Vol. 19: 179–192, 2002 | CLIMATE RESEARCH Clim Res | Published January 16

Future climate change and its impacts over small island states

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ABSTRACT: This paper examines the response of the climate of Small Island States (SIS) to transient increases in anthropogenic radiative forcing due to increases in atmospheric concentrations of greenhouse gases and/or sulfate aerosols using the data generated in a set of numerical experiments performed with a range of coupled atmosphere-ocean global climate models. Five of the 7 models considered in our validation exercise are found to have fair skill as regards their ability to simulate the broad features of present-day observed surface climatological features over the SIS in the Indian Ocean, the Mediterranean Sea, the Atlantic Ocean and the Pacific Ocean. The transient experiments with these models, which include the time-varying future anthropogenic radiative forcings, have been used here to develop regional projections of future climate change. An area-averaged annual mean warming of ca 2°C or higher for the 2050s and ca 3°C or higher for the 2080s are projected for the SIS as a consequence of increases in atmospheric concentration of greenhouse gases. In general, seasonal variations of the projected surface warming over the SIS are minimal. No significant change in diurnal temperature range is likely with an increase in surface temperatures. An increase in mean temperature would be accompanied by an increase in the frequency of extremely high temperatures. The aerosol forcing will only marginally reduce the surface warming. The models simulate only a marginal change (<10%) in annual mean rainfall over most of the SIS. During the northern hemisphere summer, however, rainfall is projected to decline (except over Pacific Ocean islands). An increase in daily rainfall intensity leading to more heavy rainfall events is also projected. The projected changes in temperature and rainfall could disrupt the terrestrial and marine ecosystems in most SIS. An integrated study of vulnerability assessment for SIS based on a better understanding of the precise magnitude of increase in surface air temperature and associated sea level rise is warranted for developing appropriate adaptation strategies.

KEY WORDS: Global climate models · Regional climate change · Small Island States · Anthropogenic radiative forcings · Impact Assessment · Sea level rise

1. INTRODUCTION

The majority of the world's Small Island States (SIS) are concentrated in tropical regions, except for a few islands such as Malta and Cyprus. The 4 regions of the world in which key SIS are located are: the Atlantic Ocean and Caribbean Sea Islands, which include Cape Verde, the Bahamas, Cuba, the Dominican Republic, Haiti, Jamaica, etc.; the Pacific Ocean Islands, which include Fiji, Samoa, the Solomon Islands, Vanuatu, etc.; the Indian Ocean Islands, which include Comoros, the Maldives, Mauritius and the Seychelles; and the Mediterranean Sea Islands, which include Cyprus and Malta. Many of these SIS have small land areas with a high population density, a limited range of natural resources and a fragile resource base, a narrow range of skills and low economic resilience, and are susceptible to natural hazards such as hurricanes and tsunamis (Hess 1990). Interannual variability in temperature,

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rainfall and sea level related to the ENSO (El Niño/ Southern Oscillation) phenomenon makes these regions increasingly vulnerable to climate change (Nurse et al. 1998). The impacts of climate change are likely to be felt more severely in SIS, which are already under stress due to current anthropogenic pressures. A rise in mean sea level appears to be one of the more certain of all potential consequences of global warming, due to the increases in atmospheric concentrations of greenhouse gases (GHGs) and other pollutants in the earth-atmosphere system (Warrick et al. 1996). The rising sea levels in the face of growing coastal populations could place an increasing strain on the low-lying land masses of the world in the decades to come. The loss of habitable land due to sea level rise for a majority of the SIS of the world is likely to be inevitable. This concern has produced an increasingly urgent demand for a confident projection of the regional climate change for SIS and an accurate assessment of the possible impacts due to this change, so that appropriate adaptation strategies for long-term planning of infrastructure and economic resources could be formulated for sustainable development.

Fully coupled atmosphere-ocean global climate models (A-O GCMs) are the starting point for developing confident projections of future climate due to anthropogenic radiative forcing. The disparity between the A-O GCMs in simulating the observed global-scale climatological features has reduced significantly, and considerable improvements in their predictive skill have been noted in recent years (Barnett 1999, Gates et al. 1999). The majority of climate change impact assessment studies are now making use of climate information provided by transient runs with coupled A-O GCMs (Watson et al. 1998). However, the GCMs still have limitations in realistic simulation of the spatial and temporal structure of the regional climate particularly in areas with complex topographical features. Appropriate validation exercises based on numerical experiments with time-dependent radiative forcing representing the present-day atmosphere must, therefore, be carried out in order to have some confidence in the projected scenarios of regional climate variability and change.

In this paper we first evaluate the skill of a selected list of currently available coupled A-O GCMs, namely the CCCma model (Canada), the CCSR/NIES model (Japan), the CSIRO model (Australia), the ECHAM4 model (Germany), the GFDL model (USA), the HadCM2 model (UK) and the NCAR model (USA), in terms of their ability to realistically simulate the present-day circulation and climatological features over the 4 regions of SIS to ensure that they portray an adequate simulation of observed present-day climatology on regional scales. The data generated in transient experiments with the more skilful A-O GCMs, which include the time-varying future anthropogenic radiative forcing, are used to provide a plausible climate change scenario for the 2020s, 2050s and 2080s in terms of the surface air temperature and precipitation over the SIS. The principal advantage of obtaining regional climate information directly from A-O GCMs is the knowledge that internal consistency between physical and dynamical processes in the model as well as the feedbacks and interactions is maintained (Giorgi & Mearns 1991). The vulnerability of SIS to projected climate changes is also discussed here against the backdrop of the physical, economical and societal environment of the countries in the region.

The data sets generated in transient control and anomaly numerical experiments from the A-O GCMs, conforming to a set of criteria outlined by the Task Group on Climate scenarios for Impacts Assessment (TGCIA) of the Intergovernmental Panel on Climate Change (IPCC), have been lodged at the Data Distribution Centre (DDC) hosted by the websites of the Climatic Research Unit (CRU) in the United Kingdom and the Deutsche Klimarechenzentrum (DKRZ) in Germany. The DDC, established in 1998, contains and makes available quality-controlled climate change and socio-economic data for fast-track regional climate impact assessment studies (see: http://ipcc-ddc.cru.uea.ac.uk and http://www.dkrz.de). We have used the data sets generated from numerical experiments with 7 A-O GCMs, which have been developed by various modeling groups of the world with varying vertical and horizontal resolutions and physical parameterisation schemes. The numerical experiments are historically forced (warm start, i.e. accounting for the past changes in radiative forcing due to increases in GHGs to date) integrations, use an IS92a-type forcing scenario with and without aerosol forcings (Alcamo et al. 1995) and extend to the middle of the 21st century and beyond. A brief introduction to these A-O GCMs and the details of numerical experiments performed with them is listed in Table 1. Further details on the model and appropriate references in the scientific literature on simulation details with individual models can be found at the Websites given above.

In the next section, we shall describe the domain size of each of the 4 regions of SIS considered here, the sources of observed climatological data used for comparison purposes and the climatic elements considered in our model validation and scenario development exercises.

2. THE REGIONS AND CLIMATE ELEMENTS

The 4 geographic regions of interest (Fig. 1) considered in this study are those which encompass the SIS, namely the Atlantic Ocean and Caribbean Sea Islands (9–29°N, 58–85°W), the Pacific Ocean Islands (23°S–23°N, 120°E–145°W), the Indian Ocean Islands (20°S–15°N, 40–80°E) and the Mediterranean Sea Islands (32–39°N, 20–36°E). For all purposes, we have analyzed the model-generated data (all grid points within the domain of the region) for the 4 seasons as well as on an annual mean basis. Part of the exercise also involves using the daily and monthly mean simulated surface climatology. We have used the model data from the historical experiments with combined GHG and sulfate aerosol forcings for validation analyses. This experiment was selected on the basis of recent findings which suggest that the global warming realized for the present-day atmosphere with respect to the pre-industrial times can be reconciled only when the combined GHG and aerosol forcings are considered (Mitchell & Johns 1997, Shine & Forster 1999). The data from the simulation experiments with GHG only forcings and also with combined GHG and sulfate aerosol forcings have been considered in order to obtain the future changes in the mean and/or variance of the key climatological elements.

The primary climatic elements considered in this study from among the model-simulated data sets are maximum, minimum and mean surface air temperatures and precipitation. The elements considered here are chosen based on their relevance for impact assessment purposes and are limited by data availability. The simulated data sets are interpolated onto a 1° grid in latitude and longitude using a third-order polynomial interpolation scheme (this produces minimal modification of the original field) and then regionally averaged over the selected domains. For all comparison purposes, the observed surface air temperature and precipitation climatology is based on the data sets compiled by New et al. (1999). Over the oceans and at higher altitudes, precipitation climatology is less reliable due to the sparsity of observations and the practical complexity of the measurement procedures. Temperature, unlike

Table 1. Summary of control, GHG (greenhouse gas) and GHG+aerosol forcings experiments with coupled A-O GCMs. CLW: cloud liquid water

	ECHAM4	HadCM2	CSIRO	CCCma	GFDL	NCAR	CCSR/NIES
AGCM	2.8° × 2.8° L19	2.5° × 3.75° L19	3.2° × 5.6° L9	3.7° × 3.7° L10	4.5° × 7.5° L9	4.5° × 7.5° L9	5.6° × 5.6° L20
OGCM	2.8° × 2.8° L11	2.5° × 3.75° L20	3.2° × 5.6° L21	1.8° × 1.8° L29	4.5° × 3.75° L12	1° × 1° L20	2.8° × 2.8° L17
Features	Prognostic CLW, geostrophic ocean	Prognostic CLW, isopycnal ocean diffusion			No diurnal cycle, isopycnal ocean diffusion	No diurnal cycle	Prognostic CLW, explicit sulfate scattering
Flux correction	Monthly mean heat, fresh water, stress	Monthly mean heat, fresh water	Heat, fresh water, momentum	Heat, fresh water	Monthly mean heat, fresh water	None	Monthly mean heat, fresh water
Control CO_2	354 ppmv	323 ppmv	330 ppmv	295 ppmv	300 ppmv	330 ppmv	345 ppmv
Transient CO_2	1.0 % yr^{-1} (compound)	1 % yr^{-1} (compound)	0.9 % yr^{-1}	1 % yr^{-1}	1 % yr^{-1} (compound)	1 % yr^{-1} (linear)	1 % yr^{-1} (compound)
GHGs	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
Historic:	1860–1989	1860–1989	1881–1989	1900–1989		1901–1989	1890–1989
IS92a:	1990–2099	1990–2099	1990–2100	1990–2100	1958–2057	1990–2036	1990–2099
GHGs + sulphate aerosols	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
Historic:	1860–1989	1860–1989	1860–1989	1860–1989	1881–1989	1860–1989	1900–1989
IS92a:	1990–2049	1990–2049	1990–2099	1990–2099	1990–2049	1990–2100	1990–2100
	SO_4	SO_4	SO_4	SO_4	SO_4	SO_4	SO_4
Historic:	1860–1989	1766–1989	1766–1989	1901–1989	1901–1989	1890–1989	1890–1989
IS92a:	1990–2100	1990–2065	1990–2065	1990–2036	1990–2036	1990–2099	1990–2099
Simulation length (yr) Control:	240	240	219	200	1000	136	210
GHGs:	240	240	219	200	100	136	210
GHGs+Aero.:	240	240	219	200	300	136	210
Warming (°C) at CO_2 doubling	1.3	1.7	2.0	2.7	2.3	2.3 (est.)	2.4
$2 \times CO^2$ sensitivity (°C)	2.6	2.5	4.3	3.5	3.7	4.6	3.5

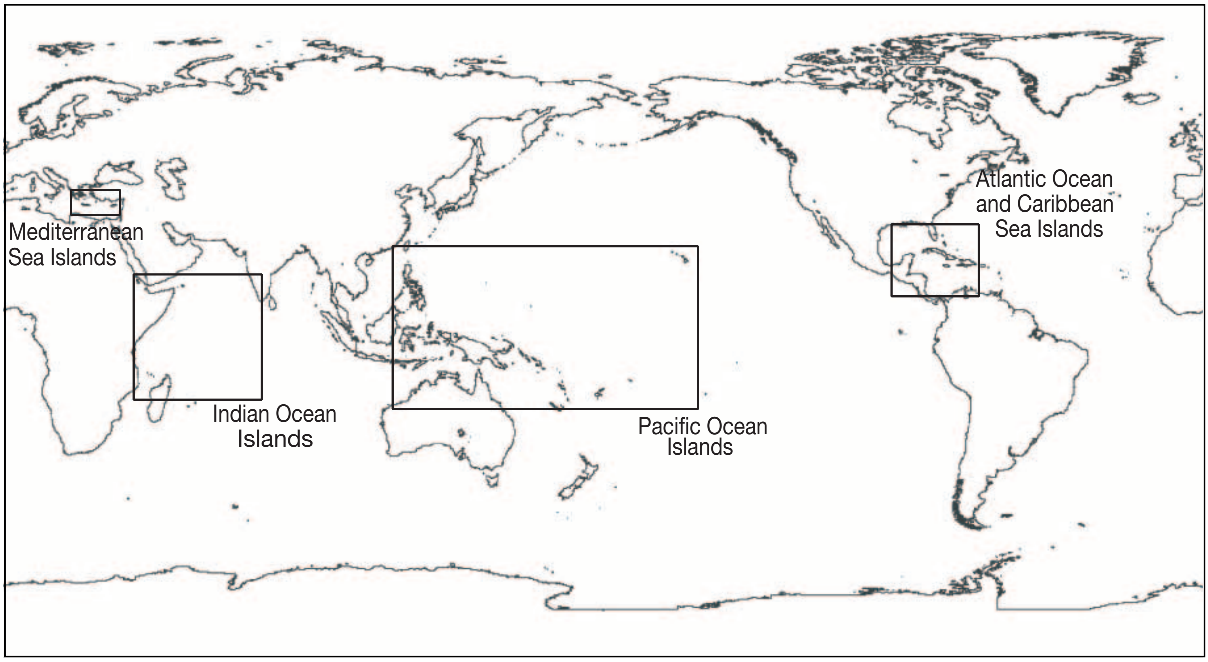

Fig. 1. The key regions of the world in which Small Island States are located

precipitation, is mainly dependent on altitude, latitude and season. However, temperature estimates are also less realistic over mountainous and oceanic regions. The time period of 30 yr (1961–1990) as a baseline climatology has been used for the purpose of the model validation exercise. In addition, 3 future 30 yr time periods centred around the 2020s (2010–2029), 2050s (2040–2069) and 2080s (2070–2099) have been considered in this study for developing climate change scenarios.

3. SIMULATION OF GLOBAL CLIMATOLOGY IN A-O GCMs

In order to develop confident climate change scenarios, it is first necessary to examine whether the models are able to simulate the present-day climatology on global and regional scales. The multi-century historic integration of A-O GCMs forced by observed anthropogenic changes in atmospheric composition offers an excellent opportunity to examine the skill of individual models in simulating the present-day climate and its variability (Mitchell et al. 1995). Prior to examining the skill of models over the SIS, we examined the long-term trends in the global and annual mean surface temperature simulated by each of the A-O GCMs in their control experiment. While the annual mean global surface temperature was rather high in the NCAR model, the GFDL model simulated a relatively lower surface air temperature. The global and annual mean surface air temperatures simulated by the other 5 models were within a range of 1.5°C. Moreover, climate drift in the 220 yr trends of surface air temperature in these 5 A-O GCMs ranged between 0.1 and 0.5°C, suggesting negligible distortion of the major climate feedback in multi-year simulations (not shown). The latitudinal cross-section of zonal mean surface air temperature simulated by each of the 7 GCMs suggests that, in general, the models simulate the surface temperature within 3°C of the observed zonal mean surface temperature climatology all through the globe except in the vicinity of polar regions (Fig. 2). The inter-model variability in the simulated surface air temperature climatology is within 2°C over the tropics as well as the mid-latitude regions except in the case of the NCAR and the GFDL models. The inter-model differences in the zonal mean rainfall simulated by the 7 GCMs are, however, relatively large, particularly over the tropics. Moreover, the difference between observed and model-simulated annual mean rainfall climatology is also rather large, particularly in the NCAR and the GFDL models. This suggests that, while problems still remain with regard to the realism of present-day global climate simulation by some A-O GCMs, the models are able to simulate the surface temperature climatology better than the precipitation climatology and higher confidence can be placed in projections of temperature changes than in those of hydrological changes.

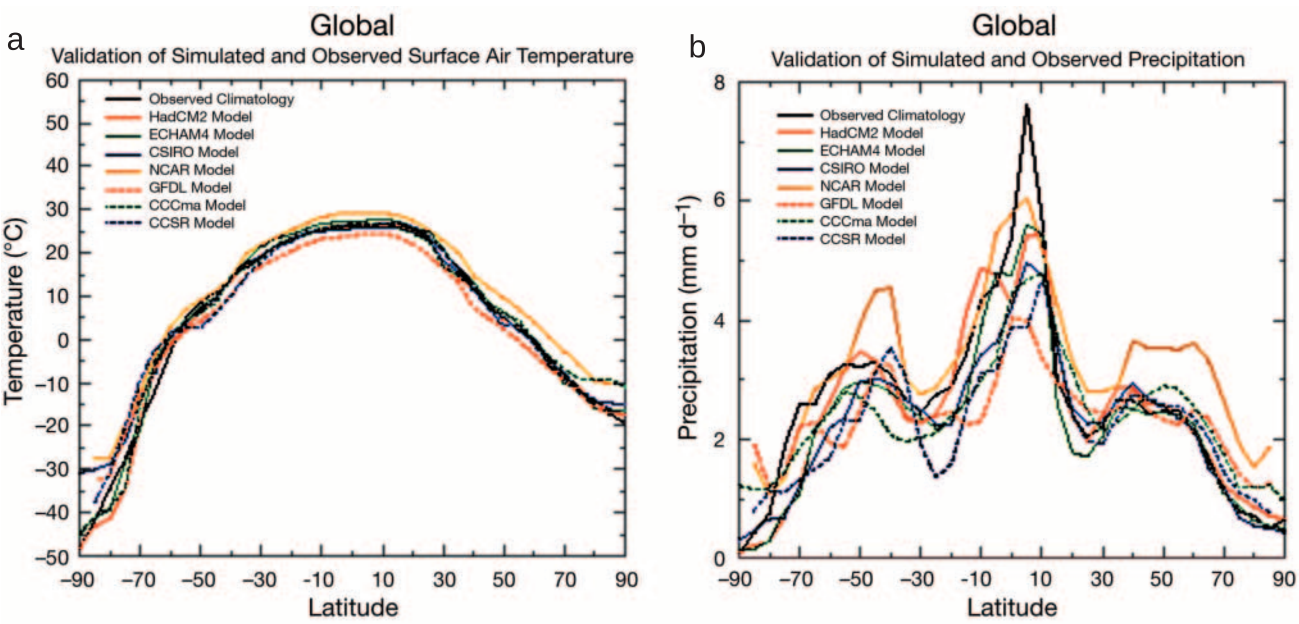

Fig. 2. Latitudinal cross-sections of the annual zonal mean (a) surface air temperature and (b) precipitation as simulated by the A-O GCMs and the observed climatology

4. REGION-SPECIFIC MODEL VALIDATION

The model validation exercise for the 4 regions of SIS includes the Atlantic Ocean and Caribbean Sea Islands, the Pacific Ocean Islands, the Indian Ocean Islands and the Mediterranean Sea Islands. Fig. 3 compares the monthly mean climatology of surface air temperature and rainfall area-averaged over the Atlantic Ocean and Caribbean Sea Islands as observed and as simulated by the 7 A-O GCMs. The monthly mean surface air temperatures simulated by the GFDL model are lower than the observed climatology by ca 4°C throughout the year. The NCAR model simulates lower than observed surface temperatures for the first 6 mo and higher than observed surface temperatures for the latter half of the year. The simulated precipitation during the northern hemisphere (NH) summer in both these models is also significantly lower (by about 2 mm d^{-1}) than the observed climatology. For the Pacific Ocean Islands, the area-averaged monthly mean observed and simulated climatology of surface air temperature and rainfall is depicted in Fig. 4. The performance of the GFDL and the NCAR model experiments in representing the monthly mean observed surface temperature and precipitation climatology over this region is also notably poor. For the Indian Ocean Islands and the Mediterranean Sea Islands, the area-averaged monthly mean observed and simulated climatology of surface air temperature and rainfall are compared in Figs 5 & 6 respectively. Here again, the GFDL and the NCAR models fail to realistically simulate the observed surface temperature and precipita-

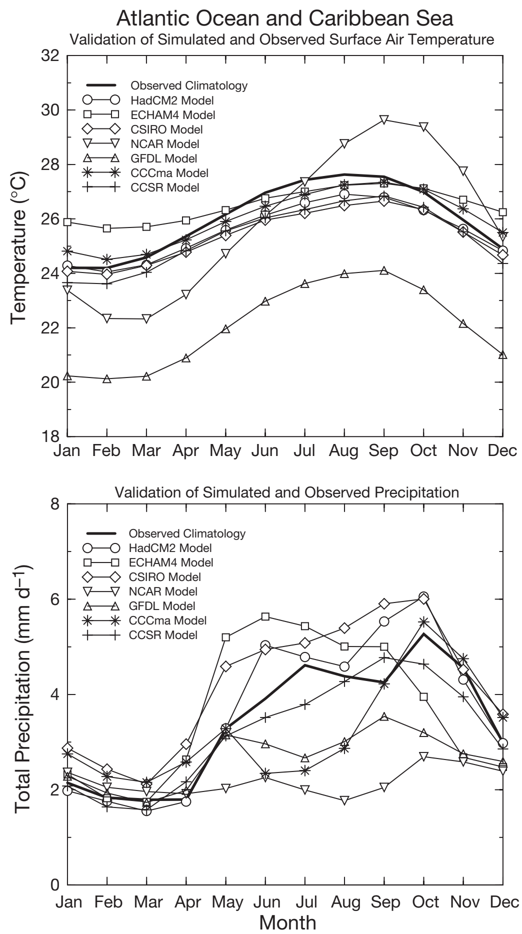

Fig. 3. Area-averaged monthly mean observed and simulated surface air temperature and precipitation climatology over the Atlantic Ocean and Caribbean Sea Islands

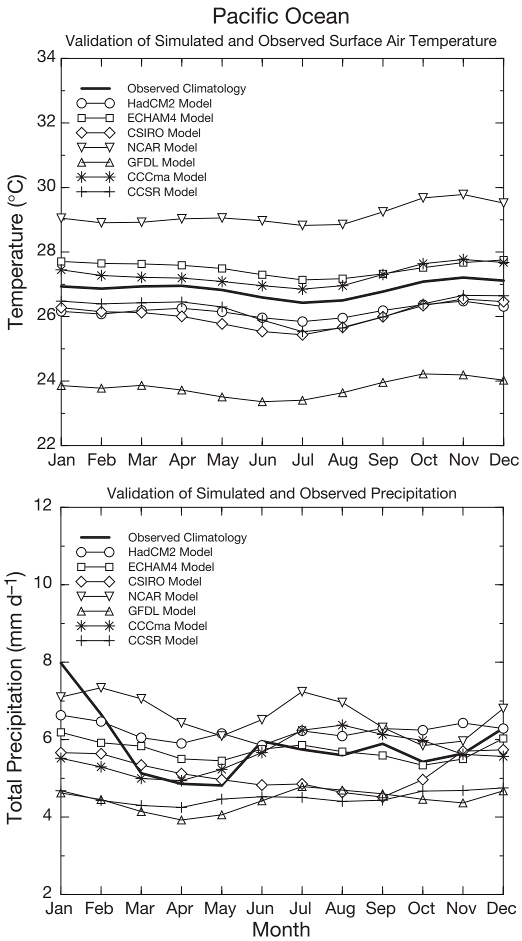

Fig. 4. As Fig. 3 but for the Pacific Ocean Islands

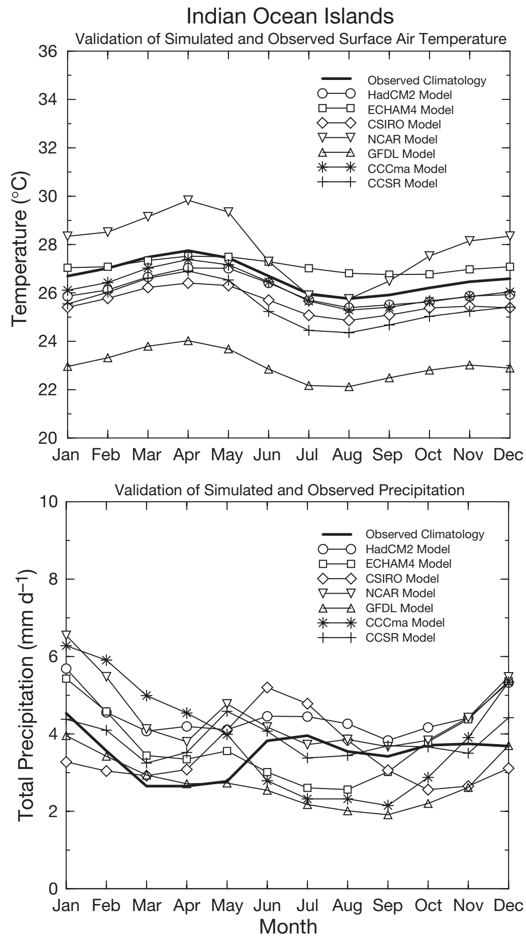

Fig. 5. As Fig. 3 but for the Indian Ocean Islands

tion climatology for both the regions. The CCCma model also simulates the monthly mean precipitation for these 2 regions rather poorly. Problems in the simulation of clouds and other hydrological parameters and the associated feedback processes could perhaps explain the poor skill in the NCAR and the GFDL models. The limitation in the availability of detailed model outputs restricted further investigation.

From the validation exercise presented above, it is evident that the A-O GCMs considered in this study still show deficiencies in reproducing present-day climate, with biases widely varying among models and regions. However, the realism in simulation of present-day regional surface air temperature is better than that for precipitation in these A-O GCMs. There is considerable variability among the available A-O GCMs in simulation of the present-day surface climatology over the selected regions representing the key SIS. This could be attributed at least partly to the differences in representation of feedbacks associated with clouds, oceans and sea ice in the models (Hulme & Brown 1998). In general, the CCCma, the CCSR/NIES, the CSIRO, the ECHAM4 and the HadCM2 A-O GCMs demonstrate some skill in simulating the present-day area-averaged monthly mean climatology in terms of surface temperature and rainfall for the 4 selected regions.

The uncertainties in deterministic projection of changes due to nonlinear processes in the climate system can be partially quantified from ensembles of integrations made using different models such that the probabilistic estimates of climate change thus obtained should lead to more reliable projections (Kittel et al. 1998, Mitchell et al. 1999). The climate change scenarios for the SIS based on an ensemble of results as inferred from the 5 A-O GCMs are likely to be more plausible provided we assume that they treat the dominant feedbacks initiated by the anthropogenic radiative forcing realistically. The model projections discussed in the next section are the climate change scenarios due to GHG-induced positive radiative forcing and also those that take into account the negative radiative forcing of sulfate aerosols.

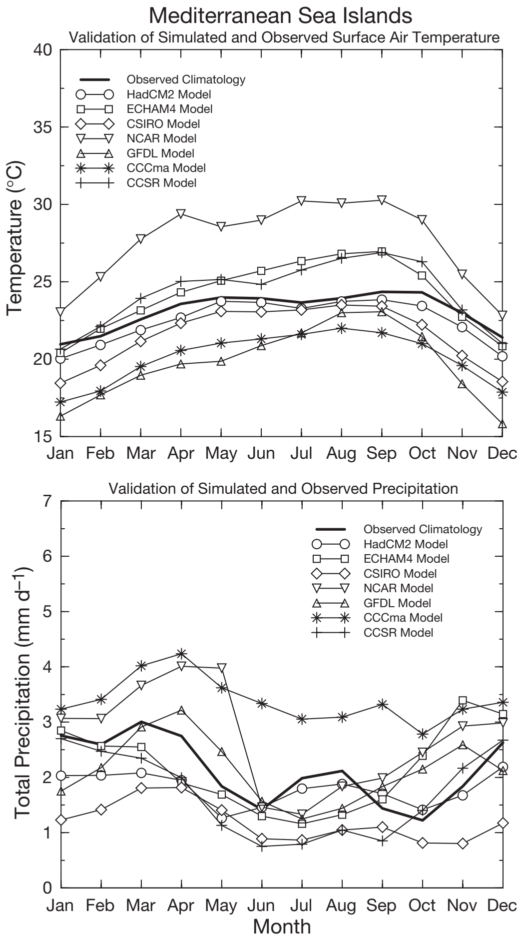

Fig. 6. As Fig. 3 but for the Mediterranean Sea Islands

5. PROJECTIONS OF FUTURE CLIMATE CHANGE

5.1. Surface air temperature

The climate change scenarios for 3 future time slices based on an ensemble of results as inferred from the mean of the 5 skilful A-O GCMs for each of the 4 regions encompassing the key SIS on annual mean basis are presented in Table 2. Tables 3 & 4 list the seasonal mean changes in surface air temperature and precipitation during the 2050s and 2080s respectively. The projected area-averaged annual mean warming as a consequence of increases in atmospheric concentration of GHGs over the 4 regions covering key SIS, namely, the Atlantic Ocean and the Caribbean Sea Islands, the Pacific Ocean Islands, the Indian Ocean Islands and the Mediterranean Sea Islands is 2.03, 1.98, 2.10 and 2.83°C for the 2050s and 3.06, 2.99, 3.16 and 4.27°C for the 2080s respectively (Table 2). The area-averaged annual mean surface temperature rise due to future increase in GHGs is projected to be the least over the Pacific Ocean Islands and highest over the Mediterranean Sea Islands among all the SIS. In general, the projected surface warming over the SIS is more or less uniform over the year, and the seasonal variations are minimal (Tables 3 & 4). The projected warming over the Mediterranean Sea Islands is, however, relatively higher during NH summer than during NH winter for both the time periods, particularly in the GHG-only simulations. It is evident from Tables 2–4 that even though the aerosol forcing marginally reduces the surface warming, the magnitude of projected warming is still considerable and could substantially impact the SIS.

The scatter of projected annual mean surface temperature increases and the associated changes in precipitation over each of the SIS as simulated by each of the 5 skilful GCMs is depicted in Figs 7 to 10. The range of simulated interannual variability in present-day surface air temperature and precipitation (during the 30 yr period of 1961–90) are marked with a thick line about the origin of the axes. It is interesting to note here that the projected changes for each of the 4 key SIS regions in the A-O GCMs are beyond the present-day interannual variability range (the size of the 'sig-

Table 2. Plausible changes in area-averaged annual mean surface air temperature and precipitation over Small Island States due to future increases in greenhouse gases (under IS92a emission scenarios) as inferred from an ensemble of data generated in 5 skilful A-O GCM experiments. Numbers in brackets are the area-averaged changes when the direct effect of sulfate aerosols is included

Region	Annual mean temperature change (°C)			Annual mean precipitation change (%)		
	2020s	2050s	2080s	2020s	2050s	2080s
Atlantic Ocean and Caribbean Sea	0.90 ± 0.16 (0.83 ± 0.04)	2.03 ± 0.43 (1.71 ± 0.25)	3.06 ± 0.84 (2.64 ± 0.61)	–2.2 ± 7.3 (–0.9 ± 4.4)	–5.2 ± 11.9 (–1.3 ± 7.8)	–6.8 ± 15.8 (–0.7 ± 12.3)
Pacific Ocean	0.93 ± 0.12 (0.79 ± 0.05)	1.98 ± 0.41 (1.63 ± 0.23)	2.99 ± 0.87 (2.54 ± 0.63)	2.9 ± 1.0 (1.9 ± 0.8)	5.5 ± 2.5 (4.9 ± 0.8)	7.6 ± 3.3 (7.0 ± 1.9)
Indian Ocean	0.97 ± 0.09 (0.83 ± 0.07)	2.10 ± 0.43 (1.64 ± 0.23)	3.16 ± 0.89 (2.61 ± 0.65)	1.9 ± 0.6 (1.6 ± 2.3)	3.1 ± 4.5 (1.6 ± 3.9)	5.1 ± 4.3 (4.3 ± 4.9)
Mediterranean Sea	1.28 ± 0.15 (1.11 ± 0.03)	2.83 ± 0.62 (2.31 ± 0.29)	4.27 ± 1.26 (3.57 ± 0.83)	0.5 ± 2.9 (–0.2 ± 2.4)	1.0 ± 11.0 (–2.4 ± 8.6)	4.3 ± 14.9 (–0.1 ± 12.9)

Table 3. Plausible changes in area-averaged seasonal mean surface air temperature and precipitation over Small Island States for the 2050s due to future increases in greenhouse gases (under IS92a emission scenarios) as inferred from an ensemble of data generated in 5 skilful A-O GCM experiments. Numbers in brackets are the area-averaged changes when the direct effect of sulfate aerosols is included

Region	Temperature change (°C)				Precipitation change (%)			
	NH winter	NH spring	NH summer	NH autumn	NH winter	NH spring	NH summer	NH autumn
Atlantic Ocean and Caribbean Sea	2.00 ± 0.46 (1.68 ± 0.32)	2.01 ± 0.46 (1.68 ± 0.31)	2.02 ± 0.44 (1.71 ± 0.21)	2.07 ± 0.41 (1.76 ± 0.20)	3.4 ± 14.3 (5.9 ± 7.4)	–5.9 ± 20.6 (–3.0 ± 16.9)	–14.4 ± 12.2 (–6.9 ± 11.5)	–2.9 ± 8.1 (–0.8 ± 3.2)
Pacific Ocean	1.98 ± 0.39 (1.65 ± 0.20)	2.00 ± 0.39 (1.64 ± 0.20)	1.98 ± 0.43 (1.61 ± 0.27)	1.98 ± 0.46 (1.63 ± 0.28)	4.3 ± 1.9 (3.7 ± 1.2)	4.9 ± 3.0 (4.5 ± 2.6)	7.2 ± 4.8 (6.8 ± 3.3)	5.8 ± 3.4 (4.6 ± 1.2)
Indian Ocean	2.11 ± 0.43 (1.67 ± 0.15)	2.12 ± 0.44 (1.64 ± 0.21)	2.09 ± 0.44 (1.63 ± 0.30)	2.07 ± 0.45 (1.63 ± 0.28)	3.5 ± 6.1 (2.0 ± 7.5)	8.0 ± 8.7 (7.8 ± 8.2)	–1.8 ± 10.0 (–4.7 ± 4.5)	3.9 ± 7.0 (1.1 ± 2.8)
Mediterranean Sea	2.64 ± 0.72 (2.27 ± 0.44)	2.66 ± 0.63 (2.16 ± 0.36)	2.93 ± 0.53 (2.27 ± 0.17)	3.08 ± 0.64 (2.52 ± 0.30)	8.1 ± 14.7 (2.6 ± 15.7)	2.1 ± 12.4 (1.9 ± 7.8)	–4.8 ± 10.3 (–8.9 ± 6.0)	–3.2 ± 14.3 (–7.7 ± 13.2)

nal' due to anthropogenic forcing is larger than the 'noise' due to internal variability), suggesting thereby that the impact of climate change over the selected regions could be noticed by as early as the 2020s. The inter-model variability (the apparent disagreement between different A-O GCMs) in the projected changes in annual and seasonal mean surface air temperatures is found to increase with time.

Associated with the rise in mean surface air temperatures, a relatively more pronounced increase in minimum temperature than in maximum temperature and hence a marginal decrease in diurnal temperature range (between 0.2 and 0.7°C) is also projected over the SIS on an annual mean as well as on a seasonal mean basis for the 2020s, 2050s and 2080s. The projected reduction in diurnal temperature range is, however, not statistically significant in the time period considered here. Furthermore, an analysis of model-simulated daily temperature data (from the CSIRO and the ECHAM A-O GCM experiments) for the present-day atmosphere and for the 3 future time slices (2020s, 2050s and 2080s) suggests that the increase in mean temperature is likely to be accompanied by an increase in the frequency of extreme high temperatures. The frequency of extreme high temperatures in NH summer is projected to increase in future for the 4 SIS, thereby increasing the probability of heat stress conditions.

5.2. Precipitation

In general, all A-O GCMs simulate only a marginal change (<10%) in annual rainfall over most of the SIS. An area-averaged annual mean increase in precipitation of 2.9% for the 2020s, 5.5% for the 2050s and 7.6% for the decade of the 2080s over the Pacific Ocean Islands is projected as a consequence of future increases in GHGs (Table 2). The projected increase here is marginally lower under the combined influence of GHGs and sulfate aerosols. The projected increase in annual mean precipitation is limited to within 3 and

Table 4. Plausible changes in area-averaged seasonal mean surface air temperature and precipitation over Small Island States for the 2080s due to future increases in greenhouse gases (under IS92a emission scenarios) as inferred from an ensemble of data generated in 5 skilful A-O GCM experiments. Numbers in brackets are the area-averaged changes when the direct effect of sulfate aerosols is included

Region	Temperature change (°C)				Precipitation change (%)			
	NH winter	NH spring	NH summer	NH autumn	NH winter	NH spring	NH summer	NH autumn
Atlantic Ocean and Caribbean Sea	3.01 ± 0.87 (2.61 ± 0.66)	3.02 ± 0.91 (2.59 ± 0.70)	3.07 ± 0.86 (2.64 ± 0.61)	3.12 ± 0.77 (2.71 ± 0.51)	4.8 ± 14.6 (8.4 ± 12.9)	–7.9 ± 27.7 (–0.6 ± 26.2)	–19.2 ± 18.8 (–8.2 ± 17.1)	–2.5 ± 14.3 (–0.1 ± 10.2)
Pacific Ocean	2.97 ± 0.82 (2.56 ± 0.57)	3.01 ± 0.85 (2.53 ± 0.59)	2.98 ± 0.90 (2.52 ± 0.67)	2.97 ± 0.90 (2.54 ± 0.69)	6.0 ± 1.5 (5.6 ± 1.6)	5.3 ± 4.5 (5.9 ± 3.5)	10.2 ± 6.9 (8.9 ± 5.8)	8.9 ± 4.9 (7.3 ± 2.6)
Indian Ocean	3.18 ± 0.88 (2.61 ± 0.60)	3.21 ± 0.89 (2.61 ± 0.62)	3.16 ± 0.90 (2.62 ± 0.69)	3.11 ± 0.91 (2.58 ± 0.68)	5.8 ± 10.3 (6.2 ± 10.5)	12.5 ± 12.3 (11.1 ± 10.9)	–2.6 ± 12.6 (–5.9 ± 7.4)	6.9 ± 6.3 (5.4 ± 6.4)
Mediterranean Sea	3.94 ± 1.34 (3.31 ± 1.01)	4.05 ± 1.18 (3.37 ± 0.76)	4.52 ± 1.16 (3.70 ± 0.72)	4.57 ± 1.36 (3.87 ± 0.88)	16.0 ± 21.1 (9.9 ± 21.6)	5.0 ± 17.4 (4.1 ± 12.8)	–7.4 ± 16.2 (–11.6 ± 10.7)	0.6 ± 19.9 (–4.7 ± 18.5)

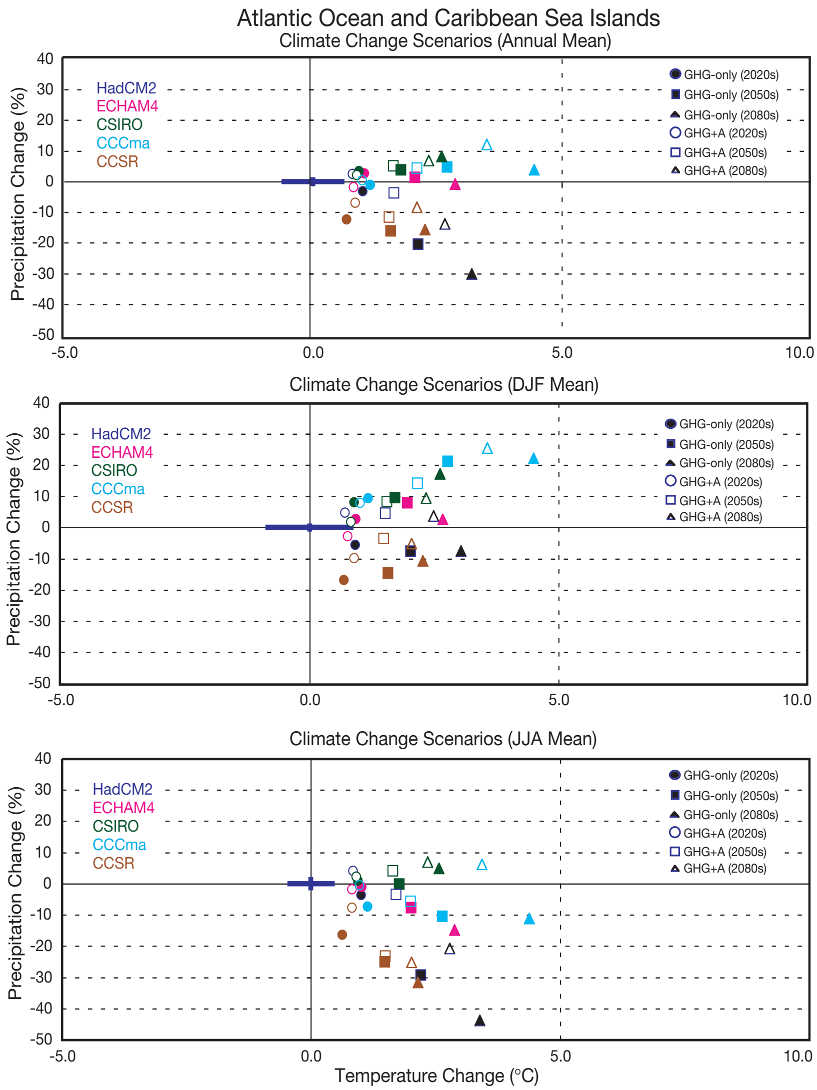

Fig. 7. The projected changes in area-averaged annual and seasonal mean surface air temperature and precipitation over the Atlantic Ocean and Caribbean Sea Islands as simulated by the selected A-O GCMs. Thick lines along the origin of axes give the range of present day simulated interannual variability in surface air temperature and rainfall during the 30 yr period

5% over the Indian Ocean and the Mediterranean Sea Islands during the 2050s and 2080s respectively. The A-O GCM simulations project a decline of about 5 and 7% in annual mean precipitation by the 2050s and 2080s respectively over the Atlantic Ocean and Caribbean Sea Islands. On a seasonal basis, enhanced rainfall is expected during the NH winter over most SIS. The wintertime increase in precipitation is more pronounced over the Mediterranean Sea Islands (an increase of about 8% by the 2050s and 16% by the 2080s). A decline in precipitation is projected for the Atlantic Ocean and Caribbean Sea, the Indian Ocean and the Mediterranean Sea Island States during the NH summer (Tables 3 & 4). The decline in NH summer precipitation could be 9% by the 2050s and 12% by the 2080s (under the combined influence of GHGs and aerosols) over the Mediterranean Sea Islands, suggesting thereby a possibility of severe water stress in this region. It is important to note here that the spread associated with inter-model projections of precipitation change is quite high (standard deviation in projections of precipitation change simulated by the 5 A-O GCMs is as high as ±25% in some cases). Further, the A-O GCMs agree in the sign of the precipitation change only in the case of Pacific Ocean Islands (Fig. 8). It may be noted here that the regional precipitation is strongly modulated by the local orography and in this respect the coarse horizontal resolution of the A-O GCMs considerably enhances the uncertainty in future projections of regional precipitation. Therefore, the degree of confidence that can be placed in future projections of regional precipitation change remains relatively low.

The major concern for impacts in the SIS region is not with the mean climate changes described above, but is with the extremes that are superimposed on those mean changes. Numerous studies have described the likely intensification of rainfall when the mean change ranges from a slight decrease to an increase over Tropical Pacific Ocean and adjoining land regions (e.g. Meehl et al. 1993, Hennessy et al. 1997, Walsh & Pittock 1998). A UK Meteorological Office high-resolution atmospheric GCM (UKHI AGCM) with a mixed layer ocean projected a mean decrease in precipitation of 3.5% over South Polynesia but produced little change in intensity, while an increase of 7.5% over Micronesia halved the return period of heavy rainfall events (Jones et al. 1999). Our analysis of daily precipitation data (available for only the CSIRO and the ECHAM model experiments) suggests that, while there appears a strong probability of lesser number of rainy days in a year in the future for all the selected SIS, an increase in the daily intensity of precipitation is possible over the SIS of the Pacific Ocean and the Indian Ocean. An increase in the probability of occurrence of droughts over the Mediterranean Sea Island is also projected for the future.

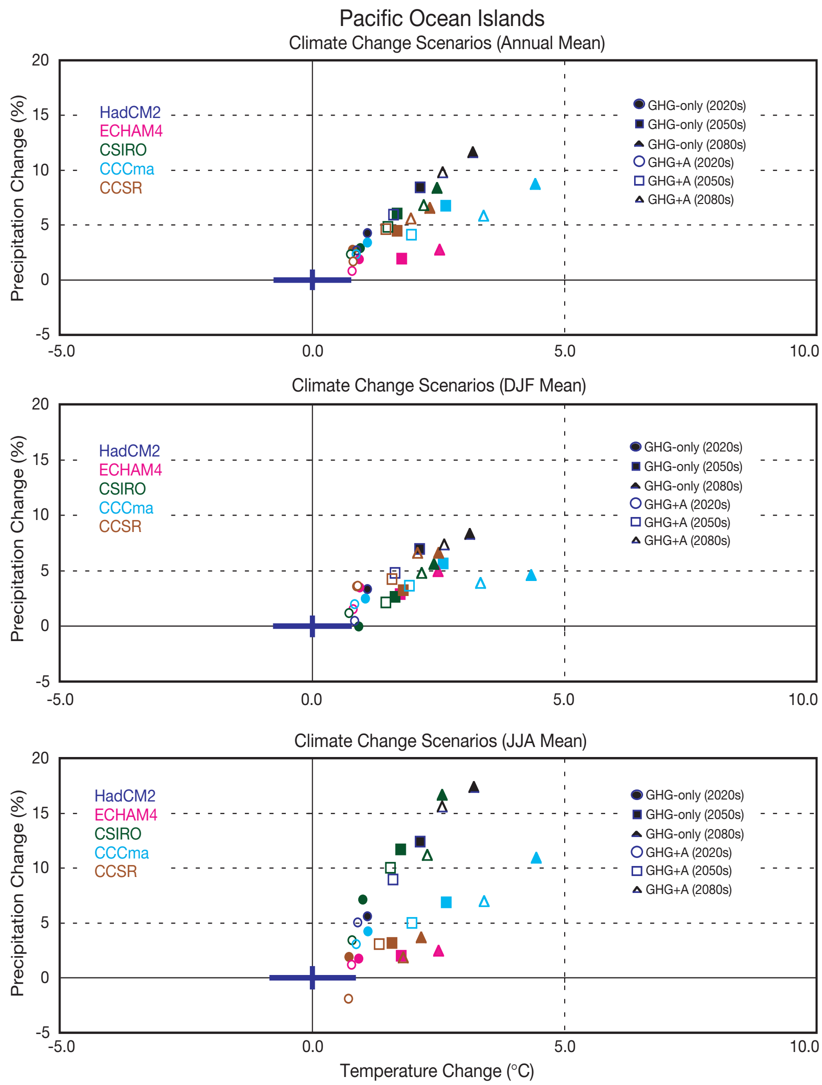

Fig. 8. As Fig. 7 but for the Pacific Ocean Islands

6. IMPLICATION OF THE CLIMATE CHANGE FOR SMALL ISLAND STATES

The economy of most SIS is intrinsically linked with the subsistence agricultural production, aquaculture, fisheries and tourism (Hess 1990). The heat stress due to a rise in surface air temperature stands a good chance of disrupting the terrestrial, marine and agro-ecosystems in SIS (Benioff et al. 1996). The projected annual and seasonal mean surface temperature increases and the associated changes in precipitation over the Mediterranean Sea Islands and Atlantic Ocean and Caribbean Sea Islands suggest that, during the NH summer, the decreased precipitation coupled with the increased evaporation caused by the surface temperature rise may cause a significant decrease in surface runoff, which directly affects available water resources and agriculture. The projected rise in mean surface air temperature over the SIS in tropical regions would have negative effects on human health too (Bouma et al. 1994). The rise in mean temperature will lead to more frequent occurrences of extreme heat waves and consequently higher incidences of related illness and mortality (Bijlsma et al. 1996). Higher surface air temperatures would affect the abundance and distribution of disease vectors or disease-causing microbes as well as the vulnerability of populations (Hales et al. 1996, Epstein et al. 1998). Malaria and dengue are likely to spread into large swaths of SIS in the temperate zone (McMichael et al. 1996, Reiter 1998). Water-borne diseases including cholera and the suite of diarrheal diseases caused by organisms such as giardia, salmonella and cryptosporidium could also become more common (Epstein 1992, Echeverria et al. 1995, Colwell 1996). Higher sea surface temperatures would significantly reduce the fish catch and would lead to bleaching of coral reefs (Gamo 1999, Middleton 1999).

The SIS in the tropical oceans could also be subjected to risk from a change in climate variability. El Niño, a phenomenon in the Pacific Ocean resulting from interactions between the oceans and atmosphere, is now widely recognized as the recurring cause of major natural perturbations to the climate system resulting in a combination of seasonal, multi-annual and decadal variability, the latter influencing the El Niño phenomenon itself (Trenberth & Hoar 1997). How will El Niño manifest itself in changes to climate and its variability? Recent variations in climate over the tropical Pacific Ocean are related to the fact that warm episodes (El Niño) have been relatively more frequent or persistent than the opposite phase (La Niña) since the mid-1970s (Kestin et al. 1998, Trenberth 1998). El Niño is the primary mode of tropical climate variability on the 2 to 5 yr time scale. Meehl et al. (1993) and Meehl & Washington (1996) indicated that future seasonal precipitation extremes associated with a given El Niño event are likely to be more intense due to the warmer more El-Niño-like mean base state in a future climate. Collins (1999) found an increased frequency of ENSO events and a shift in their seasonal cycle in a warmer atmosphere, so that the maximum occurs between August and October rather than around January as currently observed. At present it is

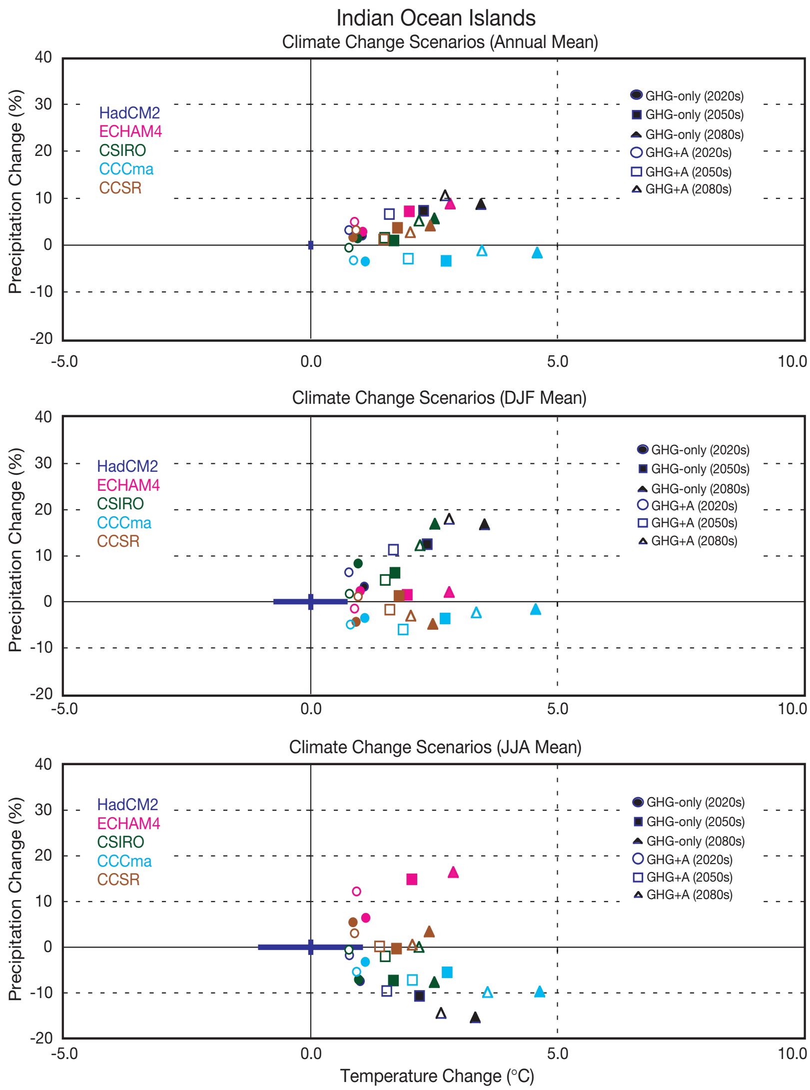

Fig. 9. As Fig. 7 but for the Indian Ocean Islands

uncertain whether there will be any significant change to the amplitude or frequency of El Niño events in the future. Perhaps the enhanced interannual variability in the rainfall associated with future El Niño may exacerbate the frequency of droughts, floods and other extreme weather events in SIS due to global warming (Dilley & Heyman 1995).

Tropical cyclone activity in the central North Pacific has recently been found to be rising (Chu & Clark 1999). Although there is no consensus as yet regarding the behaviour of tropical cyclones in a warmer world, recent studies indicate a decline in frequency but an increase of about 10 to 20% in intensity of the tropical cyclones under enhanced CO_2 conditions (Holland 1997, Knutson et al. 1998, Krishnamurti et al. 1998, Royer et al. 1998, Schubert et al. 1998, Jones et al. 1999). Projected increases in the intensity of tropical cyclones and associated storm surges will affect coastal agriculture. Seawater intrusion associated with storm surges will also amplify the negative impacts of climate change on food productivity in the SIS (Nurse et al. 1998). The likely increase in frequency of heavy precipitation may produce a benefit with an increase in recharge to lens aquifers and water supply but may also cause problems associated with soil erosion, waste disposal and flash flooding (Nicholls & Mimura 1998).

Sea level rise (due to thermal expansion of the oceans resulting from global warming and the melting of glaciers and ice caps) poses significant risk to the SIS (Raper et al. 1996). The projected global rate of mean sea level rise of 5 mm yr^{-1} (with a probability range of 2 to 9 mm yr^{-1}) is 2 to 4 times greater than the rate experienced in the previous 100 yr (Warrick et al. 1996). Many of the key islands rarely exceed 3 to 4 m above present mean sea level, and even on the islands with higher elevation, most of the settlements, economic activity, infrastructure and services are located at or near the coast. While the severity of the risk will vary from island to island, sea level rise of the magnitude currently projected is expected to have a disproportionately large impact on the economic and social development of many SIS (Nurse et al. 1998). Coastal land loss and beach erosion is likely to have widespread adverse consequences, including displacement of communities. Indeed, it is argued that land loss from sea level rise especially on low-lying atolls (e.g., those in the Pacific and Indian Oceans) and low limestone islands (e.g., those in the Caribbean) is likely to be of a magnitude which would disrupt virtually all economic and social sectors in these countries (Leatherman & Beller-Simms 1997). Estimates indicate that with a 1 m sea level rise, as many as 1190 tiny islands that constitute the Republic of Maldives may be submerged (Pernetta 1992). In low-lying atolls of Marshall Islands land loss is estimated to be nearly 60 ha of dry land (8.6% of the total land area). In Trinidad and Tobago (South Caribbean), beach erosion rates of 2 to 4 m yr^{-1} have already been reported in recent years (Singh 1997).

The impacts of regional climate change on SIS are many and some even irreversible. One of the most serious considerations for some SIS is whether they will have adequate potential to adapt to sea level rise within their own national boundaries (Nurse et al.

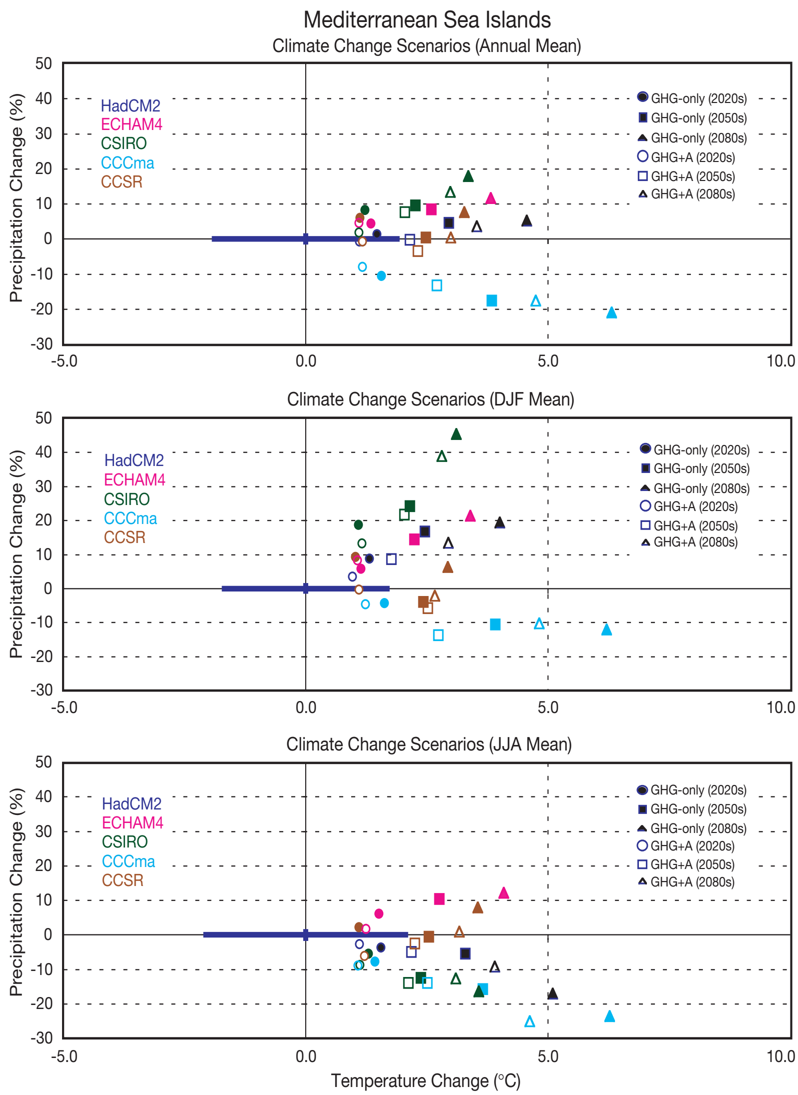

Fig. 10. As Fig. 7 but for the Mediterranean Sea Islands

1998). Most SIS already lack the necessary level of services for preparedness against climate extremes. In tiny islands where physical space is already very scarce, adaptation measures such as retreat to higher ground, raising of the land (which requires sand and other aggregates which may be unavailable) and the use of building setbacks would appear to have little practical utility (Bird 1993). Protection costs for settlement, critical infrastructure and economic activities at risk from sea level rise are expected to be burdensome for most SIS. In extreme circumstances, sea level rise and its associated consequences could trigger abandonment and migration at great economic and social costs (Nicholls & Mimura 1998). A better understanding of the precise magnitude of regional projections of climate change and associated sea level rise for an integrated impact assessment study aimed at reducing the vulnerability to climate change is, therefore, crucial to economic planning, disaster mitigation and developing adaptation strategies for sustainable development in the SIS. The plausible climate change scenarios for the SIS given here should be useful in this respect.

7. CONCLUSIONS

We have examined the response of the SIS to transient increases in anthropogenic radiative forcings due to increases in atmospheric concentration of GHGs and/or sulfate aerosols using the data generated in a set of numerical experiments performed with a range of coupled atmosphere-ocean global climate models. Five of the 7 models considered in our validation exercise are found to have fair skill as regards their ability to simulate the broad features of present-day observed surface climatological features over the SIS in the Indian Ocean, the Mediterranean Sea, the Atlantic Ocean and the Pacific Ocean.

An area-averaged annual mean warming of about 2°C or higher for the 2050s and about 3°C or higher for the 2080s are projected for the Island States as a consequence of increases in atmospheric concentration of GHGs. The surface temperature increase is likely to be least over the Pacific Ocean Islands and highest over the Mediterranean Sea Islands. The seasonal variations of the projected surface warming over the SIS are minimal. No significant change in diurnal temperature range is likely with the increase in surface temperatures. An increase in mean temperature would be accompanied by an increase in the frequency of extreme high temperatures. The aerosol forcing will only marginally reduce the surface warming. The models simulate only a marginal change (<10%) in annual mean rainfall over most of the SIS. During the NH summer, however, rainfall is projected to decline (except over Pacific Ocean Islands). An increase in daily rainfall intensity leading to more heavy rainfall events is also projected.

There are several levels of uncertainty in the regional climate change information presented here. The uncertainties linked to A-O GCMs are those due to rather coarse model resolution and poor representation of physical processes. The inter-model differences in the simulation of climate response to given forcings as obtained in our analysis as well as unrealistic simulation of the natural variability of the climate system could be attributed to these uncertainties. These uncertainties would be transmitted to any regionalization technique applied to enhance the regional information of A-O GCMs (Shackley et al. 1998). In view of these constraints, the regional climate change scenarios presented here should not be regarded as a prediction but only as a plausible projection for broader scale impact assessments.

Heat stress stands a good chance of disrupting the terrestrial and marine ecosystems in most SIS. Sea level rise could inundate many SIS, increase storm damage to the remaining land and contaminate freshwater supplies in aquifers. Higher sea surface temperatures would significantly reduce fish catch and would also lead to bleaching of coral reefs. Higher surface air temperatures would also affect abundance and distribution of disease vectors or disease-causing microbes. An integrated study of climate impact assessment based on a better understanding of the precise magnitude of increase in surface air temperature and associated sea level rise is warranted for developing adaptation strategies in SIS to cope with climate change.

Acknowledgements. The authors acknowledge the efforts of all those who made it possible to put the model simulation results on the Data Distribution Centre websites in Norwich and Hamburg. The Japan Science and Technology Agency supported the visit of M.L. to NIES during the time this study was initiated. M.L. appreciates the facilities and scientific advice rendered to him by Prof. T. Morita at NIES and Prof. A. Sumi at CCSR during the course of this study.

LITERATURE CITED

Alcamo J, Bouwman A, Edmonds J, Grubler A, Morita T, Sugandhy A (1995) An evaluation of the IPCC IS92a emission scenario. In: Houghton JT, Meira Filho LG, Bruce J, Lee H, Callander BA, Haites E, Harris N, Maskell K (eds) Climate change 1994 — contribution of the Working Groups I and III of the Intergovernmental Panel on Climate Change. WMO-UNEP Report, Cambridge University Press, Cambridge, p 247–304

Barnett TP (1999) Comparison of near-surface air temperature variability in 11 coupled global climate models. J Clim 12:511–518

Benioff R, Guill S, Lee J (eds) (1996) Vulnerability and adaptation assessments — an international guidebook. Kluwer Academic Publisher, Dordrecht

Bijlsma L (1996) Coastal zones and small islands. In: Watson RT, Zinyowera MC, Moss RH, Dokken DJ (eds) Climate change — 1995: impacts, adaptations and mitigation of climate change — contribution of the Working Group II to the Second Scientific Assessment Report of the Intergovernmental Panel on Climate Change. WMO-UNEP Report, Cambridge University Press, Cambridge, p 288–324

Bird ECF (1993) Submerging coasts — the effects of a rising sea level on coastal environments. John Wiley & Sons, Chichester

Bouma MJ, Sondorp HE, Van der Kaay HJ (1994) Health and climate change. Lancet 343:302

Chu PS, Clark JD (1999) Decadal variations of tropical cyclone activity over the central North Pacific. Bull Am Meteorol Soc 80:1875–1881

Collins M (1999) The El-Niño Southern Oscillation in the second Hadley Centre coupled model and its response to greenhouse warming. J Clim 13:1299–1312

Colwell R (1996) Global climate and infectious disease: the cholera paradigm. Science 274:2025–2031

Dilley M, Heyman BN (1995) ENSO and disasters – droughts, floods and El Niño-Southern Oscillation warm events. Disasters 19(3):181–193

Echeverria P, Hoge CW, Bodhidatta L, Serichantalergs O and 6 others (1995) Molecular characterization of Vibrio cholerae 0139 isolates from Asia. Am J Trop Med Hyg 52(2):124–127

Epstein PR (1992) Cholera and the environment. Lancet 339:1167–1168

Gamo T (1999) Global warming may have slowed down the deep conveyer belt of a marginal sea of the northwestern Pacific: Japan Sea. Geophys Res Lett 26(20):3137–3140

Gates WL, Boyle J, Covey C, Dease C and 12 others (1999) An overview of the results of the Atmospheric Model Intercomparison Project (AMIP I). Bull Am Meteorol Soc 80: 29–55

Giorgi F, Mearns LO (1991) Approaches to regional climate change simulation — a review. Rev Geophys 29:191–216

Hales S, Weinstein P, Woodward A (1996) Dengue fever in the south Pacific: driven by El Niño-Southern Oscillation? Lancet 348:1664–1665

Hennessy KJ, Gregory JM, Mitchell JFB (1997) Changes in daily precipitation under enhanced greenhouse conditions. Clim Dyn 13:667–680

Hess A (1990) Sustainable development and environmental management of small islands — an overview. In: Beller W, D'ayala P, Hein P (eds) Sustainable development and environmental management of small islands. UNESCO, Paris, p 3–14

Holland GJ (1997) The maximum potential intensity of tropical cyclones. J Atmos Sci 54:2519–2541

Hulme M, Brown O (1998) Portraying climate scenario uncertainties in relation to tolerable regional climate change. Clim Res 10:1–14

Jones RN, Hennessy KJ, Page CM, Pittock AB, Suppiah R, Walsh KJE, Whetton PH (1999) An analysis on the effects of the Kyoto Protocol on Pacific Island Countries, Part Two: regional climate change scenarios and risk assessment methods. CSIRO Atmospheric Research Report to the South Pacific Regional Environment Programme, CSIRO, Aspendale

Kestin TS, Karoly DJ, Jano JI, Rayner NA (1998) Time-frequency variability of ENSO and stochastic simulations. J Clim 11:2258–2272

Kittel TGF, Giorgi F, Meehl GA (1998) Intercomparison of regional biases and doubled CO_2 sensitivity of coupled atmosphere-ocean general circulation model experiments. Clim Dyn 14:1–15

Knutson R, Tuleya RE, Kurihara Y (1998) Simulated increase of hurricane intensities in a CO_2-warmed climate. Science 279:1018–1020

Krishnamurti TN, Correa-Torres R, Latif M, Daughenbaugh G (1998) The impact of current and possibly future sea surface temperature anomalies on the frequency of Atlantic hurricanes. Tellus 50A:186–210

Leatherman SP, Beller-Simms N (1997) Sea level rise and small island states — an overview. J Coastal Res 24:1–16

McMichael AJ, Haines A, Sloof R, Kovats S (1996) Climate change and human health. World Health Organization, Geneva

Meehl GA, Washington WM (1996) El Niño-like climate change in a model with increased atmospheric CO_2-concentrations. Nature 382:56–60

Meehl GA, Branstator GW, Washington WM (1993) Tropical Pacific interannual variability and CO_2 climate change. J Clim 6:42–63

Middleton N (1999) The global casino: an introduction to environmental issues. 2nd edn. Arnold, London

Mitchell JFB, Johns TC (1997) On modification of global warming by sulfate aerosols. J Clim 10:245–267

Mitchell JFB, Johns TC, Gregory JM, Tett SFB (1995) Climate response to increasing levels of greenhouse gases and sulfate aerosols. Nature 376:501–504

Mitchell JFB, Johns TC, Eagles M, Ingram WJ, Davis RA (1999) Towards the construction of climate change scenarios. Clim Change 41 547–581

New M, Hulme M, Jones PD (1999) Representing twentieth-century space-time climate variability: Part I.—Development of a 1961–1990 mean monthly terrestrial climatology. J Clim 12:829–856

Nicholls RJ, Mimura N (1998) Regional issues raised by sea level rise and their policy implications. Clim Res 11:5–18

Nurse LA, McLean RF, Suarez AG (1998) Small island states. In: Watson RT, Zinyowera MC, Moss RH (eds) The regional impacts of climate change: an assessment of vulnerability. A special report of IPCC Working Group II and WMO/UNEP. Cambridge University Press, Cambridge, p 331–354

Pernetta JC (1992) Impacts of climate change and sea level rise on Small Island States. National and international responses Global Environ Change 2:19–31

Raper SCB, Wigley TML, Warrick RA (1996) Global sea-level rise: past and future. In: Milliman JD, Haq BU (eds) Sea level rise and coastal subsidence. causes, consequences and strategies. Kluwer Academic Publishers, Dordrecht

Reiter P (1998) Global warming and vector-borne disease in temperate regions and at high altitude. Lancet 351: 839–840

Royer JF, Chauvin F, Timbal B, Araspin P, Grimal D (1998) A GCM study of the impact of greenhouse gas increase on the frequency of occurrence of tropical cyclones. Clim Change 38:307–343

Schubert M, Perlwitz J, Blender R, Fraedrich K, Lunkeit F (1998) North Atlantic cyclones in CO_2-induced warm climate simulations: frequency, intensity and tracks. Clim Dyn 14:827–837

Shackley S, Young P, Parkinson S, Wynne B (1998) Uncertainty, complexity and concepts of good science in climate change modelling: Are GCMs the best tools? Clim Change 38:159–205

Shine KP, Forster PMF (1999) The effect of human activity on radiative forcing of climate change: a review of recent developments. Global Planet Change 20:205–225

Singh B (1997) Climate changes in the Greater and Southern Caribbean. Int J Climatol 17:1093–1114

Trenberth KE, Hoar TJ (1997) El Niño and climate change. Geophys Res Lett 24:3057–3060

Trenberth KE (1998) El Niño and global warming. J Mar Educ 15:12–18

Walsh K, Pittock AB (1998) Potential changes in tropical storms, hurricanes, and extreme rainfall events as a result of climate change. Clim Change 39:199–213

Warrick RA, Le Provost C, Meier MF, Oerlemans J, Woodworth PL (1996) Changes in sea level. In: Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A, Maskell K (eds) Climate change — 1995: the science of climate change – contribution of the Working Group I to the Second Scientific Assessment Report of the Intergovernmental Panel on Climate Change. WMO-UNEP Report, Cambridge University Press, Cambridge, p 359–405

Watson RT, Zinyowera MC, Moss RH (eds) (1998) The regional impacts of climate change: an assessment of vulnerability. A special report of IPCC Working Group II WMO/UNEP. Cambridge University Press, Cambridge

Editorial responsibility: Peter Whetton, Victoria, Australia

Submitted: August 30, 2000; Accepted: May 17, 2001
Proofs received from author(s): October 9, 2001