The Sensitivity of the Regional Coupled Ocean-Atmosphere
Downscaling of Global Reanalysis over the Intra-Americas Seas to the
Prescribed Bathymetry

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Abstract
Two multi-decadal, high-resolution (15km grid interval), regional coupled ocean-atmosphere model integrations centered over the Intra-Americas Seas are compared that differ only in their bathymetry. Both of these model integrations are forced by identical global atmospheric and oceanic reanalysis at the lateral boundaries. It is observed that the model integration with a smoother and coarser bathymetry in the region (EXP) results in a larger SST bias over most parts of the IAS. This exacerbation of the cold SST bias in the model integration can be partly explained by the changes in the prevalent surface and deep ocean currents. The EXP integration uses a bathymetry with a shallower Yucatan Channel, which tends to produce strong eddies south of the Channel that consequently weakens the flow through the Yucatan Channel and the loop current. In addition, in this version of the model integration (EXP) the surface eddy kinetic energy in the western Gulf of Mexico is appreciably reduced compared to the other model integration. As a consequence the upper ocean heat content in the IAS is underestimated in EXP relative to the control integration (CTL) that uses a higher resolution bathymetry. As a consequence the upper heat content in most parts of the IAS is underestimated in EXP compared to CTL. These results illuminate the important role of the prescribed bathymetry in addition to the grid resolution of the regional models to simulate the IAS.
1. Introduction

The Intra-Americas Seas (IAS) which comprises of the Gulf of Mexico (GoM), Caribbean Sea and parts of the northwestern tropical Atlantic Ocean is a major source of moisture for continental North America (Ruiz-Barradas and Nigam 2005; Mo et al. 2005; Wang et al. 2006; Chan and Misra 2010; Misra et al. 2014). For example, Chang and Oey (2005) claim that corn belt of the US would not be probably so named without the GoM. Even some of the most severe winter storms that affected eastern United States have had their origins in GoM (Bosart and Lin 1984; Businger et al. 1990). Similarly the ocean heat content in the IAS plays an important role in the intensity changes of several Atlantic tropical cyclones (Shay et al. 2000; Mainelli et al. 2008; Shay 2009; Rappaport et al. 2010). Therefore the importance of the IAS in regulating the climate and weather over major part of the continental North America cannot be overemphasized.

The IAS is also a region that hosts the largest western hemisphere warm pool (Wang and Enfield 2001). This Atlantic Warm Pool (AWP) is objectively defined as the area enclosed by 28.5°C isotherm in the IAS region (Wang and Enfield 2001, 2003). The AWP is a seasonal feature that appears in the boreal summer season, which peaks in middle of summer and disappears by late fall or early winter (Lee et al. 2005; Misra et al. 2013, 2014). The size of the AWP exhibits distinct interannual (Wang and Enfield 2001; 2003; Wang et al. 2006, 2007, 2008a) and decadal (Wang et al. 2008b; Zhang et al. 2012) variability. Diagnostic studies of the surface heat budget from ocean reanalysis and Ocean General Circulation Model (OGCM) simulations suggest that the cloud radiative fluxes play a dominant role in the seasonal cycle and interannual variability of the AWP.
Several studies have shown that invariably all current and earlier versions of Coupled ocean-atmosphere General Circulation Models (CGCMs) display a very cold bias in the IAS region resulting in much smaller AWP than observed (Misra et al. 2009; Kozar and Misra 2012; Liu et al. 2012, 2013). Many of these studies point to erroneous cloud-radiative feedbacks as a potential cause for this rather systematic cold bias displayed by the general circulation models.

A complimentary theory for this pervasive cold bias in the IAS region displayed by the CGCMs could also be a result of not resolving the ocean currents in the region. There is a growing consensus that a grid resolution of 20km or less is required at the very least to resolve the loop current and the eddies that it spawns (Hurlburt and Thompson 1980; Cherubin et al. 2005, 2006). The first successful numerical simulation of loop current and its eddies follows from Hurlburt and Thompson (1980), which was at 20 km grid resolution. Subsequent studies have clearly shown the benefit of high resolution ocean models in resolving these oceanic circulation features in the IAS region (Cherubin et al. 2005, 2006). In a detailed study that included using a hierarchy of atmosphere and ocean models, Clement et al. (2005) showed that ocean dynamics play a very important role in sustaining the warm pool in the western Pacific Ocean. They showed that the ocean dynamics through poleward Ekman transport and compensatory Sverdrup dynamics of equatorward geostrophic flow below and linked by equatorial upwelling negate the homogenizing effects of the atmospheric processes to sustain the warm pool in the tropical Pacific. While their study could be generalized for all warm pools, the geography and the bathymetry of the IAS is far different from the tropical Pacific to
exactly relate it to the AWP. Nonetheless the ocean transport of heat into and out of the
IAS is fundamental for the regulation of its SST (Jayne and Marotzke 2002; Chang and
Oey 2010). The loop current essentially brings the warm and saline water from the
equatorial Atlantic to the Gulf of Mexico (GoM). It may be mentioned that the prevailing
loop current that enters through the Yucatan Channel and exits through the Florida Straits
represents the upper limb of the global thermohaline circulation in the North Atlantic, a
major source of the Gulf Stream, and constitutes a major part of the Western boundary
current of the North Atlantic Subtropical Gyre.

The purpose of this study is to highlight the importance of these ocean currents in
the regulation of the IAS SST from comparing two 32 year integrations of a regional
coupled ocean-atmosphere model simulations at 15km grid resolution that are identical to
each other except for the bathymetry it uses. The model integrations produce two
significantly different simulations of the ocean circulations in the IAS. Therefore their
comparison will illuminate the impact of these ocean currents in the regulation of the SST
in the IAS. The model integrations and the models are described in Section 2. The model
simulations are then compared with each other and with observations (where available)
and reanalysis that is used in forcing the regional model in Section 3 followed by
summary and conclusions in Section 4.

2. The Model Integrations

a) Model description

The regional coupled ocean-atmosphere model we have adopted for this study is
the Regional Spectral Model-Regional Ocean Modeling System (RSM-ROMS; Li and
Misra 2014). The RSM-ROMS has been widely used for regional coupled integrations
over California and northeast Pacific Ocean (Li et al. 2014; 2013; 2012) and over the IAS (Li and Misra 2014). The RSM, which is the atmospheric component of the coupled model is a primitive equation model on a stereographic projection that uses sine-cosine series as the horizontal basis function with a terrain following vertical co-ordinate system of 28 sigma levels (Juang and Kanamitsu 1994). It has however gone through several upgrades in its parameterized atmospheric physics and dynamical core over the years. The readers are referred to Kanamitsu et al. (2010) for further details on the RSM.

The ocean component of the coupled model, ROMS version 3.0 is a free-surface, terrain-following, primitive equation ocean model (Haidvogel et al. 2000; Shchepetkin and McWilliams 2005). The equations are solved using the split-explicit time stepping scheme. The primitive equations are discretized in the vertical by using stretched, terrain following coordinates. There are 40 vertical layers in ROMS. The ROMS contain several sub-grid parameterizations, which include local closure schemes based on the level 2.5 turbulent kinetic energy equations (Mellor and Yamada, 1982) and generic length scale parameterization following Umlauf and Burchard (2003). The nonlocal closure scheme is based on the K-profile, boundary layer formulation developed by Large et al. (1994). The K-profile scheme has been expanded to include both surface and bottom oceanic boundary layers.

The RSM and ROMS are coupled to each other with a coupling interval of 24 hours. The atmospheric fluxes and SST are directly exchanged between RSM and ROMS without the use of any flux coupler. The RSM and ROMS share identical domain and horizontal resolution, which avoids periodic interpolation of the variables exchanged between the two components of the coupled model.
b) Experiment design

In this study we deploy RSM-ROMS at 15km grid resolution over a domain shown in Fig. 1a. Two separate integrations of the RSM-ROMS are conducted with identical domain and resolution (as in Fig. 1a) in this study. One of them will be called CTL and the other EXP. Both these integrations are conducted for a 32-year period from 1979 through 2010. In both these integrations we use the 6 hourly atmospheric fields of the National Centers for Environmental Prediction-Department of Energy atmospheric reanalysis (NCEP-R2; Kanamitsu et al. 2002) as the lateral boundary condition for the RSM. Similarly we use the monthly mean Simple Ocean Data Assimilation version 2.2.4 (SODA; Carton and Giese 2008; Carton and Ray 2011) as the lateral boundary forcing for ROMS. We also use the SODA ocean reanalysis to compare with the multi-decadal CTL and EXP model integrations. The SODA ocean reanalysis serves as a good verification dataset given its availability for a relatively long time record despite its prevalent uncertainties prevalent (Giese et al. 2011). The alternative of using data from relatively short field campaigns (e.g. CANEK following Sheinbaum et al. 2002) for verification is not so tenable, when the intent is to verify the ocean climate from the conducted multi-decadal model simulations. The initial conditions for RSM-ROMS are interpolated from the corresponding global atmospheric and oceanic reanalysis for 1 January 1979. These initial conditions are identical for both CTL and EXP.

In CTL and EXP the source of the bathymetry is from ETOPO5 (http://www.ngdc.noaa.gov/mgg/global/etopo5.HTML), which is available at 5-minute resolution. However in CTL we smooth this bathymetry by running a 5-point smoother
once before interpolating to the 15km grid of the ROMS while in the EXP we linearly
interpolate the original bathymetry to ~200km grid resolution (or T62 spectral truncation)
before we interpolate it to the 15km ROMS grid. The CTL bathymetry had to be
smoothed once with a 5-point smoother to avoid some numerical instability issues that
arose without it. The point of this exercise was to make the bathymetry sufficiently
different in the EXP and CTL version of the model integration to investigate the
sensitivity of the simulation to the prescribed bathymetry. Figs. 1a and b show the
bathymetry of CTL and EXP and their differences in Fig. 1c. The differences in Fig. 1c
are apparent over several regions including the Columbian Basin, Cayman Basin,
Nicaraguan Rise, Yucatan Channel, Sigsbee Deep, Bay of Campeche, Continental Shelf
areas of the GoM and over the Florida Straits. In all of these regions the differences in the
bathymetry range from a few meters to 1500m or more. It may be noted in Fig. 1c that
the Yucatan Channel in CTL is narrower in width and deeper in depth than in the EXP
bathymetry. Similarly in Fig. 1c we find that the bathymetry in the Florida Strait between
Florida and Cuba is shallower in CTL compared to EXP. Furthermore the continental
shelf along Louisiana and Texas (LATEX shelf) and Tamaulipas-Veracruz in Mexico
(TAVE shelf) is shallower and extends further out in the Gulf of Mexico in CTL
compared to EXP. As will be shown in the following section, these differences in the
bathymetry lead to some significant changes in the ocean simulation despite the identical
grid resolution of CTL and EXP.

For verification of the ocean surface currents we make use of the Ocean Surface
Current Analysis (OSCAR; Bonjean and Lagerloef 2002), which is available at one-third
degree grid resolution and derived from satellite altimeter and scatterometer winds.
Similarly we use the optimally interpolated SST version 2 (OISSTv2; Reynolds et al. 2007) available at 0.25° grid resolution for verification of the SST. It may also be mentioned that the discussion in the rest of the paper will focus on the IAS despite the fact that the regional domain covers parts of the tropical eastern Pacific Ocean.

3. Results

a) Ocean Temperature

The climatological annual mean SST bias from CTL is shown in Fig. 2a. The observed SST is the NOAA Optimally Interpolated SST (OISST; Reynolds et al. 2007) available at 0.25° grid interval. Fig. 2a shows a uniform cold bias displayed by CTL over the IAS, which is larger along the coastal regions of the Bay of Campeche, the Florida Shelf, along the Mesoamerican coasts, the northern coast of South America and along the southern limb of the Gulf Stream. It may be however noted that the differences along the coasts in Fig. 2a may also be partly on account of the differences in the resolution of the RSM-ROMS and OISSTv2. In the EXP (Fig. 2b) the cold bias is far more acute than in CTL especially, along the southern limb of the Gulf Stream, and followed by that over the GoM and the Caribbean Sea. These systematic differences in SST between CTL and EXP merit further investigation of the sensitivity climate simulation to bathymetry. In fact the differences in the annual mean SST between CTL and EXP in Fig. 1b show striking resemblance to SST bias in global climate models over IAS (Misra et al. 2009; Kozar and Misra 2012).

The annual mean temperature difference between CTL and EXP at 500m, 1000m and 1500m below the ocean surface is shown in Figs. 3a, b, and c. It may be mentioned that some studies have sought distinction of the water entering the Gulf of Mexico...
through the Yucatan Channel at roughly above and below 1000m or the 6°C isotherm, which is the maximum depth (see Fig. 1) and isotherm intersecting the bottom of the Florida Strait (Niiler and Richardson 1973; Bunge et al. 2002; Candela et al. 2003). At 500m (Fig. 3a) the difference between CTL and EXP is relatively large around Cuba, the northern and the western GoM, around Bahamas, and along the Gulf Stream region. The EXP integration is colder than the CTL integration at 500m around Cuba, Yucatan Channel and along the lower limb of the Gulf Stream, while it is warmer than CTL in northern and western Gulf of Mexico. Even at 1000m (Fig. 3b) a similar north-south gradient (albeit weaker than at 500m) in the temperature differences between CTL and EXP are maintained with the southern part of the domain being warmer than the northern part of the regional domain. However, at 1500m (Fig. 3c) this gradient in the differences becomes much weaker, with the temperatures in the Caribbean being now colder in CTL relative to EXP. In other words, roughly above the northward Yucatan channel flow we observe the Caribbean Sea to be warmer in CTL compared to EXP.

A cross-section along 25°N in the central GoM from CTL, EXP and their difference is shown in Figs. 4a, b, and c respectively. The figure clearly indicates that the relative warming in the central GoM is shallow. This relatively shallow warming of the surface layer over the GoM in the CTL is in fact despite unfavorable atmospheric net heat flux in the region relative to EXP (Fig. 5). As seen in Fig. 5a the annual mean climatological net heat flux is negative (i.e., upward from the ocean surface) in northern GoM and positive (i.e., downward into the ocean surface) over southern GoM and further south in the tropical waters of the Caribbean Sea. However, in Fig. 5b we observe that climatological fluxes in EXP is less negative over northern GoM and more positive in
southern GoM. This shallow warming in the central GoM in the CTL (Fig. 4) is largely on account of stronger surface currents (discussed in the next subsection) that leads to a more stable stratification of the ocean. However, a more detailed study of the differences in the deep ocean currents and its interaction with the topography is warranted to possibly understand these differences further near the ocean abyss (e.g. Zavala-Hidalgo et al. 2003; Morey and Dukhovskoy 2013).

In Figs. 6a and b we show the annual mean climatological depth of the 20°C (a proxy for the upper ocean heat content) from the SODA ocean reanalysis and the CTL integration respectively. The corresponding climatological difference in the depth of the 20°C isotherm between CTL and EXP is shown in Fig. 6c. In relation to the SODA ocean reanalysis (Fig. 6a), the CTL integration underestimates the heat content in the IAS region, with the largest differences in the Caribbean Sea and in tropical northwestern Atlantic Ocean, along the lower limb of the Gulf Stream. However in the EXPT integration, this depth is further underestimated relative to CTL over the IAS (Fig. 6c). The improvements of the upper ocean heat content simulation in the CTL relative to the EXP coincides approximately with the location of the surface Caribbean, Loop, and Florida currents and the purported westward drift of the eddies coming off of the loop current in the Bay of Campeche and the TAVE shelf.

b) Ocean Currents

The climatological annual mean surface meridional and zonal ocean currents from observations (Bonjean and Lagerloef 2002), SODA ocean reanalysis, CTL, and EXP are shown in Fig. 7. The zonal currents indicate that the westward Caribbean current is
stronger both in CTL (Fig. 7c) and EXP (Fig. 7d) compared to SODA (Fig. 7b) and observations (Fig. 7a). Since the observations in Fig. 7a are derived off of altimeter observations from satellite, they represent only the geostrophic component of the current. Therefore differences of the total surface currents in the model simulations (Figs. 7c and d) and SODA reanalysis (Fig. 7b) from observations (Fig. 7a) are expected. However SODA ocean reanalysis also displays weaker zonal currents than either CTL or EXP. But it should be mentioned SODA ocean reanalysis is available at a coarser horizontal resolution of 0.5° than either CTL or EXP, which could underestimate the strength of the currents in the reanalysis. Likewise the meridional current through the Yucatan Channel shows the asymmetric maximum northward flow on the westward side of the channel in observations (Fig. 7e), SODA ocean reanalysis (Fig. 7f) and CTL (Fig. 7g). However, in EXP (Fig. 7h) the northward flow through the Yucatan channel is much weaker just north of the channel. Furthermore, the northward extension of the loop current is extremely weak in EXP. The corresponding standard deviation about the climatological annual mean surface ocean currents is shown in Fig. 8. Here we note that the variability of the Loop and the Caribbean current system is grossly overestimated by both the CTL and EXP integrations for both the zonal and the meridional components relative to either the observations or SODA ocean reanalysis. But once again we notice that the variability of the surface meridional and zonal current is stronger north of the Yucatan Channel in CTL (Fig. 8g) relative to EXP (Fig. 8h), which is more consistent with SODA ocean reanalysis (Fig. 8f) and satellite observations (Fig. 8e). Furthermore, we also observe greater variability of the surface currents in the western GoM in CTL compared to EXP.
Figs. 9a, b, and c show the cross-section of the climatological annual mean flow through the Yucatan channel in SODA ocean reanalysis, CTL, and EXP integrations respectively. The differences in the bathymetry are quite apparent from the different depth of the channel in the three panels of Fig. 9. In EXP (Fig. 9c) the channel depth is appreciably shallower than in CTL and SODA ocean reanalysis. The meridional flow through the channel is also therefore significantly different in EXP relative to CTL and SODA. For example, the asymmetry in the flow with the maximum along the western edge of the channel is observed in the cross-section from SODA (Fig. 9a) and CTL (Fig. 9b), while it is not apparent in EXP (Fig. 9c). Furthermore, the current speed in EXP is also appreciably smaller than in CTL and SODA. In the CTL the maximum surface meridional speed is approximately $0.7 \text{ms}^{-1}$, which is less than the maximum in SODA that display a maximum of around $1.1 \text{ms}^{-1}$. The CTL also produces counter currents on both the Yucatan and Cuban sides of the channel that is mentioned in the observational study of Candela et al. (2003). The SODA reanalysis shows the counter current across the channel, which is contrary to the observations made in Candela et al. (2003) that claim that there is a persistent weak flow toward the GoM in the central deepest part of the channel surrounded by the counter currents on either side. In Fig. 9a, we also notice a surface counter current identified in Candela et al. (2003) as the Cuban counter current, which extends to 200m in depth. The CTL integration shows this feature (Fig. 9b), although far more confined to the eastern edge of the channel. The absence of this feature is quite apparent in the EXP integration (Fig. 9c).

\textit{c) The ocean eddies}

The loop current irregularly sheds eddies or rings that slowly move westward
where they eventually decay through interactions with the continental shelf. The mechanism for the generation of these eddies is not exactly known. However theories exist that relate them to the increase in the potential vorticity fluxes into the GoM through the Yucatan channel (Candela et al. 2002; Oey and Lee 2002; Oey 2004), the role of the wind forcing (Oey et al. 2003; Chang and Oey 2010) and strength of the transport through the Yucatan Channel (Bunge et al. 2002; Ezer et al. 2003). In Fig. 10 we show an example of the loop current shedding an eddy in July 2003. The loop current tilts far to the northwest and pinches off with an anticyclonic eddy in the northern GoM in the OSCAR observations (Fig. 10a) and in the CTL simulation (Fig. 10b). The SODA ocean reanalysis shows less of a tilt of the loop current (Fig. 10b) while in the EXP, the loop current has shed the eddy in the western GoM. However there is significant eddy generation to the south of the Yucatan channel in the EXP evident in Fig. 10d. This erroneously excessive eddy activity south of the channel the EXP simulation, obstructs the northward flow through the channel, thereby weakening the meridional flow through the channel relative to CTL. A significant part of this problem in EXP is a result of the shallow depth of the Yucatan channel relative to that in SODA (Fig. 10a) or CTL simulation (Fig. 10b).

Similarly, the surface eddy kinetic energy in the region from satellite OSCAR observations, SODA ocean reanalysis, EXP and CTL are shown in Figs. 11a, b, c, and d respectively. From this figure, it can be seen that EXP clearly underestimates the surface kinetic energy northwest of the Yucatan Channel in the GoM as a result of the weakening of the flow through the channel. Consequently, the westward propagation of the eddies in EXP is relatively muted in the GoM, which can explain to some extent its relatively
colder SST’s in the western Gulf of Mexico. As pointed in Chang and Oey (2010), eddies are effective transporters of heat across the central Gulf of Mexico. It may be noted that Cherubin et al. (2006) in conducting idealized modeling studies found that the presence of the northern Campeche shelf acts as a waveguide that increases anticyclone advection to the west. They further suggest that the presence of the northern Campeche shelf west of the Campeche Cape contributes to the passage of the eddies west of the Cape. Considering the differences in the Campeche shelf between CTL and EXP in Fig. 1c, the results of the relatively muted surface kinetic energy in the EXP compared to CTL is consistent with the conclusions drawn in Cherubin et al. (2006).

4. Summary and conclusions

In this study we have conducted two multi-decadal integrations (of 32 years duration) with a relatively high resolution regional coupled ocean-atmosphere model centered over the Intra-Americas Seas. Both these model integrations are conducted with the same numerical model and with identical lateral boundary conditions of the atmosphere and ocean. However the important difference in the two integrations was that one had a smoother and coarser bathymetry than the other. As a result some of the topographical features including the depth of the Yucatan Channel, Florida Straits, and the slope of the continental shelves were modified. This had a significant impact on the ocean circulation and temperature in the region.

This study draws attention to the surface manifestation of colder SST’s generated by the smoother bathymetry over most parts of the IAS, which is similar to the bias displayed by majority of the general circulation models. In the case of the RSM-ROMS integration with the smoother bathymetry (EXP), it is seen that this surface manifestation
of colder SST is sustained through a depth of 1000m of the Caribbean Sea. In the northern and western GoM, however, the CTL integration displays a much shallower depth of warming than EXP, which is related to the shallow relatively stable ocean stratification than EXP. Furthermore, in EXP the eddies form just south of the Yucatan channel, which hinders the meridional flow through the channel that ultimately weakens the loop current significantly compared to the CTL. In addition, the eddies generated off the loop current, north of the Yucatan Channel are extremely weak, relatively infrequent in EXP relative to the CTL. This is also corroborated from the displayed differences in the surface eddy kinetic energy between CTL and EXP. The significantly divergent solutions of the mean ocean climate between the CTL and EXP clearly indicate the importance of the bathymetry in the region. Furthermore, the resemblance of the cold SST differences between EXP and CTL to cold bias displayed by the global climate models over the IAS (Kozar and Misra 2012) does raise the motivation for examining in further detail the ocean circulation in the region from the global climate models. It may however be mentioned that CTL continues to display a cold bias in the SST, albeit weaker than EXP, which points to the fact that sensitivity to bathymetry alone cannot explain the prevalent bias in the region exhibited by RSM-ROMS. Other factors like atmospheric fluxes, vertical mixing in the ocean, and air sea coupling issues could also play equally important role, which will be examined in future studies.

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Figure Captions

Figure 1: The regional domain overlaid with bathymetry used in a) CTL and b) EXP coupled downscaling integrations and c) the difference in the bathymetry between CTL and EXP. The units are in meters.

Figure 2: The climatological annual mean seasonal mean SST difference (°C) between a) CTL and Observations (OISSTv2; CTL-Obs) and b) CTL and EXP (CTL-EXP).

Figure 3: The annual mean temperature difference between CTL and EXP (CTL-EXP) at a) 500 m, b) 1000m, and c) 1500m. The units are in °C.

Figure 4: Vertical cross-section of the climatological annual mean temperature (°C) at 25°N from a) CTL, b) EXP and c) their differences (CTL-EXP).

Figure 5: a) The net heat climatological annual mean atmospheric flux from the CTL simulation and b) the corresponding difference with EXP simulation. The units are in Wm⁻².

Figure 6: The annual mean climatological depth of the 20°C isotherm in the a) SODA ocean reanalysis, b) CTL integration, and c) is the corresponding difference between CTL and EXP. The units are in m.

Figure 7: Climatological annual mean zonal surface ocean current from a) OSCAR (satellite observations), b) SODA, c) CTL, and d) EXP. Similarly climatological annual mean meridional surface ocean current from e) OSCAR, f) SODA, g) CTL, and h) EXP. The units are in m/s.
Figure 8: Same as Fig. 7 but showing standard deviation.

Figure 9: Vertical cross section of the meridional flow (m s\(^{-1}\)) through the Yucatan Channel from a) SODA ocean reanalysis, b) CTL and c) EXP integrations.

Figure 10: The surface ocean currents (m s\(^{-1}\)) in July 2003 from a) OSCAR satellite observations, b) SODA Ocean reanalysis, c) CTL, and d) EXP model integrations.

Figure 11: The surface eddy kinetic energy from a) OSCAR satellite observations, b) SODA ocean reanalysis, c) EXP, and d) CTL integrations. The units are in m\(^2\)/s\(^2\).
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