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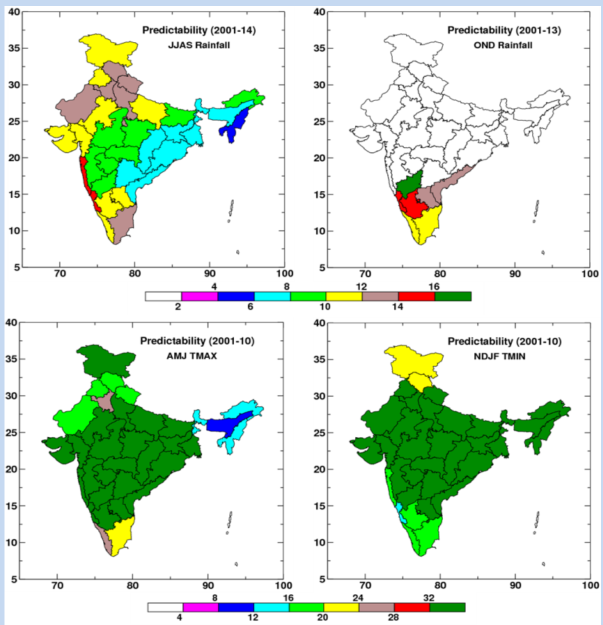

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Abstract

The present study documents the skill of the Extended Range Ensemble Prediction System (EPS) at Indian Institute of Tropical Meteorology (IITM) in predicting the rainfall and temperature during various seasons. The skill of the EPS in predicting rainfall during southwest and northeast monsoon seasons and that of temperature during summer and winter seasons over different meteorological subdivisions of India has been evaluated on pentad lead scale using various skill scores. The EPS is found to be skillful up to 4th pentad lead in predicting rainfall/temperature during the relevant seasons and hence can be used for operational purposes.

Summary

The sub-seasonal or extended range prediction (ERP) refers to a meteorological forecast more than 10 days in advance. Under the National Monsoon Mission Project initiated by Ministry of Earth Sciences (MoES), Govt. of India, the ERP group at IITM developed an indigenous dynamical ensemble prediction system (EPS) in 2011 based on the state-of-the-art coupled model - Climate Forecast System Model Version 2 (CFSv2). The forecasts are being generated for the whole year during pre-monsoon, post-monsoon, southwest monsoon, northeast monsoon, summer and winter seasons. The major forecast products include rainfall and temperature (both maximum and minimum). Since the forecast of rainfall is important during southwest and northeast monsoon seasons, and that of temperature during summer and winter seasons, it is required to document the skill of the EPS in predicting them in the respective seasons. In the present study, skill of the EPS in predicting rainfall and temperature on various subdivisions over India has been analysed on pentad lead time scale. The EPS is found to be skillful up to 4th pentad lead in predicting the rainfall during southwest and northeast monsoon seasons, and temperature during summer and winter seasons, over different meteorological subdivisions of India. This affirms the reliability and usefulness of the present EPS system in operational perspective.

Contents

1. Introduction

Extended range prediction (ERP; ~10-15 days in advance) of rainfall and temperature are of great importance due to its widespread applications in agriculture, water management, urban planning, energy sector etc. India receives 80% of its annual rainfall in Southwest (SW) monsoon season (June-September; *hereafter termed as* JJAS) and remaining 20% during Northeast (NE) monsoon season (October-December; *hereafter termed as* OND). Since most of the farm lands over the country are rain-fed, the accurate prediction of the intraseasonal fluctuations, i.e., *wet* and *dry* spells, within these two seasons on extended range can be useful to user community in agricultural sector and in turn to policy makers. It is also beneficial to the water management sector. Similarly, the useful prediction of extreme temperatures during hot season (April-June; *hereafter termed as* AMJ) and cold season (November-February; *hereafter termed as* NDJF) can be advantageous in health and energy sector in addition to agriculture and water management. The extreme temperature events are known as Heat Waves during AMJ and Cold Waves during NDJF.

Under the National Monsoon Mission (http://www.tropmet.res.in/monsoon/), the Indian Institute of Tropical Meteorology (IITM) has indigenously developed an ensemble prediction system (EPS) for the ERP (Abhilash et al., 2014a), based on the Climate Forecast system version 2 (CFSv2) of National Centre for Environmental Prediction (NCEP). The current EPS is a Mutimodel Ensemble (MME) that combines the coupled model CFS at two resolutions - T126 and T382, along with the atmospheric component (GFS) forced with the bias-corrected SST from CFS, at both resolutions. Thus the CFS based Grand EPS (CGEPS) MME has four variants of the same model having diversity in physics.

The EPS generates the forecasts at 5 day interval (starting from 01 January of each year) for the next 45 days. The pentad (5-day mean) prediction skill may be considered as the intraseasonal variability prediction skill and is a more rigorous way of evaluating the model's hindcast skill. Since our focus is on extended range, the forecasts are being generated on pentad scale for pentad 1 (P1; day 1-5 average), pentad 2 (P2; day 6-10 average), pentad 3 (P3; day 11-15 average) and pentad 4 (P4; day 16-20 average). The main forecast products are rainfall and temperature. Since the forecast of rainfall is important during SW and NE monsoon seasons, and that of temperature during summer and winter seasons, it is required to document the skill of the EPS in predicting them in the respective seasons.

Initially, the MME forecasts were generated during SW monsoon season alone. The CGEPS MME as well as its individual contributing models have shown reasonable skill in predicting the JJAS rainfall over various homogenous regions over India (viz, Central India, Monsoon Zone of India (Rajeevan et al. 2010); Northeast India, Northwest India and South Peninsula) (Abhilash et al. 2014a,b,c; Abhilash et al. 2015a,b; Sahai et al. 2013, 2015a,b). The skill of the EPS in predicting extreme rainfall events during JJAS has also been reported by Joseph et al. (2015). Since there is an increasing demand from user community for the forecast on subdivisional scale or even block/taluka level, it is essential to assess the ERP skill of the EPS over different meteorological subdivisions of India (shown in **Figure 1**), so as to understand the confidence level in utilising the forecasts over these regions.

Some earlier studies have analysed the skill of dynamical forecast products on subdivisional scale (Saseendran et al. 2002; Mohanty et al. 2013; Pattanaik 2014). Saseendran et al. (2002) has documented the skill of NCMRWF T80 spectral model in predicting the weekly cumulative rainfall over the different subdivisions, during the SW monsoons of 1994-1999. Mohanty et al. (2013) and Pattanaik (2014) analysed the skill of extended range rainfall forecasts during SW monsoon season. Mohanty et al. (2013) attempted to predict monsoon rainfall (month-wise and season as a whole) in extended range scale, while Pattanaik et al. (2014) analysed the skill of weekly extended range forecasts. But both of them were case studies and examined only one monsoon season. Nevertheless, no detailed study is available on the skill evaluation of extended range rainfall and temperature forecasts for different seasons on subdivisional scale. The present study is a *first-of-its-kind* attempt in this regard.

2. Data and Methodology

2.1. Data

As mentioned in the previous section, this study uses the extended range forecasts from the MME enrooted on CFS based Grand EPS (CGEPS; Abhilash et al. 2015a,b). CGEPS combines the CFS as well as the stand-alone atmospheric component of CFS (i.e.: GFS) forced with bias corrected CFS-forecasted sea surface temperature (SST; hereafter GFSbc) at T126 and T382 horizontal resolutions. Detailed skill analysis, improved spread-error relationship and probability prediction from CGEPS MME can be found from Abhilash et al. (2015a). Real-time implementation of this system and its performance during 2014 monsoon season can be found from Sahai et al. (2015). In order to give equal weights to all models and to add more diversity, the CGEPS has a total of 44 ensemble members with 11 members each from CFST126, CFST382, GFSbcT126 and GFSbcT382 for the ERP. The initial conditions have been prepared from coupled data assimilation system (CDAS) with T574L64 resolution atmospheric assimilation and MOM4 based oceanic assimilation, which is real-time extension of the CFS Reanalysis (CFSR) (Saha and Coauthors 2010).

The hindcast runs are available from 2001 onwards. Since the forecasts were initially generated during SW monsoon season alone, the hindcast sets are different for different seasons. For SW monsoon, the hindcasts are available till 2014. For NE monsoon season, the hindcast are available only till 2013. For both hot and cold seasons, the hindcast period is 2001-2010.

For verification purposes, we use the following: gridded rainfall from IMD at 1°X1° resolution (Rajeevan et al. 2006), maximum and minimum temperature dataset from IMD at 1°X1° resolution (Srivastava et al. 2008). Both rainfall and temperature datasets cover Indian land points only.

2.2. Methodology

To assess the skill of the MME, the present study uses different skill scores such as anomaly correlation coefficient (ACC), root mean skill score (RMSS), signal to noise ratio or predictability, Brier skill score (BSS), relative operative characteristic (ROC) area skill score. The first three skill scores represents the deterministic forecast, whereas the last two represents the probabilistic forecast.

a. Anomaly Correlation Coefficient (ACC)

This is a common verification metric used to evaluate the deterministic extended range forecasts, and is used to find out similarities in the patterns of departures from the climatological mean field (Wilks 2011). If the variation pattern of the anomalies of forecast is perfectly coincident with that of the anomalies of verifying value, ACC will take the maximum value of 1. Conversely, if the variation pattern is completely reversed, ACC takes the minimum value of -1.

ACC can be defined as:

$$ACC = \frac{\sum_{i=1}^{n} \frac{1}{n}\left(f_i - \bar{f}\right)\left(o_i - \bar{o}\right)}{\sqrt{\sum_{i=1}^{n} \frac{1}{n}\left(f_i - \bar{f}\right)^2 \sum_{i=1}^{n} \frac{1}{n}\left(o_i - \bar{o}\right)^2}}$$

where, n is the number of samples, $\left(f_i - \bar{f}\right)$ is forecasted anomaly from its own climatology and $\left(o_i - \bar{o}\right)$ is the observed anomaly from its own climatology.

b. Root Mean Skill Score (RMSS)

The RMSS is essentially the root mean square error (RMSE) of the forecasts compared to the RMSE of the climatology (i.e., standard deviation). This metric is applicable to deterministic forecasts alone. Closer to unity values are indicative of better skill of the forecasts, and any value greater than zero represents a forecast better than climatology.

RMSS can be expressed as:

$$RMSS = 1 - \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(f_i - o_i\right)^2}}{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(o_i - \bar{o}\right)^2}}$$

c. Predictability

The limit of potential predictability is generally considered as the lead time at which the signal to noise ratio (SNR) becomes less than one. The signal is defined as the standard deviation of ensemble mean forecasts valid at the same forecast lead time and noise as standard deviation of ensemble members from ensemble mean forecast.

$$SNR = \frac{Signal}{Noise}$$

d. Brier Skill Score (BSS)

BSS measures the relative skill of forecasts compared to a standard or climatological or persistence forecast (Wilks 2011).

BSS can be expressed as:

$$BSS = 1 - \frac{BS}{BS_{ref}}$$

where $BS = \frac{1}{n}\sum_{k=1}^{n}\left(f_k - o_k\right)^2$ is the Brier score that averages the squared differences between pairs of forecast probabilities and the subsequent observations.

A positive value of BSS refers to forecast better than climatology and hence is considered as skillful. BSS has a negative value if the forecast error is more than that of climatological forecast.

e. Relative Operative Characteristic (ROC) Area Skill Score

The ROC diagram represents the ability of a set of probabilistic forecasts to discriminate a dichotomous event, relating the hit rate (HR) and the false alarm rate (FAR) (Kharin and Zwiers 2003). HR is defined as the proportion of occurrences, when both the observed rainfall and the forecasted rainfall are in the same category. Similarly, FAR is defined as the proportion of non-occurrences, i.e. when forecasted rainfall is not in the observed category. In a ROC curve, the closer clustering of probability values indicates less spread among the ensemble members. ROC Area Skill Score is a validation index in reference to the probability forecasts with no value of information, i.e. when HR equals FAR.

$$ROC = \frac{HR}{FAR}$$

The index is unity for perfect forecast, and values greater than 0.5 (i.e., when HR > FAR) are considered to be skillful.

3. Skill over meteorological subdivisions of India

In this section, we discuss the season-wise skill of the EPS over the different meteorological subdivisions shown in Figure 1, except Andaman and Nicobar islands and Lakshadeep.

3.1 SW Monsoon Season

SW monsoon season is the main rainy season over most parts of the country, except southeast peninsula. **Figure 2** shows the ACC of rainfall for 14 year (2001-2014) period for all pentads during JJAS. Correlations significant at 99.9% significance level are only shaded in the figure. It is clear from the figure that the MME has considerable skill over most parts of the country till P3 lead, and reasonable skill at P4 lead. RMSS values greater than zero are considered to be skillful and the MME has reasonable RMSS during first two pentads (**Figure 3**). Even at P4 lead, some subdivisions over western parts of the country show sensible skill. **Figure**

4 depicts the predictability limit of JJAS rainfall over the different subdivisions. It is found that the central, eastern and northeastern parts of the country (which are mainly affected by lows and depressions) has predictability of only 6-10 days. The maximum predictability (of 14-16 days) is noticed over coastal Karnataka and Konkan & Goa regions.

Figures 5-8 illustrate the probabilistic skill scores - BSS and ROC for the above normal (AN) and below normal (BN) categories of JJAS rainfall. **Figures 5** and **6** represent the BSS for AN and BN categories respectively. Most parts of the country has better BSS till P3 lead. Till P4 lead, the northwestern and central parts show reasonable BSS for both AN and BN categories. The subdivisions over west coast has better-than-climatology skill up to P3 lead. The ROC area skill score for the AN and BN categories for the JJAS rainfall is shown in **Figures 7** and **8** correspondingly. As mentioned in Section 2.2, values greater than 0.5 designate useful skill. It is interesting to note that the MME has valuable skill for both categories till P4 lead, with an exception over Nagaland-Manipur-Mizoram-Tripura region in P4 lead.

3.2 NE Monsoon Season

NE monsoon season is the main rain-giving season for southeast peninsular India, especially for the state of Tamil Nadu. According to Kripalani and Kumar (2004), the subdivisions affected by NE monsoon are Kerala, Tamil Nadu, North Interior Karnataka, South Interior Karnataka, Coastal Karnataka, Rayalaseema and Coastal Andhra Pradesh (AP). Therefore, we have plotted the skill scores (calculated based on the hindcast period of 2001-2013) only over those regions.

Figure 9 depicts the ACC of OND rainfall for all pentads during the hindcast period. It is clear from the figure that the CGEPS MME has significant correlations over all relevant subdivisions up to P3 lead. During P4 lead, the ACC becomes insignificant for North Interior Karnataka, Rayalaseema and Coastal AP. Similar results are seen for RMSS for the first two pentads (**Figure 10**). The RMSS values indicate that the forecasts are skillful over Kerala, Tamil Nadu and coastal Karnataka till P4 lead. **Figure 11** indicates that the predictability of OND rainfall is more than 10 days for all the subdivisions. The predictability is maximum over north Interior Karnataka, with decreasing values over coastal and south Interior Karnataka, followed by Rayalaseema and coastal AP, and then Kerala and Tamil Nadu.

The BSS for OND rainfall for AN ad BN categories are shown plotted in **Figures 12** and **13**. Skillful BSS for AN for all pentad leads is observed only over Kerala, while for BN category, it is over north Interior Karnataka and coastal AP. For BN category, all regions possess skillful BSS till P3 lead. The ROC skill score for AN and BN categories shows acceptable skill for all pentad leads, which is very good indication that the MME is capable of predicting the extremes of OND rainfall (**Figures 14** and **15**).

3.3 Hot Season

India experiences spells of hot weather, known as *heat waves* during AMJ, especially over the northwestern, central and southeast regions of the country. Maximum temperature (Tmax) is the important weather parameter that determines the severity of heat waves. Therefore, this section examines the hindcast (2001-2010) skill of the CGEPS MME in predicting Tmax during all pentads of AMJ.

Figure 16 shows the ACC of Tmax during AMJ. It is remarkable that the MME has significant skill up to P4 lead almost all over the country, except northeastern parts and Jammu and Kashmir regions. The regions that experience heat wave conditions has remarkable ACC during all 4 pentad leads, which gives us the confidence to use the MME for heatwave predictions. The RMSS values also demonstrate similar results (**Figure 17**). At P1 lead, the RMSS reach even up to 0.8 over northwestern parts of the country. However over Orissa where severe heat wave conditions occur, the useful RMSS is till P2 lead only. The predictability figure (**Figure 18**) for AMJ is very interesting. Most parts of the country has predictability of more than 16 days, with almost whole of central India having predictability of >32 days.

Since for the prediction of heat waves the *higher-than-normal* temperature is seminal, we examine the probabilistic prediction skill of Tmax for AN category in **Figures 19-20**. The BSS for AN category is shown in **Figure 19**. It is found that the heat wave region (i.e, northwestern, central and southeastern parts) has useful skill up to P3 lead. For northwestern and central India, the skill extends till P4 lead. The ROC area skill score plotted in **Figure 20** affirms the usefulness of the Tmax forecasts till P4 lead.

3.4 Cold Season

During the winter season, the northern parts of the country experience spells of extremely cold weather known as *cold* waves, due to the passage of *western disturbances*. At times, they even move up to central India. Minimum temperature (Tmin) is the main weather parameter that determines the severity of cold waves and hence in this section, we examine the prediction skill of Tmin for all pentads during NDJF of hindcast period 2001-2010.

Figure 21 portrays the ACC for Tmin during NDJF and the figure clearly shows that the correlations are significant all over the country till P3 lead. At P4 lead, the ACC becomes insignificant at Konkan & Goa, Telengana, north interior Karnataka, Orissa and Chattisgarh. However, these regions are generally not affected by cold waves. Compared to other seasons, skillful RMSS values are noticed over many parts of the country till P4 lead during NDJF (**Figure 22**). At P1 lead, the RMSS values of more than 0.5 are noted almost all over the country. This is indicative of the remarkable skill of the CGEPS MME in predicting Tmin. The predictability of Tmin is also noteworthy (>20 days) over most parts of the country (**Figure 23**).

Since cold waves are related to *lower-than-normal* temperatures, the probabilistic skill scores are evaluated for BN category alone in **Figures 24-25**. The northern subdivisions over the country that are generally affected by cold waves have useful BSS for BN category up to P3 lead (**Figure 24**). The skill becomes inept at P4 lead. The ROC skill scores for BN category are competent up to P4 lead (**Figure 25**), which is remarkable.

4 Conclusions

With the increasing demand from user community for the availability of forecast products on smaller spatial scales, it is necessary to document the forecast skill at these domains. This study assesses the ERP skill of CGEPS MME indigenously developed at IITM. The hindcast skill of rainfall during SW and NE monsoon seasons and temperature during hot and cold seasons over different meteorological subdivisions are examined here, so as to understand the confidence level of using these forecasts over these regions. The deterministic as well as probabilistic skill scores are assessed for all the seasons. For the assessment of deterministic forecast skill, we use ACC, RMSS and signal to noise ratio; whereas for probabilistic forecast, BSS and ROC area skill scores are used.

It is found that the CGEPS MME possesses useful prediction skill for JJAS rainfall till P3 lead, and for some subdivisions, the skill extends even up to P4 lead. For OND rainfall, the deterministic and probabilistic skill scores indicate that the prediction is skillful over the relevant subdivisions, till P2 lead. The skill reduces for longer leads, especially for probabilistic prediction of AN and BN categories. During the hot season, the Tmax over the subdivisions affected by heat wave conditions, have significant ACC, RMSS, BSS and ROC skill score for P1-P4 pentad leads. The Tmin during NDJF possesses significant values of ACC, RMSS and ROC till P4 lead. However, the BSS for BN category over the cold wave region is skillful only up to P3 leads. The predictability of Tmax (Tmin) is more (>32days) during AMJ (NDJF), compared to JJAS and OND rainfall.

Thus, the present study reveals that the present CGEPS MME has appreciable skill (both probabilistic and deterministic) in predicting the rainfall during SW and NE monsoon seasons, maximum temperature during summer season, and minimum temperature during winter season over the different meteorological subdivisions of India. This provides the optimism to use this EPS for the operational purpose, at smaller spatial scales.

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Figure Captions

Figure 1: Meteorological subdivisions of India. Figure courtesy - IITM Pune

Figure 2: Pentad wise anomaly correlation coefficient (ACC) of JJAS rainfall for all pentads during 2001-2014

Figure 3: Pentad wise Root Mean Skill Score (RMSS) of JJAS rainfall for all pentads during 2001-2014

Figure 4: Predictability limit (day when signal equals noise) of JJAS rainfall for all pentads during 2001-2014

Figure 5: Pentad wise Brier Skill Score (BSS) of JJAS rainfall in above normal (AN) category for all pentads during 2001-2014

Figure 6: Pentad wise Brier Skill Score (BSS) of JJAS rainfall in below normal (BN) category for all pentads during 2001-2014

Figure 7: Pentad wise Relative Operative Characteristic (ROC) Area Skill Score of JJAS rainfall in above normal (AN) category for all pentads during 2001-2014

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Figure 10: Same as Figure 3, but for OND rainfall for all pentads during 2001-2013

Figure 11: Same as Figure 4, but for OND rainfall for all pentads during 2001-2013

Figure 12: Same as Figure 5, but for OND rainfall for all pentads during 2001-2013

Figure 13: Same as Figure 6, but for OND rainfall for all pentads during 2001-2013

Figure 14: Same as Figure 7, but for OND rainfall for all pentads during 2001-2013

Figure 15: Same as Figure 8, but for OND rainfall for all pentads during 2001-2013

Figure 16: Same as Figure 2, but for maximum temperature (Tmax) for all pentads of AMJ during 2001-2010

Figure 17: Same as Figure 3, but for maximum temperature (Tmax) for all pentads of AMJ during 2001-2010

Figure 18: Same as Figure 4, but for maximum temperature (Tmax) for all pentads of AMJ during 2001-2010

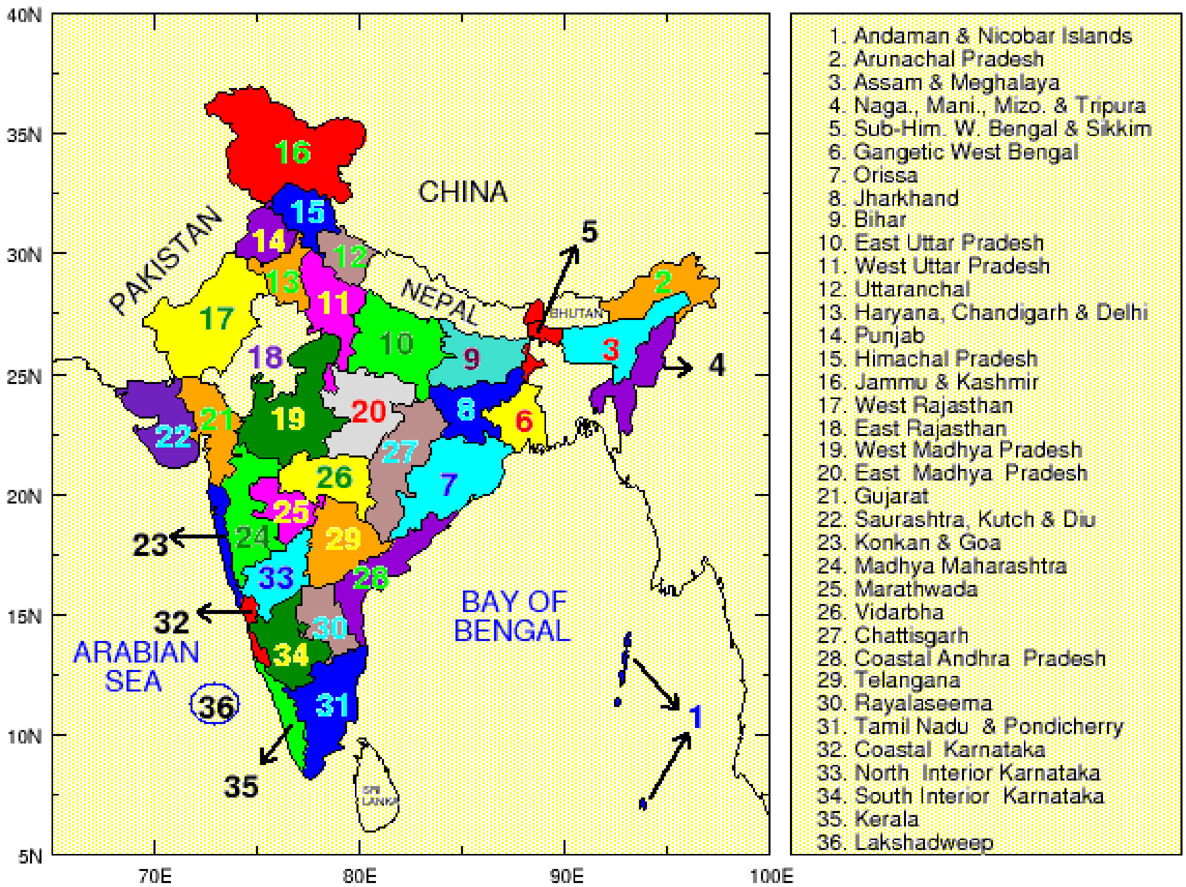

Figure 1: Meteorological subdivisions of India. Figure courtesy - IITM Pune

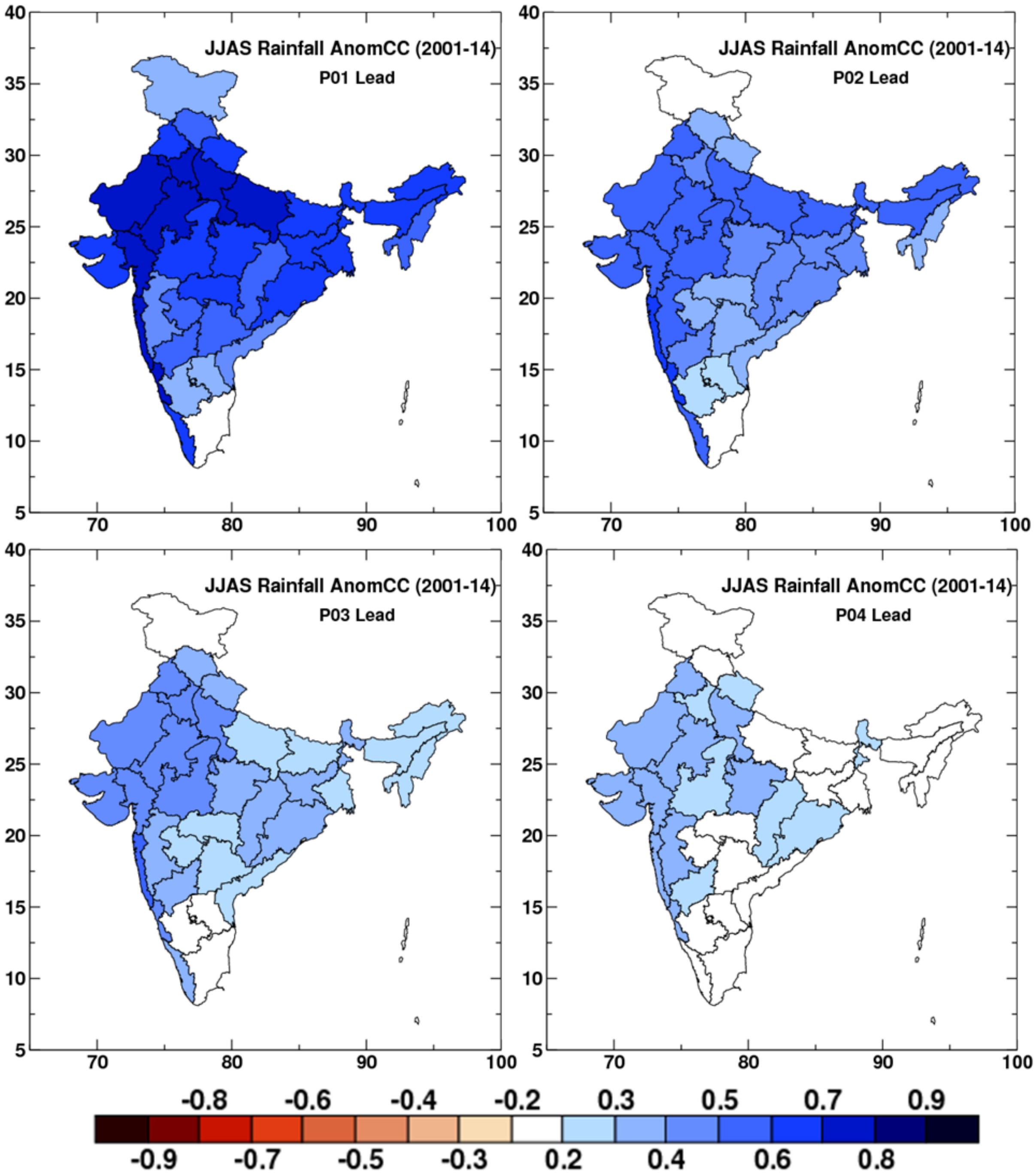

Figure 2: Pentad wise anomaly correlation coefficient (ACC) of JJAS rainfall for all pentads during 2001-2014

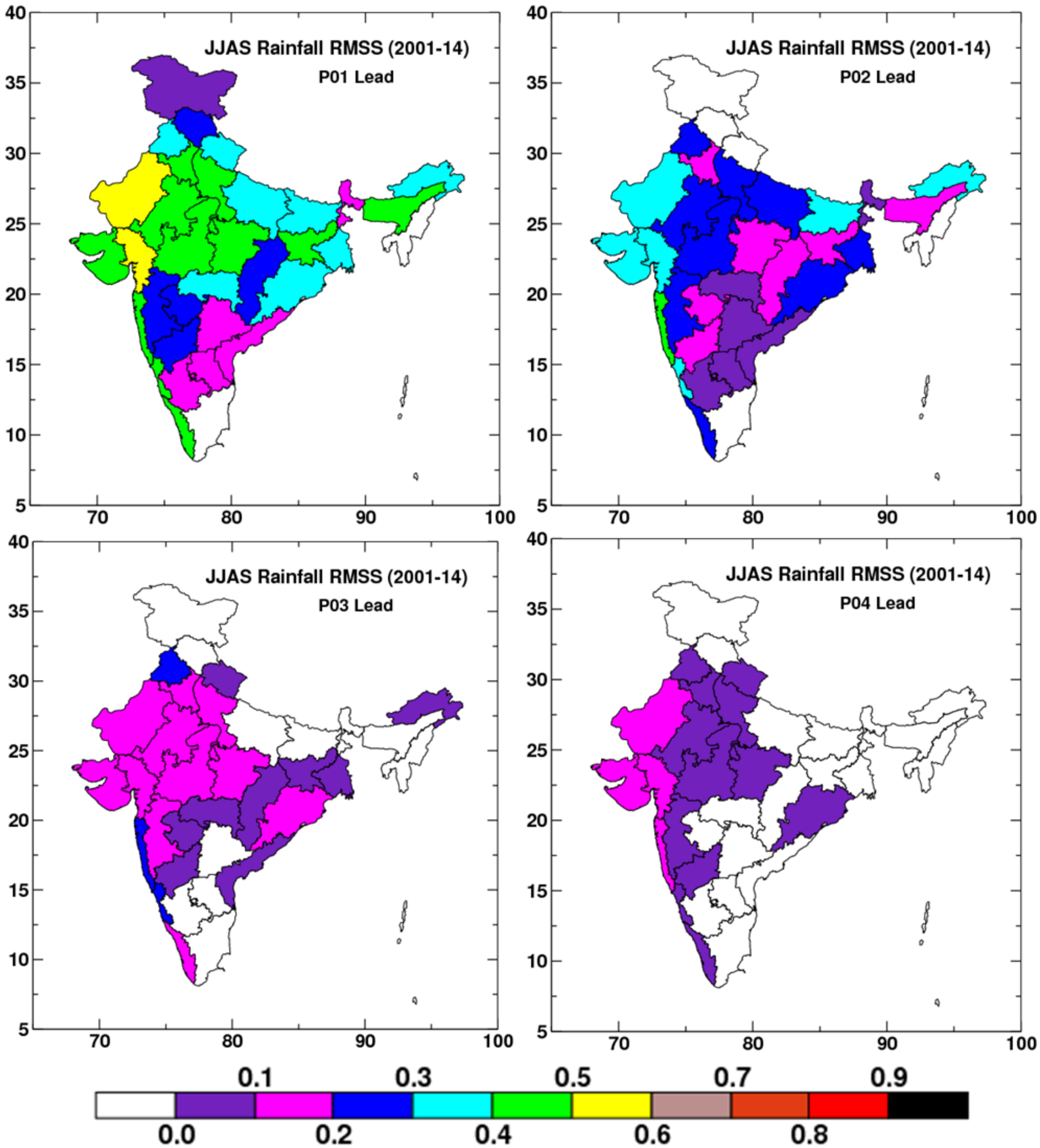

Figure 3: Pentad wise Root Mean Skill Score (RMSS) of JJAS rainfall for all pentads during 2001-2014

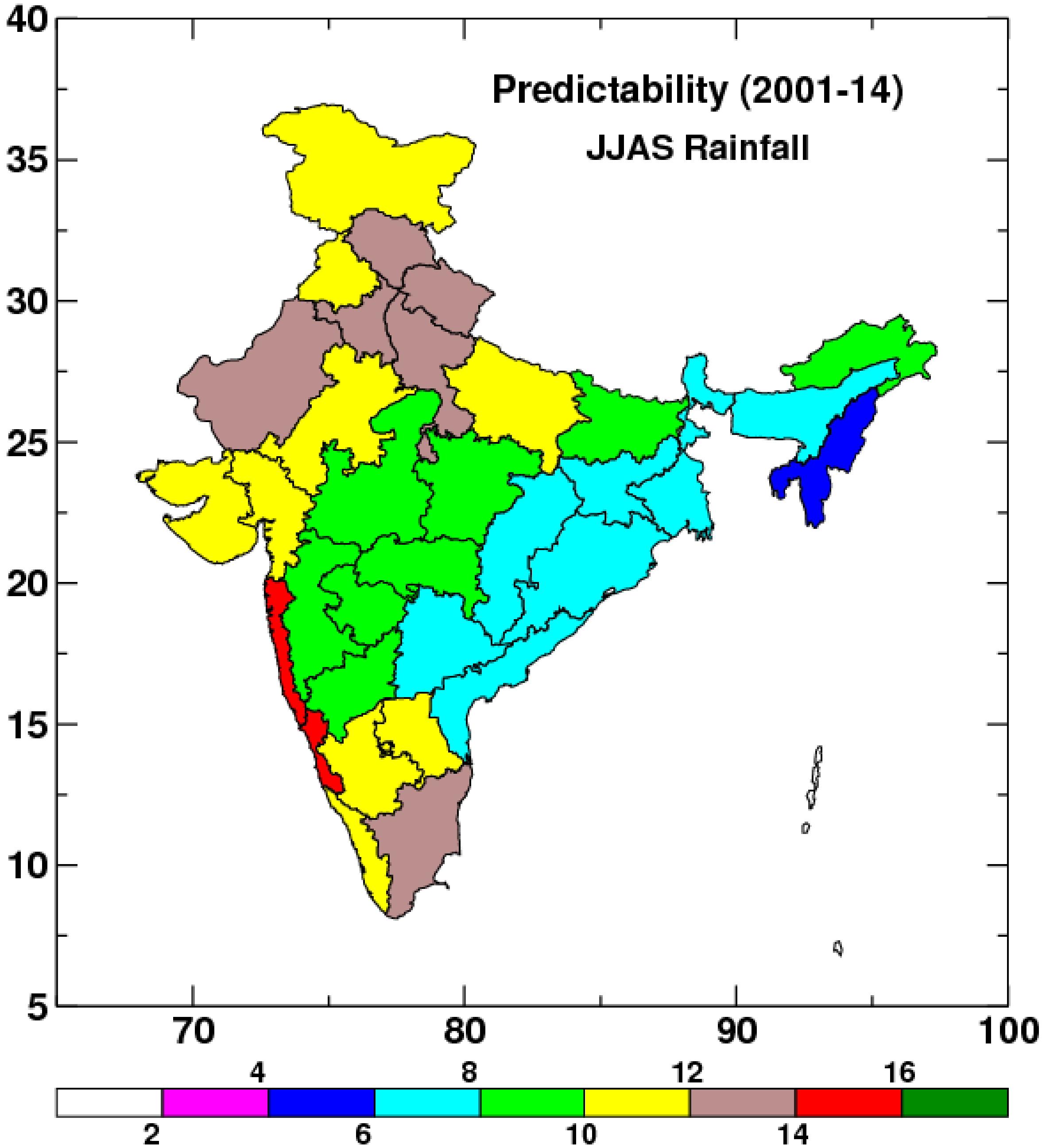

Figure 4: Predictability limit (day when signal equals noise) of JJAS rainfall for all pentads during 2001-2014

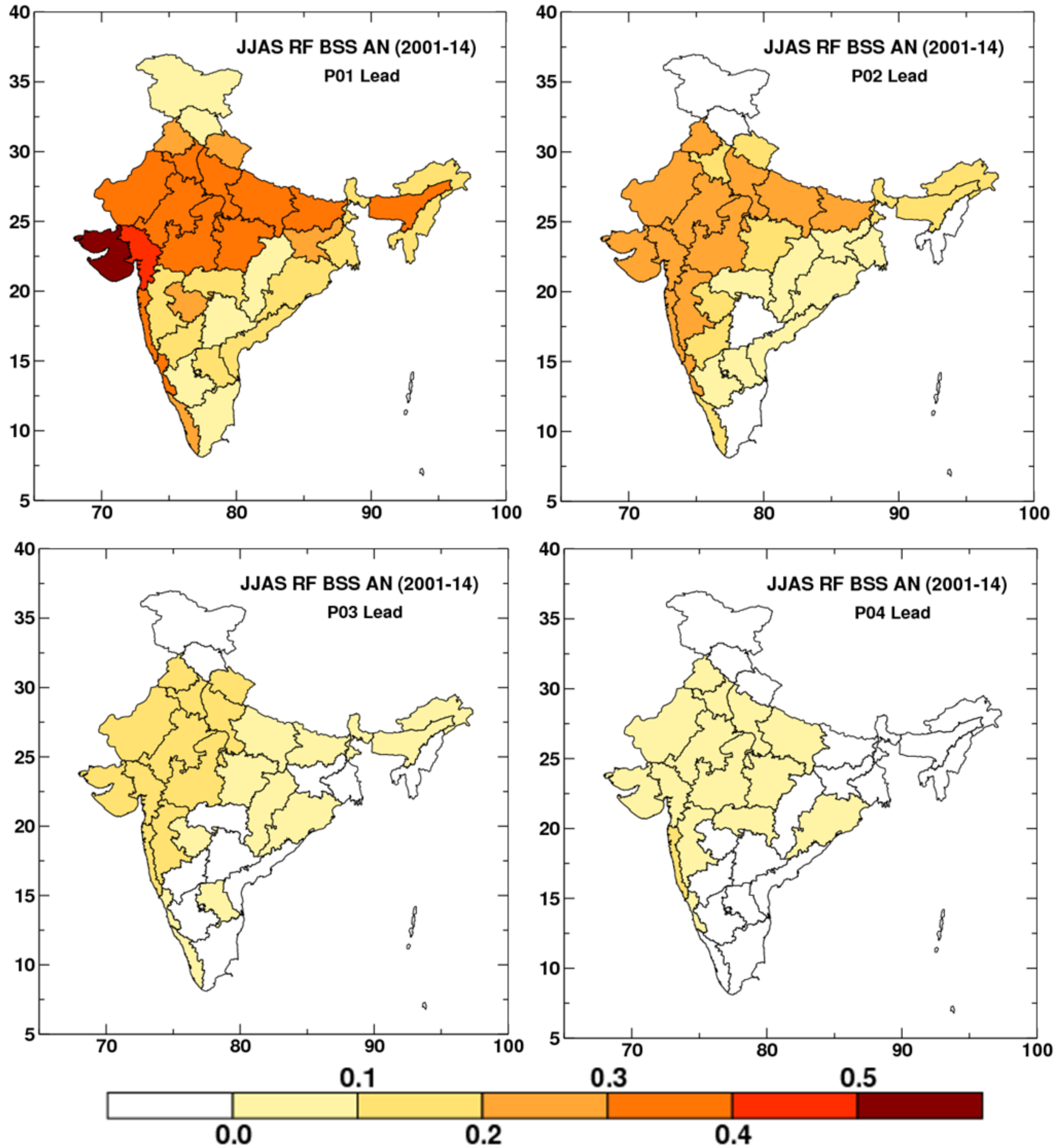

Figure 5: Pentad wise Brier Skill Score (BSS) of JJAS rainfall in above normal (AN) category for all pentads during 2001-2014

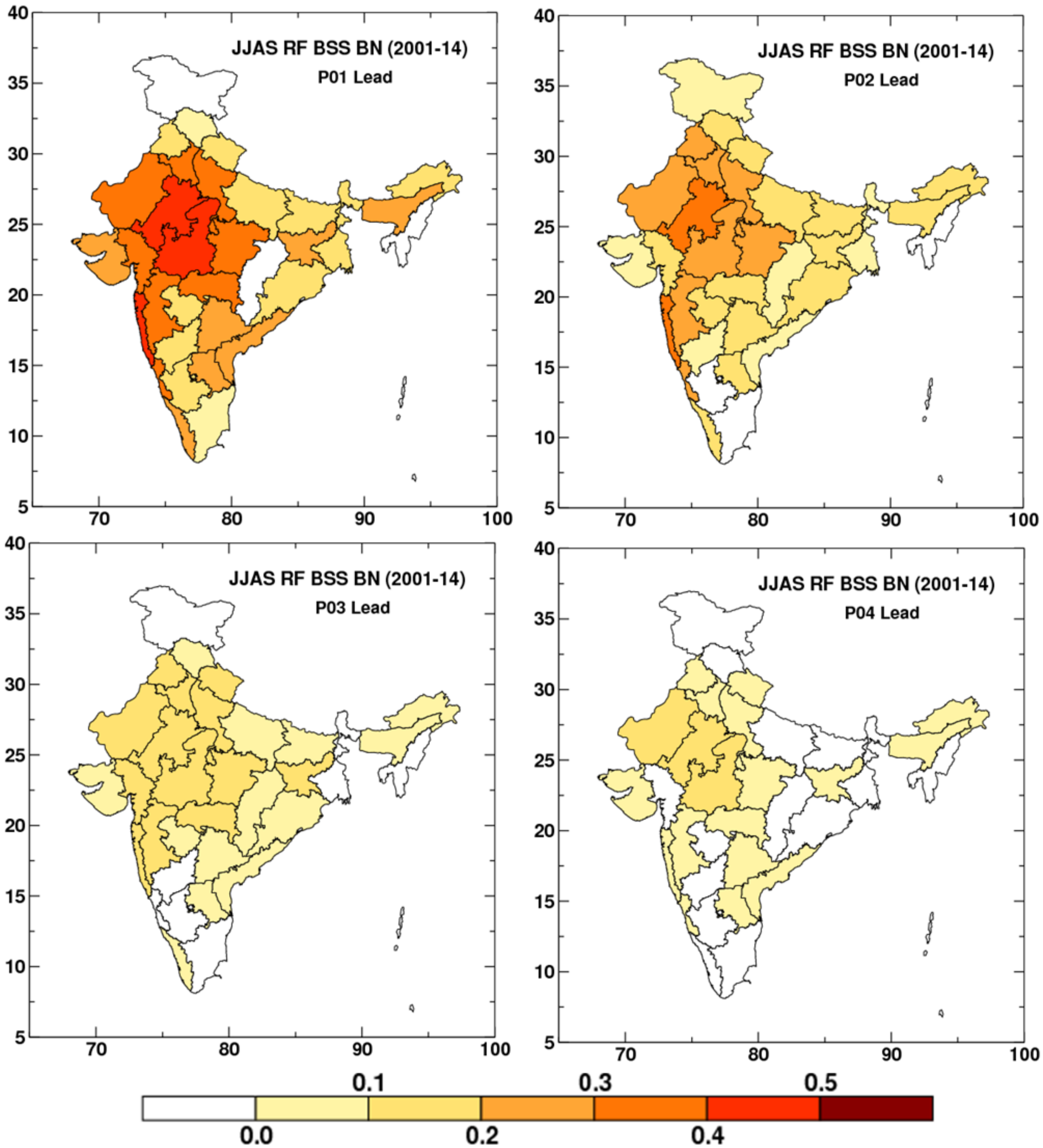

Figure 6: Pentad wise Brier Skill Score (BSS) of JJAS rainfall in below normal (BN) category for all pentads during 2001-2014

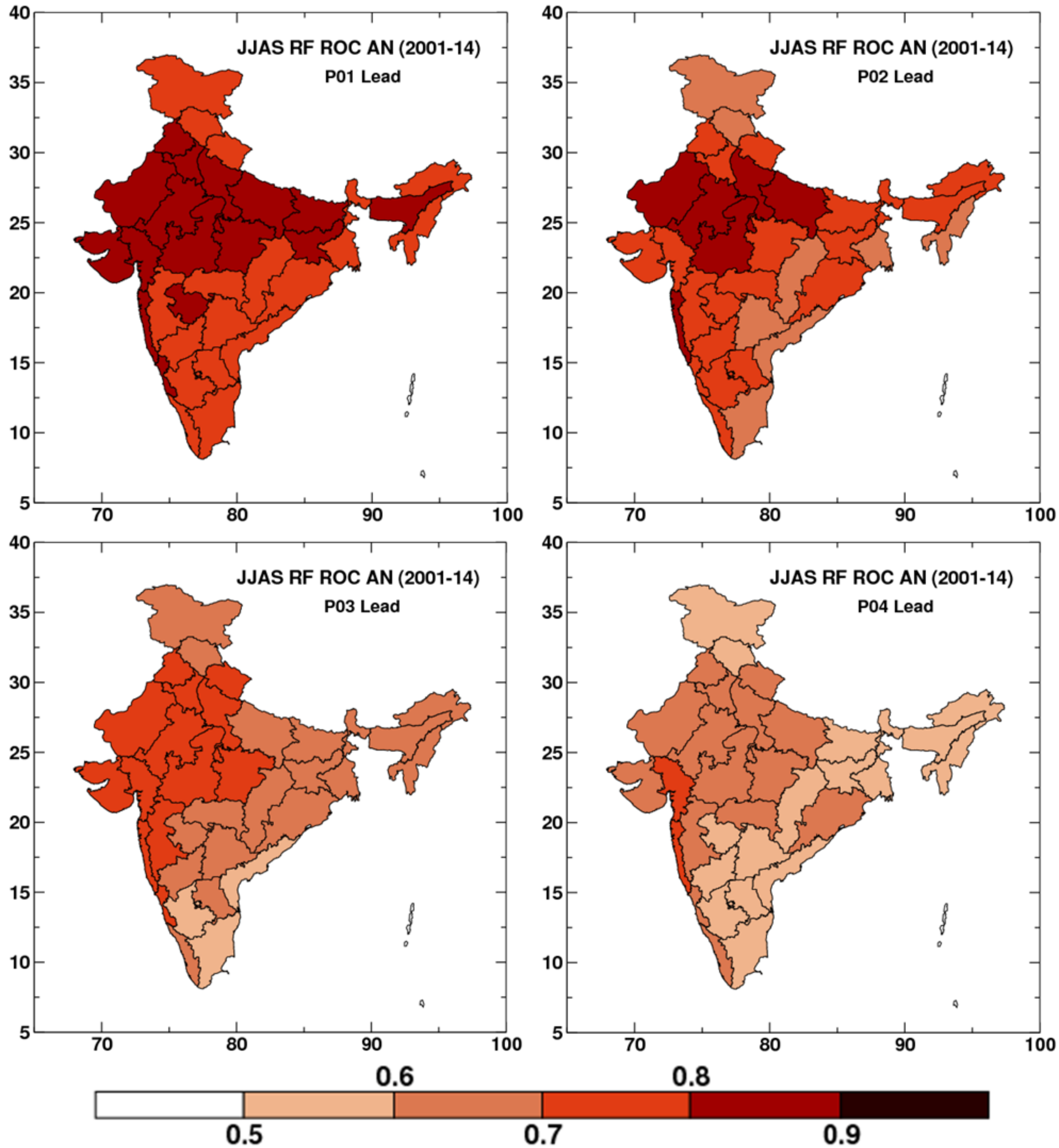

Figure 7: Pentad wise Relative Operative Characteristic (ROC) Area Skill Score of JJAS rainfall in above normal (AN) category for all pentads during 2001-2014

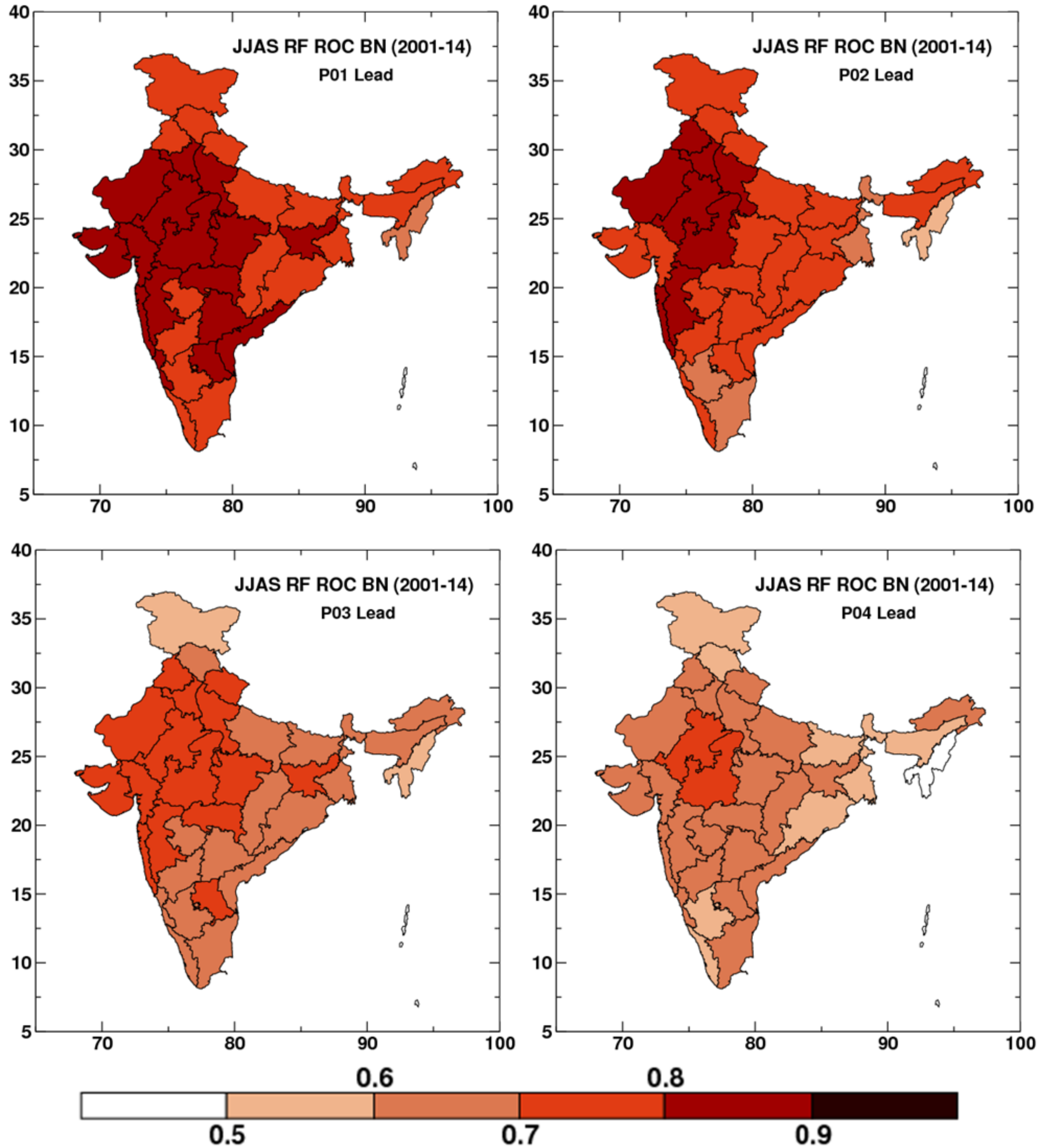

Figure 8: Pentad wise Relative Operative Characteristic (ROC) Area Skill Score of JJAS rainfall in below normal (BN) category for all pentads during 2001-2014

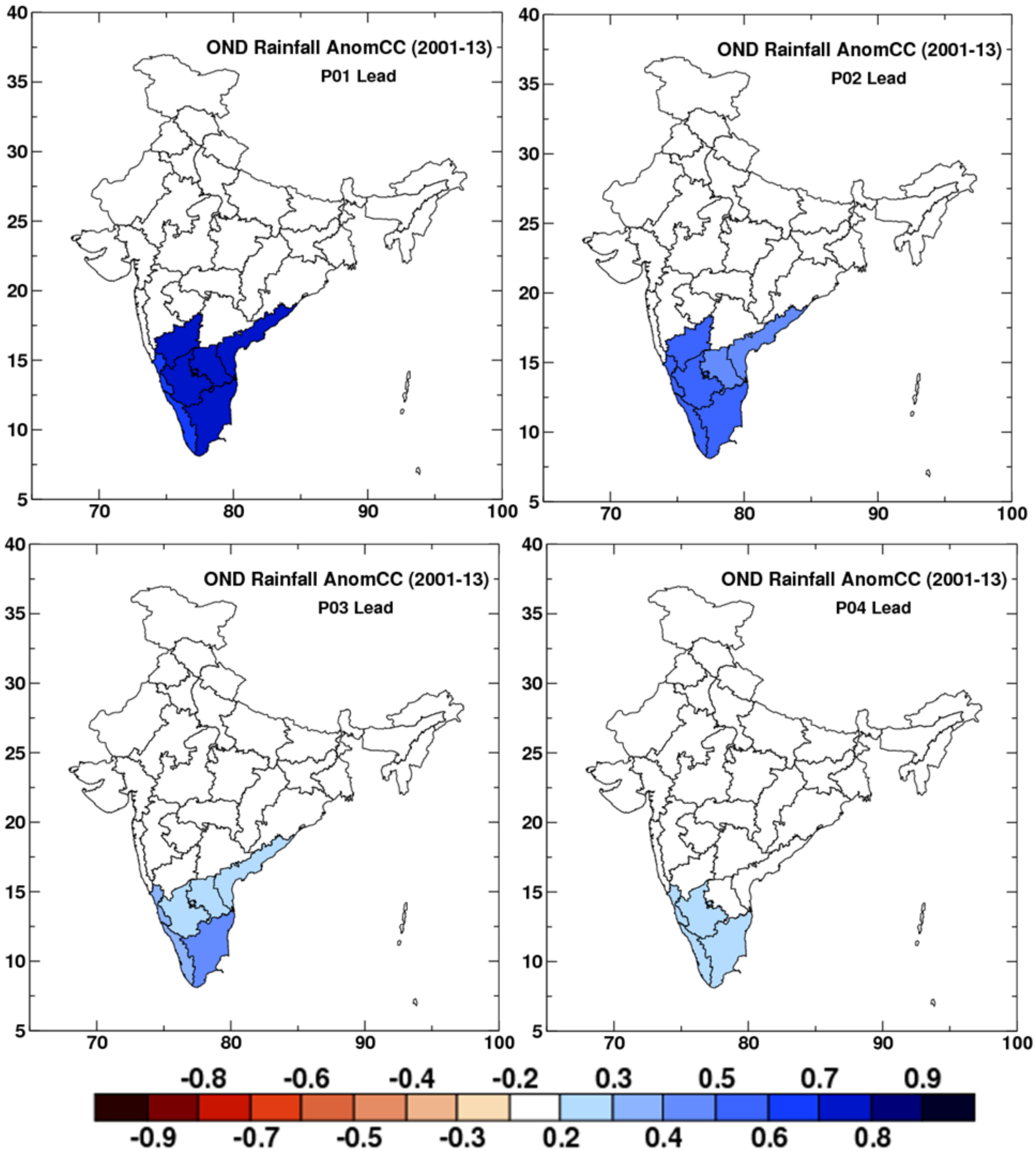

Figure 9: Same as Figure 2, but for OND rainfall for all pentads during 2001-2013

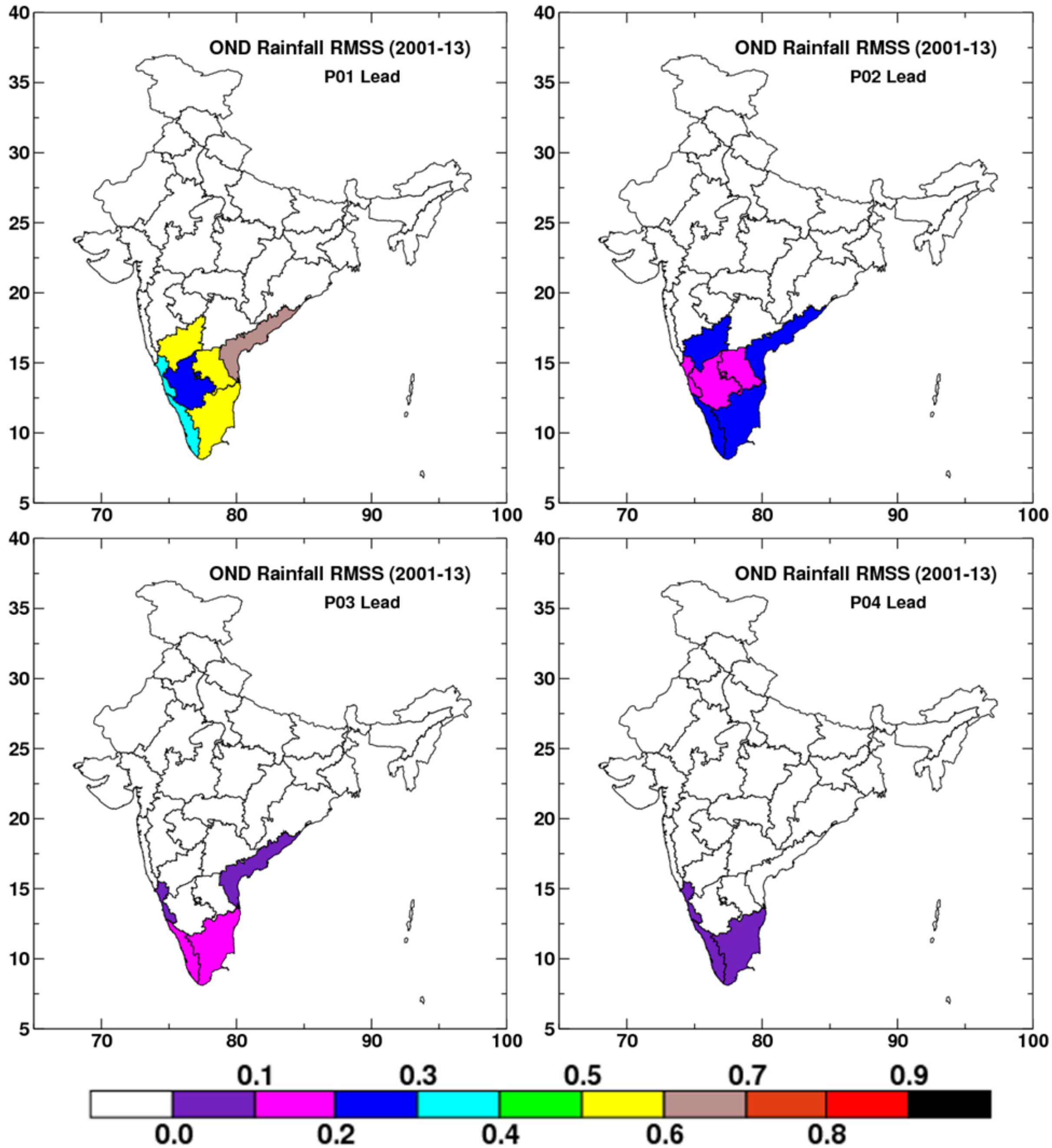

Figure 10: Same as Figure 3, but for OND rainfall for all pentads during 2001-2013

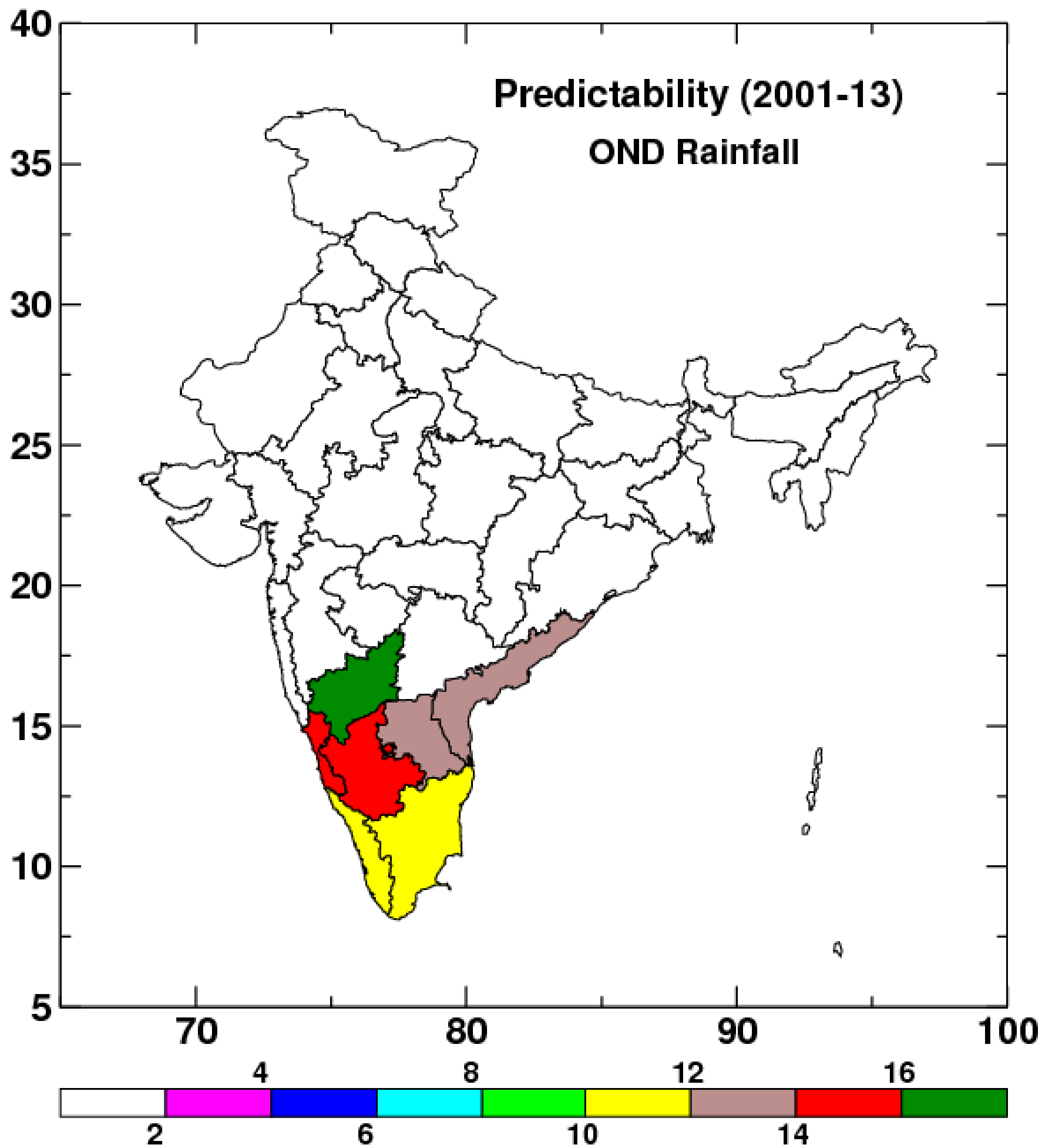

Figure 11: Same as Figure 4, but for OND rainfall for all pentads during 2001-2013

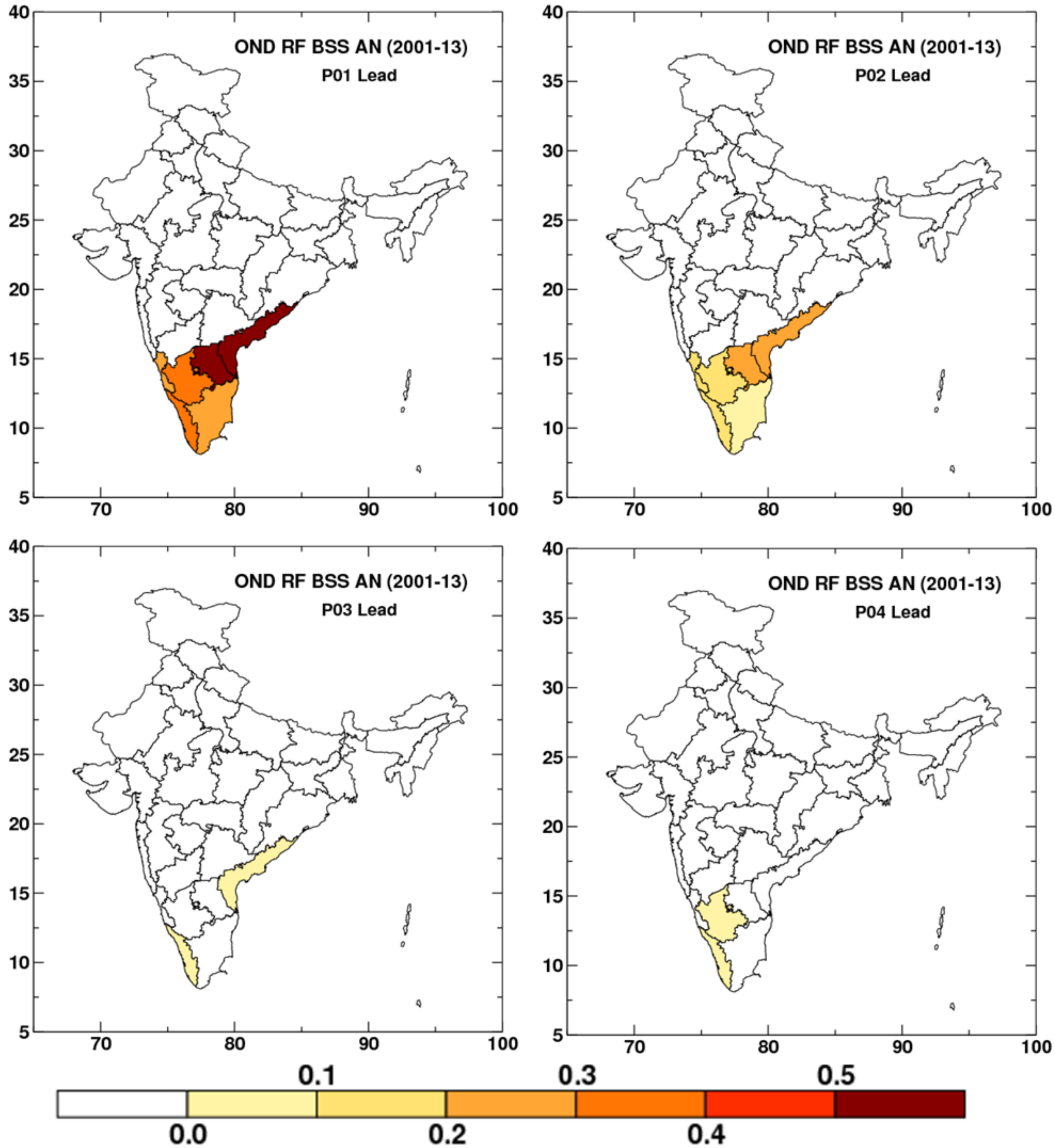

Figure 12: Same as Figure 5, but for OND rainfall for all pentads during 2001-2013

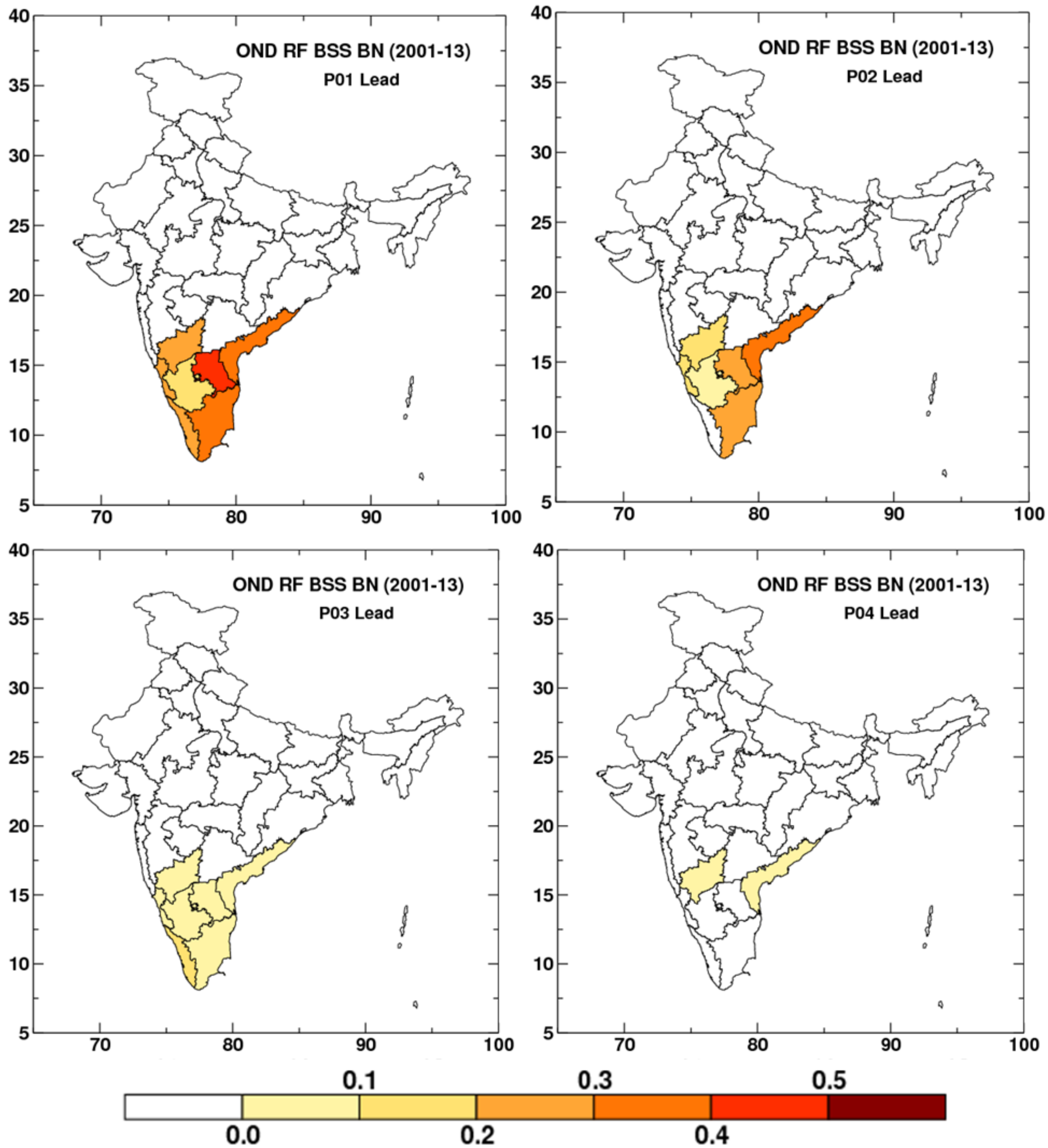

Figure 13: Same as Figure 6, but for OND rainfall for all pentads during 2001-2013

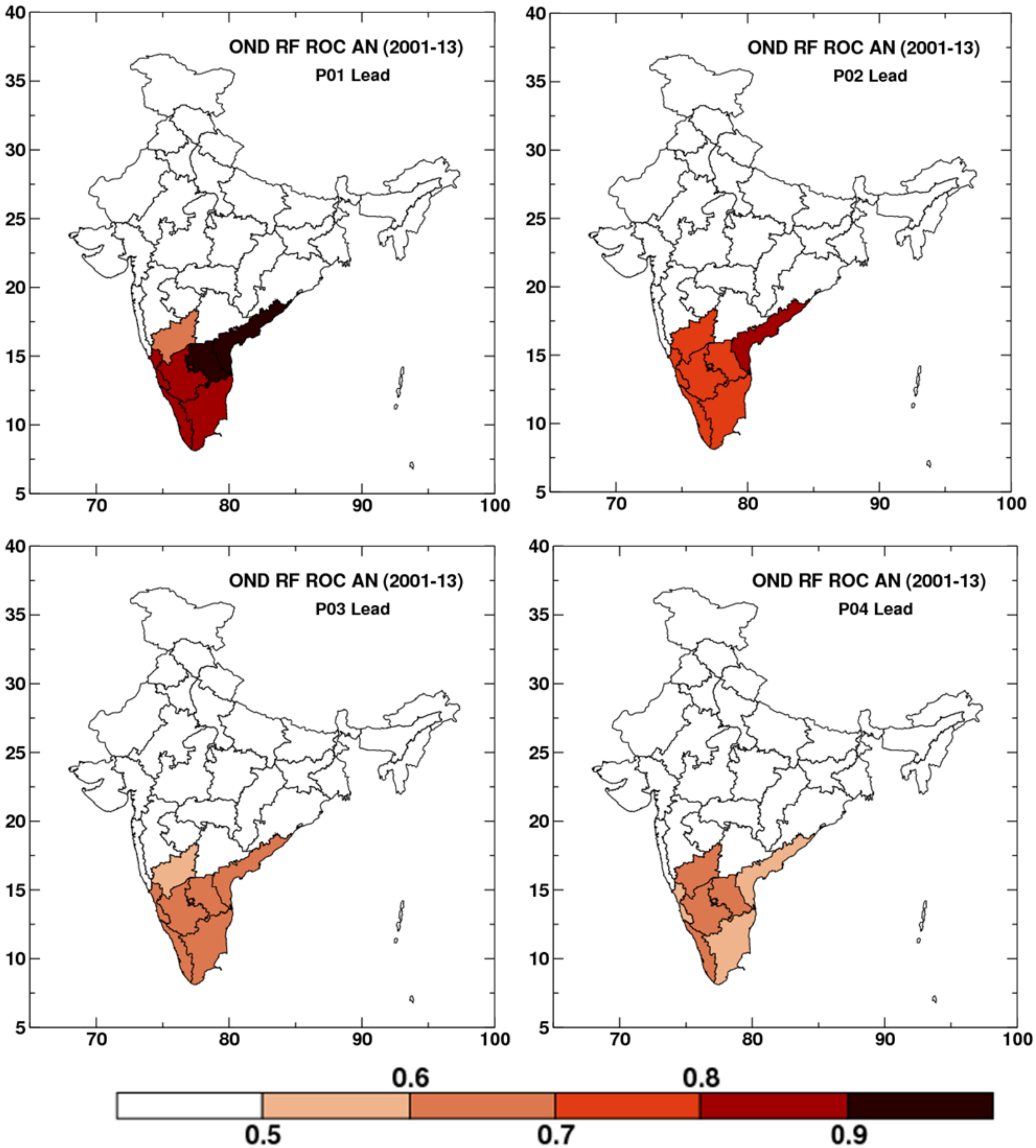

Figure 14: Same as Figure 7, but for OND rainfall for all pentads during 2001-2013

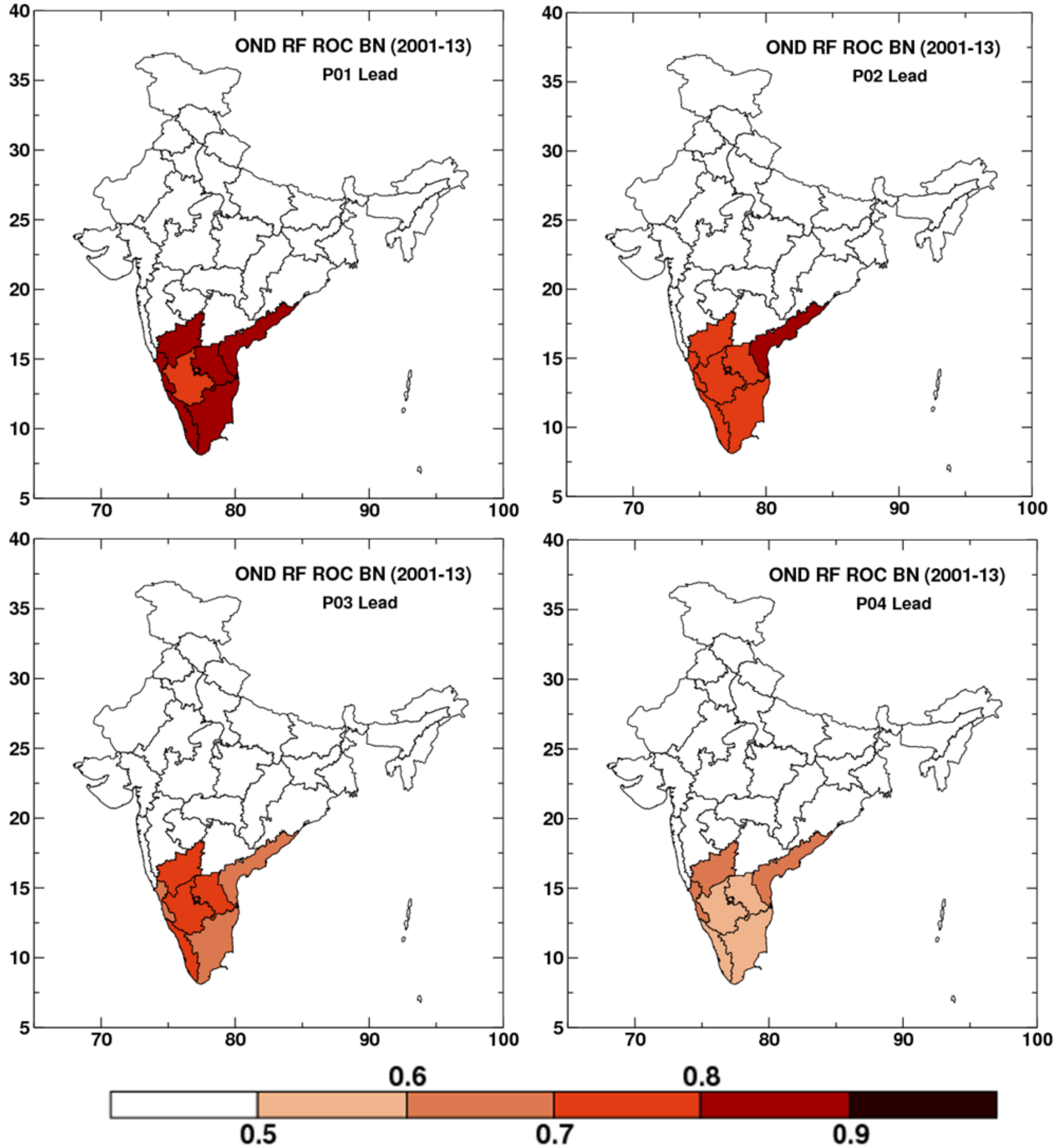

Figure 15: Same as Figure 8, but for OND rainfall for all pentads during 2001-2013

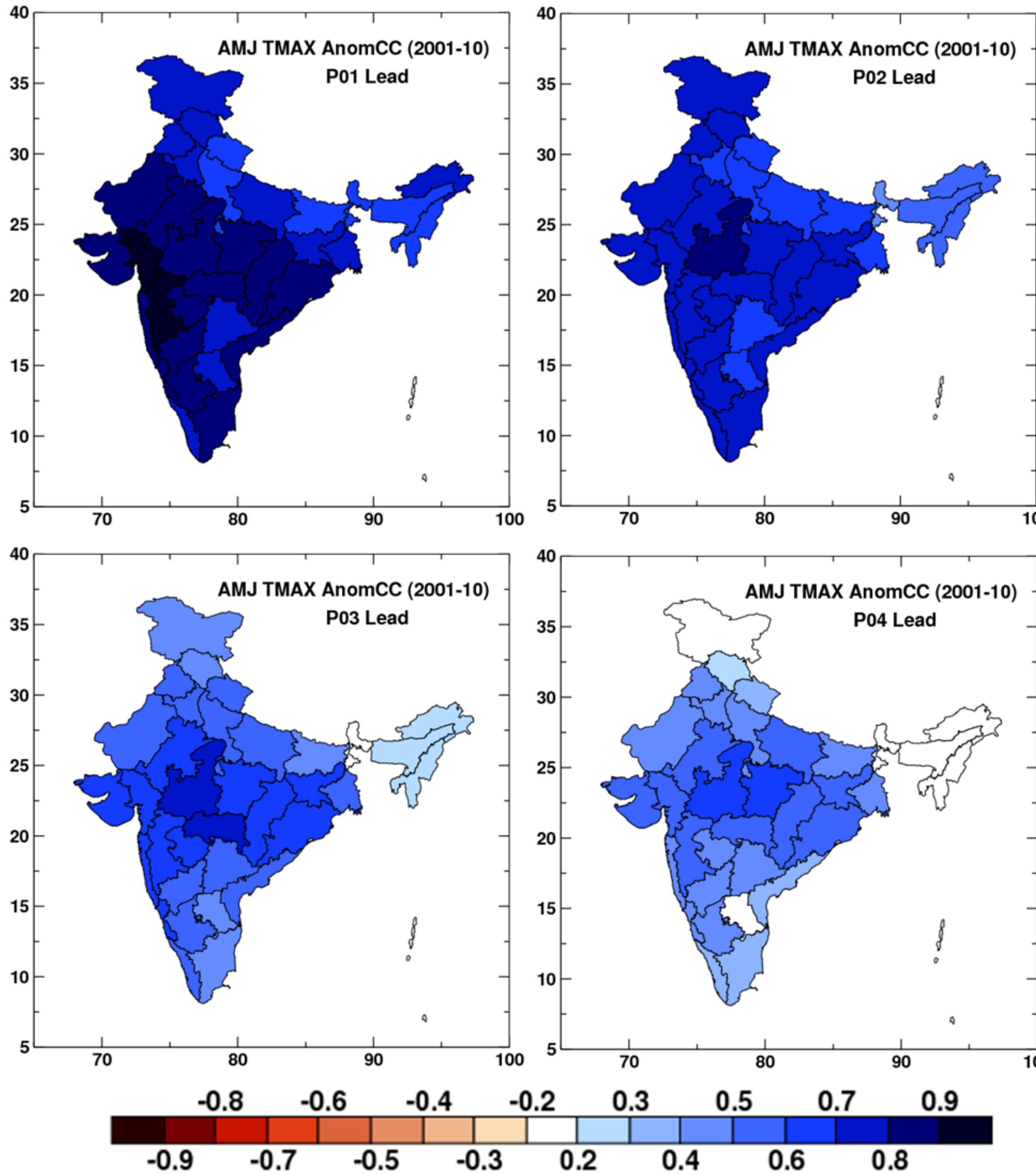

Figure 16: Same as Figure 2, but for maximum temperature (Tmax) for all pentads of AMJ during 2001-2010

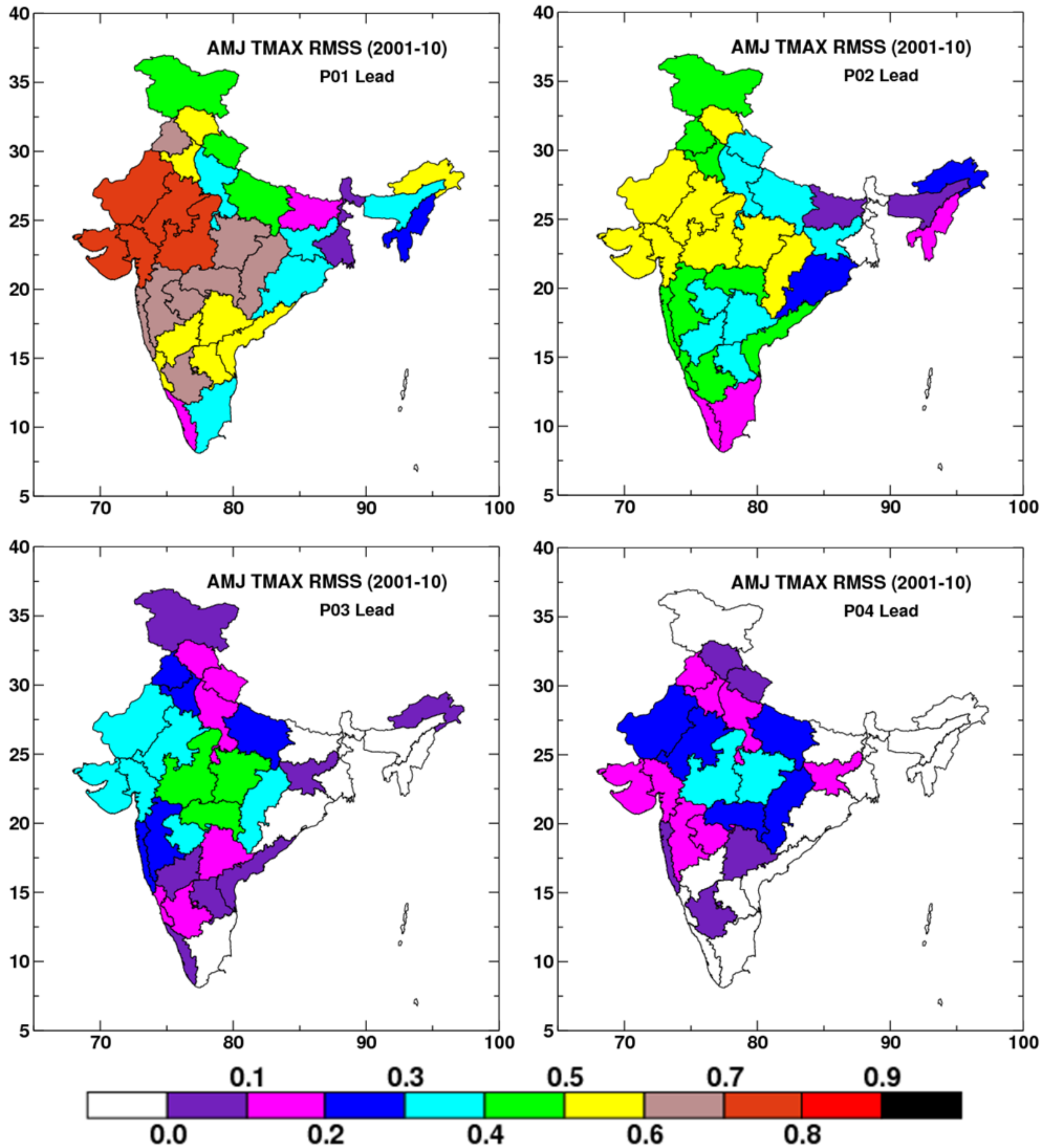

Figure 17: Same as Figure 3, but for maximum temperature (Tmax) for all pentads of AMJ during 2001-2010

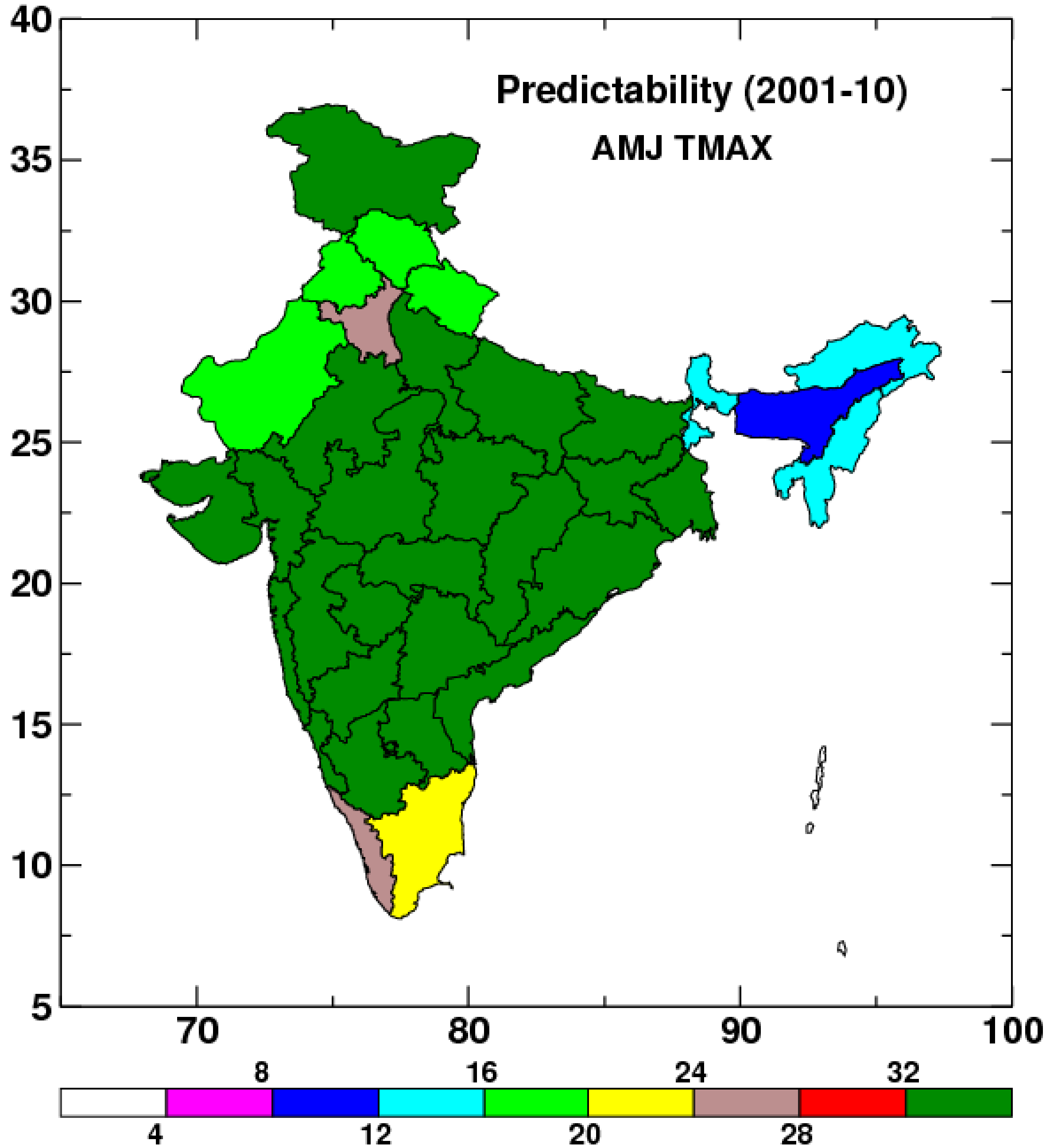

Figure 18: Same as Figure 4, but for maximum temperature (Tmax) for all pentads of AMJ during 2001-2010

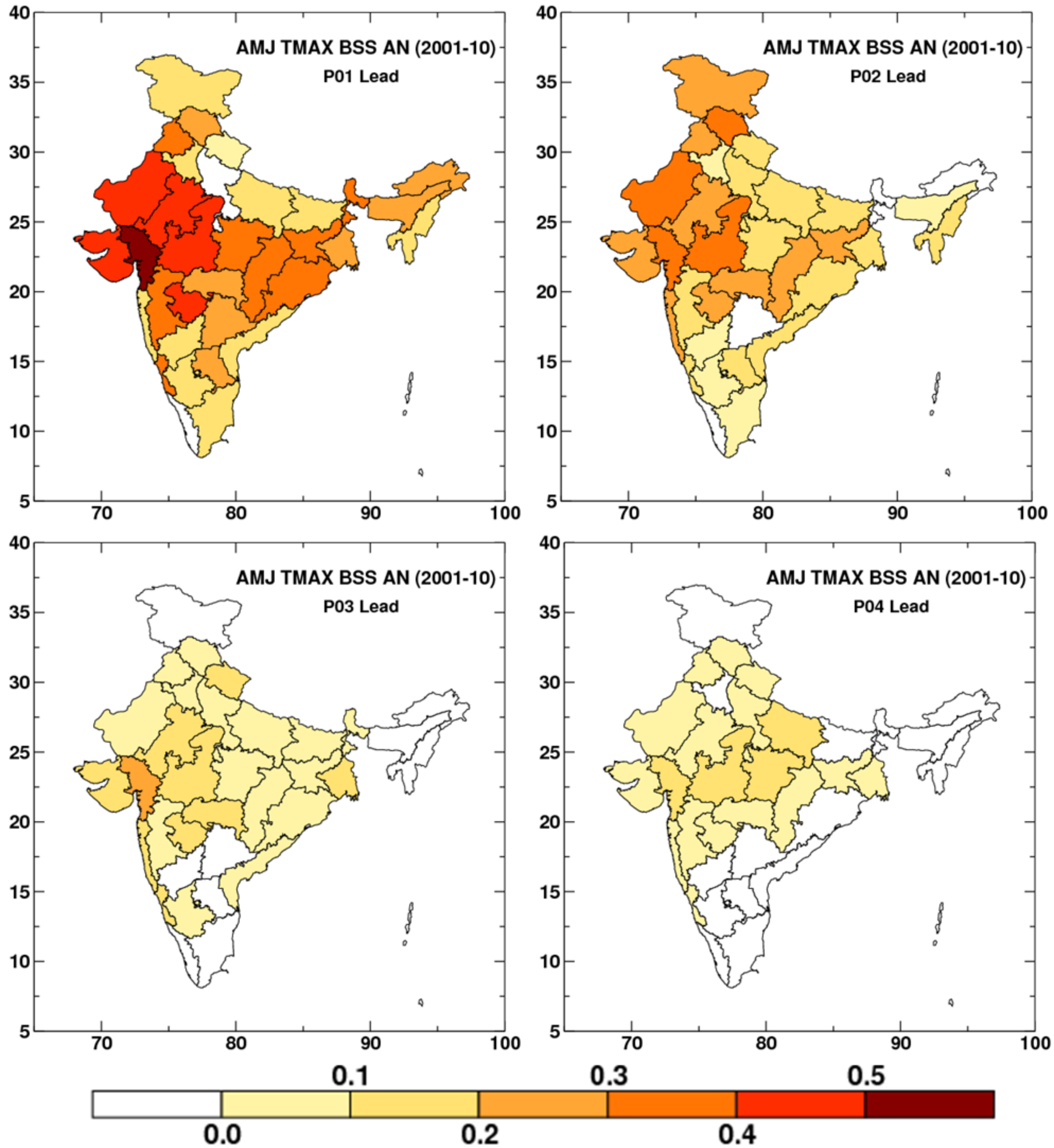

Figure 19: Same as Figure 5, but for maximum temperature (Tmax) for all pentads of AMJ during 2001-2010

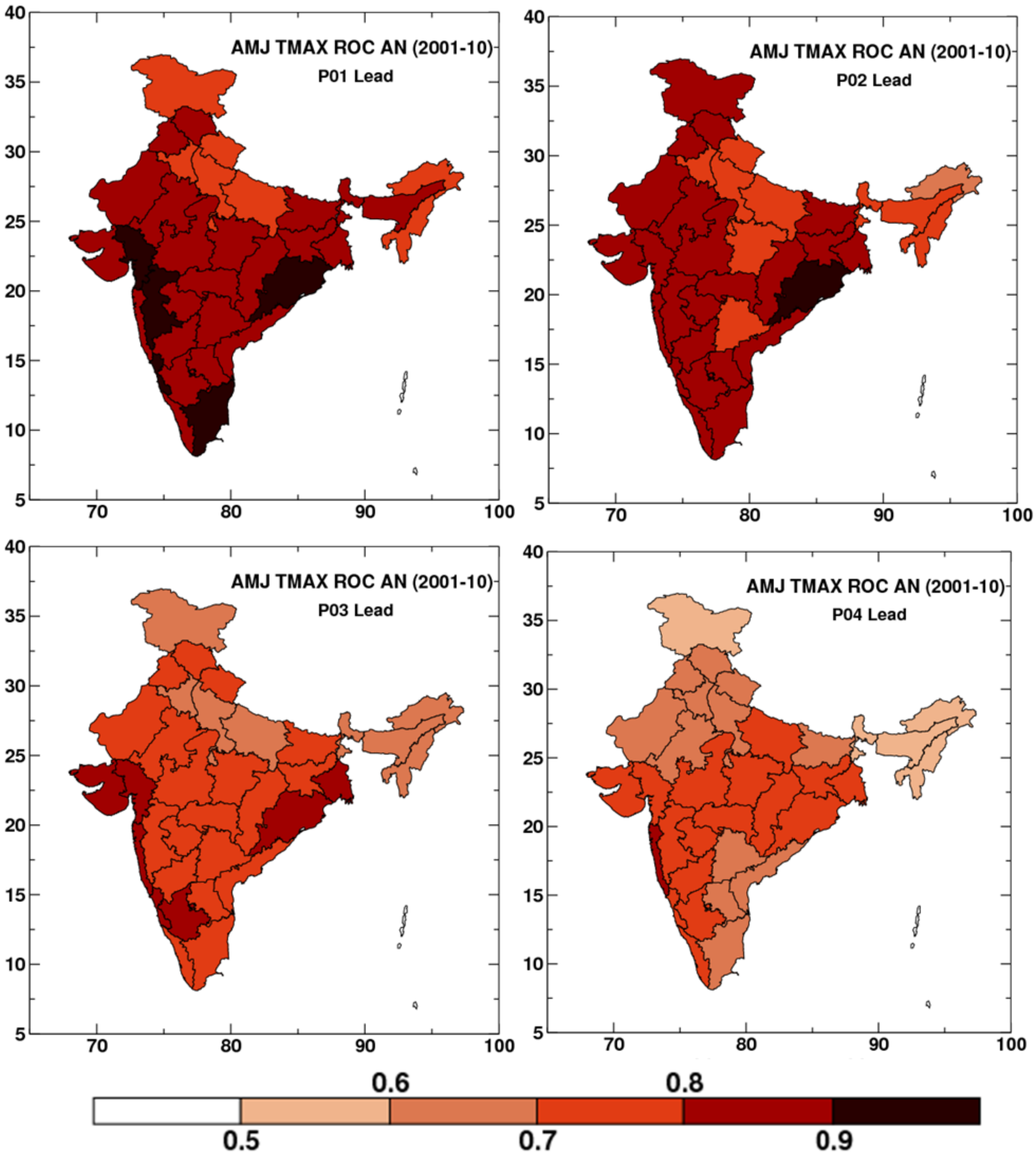

Figure 20: Same as Figure 7, but for maximum temperature (Tmax) for all pentads of AMJ during 2001-2010

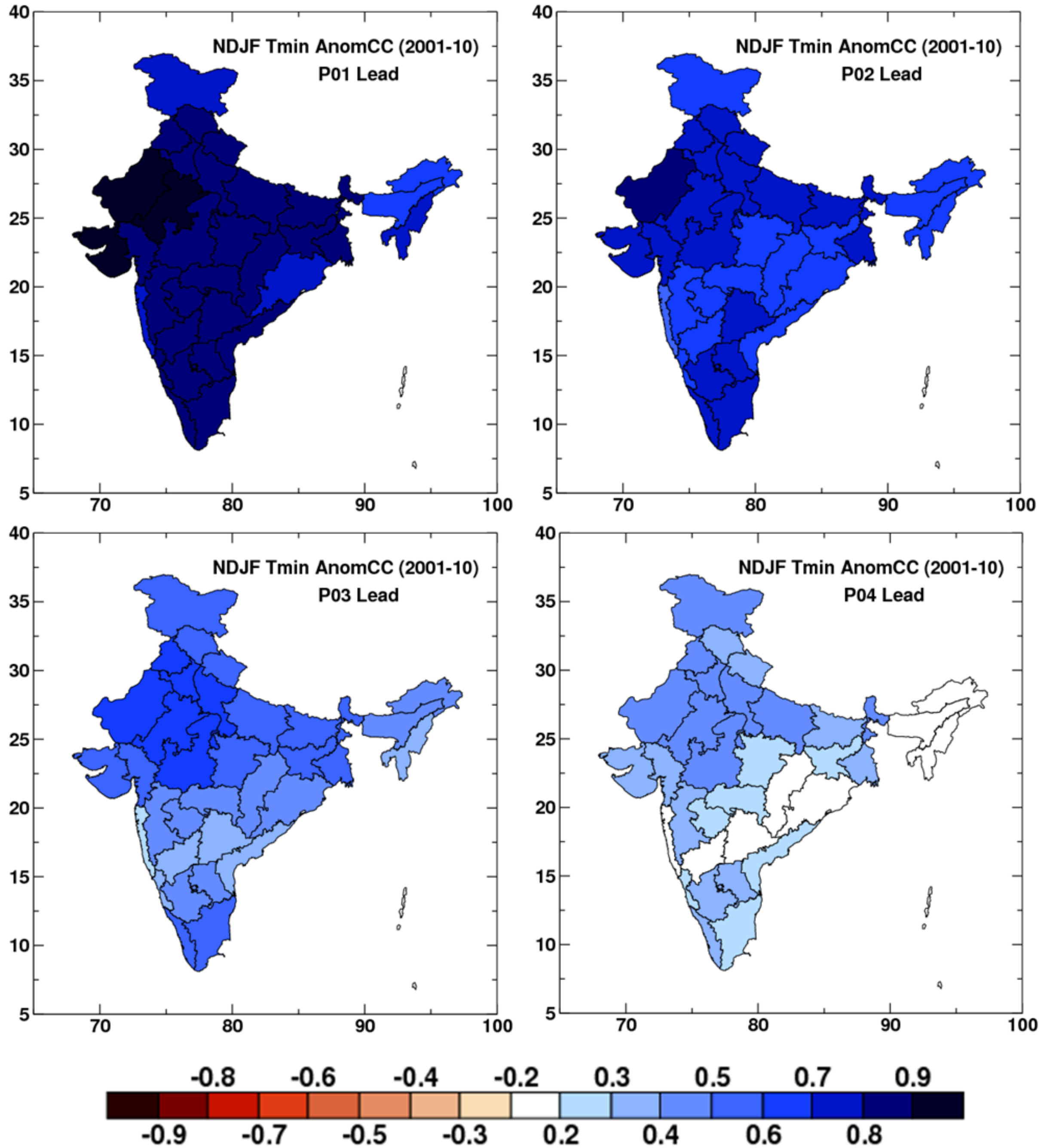

Figure 21: Same as Figure 2, but for minimum temperature (Tmin) for all pentads of NDJF during 2001-2010

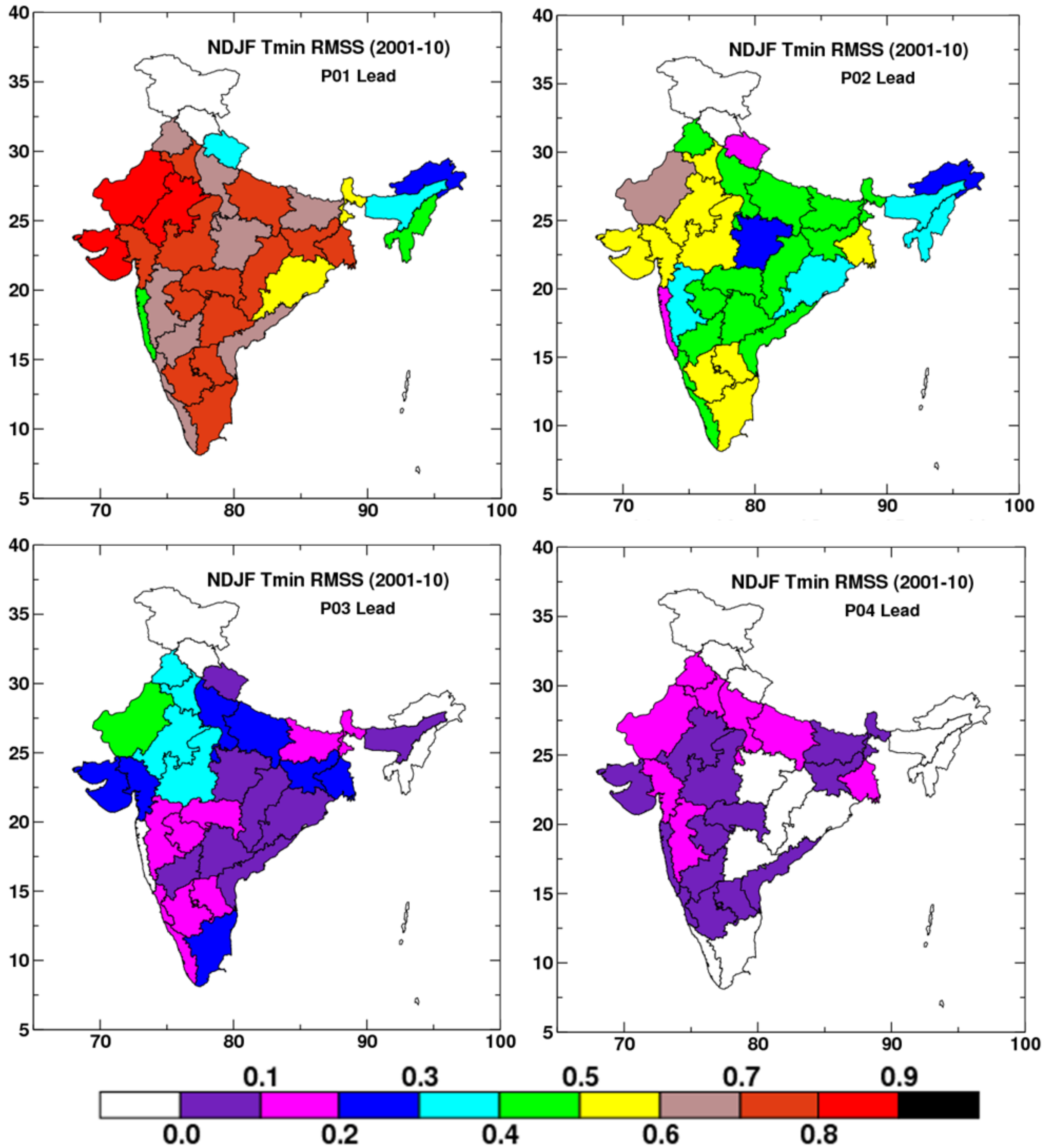

Figure 22: Same as Figure 3, but for minimum temperature (Tmin) for all pentads of NDJF during 2001-2010

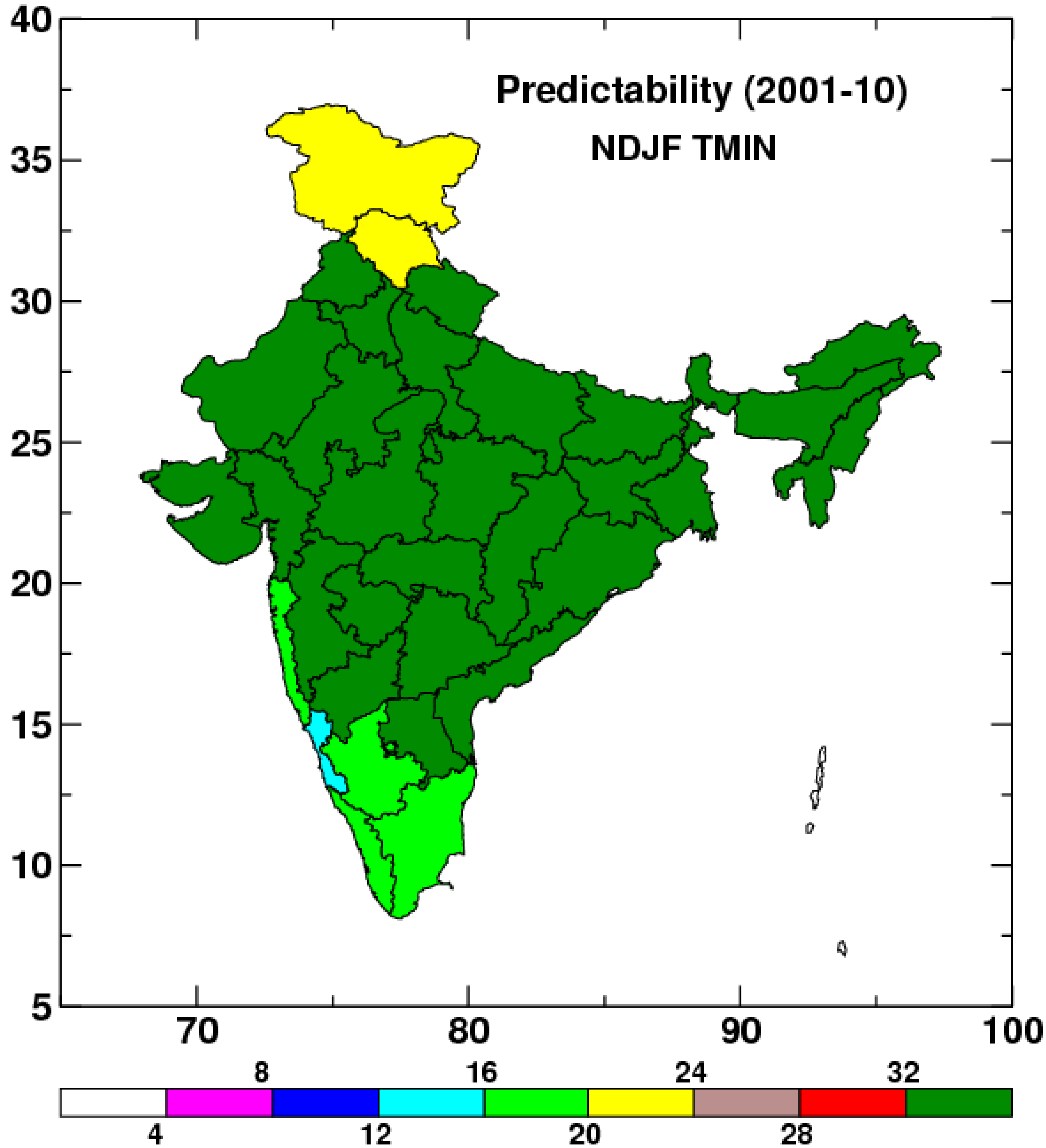

Figure 23: Same as Figure 4, but for minimum temperature (Tmin) for all pentads of NDJF during 2001-2010

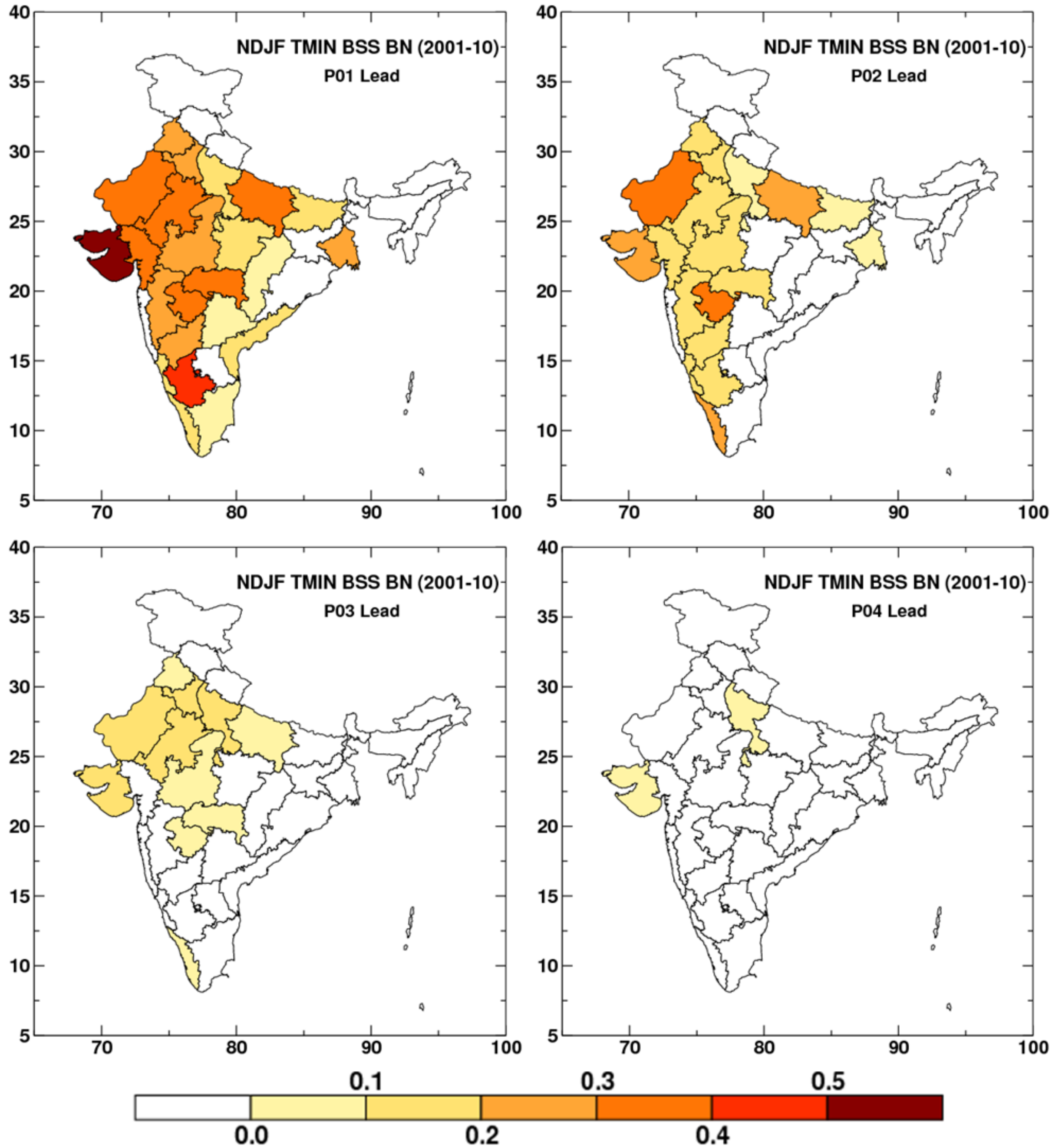

Figure 24: Same as Figure 6, but for minimum temperature (Tmin) for all pentads of NDJF during 2001-2010

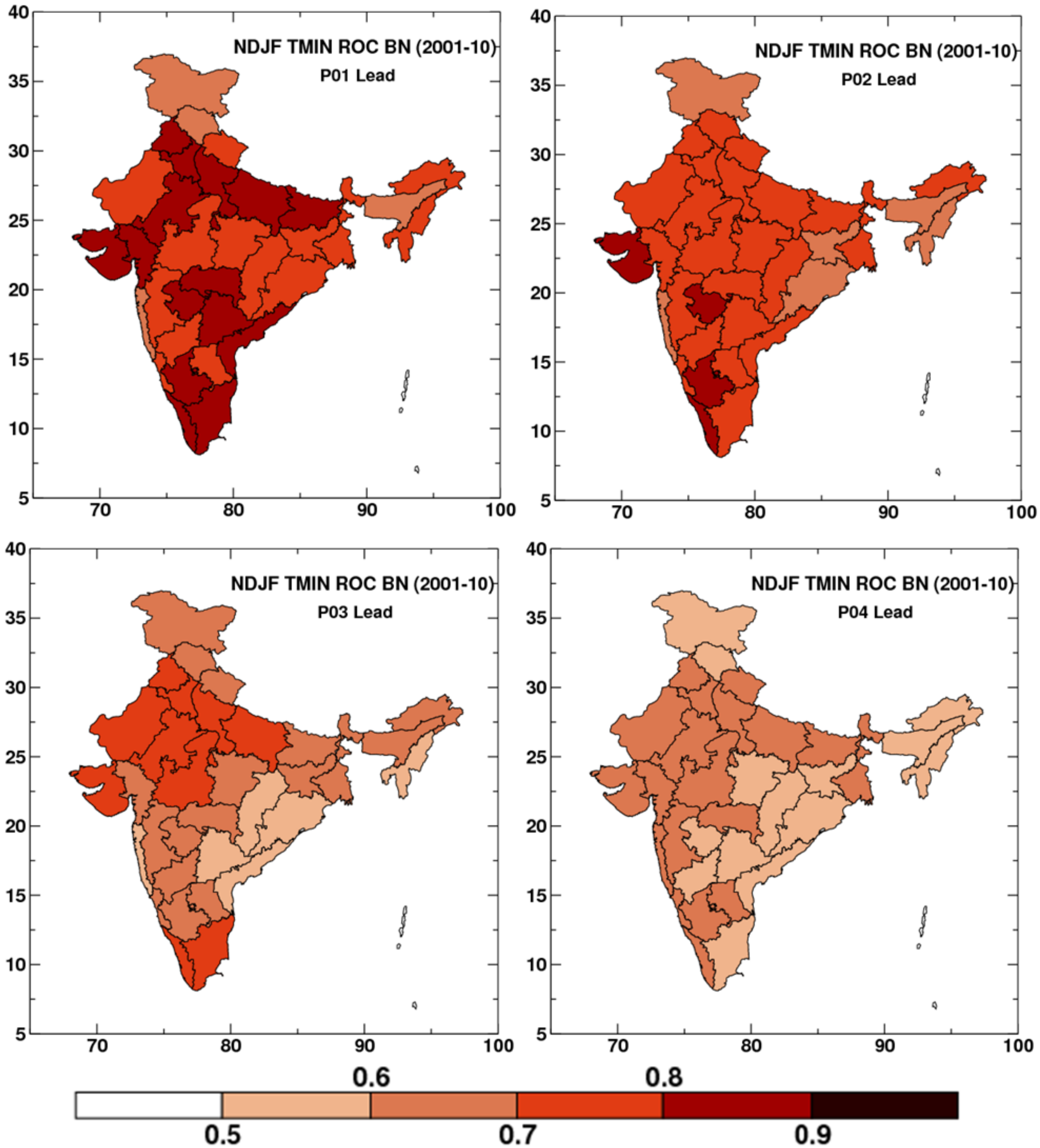

Figure 25: Same as Figure 8, but for minimum temperature (Tmin) for all pentads of NDJF during 2001-2010