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COSTRICE – an atmosphere – ocean – sea ice model coupled system using OASIS3

(Institute for Coastal Research, Helmholtz-Zentrum Geesthacht, Geesthacht, Germany)

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26 Seiten mit 7 Abbildungen und 5 Tabellen

Abstract

The coupled system COSTRICE, which contains three component models of atmosphere, ocean and sea ice, was developed to reproduce the interactions and feedback among the atmosphere, ocean and sea ice using a two-way online coupled model system for regional climate simulations of Baltic Sea and North Sea regions. The regional climate model CCLM is coupled with the regional ocean model TRIMNP and the sea ice model CICE via the coupler OASIS3. In this study, CCLM is setup with a horizontal grid mesh size of 50 km and 32 vertical atmosphere layers and is driven by the 6-h ERA-interim re-analysis data as initial and boundary conditions. TRIMNP is constructed with a horizontal grid mesh size of 12.8 km and 50 vertical ocean levels. CICE calculates 5 categories of ice and operates with the same horizontal resolution as TRIMNP, but CICE only simulates the Baltic Sea and Kattegat, a part of the North Sea. In a two-way online coupling process, CCLM is linked to TRIMNP by sea surface temperature (SST) as a lower boundary condition while TRIMNP and CICE are driven by atmospheric state variables and fluxes of CCLM. The coupled system is designed to run in parallel on the supercomputing system IBM-power 6 at the German Climate Computing Centre (DKRZ).

Keyword: coupling, OASIS3, atmosphere, ocean, sea ice, Baltic Sea, North Sea

COSTRICE – Ein gekoppeltes Modell-System für Atmosphäre, Ozean und Meereis unter Verwendung von OASIS3

Zusammenfassung

Das gekoppelte System COSTRICE, bestehend aus drei Modellkomponenten für Atmosphäre, Ozean und Meereis, wurde entwickelt, um die Wechselwirkungen und Rückkopplungen zwischen Atmosphäre, Ozean und Meereis zu reproduzieren. Dieses ist ein gekoppeltes Zwei-Wege Modellsystem, das das regionale Klima über den Gebieten von Ost-und Nordsee simulieren kann. Hierin ist das regionale Klimamodell CCLM mit dem regionalen Ozeanmodell TRIMNP und dem Meereismodell CICE mittels des OASIS3-Kopplers gekoppelt. In der vorliegenden Studie wird das CCLM mit einer horizontalen Gitterauflösung von 50 km und 32 vertikalen atmosphärischen Schichten betrieben. Anfangsbedingungen und der laterale Antrieb am Rand des regionalen Modellgebietes werden den sechsstündigen ERA-Interim-Renalyse-Daten entnommen. TRIMNP nutzt eine horizontale Gitterauflösung von 12,8 km und 50 vertikale Ozeanschichten. CICE berechnet fünf Eiskategorien und arbeitet mit der gleichen horizontalen Auflösung wie TRIMNP, allerdings ist die CICE-Simulation auf die Ostsee und den Kattegat, einem Teil der Nordsee, beschränkt. In dem Zwei-Wege-Kopplungsprozess stellt TRIMNP die Meeresoberflächentemperatur als untere Randbedingung für CCLM zur Verfügung, während TRIMNP und CICE durch in CCLM simulierte atmosphärische Zustandsvariablen und Flüsse angetrieben werden. Das gekoppelte System wurde technisch so konstruiert, dass es parallelisiert auf dem IBM-Power 6 Supercomputer des deutschen Klimarechenzentrums (DKRZ) betrieben werden kann.

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1 Introduction

This paper introduces the initial development of a two-way online coupled system from three models of atmosphere, ocean and sea ice (CCLM, TRIMNP and CICE, respectively) using the coupler OASIS version 3 (Fig. 1) for regional climate simulations. This study provides an overview of the coupling mechanism in terms of online (i.e., all three component models run concurrently) and two-way interactions and feedback (i.e., each pair exchanges data at every coupling time step). Subsequent to the coupling mechanism, source codes of component models are adapted accordingly, and libraries of the coupler OASIS3 are used to link the three models.

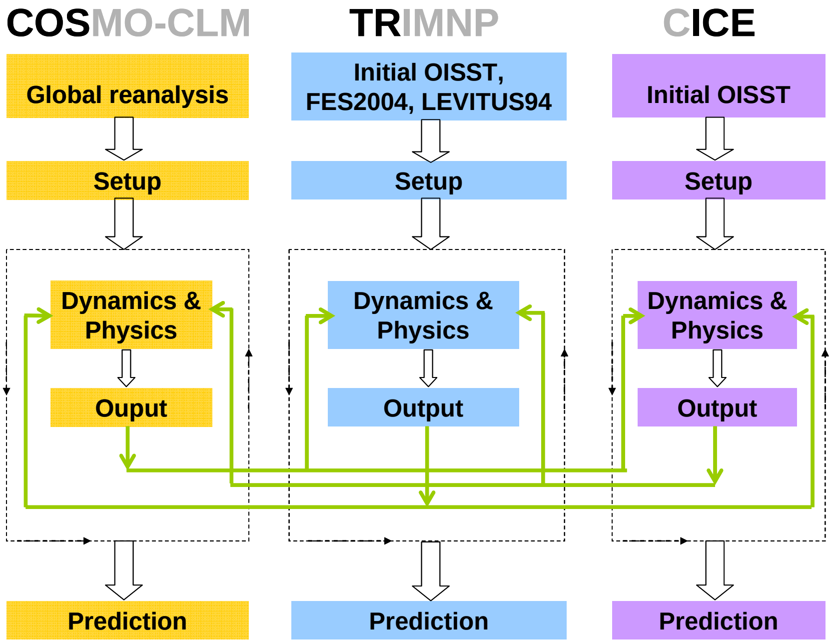

Figure 1. Schematic of the coupled system COSTRICE. Dashed boxes describe time loops in each component model. OASIS3 couples component models via green routes.

Air–sea interactions over the North Atlantic and Pacific Oceans are investigated by Zhang (1996) using observed data. The study demonstrated that the dominant process of air–sea interactions for both oceans during the winter is the atmospheric forcing of the ocean through modulation of the latent and sensible heat fluxes. Kirtman and Vecchi (2011) also indicated that SST anomalies can induce anomalous convection through surface evaporation and low-level moisture convergence. The anomalous atmospheric convection can modify the SST through cloud-radiation and wind-evaporation effects as well as through wind-induced oceanic mixing and upwelling. As air–sea interactions are critical in maintaining the entire climate system in equilibrium, it is necessary to consider air–sea interactions in a climate model or to couple different numerical component models in one model system.

Coupling is frequently applied in climate modelling research. The components of coupling include the atmosphere, ocean, sea ice, soil, chemistry, waves, etc. Numerous studies on coupled climate models exist on a global scale (e.g., Manabe and Bryan, 1969, 1979; Taylor et al., 2009, 2012) or for limited areas on a regional scale (e.g., Gustafsson et al., 1998; Artale et al., 2009; Elizalde and Jacob, 2012). Coupling in the Baltic region is presented in Gustafsson et al. (1998), Hagedorn et al. (2000), Omstedt and Rutgersson (2000), Jacob et al. (2001), Schrum et al. (2001, 2003), Döscher et al. (2002), Meier et al. (2002, 2003, 2004), Lehmann et al. (2004), and Bennartz et al. (2009). These studies focused on this region as the Baltic Sea area is subject to global influences, whereas the climate of the Baltic Sea basin comprises a mixture of continental and maritime climates due to its geographical location, variable orography, and land-sea contrasts (HELCOM, 2007). Gustafsson et al. (1998) provided specific examples of “changing ice boundaries” in the winter and “changing SSTs” in the summer for the Baltic catchment from 1993–1995 to prove that coupling is necessary for numerical weather predictions and climate simulations for this region, as the interactions and feedback among climate components might produce errors in the entire system if a component is represented unrealistically. Several studies have also focused on the North Sea (e.g., Rodenhuis, 1978, and Pohlmann, 1996), which is often considered with the Baltic Sea (Woth et al., 2006; Schrum et al., 2003).

Coupling may be accomplished in two different strategies, offline and online. A simple offline coupling involves running the atmospheric model for a month and using the output as the input for the ocean model. The ocean model provides the SST to run the atmospheric model again for that month. However, this method consumes a substantial amount of computing time and only demonstrates how well the ocean model reproduces SST and how the SST influences the results of the atmospheric model. Another similar coupling involves running the atmospheric model for one day and transferring the output to the ocean model, which runs and returns the SST to the atmospheric model at the end of the day to simulate the next day (Tian et al., 2013). In this case, two models do not run concurrently, the SST is updated once per day in the atmospheric model. The online coupling is defined as a process in which two or more models run concurrently and exchange data to take interactions and feedback into account. Our study focuses on this process.

The online coupling may operate by source code combination or by an alternate method of data transfer. The former method requires software interfaces (e.g., Gustafsson et al., 1998). The latter method only requires an exchange of the data; thus, it is more flexible and source code changes are not required. However, prior to the popularity of coupler programs, data were transferred via files (e.g., Schrum et al., 2003). This process typically requires a vast amount of storage and substantial computing time. By using a coupler such as OASIS, the complex technical problems produced by an all-in-one code are prevented (Döscher et al., 2002). The coupler facilitates the direct exchange of data directly among component models and performs the required interpolation among different model grids. If component models possess the same grid, data are passed directly from the source grid to the target grid. The advantage of using a coupler is evident when more than two models are coupled together. In our case, sea ice is created in the Baltic Sea during winter; however, the chosen ocean model does not consider sea ice calculations. Hence, a sea ice model has to be coupled to the RCM system in addition to the atmosphere and ocean models. Additionally, an individual sea ice model coupled in the system might reproduce ice formation, retreat and shifting more adequately than a simple sea ice parameterisation scheme, which is often employed in ocean models.

Sect. 2 describes invidually three model components of COSTRICE. Sect. 3 demonstrates how the model components coupled together via OASIS3. Experiment settings for a case study and intial simulation results are discussed in Sect. 4. Some conclusions and suggestions are presented in Sect. 5.

2 Components of COSTRICE

+ Atmosphere model:

The atmospheric model used in the current study is the non-hydrostatic regional climate model CCLM (Consortium for Small-scale Modeling in CLimate Mode, Rockel et al., 2008) version cosmo 4.8 clm11, which was developed by COSMO (http://www.cosmo-model.org) and the CLM-community (http://www.clm-community.eu). CCLM is based on the primitive thermo-hydrodynamical equations that describe compressible flow in a moist atmosphere. The model equations are formulated in rotated geographical coordinates and a generalised terrain following height coordinate. A variety of physical processes (e.g., vertical radiation fluxes, vertical turbulent mixing, and moisture convection) are considered by parameterisation schemes. In a case study using COSTRICE, CCLM is driven by lateral boundary conditions from 6-h ERA-interim reanalysis data (Dee et al., 2011) using the Davies relaxation scheme (Davies, 1976). However, in an uncoupled simulation for 1948-2010, CCLM is driven by 6-h NCEP reanalysis data (Kalnay et al., 1996). Source code of CCLM is written in FORTRAN90 and employs a standard MPI library for parallel runs. A list of published papers using CCLM is available on the web page of the CLM-community.

+ Ocean model:

The ocean model TRIMNP used for the coupled system is the "nested and parallel" version of the non-hydrostatic regional ocean model which was developed at Helmholtz-Zentrum Geesthacht, Germany. It is based on the Tidal Residual and Intertidal Mudflat Simulations in 3 Dimensions (TRIM3D) model of the University of Trento, Italy (Casulli and Cattani, 1994). TRIMNP is based on the 3-D Navier-Stokes equations with switchable baroclinic terms and non-hydrostatic terms. TRIMNP is formulated on a Cartesian Arakawa-C grid using vertical z-coordinates without constraints on top layer thickness. A domain decomposition with explicit message passing is considered using the MPI-Library. The vertical turbulent mixing is parameterised on the basis of the General Ocean Turbulence Model (GOTM) (http://www.gotm.net). More details on TRIMNP can be found in Kapitza (2008) and Kapitza and Eppel (2000). In this study, the surface boundary conditions (e.g., pressure, wind, and temperature) are obtained from a CCLM simulation every hour. The boundary conditions of water temperature, salinity, currents, etc. for ocean layers are obtained from the results of FES2004, which is the latest version of the finite element solution (FES) global tide model that utilises tidal hydrodynamic equations and data assimilation (Lyard et al, 2006; Lefevre et al., 2002), and from the LEVITUS94 Ocean Climatology data (http://iridl.ldeo.columbia.edu/SOURCES/.LEVITUS94). The lateral boundary treatment for TRIMNP is based on the nudging technique by Davies (1973).

+ Sea ice model:

CICE is the Los Alamos sea ice model version 4.1 from Los Alamos National Laboratory in the USA (http://oceans11.lanl.gov/trac/CICE). Although CICE is designed as the sea ice component of global climate models, it can also be employed for regional sea ice simulations in standalone mode. It is a thermodynamic model that computes local growth rates of snow and ice, due to vertical conductive, radiative, and turbulent fluxes, along with snowfall. It also includes a model of ice dynamics, which predicts the velocity field of the ice pack based on a model of the material strength of the ice, a transport model, which describes advection of the areal concentration, ice volumes and other state variables, and a ridging parameterisation that transfers ice among thickness categories based on energetic balances and rates of strain (Hunke and Lipscomb, 2008).

In this study, CICE is designed for sea ice simulations of the North Sea and the Baltic Sea. However, the current version of CICE does not consider leap years and only considers years with 360 or 365 days. When CICE was initially coupled to CCLM and TRIMNP in COSTRICE, an inconsistency in model time among the three models was produced: for a leap year simulation, the model time of CICE is shifted one day at the end of the year. Therefore, CICE could not restart correctly on the first day of the next year as CCLM and TRIMNP. To resolve this problem, a modified code was supplemented with a routine of CICE4.1.

+ Coupler:

The three models are coupled through the coupler OASIS3 model (The Ocean Atmosphere Sea Ice Soil model version 3) of CERFACS in France (http://oasis.enes.org), which is currently used by approximately 30 climate modelling groups in Europe, the USA, Canada, Australia, India and Brazil. OASIS3 is a portable set of Fortran 77, Fortran 90 and C routines and only supports 2-D coupling fields (Valcke, 2006, 2013). In our study, OASIS3 is compiled and run on IBM Power6 at DKRZ. The main task of OASIS3 is to interpolate the fields from a source grid to a target grid, which usually exhibit different resolutions and provides a mechanism for data transfer between models while they are running concurrently.

Various interpolation methods are available in OASIS3, which are offered by the Los Alamos National Laboratory SCRIP 1.4 library (http://gcmd.nasa.gov/records/LANL-SCRIP.html).

3 Coupling of three component models via OASIS3

This section details the technical coupling of the three component models via the coupler OASIS3. The advantages of the coupler OASIS is that the three component models maintain their own executables and OASIS3 acts as an additional executable and as a communication library, the PSMILe, that is linked to the models. Using OASIS, the complex technical problems generated from an all-in-one code are prevented (Döscher et al., 2002). Previous research has applied OASIS for coupling an atmospheric model to an ocean model that already includes already a sea ice scheme. In this study, we introduce a detailed technique and provide some useful tips for coupling three components in one system.

First, OASIS3 has to be downloaded and compiled on a computer system to link to the PSMILe library. Second, a few specific PSMILe calls need to be included in all component models to enable communications between a model component with OASIS3 or directly with other models. To accomplish this step, several changes are made in the source code of component models (example in Table B1). In this example, which shows a subset of exchange variables, the sending fields of CCLM are the mean sea level pressure (PMSLCCLM), the total precipitation (PRECCCLM), the rain rate (RAINCCLM) and the snow rate (SNOWCCLM), whereas the received field consists of only the surface temperature (T_S_CCLM). Note the following details: (i) in this initial study, CCLM is linked to TRIMNP by SST as a lower boundary condition for ice-free conditions, and is linked to CICE by the sea ice skin temperature. Where sea ice exists, the albedo parameterisation in CCLM switches from ocean to sea ice. However, partial sea ice cover, snow on sea ice and water on sea ice are not currently considered in CCLM, they, however, are items for future refinement of the model system; (ii) both individual models, TRIMNP and CICE, are driven by the atmospheric state variables (near-surface pressure, wind, temperature, humidity, air density, and cloud fraction), the lowest atmospheric level height, and fluxes (precipitation, snow, short and long wave radiation, and heat) of the CCLM; and (iii) CICE requires the SST, salinity, currents, ocean surface slope, and freezing/melting potential energy from TRIMNP and returns to

TRIMNP the water and ice temperature, ice concentration, fresh water flux, ice to ocean heat flux, short wave flux through ice to ocean, and ice stress components. A schematic diagram showing the data exchange is displayed in Fig. 3. In this study, the output of CCLM is passed to TRIMNP every hour and other exchange processes operate with an interval of 3 h (TRIMNP to CCLM, CCLM exchanges with CICE, and TRIMNP exchanges with CICE).

The names of variables defined in the source codes of the component models should correspond to the name list file of OASIS3, which is named “namcouple”. Figure 4 shows an example of the variable names that are defined and then announced by the “prism def var proto” call of OASIS3 in the source code of the three models (see Table B1). Another routine of OASIS3, “prism def partition proto”, is used by each process to describe the partition corresponding to the coupling field that will be sent or received by the process. In our construction of COSTRICE, only the master process will send/receive the field; thus, only the master process calls “prism def partition proto” to describe a partition covering the entire grid.

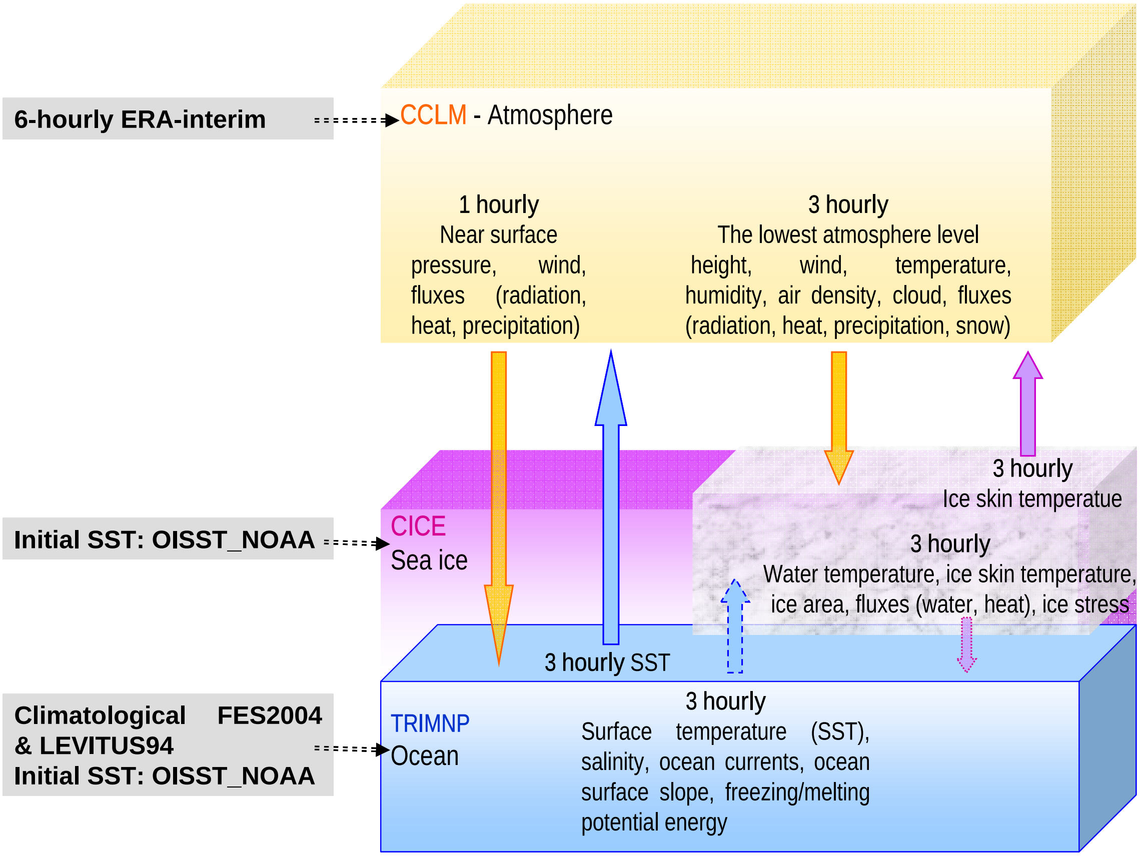

Figure 3. A schematic diagram for two-way regional model coupling.

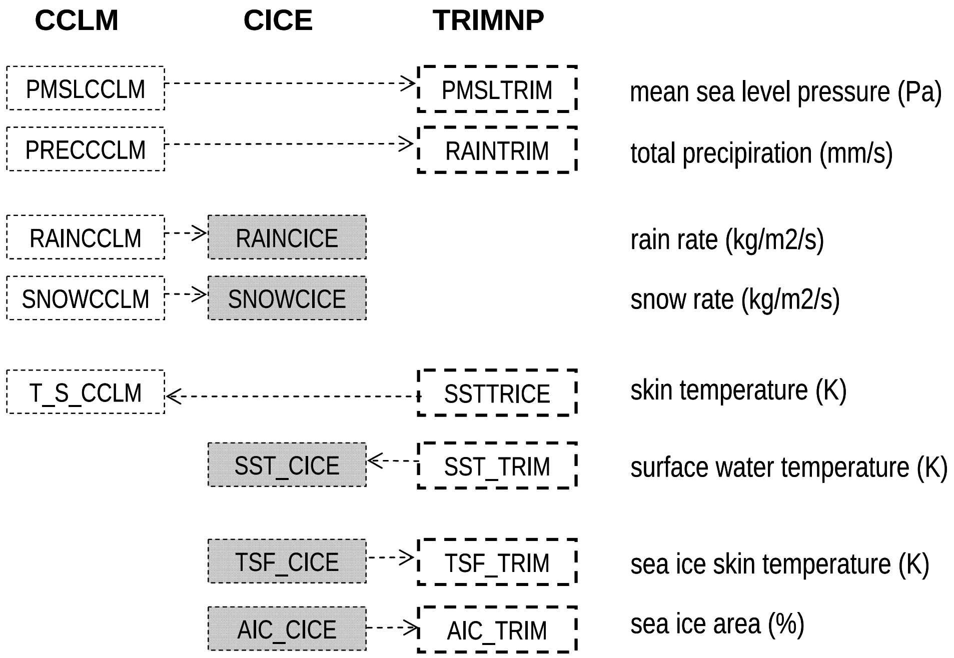

Figure 4: An example of name of variables defined in the three models. Arrows display the direction of sending.

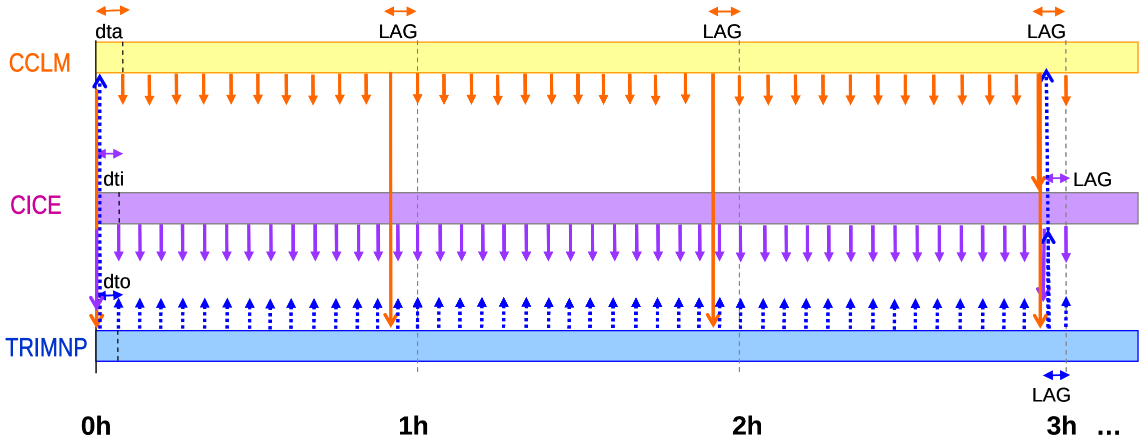

Figure 5. A schematic diagram for the online coupling process among the three component models, where dta, dti, and dto are running time steps of CCLM, CICE and TRIMNP, respectively. The coupling time step of CCLM to TRIMNP is 1 h. Other coupling time steps are 3 h. LAG is the lagged time prior to each coupling time step.

The next step is to choose the coupling parameters, such as source and target grids, coupling frequency, and field interpolation that are described in the file “namcouple” of OASIS3.

Examples of the file “namcouple” are shown in Tables C1 and C2 and by Valcke (2006, 2013). The interpolation method employed in this study is the N-nearest-neighbour distance-weighted interpolation (DISTWGT), which is required for the local multiple rotated coordinates of TRIMNP.

Among the three component models, the temporal coupling algorithm controlled by OASIS3 is displayed in Fig. 5. The running time steps of CCLM (dta), CICE (dti) and TRIMNP (dto) are 300 s, 240 s, and 240 s, respectively, and the coupling time step of CCLM to TRIMNP is 1 h whereas other coupling time steps are 3 h. At every running time step, each model sends the required exchange variables to OASIS3. However, OASIS only sends data to the respective receiving model at the coupling timestep of each model. If LAG is set to 0, data are derived exactly at the coupling time step. To prevent deadlock situations, the sequence index must be defined for each of the coupled fields corresponding to the given order. For example, first, the state variables and fluxes from CCLM were sent to TRIMNP (SEQ = 1); next, the SST and the salinity of TRIMNP were passed to CICE (SEQ = 2); and, last, sea ice skin and water temperature of CICE were passed to TRIMNP (SEQ = 3). Unfortunately, this initial set-up of our coupled system created deadlocks after running 3 h as all three models simultaneously sent and required data, which resulted in a loop of waiting. To prevent this deadlock, the three models are set to run simultaneously (SEQ = 1 for all exchanged fields) and LAG is set to the running time step (in seconds) of the component model that sends the data. Consequently, the sending time is one running time step earlier than the receiving time step, and no model has to wait in the loop as it already receives data from the previous step from the sending model to calculate the current step. However, due to the LAG, OASIS reads data from the restart files at the first running step and sends data to all three models.

Data sent at the coupling time consist of instantaneous, averaged or accumulated values since the last coupling time is dependent on the status of the variables. For example, rain and snow rates or heat fluxes are averaged for the period between the last and the current coupling time as they alter significantly over timesteps, total precipitation is passed instantaneously as it is already accumulated hourly in CCLM, and wind components are passed instantaneously as alternating changes in wind direction during one coupling time step might obscure actual wind speed values if wind components are averaged. At the end of each month, data are written in the restart file to initiate the coupling for the next month.

At the beginning of the coupling process (January 1, 1997 in this case study), the atmospheric forcings are passed from CCLM to TRIMNP and CICE, but the SST of TRIMNP is initialised from the uncoupled TRIMNP simulation. For this reason, the SST is too cold due to the direct influence of the cold air temperature above (due to the lack of a sea ice scheme in TRIMNP); thus, the sea ice concentration that formed based on the surface temperature of Bothnian Bay of TRIMNP is overestimated. Additionally, the skin temperature in CICE is set to $-1.8\ ^\circ$C everywhere over the sea ice. To prevent incorrect feedback to the atmospheric model, these unrealistic phenomena should not be considered. For this reason, the first simulation month (January 1997) is considered as an adjustment time for the upper ocean conditions in the ocean model prior to the beginning of the two-way coupling. From the second month onward, CCLM receives SST from TRIMNP. In principle, the ocean model requires a longer spin-up time as it is initialised with climatological data. As the Baltic Sea has a response time scale of 30 yrs (Meier et al., 2006), we will analyse the spin-up behaviour in further detail for the longer runs and select the spin-up time accordingly.

Instead of only SST (as in TRIMNP without sea ice), the feedback mechanism from ocean and sea ice to atmosphere is transferred by the combination of the sea water temperature T_{Oce} from TRIMNP and the sea ice skin temperature T_{Ice} from CICE, which is weighted by the sea ice area A_{Ice} . The basic equation employed here is the Stefan- Boltzmann Law

$$HFL = \varepsilon\sigma TS^4 \tag{1}$$

where TS is the skin temperature sent to CCLM at a grid point, and HFL is the heat flux from surface to atmosphere in the grid box. TS can be formulated from Eq. (1) as follows:

$$TS = \sqrt[4]{\frac{HFL}{\varepsilon\sigma}} \tag{2}$$

As in winter, both ice and sea water exist in the grid box, and the heat flux is calculated as:

$$HFL = \varepsilon\sigma T_{Ice}^4 \times A_{Ice} + \varepsilon\sigma T_{Oce}^4 \times (1 - A_{Ice}) \tag{3}$$

where T_{Ice} is the sea ice skin temperature, A_{Ice} is the sea ice area, and T_{Oce} is the sea water temperature. Note that the existence of sea ice in the grid box also affects the surface albedo, which is important for the calculation of surface radiation fluxes in the atmospheric model. Presently, the CCLM does not include a tile approach and does not consider partial sea ice in an atmospheric grid box. Additionally, when the COSTRICE was designed, CCLM only included a constant albedo of 70 % for sea ice. In the new CCLM version, a temperature-dependent sea ice albedo is implemented, which should be considered for long-term simulations of COSTRICE.

4 Experiment settings and initial simulations

The coupled system is applied in a technical test case study for climate simulations of the Baltic Sea and North Sea regions for 1997-2002. Table 1 presents the specifications of the three models. The considered domain is presented in Fig. 2.

Table 1. The configuration of the three component models

	CCLM	**TRIMNP**	**CICE**
Horizontal resolution	0.44^0 x 0.44^0	12.8 km	12.8 km
Vertical resolution	32 layers	50 layers	5 ice-categories
Domain (grid points)	126 x 123	200 x 230	120 x 120
Running time step	300 s	240 s	240 s
Computing resource	9 x 9 = 81 tasks	7 x 14 = 98 tasks	6 x 2 = 12 tasks
Boundary conditions	+ 6 hourly ERA-interim; + 3 hourly SST from TRIMNP (ERA-interim for none matching areas between the two domains); + 3 hourly sea ice skin temperature from CICE	+ 1 hourly data from CCLM; + 3 hourly data from CICE; + climatological data from FES2004 and LEVITUS94; + initial SST from NOAA	+ 3 hourly data from CCLM and TRIMNP; + open lateral boundary + initial SST from NOAA

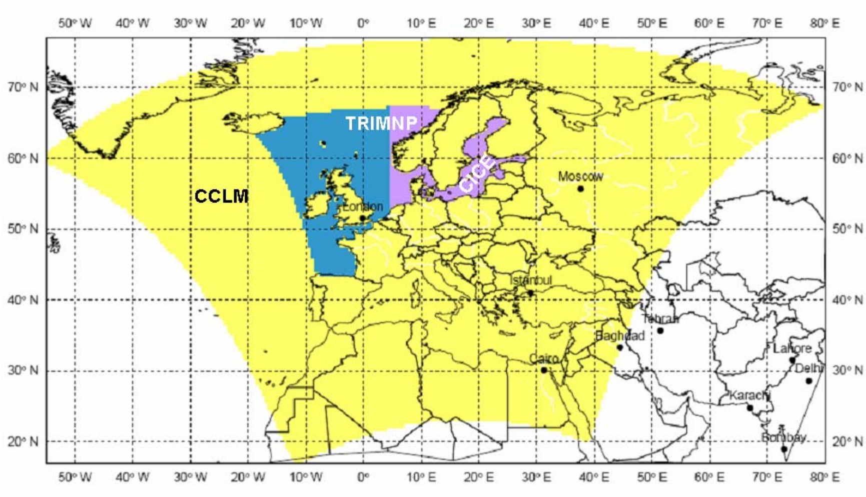

Figure 2. Domains for the atmosphere (CCLM), ocean (TRIMNP) and sea ice (CICE) models.

The atmospheric model CCLM has a horizontal grid mesh size of 50 km and 32 vertical hybrid levels and is driven by the 6-h ERA-interim re-analysis data as initial and lateral boundary conditions using the Davies relaxation scheme (Davies, 1976). The running time step of CCLM is 300 s and the domain of CCLM encompasses all of Europe. The ocean model TRIMNP is designed with a horizontal grid mesh size of 12.8 km and 50 vertical layers to simulate the Baltic Sea and the North Sea. The sea ice model CICE operates with the same horizontal resolution as TRIMNP but covers only Baltic Sea and Kattegat, which is part of the North Sea. Therefore, CICE is applied only to areas that may be covered by sea ice in winter. A time step of 240 s is employed for TRIMNP and CICE. For none matching areas between the two domains of CCLM and TRIMNP, the ERA-interim reanalysis SST is used.

To see impacts of coupling on simulated climate of the Baltic and North Sea regions, two experiments are set up: CPERAi is a coupled run of COSTRICE and STERAi is a standalone run of TRIMNP. In STERAi, atmosphere state variables and fluxes are obtained from a simulation, in which CCLM was forced by ERA-interim SST, and are subsequently provided to TRIMNP. In turn, TRIMNP calculates SSTs without a sea ice scheme and does not pass them to CCLM. CPERAi is a coupled run in which all fluxes, including heat fluxes, are passed from CCLM to TRIMNP and CICE via OASIS3. Exceptionally, longwave upward radiation flux is calculated by TRIMNP based on SSTs. This method was applied in Döscher et al.

(2002) in which the fluxes are calculated within the atmosphere on an atmospheric grid (44 km), which is coarser than the ocean grid (11.1 km), to neglect the sub-atmosphere-grid scale variability of the sea surface. This method is necessary for COSTRICE as the ocean model TRIMNP does not consider sea ice, therefore if fluxes are calculated in TRIMNP instead of passed from CCLM to CICE, they will be incorrect, especially for surface short wave radiation and downward long wave radiation in winter due to the sea ice albedo. In CPERAi, the SST provided to CCLM for the coupled area is a combination of surface water temperatures from TRIMNP and sea ice skin temperatures from CICE.

COSTRICE is designed to operate in parallel on the supercomputing system IBM-power 6 at DKRZ. In this study, we used 3 nodes with 64 tasks per node to run the entire system, in which CCLM, TRIMNP, CICE and OASIS run on 81, 98, 12 and 1 tasks, respectively (see Table 1). The distribution of tasks will vary when CCLM runs with a higher resolution. For an initial evaluation of the capability of COSTRICE, simulations of the case study are compared with the SST and sea ice concentration data sets from the daily high-resolution (1/4◦ ×1/4◦) data from the NOAA Optimum Interpolation Sea Sur face Temperature (OISST) version (http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.OISST/.version2/.AVHRR/).

As an example of the proficiency of the coupled system, Fig. 6 presents the daily area averaged SST of NOAA OISST data and of TRIMNP in the uncoupled STERAi run (using ERA-interim data) and in the coupled CPERAi run from 1998 to 2002. In general, COSTRICE has capability to reproduce SST and sea-ice over the North- and Baltic. In this example, over the Baltic Proper, a sea ice free area, the uncoupled version of TRIMNP tends to overestimate OISST in the summer months and to underestimate in the remaining months of the year, while the SST of CPERAi approximates better the OISST of NOAA data. Over the Bothnian Bay, where is often covered by sea ice in winter, sea ice concentration of NOAA data is reproduced better in CPERAi than in STERAi. Note that TRIMNP doesn't have a sea ice module, sea ice concentration is defined based on the SSTs and freezing threshold temperature of -1^{o}C.

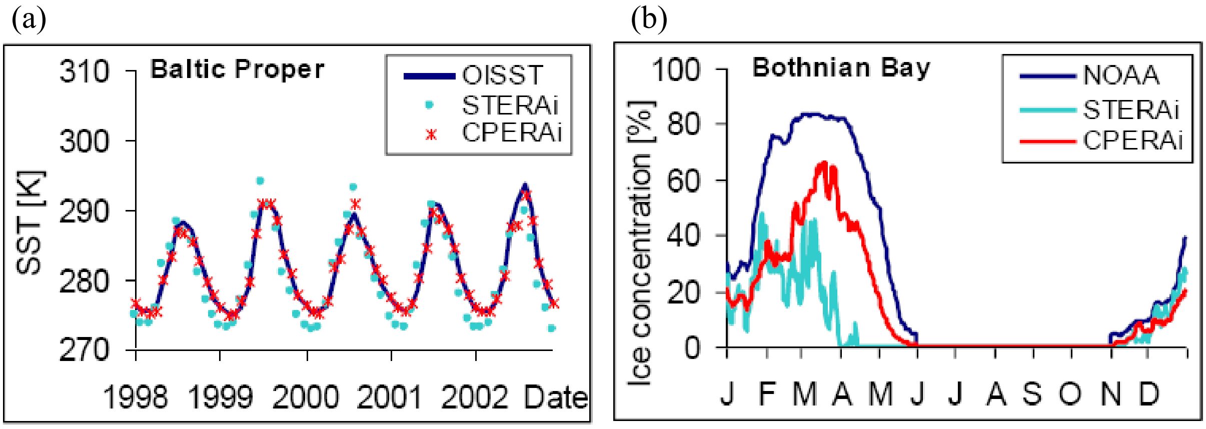

Figure 6. The daily SST (K) of OISST, STERAi and CPERAi for the time period of 1998-2002, averaged over the Baltic Proper (a) and the Bothnian Bay (b).

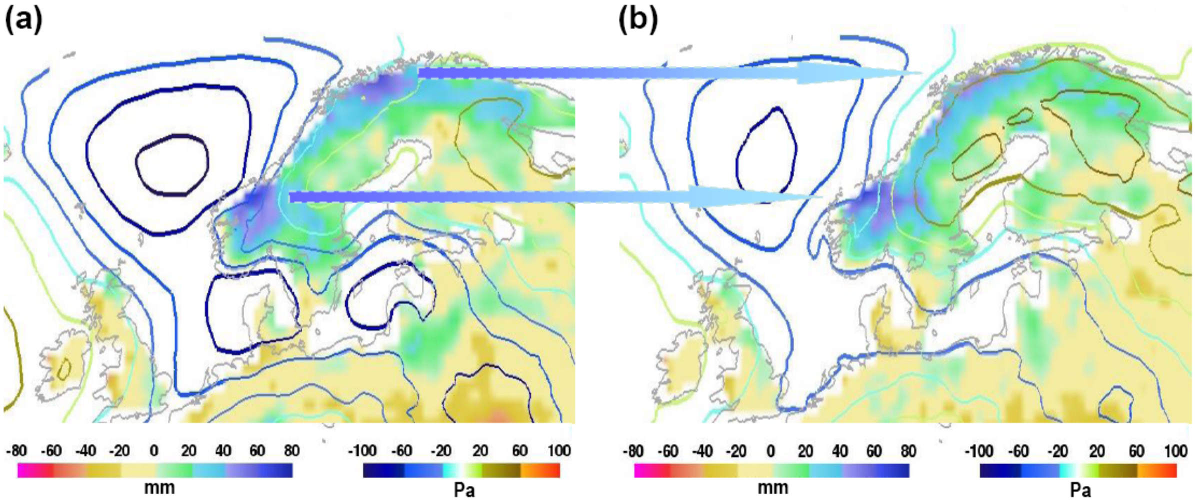

Figure 7. Differences of MSLP [Pa] from ERA-interim (contours) and precipitation [mm/month] from WATCH data (shaded) of STERAi (a) and CPERAi (b) for JJA 1998-2002.

Similar to the standalone run of CCLM (STERAi), COSTRICE captures well the NAO-like pattern when comparing the simulated mean sea level pressure (MSLP) to ERA-interim data (not shown here). However, STERAi has negative MSLP biases over North Atlantic Ocean, the North- and Baltic Seas (Fig. 7a), which may causes strong wet biases over Scandinavia, due to the relationship between NAO and rainfall over Europe. Figure 7 presents difference of MSLP from ERA-interim and the difference of precipitation from WATCH data (Weedon et al, 2011) for JJA 1998-2002 of STERAi and CPERAi. The negative MSLP biases of the uncoupled CCLM are reduced by COSTRICE (Fig. 7b). Consequently, COSTRICE has reduced precipitation biases over Baltic catchment areas. However, a robust conclusion may be attained after a long-term run of CPERAi is conducted in the future.

5 Conclusions and outlook

This paper introduces the two-way online coupled system COSTRICE, which comprises three model components: the atmospheric RCM CCLM, the ocean model TRIMNP and the sea ice model CICE. COSTRICE is designed to run in parallel on the supercomputing system IBM-power 6 of DKRZ. Using the coupler OASIS3, minor changes to the original source code of the component models were primarily limited to a few additional calls regarding the library of OASIS3. The coupled system was designed to run an experiment (CPERAi) for a test case study for 1997-2002. In general, compared to the standalone version of TRIMNP, CPERAi improves the SST of the ice-free area and sea ice concentrations over sea ice areas. Due to the interactions and feedback of atmosphere, ocean and sea ice represented in the coupled system, CPERAi reduces the negative MSLP bias over North Atlantic Ocean, the North- and Baltic Seas of the standalone run of CCLM, therefore, reduces the precipitation biases over Baltic catchment areas. A more robust conclusion might be attained after results from future long-term runs of CPERAi are available.

Additional sensitivity tests need to be conducted are the tests of coupling time steps and the spin-up time for the ocean model, and the adjustment time for the coupled system. Moreover, in our study, the feedback of the ocean to the atmosphere is taken into account via SST but the exchange of momentum between the atmosphere and the ocean is critical in determining climate (e.g., Gill, 1982). The wind-dependent roughness of the surface directly influences the air–sea fluxes of all other quantities (e.g., sensible and latent heat, water, and gases) (Rothrock et al., 1999). In the future, the momentum exchange should be included in the system.

Another component currently missing is a hydrological discharge (HD) model. In this study, TRIMNP uses measured freshwater inflows. However, for climate projections in future studies, a HD model is required to provide freshwater information to TRIMNP. As reported in HELCOM (2007), the external water budget of the Baltic Sea is dominated by water imports from riverine discharges, inflowing North Sea water, and net precipitation (precipitation minus evaporation) and export by Baltic Sea water outflows into the North Sea. Regionally, the Nordic part of the Baltic drainage basin has exhibited an increasing trend in runoff during winter (December–February) and spring (March–May) from 1921–2004; thus, variable runoff conditions should be considered in climate simulations, especially as the large amount of freshwater inflow into the Baltic Sea controls the low salinity of the Baltic Sea surface water, which strongly effects the freezing potential capacity of water in this region. Therefore, it is strongly recommended that a HD model is included in the future versions of the coupled system COSTRICE. It is planned that COSTRICE will be upgraded to the next generation using the new released version of the coupler OASIS3-MCT.

Table A1: List of acronyms

Acronyms	Full name
BALTEX	The Baltic Sea Experiment
CCLM	Consortium for Small-scale Modeling model in CLimate Mode
CERFACS	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, France
CICE	Los Alamos sea ice model
COSTRICE	CCLM + TRIMNP + CICE
DKRZ	The German Climate Computing Center
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA	ECMWF reanalysis data
GCM	Global climate model / General cirlation model
HAMSOM	The regional ‘Hamburg Shelf Ocean Model’ of University of Hamburg, Germany
HELCOM	The Baltic Marine Environment Protection Commission or ‘Helsinki Commission’
HD	Hydrological Discharge (model)
HIRLAM	The high resolution limited area model of Sweden's Meteorological and Hydrological Institute
MITgcm	The general cirlation model of Massachusetts Institute of Technology, US
OASIS3	The Ocean Amosphere Sea Ice Soil model version 3 of CERFACS, France
OISST	NOAA Optimum Interpolation Sea Surface Temperature (OISST) version 2
RCM	Regional climate model
RegCM3	Regional climate model version 3 of International Centre for Theoretical Physics (ICTP), Italy
REMO	Regional model of Max-Planck Institute for Meteorology, Germany
SST	Sea surface temperature
TRIMNP	The “Nested and Parallel” mode of the Tidal Residual and Intertidal Mudflat Simulations in 3 Dimensions model

Table B1: An example of the source code changes of CCLM using specific PSMILe calls of OASIS3

Source code changes	Stand–alone CCLM	Coupled CCLM
+ Initialization: (sub. init_environtment in "environtment.f90")	! ----- start ------ **Call** *MPI_INIT* icomm_world = MPI_COMM_WORLD	! ----- start ------ **Call** *MPI_INIT* **Call** prism_init_comp_proto (…) **Call** prism_get_localcomm_proto (…) ! → kl_comm icomm_world = kl_comm
+ Local partition definition	x	paral (clim_strategy) = clim_serial paral (clim_length) = ie_tot *je_tot paral (clim_offset) = 0 **Call** prism_def_partition_proto (id_part, paral, ierror) inodims(1)= 1 ! rank of coupling field inodims(2)= 1 ishape(1) = 1 ! min index for the coupling field local dimension ishape(2) = ie_tot *je_tot ! max index
+ Coupling field declaration	x	ssnd(1)%clname = '*PMSLCCLM*' ! sending ssnd(2)%clname = '*PRECCCLM*' ! sending ssnd(3)%clname = '*RAINCCLM*' ! sending ssnd(4)%clname = '*SNOWCCLM*' ! sending DO i=1,4 ! 4 vars are sent **Call** prism_def_var_proto (ssnd(i)%id,ssnd(i)%clname, id_part,inodims,PRISM_Out,ishape,PRISM_REAL, ierror) ENDDO srcv(1)%clname = '*T_S_CCLM*' ! receive **Call** prism_def_var_proto (srcv(1)%id,srcv(1)%clname, id_part,inodims, PRISM_In, ishape, PRISM_REAL, ierror)
+ End of definition phase	x	Call prism_enddef_proto (…)
+ Main program, time stepping loop: - to get fields from OASIS - to send fields to OASIS	DO istep = nstart, nstop …. ! …. = SST(ib:je,jb:je) * .... !--- pmsl (ib:je,jb:je)=…. !--- rain_total(ib:je,jb:je)=… !--- rain (ib:je,jb:je)= … !--- snow (ib:je,jb:je)= … ….. ENDDO	DO istep = nstart, nstop …. **Call** prism_get_proto (..., istep, *T_S_CCLM*, …) **Call** distribute_filed (*T_S_CCLM*, ie_tot, je_tot, SST, ie,je) ! …. = SST(ib:je,jb:je) * ..... ….. !--- pmsl (ib:je,jb:je)=…. !--- rain_total (ib:je,jb:je)= prr_con+prr_grp+ prs_con+prs_grp !--- rain (ib:je,jb:je)= prr_con+prr_grp !--- snow (ib:je,jb:je)= prs_con+prs_grp **Call** gather_filed (PMSL,ie,je,*PMSLCCLM*,ie_tot,je_tot) **Call** gather_filed (rain_total,ie,je,*PRECCCLM*,ie_tot,je_tot) **Call** gather_filed (rain,ie,je,*RAINCCLM*,ie_tot,je_tot) **Call** gather_filed (snow,ie,je,*SNOWCCLM*,ie_tot,je_tot) **Call** prism_put_proto (…, istep, *PMSLCCLM*, …) **Call** prism_put_proto (…, istep, *PRECCCLM*, …) **Call** prism_put_proto (…, istep, *RAINCCLM*, …) **Call** prism_put_proto (…, istep, *SNOWCCLM*, …) ….. ENDDO
+ Termination: (sub. final_environtment in "environtment.f90")	! ------ finish ------ **Call** *MPI_FINALIZE*	! ------ finish ------ **Call** prism_terminate_proto (…) **Call** *MPI_FINALIZE*

Table C1: Passing SSTTRICE on the grid ocng of TRIMNP (after combined SST of TRIMNP with the sea ice temperature of CICE) to the grid atmg of CCLM. The Lines are in the "namcouple" file. An explanation of each Line is provided in the shaded box below..

Line 1	SSTTRICE Var. name in TRIMNP	T_S_CCLM Var. name in CCLM	1 Index of field in cf_name_table	10800 Coupling time (= 3 hours)	2 Number of analysis in Line 4	sstoc.nc Input/restart file's name	EXPORTED Exchanged via OASIS
Line 2	ocng Souce grid	atmg Target grid	LAG=+240 Lagged time (s) = timestep of TRIMNP	SEQ=1 Run in parallel			
Line 3	R Regional	0 No overlap	R Regional	0 No overlap			
Line 4	LOCTRANS Analysis 1	SCRIPR Analysis 2					
Line 5	INSTANT Field status						
Line 6	DISTWGT Interpolation method	LR Source grid type	SCALAR Field type	LATLON Search restriction type	10 Number of restriction bins	4 Number of neighbour points used	

Table C2: Passing PMSL on the grid atmg of CCLM to the grid ocng of TRIMNP. Others detail are similar to Table C1.

Line 1	PMSLCCLM Var. name in CCLM	PMSLTRIM Var. name in TRIMNP	33 Index of field in cf_name_table	3600 Coupling time (= 1 hours)	2 Number of analysis in Line 4	atmin.nc Input/restart file's name	EXPORTED Exchanged via OASIS
Line 2	atmg Souce grid	ocng Target grid	LAG=+300 Lagged time (s) = timestep of CCLM	SEQ=1 Run in parallel			
Line 3	R Regional	0 No overlap	R Regional	0 No overlap			
Line 4	LOCTRANS Analysis 1	SCRIPR Analysis 2					
Line 5	INSTANT Field status						
Line 6	DISTWGT Interpolation method	LR Source grid type	SCALAR Field type	LATLON Search restriction type	10 Number of restriction bins	4 Number of neighbour points used	

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