Environmental stresses from detailed climate model simulations for the Middle East and Gulf region

Deliverable: MOEN/04/04/02/02b

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Contract: RT/COM/4/5015

Version Number: 2

Number of Pages: 38 including cover pages

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Summary

This report examines high resolution climate change projections from the Hadley Centre's Regional Climate Model centered over the Near East and Gulf region. The focus is on regional changes of annual and seasonal temperature and precipitation, and extreme maximum and minimum temperatures by the 2020s, 2040s and 2070s. Results discussed here are for one particular model and future emissions scenario (see Background and Methodology for further details), and it is important to note that different models and scenarios encompass significant uncertainties in the future climate projections. These are discussed in detail in an earlier report ('Uncertainties in Global Model Predictions and Environmental Stresses' - MOEN04/04/02/07).

The key points from this report are detailed below:

Temperature

Annual average

- During the 1990s, the highest temperatures (>35ºC during summer) occur in Iraq, Saudi Arabia, United Arab Emirates, Oman, Egypt, and parts of central Iran (Figure 5). Coldest temperatures, <0ºC occur during winter across Turkey, and north-west Iran (Figure 7).

- Long-term average temperature is projected to increase progressively over the whole Gulf region from 21.9 ºC during the 1990s, 23.1 ºC in the 2020s, 23.9 ºC in the 2040s and 25.1 ºC in the 2070s (Table 1).

- The largest increases in average temperature; up to 1.8ºC by the 2020s, 2.9ºC by the 2040s and 4.2ºC by the 2070s, are projected in the north-west of the region. Initially, this is focused within Turkey, but extends south and east across Syria, Iraq, Jordan and northern Saudi Arabia by the 2070s (Figure 3).

- Regional and Global Climate Model temperature projections are similar, both spatially and temporally (Table1-4, Figures 1-3).

Seasonal

- Seasonal increases in temperature across the whole Gulf region are expected to be reasonably similar between seasons; slightly higher during summer and autumn (1.4ºC by 2020s, 2.3ºC by 2040s and 3.6-3.7ºC by 2070s) than during winter (1.2ºC by 2020s, 2.1ºC by 2040s and 3.3ºC by 2070s), (Figure 8, Table 4).

- Regionally, the greatest increases in summer temperatures (up to 2.8ºC by the 2020s, 3.6ºC by 2040s and 5.0ºC by the 2070s) are projected across Turkey. Relatively rapid summer warming is also projected across Syria, Iraq, northern Iran, Caucasus and Egypt (Figure 8).

Extremes

- Average maximum and minimum temperatures across the Gulf region range from ~19ºC and 4.1ºC during winter to ~37ºC and 22ºC during summer, respectively (Table 5).

- Minimum temperature is expected to increase more rapidly than maximum temperature throughout the 21st century: Projected minimum temperature changes are 1.6ºC by 2020s, 2.7ºC by 2040s, and 4.3ºC by 2070s; maximum temperature changes are 1.4ºC by 2020s, 2.4ºC by 2040s, and 3.8ºC by 2070s (Table 6).

- Spatially, the largest increases in maximum and minimum temperatures are expected across Turkey, Syria, north-west Iraq, the Caucasus, Jordan and northern Saudi Arabia during spring and summer (Figures 13 to 14). Over this period, maximum temperatures increase by less in coastal zones, as a result of the moderating influence of ocean temperatures in these regions.

- The highest maximum temperatures during the summer are currently ~48ºC, and they occur in southern Iraq, north-east Saudi Arabia and southern Egypt (Figure 9). Projections indicate that by 2020s typical summer maximum temperatures will exceed 50ºC in the extreme south and east of Iraq, and this temperature zone will extend further north in Iraq by 2040s, and also into eastern Saudi Arabia by 2070s (Figures 9 to 12).

Precipitation

Annual average

- During the 1990s, the lowest precipitation, below 50 mm/yr, was distributed across Egypt, Jordan, the north-west of Saudi Arabia and parts of central Iran. Areas with the highest annual precipitation, greater than 1000 mm/yr, tend to be in high mountainous terrain, e.g. the Ethiopian highlands, the south-west coastal region of the Arabian peninsular, southern and eastern Turkey, the Zagros, Alborz and Caucases mountain ranges in north and west of Iran, and the Hindu Kush region of north-east Afghanistan.

- The enhanced resolution of the RCM results in precipitation projections for the whole Gulf region that are approximately 40 mm/yr higher than the corresponding GCM projections (Table 7). This is focussed over the mountainous terrain and during the summer (Table 9).

- Average precipitation is generally projected to decrease throughout the 21st century (Table 8). These region-wide changes are deceptive as they mask large spatial variability in the precipitation responses (see Figures 19 and 20).

- Increases in precipitation of up to 100 mm/yr (~30%) by 2020s and 130 mm/yr (~35%) by 2040s are projected for the Ethiopian highlands and south-west coastal fringe of the Arabian peninsular.

- Decreases in precipitation of up to -100 mm/yr (~20%) by 2020s, and -140 mm/yr (~30%) by 2040s are shown across Turkey, Lebanon, northern Syria, the Zagros mountain region of western Iran, the Hindu Kush region of Afghanistan, as well as other areas within central Iran and Afghanistan.

Seasonal

- Average precipitation over the Gulf region throughout the 21st century is projected to decrease during winter and spring, and increase during summer and autumn (Table 10).

- The largest increases in seasonal precipitation amounts (90 to 120mm by 2020s, 100 to 150mm by 2040s, and 110 to 180mm by 2070s) are expected over the Ethiopian highlands during summer, and eastern Turkey and north-western Iran during autumn (Figure 25).

- The largest decreases in precipitation amounts (-30 to -80mm by 2020s, -60 to -100mm by 2040s, and -80 to -130mm by 2070s) are expected over Turkey, Iran and southern Sudan during spring, and Yemen, Oman and southern Saudi Arabia during autumn (Figure 25).

- The largest percentage increases in precipitation (80 to 150% by 2020s, 120 to 300% by 2040s, and 150 to 500% by 2070s) are projected over central Iran during summer, and eastern Sudan during winter (Figure 26).

- The largest percentage decreases in precipitation (-30 to -80% by 2020s, -40 to -100% by 2040s, and -60 to -130% by 2070s) are projected for Turkey and the coastal regions surrounding the eastern Mediterranean during summer, southern Saudi Arabia during autumn, and central Egypt and Afghanistan during winter (Figure 26).

Background & Methodology

A Regional Climate Model (RCM) is a tool to add small-scale detailed information of future climate change to the large-scale projections of a Global Climate Model (GCM). RCMs are full, physically-based climate models, representing most or all of the processes, interactions and feedbacks between the climate system components that are represented in GCMs. In general, RCMs do not model oceans, as this would substantially increase the computing costs, and in many places would make little difference to projections over land. Instead, changes in ocean conditions are prescribed by the GCM results.

Where terrain is flat for thousands of kilometres and away from coasts, the coarse resolution of a GCM may mean RCM and GCM projections are similar. However, in most land areas, surface features, such as mountains and coastlines are on scales of less that 100 km. The finer resolution of RCMs enables the influence of such features on climate in the region to be more realistically captured. This is particularly important over mountainous terrain, which can significantly affect climate indicators, such as temperature and precipitation. RCMs are also able to represent smaller land areas, such as islands and peninsulas, and have been shown to provide more credible simulations of extremes of weather, such as heavy rainfall or high temperatures, and mesoscale weather features, such as cyclones and hurricanes (Jones et al., 2004, see footnote).

This report focuses on high resolution climate (temperature and precipitation) change projections from the Hadley Centre's Regional Climate Model (RCM), 'HadRM3P', centered over the Near East and Gulf region; including Egypt, Lebanon, Syria, Jordan, Iran, Iraq, Saudi Arabia, Kuwait, Oman, Yemen and the United Arab Emirates (see Map 1). Results are discussed with particular reference to these countries, although where important features are observed in surrounding countries these are also highlighted.

The horizontal resolution of the RCM is 0.44º latitude by 0.44º longitude, which corresponds with approximately 50 km^2. At its lateral boundaries, the RCM was driven by coarse resolution climate data from 'HadAM3', which is the atmosphere component of the Hadley Centre's Global Climate Model (GCM), 'HadCM3'. The model was run for two time slices; 1970 to 2000 and 2070 to 2080, and at each grid box the values for the 2020s and 2040s were interpolated between these. Note, time constraints did not allow full transient runs of the RCM, for the whole period between 1970 and 2080, to be completed. This is recommended for a more detailed understanding of the evolution of climate change projections into the future.

Results discussed here are for RCM runs that were forced with the 'A2' future emissions scenario as defined by the Special Report on Emissions Scenarios (SRES). Relative to the other scenarios, A2 describes a future of high population growth, reasonably high global primary energy requirements, high greenhouse gas emissions and low global gross domestic product (see Box 1 for details). Climate changes associated with the A2 scenario can, therefore, be expected to be more extreme that for the other scenarios. Differences in climate projections among scenarios encompass a significant portion of the underlying uncertainties in the main driving forces of climate change. This is discussed in detail in an earlier report ('Uncertainties in Global Model Predictions and Environmental Stresses' - MOEN04/04/02/07).

Jones RG, Noguer M, Hassell DC, Hudson D, Wilson SS, Jenkins GJ and Mitchell JFB. 2004. Generating high resolution climate change scenarios using PRECIS, Met Office Hadley Centre, Exeter, UK, 40pp.

This report focuses on changes in projected annual and seasonal temperature and precipitation, and extreme maximum and minimum temperatures over the Near East and Gulf region for the periods 1990 to 2000 (1990s), 2020 to 2030 (2020s), 2040 to 2050 (2040s), and 2070 to 2080 (2070s). Comparisons are made of regional average values and spatial variations, as well as the changes in future projections relative to the 1990s. To assess the additional utility of the higher resolution RCM results compared to the coarser resolution GCM results, comparisons between the RCM and GCM projections are made throughout.

Map 1. Reference map of Middle East and Gulf region.

Box 1. The A2 emissions scenario of the Special Report on Emissions Scenarios (SRES)

Greenhouse gas (GHG) emissions are the main anthropogenic drivers of climate change. We will never know exactly how anthropogenic emissions of GHGs will change in the future. However, the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) has developed a range of plausible scenarios of future emissions of GHGs and other substances that may affect GHGs (e.g. sulphur dioxide which forms sulphate aerosols). Each scenario is based on coherent and internally consistent assumptions about the driving forces on emissions, such as population growth, energy use, and technological development. It should be noted that all scenarios are considered plausible and there is no way of currently assessing their relative likelihoods.

There are four SRES scenario families: A1, A2, B1 and B2. The A2 storyline and scenario family describes a very heterogeneous future world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally orientated and per capita economic growth and technological change more fragmented and slower than for other scenarios. Relative to the other SRES scenarios, A2 describes a future of high population growth (global population between 12-15 trillion by 2100), reasonably high global primary energy requirements, high GHG emissions and low global Gross Domestic Product (GDP).

Future Climate Projections

Temperature

Annual

RCM projections show progressive increases in long-term average temperature (decadal averages of 1.5m air temperature) over the Gulf region from 21.9 ºC during the 1990s, 23.1 ºC in the 2020s, 23.9 ºC in the 2040s and 25.1 ºC in the 2070s (Table 1). Relative to the 1990s value, these correspond with temperature increases of 1.2 ºC by the 2020s, 2.0 ºC by the 2040s and 3.2 ºC by the 2070s (Table 2). The GCM temperature projections for the same region are in close agreement with these RCM values (see Tables 1 and 2).

Table 1. Decadal average temperature (T), in degrees Celsius at 1.5m above ground level for land areas only across the Gulf region. Projections are made, using the A2 SRES emissions scenario (see Methodology), for the 1990s, 2020s, 2040s and 2070s decades with the PRECIS Regional Climate Model (RCM) and the HadCM3 Global Climate Model (GCM).

	1990s	**2020s**	**2040s**	**2070s**
RCM T	21.9	23.1	23.9	25.1
GCM T	21.3	22.4	23.2	24.9

Table 2. Changes in decadal average temperature (see Table 1) for the 2020s, 2040s and 2070s relative to the 1990s. Climate projections are from runs of the PRECIS Regional Climate Model (RCM) and the HadCM3 Global Climate Model (GCM) driven with the A2 SRES emissions scenario (see Methodology).

	2020s-1990s	**2040s-1990s**	**2070s-1990s**
RCM T	1.2	2.0	3.2
GCM T	1.1	1.8	3.6

Spatially, average temperatures are projected to rise throughout the 21st century across all areas of the Gulf region (Figure 1). The enhanced resolution of the RCM projections provide significantly more detail on the spatial distribution of climate than the GCM results (Figure 2). For example, the influence of high mountainous terrain on temperatures is clearly evident in Iran, Eastern Turkey, the highlands of Ethiopia, and the coastal mountain ranges in the south-west of the Arabian peninsular.

The largest increases in temperatures, up to 1.8ºC by the 2020s, 2.9ºC by the 2040s and 4.2ºC by the 2070s, are projected in the north-west of the region; initially focused within Turkey, but extending south and east across Syria, Iraq, Jordan and northern Saudi Arabia by the 2070s (Figure 3). The smallest temperature increases, of 1.0ºC by the 2020s, 1.8ºC by 2040s and 2.0ºC by 2070s, are projected in the coastal zones mainly to the south of the region; the coasts of Iran, Oman, Yemen, and the horn of Africa (Figure 3). This is likely related to the moderating influence of oceanic temperatures on coastal land temperatures.

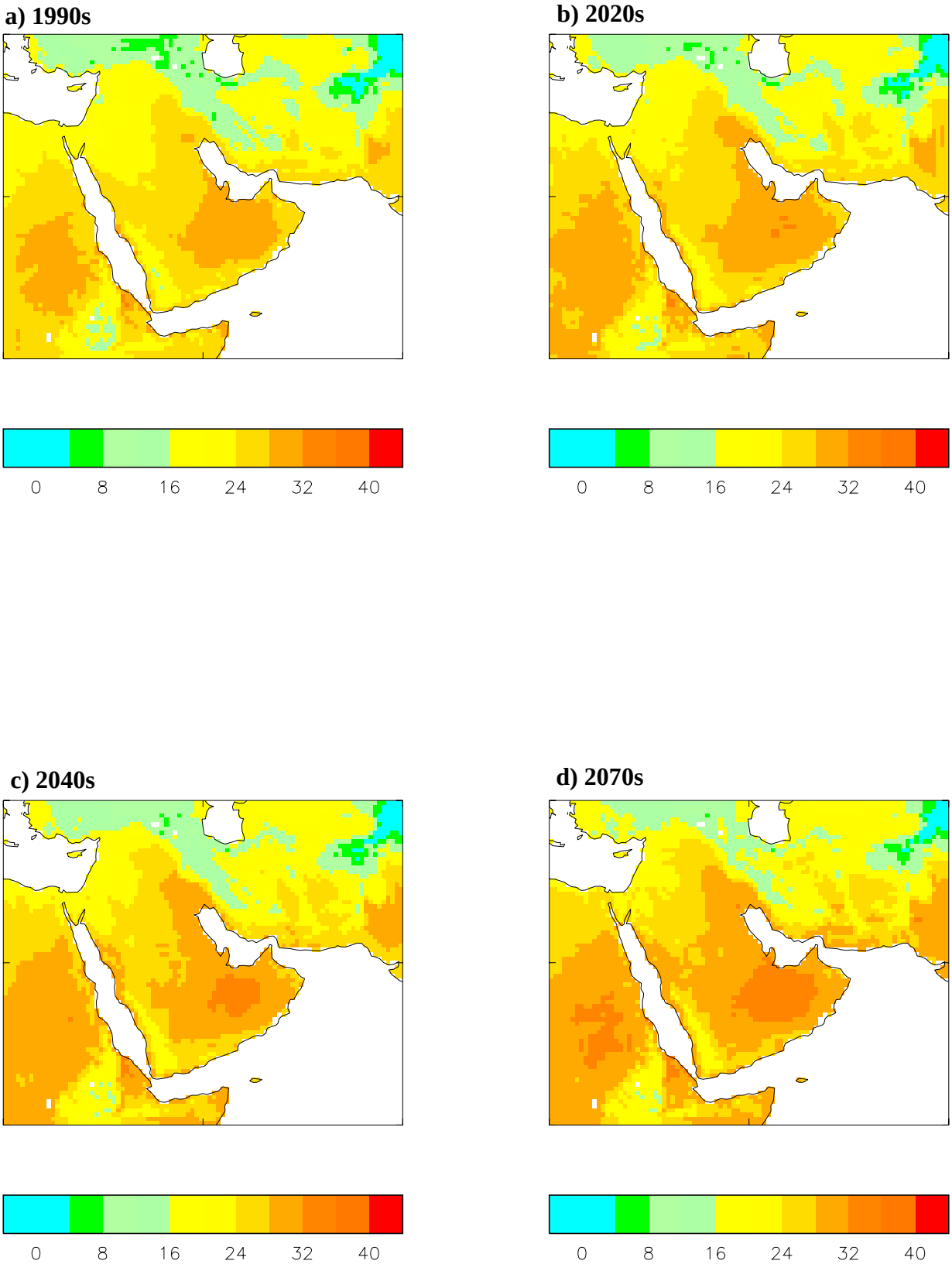

Figure 1. Regional Climate Model projections of decadal average air temperature (ºC at 1.5m above the surface) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

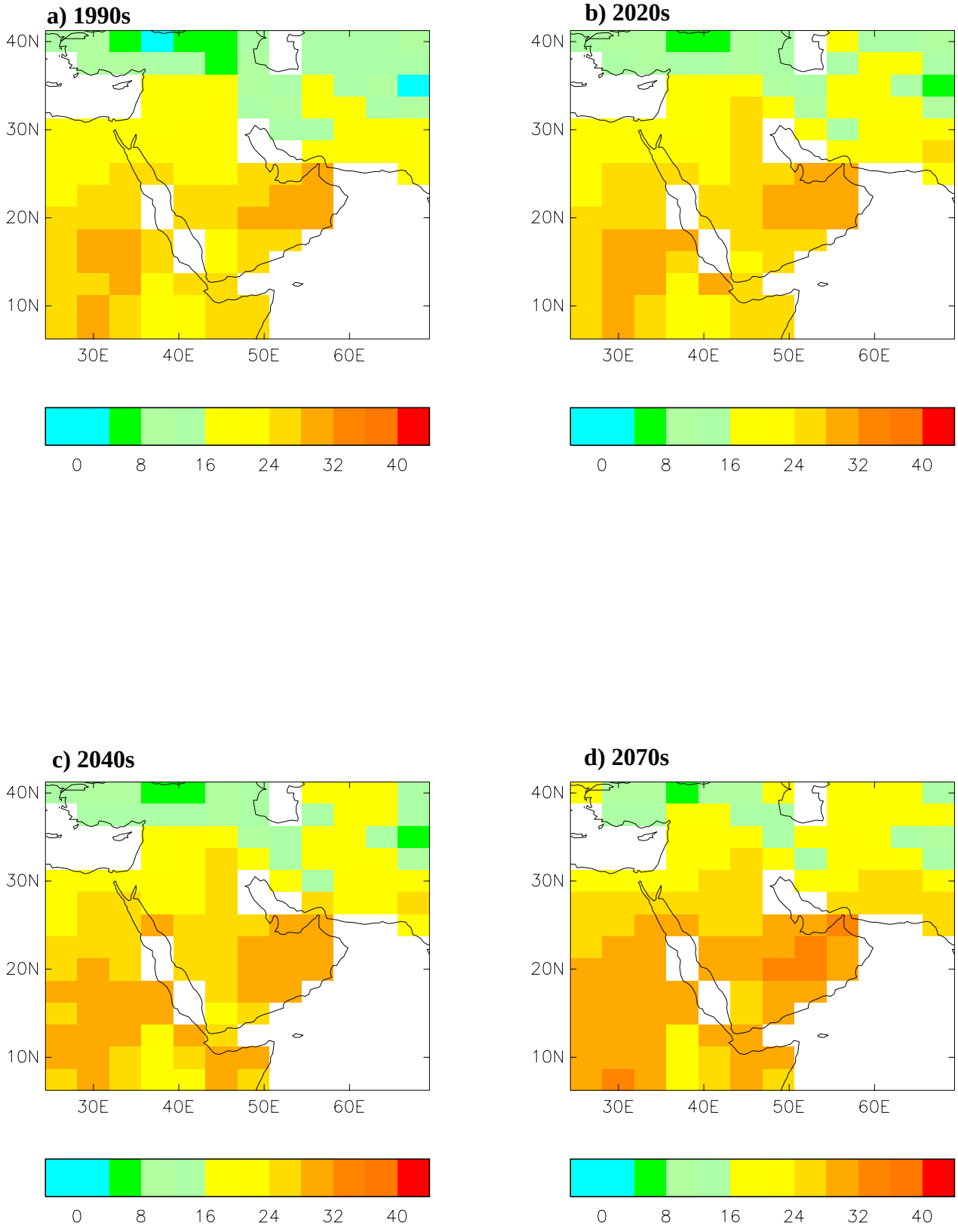

Figure 2. Global Climate Model projections of decadal average air temperature (ºC at 1.5m above the surface) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

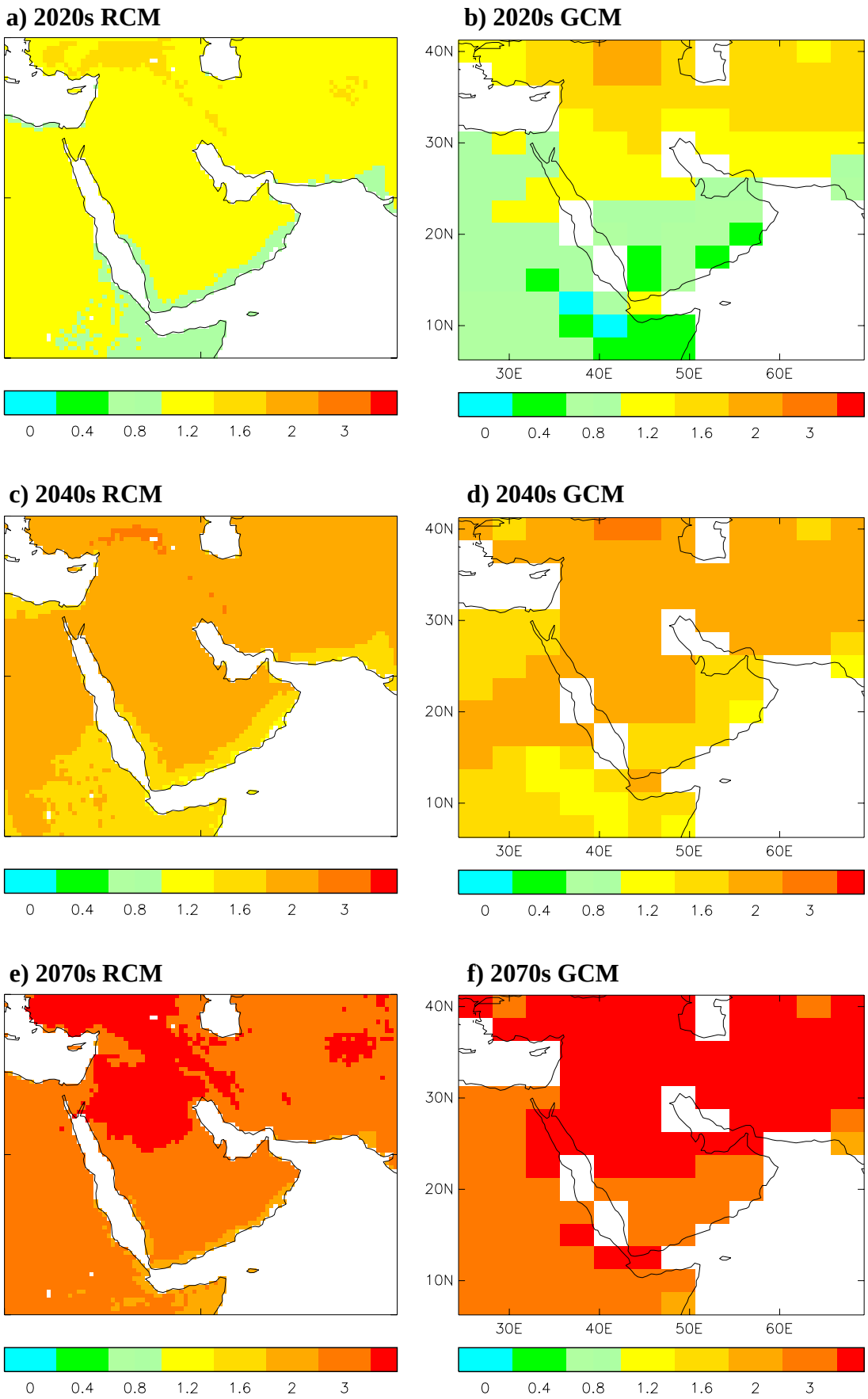

Figure 3. Regional & Global Climate Model projections of average temperature changes (ºC) across the Gulf region for a) & b) 2020s, c) & d) 2040s, and e) & f) 2070s, relative to the 1990s.

Seasonal

Seasonal average temperatures across the whole Gulf region currently range from ~12ºC during winter (December to February) to ~30ºC during summer (June to August) (Table 3). Spring (March to May) temperatures average ~23ºC and autumn (September to November) temperatures are ~22ºC. Spatially, the hottest temperatures (>35ºC during summer) occur in Iraq, Saudi Arabia, United Arab Emirates, Oman, Egypt, and parts of central Iran (Figure 5). The coldest seasonal temperatures (<0ºC during winter) occur across Turkey, and northern and western Iran (Figure 7).

The RCM and GCM results show similar seasonal average temperatures and projected temperature changes across the region (Tables 3 and 4), and spatially within the region (data not shown). Seasonal increases in temperature (RCM) across the region as a whole are projected to be reasonably similar between seasons; slightly larger during summer and autumn (1.4ºC by 2020s, 2.3ºC by 2040s and 3.6-3.7ºC by 2070s) than during winter (1.2ºC by 2020s, 2.1ºC by 2040s and 3.3ºC by 2070s), (Figure 8, Table 4).

Regionally, the greatest increases in summer temperatures (up to 2.8ºC by the 2020s, 3.6ºC by 2040s and 5.0ºC by the 2070s) are projected across Turkey (Figure 8). Relatively rapid summer warming is also projected across Syria, Iraq, northern Iran, the Caucasus and Egypt. Note that the hottest seasonal average temperatures in this region, summer average >40ºC, currently occur in south-eastern Iraq, and this temperature zone is projected to extend across large parts of eastern Iraq and Saudi Arabia throughout the 21st century. During other seasons, the most rapid temperature increases are projected across Turkey, Syria, Iraq and western Iran during spring, and Saudi Arabia and Egypt during autumn. Temperature increases during winter are generally expected to be the smallest across the region (Figure 8).

Table 3. Regional Climate Model (RCM) and Global Climate Model (GCM) projections of decadal average temperature (ºC) for the Gulf region in different seasons; winter - DJF, spring - MAM, summer - JJA, autumn – SON, for the 1990s, 2020s, 2040s and 2070s.

	1990s				2020s				2040s				2070s			
	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF
RCM T	22.7	30.1	21.7	11.8	24.0	31.4	23.1	13.1	24.9	32.3	24.0	13.9	26.2	33.7	25.4	15.1
GCM T	22.3	29.4	21.5	12.2	23.1	30.5	22.6	13.5	23.6	31.4	23.3	14.4	25.4	33.5	24.9	15.9

Table 4. Changes in the Regional Climate Model (RCM) and Global Climate Model (GCM) projections of decadal average temperature (ºC) for the Gulf region in different seasons; winter - DJF, spring - MAM, summer - JJA, autumn – SON, for the 2020s, 2040s and 2070s relative to the 1990s.

	2020s-1990s				2040s-1990s				2070s-1990s			
	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF
RCM T	1.3	1.4	1.4	1.2	2.2	2.3	2.3	2.1	3.5	3.6	3.7	3.3
GCM T	0.8	1.1	1.1	1.3	1.3	2.0	1.8	2.2	3.1	4.1	3.4	3.7

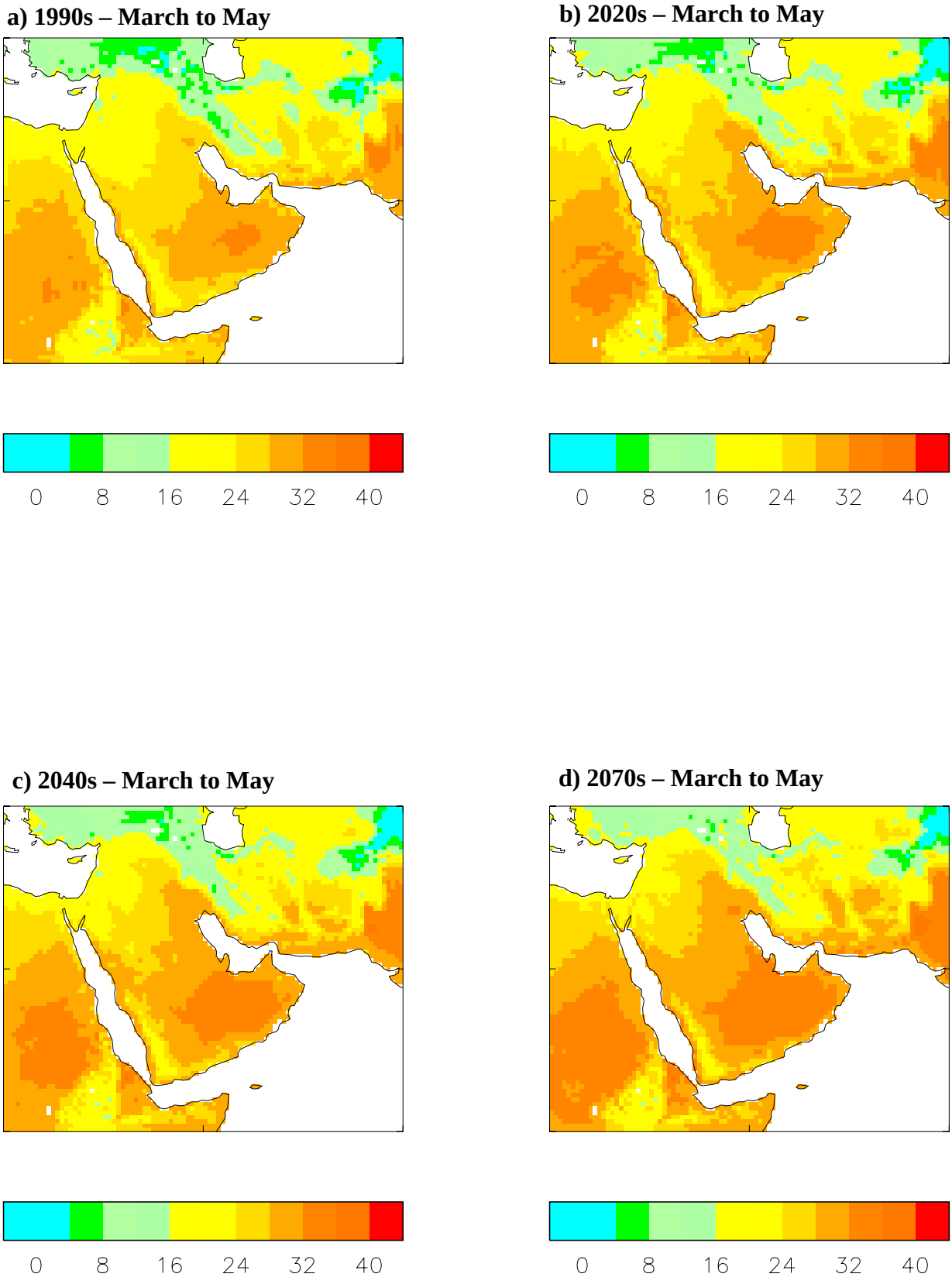

Figure 4. Regional Climate Model projections of spring (March, April, May) average air temperature (ºC) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

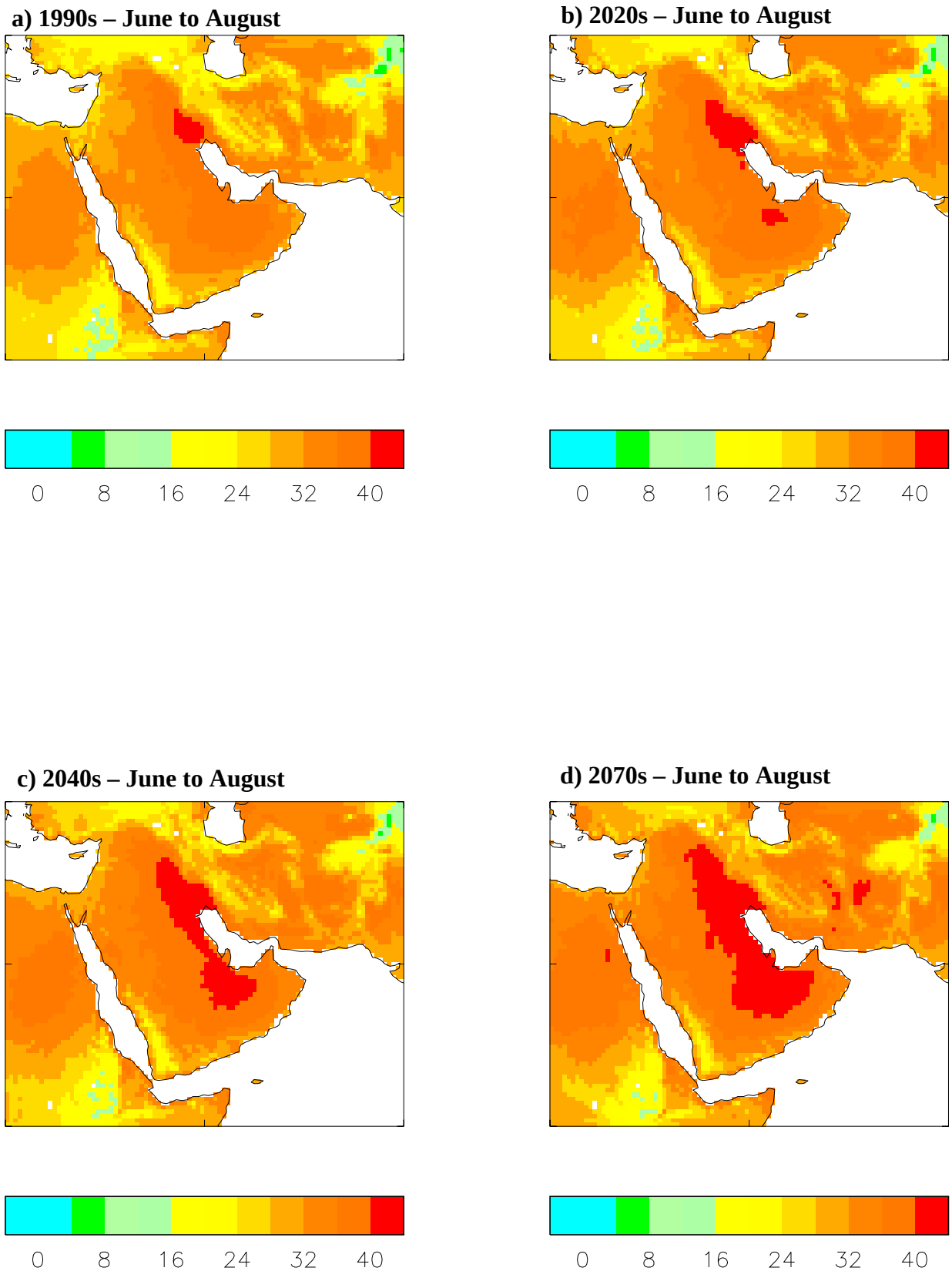

Figure 5. Regional Climate Model projections of summer (June, July August) average air temperature (ºC) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

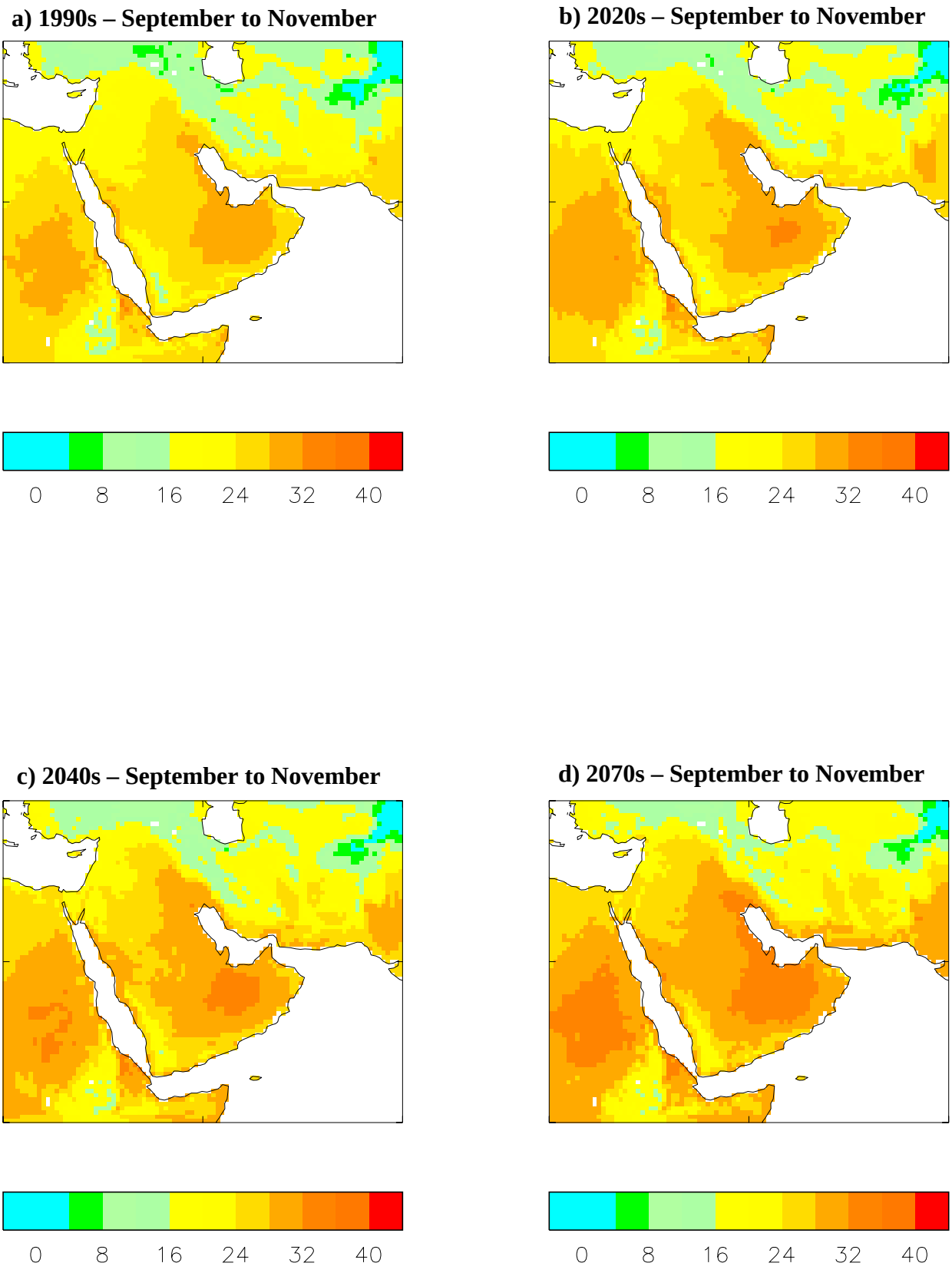

Figure 6. Regional Climate Model projections of autumn (September, October, November) average air temperature (ºC) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

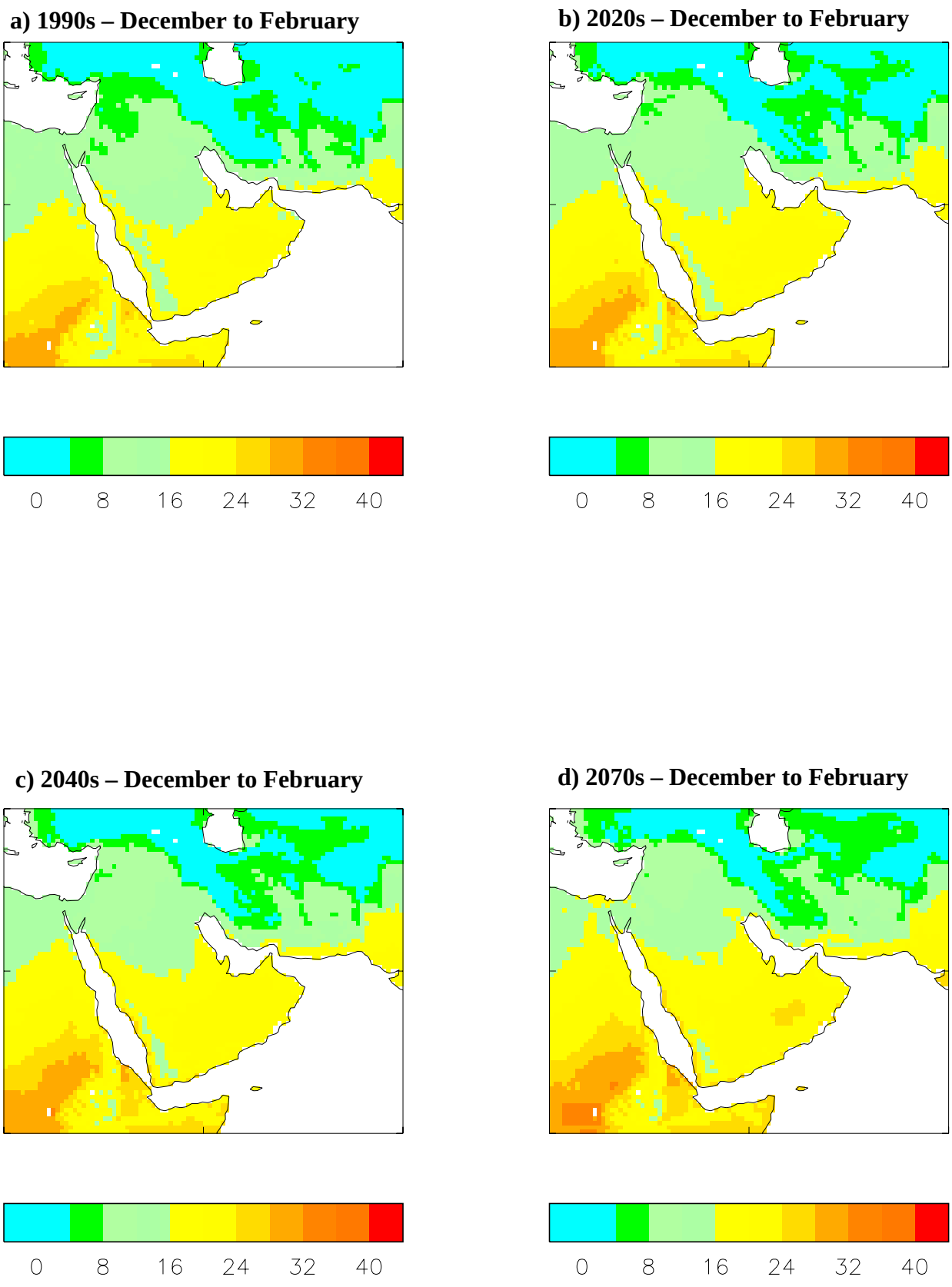

Figure 7. Regional Climate Model projections of winter (December, January, February) average air temperature (ºC) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

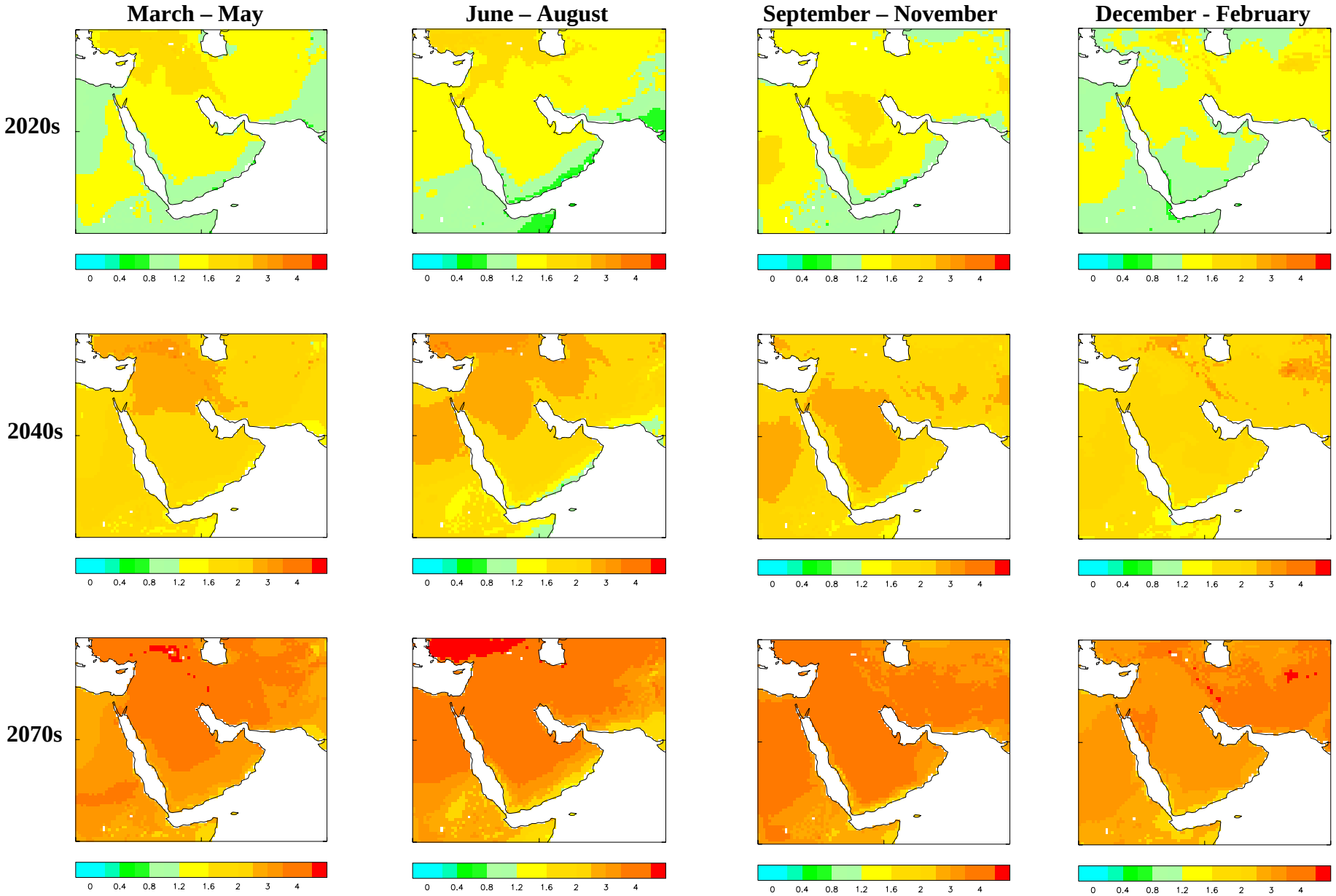

Figure 8. Regional Climate Model projections of seasonal average temperature changes (ºC) across the Gulf region for the 2020s, 2040s and 2070s, relative to the 1990s.

Extreme temperatures

The values of minimum and maximum temperature discussed here correspond with the average of each day's minimum (usually nighttime) and maximum (usually daytime) temperature throughout the decade in question. It is therefore a measure of typical diurnal temperature minima and maxima during the decade.

Average maximum and minimum temperatures across the Gulf region range from ~19ºC and 4.1ºC during winter to ~37ºC and 22ºC during summer, respectively (Table 5). Both maximum and minimum temperatures are projected to increase across the Gulf region throughout the 21st century, and these increases are similar across the seasons (Table 6).

Minimum temperature is expected to increase more rapidly than maximum temperature throughout the 21st century: Projected minimum temperature changes are 1.6ºC by 2020s, 2.7ºC by 2040s, and 4.3ºC by 2070s; maximum temperature changes are 1.4ºC by 2020s, 2.4ºC by 2040s, and 3.8ºC by 2070s (Table 6).

Spatially, the largest increases in maximum and minimum temperatures are expected across Turkey, Syria, north-west Iraq, the Caucasus, Jordan and northern Saudi Arabia during spring and summer (Figures 13 to 14). Over this period, maximum temperatures increase by less in coastal zones, as a result of the moderating influence of ocean temperatures in these regions. During autumn and winter, increases in maximum and minimum temperature tend to be more uniform across the region (Figures 15 to 16).

The highest maximum temperatures during the summer are currently ~48ºC, and they occur in southern Iraq, north-east Saudi Arabia and southern Egypt (Figure 9). Projections indicate that by 2020s typical summer maximum temperatures will exceed 50ºC in the extreme south and east of Iraq, and this temperature zone will extend further north in Iraq by 2040s, and also into eastern Saudi Arabia by 2070s (Figures 9 to 12).

Table 5. Regional Climate Model projections of decadal average maximum and minimum temperature (ºC) for the Gulf region for different seasons; winter - DJF, spring - MAM, summer - JJA, autumn – SON, for the 1990s, 2020s, 2040s and 2070s.

	1990s				2020s				2040s				2070s			
	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF
MAX T	30.0	37.0	29.3	18.6	31.4	38.4	30.7	20.1	32.3	39.3	31.6	21.1	33.7	40.7	32.9	22.6
MIN T	14.4	21.9	14.1	4.1	15.8	23.6	15.7	5.7	16.8	24.6	16.8	6.8	18.3	26.3	18.4	8.4

Table 6. Changes in Regional Climate Model projections of decadal average maximum and minimum temperature (ºC) for the Gulf region for different seasons; winter - DJF, spring - MAM, summer - JJA, autumn – SON, for the 2020s, 2040s and 2070s relative to the 1990s.

	2020s-1990s				2040s-1990s				2070s-1990s			
	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF
MAX T	1.4	1.4	1.3	1.5	2.3	2.4	2.2	2.6	3.7	3.8	3.5	4.1
MIN T	1.5	1.6	1.6	1.6	2.4	2.7	2.7	2.7	3.9	4.3	4.3	4.3

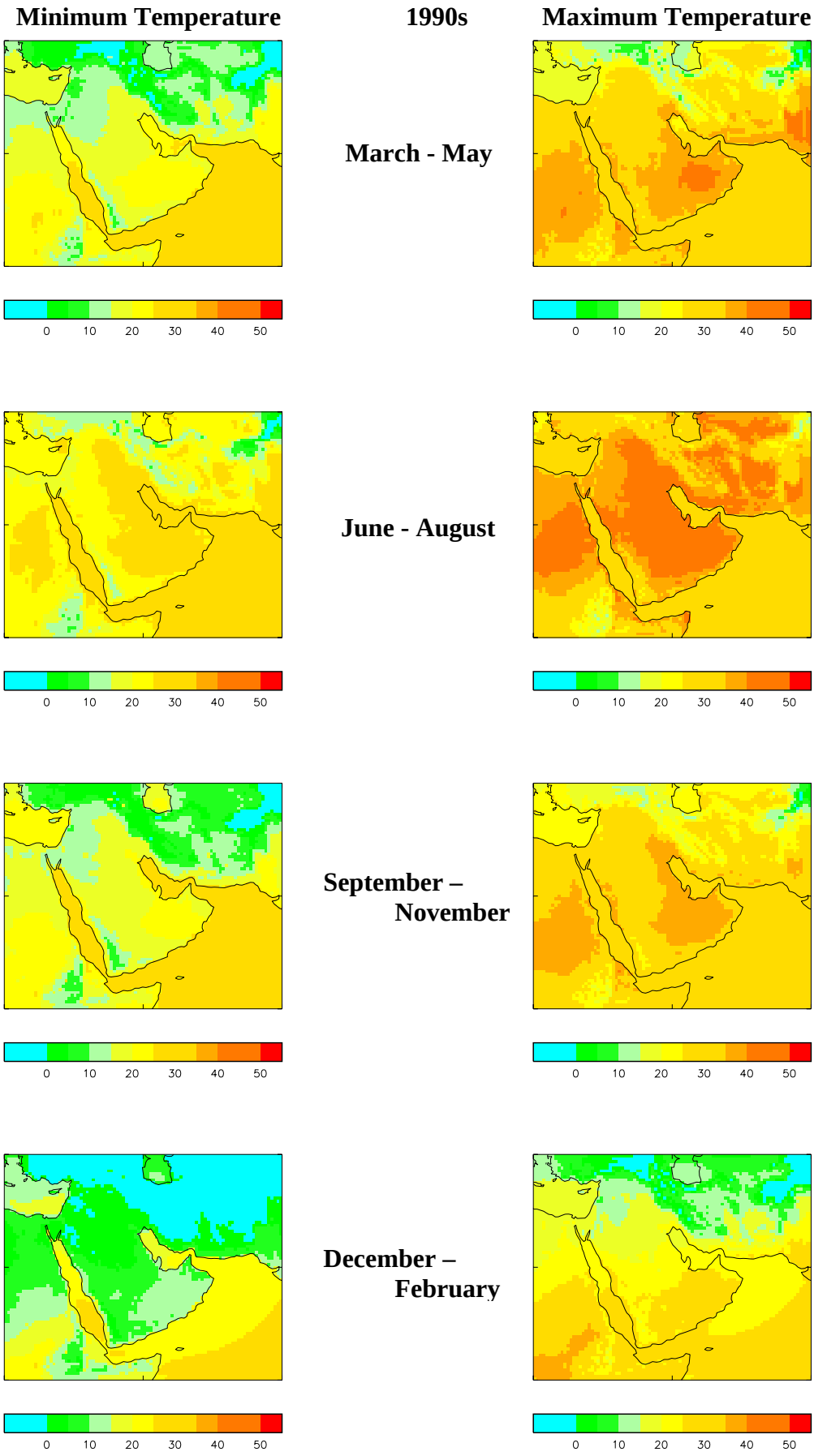

Figure 9. Regional Climate Model projections of seasonal average minimum and maximum temperatures during 1990s.

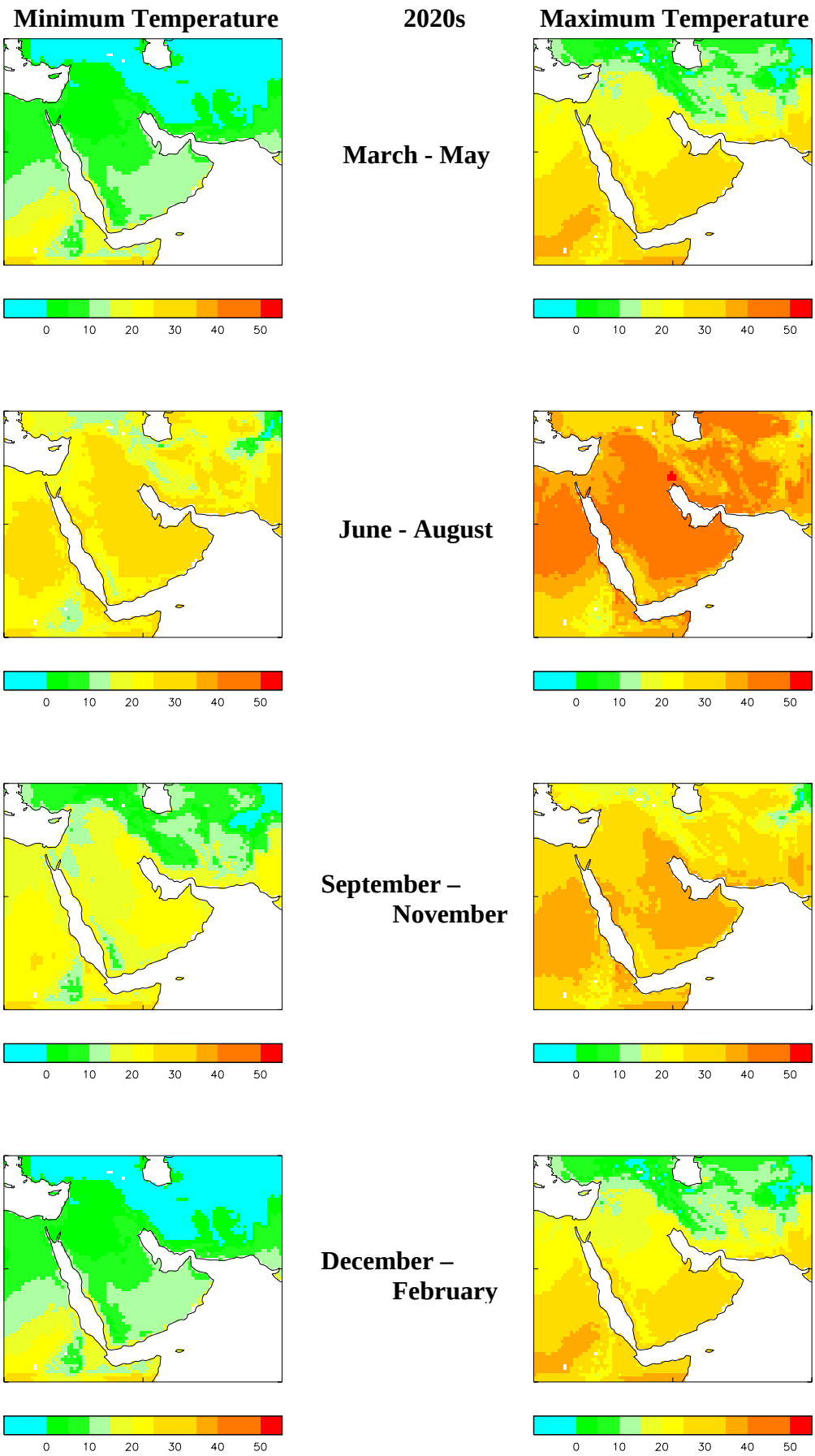

Figure 10. Regional Climate Model projections of seasonal average minimum and maximum temperatures by the 2020s.

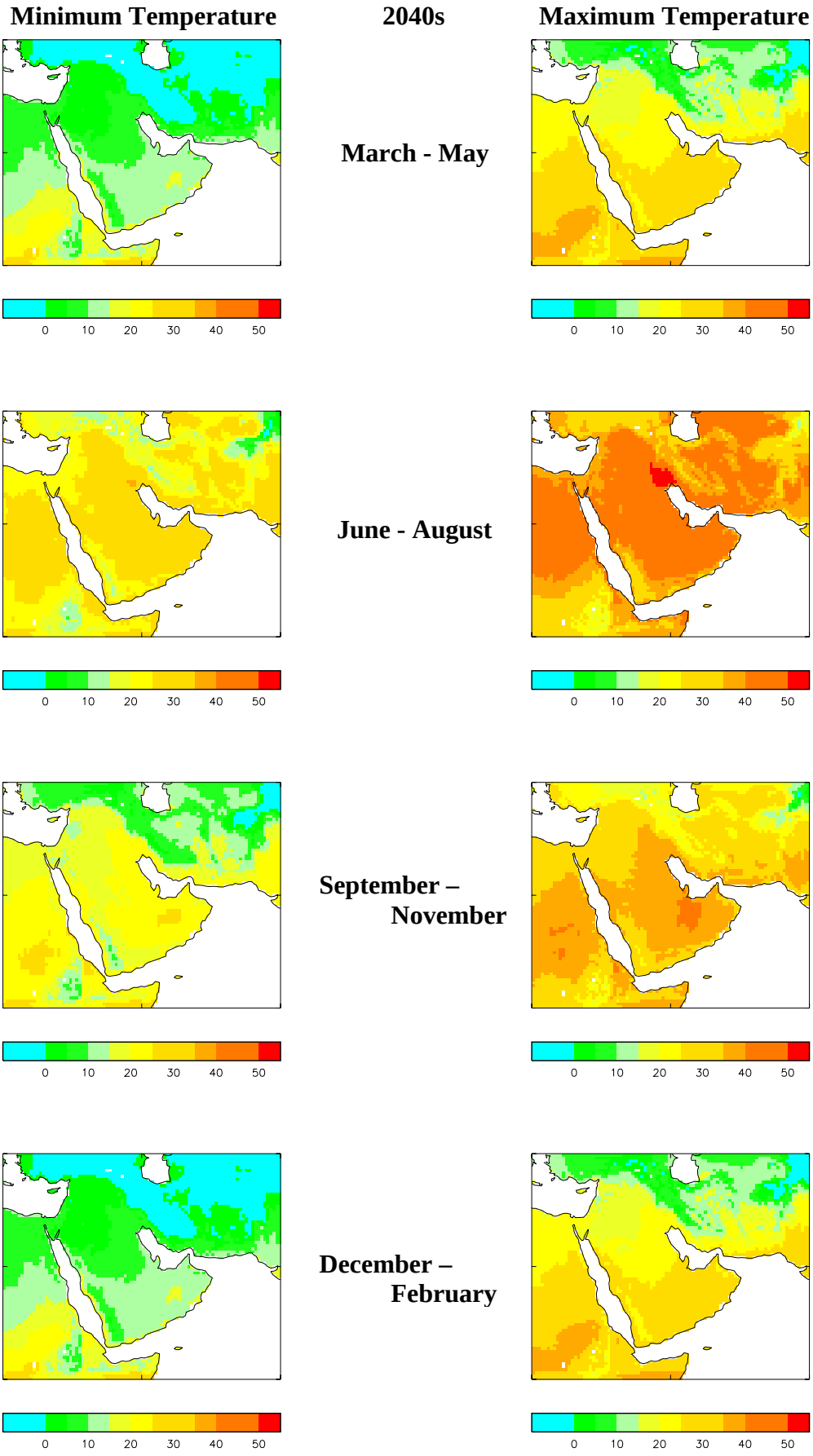

Figure 11. Regional Climate Model projections of seasonal average minimum and maximum temperatures by the 2040s.

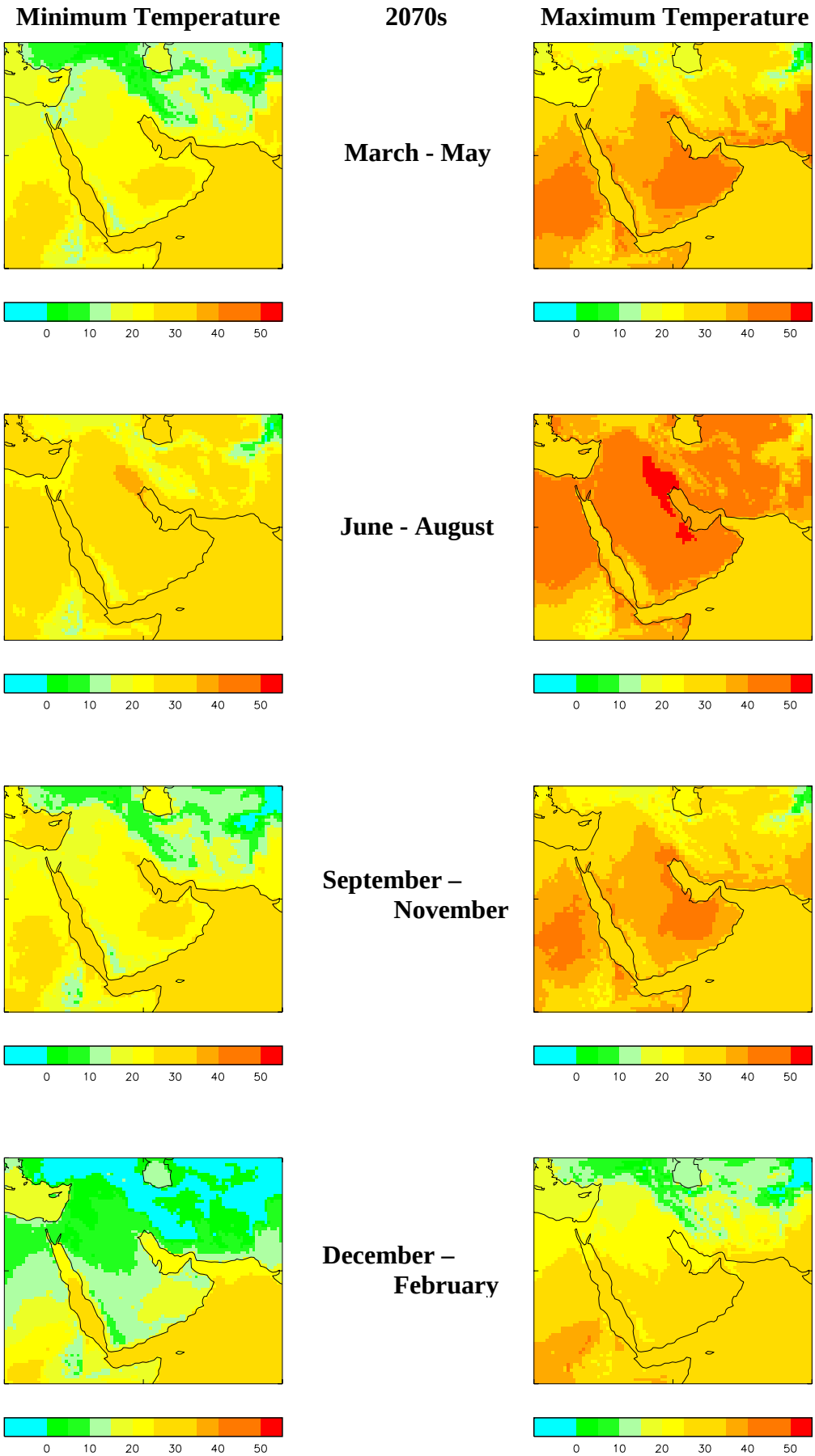

Figure 12. Regional Climate Model projections of seasonal average minimum and maximum temperatures by the 2070s.

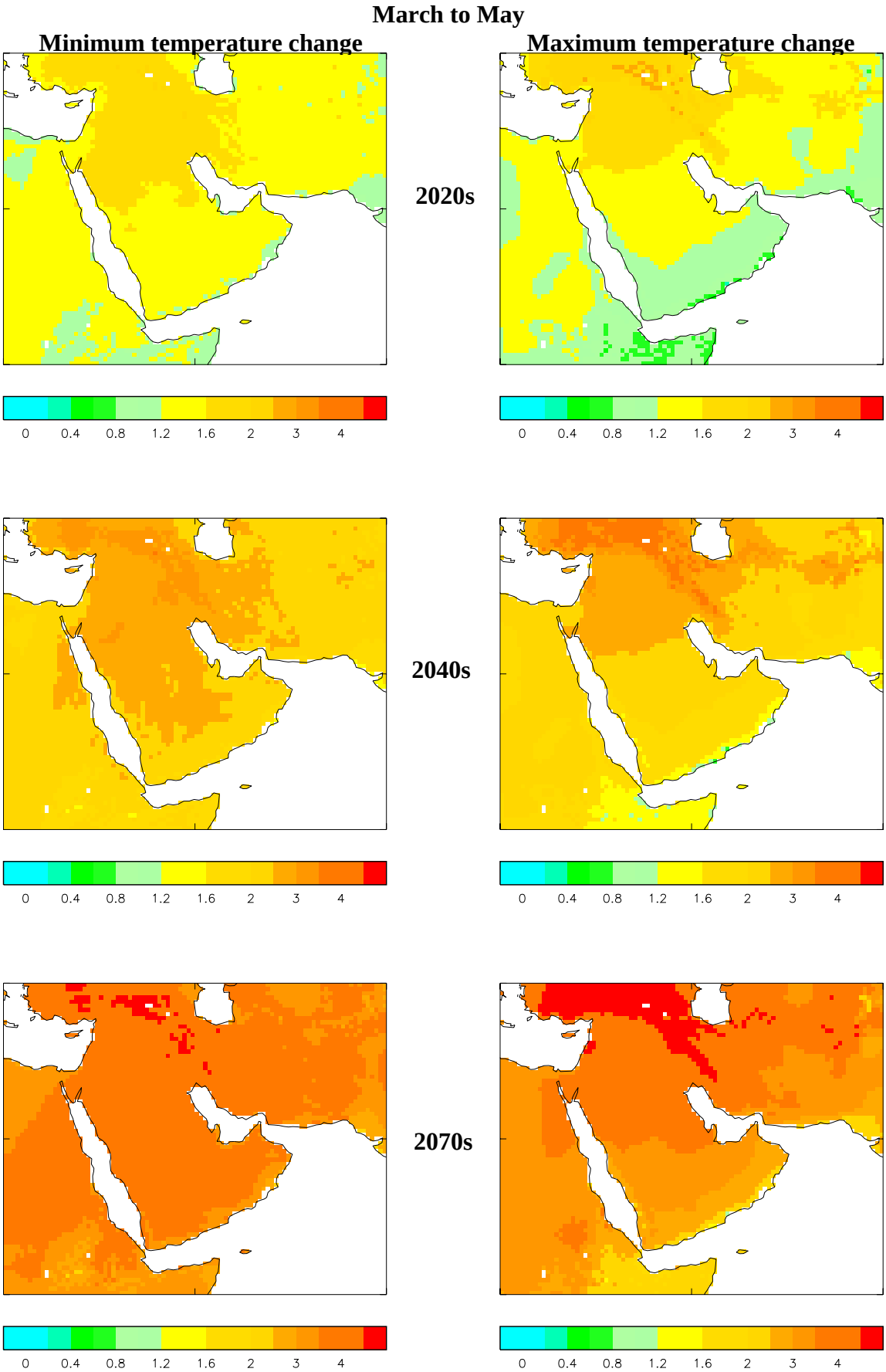

Figure 13. Regional Climate Model projections of changes in seasonal average minimum and maximum temperature (ºC) during **March to May**, across the Gulf region by 2020s, 2040s, and 2070s, relative to the 1990s.

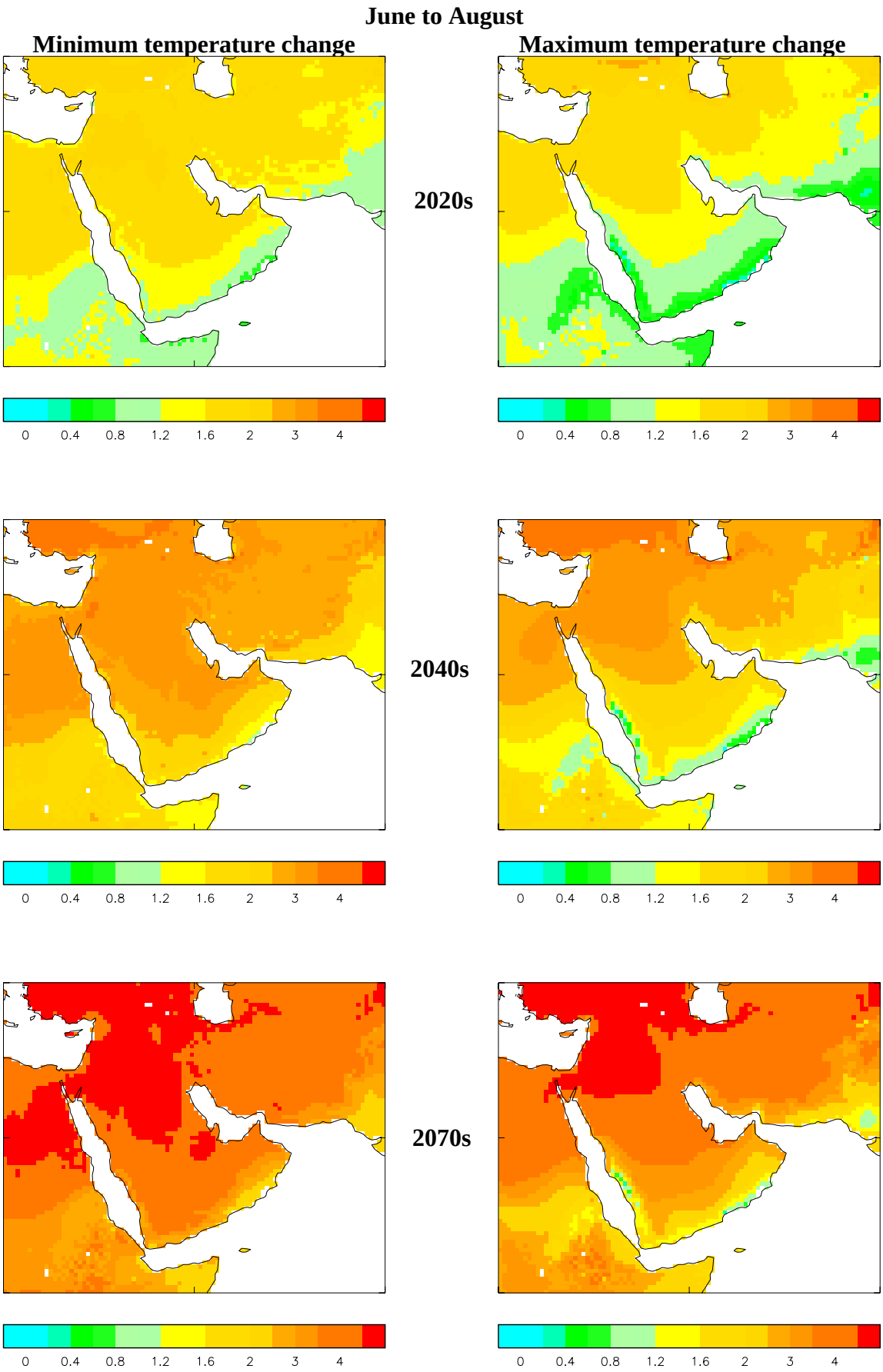

Figure 14. Regional Climate Model projections of changes in seasonal average minimum and maximum temperature (ºC) during **June to August**, across the Gulf region by 2020s, 2040s, and 2070s, relative to the 1990s.

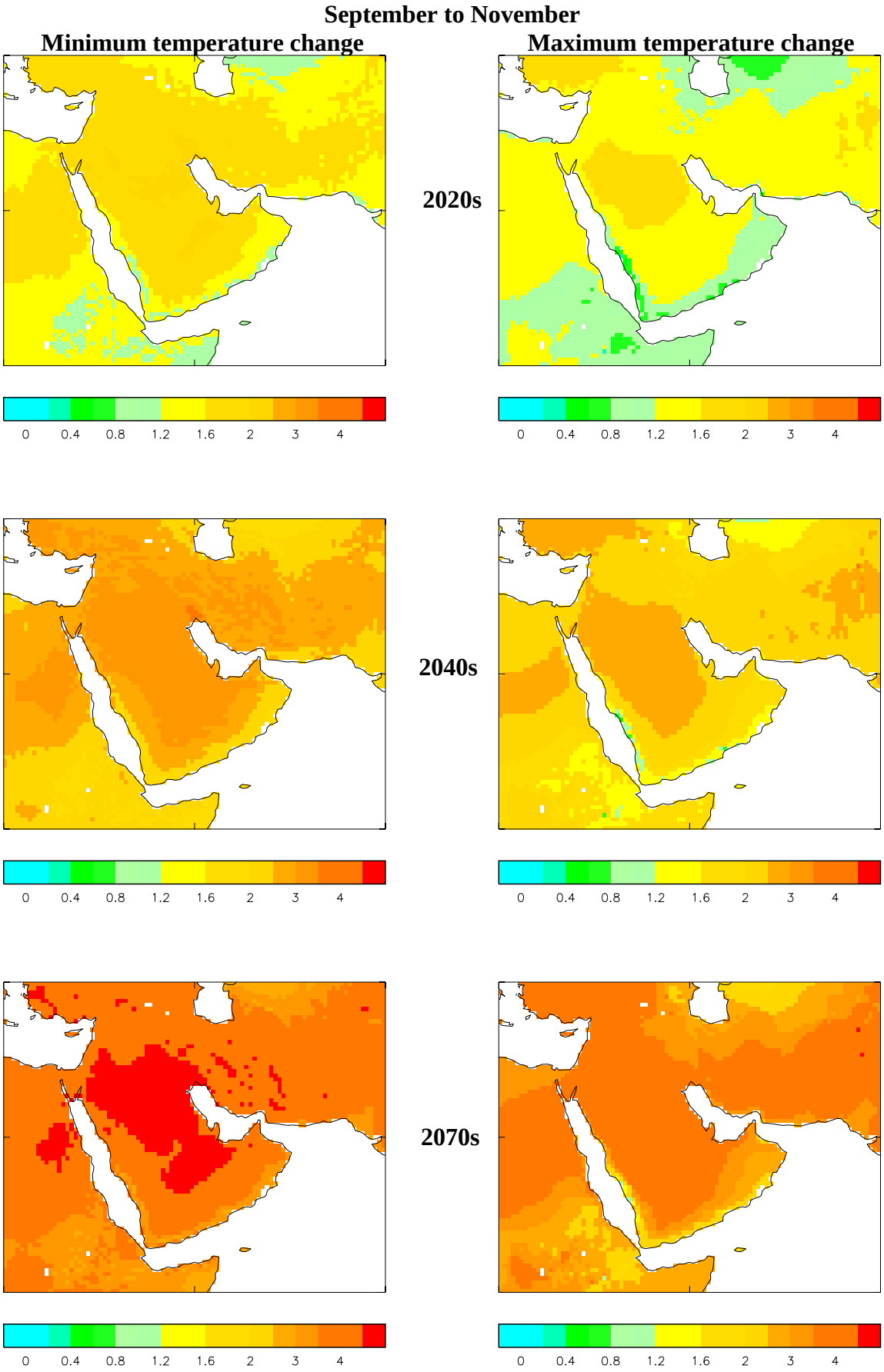

Figure 15. Regional Climate Model projections of changes in seasonal average minimum and maximum temperature (ºC) during **September to November** across the Gulf region by 2020s, 2040s, and 2070s, relative to the 1990s.

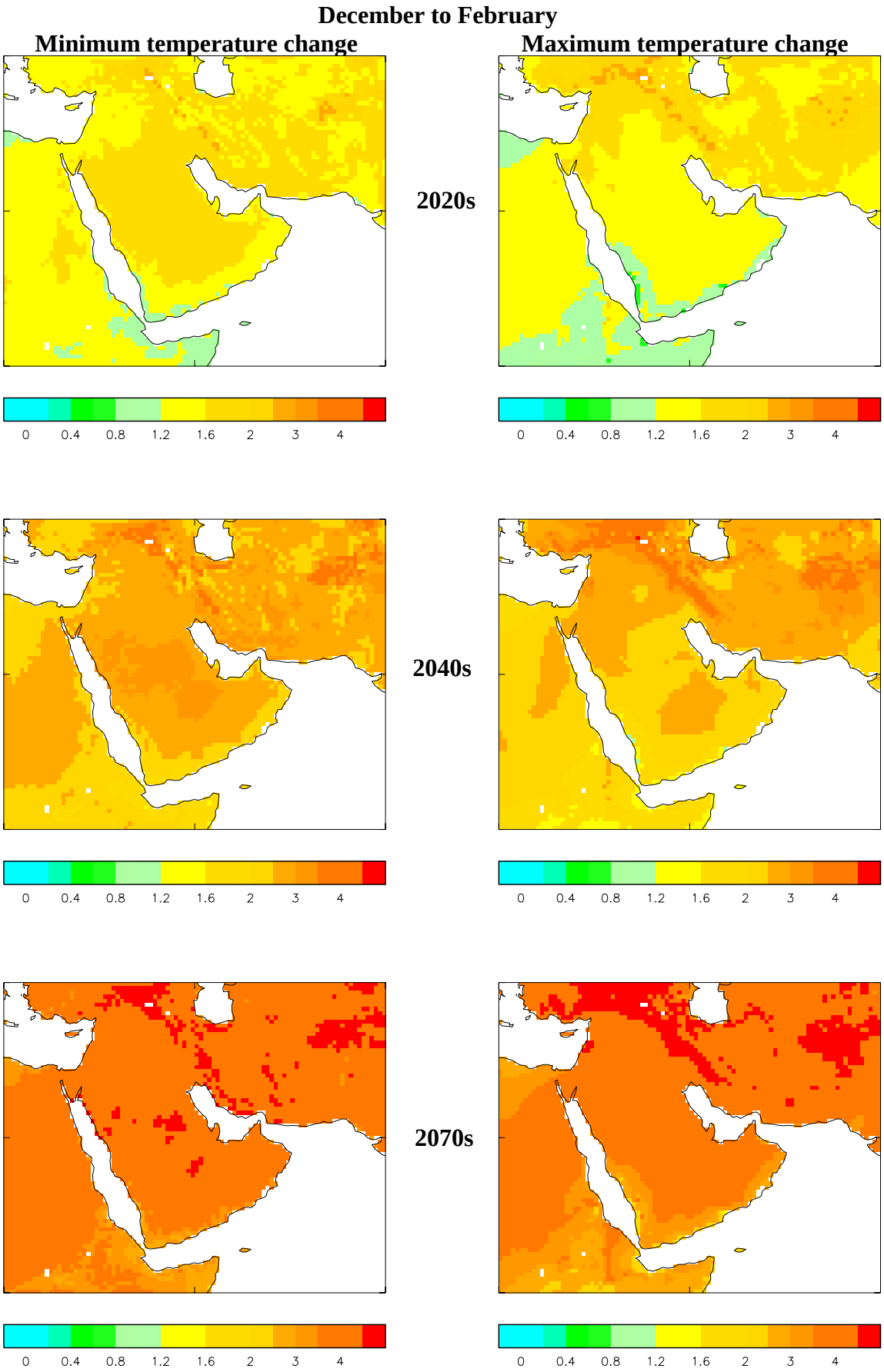

Figure 16. Regional Climate Model projections of changes in seasonal average minimum and maximum temperature (ºC) during **December to February**, across the Gulf region by 2020s, 2040s and 2070s, relative to the 1990s.

Precipitation

Annual

Large spatial variability is a key feature of precipitation across the Gulf region (Figure 17 and 18). RCM projections of decadally-averaged annual precipitation (mm/yr) indicate that the lowest precipitation, below 50 mm/yr, occurs across Egypt, Jordan, the north-west of Saudi Arabia and parts of central Iran. Areas with the highest annual precipitation, greater than 1000 mm/yr, tend to be in high mountainous terrain, e.g. the Ethiopian highlands, the south-west coastal region of the Arabian peninsular, southern and eastern Turkey, the Zagros, Alborz and Caucases mountain ranges in north and west of Iran, and the Hindu Kush region of north-east Afghanistan.

The enhanced resolution of the RCM results in precipitation projections for the whole Gulf region that are approximately 40 mm/yr higher than the corresponding GCM projections (Table 7). This is associated with more detailed topography in the RCM, which enhances precipitation over high mountainous terrain, and improved representation of precipitation from convection and tropical cyclone activity in the RCM, which cannot be captured at the GCM resolution.

Across the whole Gulf region, decadal average precipitation is generally projected to decrease throughout the 21st century (Table 8). These region-wide changes are deceptive as they mask large spatial variability in the precipitation responses (see Figures 19 and 20). Increases in precipitation of up to 100 mm/yr (30%) by 2020s and 130 mm/yr (35%) by 2040s are projected for the Ethiopian highlands and south-west coastal fringe of the Arabian peninsular, while decreases of up to -100 mm/yr (-20%) by 2020s enhancing to -140 mm/yr (-30%) by 2040s are shown across Turkey, Lebanon, northern Syria, the Zagros mountain region of western Iran, the Hindu Kush region of Afghanistan, as well as other areas within central Iran and Afghanistan. By 2040s, precipitation decreases of between 10 and 20 % are widespread across the northern half of the Gulf region. This is of particular importance to fresh water supplies in the region because it includes a large portion of the catchment areas of the Tigris and Euphrates rivers.

Table 7. Decadal average precipitation (in mm/yr) over land areas only across the Gulf region. Projections are made, using the A2 SRES emissions scenario (see Methodology), for the 1990s, 2020s, 2040s and 2070s decades with the PRECIS Regional Climate Model (RCM) and the HadCM3 Global Climate Model (GCM).

	1990s	**2020s**	**2040s**	**2070s**
RCM P	314.5	312.7	311.5	309.6
GCM P	273.7	271.1	276.1	257.9

Table 8. Changes in decadal average precipitation (see Table 7) for the 2020s, 2040s and 2070s relative to the 1990s. Climate projections are from runs of the PRECIS Regional Climate Model (RCM) and the HadCM3 Global Climate Model (GCM) driven with the A2 SRES emissions scenario (see Methodology).

	2020s-1990s	**2040s-1990s**	**2070s-1990s**
RCM P	-1.8	-3.0	-4.9
RCM P %	-0.6	-1.0	-1.6
GCM P	-2.6	2.4	-15.8
GCM P %	-0.9	0.9	-5.8

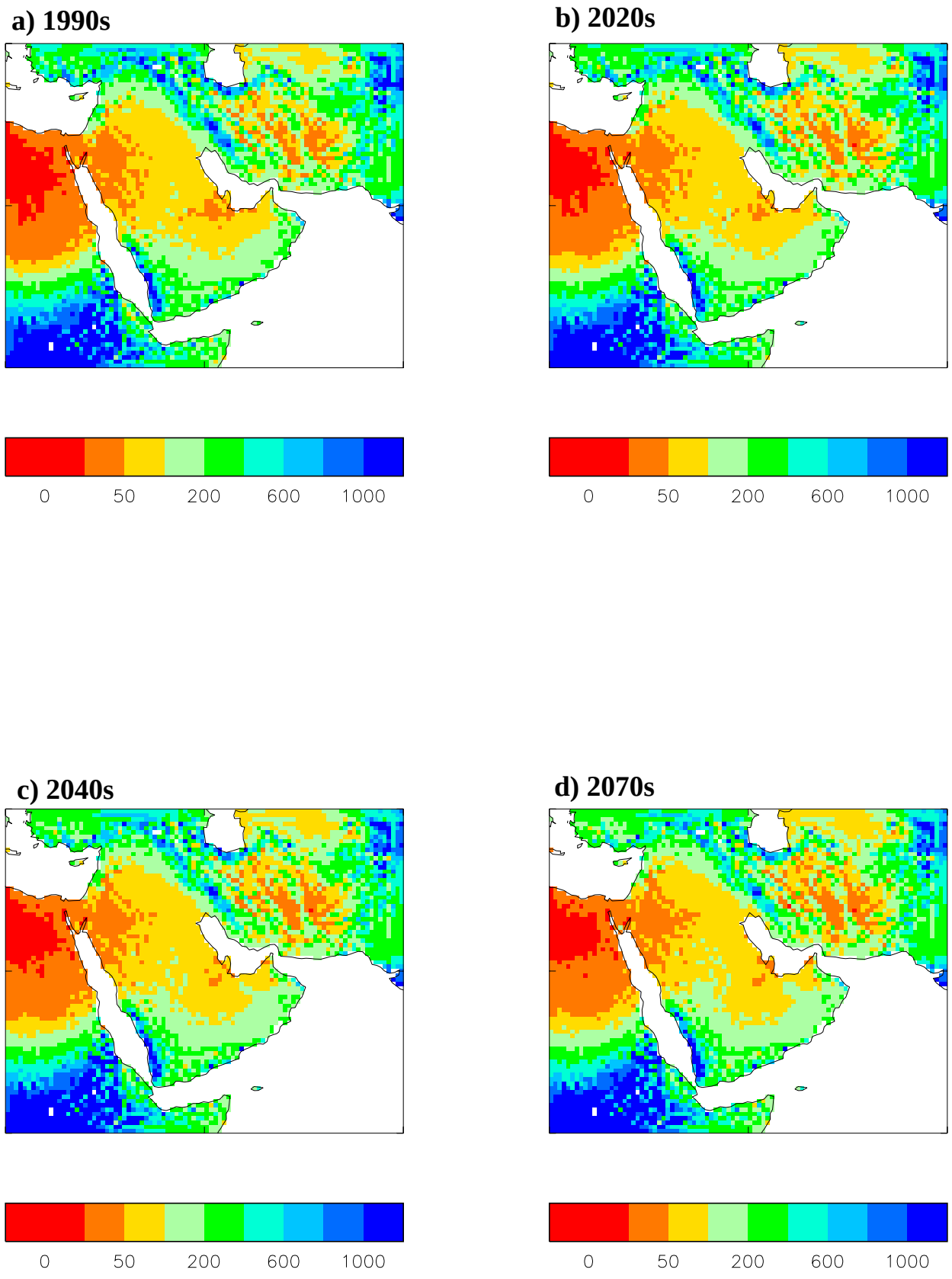

Figure 17. Regional Climate Model projections of decadal average precipitation (mm/yr) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

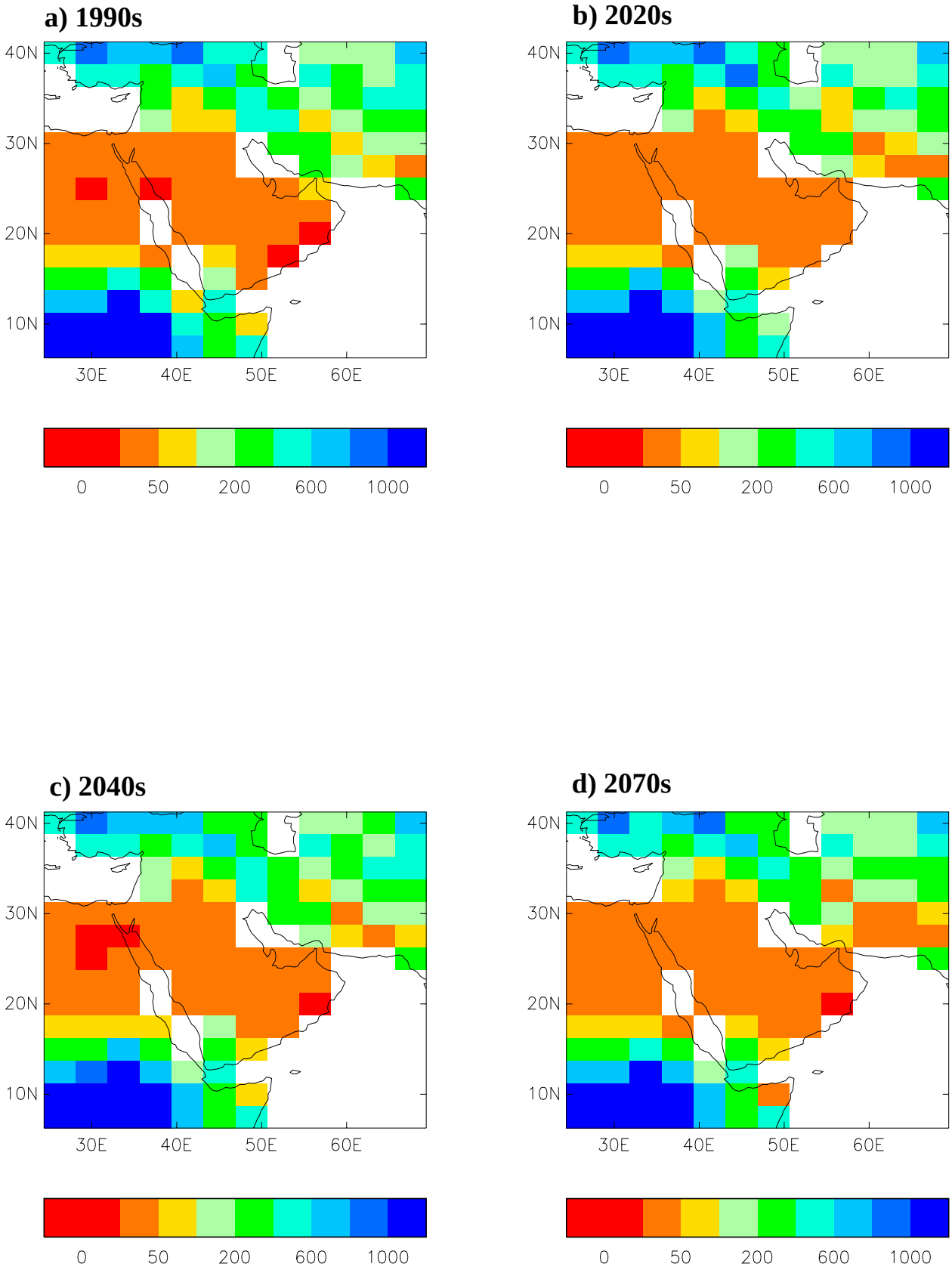

Figure 18. Global Climate Model projections of decadal average precipitation (mm/yr) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

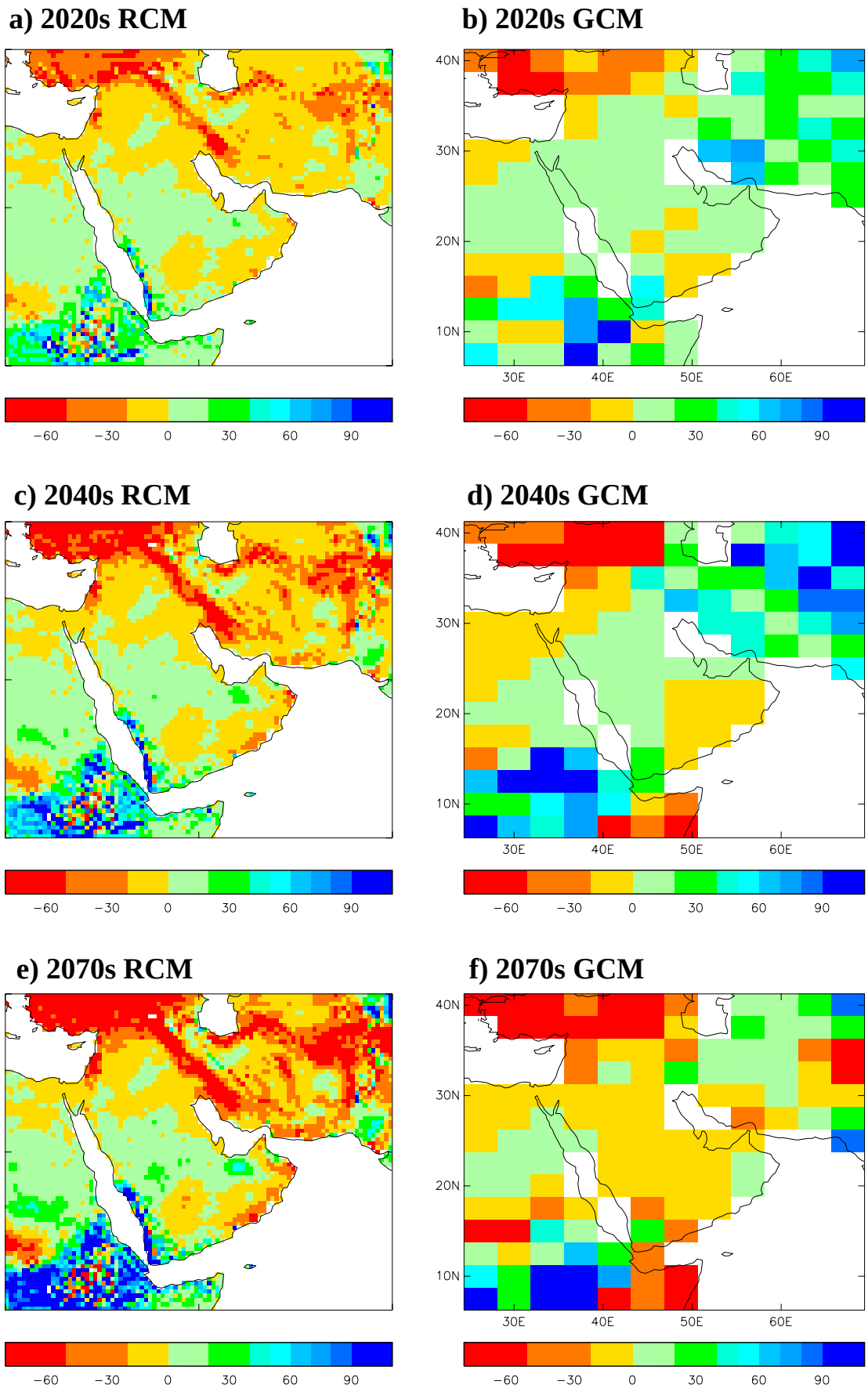

Figure 19. Regional & Global Climate Model projections of precipitation changes (mm/yr) across the Gulf region for a) & b) 2020s, c) & d) 2040s, and e) & f) 2070s, relative to the 1990s.

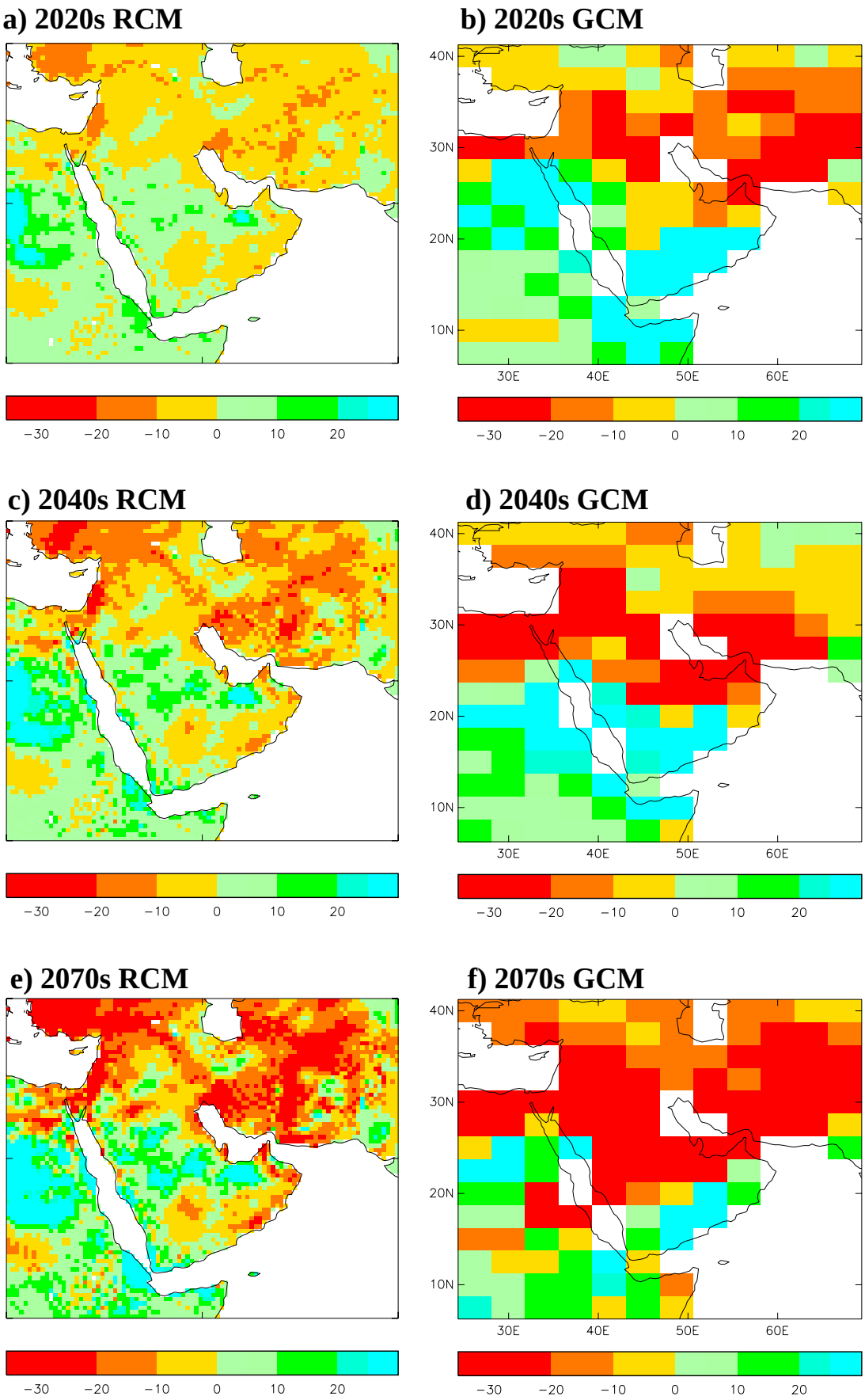

Figure 20. Regional & Global Climate Model projections of precipitation changes (%) across the Gulf region for a) & b) 2020s, c) & d) 2040s, and e) & f) 2070s, relative to the 1990s.

Seasonal

The Gulf region is characterized by large seasonal, as well as spatial, variability in precipitation (Table 9, Figures 21 to 24). The higher annual precipitation amounts, noted earlier, for the RCM compared to the GCM (see Table 7), are clearly focused during the summer months (June, to August) when RCM precipitation amounts are nearly double those of the GCM (Table 9). Spatially, the enhanced RCM precipitation occurs over regions south of 20ºN, i.e. Ethiopia, Eritrea, Dubouti, western Somalia, southern Sudan, Yeman and Oman, and east of 60ºE, i.e. over Afghanistan. This occurs as a result of the improved representation of topography in the RCM which significantly enhances the summer monsoonal precipitation, providing more realistic 1990s amounts, over these regions. As the RCM model results are more realistic they will be used for further discussions.

Over the Gulf region as a whole, RCM projections of precipitation changes from 1990s to 2020s, 2040s and 2070s indicate progressive decreases during winter and spring, and increases during summer and autumn (Table 10). Over all seasons the decreases in precipitation are larger than the increases, hence, annual precipitation across the region is projected to decrease throughout the 21st century (Table 8).

Spatially, the largest increases in seasonal precipitation amounts (90 to 120mm by 2020s, 100 to 150mm by 2040s, and 110 to 180mm by 2070s) are expected over the Ethiopian highlands during summer, and eastern Turkey and north-western Iran during autumn (Figure 25). Likewise, the largest decreases in precipitation amounts (-30 to -80mm by 2020s, -60 to -100mm by 2040s, and -80 to -130mm by 2070s) are expected over Turkey, Iran and southern Sudan during spring, and Yemen, Oman and southern Saudi Arabia during autumn (Figure 25). However, these changes in precipitation amount do not always correspond with the highest percentage changes in precipitation, which is a better indication of the impacts of precipitation changes on regional water supplies.

The largest percentage increases in precipitation (80 to 150% by 2020s, 120 to 300% by 2040s, and 150 to 500% by 2070s) are projected over central Iran during summer, and eastern Sudan during winter (Figure 26). Likewise, the largest percentage decreases in precipitation (-30 to -80% by 2020s, -40 to -100% by 2040s, and -60 to -130% by 2070s) are projected for Turkey and the coastal regions surrounding the eastern Mediterranean during summer, southern Saudi Arabia during autumn, and central Egypt and Afghanistan during winter (Figure 26).

Table 9. Regional Climate Model (RCM) and Global Climate Model (GCM) projections of decadal average precipitation (mm/year) for the Gulf region in different seasons; winter - DJF, spring - MAM, summer - JJA, autumn – SON, for the 1990s, 2020s, 2040s and 2070s.

	1990s				2020s				2040s				2070s			
	MAM	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**
RCM T	90.2	119.1	62.1	45.8	86.2	120.8	63.0	44.3	83.6	121.9	63.6	43.4	79.7	123.6	64.5	41.9
GCM T	94.5	67.6	60.0	51.7	90.0	71.4	61.6	48.0	98.0	71.4	56.6	50.1	76.3	73.7	58.0	49.9

Table 10. Changes in the Regional Climate Model (RCM) and Global Climate Model (GCM) projections of decadal average precipitation (mm/season) for the Gulf region in different seasons; winter - DJF, spring - MAM, summer - JJA, autumn – SON, for the 2020s, 2040s and 2070s relative to the 1990s.

	2020s-1990s				2040s-1990s				2070s-1990s			
	MAM	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**	**MAM**	**JJA**	**SON**	**DJF**
RCM P	-4.0	1.7	0.9	-1.5	-6.6	2.8	1.5	-2.4	-10.5	4.5	2.5	-3.9
RCM P %	-4.4	1.8	1.0	-1.6	-7.3	3.1	1.7	-2.7	-11.7	4.9	2.7	-4.3
GCM P	-4.5	3.9	1.7	-3.7	3.5	3.8	-3.4	-1.6	-18.3	6.2	-1.9	-1.8
GCM P %	-4.8	4.1	1.7	-3.9	3.7	4.0	-3.6	-1.7	-19.3	6.5	-2.0	-1.9

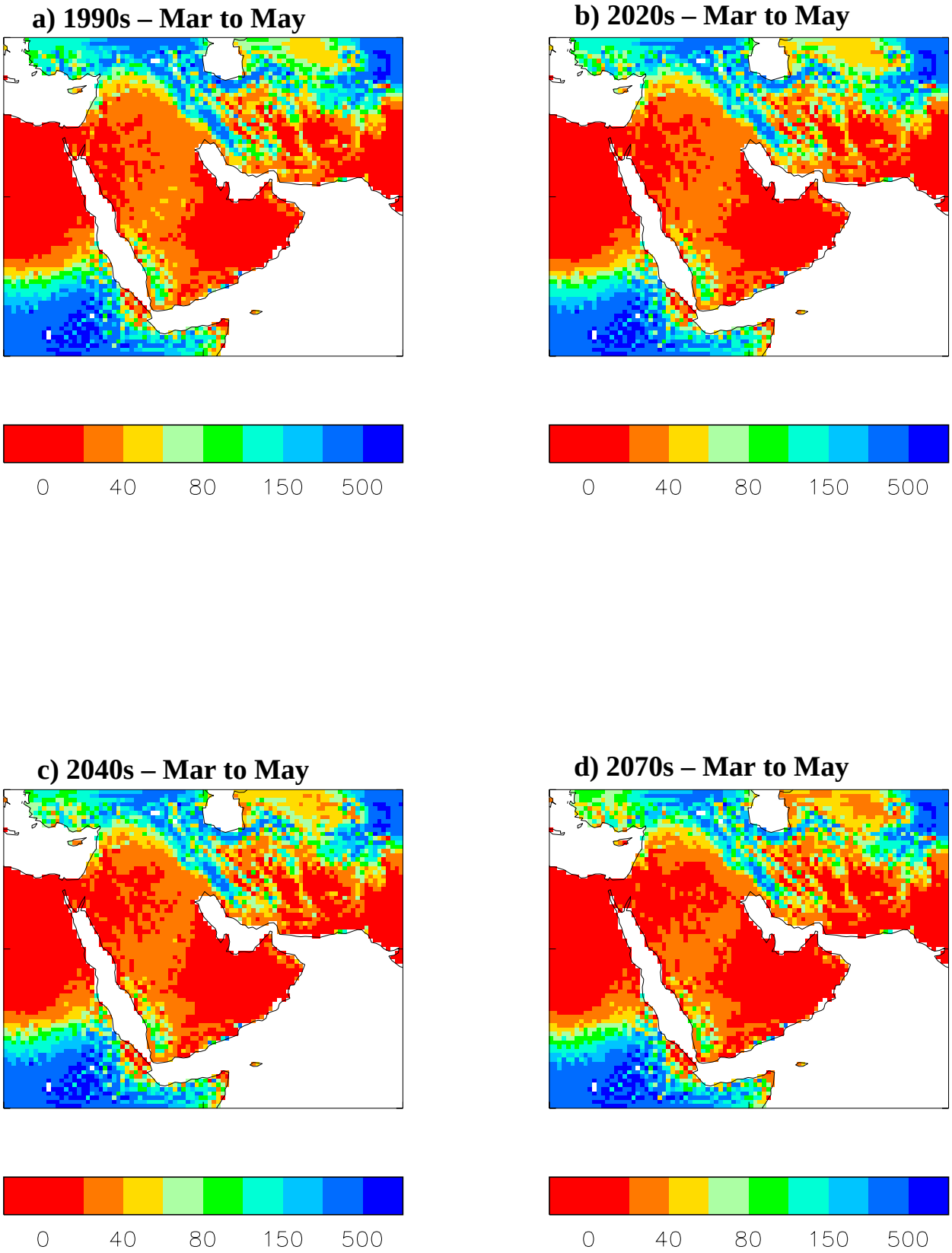

Figure 21. Regional Climate Model projections of spring (March, April, May) average precipitation (mm/yr) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

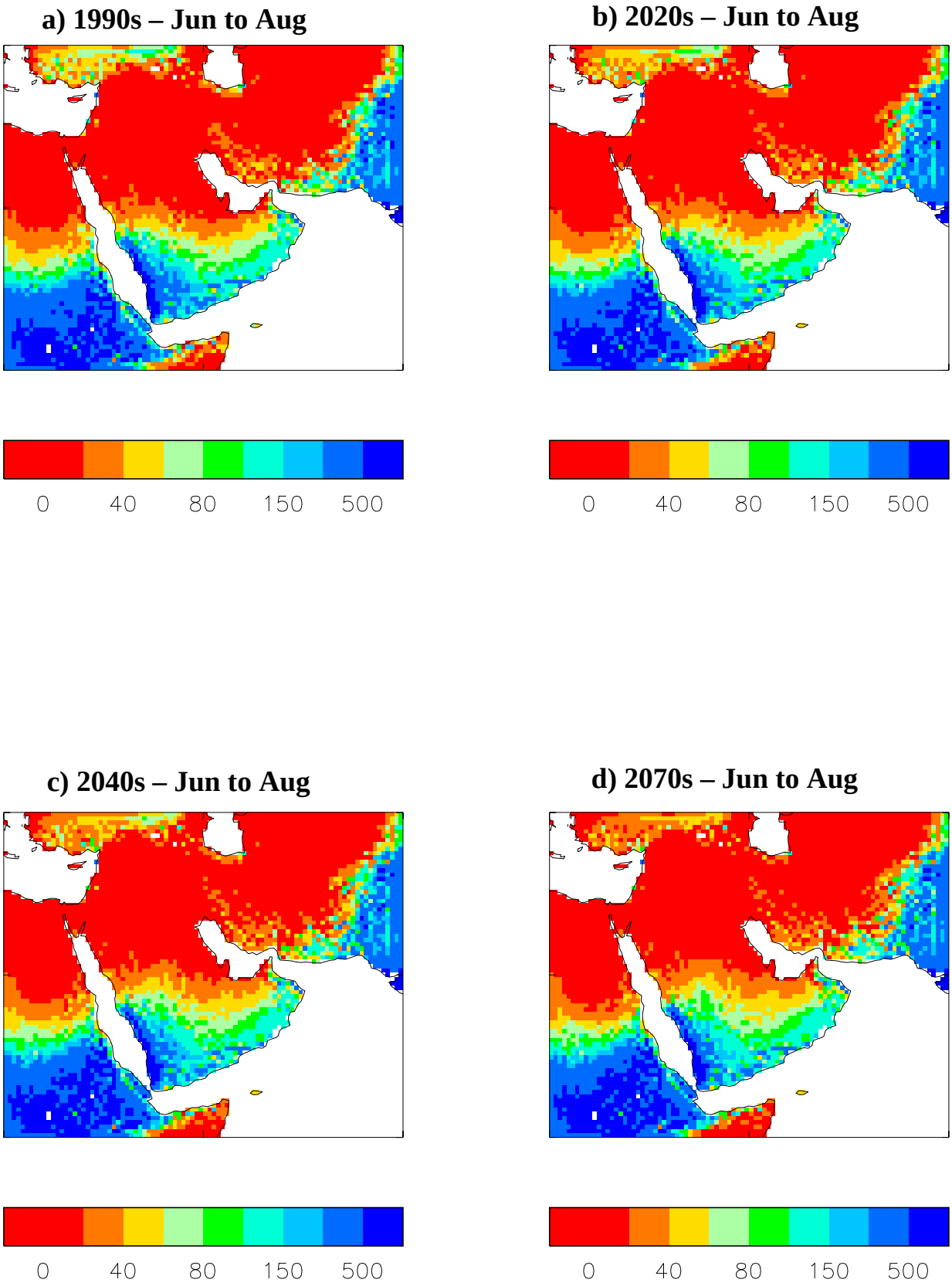

Figure 22. Regional Climate Model projections of summer (June, July August) average precipitation (mm/yr) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

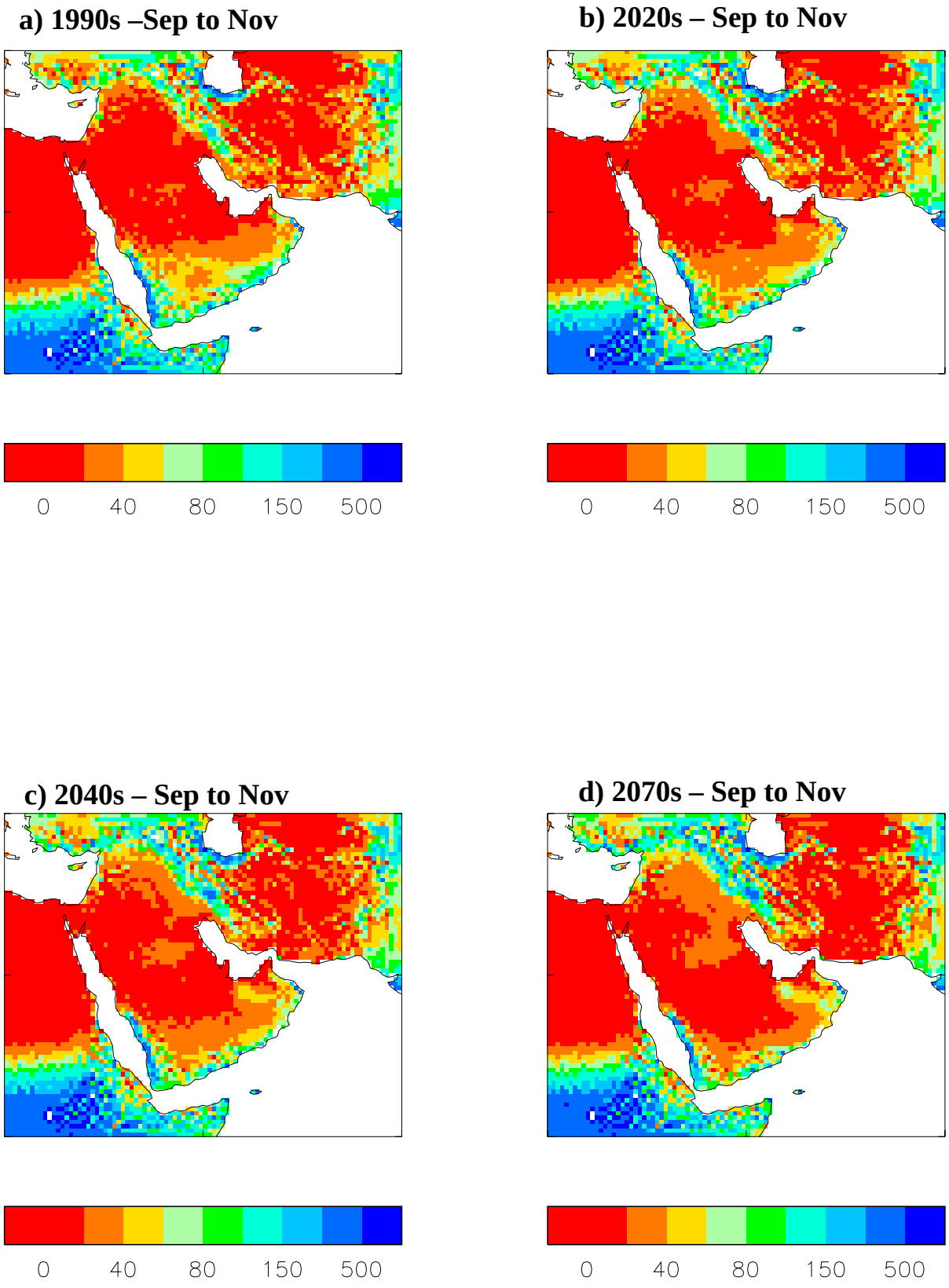

Figure 23. Regional Climate Model projections of autumn (September, October, November) average precipitation (mm/yr) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

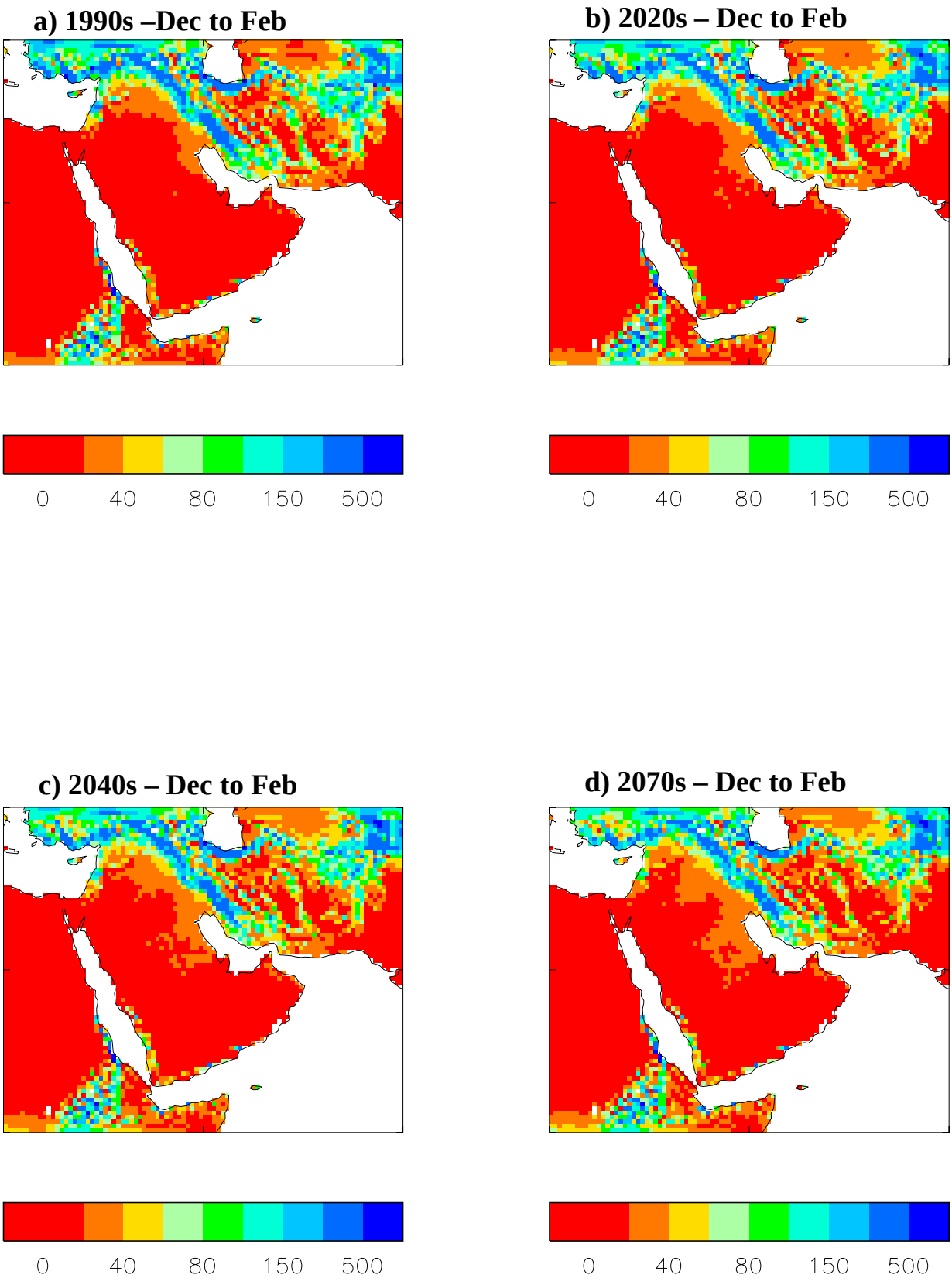

Figure 24. Regional Climate Model projections of winter (December, January, February) average precipitation mm/yr) across the Gulf region for a) 1990s, b) 2020s, c) 2040s, and d) 2070s.

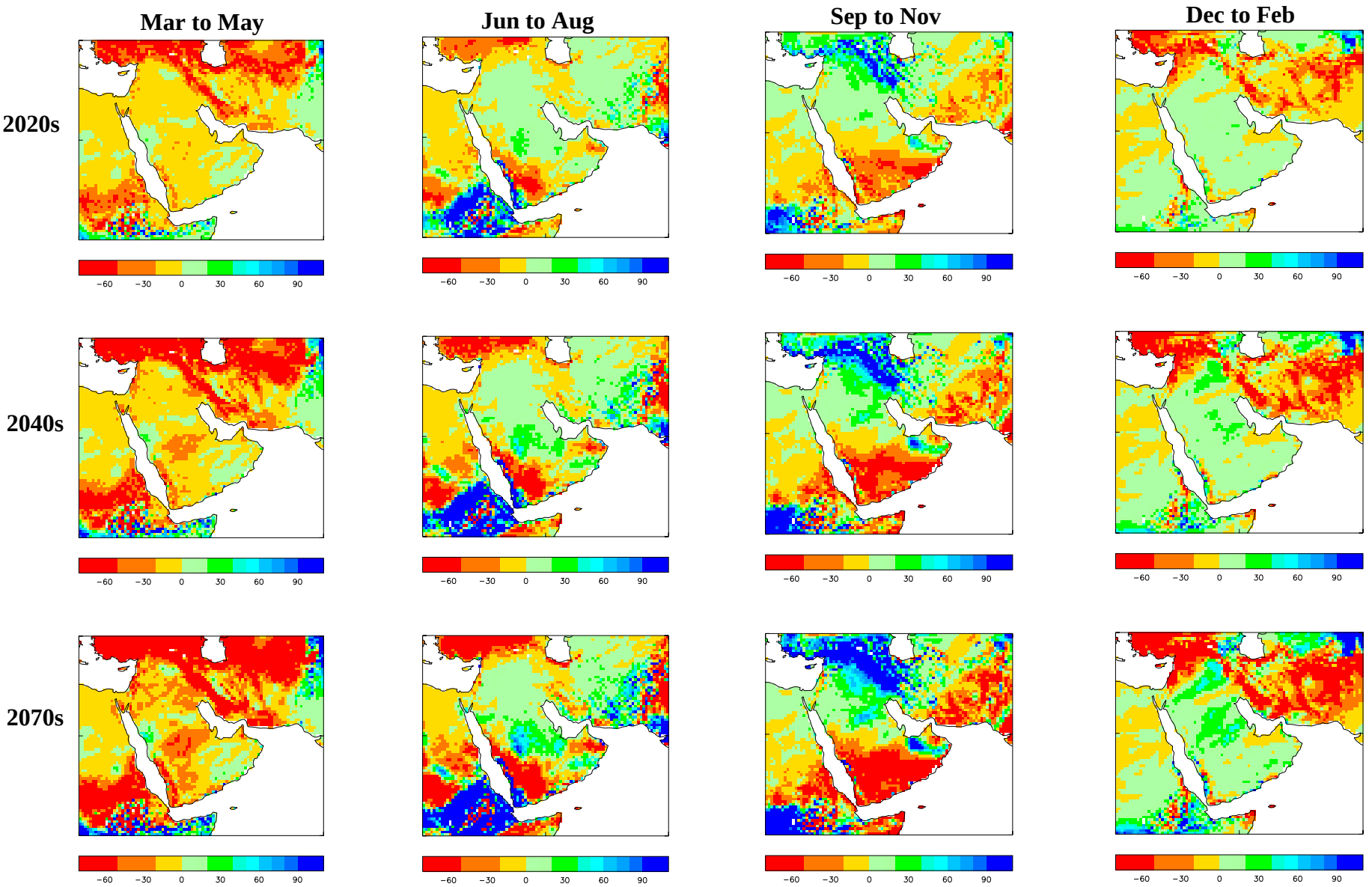

Figure 25. Changes in Regional Climate Model projections of seasonal precipitation (mm/season) across the Gulf region for the 2020s, 2040s, and 2070s, relative to the 1990s.

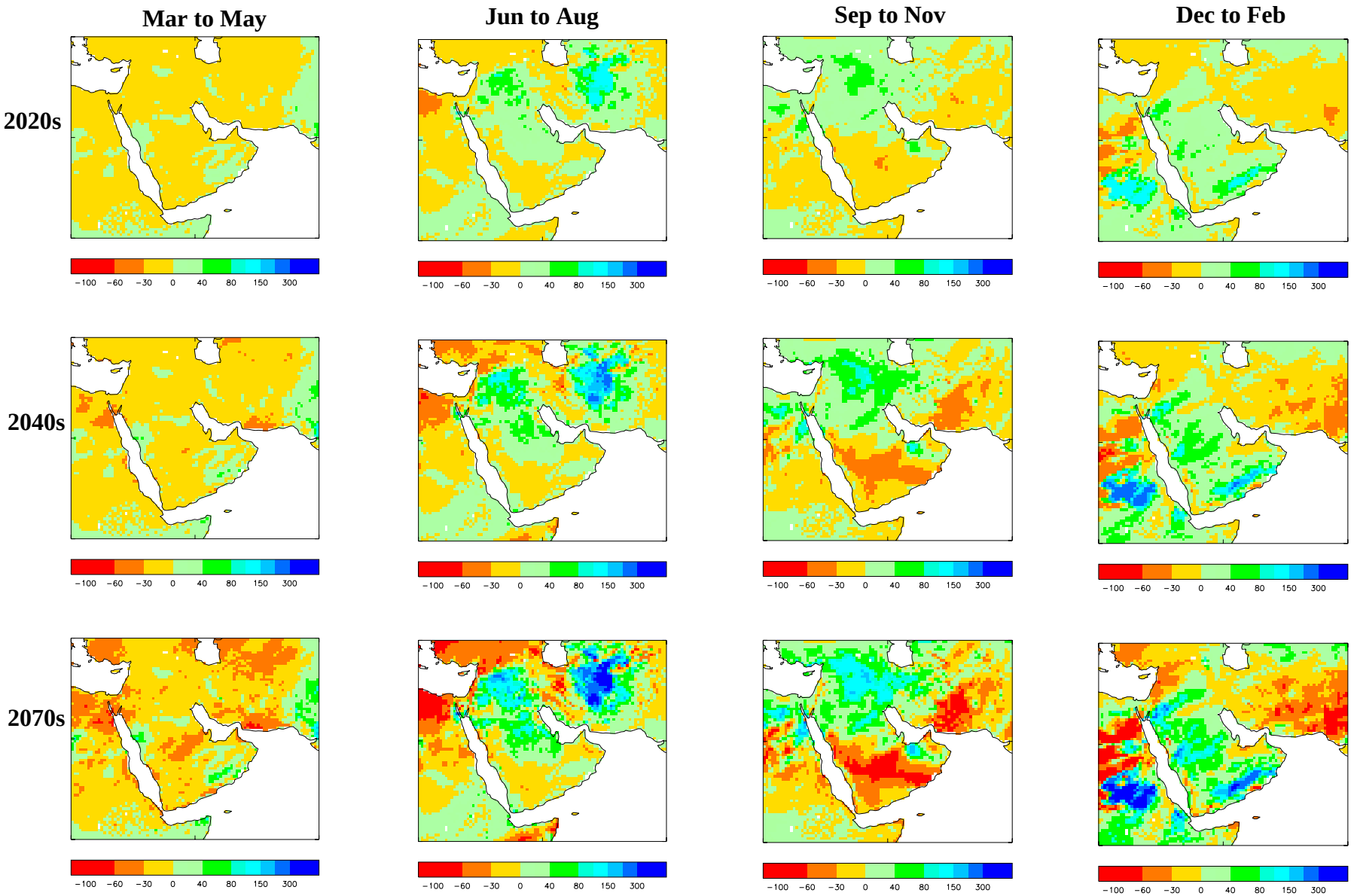

Figure 26. Percentage changes in Regional Climate Model projections of seasonal precipitation (%) across the Gulf region for the 2020s, 2040s, and 2070s, relative to the 1990.