

A simple regional coupled model experiment for summer-time climate simulation over southern Africa

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Abstract The main aim of this paper is to evaluate the Advanced Research Weather Research and Forecasting (WRF) regional model in simulating the precipitation over southern Africa during austral summer. The model's ability to reproduce the southern African mean climate and its variability around this mean state was evaluated by using the two-tier approach of specifying sea surface temperature (SST) to WRF and by using the one-tier approach of coupling the WRF with a simple mixed-layer ocean model. The boundary conditions provided by the reanalysis-II data were used for the simulations. Model experiments were conducted for twelve austral summers from DJF1998-99 to DJF2009-10. The experiments using both the two-tier and one-tier approaches simulated the spatial and temporal distributions of the precipitation realistically. However, both experiments simulated negative biases over Mozambique. Furthermore, analysis of the wet and dry spells revealed that the one-tier approach is superior to the two-tier approach. Based on the analysis of the surface temperature and the zonal wind shear it is noted that the simple mixed-layer ocean model coupled to WRF can be effectively used in place of two-tier WRF to simulate the climate of southern Africa. This is an important result

because specification of SST at higher temporal resolutions in the subtropics is the most difficult task in the two-tier approach for most regional prediction models. The one-tier approach with the simple mixed-layer model can effectively reduce the complicity of finding good SST predictions.

Keywords WRF · Mixed layer ocean model · Southern Africa

1 Introduction

Much of the southern Africa (SA) receives its precipitation during the austral summer (December to February; DJF) and any large variability in the seasonal rainfall has impacts on the economy of the region. The precipitation variations over SA can be partly explained by the variations in the Sea Surface Temperature (SST) variations in the surrounding oceans, viz. the southern Indian Ocean (Reason and Mulenga 1999; Behera and Yamagata 2001; Reason 2001) and the Atlantic Ocean (Hirst and Hastenrath 1983; Rouault et al. 2003a; Reason et al. 2006). The variations in the SST are also known to affect the frequency and position of the rain bearing synoptic scale systems (Todd and Washington 1999; Cook 2000; Fauchereau et al. 2009; Pohl et al. 2009) and hence the seasonal rainfall. In addition, the Pacific Ocean exerts a remote forcing to cause the variations of the precipitation over this region (Nicholson and Kim 1997; Cook 2001; Reason and Jagadeesha 2005; Fauchereau et al. 2009). Hence, it is essential to correctly specify the spatial (Rouault et al. 2003b) and temporal variations in the SST to the dynamical models to simulate the intraseasonal and inter annual variations in the climate of southern Africa.

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There have been many studies to simulate the climate of southern Africa using General Circulation Models (GCM; Joubert and Hewitson 1997; Mason and Joubert 1997). However, because of their coarse resolutions GCM's have biases in representing the detailed regional features. To reduce these biases, the GCM simulations are usually downscaled using dynamical regional climate models (RCMs; e.g. Giorgi 1990). The RCMs have been successfully used in the past for the simulation of the regional climate of southern Africa (Joubert et al. 1999; Hansingo and Reason 2008; Kgatuke et al. 2008; Landman and Beraki 2010; Cr  tat et al. 2011a, b). However, all these regional modeling studies used the two-tier approach of specifying the observed or forecasted SST to those atmospheric regional models.

The dynamical downscaling using the two-tier approach is limited by availability of the spatial and temporal distribution of the Atmospheric and Oceanic fields and also by the errors in the forecast fields. To overcome the limitations of the Oceanic data, viz. SST, coupled regional models are used (e.g. Seo et al. 2007; Xie et al. 2007; Ratnam et al. 2009). However, the coupled models are computationally demanding and the results are often dictated by the fidelity of the regional ocean models in representing the SSTs. The SSTs simulated by the regional ocean models often depend on the physical parameterizations used in the model and also on the initial and boundary conditions specified to the models, which may be subject to the biases inherited from the global models. In this study we use a simple mixed-layer ocean model of Pollard et al. (1973), as implemented by Davis et al. (2008) in Advanced Research Weather Research and Forecasting (WRF) Model (ARW, see Skamarock et al. 2008) to simulate the climate of southern Africa during the austral summer. Recently, the WRF model with such a simple mixed-layer ocean model was successfully used to study the impact of the air-sea interactions on the East Asian summer monsoon (Kim and Hong 2010). That study motivated us to use a similar approach to improve the regional seasonal forecasts over southern Africa. The aim of our study is two-fold; the first is to see if the WRF model with specified observed SST (WRFOSST hereafter) can reproduce the climate of southern Africa during the austral summer and the second is to see if the WRF with the mixed-layer ocean model (WRFOML) can simulate the regional climate reasonably well.

2 Model and methodology

For the simulation of the regional climate over southern Africa, we used the Advanced Research Weather Research and Forecasting (WRF) Model (ARW; Skamarock et al.

2008) version 3.2.1. A domain covering the area 40°S–4°S; 3°E–60°E was chosen for the study. The model integrations were made with a horizontal resolution of 30 km and with 23 vertical levels. The physics packages used in this study include the Rapid Radiative Transfer Model (RRTM) for the longwave radiation (Mlawer et al. 1997), a simple cloud-interactive shortwave radiation scheme (Dudhia 1989), Kain-Fritsch cumulus parameterization scheme (Kain 2004), the Yonsei University (YSU) planetary boundary layer scheme (Hong et al. 2006), the Noah land-surface scheme (Chen and Dudhia 2001) and the WRF single-moment 3-class (WSM3) microphysics scheme (Hong et al. 2004). The choice of these physics packages is consistent with that of Cr  tat et al. (2011b) for the simulation of climate of southern Africa.

The mixed-layer ocean model used in the WRF follows that of Pollard et al. (1973) except that the implementation in WRF allows for the non-zero mixed-layer depth (Davis et al. 2008). In the scheme, the mixed layer deepens and surface water cools due to wind-driven mixing. The mixed-layer ocean model includes the Coriolis effect on the current and a mixed-layer heat budget. For our study, the mixed-layer depth was initialized at 50 m. The mixed-layer model was called every time step, however the WRF model was updated with the averaged simulated SST from the mixed-layer ocean model once every 24 h. This was done for consistency with the temporal resolution of observed SST and for the ease of comparison of the results from two-tier and one-tier approaches. Experiments with SST updated at higher frequencies of 12, 6 h and every time step were also carried out to understand the model sensitivity to the coupling frequency as discussed in Sect. 3.

Both the experiments, with either the prescribed SST (WRFOSST) or the mixed-layer ocean model (WRFOML), were integrated for a period of 12 years (DJF1998-99 to DJF2009-10) using the initial and the 6-hourly boundary conditions provided by the NCEP-DOE Reanalysis-II (Kanamitsu et al. 2002). The daily SST dataset of Reynolds et al. (2007) was used as the lower boundary condition for the WRFOSST experiment. All the experiments were initialized on 15th Nov of each year and integrated till 28th Feb of the following year.

The model simulated precipitation is compared with the Tropical Rainfall Measuring Mission (TRMM) estimated daily precipitation (3B42V6; Huffman et al. 2007). The large-scale atmospheric fields simulated by the model are compared with the Reanalysis-II data by interpolating the model data to the Reanalysis grid. The TRMM estimated precipitation and the Reanalysis-II fields are referred to as “observations” hereafter. Model biases are calculated by subtracting the observations from the model simulated results and Student's *t* test is used to test the significance of these biases.

3 Model results

3.1 Spatial and temporal distribution of precipitation

The spatial distribution of the observed mean precipitation during the austral summer months of DJF computed for the period 1998–1999 to 2009–2010 (Fig. 1a) shows that most parts of southern Africa receive rainfall during DJF except for the western parts of the South Africa and Namibia. During DJF, high precipitation regions are located over northern Mozambique, Zambia, parts of Congo and northern Madagascar. Also seen in the Fig. 1a is the South Indian Convergence Zone (SICZ), a region of enhanced precipitation extending off the southeast coast of southern Africa. The variability in its position partly explains the variability of rainfall over southern Africa (Cook 2000, 2001). The SICZ forms due to the interaction between the tropical convection zone and the mid-latitude transients. The WRFOSST simulated precipitation as compared to the observations (Fig. 1b) shows that the experiment has positive bias in simulating the precipitation over most parts of southern Africa except over Tanzania and Mozambique. Interestingly, the WRFOML (Fig. 1c) could simulate the precipitation distribution realistically with slight negative biases over the Mozambique and Tanzania. To bring out the affect of the air-sea interaction in neighboring seas on the distribution of the precipitation over southern Africa, we plotted the differences in the mean precipitation simulated by the WRFOML and the WRFOSST experiments (Fig. 1d). Figure 1d clearly shows improvement in the simulation of the mean precipitation over most parts of southern Africa. Over parts of Mozambique and Angola there is a reduction in the negative bias due to the air-sea interaction and positive biases simulated by the WRFOSST (Fig. 1b) are reduced due to the mixed-layer coupling. However, the precipitation over the Mozambique Channel and the tropical oceans are higher in the WRFOML.

The spatial patterns of the standard deviation of the observed daily precipitation rates from the mean climate state (Fig. 2a), DJF 1998–99 to DJF 2009–10, shows high variability over Mozambique, Madagascar and north Angola. The corresponding standard deviation of the WRFOSST simulated daily precipitation from the mean climate state (Fig. 2b) shows high variability over most parts of southern Africa and over the southwest Indian Ocean. The WRFOML (Fig. 2c) simulated variability lies between that of WROSST and the observation. This moderate improvement can be attributed to the air-sea interactions in the WRFOML experiment. The air-sea interactions help to reduce the variability in the coupled WRFOML as compared to that in the uncoupled WRFOSST results. However, the variability over the southwest Indian Ocean in WRFOML is higher compared to that in WRFOSST.

The skill of the model in simulating the southern African precipitation is further evaluated by correlating the observed daily precipitation with that of the WRFOSST simulated results (Fig. 3a). From the figure it can be seen that WRFOSST has significant correlations only over South Africa and Tanzania with little or no correlation over other parts of southern Africa. The significant correlations over the South Africa may partly be due to the nearness of model boundaries (Leduc and Laprise 2009). Interestingly, the WRFOML (Fig. 3b) also shows a similar but somewhat better distribution of the correlations. The WRFOML simulated correlations are improved compared to WRFOSST in the regions where the biases in the precipitation were improved due to the air-sea interaction (Fig. 1d). These results indicate that the precipitation simulations over South Africa are not that much dependent on the short-term variability of the SST within the domain considered for the study; it is therefore possible to replace two-tier simulations/predictions with a simple one-tier simulation/prediction.

Based on the above findings, in the following we mostly focus on the climate variability of South Africa. We chose two regions for the analysis, one is a region covering the area 32°S–23°S, 24°E–32°E (shown in Fig. 1a black bordered rectangular box; we call this region South Africa as it is representative of South African precipitation; Cook et al. 2004) and the second covers the Limpopo region (22°S–25°S, 27°E–32°E; Fig. 1a red bordered rectangular box) over the northeastern South Africa. Limpopo region is largely dependent on the summer rainfall for its agricultural related economy. Because of the large climate variations over this region, the subsistence farming is prone to severe droughts and floods (Reason et al. 2005). Figure 4a shows the area averaged precipitation over the South African region during the period DJF1998/99 to DJF2009/10. The WRFOSST experiment (mean 5.16 mm/day; standard deviation 0.72) simulated higher precipitation during all the years compared to the observations (mean 3.03 mm/day; standard deviation 0.689). The WRFOML experiment simulated precipitation (mean 4.728 mm/day; standard deviation 0.741) was less than that of WRFOSST for most of the years though it was higher than that of the observed. Similar results are seen for the area averaged precipitation over Limpopo (Fig. 4b). Over Limpopo, the WRFOSST experiment simulated a mean precipitation of 4.61 mm/day (standard deviation 1.26) which is higher than the observed precipitation of 2.91 mm/day (standard deviation 1.34). The WRFOML simulated precipitation (mean 4.00, standard deviation 1.25) is less than the WRFOSST simulated precipitation. Using the same definition of US Aid Famine and Early Warning System and Usman and Reason (2004), if we define a day to be dry (wet) if it receives less (more) than 1 mm (5 mm) precipitation, then the number of wet days simulated by the

Fig. 1 **a** Observed DJF1998-99 to DJF2009-10 mean precipitation (mm/day) **b** WRFOSSST simulated precipitation bias (mm/day) **c** same as **b** but simulated by WRFOML **d** difference of the precipitation simulated by WRFOML and WRFOSSST. Precipitation in figs **b**, **c** and **d** is significant at 90% using *t* test. The black border box is representative of the “South Africa” region and the red border box represents the Limpopo region

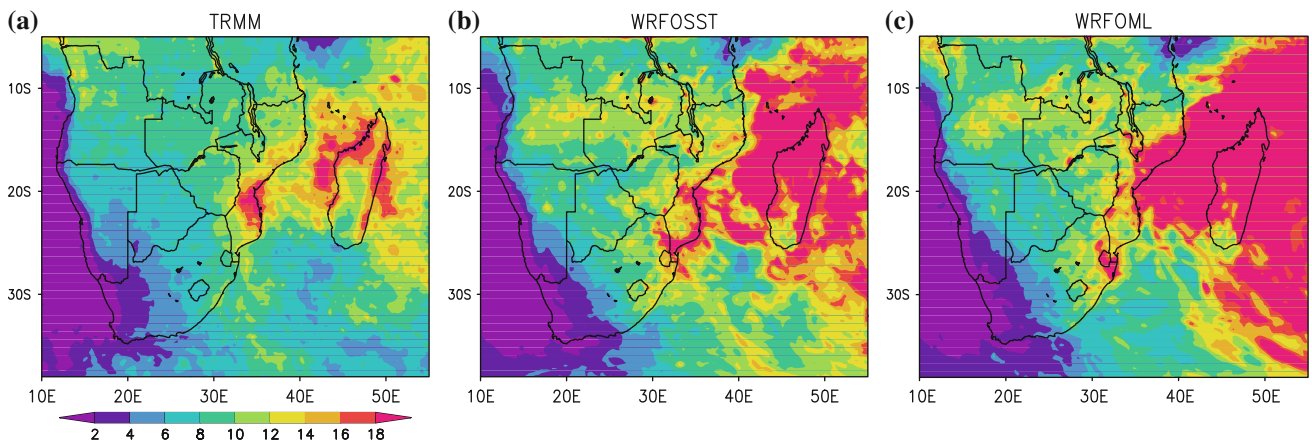
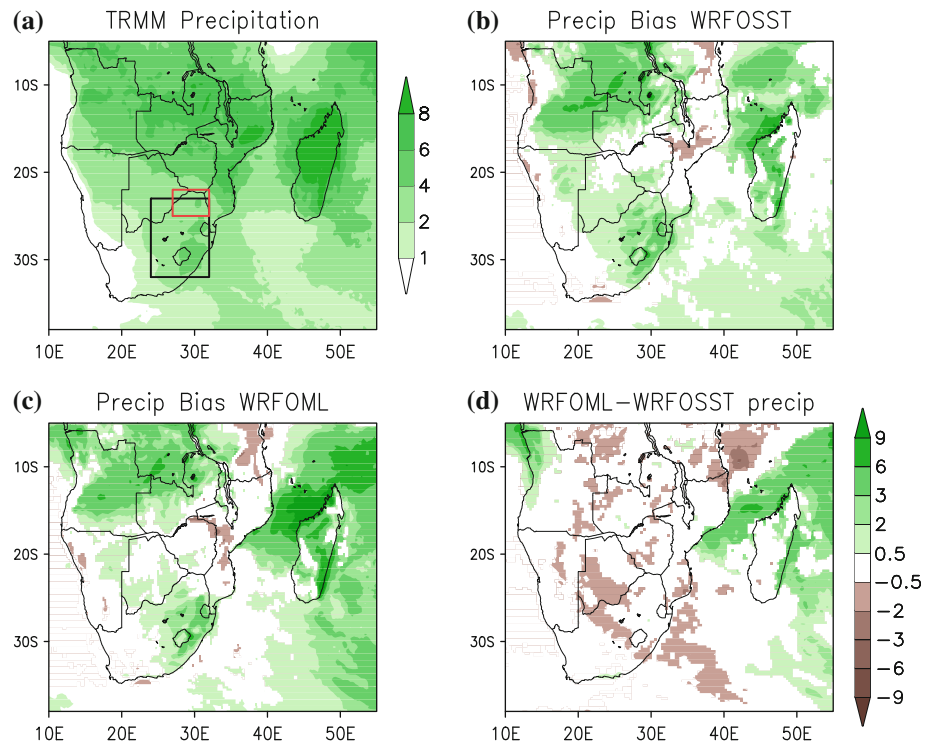


Fig. 2 **a** Observed daily standard deviation (mm/day) **b** same as **a** but simulated by WRFOSSST **c** same as **a** but simulated by WRFOML

Fig. 3 **a** Correlations between daily observed precipitation and WRFOSSST simulated precipitation **b** same as **a** but WRFOML simulated. Correlations significant at 99% using *t* test

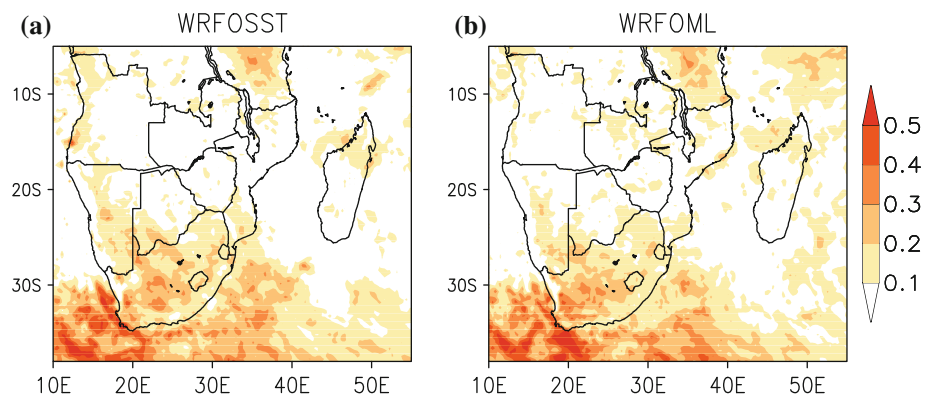
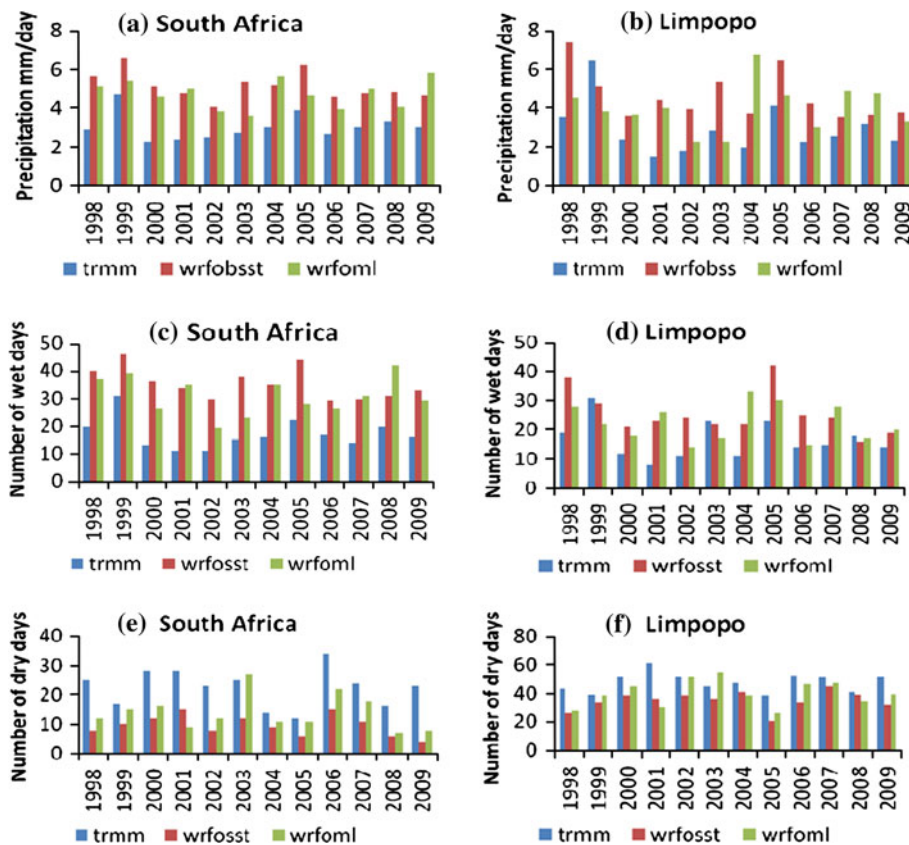


Fig. 4 **a** Area averaged precipitation simulated by the model experiments over South Africa during the period DJF1998/99 to DJF2009/10. **b** Same as **a** but over Limpopo. **c** Number of wet days simulated by the models over South Africa **d** same as **c** but over Limpopo. **e** Number of dry days simulated by models over South Africa **f** same as **e** but over Limpopo. Years are labeled using the year to which December belongs



experiments over South Africa (Table 1; Fig. 4c) and Limpopo (Table 2; Fig. 4d) are higher compared to the observed number of wet days, in agreement with the higher precipitation simulated by the experiments. The number of simulated dry days over South Africa (Table 1; Fig. 4e) and Limpopo (Table 2; Fig. 4f) by WRFOSSST experiment is less than observed. The WRFOML experiment shows a slight improvement in the number of dry days in most of the years. These results show that the WRFOSSST has wet biases in the simulation of precipitation over South Africa and Limpopo regions, which are slightly reduced by air-sea interaction in the WRFOML experiment.

A comparison of the spatial and temporal distribution of the simulated precipitation shows that both the WRFOSSST and WRFOML experiments could simulate realistic results except for the slight overestimation in several regions of southern Africa. It is, however, interesting to note that the WRFOML shows improvement in the simulation of the wet and dry days over South Africa and Limpopo compared to the WRFOSSST experiment.

In order to understand the causes of the biases we analyzed the low level (850 hPa) observed and simulated moisture fluxes together with the moisture convergence. The observed mean (Fig. 5a) for the study period shows that the moisture is transported into southern Africa from the tropics, particularly from the southwest Indian Ocean. The moisture is also

transported into southern Africa from the southeast tropical Atlantic Ocean (Reason et al. 2006; Morioka et al. 2011) through the Angola low (Cook et al. 2004; Reason and Jagadeesha 2005), seen in Fig. 5a as cyclonic circulation over Angola and Namibia. The Angola low also acts to regulate the transport of the tropical wet air into southern Africa. In addition, a cyclonic circulation over the Mozambique Channel transports the wet winds from the southwest Indian Ocean and prevents the dry subtropical air from penetrating into southern Africa. The transport of moisture explains the spatial distribution of the precipitation over southern Africa (Fig. 1a). The region of high precipitation seen over southern Africa is at the intersection of the wet moisture from the equatorial region, the southeast Atlantic and the southwest Indian Ocean. On the other hand, the high precipitation over the Madagascar is mainly due to the southward movement of the ITCZ during austral summer. The regions of high moisture convergence at 850 hPa (Fig. 5a) also coincide with the regions of high precipitation. One can clearly see three regions of maximum moisture convergence in Fig. 5a, one is to the east of Congo basin around 30°E, second is in the southeastern Angola region around 17°S and the third is to south of Botswana around 25°E (Vigaud et al. 2007).

In comparison to the observations, WRFOSSST simulated stronger fluxes over southern Congo, northern Angola and northern Zambia (Fig. 5b) creating a region of high

Table 1 Statistics of dry and wet days over South Africa during DJF1998-99 to DJF2009-10

South Africa (DJF1998-99 to DJF2009-10)	Obs	WRFOSST	WRFOML
Mean number of dry days	22.41	9.66	14.0
Mean number of wet days	17.16	35.5	30.83
Standard deviation of number of dry days	6.48	3.49	5.95
Standard deviation of number of wet days	5.57	5.56	6.89

Table 2 Statistics of dry and wet days over Limpopo during DJF1998-99 to DJF2009-10

Limpopo (DJF1998-99 to DJF2009-10)	Obs	WRFOSST	WRFOML
Mean number of dry days	47.91	35.08	40.25
Mean number of wet days	16.58	25.41	22.33
Standard deviation of number of dry days	6.84	6.34	9.30
Standard deviation of number of wet days	6.54	7.56	6.42

moisture convergence and hence positive bias in precipitation (Fig. 1b). However, near Tanzania, the fluxes are more southward (Fig. 5b) compared to the observations, thereby reducing the moisture and hence the precipitation over that region (Fig. 1b). The region of divergence over southern Mozambique (Fig. 5a) is more intense in the WRFOSST simulation (Fig. 5b) creating a region of less precipitation (Fig. 1b) over southern Mozambique. The moisture fluxes simulated by WRFOML (Fig. 5c) are similar to the WRFOSST simulations. However, the bias in the moisture fluxes and their divergence over the southern Mozambique and Zimbabwe in the WRFOML experiment leads to a wider region of negative bias in precipitation.

3.2 Surface temperature

The spatial distribution of the mean surface temperature from the NCEP reanalysis and the model simulated biases are shown in Fig. 6. It may be recalled here that the surface temperature in the WRFOSST simulations is the observed Reynolds et al. (2007) SST over the oceans and the WRF model simulated temperature over the land. In the case of WRFOML, the surface temperature over land is simulated by WRF but the SST is simulated by the ocean mixed layer model in response to the fluxes provided by the atmospheric component of the model. The observed mean surface temperature (Fig. 6a) over the oceans shows high temperatures over the southwest Indian Ocean extending from the equatorial regions to the subtropics and over the equatorial South Atlantic Ocean. The cool oceanic temperatures over the mid-latitudes extend over the western coast of southern Africa till 18°S. The observed surface land temperature over Angola and South Africa is about 18–21°C and warmer surface temperatures are observed over Mozambique, Zambia, and Namibia and over western South Africa. The WRFOSST simulated surface temperature (Fig. 6b) over land shows positive bias over most parts of southern Africa with comparatively higher biases over Mozambique, Zambia, Namibia and western South Africa. Also, a difference in the SST distribution is seen between the observed and the model prescribed SST near the Mozambique Channel. These differences are mainly due to the difference in the sources and resolution of SST used in the reanalysis and in our model runs. Interestingly, the oceanic temperatures simulated by WRFOML (Fig. 6c) are quantitatively comparable to the ocean temperatures prescribed to the WRFOSST experiment but with higher temperatures over the Mozambique Channel. Similar to the WRFOSST experiment, the WRFOML simulated land temperatures are overestimated over most parts of southern Africa. The regions with positive model bias in the surface

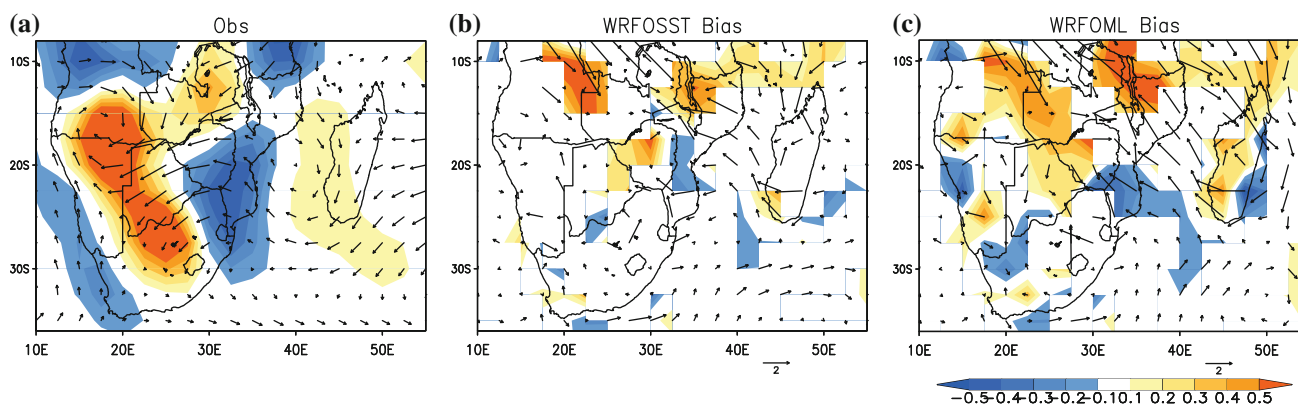


Fig. 5 **a** Observed mean DJF1998-99 to DJF2009-10 850 hPa moisture convergence (g/Kg s^{-1} ; shaded) and 850 hPa moisture flux (g/Kg m/s ; vector) **b** same as **a** but WRFOSST simulated bias. **c** Same

as **a** but WRFOML simulated bias. Moisture convergence in **b** and **c** is significant at 90% using t test

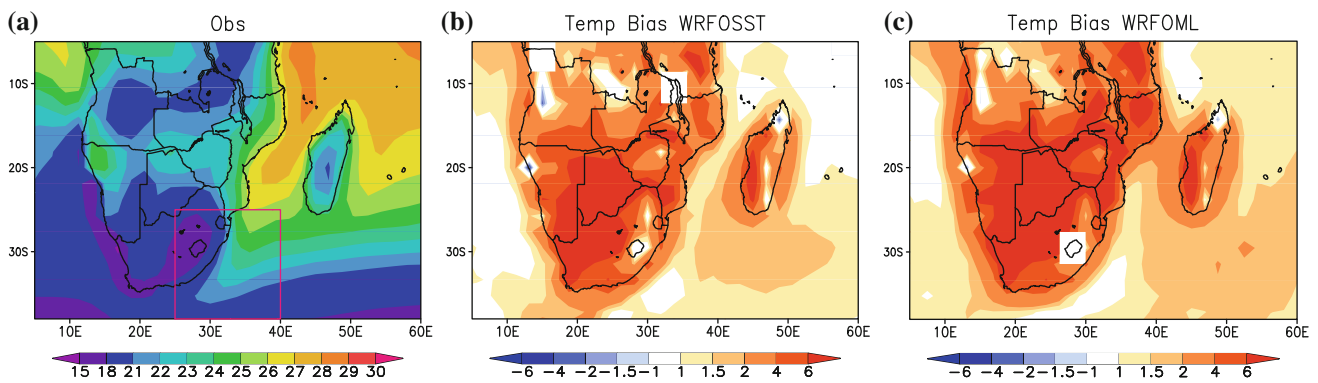


Fig. 6 a Observed mean DJF1998-99 to DJF2009-10 surface temperature (°C) b same as (a) but WRFOSST simulated bias. c Same as (a) but WRFOML simulated bias. Temperature bias in b and c is significant at 90% using *t* test

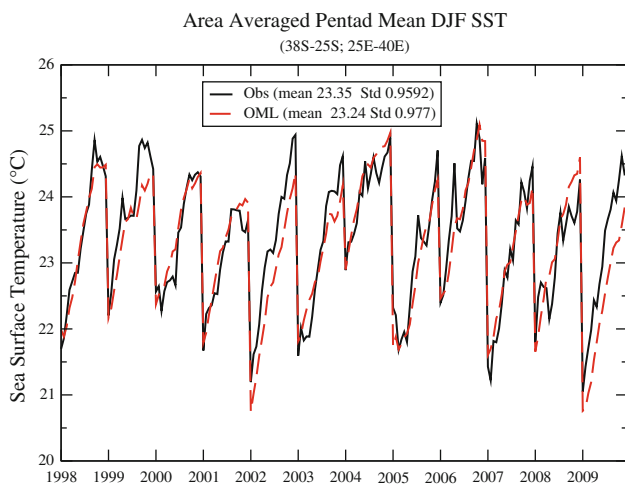


Fig. 7 Observed and WRFOML simulated pentad sea surface temperature (°C) over 38°S–25°S, 25°E–40°E region. Years are labeled using the year to which December belongs

temperature correspond to those with negative model bias in the precipitation (Fig. 1).

The variability in the sea surface temperature simulated by the WRFOML is further analyzed to understand the spatial and temporal variations. We plotted the pentad area-averaged SST over the domain covering 38°S–25°S; 25°E–40°E (region shown in Fig. 6a) for the entire study period from the WRFOML and WRFOSST experiments. This region covers the Agulhas current, which plays an important role in the SA climate (Rouault et al. 2003b). From Fig. 7, it is seen that the pentad SST simulated by the WRFOML (mean 23.24 and standard deviation 0.977) corresponds well with that of the observation (mean 23.35; standard deviation 0.959) over the study domain.

3.3 Zonal wind shear

A westerly zonal shear (200–850 hPa) in subtropical southern Africa is favorable for the formation of the Tropical

Temperate Troughs (Todd and Washington 1999; Hansingo and Reason 2008), which are the main rain bearing synoptic systems over southern Africa during the austral summer season. Figure 8a shows the presence of a strong westerly shear, near the southern coast of South Africa, which favors the formation of the rain bearing system across South Africa. Both the WRFOSST and WRFOML (Fig. 8b and c respectively) simulated a weaker westerly shear near the southern parts of South Africa. Unlike in the observations, in which the region of the high shear is situated over the ocean, the strong westerly shear is situated over the landmass though not very significant. These results indicate that the model biases need to be reduced in order to correctly simulate/predict the genesis of main rain bearing systems such as Tropical Temperate Troughs over southern Africa. Also, as was shown in the studies of Crétat et al. (2011a), the simulation of the intensity and position of the TTT events in WRF is dominated by the internal variability and hence dependent on the initial conditions.

3.4 Sensitivity to coupling frequency and initial depth

Many studies have shown that the frequency of coupling between the ocean and atmosphere influences the simulations of the global atmosphere–ocean coupled models (Kawai and Wada 2007; Ham et al. 2010). These studies found that the introduction of diurnal variation of SST into a coupled global atmosphere–ocean model resulted in a better representation of the climate. The improvements were attributed to the better representation of the air-sea sensible heat flux. To check if we can get similar improvements in the simulation of the climate of southern Africa using WRF, we updated the WRF model with the SST simulated by the mixed layer ocean model at the intervals of 12 h (hereafter WRFOML12HR), 6 h (WRFOML6HR) and every time step (WRFOMLESTEP). Figure 9 shows the precipitation, moisture convergence and skin temperature differences between the experiments. From the figure it can be clearly

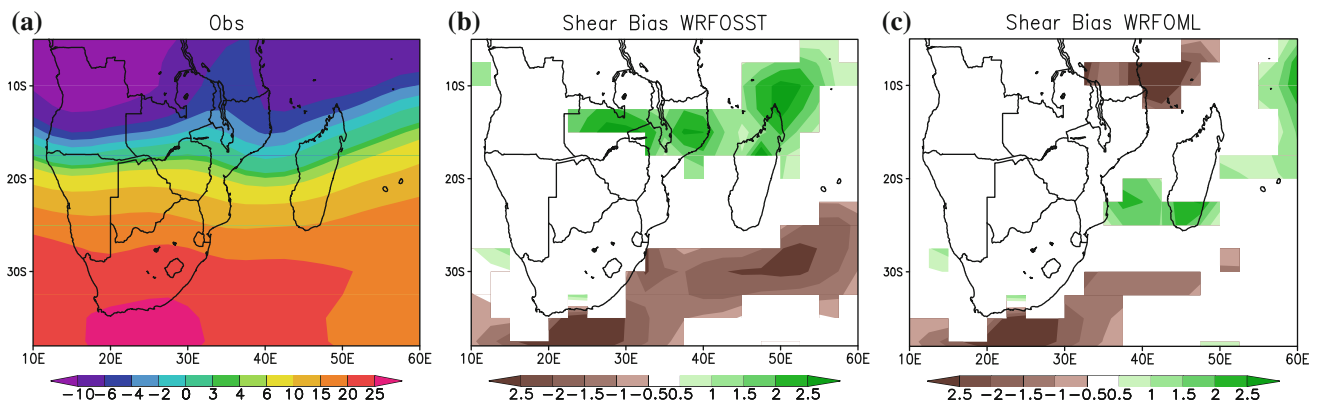


Fig. 8 **a** Observed mean DJF1998-99 to DJF2009-10 zonal wind shear (200–850 hPa; m/s) **b** same as **a** but WRFOSST simulated bias. **c** Same as **a** but WRFOML simulated bias. **b** and **c** significant at 90% using *t* test

seen that the coupling frequency has negligible effect on the model simulations in the present study. This result is partly due to the influence of the forcing from the boundaries which drive the regional climate model and also due to the fact that the ocean mixed layer model was called every time step even though the WRF SST was updated at different frequencies. The decision to call the ocean mixed layer model every time step was based on the results of the experiment in which the ocean mixed layer model was called only once in a day and the WRF SST was also updated once in a day (WRFOML1DAYCALL; Fig. 10) for the entire period of the study, DJF1998/99 to DJF 2009/10. From Fig. 10a it can be clearly seen that calling the mixed layer ocean model infrequently results in large negative bias in precipitation over the Indian Ocean and over large parts of the southern Africa unlike when the mixed layer model is called every time step and the WRF SST was updated once in a day (Fig. 1c). Also, the moisture fluxes (Fig. 10b) are directed away from the landmass compared to the observations.

To check the sensitivity of the WRFOML simulated results to the initial depth specified to the mixed layer ocean model, we carried out additional model runs with an initial depth of 30 m (WRFOML30M), for the entire period of study, DJF 1998/99 to DJF 2009/10. The difference in the precipitation between the WRFOML30M and WRFOML simulations are shown in Fig. 11. It may be recalled, the WRFOML simulations were with an initial depth of 50 m. From the figure one can see significant increase in precipitation only over parts of Angola (Fig. 11a). The differences in the 850 hPa moisture convergence (Fig. 11b) are in agreement with the differences in precipitation. However, the precipitation and moisture differences are very small, indicating that the initial depth does not have much influence on the simulated results. This is partly due to the dominance of the boundary forcing which drive the WRF model.

4 Conclusions

The main aim of this paper was to evaluate the WRF regional model in simulating the precipitation over southern Africa during austral summer using the two-tier approach of specifying SST's and also the one-tier approach by coupling the WRF with a simple mixed-layer ocean model. We used the boundary conditions provided by the Reanalysis-II data for the simulations. The model was integrated for twelve austral summer seasons from DJF1998-99 to DJF2009-10.

The mean spatial distribution of the precipitation simulated by WRFOSST and WRFOML showed negative precipitation bias over Mozambique with positive bias over Angola, southern Congo and South Africa. However, the WRFOML showed improvements in the spatial distribution of the precipitation over Mozambique due to the air-sea interactions. The model simulated low level moisture convergence and moisture fluxes were consistent with the precipitation distribution across southern Africa. Significant correlations are found over South Africa for all the experiments in the point-to-point correlation between the daily-observed precipitation and the model simulated daily precipitation. However, a detailed validation of the inter-annual variability revealed that the two-tier approach of specifying SST has wet biases for both dry and wet spells over South Africa. The simple one-tier approach of coupling WRF with a simple mixed-layer ocean model reduced the number of wet days.

Comparison of the simulated surface temperature with the observed surface temperature showed that the WRFOML experiment was capable of simulating a realistic distribution of temperatures over the oceans. The experiment also realistically simulated the oceanic temperature near the coast of South Africa. Nevertheless, consistent with the precipitation biases, the WRF model has warm biases over the southern African landmass.

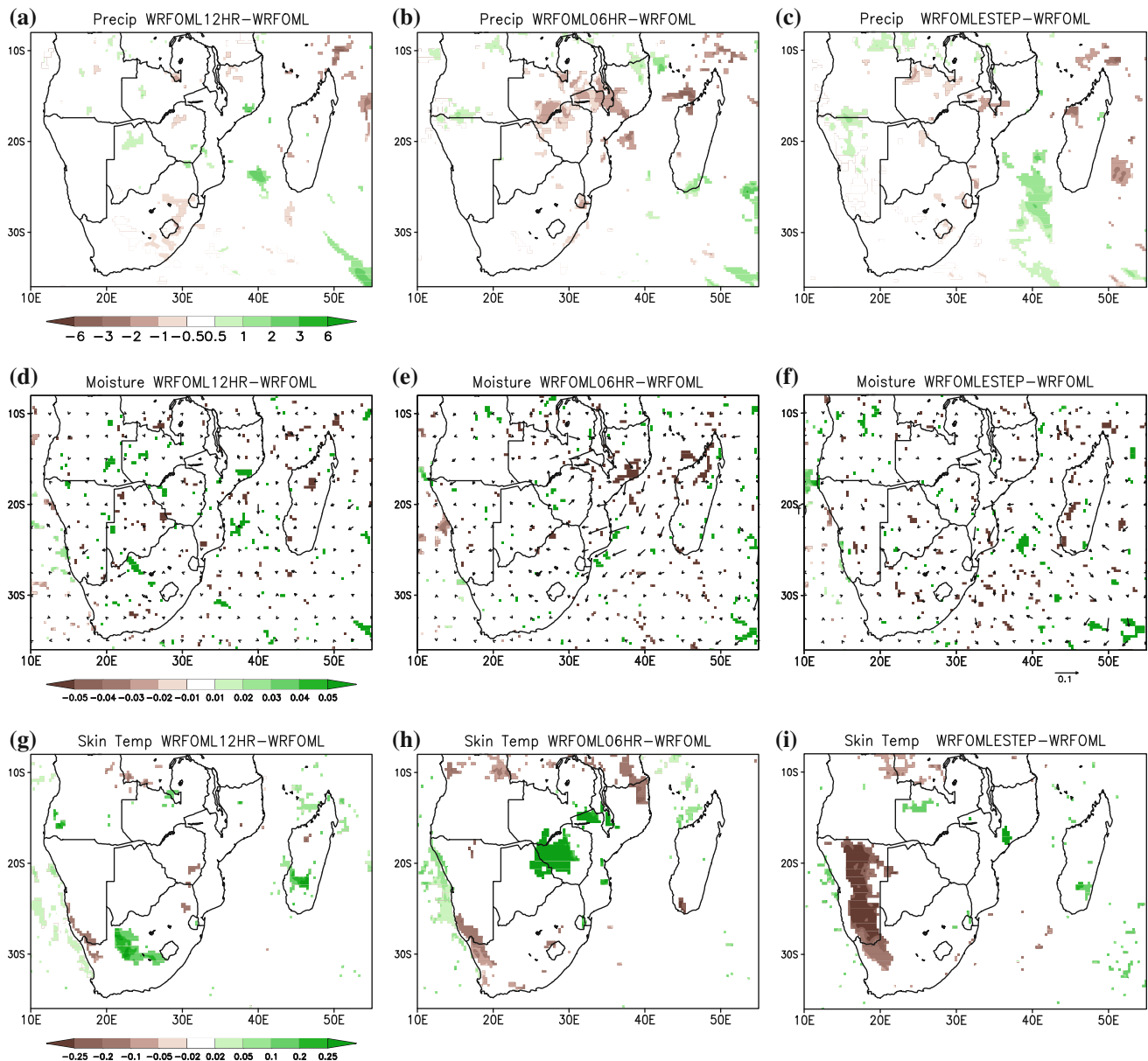


Fig. 9 **a** Difference between WRFOML12HR and WRFOML simulated average precipitation (mm/day). **b** Same as **a** but difference between WRFOML6HR and WRFOML **c** same as **a** but difference between WRFOMLESTEP and WRFOML. **d** Difference between WRFOML12HR and WRFOML simulated 850 hPa moisture convergence (g/Kg s^{-1} ; shaded) and moisture fluxes (g/Kg m/s ; vector).

e Same as **d** but difference between WRFOML6HR and WRFOML **f** same as **d** but difference between WRFOMLESTEP and WRFOML. **g** Skin temp difference between WRFOML12HR and WRFOML experiment **h** same as **g** but difference between WRFOML6HR and WRFOML **i** same as **g** but difference between WRFOMLESTEP and WRFOML. All the differences are significant at 90% using *t* test

The model simulated results were found to be insensitive to the initial depth specified to the mixed layer ocean model and also to the frequency of update of the WRF SST with the SST simulated by the simple mixed layer ocean model, partly due to the dominance of the boundary forcing which drive the WRF model.

The results of this study suggest that coupled WRF shows promise in simulating the regional climate of southern Africa during the austral summer season. Even the simple one-tier approach of coupling WRF with an ocean mixed-layer ocean

model provided encouraging results. These results assume significance for the downscaling of the seasonal forecasts over southern Africa. The two-tier approach of specifying SST forecasts issued by the various centers are prone to the biases in the forecasting models. Besides the difficulties in obtaining timely SST analyses, any faulty prescription of them would cause further error in the downscaled predictions. The SST simulated by WRFMOL with a simple mixed-layer model tends to adjust to the biases of the regional atmospheric model due to the activation of air-sea

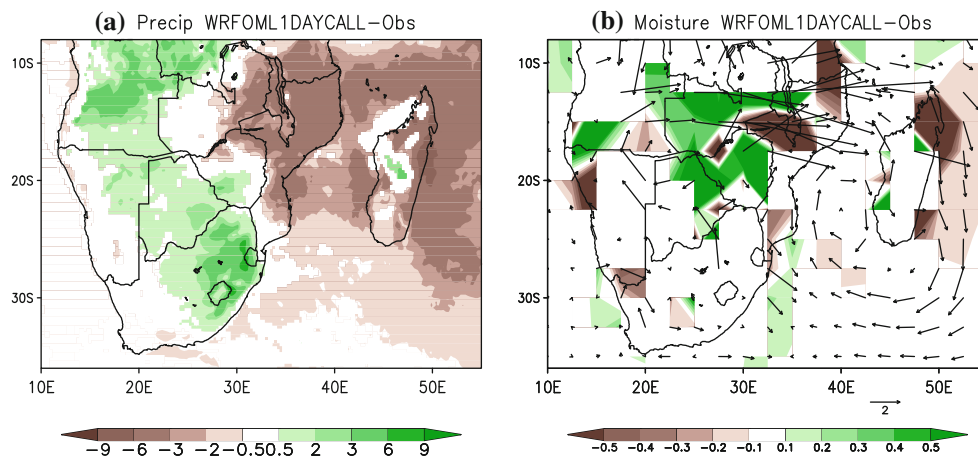


Fig. 10 **a** Precipitation bias (mm/day) simulated by the WRFOML1DAYCALL experiment. **b** WRFOML1DAYCALL simulated 850 hPa moisture convergence bias (g/Kg s^{-1} ; shaded) and moisture flux bias (g/Kg m/s ; vector). **a** and **b** are significant at 90% using t test

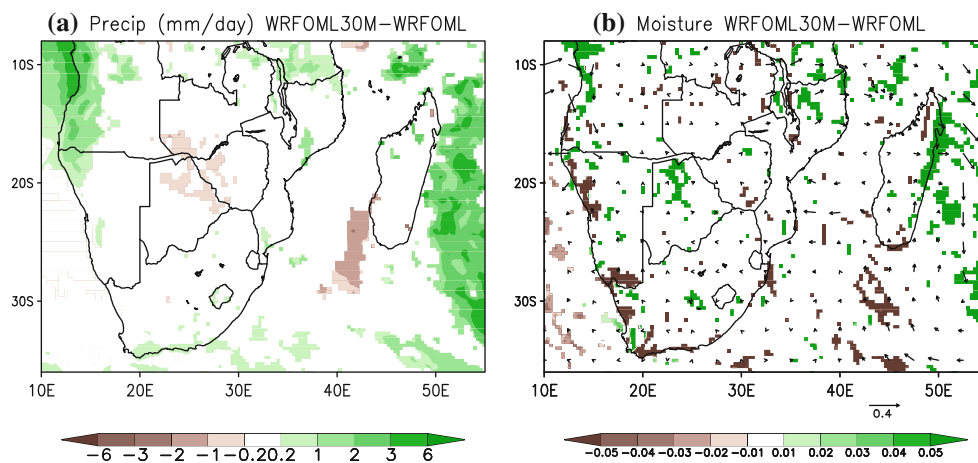


Fig. 11 **a** Difference between WRFOML30M and WRFOML simulated average precipitation (mm/day) **b** Difference between WRFOML30M and WRFOML simulated 850 hPa moisture

convergence (g/Kg s^{-1} ; shaded) and moisture fluxes (g/Kg m/s ; vector). Differences are shaded only if significant at 90% using t test

interactions, resulting in improved downscaled products. This is encouraging because, in the higher latitudes, the ocean dynamics has less influence on the atmosphere.

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