Atmospheric and Oceanic Science Letters

ISSN: 1674-2834 (Print) 2376-6123 (Online) Journal homepage: http://www.tandfonline.com/loi/taos20

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To cite this article: Filippo GIORGI & Xue-Jie GAO (2018): Regional earth system modeling: review and future directions, Atmospheric and Oceanic Science Letters, DOI: 10.1080/16742834.2018.1452520

To link to this article: https://doi.org/10.1080/16742834.2018.1452520

Published online: 09 Apr 2018.

ATMOSPHERIC AND OCEANIC SCIENCE LETTERS, 2018
https://doi.org/10.1080/16742834.2018.1452520

Regional earth system modeling: review and future directions

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ABSTRACT

The authors review recent advances in the development of coupled Regional Earth System Models (RESMs), a field that is still in its early stages. To date, coupled regional atmosphere-ocean-sea ice, atmosphere-aerosol and atmosphere-biosphere models have been developed, but they have been applied only to limited regional settings. Much more work is thus needed to assess their transferability to a wide range of settings. Future challenges in regional climate modeling are identified, including the development of fully coupled RESMs encompassing not only atmosphere, ocean, cryosphere, biosphere, chemosphere, but also the human component in a fully interactive way.

摘要

耦合区域地球系统模式（RESM）现在仍处于早期的发展阶段，在本文中，我们对其近期相关进展进行了回顾。到目前为止，已经开发出了耦合的区域大气–海洋–海冰、大气–气溶胶和大气–生物圈模式，但总体它们仅在有限的区域得到应用，需要更多的工作来评估其在更多区域的可移植性。我们认为RESM发展中的未来挑战，是在大气、海洋、冰冻圈、生物圈、化学圈以外，同时将人类及其活动成分以完全相互作用的方式引入进来。

ARTICLE HISTORY
Received 30 November 2017
Revised 10 February 2018
Accepted 9 March 2018

KEYWORDS
Regional climate model; regional earth system model; atmosphere-ocean coupling; atmosphere-aerosol coupling

1. Introduction

Since the pioneering work of Dickinson et al. (1989), Giorgi and Bates (1989) and Giorgi (1990), the field of regional climate modeling has tremendously grown. Today a number of regional climate models (RCMs) from laboratories around the world are used for a wide variety of applications, from process studies at the seasonal to interannual scale, to multicentennial climate projections, with resolutions varying from ~50 km to convection permitting (<5 km) (Giorgi and Gutowski 2015). A number of intercomparison projects, culminating into the international Coordinated Regional Downscaling EXperiment (CORDEX, Giorgi, Jones, and Asrar 2009; Jones, Giorgi, and Asrar 2011; Gutowski et al. 2016), have enabled the RCM community to explore key issues in regional modeling and assess the potential of this technique to produce climate information relevant for impact and adaptation studies. The evolution of regional modeling is discussed in a number of review papers (See Giorgi and Gutowski 2015, and papers cited therein) to which the reader is referred to have an overview of the status of this field of research.

Here we focus on what is considered to be one of the main future directions in RCM research, namely the development of interactively coupled Regional Earth System Models (RESM) (Giorgi and Gutowski 2015). The great opportunity represented by RCMs in describing the regional interactions across different components of the climate system was already recognized in the early stages of RCM development (Giorgi 1995). This is because many of these interactions take place at spatial scales that are not resolved by global models, and are more closely captured at the high resolution achievable with RCMs. Typical examples are the presence of complex vegetation structures, small river and ocean basins, lakes, tropospheric aerosols, mesoscale atmosphere, and ocean circulation features, etc.

Recognizing this opportunity, the RCM modeling community has actively engaged in the development of RESM systems usable in different regional contexts. Today several coupled RESMs exist, including varying sets of components, which have been applied to a wide range of different regions (e.g. Peng et al. 2012; Giorgi and Gutowski 2015; Schrum 2017). Some models, in particular, include multiple Earth system components, such as atmosphere, oceans, sea ice, hydrology, and land and/or marine biogeochemistry (Drobinski et al. 2012; Zou and Zhou 2012; Lorenz and Jacob 2014; Sevault et al. 2014; Sein et al. 2015; Sitz et al. 2017).

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In this paper we thus review the status and perspectives of RESM development by first describing the basic modeling structure of a coupled RESM (Section 2), then presenting illustrative examples of studies addressing the regional interactions across different climate system components (Section 3), and finally discussing future directions.

2. The basic structure of a coupled RESM

Figure 1 illustrates the basic structure of a coupled RESM. The main components of the model are the atmosphere, ocean, land surface and hydrology, cryosphere, chemosphere (gaseous compounds and aerosols), and biosphere. The atmosphere interacts with the oceans, land, and cryosphere through exchanges of energy and mass; with chemistry/aerosols through processes of emission, transport, and removal; and with the biosphere through its effects on the biogeochemical cycles. Similar interactions are found for the oceans and cryospheric components, with the addition of a direct coupling of oceans and land through river discharge. Atmospheric constituents and aerosols can have strong interactions with the atmosphere and regional climate, as well as the biosphere, both terrestrial and marine, through radiative, microphysical, and chemical processes. It is also important to emphasize that many of the interactions described above are highly non-linear due to the presence of strong feedbacks, such as the ice-albedo one.

The main difference between the RESM structure of Figure 1 and the structure of global Earth System Models (ESM) is that RESMs, being run only over a limited area domain, require time-dependent lateral boundary conditions for those components regulated by three-dimensional dynamical equations, such as the atmosphere, oceans, and chemosphere. These have to be provided either by global ESMs or by analyses of observations.

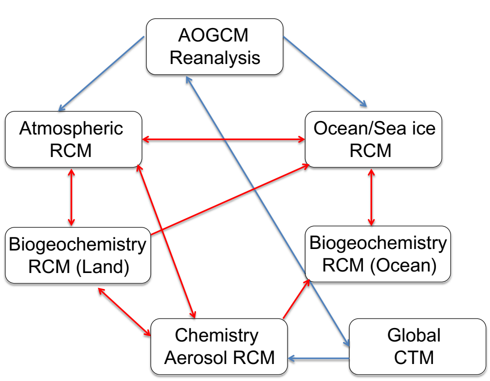

Figure 1. Schematic depiction of a coupled Regional Earth System Model framework and the interactions across it's different components and GCM drivers (CTM: Chemical transport model). Arrows indicate the flow of information. Blue arrow: the interaction with driving global models; red arrow: the interaction inside the RESM.

Two technical aspects make coupled modeling particularly difficult. The first is that most often, the different components are run on different spatial grids, resolutions and domains. For example, in order to resolve mesoscale ocean eddies, often the ocean models are run at higher horizontal resolution than the atmospheric counterparts. Therefore variables exchanged at their interfaces (for example, energy fluxes and wind stress at the ocean-atmosphere interface) need to be interpolated from one domain grid to another. This is usually achieved either using ad hoc procedures or general interpolator packages that can actually be quite complex. It should be remembered, however, that there might be errors or excessive approximations in the spatial interpolation introduced as a result of the different scales characteristic of different phenomena. For example, given interface fields may have to be disaggregated or upscaled in the exchange process. These may result in an imbalance across the models, which calls for careful interpolation procedures or suitable correction techniques (e.g. flux correction).

The second difficulty is related to the different temporal scales of evolution across components. For example, the atmosphere evolves and responds to external forcings much more rapidly than the oceans, which have a higher thermal and dynamical inertia, and thus longer evolution times. In fact, some chemical reactions can occur at extremely fast temporal scales. On the one hand, this implies that each component runs with different time steps, and thus some temporal interpolation is necessary in the information exchange. In the meantime, relatively long simulation times are needed to equilibrate the atmosphere and ocean components which, for a high resolution model, can prove to be a daunting computational task. This problem has been often bypassed through the so-called asynchronous coupling, in which ocean and atmosphere components are not coupled at each time step, but at different temporal scales.

Without going into greater technical detail, it is clear that the development of a fully coupled comprehensive RESM system is a formidable modeling task, which has been so far approached by incremental steps in which various components have been incrementally added to a base modeling framework. This has resulted in studies addressing different interactions across the components, as will be reviewed in the next section.

3. Illustrative examples of coupled regional modeling studies

3.1. Atmosphere-ocean coupling

The development of the first coupled atmosphere-ocean RCMs (AORCMs) is relatively recent, late 2000s and early 2010s, however a number of coupled AORCMs are already available (e.g. Schrum 2017). An issue central to regional ocean-atmosphere coupling is weather the coupling itself improves the simulation of climate features compared to the uncoupled atmospheric model. This has been clearly shown for extreme weather phenomena, such as tropical cyclones (Bao et al. 2000; Bender and Ginis 2000; Bender et al. 2010), or in highly convective regions, such as the maritime continent (Aldrian et al. 2005; Seo, Miller, and Roads 2007; Wei et al. 2014), or the South Atlantic (Byrne et al. 2015; Ratnam et al. 2015).

A region where air-sea coupling is particularly important is the Indian ocean, and for this reason several coupled RCM development efforts focused on the Indian ocean basin. Among them, Krishna, Hoerling, and Rajagopalan (2005), Seo et al. (2008, 2009), Ratnam et al. (2009), Samala et al. (2013), Samson et al. (2014), and Di Sante (2017) built AORCMs coupling different atmospheric and ocean regional model components. Their studies indeed found that, compared to the stand alone atmospheric RCMs, the coupled models improved the simulation of the patterns and intraseasonal variability of the South Asia monsoon precipitation, as well as the simulation of tropical storms, due to the effect of air-sea coupling. It thus appears that coupled AORCMs can be especially useful in regional tropical climate settings.

A similar result was also found for the East Asia monsoon, where air-sea coupling significantly improved the simulation of the monsoon's evolution and variability (Zou and Zhou 2013, 2016). For example as shown in Figure 2, the temporal correlation coefficients of precipitation anomaly between observed and simulated over the Western North Pacific and South China Sea are 0.14 and 0.37 before the coupling, and 0.50 and 0.55 after the coupling, respectively (Zou and Zhou 2013). Several other efforts have indeed been devoted to the development of coupled atmosphere-ocean regional models for the East Asia region (Lin, Qian, and Zhang 2006; Fang et al. 2009; Yao and Zhang 2009; Li and Zhou 2010).

In addition, Seo, Miller, and Roads (2007) found that air-sea mesoscale interactions improved the simulation of frontal systems and associated precipitation patterns over the Eastern Pacific Sector, while different models have shown good performance in reproducing air-sea mesoscale interactions in coastal upwelling regions (Ribeiro, Soares, and de Oliveira 2011; Putrasahan, Miller, and Seo 2013; Li et al. 2014a, 2014b).

Another region for which coupled regional modeling has been particularly active is the Mediterranean basin, where several AORCMs have been developed as part of the European project CIRCE (Gualdi et al. 2013) as well as the MED-CORDEX initiative (Ruti et al. 2016), towards the purpose of building fully coupled RESMs. Among such AORCMs are those of Djurdjevic and Rajkovic (2008); Somot et al. (2008); Artale et al. (2010); Elizalde et al. 2010; Drobinski et al. (2012); Sevault et al. (2014). The Mediterranean basin is an optimal setting for regional coupling because many air sea interactions occur at the mesoscale, for example in the generation of deep water and extreme meteorological events (e.g. Lebeaupin Brossier et al. 2015), and because it is a semi-enclosed sea, thus reducing the importance of the provision of ocean lateral boundary conditions. Coupled AORCMs for the Mediterranean have been run for twenty-first century projections, and have indicated that the coupling can indeed modulate significantly the climate change signal from the uncoupled models (e.g. Somot et al. 2008; Dubois et al. 2012).

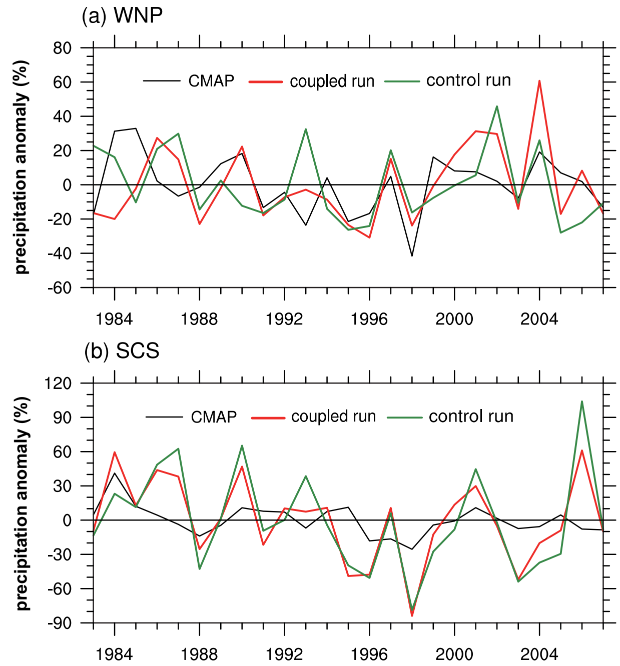

Figure 2. Precipitation anomaly over (a) the Western North Pacific (WNP, 10°N–25°N, 120°E–150°E) and (b) South China Sea (SCS, 5°N–20°N, 110°E–120°E) (units: %). Black line: CMAP observations; Red line: simulation by the atmosphere-ocean coupled RegCM3-LICOM2.0; Blue line: control run with RegCM3 (atmosphere only). Source: Zou and Zhou (2013).

Finally, since the early years of RCM development, a number of studies have investigated the interactions between atmosphere and lakes via the use of coupled RCM-lake models. This has been done for lakes in the continental U.S. (e.g. Hostetler, Bates, and Giorgi 1993; Bates, Hostetler, and Giorgi 1995; Martynov et al. 2012; Notaro et al. 2013), Central Asia (e.g. Small et al. 1999; Turuncoglu et al. 2013), Africa (e.g. Thiery et al. 2015; Diallo, Giorgi, and Stordal 2017), and Europe (e.g. Mironov et al. 2010).

3.2. Regional coupling with the cryosphere

An important component of coupled RCM development is the cryosphere. Traditionally, land surface schemes used in RCMs have included interactive snow modules, so we will not focus on snow, but on specific models of cryospheric systems, such as sea ice and glacier models. Coupled regional atmosphere-ocean-sea ice models have been developed for cold climate regions, such as the Arctic (e.g. Curry and Lynch 2002; Roberts et al. 2008), the Antarctic (Bailey and Lynch 2000), the North Sea and Baltic Sea basins (e.g. Gustafsson, Nyberg, and Omstedt 1998; Hagedorn, Lehmann, and Jacob 2000; Doscher et al. 2002; Schrum et al. 2003; Lehmann, Lorenz, and Jacob 2004; Van Pham et al. 2014; Su et al. 2014; Wang et al. 2015a), and the Caspian Sea (e.g. Turuncoglu et al. 2013).

Many of these developments have occurred within the context of multi-model intercomparison projects (e.g. Raschke et al. 2001; Curry and Lynch 2002; Rinke et al. 2006), and the models have been applied to a variety of studies, from analyses of atmosphere-ocean-sea ice coupling (Rinke et al. 2003; Mikolajewicz et al. 2005; Döscher et al. 2010; Döscher and Koenigk 2013; Gröger et al. 2015) to future climate projections (Kjellström, Döscher, and Meier 2005; Meier 2006; Bülow et al. 2014; Meier 2015; Koenigk, Do¨Scher, and Nikulin 2011; Schrum et al. 2016). All these studies clearly indicated that the interactive sea ice component substantially increases both the model varibility and the inter-model spread in the simulated response to future warming. This is mostly because of the model representation of sea ice thermodynamical processes and their response to external forcings and air-sea-ice interactions (Schrum 2017).

The development of interactive land glaciers, to date, has received less attention, mostly because of the scale mismatch between glacier processes and the resolution of RCMs (Kotlarski et al. 2010). This will likely require either the use of sub-grd scale parameterizations of land surface processes, or the move to very high resolution convection-permitting models.

More generally, increased development and testing of coupled atmosphere-ocean-cryosphere RCMs will be necessary to better describe the complex and highly non-linear interactions between the climate and the cryosphere in order to enhance the reliability of climate projections in cold-climate regions.

3.3. *Atmosphere-chemistry/aerosol coupling*

One of the areas that has received considerable attention is the interactive coupling of regional climate and chemistry/aerosol models. This is because tropospheric aerosols can exert a radiative forcing sufficient to significantly affect regional climates, especially in tropical regions. The first simplified aerosol model coupled to an RCM was developed by Qian and Giorgi (1999), who found that the direct radiative forcing of anthropogenic sulfate aerosols over East Asia is sufficient to produce a statistically significant cooling and decrease of precipitation over the region. This pioneering work was followed by a series of further RCM-based studies of direct and indirect effects of sulfate and organic aerosols over East Asia (e.g. Qian et al. 2001, 2003; Giorgi, Bi, and Qian 2003; Li et al. 2009; Ji et al. 2011, 2015; Wang et al. 2015b), as well as mineral dust emitted from the Gobi desert (e.g. Zhang et al. 2009, 2016; and Figure 3; Han et al. 2013; Ji et al. 2016b), which confirmed the important role that anthropogenic aerosol emissions have in modulating the highly polluted climate of East Asia.

Similar experiments have been conducted also over the Africa continent, where biomass burning and Saharan dust are important environmental and climate concerns. A series of coupled RCM-aerosol based studies investigated the role of biomass burning aerosols and mineral dust emissions on the West Africa monsoon precipitation (Konare et al. 2008; Solmon et al. 2008; Ji et al. 2016a). They found that the aerosol can significantly affect the monsoon development through the competing effect of surface cooling and elevated heat pumping, the former leading to an inhibition of the inland penetration of the monsoon rain band, and the latter leading to a contrary effect. Depending on the aerosol optical properties, one effect was dominant over the other, demonstrating the

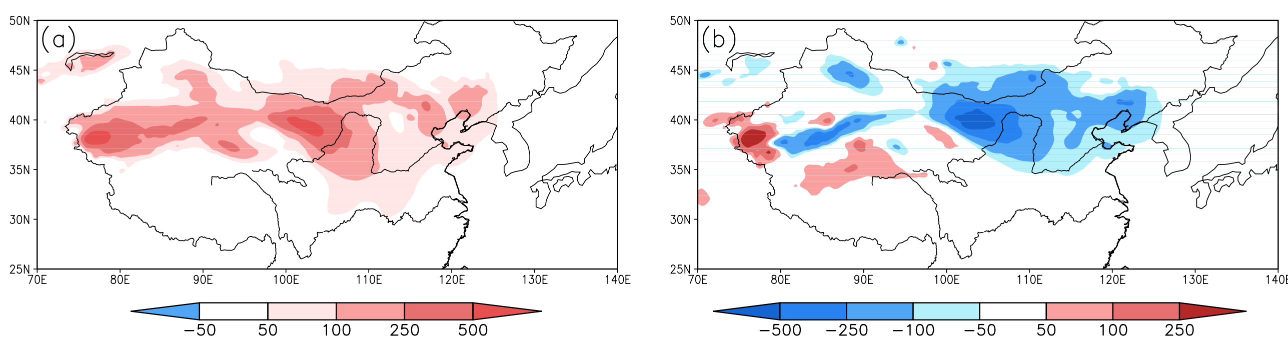

Figure 3. Changes of dust column burden in December–January–February–March (DJFM) and April–May (AM) in the end of twenty-first century (2091–2100 in relative 1991–2000) over northern China under A1B scenario as simulated by RegCM3 driven by MIROC3.2_hires (units: mg m^{-2}). Source: Zhang et al. (2016).

importance of accurately characterizing aerosol characteristics, both microphysical and optical, in order to best represent aerosol effects on regional climate.

Coupled RCM-based simulations of aerosol-climate interactions were also conducted over the European region, for example by Nabat et al. (2014, 2015) and Zanis et al. (2012), who showed that direct and semi-direct aerosol effects are key ingredients necessary to explain the spatio-temporal structure of solar radiation and temperature over Europe.

Within the context of coupled RCM-based aerosol modeling, it should be mentioned that highly simplified aerosol models have been mostly used in climate-type applications due to the computational requirements of running more complex microphysical and chemical schemes. However, efforts are under way to interactively couple within RESM systems full three-dimensional chemistry modules which will allow a more refined representation of chemistry-climate interactions (e.g. Shalaby et al. 2012).

3.4. Atmosphere-biosphere coupling

Coupling of biosphere and atmosphere components in RESMs is important because the surface characteristics can substantially affect regional and local climates. Numerous studies have addressed the effect of land surface changes in RCMs (e.g. Giorgi and Gutowski 2015), but these were imposed and thus no two-way interactions between climate and land use was allowed. Some advanced land surface modules, such as CLM (Oleson et al. 2008), include the capability of describing vegetation dynamics in response to climate input, as well as the presence of crops with annexed technology options. These land modules have been incorporated in different RCMs, and thus would allow the simulation of two-way biosphere-atmosphere interactions. Alternatively, dynamical vegetation/bioeochemistry models can be coupled to RCMs, as done for example by Smith et al. (2011) over Europe, Shi et al. (forthcoming) over China and Wang et al. (2017) over Africa.

Some early studies of regional biophysical feedbacks have been conducted (e.g. Zhang et al. 2014; Wang et al. 2017), but generally these studies present the difficulty of needing long spin-up times to bring the biosphere model to equilibrium with the RCM's climate. This is clearly an area of research that will receive increasing attention, as anthropogenic climate change and other human activities continue to substantially alter the natural biogeochemical cycle of the Earth.

4. Future directions in RESM development

Clearly, the development of RESMs is still in its beginning stages, and will undoubtedly receive increasing attention in the next years. It presents some important technical difficulties, such as the interface of models running on different grid and having a wide range of characteristics times of evolution, and the provision of lateral boundary conditions for the different components of the system. The former problem can be best addressed with the use of general-purpose interpolators, a few of which are available as community tools. The latter may require some more ad hoc solutions, especially concerning the ocean and chemistry components. In both cases, however, attention should be given to the implications of interpolating variables associated with phenomena characterized by different spatial and temporal scales.

Several coupled atmosphere-ocean-sea ice-aerosol/chemistry RESMs have been developed, but they have been tested mostly over specific domains. Much more work and intercomparison studies are needed to assess the transferability of these coupled models in different regional settings and to obtain general conclusions concerning the importance of the representation of coupled processes. In particular, the inclusion of interactive biosphere has been limited so far, but the interest in this aspect of coupled modeling is indeed growing in view of the role it will play especially within the context of future climate change, which may lead to pronounced changes in natural ecosystems.

In our opinion, the next challenge in RESM modeling is the inclusion of the human factor. Human activities such as land-use change and greenhouse gas and aerosol emissions, are currently considered in most model experiments as external players in the climate system, either as forcings or as receptors (e.g. impacts). However, there is a two-way interaction between human societies and the natural environment, whereby on the one hand human populations may migrate in response to climatic, environmental and socio-economic stresses, and on the other hand adaptation policies to respond to climate change may in turn affect climate. In an era where humans are now a key component of the climate system, these processes will have to be included in the next generation of earth system models. RESMs can be an optimal test-bed for this model development because it can focus on specific regional interactions, and the lessons learned from this exercise can eventually be extended and generalized to global models.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was jointly supported by the National Key Research and Development Program of China [grant number 2016YFA0600704], the National Natural Science Foundation of China [grant number Y71301U801].

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References

Aldrian, E., D. V. Sein, D. Jacob, L. D. Gates, and R. Podzun. 2005. “Modelling Indonesian Rainfall with a Coupled Regional Model.” *Climate Dynamics* 25: 1–17.

Artale, V., S. Calmanti, A. Carillo, A. Dell’Aquila, M. Herrmann, G. Pisacane, P. M. Ruti, et al. 2010. “An Atmosphere–Ocean Regional Climate Model for the Mediterranean Area: Assessment of a Present Climate Simulation.” *Climate Dynamics* 35: 721–740.

Bailey, D. A., and A. H. Lynch. 2000. “Development of an Antarctic Regional Climate System Model. Part I: Sea Ice and Large-Scale Circulation.” *Journal of Climate* 13: 1337–1350.

Bao, J. W., J. M. Wilczak, J. K. Choi, and L. H. Kantha. 2000. “Numerical Simulations of Air–Sea Interaction under High Wind Conditions Using a Coupled Model: A Study of Hurricane Development.” *Monthly Weather Review* 128: 2190–2210.

Bates, G. T., S. W. Hostetler, and F. Giorgi. 1995. “Two-Year Simulation of the Great Lakes Region with a Coupled Modeling System.” *Monthly Weather Review* 123: 1505–1522.

Bender, M. A., and I. Ginis. 2000. “Real-Case Simulations of Hurricane–Ocean Interaction Using a High-Resolution Coupled Model: Effects on Hurricane Intensity.” *Monthly Weather Review* 128: 917–946.

Bender, M. A., T. R. Knutson, R. E. Tuleya, J. J. Sirutis, G. A. Vecchi, S. T. Garner, and I. M. Held. 2010. “Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes.” *Science* 327: 454–458.

Bülow, K., C. Dieterich, H. Heinrich, S. Hüttl-Kabus, B. Klein, B. Mayer, H. E. M. Meier, et al. 2014. “Comparison of 3 Coupled Models in the North Sea Region under Todays and Future Climate Conditions.” *KLIWAS Schriftenreihe* 27.

Byrne, D., L. Papritz, I. Frenger, M. Munnich, and N. Gruber. 2015. “Atmospheric Response to Mesoscale Sea Surface Temperature Anomalies: Assessment of Mechanisms of Coupling Strength in a High Resolution Coupled Model over the South Atlantic.” *Journal of the Atmospheric Sciences* 72: 135–153.

Curry, J. A., and A. H. Lynch. 2002. “Comparing Arctic Regional Climate Model.” *Eos, Transactions American Geophysical Union* 83: 87–88.

Di Sante, F. 2017. “Assessing the Role of Local Air–Sea Interactions over the South Asia Region in Simulating the Indian Summer Monsoon (ISM) Using the New Earth System Model RegCM–ES.” PhD Thesis, University of Trieste, 137 pp.

Diallo, I., F. Giorgi, and F. Stordal. 2017. “Influence of Lake Malawi on Regional Climate from a Double Nested Regional Climate Model Experiment.” *Climate Dynamics* 12: 1–15.

Dickinson, R. E., R. M. Errico, F. Giorgi, and G. T. Bates. 1989. “A Regional Climate Model for the Western United–States.” *Climatic Change* 15: 383–422.

Djurdjevic, V., and B. Rajkovic. 2008. “Verification of a Coupled Atmosphere–Ocean Model Using Satellite Observations over the Adriatic Sea.” *Annales Geophysicae* 26: 1935–1954.

Döscher, R., and T. Koenigk. 2013. “Arctic Rapid Sea Ice Loss Events in Regional Coupled Climate Scenario Experiments.” *Ocean Science* 9: 217–248.

Doscher, R., U. Willén, C. Jones, A. Rutgersson, H. E. M. Meier, U. Hansson, and L. P. Graham. 2002. “The Development of the Regional Coupled Ocean–Atmosphere Model RCAO.” *Boreal Environment Research* 7: 183–192.

Döscher, R., K. Wyser, H. E. M. Meier, M. Qian, and R. Redler. 2010. “Quantifying Arctic Contributions to Climate Predictability in a Regional Coupled Ocean-Ice-Atmosphere Model.” *Climate Dynamics* 34: 1157–1176.

Drobinski, P., A. Anav, C. L. Lebeaupin Brossier, G. Samson, M. Stéfanon, S. Bastin, M. Baklouti, et al. 2012. “Model of the Regional Coupled Earth System (MORCE). Application to Process and Climate Studies in Vulnerable Regions.” *Environmental Modelling & Software* 35: 1–18.

Dubois, C., S. Somot, S. Calmanti, A. Carillo, M. Déqué, A. Dell’Aquilla, and A. Elizalde. 2012. “Future Projections of the Surface Heat and Water Budgets of the Mediterranean Sea in an Ensemble of Coupled Atmosphere-Ocean Regional Climate Models.” *Climate Dynamics* 39: 1859–1884.

Elizalde, A., D. Sein, U. Mikolajewick, and D. Jacob. 2010. “Technical Report: Atmosphere–Ocean–Hydrology Coupled Regional Climate Model.” *Max Planck Institute for Meteorology* 51 pp.

Fang, Y. J., Y. C. Zhang, J. P. Tang, and X. J. Ren. 2009. A Regional Air–Sea Coupled Model and Its Application over East Asia in the Summer of 2000. *Advances in Atmospheric Sciences* 27: 583–593.

Giorgi, F. 1990. “Simulation of Regional Climate Using a Limited Area Model Nested in a General Circulation Model.” *Journal of Climate* 3: 941–963.

Giorgi, F. 1995. “Perspectives for Regional Earth System Modeling.” *Global and Planetary Change* 10: 23–42.

Giorgi, F., C. Jones, and G. R. Asrar. 2009. “Addressing Climate Information Needs at the Regional Level: The CORDEX Framework.” *World Meteorological Organization (WMO) Bulletin* 58: 175–183.

Giorgi, F., and G. T. Bates. 1989. “The Climatological Skill of a Regional Model over Complex Terrain.” *Monthly Weather Review* 117: 2325–2347.

Giorgi, F., and W. J. Gutowski. 2015. “Regional Dynamical Downscaling and the CORDEX Initiative.” *Annual Review of Environment and Resources* 40: 467–490.

Giorgi, F., X. Q. Bi, and Y. Qian. 2003. “Indirect versus Direct Effects of Anthropogenic Sulfate on the Climate of East Asia as Simulated with a Regional Coupled Climate–Chemistry/Aerosol Model.” *Climatic Change* 58: 345–376.

Gröger, M., C. Dieterich, M. H. E. Meier, and S. Schimanke. 2015. “Thermal Air-Sea Coupling in Hindcast Simulations for the North Sea and Baltic Sea on the NW European Shelf.” *Tellus a: Dynamic Meteorology and Oceanography* 67: 26911.

Gualdi, S., S. Somot, L. Li, V. Artale, M. Adani, A. Bellucci, A. Braun, et al. 2013. “The CIRCE Simulations: Regional Climate

Change Projections with Realistic Representation of the Mediterranean Sea." *Bulletin of the American Meteorological Society* 94: 65–81.

Gustafsson, N., L. Nyberg, and A. Omstedt. 1998. "Coupling of a High-Resolution Atmospheric Model and an Ocean Model for the Baltic Sea." *Monthly Weather Review* 126: 2822–2846.

Gutowski, W. J., F. Giorgi, B. Timbal, A. Frigon, D. Jacob, H. Kang, K. Raghavan, et al. 2016. "WCRP Coordinated Regional Downscaling EXperiment (CORDEX): a Diagnostic MIP for CMIP6." *Geoscientific Model Development* 9: 4087–4095.

Hagedorn, R., A. Lehmann, and D. Jacob. 2000. "A Coupled High Resolution Atmosphere-Ocean Model for the BALTEX Region." *Meteorologische Zeitschrift* 9: 7–20.

Han, Z. W., J. W. Li, W. D. Guo, Z. Xiong, and W. Zhang. 2013. "A Study of Dust Radiative Feedback on Dust Cycle and Meteorology over East Asia by a Coupled Regional Climate–Chemistry–Aerosol Model." *Atmospheric Environment* 68: 54–63.

Hostetler, S. W., G. T. Bates, and F. Giorgi. 1993. "Interactive Coupling of a Lake Thermal Model with a Regional Climate Model." *Journal of Geophysical Research: Atmospheres* 98: 5045–5057.

Ji, Z. M., G. L. Wang, J. S. Pal, and M. Yu. 2016a. "Potential Climate Effect of Mineral Aerosols over West Africa. Part I: Model Validation and Contemporary Climate Evaluation." *Climate Dynamics* 46: 1223–1239.

Ji, Z. M., S. C. Kang, D. F. Zhang, C. Z. Zhu, J. Wu, and Y. Xu. 2011. "Simulation of the Anthropogenic Aerosols over South Asia and Their Effects on Indian Summer Monsoon." *Climate Dynamics* 36: 1633–1647.

Ji, Z. M., S. C. Kang, Q. G. Zhang, Z. Y. Cong, P. F. Chen, and M. Sillanpää. 2016b. "Investigation of Mineral Aerosols Radiative Effects over High Mountain Asia in 1990–2009 Using a Regional Climate Model." *Atmospheric Research* 179: 484–496.

Ji, Z. M., S. C. Kang, Z. Y. Cong, Q. G. Zhang, and T. D. Yao. 2015. "Simulation of Carbonaceous Aerosols over the Third Pole and Adjacent Regions: Distribution, Transportation, Deposition, and Climatic Effects." *Climate Dynamics* 45: 2831–2846.

Jones, C., F. Giorgi, and G. Asrar. 2011. "The Coordinated Regional Downscaling Experiment: CORDEX–An International Downscaling Link to CMIP5." *CLIVAR Exchanges* 56: 34–40.

Kjellström, E., R. Döscher, and H. E. M. Meier. 2005. "Atmospheric Response to Different Sea Surface Temperatures in the Baltic Sea: Coupled versus Uncoupled Regional Climate Model Experiments." *Nordic Hydrology* 36: 612–623.

Koenigk, T., R. DöScher, and G. Nikulin. 2011. "Arctic Future Scenario Experiments with a Coupled Regional Climate Model." *Tellus a: Dynamic Meteorology and Oceanography* 63: 69–86.

Konare, A., A. S. Zakey, F. Solmon, F. Giorgi, S. Rauscher, S. Ibrah, and X. Q. Bi. 2008. "A Regional Climate Modeling Study of the Effect of Desert Dust on the West African Monsoon." *Journal of Geophysical Research* 113: 23.

Kotlarski, S., D. Jacob, R. Podzun, and F. Paul. 2010. "Representing Glaciers in a Regional Climate Model." *Climate Dynamics* 34: 27–46.

Krishna, K. K., M. Hoerling, and B. Rajagopalan. 2005. "Advancing Dynamical Prediction of Indian Monsoon Rainfall." *Geophysical Research Letters* 32: L0874.

Lebeaupin Brossier, C. L., S. Bastin, K. Béranger, and P. Drobinski. 2015. "Regional Mesoscale Air–Sea Coupling Impacts and Extreme Meteorological Events Role on the Mediterranean Sea Water Budget." *Climate Dynamics* 44: 1029–1051.

Lehmann, A., P. Lorenz, and D. Jacob. 2004. "Modeling the Exceptional Baltic Sea Inflow Events in 2002–2003." *Geophysical Research Letters* 31: L21308.

Li, H., M. Kanamitsu, S.-Y. Hong, K. Yoshimura, D. R. Cayan, and V. Misra. 2014a. "A High Resolution Ocean-Atmosphere Coupled Downscaling of the Present Climate over California." *Climate Dynamics* 42: 701–714.

Li, H., M. Kanamitsu, S.-Y. Hong, K. Yoshimura, D. R. Cayan, V. Misra, and L. Sun. 2014b. "Projected Climate Change Scenario over California by a Regional Ocean-Atmosphere Coupled Model System." *Climatic Change* 122: 413–425.

Li, S., T. J. Wang, B. L. Zhuang, and Y. Han. 2009. "Indirect Radiative Forcing and Climatic Effect of the Anthropogenic Nitrate Aerosol on Regional Climate of China." *Advances in Atmospheric Sciences* 26: 543–552.

Li, T., and G. Q. Zhou. 2010. "Preliminary Results of a Regional Air–Sea Coupled Model over East Asia." *Chinese Science Bulletin* 55: 2295–2305.

Lin, H. J., Y. F. Qian, and Y. C. Zhang. 2006. "A Regional Coupled Air-Ocean Wave Model and the Simulation of the South China Sea Summer Monsoon of 1998." *International Journal of Climatology* 6: 2041–2056.

Lorenz, P., and D. Jacob. 2014. "BALTIMOS–A Coupled Modeling System for the Baltic Sea and Its Drainage Basin." *Theoretical and Applied Climatology* 118: 715–727.

Martynov, A., L. Sushama, R. Laprise, K. Winger, and B. Dugas. 2012. "Interactive Lakes in the Canadian Regional Climate Model, Version 5: The Role of Lakes in the Regional Climate of North America." *Tellus a: Dynamic Meteorology and Oceanography* 64: 16226.

Meier, H. E. M. 2006. "Baltic Sea Climate in the Late Twenty-First Century: A Dynamical Downscaling Approach Using Two Global Models and Two Emission Scenarios." *Climate Dynamics* 27: 39–68.

Meier, H. E. M. 2015. "Projected Change-Marine Physics." Chapter 13 in *Baltic Sea Climate Change Assessment*. Berlin: Springer-Verlag.

Mikolajewicz, U., D. V. Sein, D. Jacob, T. Königk, R. Podzun, and T. Semmler. 2005. "Simulating Arctic Sea Ice Variability with a Coupled Regional Atmosphere-Ocean-Sea Ice Model." *Meteorologische Zeitschrift* 14: 793–800.

Mironov, D., E. Heise, E. Kourzeneva, B. Ritter, N. Schneider, and A. Terzhevik. 2010. "Implementation of the Lake Parameterisation Scheme FLake into the Numerical Weather Prediction Model COSMO." *Boreal Environment Research* 15: 218–230.

Nabat, P., S. Somot, M. Mallet, A. Sanchez-Lorenzo, and M. Wild. 2014. "Contribution of Anthropogenic Sulfate Aerosols to the Changing Euro-Mediterranean Climate since 1980." *Geophysical Research Letters* 41: 5605–5611.

Nabat, P., S. Somot, M. Mallet, F. Sevault, M. Chiacchio, and M. Wild. 2015. "Direct and Semi–Direct Aerosol Radiative Effect on the Mediterranean Climate Variability Using a Coupled Regional Climate System Model." *Climate Dynamics* 44: 1127–1155.

Notaro, M., K. Holman, A. Zarrin, E. Fluck, S. Vavrus, and V. Bennington. 2013. "Influence of the Laurentian Great Lakes on Regional Climate." *Journal of Climate* 26: 789–804.

Oleson, K. W., G. Y. Niu, Z. L. Yang, D. M. Lawrence, P. E. Thornton, P. J. Lawrence, R. Stöckli, et al. 2008. "Improvements to the Community Land Model and Their Impact on the Hydrological Cycle." *Journal of Geophysical Research: Biogeosciences* 113: G01021.

Peng, S. Q., D. L. Liu, Z. B. Sun, and Y. Li. 2012. "Recent Advances in Regional Air-Sea Coupled Models." *Science China Earth Sciences* 55: 1391–1405.

Van Pham, T., J. Brauch, C. Dieterich, B. Frueh, and B. Ahrens. 2014. "New Coupled-Atmosphere-Ocean-Ice System COSMO-CLM/NEMO: Assessing Air Temperature Sensitivity over the North and Baltic Seas." *Oceanologia* 56: 167–189.

Putrasahan, D., A. J. Miller, and H. Seo. 2013. "Regional Coupled Ocean–Atmosphere Downscaling in the Southeast Pacific: Impacts on Upwelling, Mesoscale Air–Sea Fluxes, and Ocean Eddies." *Ocean Dynamics* 63: 463–488.

Qian, Y., and F. Giorgi. 1999. "Interactive Coupling of Regional Climate and Sulfate Aerosol Models over Eastern Asia." *Journal of Geophysical Research: Atmospheres* 104: 6477–6499.

Qian, Y., F. Giorgi, Y. Huang, W. L. Chameides, and C. Luo. 2001. "Simulation of Anthropogenic Sulfur over East Asia with a Regional Coupled Chemistry–Climate Model." *Tellus B: Chemical and Physical Meteorology* 53: 171–191.

Qian, Y., L. R. Leung, S. J. Ghan, and F. Giorgi. 2003. "Regional Climate Effects of Aerosols over China: Modeling and Observation." *Tellus B* 55: 914–934.

Raschke, E., J. Meywerk, K. Warrach, U. Andrea, S. Bergström, F. Beyrich, F. Bosveld, et al. 2001. "The Baltic Sea Experiment (BALTEX): a European Contribution to the Investigation of the Energy and Water Cycle of a Large Drainage Basin." *Bulletin of the American Meteorological Society* 82: 2389–2413.

Ratnam, J. V., F. Giorgi, A. Kaginalkar, and S. Cozzini. 2009. "Simulation of the Indian Monsoon Using RegCM3–ROMS Regional Coupled Model." *Climate Dynamics* 33: 119–139.

Ratnam, J. V., Y. Morioka, S. K. Behera, and T. Yamagata. 2015. "A Model Study of Regional Air-Sea Interaction in the Austral Summer Precipitation over Southern Africa." *Journal of Geophysical Research - Atmospheres* 120: 2342–2357.

Ribeiro, F. N. D., J. Soares, and A. P. de Oliveira. 2011. "A Coupled Numerical Model to Investigate the Air-Sea Interaction at the Coastal Upwelling Area of Cabo Frio, Brazil." *Environmental Fluid Mechanics* 11: 651–668.

Rinke, A., K. Dethloff, J. J. Cassano, J. H. Christensen, J. A. Curry, P. Du, E. Girard, et al. 2006. "Evaluation of an Ensemble of Arctic Regional Climate Models: Spatiotemporal Fields during the SHEBA Year." *Climate Dynamics* 26: 459–472.

Rinke, A., R. Gerdes, K. Dethloff, T. Kandlbinder, M. Karcher, F. Kauker, S. Frickenhaus, C. Köberle, and W. Hiller. 2003. "A Case Study of the Anomalous Arctic Sea Ice Conditions during 1990: Insights from Coupled and Uncoupled Regional Climate Model Simulations." *Journal of Geophysical Research* 108: 4275.

Roberts, A., J. E. Walsh, L. Hinzman, R. Doescher, A. Sumi, M. Holland, J. Cassano, W. Maslowski, W. Gutowski, and J. Hel. 2008. "Towards a Community Arctic System Model." *Ice and Climate News* 10: 14–15.

Ruti, P., S. Somot, F. Giorgi, C. Dubois, E. Flaounas, A. Obermann, A. Dell'Aquila, et al. 2016. "Med-CORDEX Initiative for Mediterranean Climate Studies." *Bulletin of the American Meteorological Society* 97: 1187–1208.

Samala, B. K., C. Nagaraju, S. Banerjee, A. Kaginalkar, and M. Dalvi. 2013. "Study of the Indian Summer Monsoon Using WRF–ROMS Regional Coupled Model Simulations." *Atmospheric Science Letters* 14: 20–27.

Samson, G., S. Masson, M. Lengaigne, M. G. Keerthi, J. Vialard, S. Pous, G. Madec, et al. 2014. "The NOW Regional Coupled Model: Application to the Tropical Indian Ocean Climate and Tropical Cyclone Activity." *Journal of Advances in Modeling Earth Systems* 6: 700–722.

Schrum, C. 2017. "Regional Climate Modeling and Air-Sea Coupling." *In Oxford Research Encyclopedia of Climate Science*. doi:10.1093/acrefore/9780190228620.013.3.

Schrum, C., J. Lowe, H. E. M. Meier, I. Grabemann, J. Holt, M. Mathis, T. Pohlmann, M. D. Skogen, A. Sterl, and S. Wakelin. 2016. "Projected Change - North Sea." In *North Sea Regional Climate Change Assessment*, edited by M. Quante and F. Colijn, 175–217. Berlin: Springer-Verlag. doi: 10.1007/978-3-319-39745-0_6.

Schrum, C., U. Hubner, D. Jacob, and R. Podzun. 2003. "A Coupled Atmosphere-Ice-Ocean Model for the North Sea and the Baltic Sea." *Climate Dynamica* 21: 123–145.

Sein, D. V., U. Mikolajewicz, M. Gröger, I. Fast, W. Cabos, J. G. Pinto, S. Hagemann, T. Semmler, A. Izquierdo, and D. Jacob. 2015. "Regionally Coupled Atmosphere-Ocean, Sea Ice, Marine Biogeochemistry Model ROM. 1. Description and Validation." *Journal of Advances in Modeling Earth Systems* 7: 268–304.

Seo, H., A. J. Miller, and J. O. Roads. 2007. "The Scripps Coupled Ocean-Atmosphere Regional (SOARS) Model, with Applications in the Eastern Pacific Sector." *Journal of Climate* 20: 381–402.

Seo, H., R. Murtugudde, M. Jochum, and A. J. Miller. 2008. "Modeling of Mesoscale Coupled Ocean–Atmosphere Interaction and Its Feedback to Ocean in the Western Arabian Sea." *Ocean Modelling* 25: 120–131.

Seo, H., S. P. Xie, R. Murtugudde, M. Jochum, and A. J. Miller. 2009. "Seasonal Effects of Indian Ocean Freshwater Forcing in a Regional Climate Model." *Journal of Climate* 22: 6577–6596.

Sevault, F., S. Somot, A. Alias, C. Dubois, C. Lebeaupin-Brossier, P. Nabat, F. Adloff, M. Déqué, and B. Decharme. 2014. "A Fully Coupled Mediterranean Regional Climate System Model: Design and Evaluation of the Ocean Component for the 1980–2012 Period." *Tellus a: Dynamic Meteorology and Oceanography* 66: 23967.

Shalaby, A. K., A. S. Zakey, A. B. Tawfik, F. Solmon, F. Giorgi, F. Stordal, S. Sillman, R. A. Zaveri, and A. L. Steiner. 2012. "Implementation and Evaluation of Online Gas–Phase Chemistry within a Regional Climate Model (RegCM–CHEM4)." *Geoscientific Model Development* 5: 741–760.

Shi, Y., Y. Miao, E. Amir, and G. L. Wang. forthcoming. "Modeling the Dynamic Vegetation–Climate System over China Using a Coupled Regional Model." *Journal of Climate*.

Sitz, L. E., F. Sante, R. Farneti, R. Fuentes-Franco, E. Coppola, L. Mariotti, M. Reale, et al. 2017. "Description and Evaluation of the Earth System Regional Climate Model (RegCM–ES)." *Journal of Advances in Modeling Earth Systems*. doi:10.1002/2017MS000933.

Small, E. E., L. C. Sloan, S. Hostetler, and F. Giorgi. 1999. "Simulating the Water Balance of the Aral Sea with a Coupled Regional Climate–Lake Model." *Journal of Geophysical Research: Atmospheres* 104: 6583–6602.

Smith, B., P. Samuelsson, A. Wramneby, and M. Rummukainen. 2011. "A Model of the Coupled Dynamics of Climate, Vegetation and Terrestrial Ecosystem Biogeochemistry for Regional Applications." *Tellus a: Dynamic Meteorology and Oceanography* 63: 87–106.

Solmon, F., M. Mallet, N. Elguindi, F. Giorgi, A. Zakey, and A. Konaré. 2008. "Dust Aerosol Impact on Regional Precipitation over Western Africa, Mechanisms and Sensitivity to Absorption Properties." *Geophysical Research Letters* 35: L24705.

Somot, S., F. Sevault, M. Déqué, and M. Crépon. 2008. "21st Century Climate Change Scenario for the Mediterranean Using a Coupled Atmosphere–Ocean Regional Climate Model." *Global and Planetary Change* 63: 112–126.

Su, J., H. Yang, T. Pohlmann, A. Ganske, B. Klein, H. Klein, and N. Narayan. 2014. "A Regional Coupled Atmosphere-Ocean Model System REMO/HAMSOM for the North Sea." *KLIWAS Schriftenreihe* KLIWAS-60

Thiery, W., E. L. Davin, H. J. Panitz, M. Demuzere, S. Lhermitte, and N. van Lipzig. 2015. "The Impact of the African Great Lakes on the Regional Climate." *Journal of Climate* 28: 4061–4085.

Turuncoglu, U. U., G. Giuliani, N. Elguindi, and F. Giorgi. 2013. "Modeling the Caspian Sea and Its Catchment Area Using a Coupled Regional Atmosphere–Ocean Model (RegCM–ROMS): Model Design and Preliminary Results." *Geoscientific Model Development* 6: 283–299.

Wang, G., K. F. Ahmed, L. You, M. Yu, J. Pal, and Z. Ji. 2017. "Projecting Regional Climate and Cropland Changes Using a Linked Biogeophysical-Socioeconomic Modeling Framework: 1. Model Description and an Equilibrium Application over West Africa." *Journal of Advances in Modeling Earth Systems* 9: 354–376. doi:10.1002/2016MS000712.

Wang, S., C. Dieterich, R. Döscher, A. Höglund, R. Hordoir, H. E. M. Meier, P. Samuelsson, and S. Schimanke. 2015a. "Development and Evaluation of a New Regional Coupled Atmosphere-Ocean Model in the North Sea and Baltic Sea." *Tellus a: Dynamic Meteorology and Oceanography* 67: 24284.

Wang, T. J., B. L. Zhuang, S. Li, J. Liu, M. Xie, C. Q. Yin, Y. Zhang, et al. 2015b. "The Interactions between Anthropogenic Aerosols and the East Asian Summer Monsoon Using RegCCMS." *Journal of Geophysical Research: Atmospheres* 120: 5602–5621.

Wei, J., P. Malanotte-Rizzoli, E. A. B. Eltahir, P. Xue, and D. Xu. 2014. "Coupling of a Regional Atmospheric Model (RegCM3) and a Regional Ocean Model (FVCOM) over the Maritime Continent." *Climate Dynamics* 43: 1575–1594.

Yao, S., and Y. Zhang. 2009. "Simulation of China Summer Precipitation Using a Regional Air-Sea Coupled Model." *Acta Meteorologica Sinica* 24: 203–214.

Zanis, P., C. Ntogras, A. Zakey, I. Pytharoulis, and T. Karacostas. 2012. "Regional Climate Feedbacks of Anthropogenic Aerosols over Europe Using RegCM3." *Climate Research* 52: 267–278.

Zhang, D. F., A. Zakey, X. J. Gao, F. Giorgi, and F. Solmon. 2009. "Simulation of Dust Aerosol and Its Regional Feedbacks over East Asia Using a Regional Climate Model." *Atmospheric Chemistry and Physics* 9: 1095–1110.

Zhang, D. F., X. J. Gao, A. Zakey, and F. Giorgi. 2016. "Effects of Climate Changes on Dust Aerosol over East Asia from RegCM3." *Advances in Climate Change Research* 7 (3): 145–153.

Zhang, W. X., C. Jansson, P. A. Miller, B. Smith, and P. Samuelsson. 2014. "Biogeophysical Feedbacks Enhance the Arctic Terrestrial Carbon Sink in Regional Earth System Dynamics." *Biogeosciences* 11: 5503–5519.

Zou, L. W., and T. J. Zhou. 2012. "A Review of Development and Application of Regional Ocean–Atmosphere Coupled Model." *Advances in Earth Science* 27 (8): 857–865.

Zou, L. W., and T. J. Zhou. 2013. "Can a Regional Ocean–Atmosphere Coupled Model Improve the Simulation of the Interannual Variability of the Western North Pacific Summer Monsoon?" *Journal of Climate* 26: 2353–2367.

Zou, L. W., and T. J. Zhou. 2016. "A Regional Ocean–Atmosphere Coupled Model Developed for CORDEX East Asia: Assessment of Asian Summer Monsoon Simulation." *Climate Dynamics* 47: 3627–3640.