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Projected climate change scenario over California by a regional ocean–atmosphere coupled model system

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Abstract This study examines a future climate change scenario over California in a 10-km coupled regional downscaling system of the Regional Spectral Model for the atmosphere and the Regional Ocean Modeling System for the ocean forced by the global Community Climate System Model version 3.0 (CCSM3). In summer, the coupled and uncoupled downscaled experiments capture the warming trend of surface air temperature, consistent with the driving CCSM3 forcing. However, the surface warming change along the California coast is weaker in the coupled downscaled experiment than it is in the uncoupled downscaling. Atmospheric cooling due to upwelling along the coast commonly appears in both the present and future climates, but the effect of upwelling is not fully compensated for by the projected large-scale warming in the coupled downscaling experiment. The projected change of extreme warm events is quite different between the coupled and uncoupled downscaling experiments, with the former projecting a more moderate change. The projected future change in precipitation is not significantly different between coupled and uncoupled downscaling. Both the coupled and uncoupled downscaling integrations predict increased onshore sea breeze change in summer daytime and reduced offshore land breeze change in summer nighttime along the coast from the Bay area to Point Conception. Compared to the simulation of present climate, the coupled and uncoupled downscaling experiments predict 17.5 % and 27.5 % fewer Catalina eddy hours in future climate respectively.

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1 Introduction

General Circulation Models (GCMs) have been widely used to produce long-term predictions of future climate change scenarios (Held and Soden 2006; Vecchi and Soden 2007; Ho et al. 2011). However, because of their low spatial resolution (generally >100 km) GCMs cannot be used directly for climate impact assessment on a local scale. Therefore, downscaling of future climate is performed either by statistical methods (Timbal et al. 2003; Diaz-Nieto and Wilby 2005; Brands et al. 2011) or by nesting a regional climate model (RCM) in the GCM over the domain of interest (Giorgi et al. 2009; Hong et al. 2010; Hurkmans et al. 2010; Zhao et al. 2011; Sun et al. 2011). The Coordinated Regional Climate Downscaling Experiment (CORDEX) evaluates the RCM downscaling of future climate at 50 km (Giorgi et al. 2009). With the advances in computing power, high-resolution downscaling of future climate forced by GCM scenarios is possible. For example, Hong et al. (2010) downscaled the global climate change experiments using a Regional Spectral Model (RSM)-Weather Research Forecast (WRF) coupled system with the innermost domain at a 3-km horizontal grid spacing for applications in hydrology and air pollution models. Similarly, the 4-km meteorological fields for studying future air quality over California were downscaled by WRF (Zhao et al. 2011). These RCM approaches provide the regional details that cannot be achieved in coarse-resolution GCM results. However, these RCM-generated future climate scenarios lose the advantage of the high-resolution sea surface temperature (SST) that is provided by the GCM. Therefore, the low-resolution SST and the absence of the effects of regional ocean–atmosphere interaction do not address the uncertainties in the regional projection of climate change scenarios. In recent years, regional ocean–atmosphere coupled models have been developed to study regional climate change. For example, the Rossby Center Atmosphere Ocean climate model (RCAO) was used to downscale the IPCC Fourth Assessment (AR4) Arctic future scenarios (Koenigk et al. 2011). Koenigk et al. 2011 found that the large-scale pattern is very similar to the corresponding GCM, but significant local difference exists between the global and regional simulations.

A fully coupled regional downscaling system of the RSM (Juang and Kanamitsu 1994; Juang et al. 1997; Kanamitsu et al. 2010) for the atmosphere and the ROMS (Shchepetkin and McWilliams 2005) for the ocean has been developed (Li et al. 2012) for potential applications of conducting coupled downscaling of global reanalysis, global climate projections, and global seasonal forecasts. When this regional coupled modeling system was executed for the Coupled California Reanalysis downscaling at 10 km (CCaRD10; Li et al. 2012), it generated a near-realistic ocean state and showed some superiority in simulating higher moments of the SST compared to the 1° reanalysis SST. Subsequently, this regional ocean–atmosphere coupled model was also used to downscale the CCSM3 present climate to further reveal the impact of coupling along the California coast (Li et al. 2013). In this study we will demonstrate the value of coupled downscaling on climate change projections over California.

The organization of this paper is as follows. Section 2 describes the model and experimental design. The projected atmospheric climatology is provided in Section 3, and the projected future climate changes of the mesoscale circulation relative to present climate are given in Section 4. Section 5 provides a summary and conclusions.

2 Model and experiments

2.1 The RSM-ROMS

The details of the regional ocean–atmosphere coupled model are described in a study of CCaRD10 by Li et al. (2012); only a brief description of the model is provided here. The RSM is a primitive equation atmosphere model; ROMS is a free-surface, terrain-following, primitive equation ocean model. The coupling strategy is as follows. The RSM and ROMS share the same domain and resolution to avoid the land–sea mask inconsistency and avoid interpolation of fluxes and SST between the ocean and the atmosphere models. The SST-flux is directly exchanged between ROMS and RSM, avoiding the SST-flux coupler. The air-sea coupling interval is 24 h.

2.2 Experiment design

The atmospheric and oceanic large-scale boundary conditions are provided by the global coupled model of the National Center for Atmospheric Research (NCAR) Community Climate System Model 3.0 (CCSM3), which includes the NCAR Community Atmospheric Model (CAM) and the Parallel Ocean Program (POP) oceanic model. The present climate (1985–1994) is from the climate of the 20th-century CCSM3 experiment (http://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm.b30.030e.html), and the future climate (2062–2071) is from the 21st-century SRES A2 scenario (http://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm.b30.042e.html). The CAM outputs are at T85 (~1.4°) horizontal resolution and at 26 hybrid vertical levels. The POP 3-D ocean state is in 384 × 320 irregular horizontal global grids and 40 vertical levels, while the POP SST, provided by Earth System Grid, is at T85 resolution, which is the same as that of CAM. The 6-hourly CAM 26 hybrid pressure level atmospheric fields are interpolated to 28 sigma levels following the method of Yoshimura and Kanamitsu (2009), but without the vertical incremental interpolation. To use the existing pre-processing programs, the monthly irregular grid of POP 3-D ocean variables is interpolated to a 320 × 192 regular grid.

Two sets of experiments are designed with the regional coupled ocean–atmosphere model The control run comprises 10 years of the present climate (U20) and 10 years of the future climate (U21); the uncoupled RSM is forced by the corresponding 6-hourly CAM atmospheric forcing and daily POP SST. In the coupled experiment set of present (C20) and future (C21), the RSM is forced by 6-hourly CAM atmospheric forcing and ROMS is forced by the monthly POP 3-D oceanic boundary conditions. The model configuration, including the regional model domain (19.558–50.22°*N*, 135.26–103.58°*W*), and the spatial resolution (10 km) are the same as in studies by Li et al. (2012, 2013). Three domains of Northern California (NC; 38.5–41.5°*N*, 126–122°*W*), Central California (CC; 35.5–38.5°*N*, 124–120°*W*), and Southern California (SC; 32.5–35.5°*N*, 121–117°*W*) are selected for quantitative evaluation of climate change (Fig. 1b). It may be noted that atmospheric initial/boundary conditions and the physical parameterization schemes are identical for the coupled and uncoupled downscaling experiments.

The result from the first 2 years is discarded to account for the spin-up, as in the CCaRD10. The remaining 8 years (1987–1994 and 2064–2071) of the regional simulation are used in the analysis. The performance of U20 and C20, which has been studied in Li et al. (2013), demonstrates that C20 simulates more realistic present climate than U20. In this paper, we will examine the present climate versus the future climate.

3 Projection of atmospheric climatology

The performance of U20 and C20 has been demonstrated in our previous study (Li et al. 2013). The CCSM3-simulated present climate exhibits a warm SST bias as large as 10 °C along the California coast in summer. In comparison with observations, the surface air temperature from

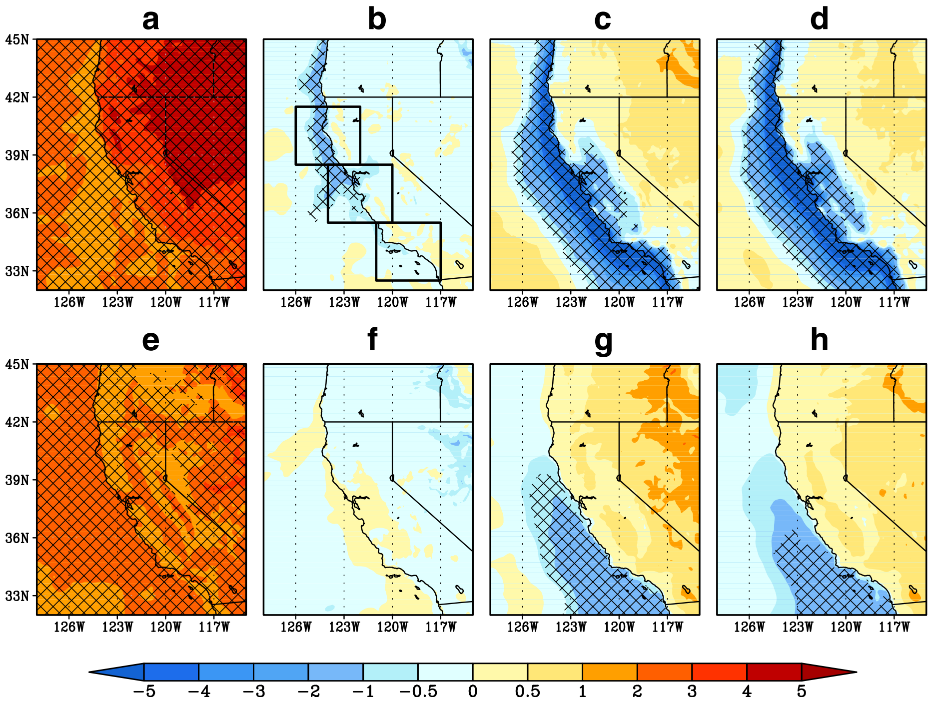

Fig. 1 T2m summer climatology difference (°C) between **a** C21–C20, **b** (C21–C20)-(U21–U20), **c** C20–U20, and **d** C21–U21; T2m winter climatology difference (°C) between **e** C21–C20, **f** (C21–C20)-(U21–U20), **g** C20–U20, and **h** C21–U21. Difference significant at 5 % confidence level under *t*-test is indicated by hatch marks

the U20 with CCSM3 SST shows unrealistic seasonal variation, with too strong a seasonal cycle during the upwelling season (May–September), while the seasonal variation of the surface air temperature from the C20 matches the observation very well. Li et al. (2013) also highlighted that air–sea coupling plays an important role in the simulation of the mesoscale circulation of the Catalina eddy over the Southern California Bight. For example, it is shown that as a result of the stronger off shore seabreeze there is an increase in the number and duration of the generated Catalina eddies in the coupled compared to uncoupled downscaling of the present climate simulation (Li et al. 2013).

3.1 Surface air temperature (T2m)

Figure 1a shows the T2m change in summer between C21 and C20 from the coupled model. It is evident that warming appears in the entire domain. The magnitude of the T2m increase is around 2 °C along the coastal ocean area, and increases progressively inland, with inland anomalies over 4 °C. In Fig. 1b, it can be seen that the air–sea coupling (C21–C20) has a cooling effect on the surface temperature in most regions in comparison with the uncoupled integration (U21–U20). The cooling is dominant along the California coast, with a maximum of around 2 °C. This cooling reflects the effect of the upwelling of colder water along the coast, seen in the present climate between C20 and U20 (Fig. 1c) and in the future climate between C21 and C20 (Fig. 1d). A close inspection of Fig. 1b–d indicates that the cooling effect induced by upwelling is not fully compensated for by the projected climate change from the CCSM3 large-scale boundary conditions of ocean and atmosphere. The uncoupled downscaling projected SST difference (U21–U20) is 2.3 °C, 2.4 °C, and 2.3 °C over NC, CC, and SC, respectively. On the other hand, the coupled downscaling projected SST from C21 relative to that from C20 over NC, CC, and SC is only 1.2 °C, 1.6 °C, and 1.8 °C, respectively. The coupled downscaling projected T2m change (C21–C20) in summer is also smaller than that projected by the uncoupled downscaling (U21–U20) over the coastal subdomains of NC, CC, and SC (not shown). In winter, the warming over land is not as large as in summer (Fig. 1a and e). In comparison to the summer season (Fig. 1b), the coupled downscaling projected change (C21–C20) in winter is relatively warm along the California coastal area and a little cool over other ocean and land areas relative to the uncoupled downscaling (Fig. 1f). The coupled downscaling in the winter simulated cooler T2m over the ocean, particularly along the coast of Southern California for both present (Fig. 1g) and future climates (Fig. 1h) in comparison with the uncoupled downscaling.

The probability distribution function (PDF) of daily mean T2m during the period 1987–1994 from the Cooperative Observer Program (COOP, http://www.nws.noaa.gov/coop/) observation, U20, and C20 over the city of Los Angeles (32.715°*N*, 117.156°*W*) is shown in Fig. 2a. Excess kurtosis is used to quantify the distribution shape of PDF (Dodge 2013). Both observation and C20 are in leptokurtic distribution with negative value of −0.44 and −1.34 respectively. In contrast, the distribution of U20 is in platykurtic with a positive value of 0.83. The PDF distributions of U21 and C21 are in leptokurtic with negative value of −0.13 and −1.42. Although an increase in the occurrence of extreme warm events during the period 2064–2071 relative to 1987–1994 is predicted by both U21 and C21, the PDF patterns between U21 and C21 are quite different (Fig. 2b). U21 shows a progressively increasing PDF towards warmer temperatures, particularly with the percentage of extreme warm events of over 30 °C increasing by as high as 16 %. In contrast, the C21 simulates a peak pattern of PDF between 18 °C and 22 °C. The PDF from C21 shows an increase of events with temperatures of over 30 °C by only 1.6 %. In the present climate, the PDF of daily T2m over 30 °C is 0.2 %, 5.5 %, and 1 % from observation, U20, and C20, respectively. A similar result is also obtained from other COOP stations in California (not shown). The analysis suggests that the coupled downscaling predicts a more moderate climate change of extreme warm events than the uncoupled downscaling.

3.2 Precipitation

Despite the fact that the effect of air-sea coupling is stronger in summer, the difference in projected summer precipitation climatology (C21–C20) is rather small (Fig. 3a) because summer is the dry season over California. The coupled downscaling projects a decrease of precipitation over Oregon and Northern California and an increase in Southern California (Fig. 3a). The differences in changes in summer precipitation between coupled (C21–C20) and uncoupled downscaling (U21–U20) are very weak along the coast (Fig. 3b) and over the subdomain regions of NC, CC, and SC. The uncoupled downscaling projected precipitation difference (U21–U20) is −0.07 mm/day, 0.04 mm/day, and 0.18 mm/day over NC, CC, and SC, respectively. The coupled downscaling projected summer precipitation change (C21–C20) over NC, CC, and SC is only −0.04 mm/day, 0.03 mm/day, and 0.11 mm/day, respectively. The air–sea coupling effect on summer precipitation in both present and future climates appears similar (Fig. 3c and d); precipitation decreases along the coast for both present (C20–U20) and future climates (C21–U21).

The air-sea coupling effect is weak in the rainy season (winter) over California as well. However the precipitation change is larger in winter than in summer between coupled and uncoupled downscaling, albeit, marginally. An increase in winter precipitation is projected by the coupled downscaling over Oregon and Northern California (Fig. 3e), while a decrease is

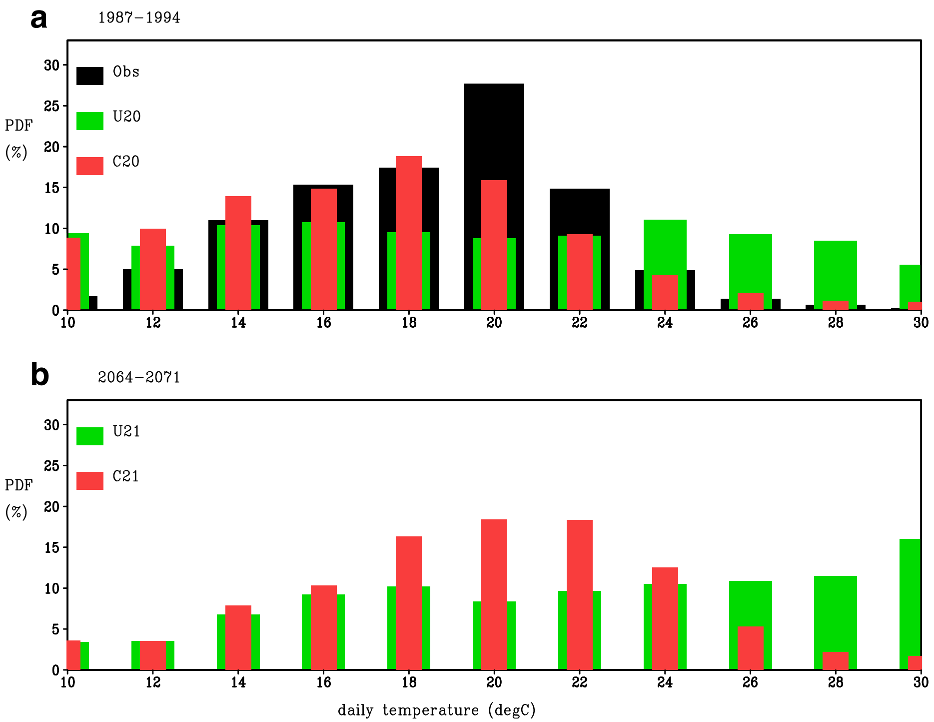

Fig. 2 Probability distribution function (PDF) of daily T2m (°C) over the Los Angeles COOP station **a** during the period 1987–1994 from observation, U20, and C20; **b** during the period 2064–2071 from U21 and C21

projected over Central and Southern California and northern Nevada in the future (Fig. 3e). The air-sea coupling results in increased winter precipitation along the coast of Central California in the future climate relative to the change projected from uncoupled downscaling (Fig. 3f). In contrast to the precipitation in the summer season in Fig. 3c and d, the air-sea coupling induces a distinct reduction of winter precipitation over the domain of interest, particularly along the coast both in the present (Fig. 3g) and future (Fig. 3h) climates. This reduction of winter precipitation coincides with the cooler surface temperature in the coupled downscaling (Fig. 1g and h)

4 Projection of mesoscale circulation

4.1 Land–sea breeze

Over the coastal areas, the temperature difference between land and sea modulates the pressure gradient in the lower troposphere, which can in turn affect low-level sea breeze circulations during the day and the land breeze at night. The land–sea breeze is perpendicular to the coastline. The coastline around the Bay area and Southern California is approximately in the northwest-to-southeast direction (45°). Thus the land-sea breeze is calculated as U*sin(45°) + V*cos(45°) during the time period of 11a.m.–4p.m PST and 11p.m.–4a.m PST in summer following Zhao et al. 2011, where U and V are the zonal and meridional wind component climatology. The land (sea) breeze is represented by the negative (positive) value of south-westerly wind.

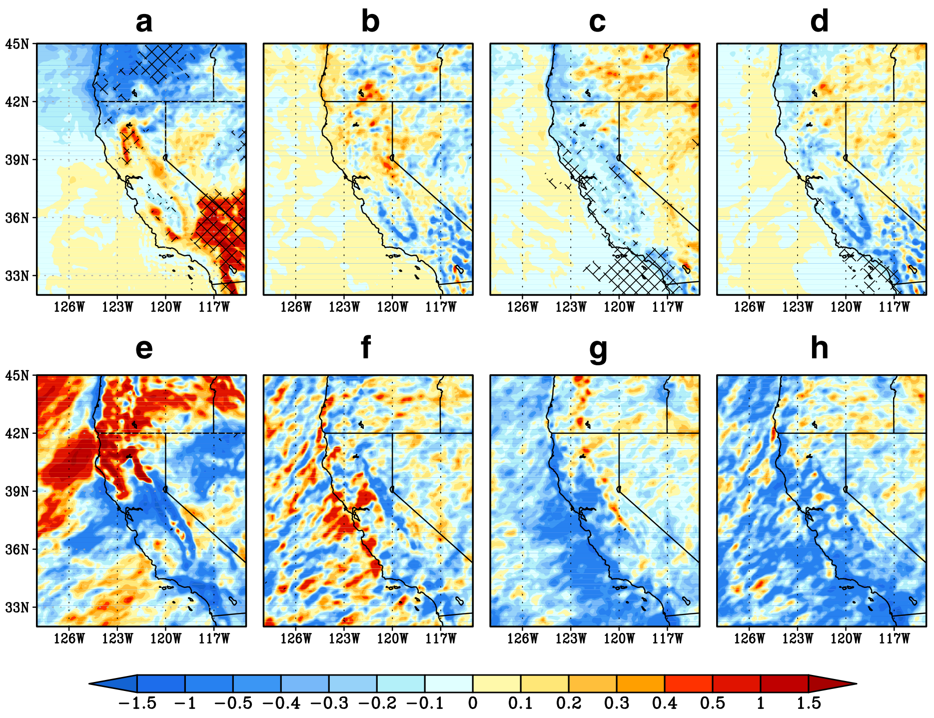

Fig. 3 Summer precipitation climatology difference (mm/day) between **a** C21–C20, **b** (C21–C20)-(U21–U20), **c** C20–U20, and **d** C21–U21. Winter precipitation climatology difference (mm/day) between **e** C21–C20, **f** (C21–C20)-(U21–U20), **g** C20–U20, and **h** C21–U21. Difference significant at 5 % confidence level under *t*-test indicated by hatch marks

During the summer daytime, the enhanced southwesterly change is observed from the San Francisco Bay area to Point Conception in C21 relative to C20 (Fig. 4a), which is consistent with the projected T2m change that is higher over land than over the ocean (Fig. 1a). The onshore sea breeze change difference is not apparent between the coupled downscaling (C21–C20) and the uncoupled downscaling (U21–U20) in Fig. 4b. In comparison with the uncoupled downscaling, the coupled downscaling shows enhanced sea breeze over the San Francisco Bay area in both the present (Fig. 4c) and future climates (Fig. 4d). During local nighttime in summer, C21 simulates weaker offshore northwesterly winds than the C20 does along the coast (Fig. 4e). The relative change of land breeze from the coupled downscaling (C21–C20) is smaller than the uncoupled downscaling of U21–U20 over Southern California Bight (Fig. 4f). The land breeze is significantly reduced near San Francisco Bay and enhanced over the Southern California Bight in the coupled downscaling in both the present (Fig. 4g) and future climates (Fig. 4h) relative to the uncoupled downscaling integration.

4.2 Catalina eddy

Catalina eddy (CE), a mesoscale circulation, is generated when the regular northwesterly flow changes direction and turns into a southerly flow along the coast of the Southern California Bight. Catalina eddies influence visibility, occasional production of light rain, variation in pollution, and lowering of coastal temperature.

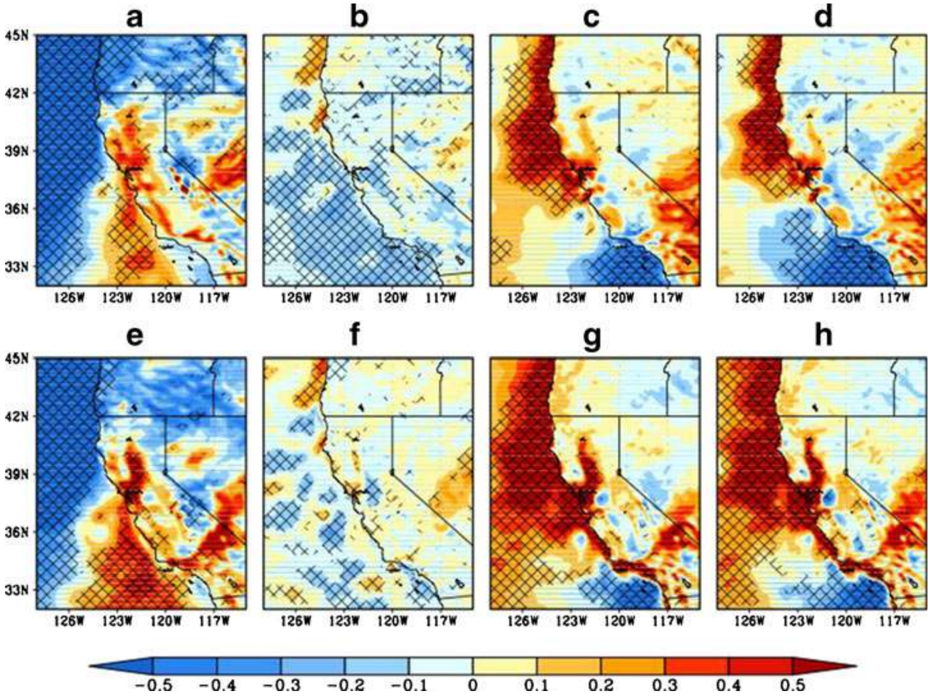

Fig. 4 The 10 m southwesterly wind component climatology difference (m/s) during the period 11a.m–4p.m. PST in summer between **a** C21–C20, **b** (C21–C20)-(U21–U20), **c** C20–U20, and **d** C21–U21; and the 10 m southwesterly wind component climatology difference (m/s) during the period 11p.m.–4a.m. PST in summer between **e** C21–C20, **f** (C21–C20)-(U21–U20), **g** C20–U20, and **h** C21–U21. Difference significant at 5 % confidence level under *t*-test is indicated by hatch marks

Kanamitsu et al. (2013) analyzed the climatological properties, dynamical and thermodynamical characteristics, and long-term variabilities of the Catalina eddy over 61 years (1948–2008) with hourly California Reanalysis Downscaling at 10 km (CaRD10, Kanamitsu and Kanamaru 2007) data. They found that the onshore/offshore sea breeze is essential for CE formation and decay. Large-scale cyclonic/anticyclonic forcing is not necessary for eddy formation and there is no apparent north–south pressure gradient anomaly that drives the southerly flow during the life cycle of a CE. Previous studies focused on the strong eddy and concluded that large-scale forcing was crucial.

In this study we use the 10-m wind fields from the composite canonical eddy to detect CE cases in the coupled and the uncoupled experiments following the methods of Kanamitsu et al. (2013). The spatial pattern correlation between the near-surface wind directions of a composite Catalina eddy with the hourly coupled and uncoupled downscaled integrations of the 10-m wind directions are then calculated within 32°N−34°N, 121°W−117°W. The Pearson product–moment correlation coefficient (Rodgers and Nicewander 1988; Stigler 1989) is used here since we are interested only in the direction of the winds, not the amplitude. It is assumed that a CE occurs if the correlation coefficient is larger than a threshold of 0.7, which represents significant cyclonic rotation over the Southern California Bight.

The simulated CE hours from U20, C20, U21, and C21 are listed in Table 1. U20 predicts only 212 CE hours per year, and C20 simulates 354 CE hours per year, 67.3 % more than U20. The CE hours in C20 are closer to the hours from the reanalysis coupled downscaling (Li et al.

Table 1 The number of detected Catalina eddy hours in the uncoupled and coupled runs

Year	U20	C20	Year	U21	C21
1987	195	400	2064	129	298
1988	218	339	2065	172	417
1989	198	355	2066	127	320
1990	171	323	2067	154	250
1991	225	346	2068	212	307
1992	245	324	2069	162	249
1993	247	351	2070	150	245
1994	205	396	2021	120	248
Average	212	354	Average	153	292

2012) in contrast to the CE hours from U20. There are 153 CE hours per year from U21 and 292 CE hours per year in C21, which is 90.8 % more than from U21. This is because the offshore land breeze is enhanced in C20 and C21 in comparison with U20 and U21, respectively. The values of reduced annual CE hours are 59 for (U21–U20) and 62 for (C21–C20). When compared with the present simulation from U20 and C20, the predicted change of CE hours is −27.8 % and −17.5 % in U21 and C21, respectively. This reduction in CE hours in coupled downscaling is consistent with the corresponding reduced offshore land breeze change over the Southern California Bight in (C21–C20) compared to (U21–U20) (Fig. 3f).

5 Conclusions

After a study of a 10-year ocean–atmosphere coupled downscaling of present climate (1985–1994) forced by CCSM3 20th century integration (Li et al. 2013), a 10-year ocean–atmosphere coupled downscaling of the SRES A2 scenario CCSM3 future climate (2062–2071) is executed with the same model configuration of the regional coupled ocean–atmosphere model with the exception that the ocean and atmosphere lateral boundary conditions are from the future climate projections of CCSM3.

There is a clear warming in the T2m variable in the coupled downscaling due to climate change. The T2m change between coupled downscaling and uncoupled downscaling is significant along the coast of California in summer, but is not significant in winter. The projected PDF change of daily T2m extreme events is quite different between the coupled and uncoupled downscaling, with the former indicating a more moderate increase. The projected future change in precipitation is not significantly different from coupled and uncoupled downscaling. This stems from the fact that air-sea coupling is strongest in the summer season, which happens to be the dry season for California. The enhanced summer daytime sea breeze change in the future climate is observed from the San Francisco Bay area to Point Conception. The offshore summer nighttime land breeze is weaker in the future climate than in the present climate along the coast. The relative change of offshore land breeze in the coupled downscaling is smaller than in the uncoupled downscaling over Southern California Bight. The future climate change in Catalina eddy hours is −27.8 % and −17.5 % in uncoupled and coupled downscaling, respectively. This change is largely due to the correspondingly weaker offshore land breeze over the Southern California Bight in the future climate. The poor performance of the uncoupled downscaling is attributed to the input SST from CCSM3. During the upwelling season of May-September, the coastal cold tongue is not well captured by the CCSM3, which is however reasonably well resolved by the high resolution coupled downscaling. The CCSM3-simulated present climate SST exhibited a warm bias in summer that was as large as 10 °C along the coast of California; this warm bias is significantly rectified by the coupled downscaling (Li et al. 2013). A similar rectification effect on the summer SST along the California coast in CCSM3's future climate projection is also seen from the coupled downscaling. An accurately simulated present climate is very important for the reliability of a projected future climate, and the results of this study suggest that a high-resolution, regional ocean–atmosphere coupled model is necessary for future climate projection, especially for the coastal areas of California.

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