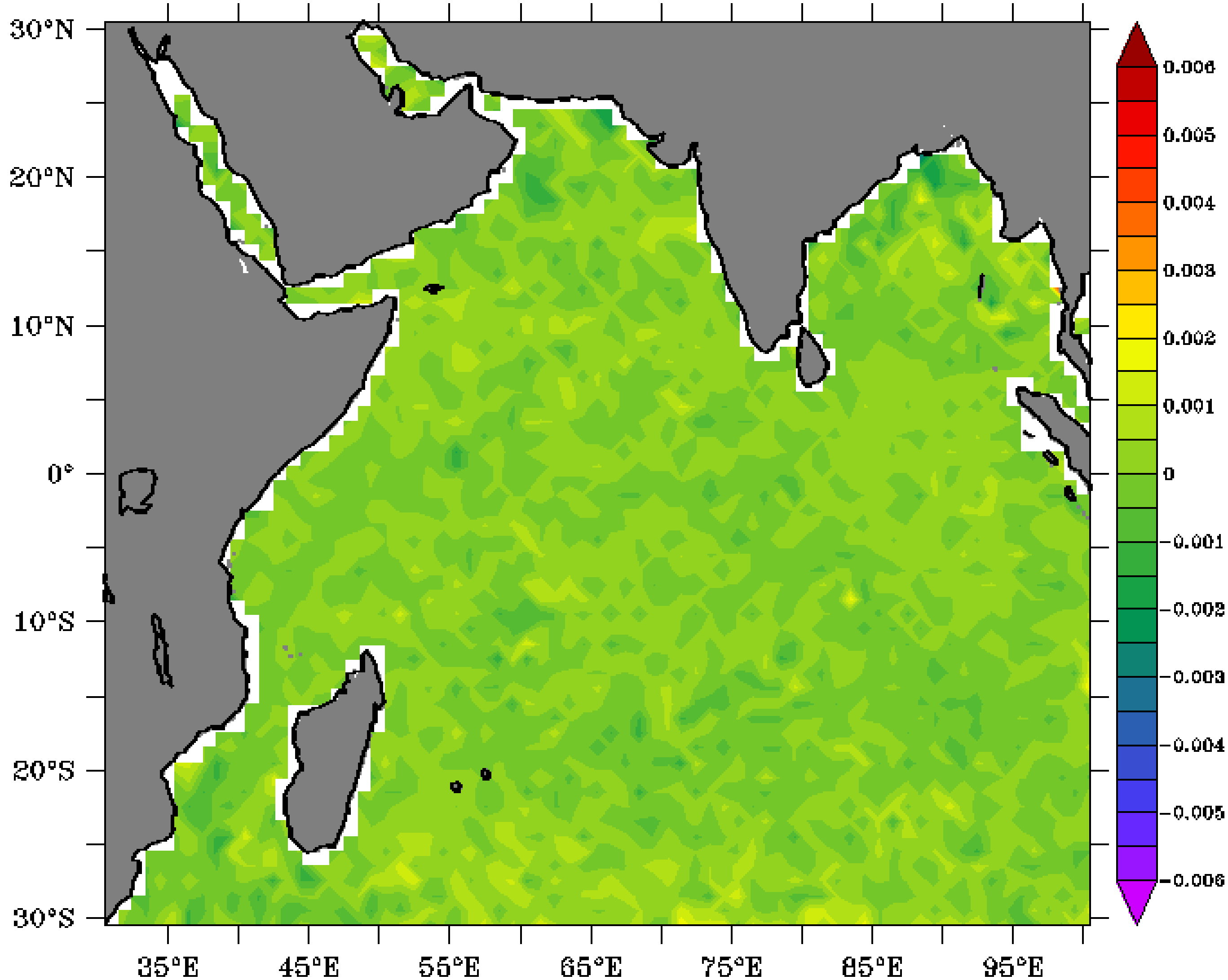
Specific Humidity (g/g) OCTOBER


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

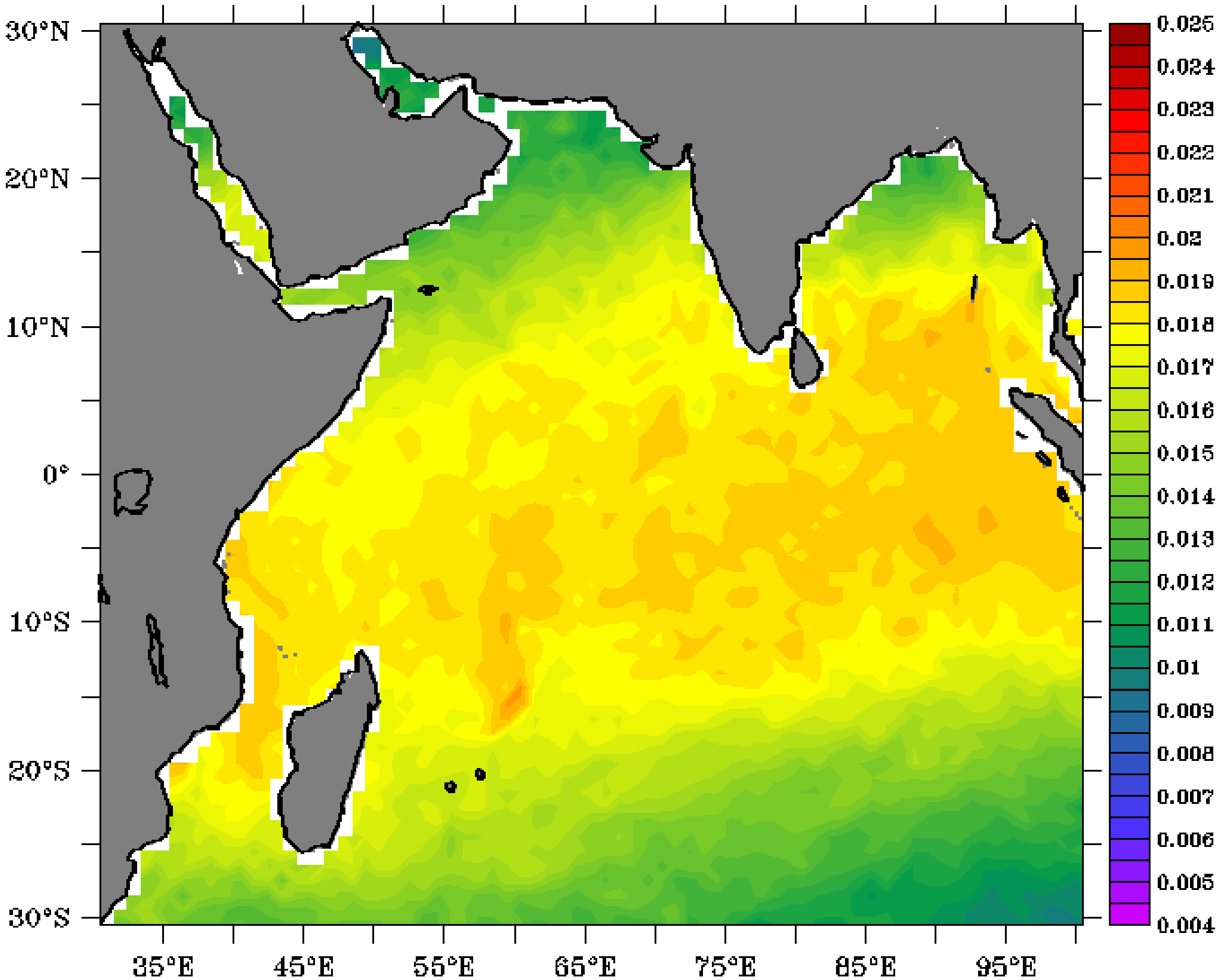
Anomaly (g/g)



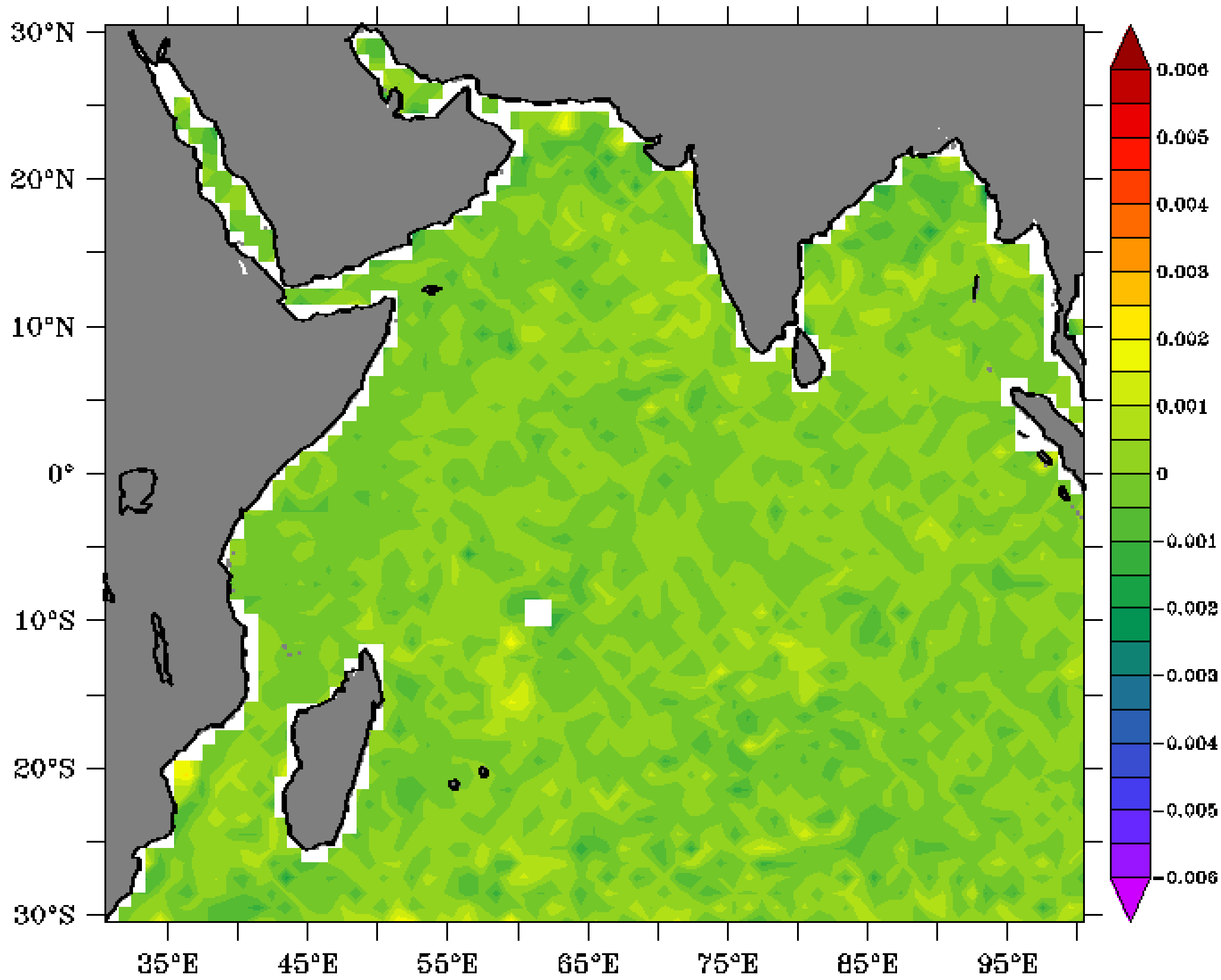
Specific Humidity (g/g) NOVEMBER


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

Anomaly (g/g)



Specific Humidity (g/g) DECEMBER


30°N
20°N
10°N
0°
10°S
20°S
30°S
35°E
45°E
55°E
65°E
75°E
85°E
95°E
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006

Anomaly (g/g)