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Downscaling experiment for the Venice lagoon. I. Validation of the present-day precipitation climatology

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ABSTRACT: We analyze the performance of a high-resolution regional climate model (RCM) in simulating the present-day (1961–1990) precipitation regime of the drainage basin of the Venice lagoon as an important component of a downscaling experiment aimed at evaluating the impact of future climate change scenarios on the main biogeochemical properties of the lagoon. Comparison of simulated data with local climatological observations shows good agreement in terms of both monthly area averages and seasonal spatial distribution of precipitation. Monthly and annual mean frequencies of rainy events are also satisfactorily reproduced by the model. The analysis demonstrates the relevance of high-resolution RCMs to catchment-scale impact applications and the feasibility of using output data of near-surface temperature and precipitation from the RCM model for impact assessment studies in the Venice lagoon.

KEY WORDS: Downscaling · Regional climate model · Model validation · Venice lagoon

1. INTRODUCTION

Projections of climate change in response to increased greenhouse gas (GHG) emissions for the 21st century show a number of potential impacts on a wide array of components of the climate system (IPCC 2007). In coastal and estuarine areas, changes in sea level are the most direct threat (Jickells et al. 2000, Grabemann et al. 2001, Uncles 2003). However, variations in precipitation patterns can be critical for the timing and amount of freshwater input as well as nutrient loads to coastal wetlands through river outflows (Scavia et al. 2003). These variations can severely affect water quality and biogeochemical processes of coastal ecosystems (Struyf et al. 2004).

The effect of changes in precipitation regimes on the biogeochemistry of coastal areas can be studied by using precipitation statistics from climate model simulations to drive coastal biogeochemistry models. Climate models, however, traditionally show difficulties in producing realistic precipitation statistics, especially at small drainage basin scales (e.g. Giorgi et al. 2001). One of the problems that severely affect global climate models in the simulation of precipitation statistics is their horizontal resolution, which is still of the order of a few 100s of km. Different regionalization techniques have been developed to regionally enhance the resolution of global models (Giorgi et al. 2001), and these can potentially provide much improved representation of precipitation for use in impact assessment studies. In particular, current regional climate models (RCMs) can reach horizontal resolutions of a few 10s of km (Giorgi 2006) and are thus important tools that provide fine-scale precipitation information.

The present study is part of a downscaling experiment, extensively described in a companion paper by

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Cossarini et al. (2008, this issue), aimed at studying the effects of future climate change due to changes in precipitation regimes on the biogeochemical properties of the Venice lagoon. This lagoon is a productive coastal ecosystem where spatial patterns and time variability of biogeochemical properties are clearly correlated with river runoff and sea–lagoon exchanges (Solidoro et al. 2004, 2005, Pastres et al. 2005). Therefore, satisfactory representation of the precipitation regime in the lagoon's drainage basin is critical in the evaluation of the reliability of the entire downscaling procedure.

The drainage basin of the Venice lagoon is part of the Veneto region, which extends from the Adriatic Sea to the Alps and belongs to the transitional climatic area between Mediterranean and continental climates (ARPAV 2000). As a consequence, different climatic elements affect the Veneto region, which can be divided in 2 main zones: the alpine zone, where climatic features are typical of the Alpine region, and the Venetian Plain, characterized by a continental climate. The latter can be further divided into 2 subzones: the inland plain, and the coastal region (including the Venice lagoon) which is mainly influenced by the Adriatic Sea. The subdivision of the Veneto region into 2 main climatic zones is supported by a recent study (Brunetti et al. 2006) based on long-term measurements of temperature and precipitation over the Italian territory. Using principal component analysis of 2 observational data sets to identify climatically homogeneous macroareas at the national scale, Brunetti et al. (2006) subdivided Veneto into macroareas defined as 'Po Plain' and 'Alps' in both data sets. Topographic gradients are also pronounced in this region (from 0 to 3000 m in <200 km) and can generate intense rainfall events, particularly when humidity is transported by southeasterly winds (ARPAV 2000, Barbi et al. 2005). Therefore, the high-resolution climate modeling provided by a RCM is essential for this area.

The aim of the present work is to assess the capability of a RCM (the ICTP RCM; Giorgi et al. 1993a,b, Pal et al. 2007) to reproduce the present-day precipitation climatology in the drainage basin of the Venice lagoon. The same model was then used to produce climate change scenarios to study related impacts on the lagoon's biogeochemistry as presented in the companion paper by Cossarini et al. (2008). The analysis was performed on the 30 yr present-day (1961–1990) climate simulation performed with the RCM by Gao et al. (2006), which provides the reference climate for the climate change scenarios also produced by Gao et al. (2006). The RCM was run at a horizontal grid spacing of 20 km over an area encompassing the entire Mediterranean region. The emphasis of our analysis is on describing the seasonal evolution of precipitation and also temperature statistics over the drainage basin. The model was validated against field measurement data produced for the Veneto region as well as additional gridded observation data sets. Compared to previous assessments of RCM performance, this is quite a stringent analysis of regional model performance due to the relatively limited extent of the Venice lagoon drainage basin and its complex physiography.

After a brief description of the RCM simulation and of the observational data sets for the area under investigation (Sections 2 and 3), we validate the climatology obtained from the model with the observational data sets in Section 4 and present final considerations in Section 5.

2. RCM MODEL AND REFERENCE SIMULATION DESIGN

The RCM has been developed over the last 15 yr for a wide range of applications (Dickinson et al. 1989, Giorgi 1990, Giorgi et al. 1993a,b, Giorgi & Mearns 1999, Giorgi et al. 2006, Pal et al. 2007). This model provides fine-scale evolution of the meteorological external forcings necessary to drive the biogeochemical transport model of the Venice lagoon system (Cossarini et al. 2008). In particular, we use the multidecadal high-resolution simulations completed by Gao et al. (2006). The model domain covers the Mediterranean region at a grid spacing of 20 km, and three 30 yr experiments are available: a reference run (hereafter referred to as RF) for the period 1961–1990 and 2 scenario runs (2071–2100) under the IPCC A2 and B2 emission scenarios. This paper is limited to the validation of the RF run over the drainage basin of the Venice lagoon, while a description of the overall simulations can be found in Gao et al. (2006).

For the present experiments, the lateral boundary conditions necessary to run the RCM are provided by analogous RCM simulations covering the entire Euro-Mediterranean domain at a grid spacing of 50 km as described by Giorgi et al. (2004a,b). The latter simulations were completed as part of the European project PRUDENCE (Christensen et al. 2002) and were driven at the lateral boundaries by the global climate model HadAM3H (see Giorgi et al. 2004a,b). Sea surface temperatures (SST) for the RF experiment are from observations, while SST anomalies were added for the scenario runs as obtained from the global climate model HadCM3. The model employs 18 vertical sigma levels and vegetation types from a global data set based on US Geological Survey satellite measurements (Loveland et al. 1991). The reader is referred to Gao et al. (2006) and Giorgi et al. (2004a,b) for more details on the experimental design. The performance of the RCM in the PRUDENCE simulations is generally in agreement with that of other RCMs participating in the PRUDENCE project, with regionally averaged temperature errors mostly <2°C and precipitation errors mostly within 35% of observations (Jacob et al. 2007).

We analysed daily and monthly precipitation data for the drainage basin of the Venice lagoon approximately covering the geographical domain between 45.1 and 45.7° N, and between 11.6 and 12.3° E (total of 10.5 grid points). The area covered by the drainage basin is indicated by a box overlaid on a map of the RCM topography (Fig. 1). In this area, land use cover is mostly dominated by cropland and such cover is reproduced in the RCM land use mask. Statistics for the drainage basin were calculated as average values of all grid points included in the geographic domain.

3. VALIDATION DATA

Different data sets for the Venice lagoon catchment basin were used to validate the RCM simulation, including both station observations and gridded data sets:

(1) A data set provided by the Regional Agency for the Environmental Protection of Veneto (ARPAV) consisting of daily data from 21 stations homogeneously distributed over the drainage basin of the Venice lagoon. These stations are part of the ARPAV meteorological network (www.arpa.veneto.it/indice.asp?l=cmt/meteo/meteo.htm). Table 1 shows a list of the stations, the periods of observation and the availability of data for precipitation (P) and air temperature (T) at 2 m. The locations of the stations are shown in Fig. 1.

(2) A data set (referred to as AMEZI) obtained from the merging of 2 different temporal series (Ciavatta 2004, 2005; Fig. 1). The first series includes daily averages of air temperature for the period 1962–1979, while the second series covers daily averages of precipitation and temperature for the period 1980–2004.

(3) The 25 km gridded precipitation climatology over the Alpine region produced by Frei & Schär (1998), which covers the period 1971–1990 and uses observational data from over 1500 stations.

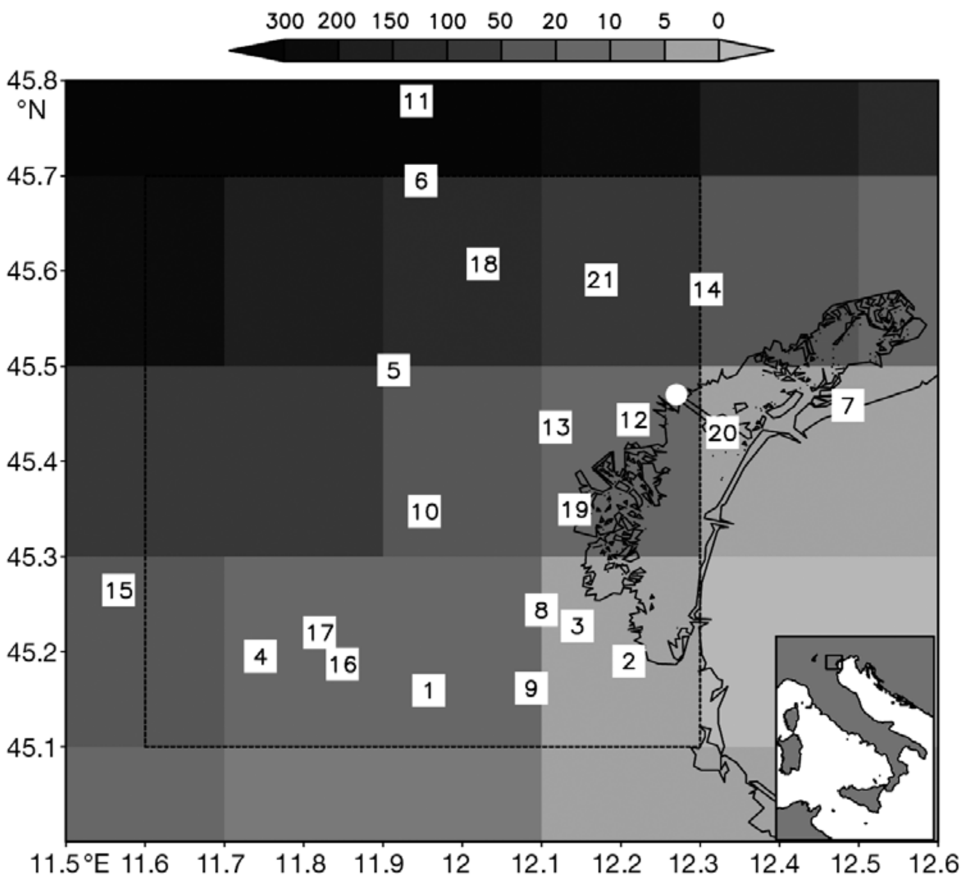


Fig. 1. Subregion of interest extracted from the RCM domain. Shading represents the regonial climate model (RCM) topography field (m); broken line box indicates the area under investigation (10.5 grid points). Positions of the stations of the ARPAV data set (squares, see Table 1) and the AMEZI data set (circle) are also shown. The Venice lagoon is at the right side of the box

Table 1. List of stations included in the ARPAV data set, and the availability of data for precipitation (P) and air temperature (T) at 2 m. Station nos. refer to the locations given in Fig. 1

	Station	Period of observation	P	T
1	Agna	1992–2005	X	X
2	Ca Bianca	1996–2003	X	—
3	Ca di Mezzo	1996–2005	X	X
4	Ca Oddo	1996–2005	X	X
5	Campodarsego	1992–2005	X	X
6	Castelfranco	1989–2005	X	X
7	Cavallino	1992–2005	X	X
8	Codevigo	1992–2005	X	X
9	Gesia	1996–2005	X	X
10	Legnaro	1991–2005	X	X
11	Maser	1992–2005	X	X
12	Mestre	1991–2005	X	X
13	Mira	1992–2005	X	X
14	Mogliano	1997–2005	X	X
15	Noventa	1991–2005	X	X
16	Ponte Zata	1996–2005	X	X
17	S. Pietro Viminario	1992–2005	X	X
18	Trebaseleghe	1995–2005	X	X
19	Valle Averto	1997–2005	X	X
20	Venezia Ist. Cav.	2000–2005	X	X
21	Zero Branco	1992–2005	X	X

(4) Data extracted from the University of East Anglia Climatic Research Unit (CRU) data set consisting of gridded 10 min temperature and precipitation climatologies for the period 1961–1990 (45.1 to 45.7° N and 11.6 to 12.3° E; 16 grid points considered) (New et al. 2002).

4. RESULTS

Our aim is to assess the applicability of the RCM output to study freshwater input into the Venice lagoon, thus our analysis mostly focuses on precipitation. We first analyze the performance of the RCM in reproducing observed spatial precipitation patterns over the region of interest which, as previously mentioned, is characterized by complex topographical features.

Fig. 2 shows the mean annual precipitation in the RF experiment over a region that includes the northeastern Alps and eastern Po Plain, and the observed annual climatology of Frei & Schär (1998), both for the period 1971–1990. The agreement between the simulated and observed spatial patterns is good, with values >4.4 mm d^{-1} over the northeastern part of the Alps above 800 m and minima located over the eastern Po Plain and in the northern part of the Adige Valley (north of 46° N, west of 11.7° E). The comparison between the RF simulation and the observational data is especially good over the drainage basin, both showing values ranging from 2 to 3.2 mm d^{-1} and a north–south gradient across the basin. The northward gradient observable over the drainage basin is consistent with previous analyses of precipitation over the Veneto region (Zuliani et al. 2005).

Seasonal simulated and observed (Frei & Schär 1998) precipitation totals are compared in Figs. 3 & 4. All seasons show a maximum over the northeastern area of the domain of analysis, with observed values

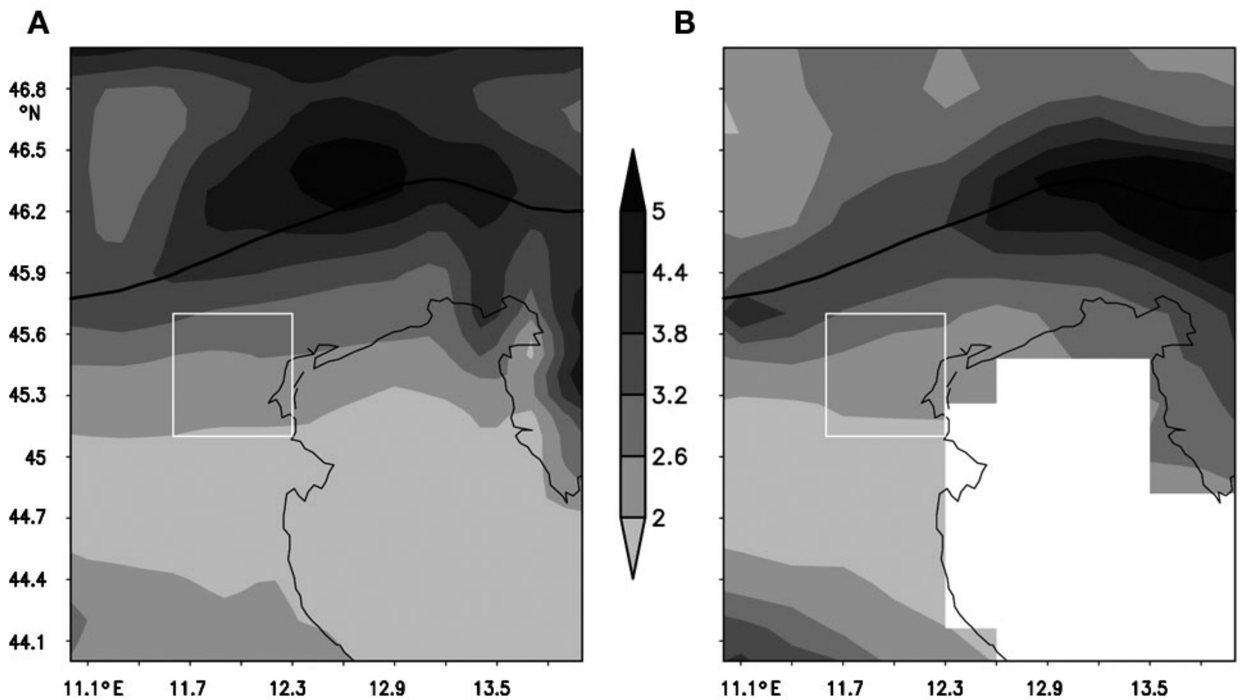


Fig. 2. Mean annual precipitation (mm d^{-1}) for the period 1971–1990. (A) Reference (RF) simulation, and (B) Frei & Schär (1998) data. Thick black line is the 800 m topographic contour; thin black line is the coastline; white frame is the area under investigation

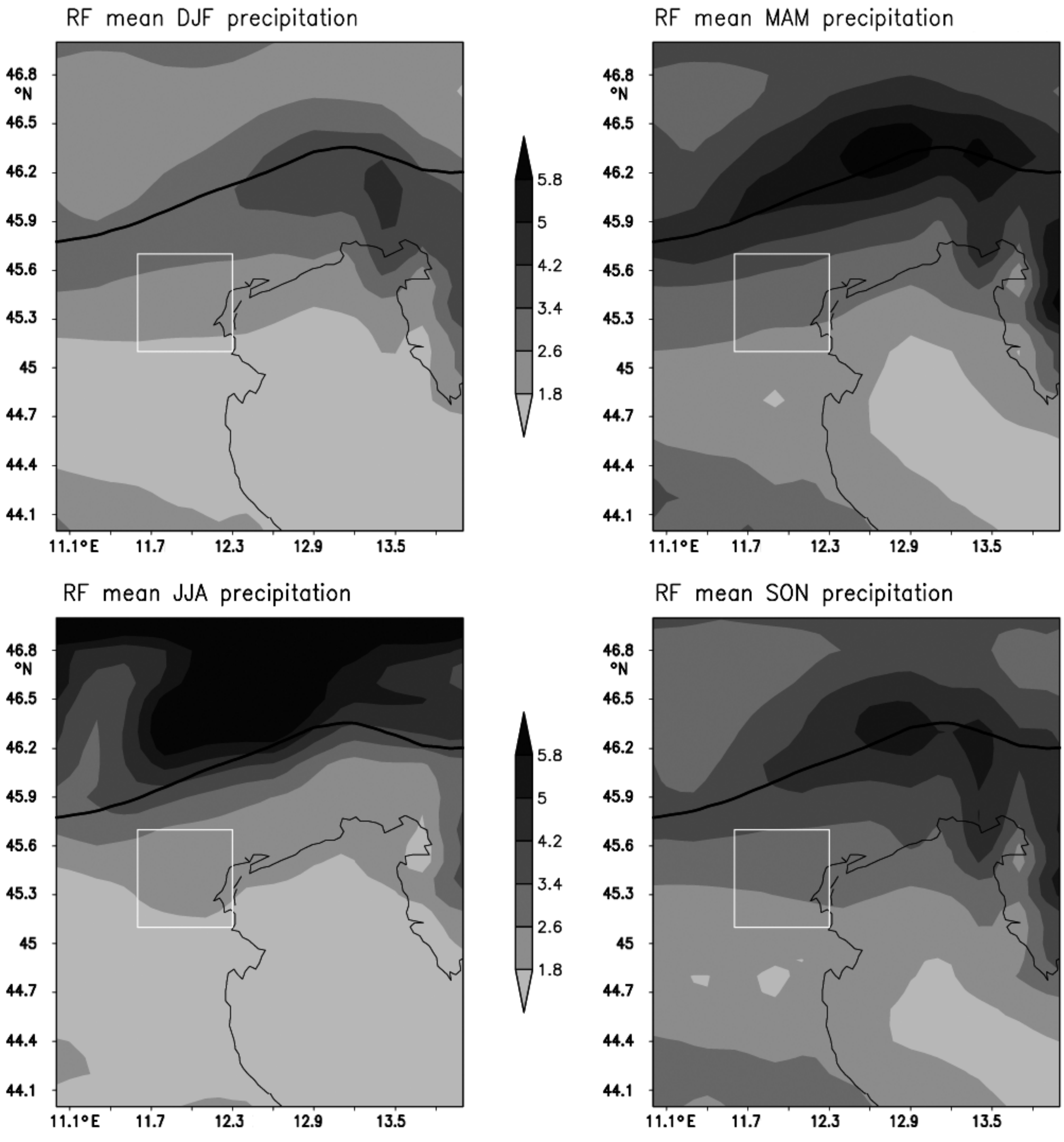


Fig. 3. Mean seasonal precipitation (mm d^{-1}) for the RF experiment, 1971–1990. Thick black line is the 800 m topographic contour; thin black line is the coastline; white frame is the area under investigation

>5 mm d^{-1} (Fig. 4), together with a decreasing precipitation gradient towards the Po Plain. The model generally reproduces these patterns (Fig. 3), with the exception of summer (JJA), when the largest precipitation values in the simulated field are higher than observed and the peak precipitation area above 800 m is displaced westward compared to observations. The agreement between simulated and observed precipitation over the drainage basin is especially good in winter (DJF), with values between 1.8 and 2.6 mm d^{-1}, and autumn (SON), with values >2.6 mm d^{-1}. Precipitation peaks are somewhat overestimated in spring (MAM) and summer (JJA).

The spatial distribution of mean winter (DJF) precipitation in the RCM (Fig. 3) over the eastern Alpine area presents a meridional gradient that agrees well with

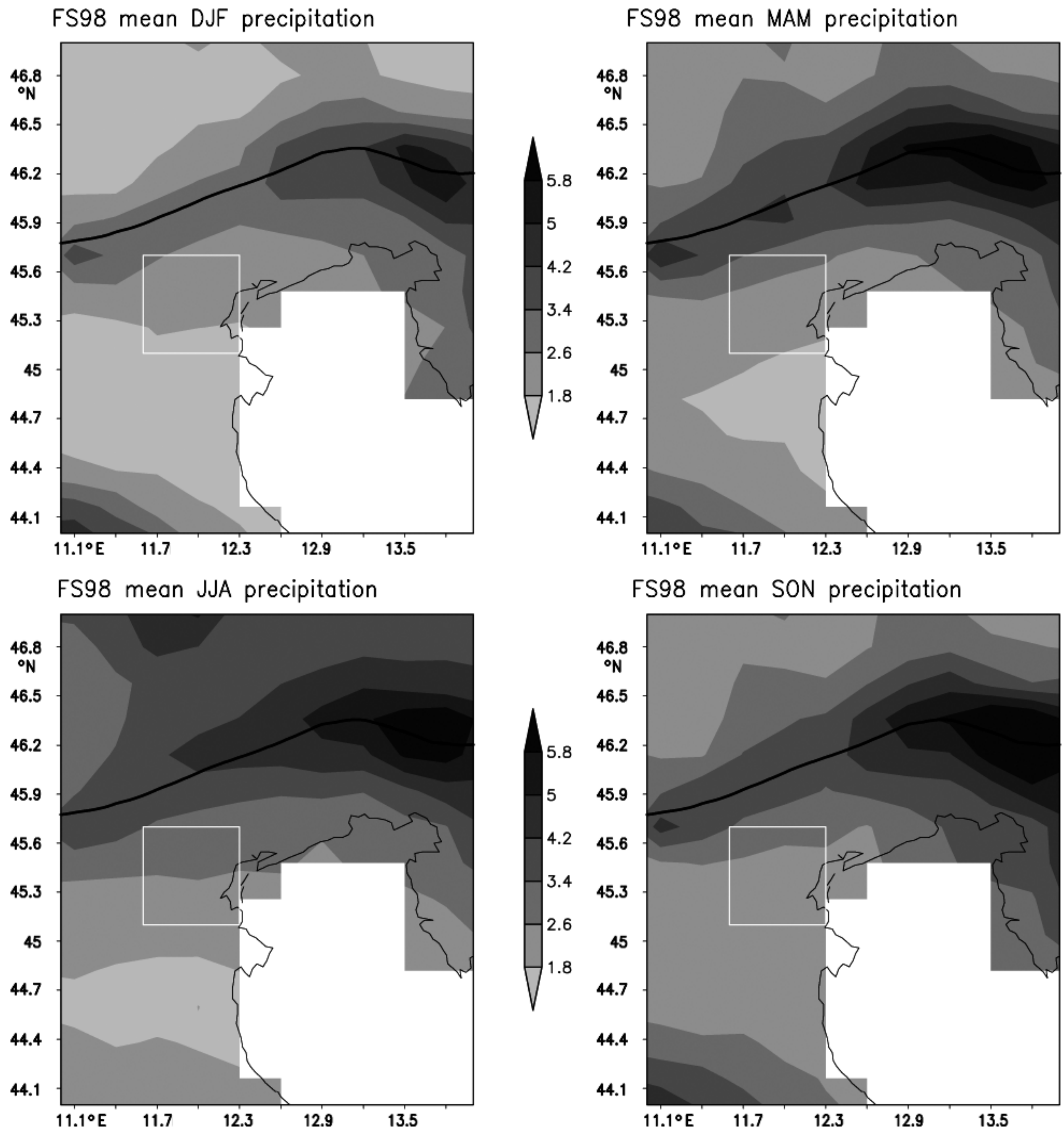
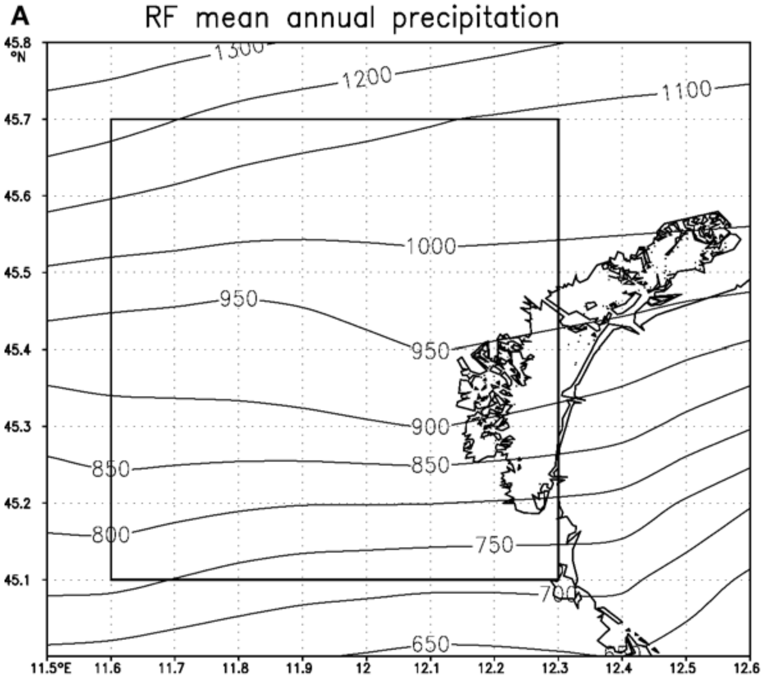


Fig. 4. Mean observed seasonal precipitation (mm d^{-1}) from Frei & Schär (1998), 1971–1990. Thick black line is the 800 m topographic contour; thin black line is the coastline; white frame is the area under investigation

the observational data set shown in Frei et al. (2003, their Fig. 6), although the RCM underestimates precipitation over the Po Plain as does the Hadley Centre regional model (HadRM, see details in Frei et al. 2003). In summer (JJA, Fig. 3), the RCM overestimates precipitation over 800 m, with a precipitation amount >5.8 mm d^{-1}, while it underestimates precipitation in the Po Plain, with amounts <1.8 mm d^{-1}. Over the drainage basin, RCM tends to underestimate summer precipitation, like other regional models, as discussed by Frei et al. (2003). The difference between the RF and observations in JJA is mostly due to the tendency of RCM to produce a strong precipitation response to topographic forcing at the relatively high resolutions considered here (Gao et al. 2006) and not to uncertainty in reproducing the large-scale circulation, that was shown to be simulated reasonably well by this modeling system (Giorgi et al. 2004a,b).



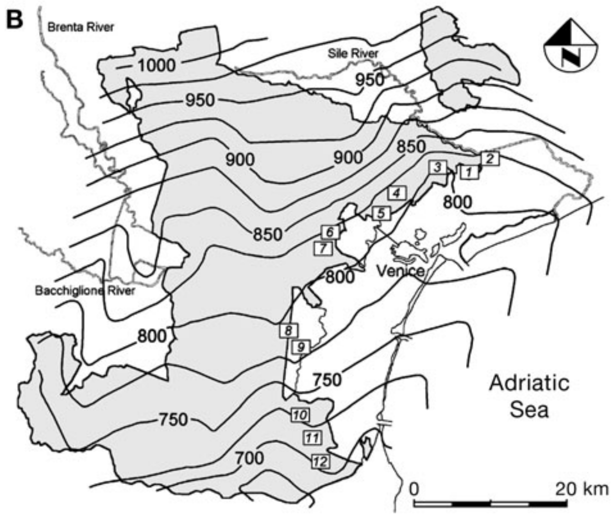


Fig. 5. Mean annual precipitation (mm) on the drainage basin. (A) RF simulation (1961–1990), and (B) Drain project climatology, 1921–2000. Panel (B) reprinted from Zuliani et al. (2005), with permission from Elsevier

Focusing on the drainage basin, Zuliani et al. (2005) found mean annual precipitation values between 700 and 1000 mm yr^{-1}, while the model simulated values between 750 and 1200 mm yr^{-1}, with the largest values occurring in the northwestern corner of the basin (Fig. 5B). The tendency of the RCM to overestimate precipitation, particularly in spring, has already been noted by Gao et al. (2006). We also noted that the model topography does not account for the presence of the lagoon (see Fig. 1) and the steep hills located in the northwestern part of the drainage basin, which induce a secondary east–west gradient in the observations that are not properly reproduced by the RF simulation (Fig. 5A).

Simulated and observed mean monthly climatologies of temperature and precipitation based on area averages over the lagoon drainage basin are presented in Fig. 6. The annual cycle of surface air temperature produced by

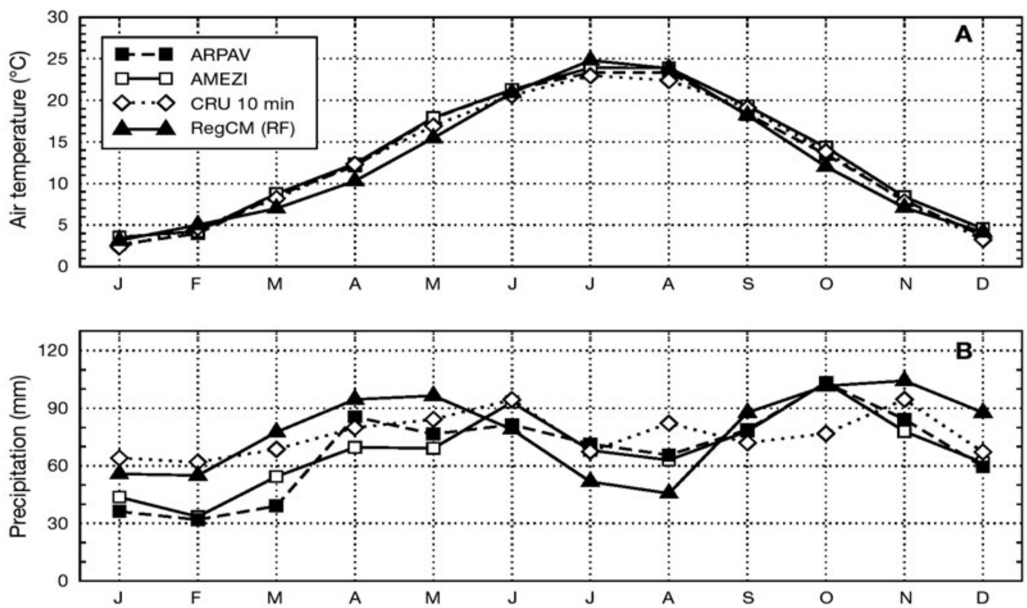


Fig. 6. Annual cycle of monthly mean climatology of (A) temperature, and (B) precipitation over the drainage basin of the Venice lagoon for the model reference simulation (RF) and different observational data sets

the RCM compares fairly well with the 3 observational data sets (ARPAV, AMEZI and CRU; Fig. 6A). Despite the different periods of observation, the ARPAV, AMEZI and CRU climatologies do not show significant discrepancies. The largest model bias is found between March and May and in October, albeit with values <2°C.

The seasonal evolution of precipitation obtained from the 2 local observation data sets are similar and exhibit 2 wet periods; late spring and autumn, separated by dry seasons in winter and summer (Fig. 6B). The wet seasons are typically characterized by synoptic events associated with the passage of baroclinic disturbances over north-central Europe that interact with the Alps and cause lee-cyclogenesis over the northern Mediterranean basin (Ligurian Sea or western Po Plain) (ARPAV 2000). The cyclonic circulation is often coupled with a southeasterly humid flow along the Adriatic Sea which is forced to ascend by the Alps and can lead to intense rainfall over the Veneto region. This in turn results in large river outflow into the Venice lagoon. The RF simulation correctly reproduces the seasonality of precipitation, with maxima in April to May and October to November. The CRU data set shows a low seasonal variability, with maxima in June and November.

The RCM tends to overestimate precipitation amounts over the basin in winter and spring and to slightly underestimate them in summer, the latter being a characteristic found in other RCMs (Frei et al. 2003). The mean annual precipitation for the drainage basin as estimated from the AMEZI and ARPAV data sets is about 68 mm mo^{-1}, while it is about 78 mm mo^{-1} for the RCM, in good agreement with the CRU data (76 mm mo^{-1}). Care must be taken in comparing the different data sets since the RF simulation and the CRU data refer to the period 1961–1990, whereas the AMEZI and ARPAV data cover the periods 1980–2004 and 1991–2005, respectively. The lower mean annual precipitation in the ARPAV and AMEZI data sets with respect to those in the RF and CRU could be related to a general decrease in total precipitation observed by Brunetti et al. (2001) over northeastern Italy during the second half of the 20th century. A similar point is also highlighted by Brunetti et al. (2004) for the southern part of northeastern Italy Macroarea (NES), which includes the drainage basin of the Venice lagoon. We also emphasize that since the model is ultimately driven by general circulation model (GCM) fields rather than analyses of observations, it cannot be expected to reproduce specific precipitation trends over small regions such as our area of interest.

As described by Cossarini et al. (2008), daily amounts of precipitation are crucial for the trophodynamics of the Venice lagoon. Moreover, Frei et al. (2003) showed that NE Italy is a hot spot of heavy daily precipitation, with autumn particularly being characterized by severe precipitation activity. To assess the model's daily precipitation statistics, we compared simulated and observed average frequency of rainy events for each month of the year, the latter being estimated based on average precipitation over the drainage basin. We specified 3 classes of intensity: (A) days with precipitation amounts <1 mm, or dry days (as also defined by Frei et al. 2003), (B) days with precipitation amounts of 1 to 15 mm, and (C) days with precipitation amounts >15 mm, defined here as intense events.

Fig. 7 shows the monthly mean number of days for the 3 classes of precipitation intensity in the AMEZI, ARPAV and RF data sets. The general distribution of rainy events reflects the climatology discussed in Fig. 6B, although the different precipitation classes are associated with different climatic configurations. Both observational data sets show that January, March, July and August have >25 dry d mo^{-1} (Class A, Fig. 7A). RF results are in good agreement with the AMEZI and ARPAV data, except in March and May when the model underestimates the number of dry days by about 3 d mo^{-1}.

Both observational data sets show a pronounced seasonal pattern of precipitation events in the intermediate Class B (Fig. 7B). This is characterized by 2 maxima (>5 d mo^{-1}); one between April and June, and one in autumn, and minima in February and August. The model shows good agreement with observations in reproducing this seasonal pattern, although the actual value is somewhat overestimated for most months.

Days with intense rain (Class C, Fig. 7C) have a seasonal pattern similar to that of Class B, with an overall maximum of 2 to 3 d mo^{-1} in October. The model is able to reproduce the maximum values of the intense events in April, May and October, when these events are associated with synoptic disturbances, but simulates an extreme minimum in August that is absent in the observations. On the other hand, some Class C events also occur in summer, when they are related to local and short-term convective precipitation cells. The RCM results are generally consistent with the evaluation of Frei et al. (2003), who found October to be the month with the highest number of days with precipitation amounts >15 mm.

Class C events are particularly important for the Venice lagoon ecosystem where intense precipitation (that can even exceed 100 mm d^{-1}; ARPAV 2000, Zuliani et al. 2005) is associated with the transport of very large amounts of nutrients by the river into the lagoon (Botter et al. 2006). Moreover, the frequency of such events has been observed to show a positive trend during the last century both at the national scale (Brunetti et al. 2004) and over the Veneto region (Barbi et al. 2005). Brunetti et al. (2001) reported a 5%

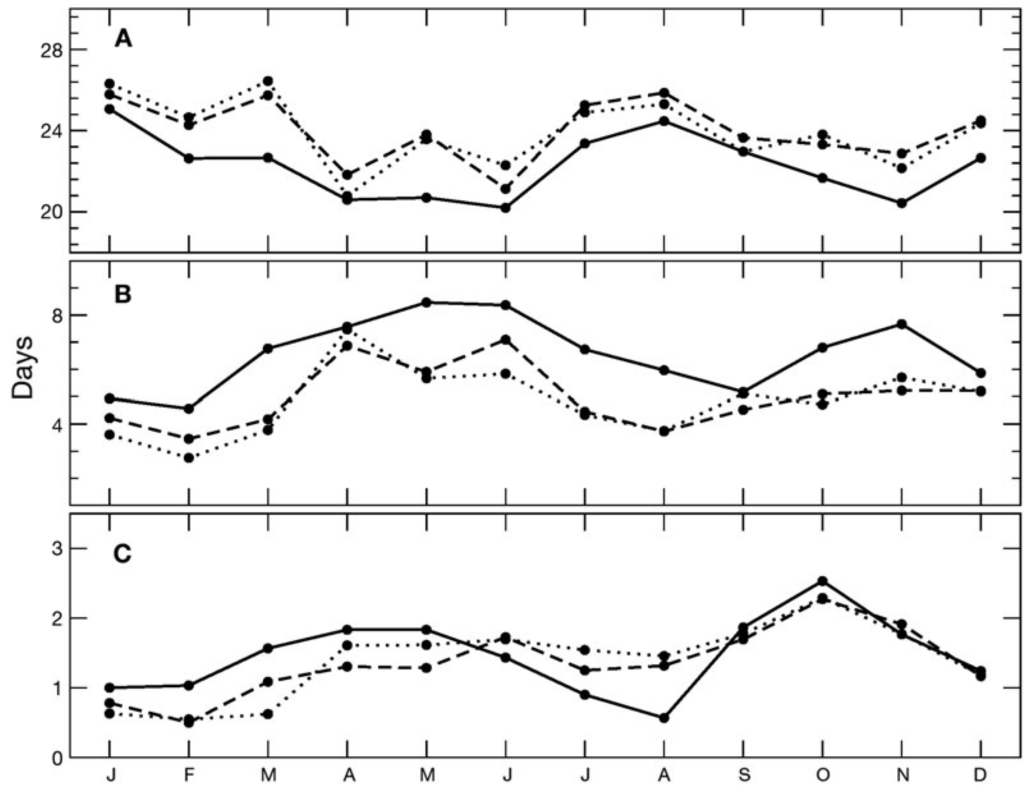


Fig. 7. Monthly mean of rainy days. (A) Class A — days with precipitation amount <1 mm, (B) Class B — days with precipitation amount of 1–15 mm, and (C) Class C — days with precipitation amount >15 mm for AMEZI (dashed lines), ARPAV (dotted lines) and RCM – RF run (solid lines)

increase in the annual mean precipitation intensity from 1920–1998 over the eastern Alpine region. This is due to increased occurrence of the most intense rainfall events (decile 10) and decreased occurrence of all the other classes (decile 1 to 9). The authors showed how the return period of extreme rainy events (99.9th percentile, corresponding to an annual mean of 70 mm d^{-1} averaged over all the rain-gauge stations) has been shortened from 11 yr in the period 1920–1950 to 5 yr in the period 1970–1998.

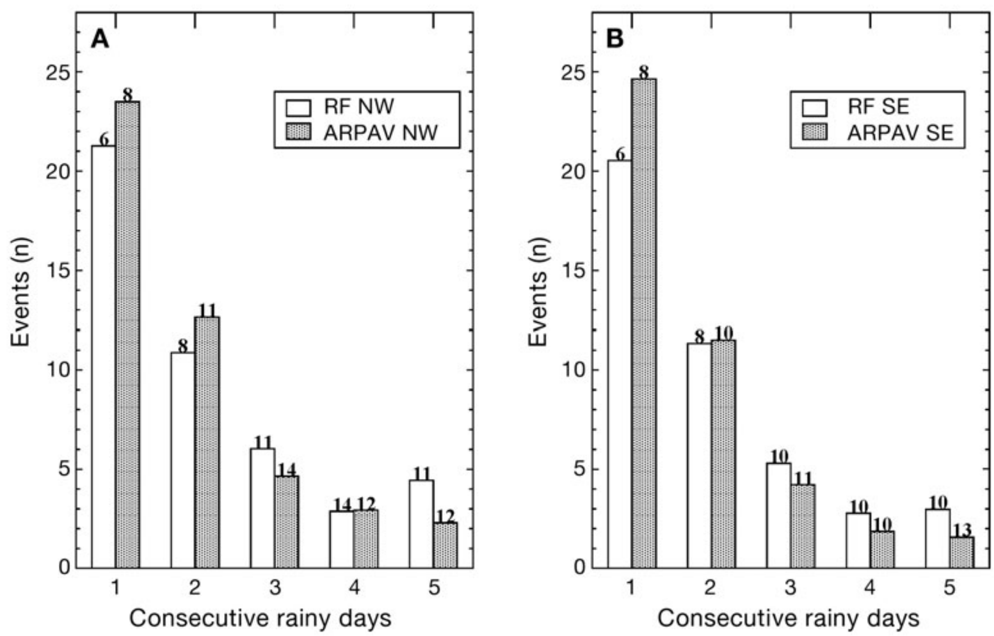


Fig. 8. Annual mean distribution of precipitation events with 1 to 5 d duration for (A) the NW drainage basin and (B) the SE drainage basin, as estimated from the RF run and the ARPAV data set. Mean daily rain intensity (mm d^{-1}) is indicated on top of the bars

The sequence of consecutive rainy days is also an important aspect that can have a strong impact on the biogeochemistry of the lagoon. The distribution of the mean annual number of precipitation events with a duration of 1 to 5 d (a single precipitation event is defined as a series of consecutive rainy days, while a rainy day is defined by a precipitation amount >1 mm) is shown in Fig. 8 for the RF simulation and the ARPAV data set. Plots are presented for the NW and SE portions of the drainage basin, respectively defined as the subdomains 45.5 to 45.7° N; 11.6 to 11.9° E and 45.1 to 45.3° N; 12 to 12.3° E for the model and corresponding to Stns 6 (Castelfranco) and 8 (Codevigo) for the ARPAV data set.

Although the period to which data refer is different, the comparison allows a first-order validation of the RCM capability to reproduce the distribution of the precipitation event durations. In both the observations and the model, short events (1 d) are most frequent, with >20 occurrences yr^{-1}. The longest events, 4 to 5 d, occur <5 times yr^{-1}. The rain intensity of 1 d events is <8 mm d^{-1} for both the RF and ARPAV data sets, while it is >8 mm d^{-1} for longer events. The comparison between the 2 areas under investigation shows that the NW part of the drainage basin is more rainy: ~930 vs. 730 mm for the SE. Also in this respect, there is good agreement between the RF and ARPAV data. In particular, the difference in the annual precipitation between the 2 subareas is mostly associated with events longer than 2 d, the cumulative rain associated with such events being greater in the NW than in the SE.

5. SUMMARY AND CONCLUSIONS

In this paper, we present the validation of a subset of data extracted from a high-resolution RCM reference simulation for the drainage basin of the Venice lagoon for the period 1961–1990. This simulation is the basis of a downscaling procedure to investigate the possible effects of changes in precipitation regimes on the biogeochemistry of the lagoon (see Cossarini et al. 2008). The validation is carried out against different observational data sets. The focus is on precipitation statistics from daily to monthly and seasonal cycles. The drainage basin of Venice lagoon in NE Italy is a relatively small region embedded in an area characterized by complex physiographic features; thus, the comparison between the RCM simulation and observations represents a stringent test to assess the capability of this regional model to reproduce small-scale climatic features.

Overall, the simulation shows good agreement with observations over the basin at all scales analyzed. Basic topographically induced precipitation gradients and the seasonal cycle of precipitation amounts are well captured. The main deficiency of the model is the overestimation of precipitation, especially in spring, which has been noted in previous work (Giorgi et al. 2004a, Gao et al. 2006). It is difficult to unambiguously attribute this error to specific simulated processes or to the effect of the driving boundary conditions, but its magnitude is within the range of biases found in other PRUDENCE models analyzed by Jacob et al. (2007). An important aspect of the simulation is that it captures the statistics and timing of intense daily rainy events during the year, as well as the typical length of rainy periods, which can be important factors in regulating the nutrient loads in the lagoon ecosystem.

Our assessment thus gives positive indications for the use of this high-resolution RCM experiment in studying the effects of climate change on the biogeochemical cycles of the Venice lagoon. However, it should be emphasized that good model performance in reproducing present-day climate does not guarantee equally good performance in simulating climate conditions different from the present. This is because model parameters are often optimized using observations, although no specific tuning was carried out in the simulation of Gao et al. (2006) analyzed here. Good performance in reproducing present-day climate is thus necessary but not sufficient to increase reliability of future climate simulations. Nevertheless, this condition has been used in the past as a measure of reliability (e.g. Giorgi et al. 2001, Giorgi & Mearns 2002).

In the companion paper by Cossarini et al. (2008), outputs from the RCM reference and future scenario simulations are used as inputs to a biogeochemical model for the lagoon to investigate possible effects of climate change on the lagoon ecosystem.

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