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Title	Revisiting the strong and weak ENSO teleconnection impacts using a high-resolution atmospheric model
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Citation	Atmospheric Environment, 270, 118866 https://doi.org/10.1016/j.atmosenv.2021.118866
Issue Date	2022-02-01
Doc URL	http://hdl.handle.net/2115/91107
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File Information	ManuscriptDraft_HIRAM_ENSO_Paper_2021_Final_CleanCopy.pdf



1	Revisiting the Strong and Weak ENSO Teleconnection Impacts using a High-Resolution			
2	Atmospheric Model			
3	Muhammad Mubashar Ahmad Dogar ^{1, 2*} , and Mansour Almazroui ^{3, 4}			
4				
5	ABSTRACT			
6	To evaluate the performance of a high-resolution atmospheric model (HiRAM) and to improve our			
7	understanding of the climatic impacts of ENSO forcing and associated teleconnections, we analyzed			
8	AMIP style HiRAM simulations conducted effectively at 25 km grid spacing. To better assess			
9	HiRAM response to ENSO climate variability; we categorized it into strong and weak El Niño/La			
10	Niña episodes. The HiRAM model reproduced the impacts of strong ENSO over global scale very			
11	well, however, it underestimated ENSO teleconnection patterns and associated changes over			
12	regional scale (e.g., MENA and South Asia), especially following weak ENSO that could be			
13	attributed to model weak response to circulation changes such as Pacific North American (PNA)			
14	and North Atlantic Oscillation (NAO). Moreover, our results emphasize that ENSO impacts are			
15	relatively stronger over the Inter-Tropical Convergence Zone (ITCZ) compared to extratropics and			
16	high-latitude regions. The positive phase of ENSO causes weakening in rainfall over the African			
17	tropical rain-belt, parts of South and Southeast Asia. Both the reanalysis and HiRAM results reveal			
18	that ENSO-induced negative (positive) NAO-like response and associated changes over Southern			
19	Europe and North Africa vary significantly following the increased intensity of El Niño (La Niña).			
20	We further found that the ENSO magnitude significantly impacts Hadley and Walker circulations.			
21	The El Niño phase of ENSO overall strengthens the Hadley Cell, and the reverse is true for the La			
22	Niña phase. This ENSO-induced strengthening and weakening of Hadley Cell induce significant			
23	impact over South Asian and African convective regions through modification of the ITCZ			
24	circulation system.			
25				
26	Key words: ENSO, El Nino/La Nina, NAO, MENA, Hadley Circulation, ITCZ, Monsoon System.			
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1 1. Introduction

El Niño-Southern Oscillation (ENSO) is an interannual climate variability pattern that has
tremendous affects on the climate of the tropical and subtropical regions (Trenberth et al. 1998;
Timmermann et al. 1999; Neelin et al. 1998; Trenberth and Caron, 2000; Lee et al. 2010, 2012;
Zhang et al. 2011). The warming and cooling phases of this Pacific inter-annual variability are
termed as El Niño and La Niña respectively. Both these phases have worldwide climatic
interactions with important ecological and socioeconomic implications (Timmermann et al., 1999).

8 The physical link between ENSO variability and associated temperature, precipitation and wind 9 changes at the global and regional scale has been assessed in many studies (Timmermann et al., 10 1999; Trenberth et al., 1998; Diaz et al., 2001; Ashok et al. 2001, 2004; Molteni et al., 2003; Bracco 11 et al., 2007, Kucharski et al., 2013; Kripalani et al., 2007; Dogar et al., 2019; Dogar and Shahid, 12 2019). Several past studies have shown a strong correlation between Eastern and Central Equatorial 13 Pacific sea surface temperature variability and rainfall pattern over the Pacific, Atlantic, Indian 14 Ocean and associated continental regions with focus on South Asia, Southeast Asia and Africa (Lee 15 et al., 2010; Kucharski et al. 2013; Zhang et al., 2011, 2012, 2013; Afzaal et al., 2013; Wang et al. 16 2012; Rasmusson and Carpenter, 1983]. ENSO is known to be the largest climatic forcing which 17 deals with variability of interannual monsoon system through the large-scale east-west displacement 18 of heat transfer in the tropics (Kumar et al. 1999a]).

19 Many recent studies have shown that the American, Asian, Indian, and Australian rainfall systems 20 are greatly influenced by the ENSO teleconnection (Lau et al., 2000; Bracco et al., 2007; Lean et 21 al., 2008; Kripalani et al., 2007). Numerous studies have shown the simultaneous association of 22 ENSO-indices and the rainfall over India (Pant and Parthasarathy, 1987; Ashok et al. 2001, 2004; 23 Kripalani et al. 2007; Wu et al., 2012). Using observation and reanalysis products, Singh et al. 24 (2013) investigated the mechanisms and teleconnections behind the long-term variability in the 25 Indian Ocean SST, with a particular focus on SST in the southwestern Indian Ocean tropics. This 26 study concludes that boral winter (DJF) SST is highly dependent on long-lived La Niña impacts, 27 indicating the importance of SSTs in the Indian Ocean, in addition to SSTs in the Pacific, to better 28 represent ENSO-induced teleconnections.

29 The original idea describing physical connection between ENSO forcing and South Asian monsoon 30 system, in particular the Indian monsoon, through large-scale dynamic circulation was initially 31 proposed by Gilbert Walker (Walker, 1925). Subsequently, several studies have shown that the 32 warm phase (El Niño) leads to the weakening of the Indian monsoon system with an overall 33 decrease in precipitation (Bhalme and Mooley, 1980; Rasmusson and Carpenter, 1983; Shukla and 34 Paolino, 1983; Ju and Slingo, 1995; Ashok et al. 2001, 2004; Dogar et al., 2017a). Conversely, the 35 cold phase (La Niña) is associated with an intensification of the Indian monsoon system and 36 increased precipitation [Shukla and Paolino 1983; Joo and Slingo, 1995). Many other studies have 37 also discussed the variations in the relationships between monsoonal rainfall and its predictors (Parthasarathy et al., 1991a, 1992, 1994; Ashok et al. 2001). These variations are attributed to
change in ENSO characteristics such as period and amplitude (Kumar et al. 1999b).

Previous studies have shown that the ENSO, which originates in the central Pacific and in the east Pacific, has significant variations and nonlinearities in its pattern, strength and associated climatic impacts (Frauen et al., 2014; Chung et al., 2013; Hoerling et al., 1997; Wu et al., 2020; Wu and Zhuoqi, 2019). However, it is difficult to distinguish weather these are caused by the different signs/types, strengths, or spatial patterns of such events (e.g., strong or weak El Niño events or by combinations of these).

9 In the past couple of decades, there has been an increase in both frequency and strength of 10 El Niño (La Niña) events with maximum warming (cooling) occurring in the central equatorial 11 Pacific (e.g., Latif et al., 1997; Afzaal et al., 2013; Lee et al., 2010). This is called as Central Pacific 12 (CP) El Niño (Yu and Kim, 2010; Kao and Yu, 2009), dateline El Niño (Larkin and Harrison, 13 2005), El Niño Modoki (Ashok et al., 2007) or warm pool El Niño (Kug et al. 2009). While 14 previous studies on ENSO events have discussed an increasing frequency of El Niño and La Niña 15 events in recent decades (Yeh et al. 2009; Lee et al. 2010; Timmermann et al., 1999), studies on the 16 magnitude and nonlinearity of El Niño and La Niña events are still evolving, and require further 17 research. Therefore, there is a need to look at the strength of ENSO variability and associated global 18 and regional climatic impacts. Being an important and leading mode of interannual climate 19 variability, El Niño Southern Oscillation produces significant impacts on global and regional 20 climate; hence there is a great interest in studying how the magnitude of the tropical Pacific sea 21 surface temperature would affect tropical global climate patterns (including large scale circulations) 22 and related changes in temperature and precipitation distribution.

23 Although the existence of the Hadley cell and its sensitivity to ENSO episodes has been 24 extensively investigated (Held and Hou 1980; Seager et al. 2003; Feng and Li, 2013; Nguyen et al., 25 2013), questions remain, as to how this thermally driven large-scale tropical Hadley circulation will 26 respond to ENSO strength (i.e., strong and weak ENSO). For this purpose, we will make use of a 27 high-resolution atmospheric model, HiRAM with a resolution that generally is used by regional 28 climate models in climate downscaling studies for better representation of regional climate 29 processes influenced by global scale patterns. The HiRAM has effectively been used to study global 30 and regional climatic changes (Bangalath et al., 2015; Dogar et al., 2017b; Dogar, 2018; Dogar and 31 Shahid, 2018; Dogar, 2020). In this study, we will see how well it can reproduce the impact of 32 strong and weak ENSO events at the global and regional scale. The use of high-resolution modeling 33 technique provides us a unique opportunity to examine how the ENSO-induced circulation 34 anomalies at various scales influence regional climate. To the best of our knowledge, there is rarely 35 any study pertaining to regional ENSO impacts using a Global Climate Model (GCM) at a spatial 36 resolution of about 25 km or better; hence, in this sense this study is very useful for its successors. 37 Besides, this version of HIRAM is effective in overcoming many of the limitations encountered by

1 coarse-resolution GCMs and RCMs. Due to their fine grid spacing, important processes such as 2 large-scale condensation, land-sea interaction, and topographical forcing are better resolved in high-3 resolution GCMs (Boyle & Klein, 2010; Lau & Ploshay, 2009; Harris et al., 2016). Recent studies 4 further emphasized that the regional convective structure and precipitation change are very sensitive 5 to the model horizontal resolution (Bui et al., 2019; Liu, Yu, & Chen, 2018). The idea of conducting 6 HIRAM AMIP simulations is to see if there could be any improvement in the simulations of ENSO 7 response especially at regional scale with improved resolution.

8 As Hadley circulation transport energy from equator to poleward and drives the climate of tropics 9 and extratropics. Hence, the main purpose of studying the magnitude of ENSO events is to 10 investigate the impact of El Niño/La Niña strength on the Hadley circulation and subsequent 11 temperature and precipitation distribution at the global and regional scale focusing on the tropics 12 and extratropics. We will also revisit ENSO-induced variation in temperature and precipitation over 13 the Middle East and North Africa (MENA) with focus on Arabian Peninsula in winter season as this 14 region is getting attention and have been focused in many studies (Kucharski et al., 2013; Zeng and 15 Ning 2003, Giannini et al., 2008; Dogar, 2019) because of its sensitivity and drought-like response 16 to such events. In addition, we will focus on the model performance in replicating known facts of 17 ENSO teleconnection pattern over Pacific and Atlantic region such as ENSO-induced PNA pattern 18 over the Pacific as well as ENSO-induced NAO-like pattern in North Atlantic region and associated 19 climatic effects particularly in Europe and Middle East region.

20 Therefore, the current paper deals with the comparative study of ENSO teleconnection over ITCZ 21 and extratropical regions and its effect on rainfall, particularly in Africa and the Middle East 22 extending to the East Asian region. The study also deals with the ENSO-induced modulation (i.e., 23 strengthening or weakening) of Hedley and Walker circulations that could initiate a significant 24 impact on Indian, Middle Eastern and African rainfall distribution. The rest of the paper is 25 organized as follows. Section 2 discusses material and methods including the description of the 26 model used in this study. Strong and weak ENSO episodes and their global and regional impacts in 27 the winter season are described in section 3. In the last Section, we summarized our results.

28

29 2. Material and Methods

30 2.1 Model Description

To study global and regional climate responses caused by ENSO forcing, we employed a Geophysical Fluid Dynamics Laboratory global High-Resolution Atmospheric Model (GFDL-HiRAM) effectively at 25 km horizontal grid resolution. The HiRAM model uses a cubed-sphere finite-volume dynamical core that is based on GFDL's Atmospheric Model version 2 (AM2; *Putman and Lin, 2007; Anderson et al., 2004*) with increased horizontal and vertical resolutions (32 vertical layers instead of 24 for better representation of stratospheric processes and its coupling with the troposphere), as well as simplified parameterizations for moist convection and large-scale stratiform cloudiness. HiRAM uses a new grid-point dynamical core along with a prognostic cloud scheme, multi-species aerosol climatology as well as components from previous models used at GFDL. However model retains the surface flux, land surface, gravity wave drag, boundary layer, radiative transfer modules, and large-scale cloud microphysics of AM2 (*Anderson et al. 2004; Zhao et al. 2009*). Soil processes considered in HiRAM are calculated using a land model known as LM3 that includes soil sensible and latent heat storage, groundwater storage, and stomata resistance (*Anderson et al., 2004*).

8 The shortwave (SW) radiation processes are calculated using Freidenreich and Ramaswamy (1999) 9 algorithm. The SW radiation spectrum ranges from 0.17 to 4.0 µm, which is divided into 25 bands, 10 10 in the near IR region, 4 bands in the visible and 11 bands in the UV region and includes 11 absorption by H₂O, CO₂, O₃, O₂ as well as Rayleigh scattering. The longwave (LW) radiation code 12 is based on a modified form of the simplified exchange approximation (Schwarzkopf and 13 Ramaswamy, 1999). It accounts for the absorption and emission by the principal gases present in 14 the atmosphere including H₂O, O₃, CO₂, N₂O, CH₄, and the halocarbons CFC-11, CFC-12, CFC-15 113, and HCFC-22. Aerosols and clouds are treated as absorbers in the longwave, with non-grey 16 absorption coefficients specified in the eight spectral bands of the transfer scheme, following the 17 methodology adopted in Ramachandran et al. (2000). A detailed description of the HiRAM model 18 and related publications is available at http://www.gfdl.noaa.gov/HiRAM.

19

20 2.2 Experimental Design and Methodology

21 In this study, we used HiRAM simulations at C360 (~25 km) horizontal resolution, typically a range 22 that most of the regional climate models (RCMs) use in climate downscaling. This allows us to 23 study global and regional climatic processes using a global climate model (GCM) that fully 24 accounts for regional and global scale interactions, which are especially important in the tropics. 25 The model is forced with observed monthly SST from the Hadley Centre Sea Ice and Sea Surface 26 Temperature (HadISST) data set (Rayner et al., 2003). Three parallel simulations each of 33 years 27 simulation period (1976-2008) are conducted by taking into account greenhouse gases and volcanic 28 forcing. The aerosol spatial time distribution and optical characteristics of volcanic aerosols (that 29 were released by the volcanic eruption events in the simulation period) are calculated following 30 Stenchikov et al. (2006). To reduce the uncertainty (due to internal noise) in the model results, an 31 ensemble averaging over three HiRAM realizations is used. These three realizations were produced 32 using different initial conditions obtained from several integrations of the atmosphere-only model. 33 The first realization uses SST of Jan 1976, whereas second and third realizations use Jan 1977 and 34 Jan 1978 respectively from HadISST. In order to avoid spin-up effects, first three years of the 35 integration (1976-1978) in each realization are not included in the analysis. Model is run in 36 Atmospheric Model Inter-comparison Project (AMIP) mode with observed SST and sea ice 37 concentration determined from the HadISST data set. The sea-ice model assumes that each grid1 point is either fully ice-covered or ice-free and also considers a uniform ice thickness of 2 meters.

Anthropogenic greenhouse gases (GHGs), natural forcings, ozone, landuse and other possible
forcings data set (anthropogenic aerosols concentration in the atmosphere etc.) used in the model
follows AMIP historical simulation setup.

5 For comparison of the HiRAM response, we used NCEP-climate forecast system reanalysis (CFSR)

6 data. CFSR is a high-resolution reanalysis data produced using NCEP coupled atmosphere-ocean-7 land surface-sea ice model (coupled with GFDL MOM version 4 and a two-layer sea ice model). 8 Most of the available in-situ and satellite observations are included in the CFSR. Satellite 9 observations are used in form of radiance, rather than retrieved values, and are bias-corrected with 10 "spin up" runs at full resolution. It is a recent NCEP reanalysis data that assimilates surface 11 observations, satellite radiances, CO₂, aerosols (including volcanic aerosols), and solar variations 12 using a high-resolution atmospheric model at T382 (~38 km) horizontal resolution with 64 vertical 13 levels ranging from the surface to 0.26 hPa. Annual averages of time-varying CO₂ concentration 14 including other radiatively absorbing gases; stratospheric volcanic aerosols and downward solar 15 radiation flux in CFSR are specified as described in Saha et al. (2010).

16 The ocean effect is included as we used observed SST that takes into account the ocean feedback. It 17 is not interactive, but it allows us to correctly account for such an aspect of natural variability as El 18 Niño. Typically, coupled models could have a problem in correctly reproducing the phase and 19 magnitude of the ENSO, so in this case we have an "ideal" observed SST forcing. Using 20 atmospheric model with the prescribed SST is, of course, an idealized approach, but fairly 21 reasonable one, as demonstrated in previous studies (Stenchikov et al., 2002; Dogar et al., 2017b). 22 The ocean effect in our simulations is not interactive but it is not absent. The observed SSTs, used 23 in the calculations, account for the ocean effect. Thus, in our simulations the atmospheric response 24 is fully interactive, and is constrained by observed ocean boundary conditions. This approach 25 allows us to more reliably evaluate the contributions of different processes and compare our results 26 with observations.

27 For strong El Niño episodes, we composited all the winter (DJF) seasons during the period 1979-28 2008 that have SST anomaly equal or greater than 1.5 K over the Nino3.4 region. Whereas for the 29 case of weak El Niño, we composited all the winter seasons with SST anomaly with magnitude 0.5 30 to 1.5 K. For the case of La Niña, a same approach is applied, however, the SST anomaly values 31 over the Nino3.4 region is negative. For details regarding strong or weak ENSO episodes, the 32 readers may visit the link https://ggweather.com/enso/oni.htm. As ENSO predominantly 33 triggers/peaks in winter, therefore, we have presented anomalous signals for strong and weak ENSO 34 episodes in boreal winter (DJF) season only. The impact of stronger and weaker ENSO magnitude 35 is calculated as a simple departure of the stronger and weaker El Niño and La Niña composited 36 averages from the long-term winter (DJF) climatology that includes all the El Niño and La Niña 37 events in the simulation period (1979-2008) and roughly corresponds to neutral phase. The HiRAM

simulation results are compared with a high-resolution CFS Reanalysis (CFSR) product.

2

3 **3.** Results and Discussion

4 Before examining the impacts of strong and weak ENSO forcing at the global and regional scale, 5 we assessed the performance of HiRAM AGCM. Figure 1 shows the climatology pattern of 2m 6 surface temperature and rainfall superimposed with wind vectors produced using CFSR and 7 HiRAM model. These climatology maps clearly show that HiRAM model reproduces both 8 qualitatively and quantitatively the basic features of temperature and precipitation very well. The 9 convergence zones and cyclonic flow patterns in the Northern Hemisphere shown by zonal and 10 meridional wind vectors are well captured by the model simulation. This comparison increased our 11 confidence in the HiRAM simulation that motivated us to use this model for the assessment of 12 ENSO magnitude at the global and regional scale. Therefore, to have a better representation of the 13 ENSO-induced teleconnection patterns, we analyzed anomalous atmospheric responses following 14 the El Niño and La Niña events composited over the period of 1979-2008 (see methodology), as 15 discussed in the following sections.

16

17 **3.1 Strong ENSO Winter Impacts**

18 Figure 2 shows the global anomalous response of surface temperature at 2m following strong El 19 Niño and La Niña forcing in CFSR and HiRAM. Both the HiRAM and CFSR results show strong 20 warming over the eastern part of the tropical Pacific extending towards North America (Eastern and 21 Central America) as well as over Eurasia with strong cooling anomalies in the western Pacific 22 Ocean as well as over the Arctic Ocean. This El Niño-induced warming pattern seen in the tropical 23 Eastern Pacific extending further into North Pacific and Central American region resembles a well-24 known horseshoe-like warming pattern. We also observed strong warming over parts of 25 Southwestern Europe, Southern Africa, the Indian Ocean, and Australia. We noticed that the model 26 well reproduced the observed features at the global scale with slight underestimation of the cooling 27 signal over the Arctic region as well as the Arabian Peninsula and North Africa. This 28 underestimation could be accounted for due to HiRAM weak response to ENSO-induced 29 stratospheric polar vortex variation (i.e., weakening or strengthening) following El Nino/La Nina 30 events and associated NAO-like pattern. The stratospheric polar vortex and associated NAO-like 31 response are underestimated in HiRAM, like other global models, and therefore the associated 32 temperature (i.e., cooling) response following El Nino in the high-latitude (i.e., mid-latitude and 33 polar regions) is underestimated in HiRAM compared to CFSR. Polar vortex is a stratospheric 34 phenomenon that is transported to surface through tropospheric-stratospheric interactions. These 35 polar vortex changes (strengthening or weakening) following ENSO events effects polar jets that in 36 turn produce strong changes in the mid-latitude and polar regions. HiRAM has a lower model top 37 (that covers lower stratosphere, model top reaches 10 hPa) compared to CFSR (that covers entire

1 stratosphere, model top reaches 0.1 hPa), which could be one of the reason that the HiRAM 2 underestimates weakening (i.e., breakdown) or strengthening of polar vortex and associated 3 circulation changes following internal or external climate forcing (Dogar, 2018; DallaSanta et al., 4 2019; Marathe & Karumuri, 2021; Dogar, 2019). Further discussion regarding HiRAM 5 underestimation to ENSO forcing can be seen in supplementary Fig. S1 and S2. A reverse 6 anomalous pattern is roughly observed following strong La Niña episode both in the HiRAM and 7 NCEP-CFSR except over the Arabian Peninsula as well as over North America and Eurasia where 8 the cooling or warming signals are not anti-symmetric following strong El Niño and La Nina 9 episodes. This ENSO-induced (El Niño/La Niña) tropical warming/cooling pattern outspreading to 10 the Arctic and North American region is caused by a well-known ENSO-induced tropically excited 11 Arctic warming/cooling mechanism following the strong El Niño/La Niña events. In this tropically 12 excited Arctic mechanism, the pole-ward propagating Rossby waves can warm/cool the Arctic 13 region through adiabatic warming/cooling mechanism, an enhanced pole-ward stationary eddy heat 14 transport, and downward infrared radiation (Saravanan, 1993; Lee et al. 2012).

15 We also noticed a strong El Niño/La Niña-induced cooling/warming pattern over 16 Northern/Southern Africa that could be accounted for by large-scale dynamic circulation and 17 associated diabatic processes driven by Walker circulation and its transport from the tropics towards 18 extratropics through the latitudinal thermal gradient. Another mechanism of this African continental 19 cooling/heating could be explicated through convectively generated Rossby waves. These waves 20 emanate from the equatorial Pacific, moving eastward in circular paths resulting in wind and 21 pressure changes that play a key role in the transport of heating or cooling anomalies in the tropics 22 and outside the tropics (Jin and Hoskin 1995; Servan, 1993; Kiladis et al. 2009; Lee, 2012). 23 Temperature anomalies induced by strong El Niño forcing are very much consistent between the 24 model and CFSR. The anomalous 2m-temperature response following the La Niña forcing is 25 roughly opposite to the El Niño forcing. It suggests that the La Niña forcing will induce stronger 26 cooling over North America, Europe, Arabian Peninsula, and the African domain. From the spatial 27 anomaly pattern of surface temperature at 2m, we noticed that the HiRAM model reproduces the 28 impact of ENSO over the Pacific, North and South America very well and our results are consistent 29 with earlier studies (Sterl et al. 2007; Lee, 2012; Wang et al. 2012). However, it underestimates 30 ENSO teleconnection pattern and associated changes over the Middle East and North Africa 31 particularly over the Arabian Peninsula region, covering the Red Sea which could be accounted for 32 by the variations of ENSO-induced circulation changes (e.g., PNA and NAO) that could not be well 33 reproduced by the model as it has been noticed that the HiRAM model, like other up-to-date climate 34 models, underestimates the response of NAO in winter (Dogar, et al., 2017b; Driscoll et al., 2012). 35 Figure 3 shows the response of precipitation in winter season following strong El Niño and La Niña

events. The pattern of precipitation anomaly following both the El Niño and La Niña shows a
stronger signal over the tropics compared to extratropics. The spatial pattern of precipitation

1 anomaly (mm/d) reveals that El Niño forcing causes an increase in precipitation over the east and 2 central equatorial Pacific region and a decrease in precipitation in the western Pacific. This is 3 consistent with the warm anomaly in the east and central equatorial Pacific and cold anomalous 4 signal in the western Pacific Ocean, respectively, as observed in the 2m-temperature pattern (Figure 5 2). These warm (cold) surface features produce more (less) moisture transport that result in 6 increased (decreased) rainfall anomalies over the equatorial regions. We find that the strong El Niño 7 (La Niña) forcing typically reduce (intensifies) precipitation over the southern Africa in particular 8 southeastern region, resulting in dry (wet) conditions, while increasing (reducing) precipitation over 9 the northeastern tropical region.

We also noticed that El Niño-induced warm anomaly over the tropics causes more precipitation over the ascending branch (i.e., ITCZ) of the Hadley cell. Subtropical regions that fall within the downward or sinking branch of Hadley cell exhibit reduced precipitation anomalies which are very much in agreement among CFSR and HiRAM. Since the latitudinal position of the rising and sinking limbs of local Hadley cell varies at the regional scale, therefore increasing and decreasing pattern of precipitation anomalies over the tropical region corresponds to the position of the ITCZ at the regional scale.

17 A positive precipitation anomaly and cyclonic circulation response are seen near the California 18 coast and Aleutian region as well as in the Gulf of Mexico, Cuba, and Florida region, extending 19 further into the western Atlantic. El Niño also causes a decrease in precipitation over Bay of 20 Bengal, Sri Lanka, Thailand, Australia, and Columbia. This ENSO-induced winter precipitation 21 anomaly for the El Niño forcing is consistent with earlier studies showing a comparison of 22 precipitation anomaly between NCEP reanalysis and SPEEDY AGCM by regressing the 23 normalized Nino3.4 index with winter precipitation (Sterl et al. 2007; Kucharski et al. 2013). The 24 overall pattern of ENSO-induced precipitation changes over global and regional scale is well 25 reflected in HiRAM simulation and is in good agreement with CFSR and earlier studies (Dogar et 26 al., 2017a; Kucharski et al., 2013). Precipitation anomalies for La Niña conditions are roughly 27 opposite to that of El Niño. A dipole pattern of precipitation anomalies in high-latitudes (between 28 30-60°N and 30-60°S) following both El Niño and La Niña forcing could be associated with the 29 ascending and descending branch of the Ferrell cell.

30 In order to have a better idea of ENSO-induced changes in the tropical Hadley circulation, we have 31 plotted vertical velocity (Omega in Pa/sec) overlaid with ascending and descending air produced by 32 globally zonal averaged meridional and vertical wind profile (Fig. 4). These results suggest that 33 both the El Niño and La Niña induce strong impact over the tropical atmospheric Hadley circulation 34 as both the vertical velocity and the intensity of the wind vectors have increased significantly 35 following strong El Niño event. We further noticed that strong El Niño forcing induces 36 strengthening and equatorward shift to Hadley cell (sinking limbs are stronger and confined within 37 10-25° latitude in both hemisphere) whereas the La Niña causes weakening to the Hadley cell

1 circulation. The structure of zonally averaged zonal wind anomaly following El Niño and La Niña 2 episode in winter season shows that the El Niño produces strengthening and equatorward shifting to 3 the jet streams (not shown). This ENSO-induced strengthening and equatorward shift of jet streams 4 leads to a narrower but intense Hadley cell circulation (Figure 4) because of increased eddy stress 5 (Lee, 2012). The response of Hadley cell to La Niña forcing is almost opposite to El Niño forcing. 6 Figure 5 presents ENSO-induced changes in tropical Walker circulation which shows consistent 7 pattern of rising and sinking limbs between CFSR and HiRAM. These El Niño-induced rising 8 patterns of the wind vectors over the tropical Pacific and the tropical Indian Ocean match with El 9 Niño-induced sea surface temperature (SST) warming in the tropical Pacific and the tropical Indian 10 Ocean (Figure 2). This ENSO-induced perturbation of the Walker circulation causes major shifts in 11 atmospheric circulations, rainfall patterns, and seasonal climate around the globe.

12 Figure 6 shows the response of geopotential height anomaly at 850 hPa following strong El Niño 13 and La Niña phases from HiRAM and NCEP-CFSR in winter (DJF) season. During strong El Niño 14 forcing geopotential height at 850 hPa shows a strong negative anomaly over the high-latitude 15 region (between 30-60N) in the Pacific Ocean extending towards the Atlantic ocean and a signature 16 of high anomalies over rest of the tropical belt particularly over the Indian Ocean focusing the 17 Arabian Sea that extends further to land areas of Africa, South, and Southeast Asia (Sterl et al., 18 2007). Similarly, we observed signature of negative anomalies in high-latitude northern polar 19 regions and positive anomalies in the Southern Ocean. The anomaly of significant high and low 20 pressure further elongates zonally to the Atlantic Ocean and resembles a positive NAO-like 21 anomalous pattern over the Atlantic Ocean (Zhang et al. 2015). This positive NAO-like pattern will 22 produce a significant impact over Northern and Southern Europe extending to the Middle East and 23 North African region and induces cold and wet anomalies as seen in 2m surface temperature and 24 precipitation (Fig. 2 and Fig. 3 respectively) patterns (Shindel et al. 2004; Yu and Zhou, 2004; 25 Fischer et al. 2007). The mechanism that could explain this positive NAO-like pattern and 26 associated effects over Europe focusing southern Europe, Arabian Peninsula and North African 27 domain is caused by the convectively generated coupled Rossby waves (Saravanan, 1993; Jin and 28 Hoskins, 1995; Kiladis et al. 2009; Lee, 2012). The La Niña phase also displays a positive NAO-29 like pattern over the North Atlantic region that will also result in cooling and drying anomalies over 30 Southern Europe and MENA region. Interestingly, the ENSO-induced NAO-like response over the 31 North Atlantic Ocean is more pronounced in the CFSR results than in HiRAM therefore associated 32 changes over Europe and MENA are also slightly underestimated in HiRAM response. These 33 results reveal that the climatic impacts of ENSO over the global and regional scale are very 34 sensitive to the intensity of ENSO and its warming and cooling phase in the tropical Pacific Ocean. 35 The geopotential height response and associated climatic patterns in the North Pacific are caused as 36 a result of a well-known boreal winter ENSO teleconnection pattern induced by the Rossby wave

1 source in the tropics that propagates towards extra-tropics and forms a quasi barotropic structure. 2 This wave train effect projects onto the Pacific North American (PNA) pattern, and the Aleutian 3 low. This prominent teleconnection associated with ENSO (El Niño/La Niña) events has been 4 referred to as the PNA pattern accompanied by an intensified Aleutian low during ENSO warm (El 5 Niño) phase. Corresponding to the ENSO (La Niña) cold phase, a positive geopotential height 6 anomaly covers the North Pacific indicating a weakened Aleutian Low during the La Niña events. 7 This type of pattern is anticipated to induce energy transport among tropics, extra-tropics and high-8 latitude regions following El Niño and La Niña forcing (Lee, 2012). Figure 7 shows the pattern of 9 geopotential height anomaly at 200 hPa following strong El Niño and La Niña forcing. This upper 10 level geopotential height anomaly is high in the tropics and low in the subtropical region because 11 the positive ENSO phase (El Niño) overall warms the tropical atmosphere. This leads to high 12 geopotential height anomalies at the upper levels as a result of hydrostatic equilibrium. The 13 geopotential height is lower in the more northern latitudes because of wave propagations of various 14 types. This upper-level geopotential height anomaly is stronger over the tropical Pacific Ocean 15 compared to the rest of the tropical regions, which is associated with the El Niño-induced strong 16 tropical Pacific warming pattern. These results are qualitatively consistent with observational, 17 reanalysis and model based studies showing Nino3.4 regressed anomalous pattern of geopotential 18 height changes (Sterl et al. 2007; Kucharski et al. 2013; Dogar et al., 2017a). Responses of 19 geopotential height anomalies following strong La Niña episodes display a mirror image to their El 20 Niño counterparts.

21 **3.2 Weak ENSO Winter Impacts**

22 Figure 8 shows the global anomalous response of 2m surface temperature following weak El Niño 23 and La Niña forcing in CFSR and HiRAM. Both the HiRAM and CFSR results show strong 24 warming over the tropical eastern Pacific extending towards North America (Eastern and Central 25 America) as well as over Eurasia with weak cooling signatures in the Western Pacific and Arctic 26 Oceans. We also noticed a strong warming pattern over parts of South Western Europe, Africa, the 27 Indian Ocean, and Australia. Model is reproducing the observed features very well at the global 28 scale with underestimation of the cooling signal over Eurasia. A circumpolar westerly jet, confining 29 the coldest temperatures over the Arctic, characterizes the wintertime stratospheric polar vortex. 30 This underestimation could be accounted for by the strength of ENSO-induced stratospheric polar 31 vortex and associated circulation changes (supplementary Figs. S1 and S2). The stratospheric polar 32 vortex in winter and associated tropospheric and surface circulations (e.g., polar jets and NAO-like 33 response at surface) are underestimated in HiRAM, and therefore the warming/cooling response 34 following weak El Nino/La Nina in the Eurasian region is not well captured by HiRAM compared 35 to CFSR. We also observed differences over northern Europe and the northern part of Eurasia 36 where the HiRAM model shows strong cooling compared to CFSR, which shows warming. A

1 reverse anomalous pattern is roughly observed following weak La Niña episode both in the model 2 and NCEP-CFSR except the Eurasian region where we saw strong warming in Model results and 3 cooling response in CFSR. Moreover, the cooling signal over the North American region following 4 weak La Niña is stronger in the CFSR results whereas it is weaker in the HiRAM results. These 5 results suggest that the HiRAM model struggles in reproducing the teleconnection response for 6 weaker ENSO, especially over Eurasia, parts of the Arabian Peninsula, and America. This ENSO 7 (El Niño/La Niña)-induced tropical warming/cooling pattern extending to the Arctic and North 8 American region is caused by a well-known ENSO-induced tropically excited Arctic 9 warming/cooling mechanism following the El Niño/La Niña forcing. In this tropically excited 10 Arctic mechanism, the pole-ward propagating Rossby waves can warm/cool the Arctic through 11 adiabatic warming/cooling mechanism, an enhanced pole-ward stationary eddy heat transport, and 12 downward infrared radiation (Saravanan, 1993; Lee et al., 2012). We noticed that the La Niña 13 forcing induces a stronger cooling over the tropical central Pacific that propagates to North 14 America, Europe, Arabian Peninsula, and South Africa. From the spatial anomaly pattern of 2m 15 surface temperature, we noticed that the HiRAM model reproduces the impact of ENSO over the 16 Pacific, North and South America reasonably well and simulated results are in agreement with 17 earlier studies (Lee, 2012; Wang et al., 2012; Sterl et al., 2007), however, it underestimates and 18 gives feeble responses to weak ENSO teleconnection pattern and associated changes over the Indian 19 subcontinent, Eurasia, parts of Southern Europe, Northern and Central America, parts of Arabian 20 Peninsula including the Red Sea, which could be accounted for by the variations in stratospheric 21 and tropospheric aerosol impact caused by two major eruptions falling in the simulation period 22 during ENSO events. It could also be attributed to ENSO-induced circulation changes (e.g., NAO) 23 that like other models are not well reproduced by HiRAM (Driscoll et al., 2012; Dogar et al., 24 2017b).

25 Figure 9 shows the response of precipitation anomaly (mm/d) in the winter season following weak 26 El Niño and La Niña events. The pattern of precipitation anomaly following both El Niño and La 27 Niña shows a stronger signal over the tropics compared to extratropics. The spatial pattern of 28 precipitation anomaly indicates that El Niño forcing is causing an increase in precipitation over the 29 east and central equatorial pacific region and decreased precipitation in the western pacific. This is 30 consistent with the warm anomalous pattern in the east and central equatorial Pacific and cold 31 anomalous pattern in the western equatorial Pacific respectively as observed in 2-m surface 32 temperature pattern (Figure 8). These warm (cold) surface features cause more (less) moisture 33 convergence, resulting in increased (decreased) rainfall anomalies over the equatorial regions. We 34 also noticed that El Niño induced warm anomaly over the tropics causes more precipitation over the 35 upward branch (i.e., ITCZ) of the Hadley cell. Subtropical regions that fall within the descending or 36 sinking branch of Hadley cell display reduced precipitation anomalies which are very much in

1 agreement among CFSR and HiRAM. As the latitudinal position of the ascending and descending 2 limbs of local Hadley cell varies at the regional scale (Schwendike, 2014), therefore, the increase 3 and decrease in precipitation anomalies over the tropical region follow the position of ITCZ at the 4 regional scale. The overall pattern of precipitation changes caused by ENSO on the global and 5 regional scale is well reflected in HiRAM simulation, and it is in good agreement with CFSR and 6 earlier studies (Kucharski et al. 2013). The precipitation anomalies obtained for La Niña conditions 7 are roughly opposite to El Niño impact, however, we noticed some differences in the model 8 responses especially following weak La Niña that could be accounted for by model underestimation 9 to circulation changes (Dogar and Sato, 2018; 2019).

10 To have a better idea of weak ENSO-induced changes in the tropical Hadley circulation, the vertical 11 velocity (Omega in Pa/sec) overlaid with rising and sinking air produced by globally zonal averaged 12 meridional and vertical wind profile are plotted (Fig. 10). These results reveal that, similar to strong 13 ENSO, both the weak El Niño and La Niña also induce a strong impact on the Hadley circulation as 14 both the vertical velocity and the intensity of the wind vectors have increased significantly 15 following the weak El Niño event. We further find that the El Niño induces strengthening and 16 equatorward shift of Hadley cell (i.e., sinking limbs are strong and confined within 10-25° latitude 17 in both hemispheres) whereas La Niña causes a reverse pattern. Although the model well captures 18 the rising and sinking branches of the Hadley cell, nevertheless the intensity is much weaker in the 19 model response compared to the CFSR. The pattern of zonally averaged zonal wind anomaly 20 following El Niño and La Niña episodes in the winter season shows that the El Niño forcing 21 produces strengthening and equatorward shift to the jet streams (not shown). This ENSO-induced 22 strengthening and shift of jet streams towards equator result in a narrower but intense Hadley cell 23 (Figure 4) because of increased eddy stress. The results of Hadley cell response to La Niña are 24 almost opposite to El Niño forcing. Figure 11 presents ENSO-induced changes in tropical Walker 25 circulation, which show a consistent pattern of rising and sinking limbs between CFSR and 26 HiRAM. However, the intensity of the model response is much weaker compared to CFSR and 27 there also exist some variations such that the model shows a rising pattern at 60°W while the 28 reanalysis shows a mixed pattern.

Figure 12 shows the response of geopotential height (GH) anomaly at 850 hPa following weak El Niño and La Niña phases from HiRAM and NCEP-CFSR in the winter season. The geopotential height at 850 hPa following weak El Niño forcing shows a negative anomaly structure over the high-latitude region (between 30-60°N) in the Pacific and North Atlantic Oceans. A signature of positive anomalies is seen over the tropical belt particularly over the Indian Ocean focusing the Arabian Sea that extends further to land areas such as Australia, Africa, South Asia, and Southeast Asia (Sterl et al. 2007). Similarly, we observed negative anomaly signature in the Arctic region and

1 slight positive anomaly signature in the Antarctic region (especially in the HiRAM response) 2 following the weak El Niño. The anomaly of high and low pressure over the Pacific region 3 elongates zonally to the Atlantic Ocean and resembles a positive NAO-like pattern over the Atlantic 4 Ocean (Zhang et al. 2015). However, the magnitude of this geopotential height anomaly is weak 5 following weak ENSO forcing. This positive NAO-like pattern produces significant impacts over 6 Northern and Southern Europe, extending to the MENA region, with cold and wet anomalies as 7 seen in 2m surface temperature and precipitation (Fig. 8 and Fig. 9 respectively). However, the 8 magnitude of these responses is much weaker. This NAO-like pattern and associated effects over 9 Europe focusing southern Europe, Arabian Peninsula, and North African domain is caused by 10 convectively generated coupled Rossby waves (Lee, 2012; Jin and Hoskins, 1995; Kiladis et al. 11 2009). The La Niña phase also exhibits a positive NAO-like pattern in the North Atlantic region, 12 leading to cooling and drying anomalies in Southern Europe and MENA region. Nevertheless, 13 HIRAM does not well capture this NAO-like response and gives different pattern following weak 14 La Niña event. As explained earlier, the ENSO-induced geopotential structure that resembles NAO-15 like response over the North Atlantic Ocean is more pronounced in CFSR than HiRAM, so the 16 associated changes over Europe and MENA are also slightly underestimated in the HiRAM 17 response. Moreover, the responses both following El Niño and La Niña are somehow varying 18 between HiRAM and CFSR. These results suggest that the climatic impacts of ENSO on the global 19 and regional scales are very sensitive to the intensity of ENSO in the tropical Pacific. The 20 geopotential height response in the North Pacific is caused as a result of a well-known winter ENSO 21 teleconnection pattern induced by the Rossby wave source in the tropics that propagates towards 22 extra-tropics and forms a quasi barotropic structure. This wave train effect is weaker following 23 weak ENSO episodes. Therefore, the PNA and NAO-like structures observed after strong ENSO 24 episodes are not much obvious after weak ENSO episodes. Figure 13 shows the pattern of 25 geopotential height at 200 hPa following weak El Niño and La Niña forcing. The response of 26 geopotential anomaly at the tropical Pacific region resembles the Matsuno-Gill type pattern in the 27 tropical Central Pacific (Gill, 1980). However, its magnitude following weak ENSO forcing is 28 weaker than strong ENSO forcing. This upper-level geopotential height anomaly following El 29 Niño/La Niña is high/low in the tropics and low/high in the subtropics because the positive/negative 30 ENSO phase overall warms/cools the tropical atmosphere. This leads to high/low geopotential 31 anomalies in the upper levels as a result of hydrostatic equilibrium. The height is lower in the more 32 northern latitudes because of wave propagations of various types. This upper-level geopotential 33 height anomaly is stronger over the tropical Pacific compared to the rest of the tropics, which is 34 associated with the El Niño-induced tropical Pacific warming pattern. These results are qualitatively 35 consistent with earlier observational and modeling studies showing Nino3.4 regressed anomalous 36 pattern of geopotential height changes (Dogar et al., 2017a; Kucharski et al. 2013; Sterl et al. 2007). 37 We noticed that the response of the geopotential height anomaly following the La Niña episode

does not reflect a reverse pattern over the tropics or extratropics. Moreover, the response of model
is also not very similar to CFSR over high-latitude regions in both hemispheres, especially in the
Arctic and Antarctic areas.

4 **3.3 Response of MENA and Asia to Strong and Weak ENSO**

5 To better highlight model response regional climate response of the HiRAM model to strong and 6 weak ENSO forcing, we looked at the response of 2m surface temperature and precipitation over 7 the MENA regions. We focused on the MENA and Asia, as these regions are among the most 8 sensitive regions and several studies previously used HiRAM model to better understand the 9 climate of these regions (Bangalath and Stenchikov, 2015; Dogar et al., 2017b; Dogar and Sato, 10 2018; 2019). Figure 14 shows the case of strong ENSO forcing over the MENA and Asian region. 11 ENSO-induced warming over Northern Europe, Russia, and the tropical Indian Ocean region and 12 cooling over Africa, the Middle East, and the Asian region is consistent among the reanalysis and 13 HiRAM. However, we noticed this warming and cooling structure is more pronounced in the 14 reanalysis compared to the model that could be associated with the global climate model's weak 15 response to ENSO-induced circulation changes (Dogar et al., 2017b; Dogar and Sato, 2018; 2019; 16 Robock, 2012; Timmreck 2012). The warming and cooling anomaly following strong La Niña is 17 also somehow consistent between the model and the reanalysis except for Central Africa, and India 18 where there appeared a different anomalous structure that could be associated to model weak 19 response to ENSO-induced circulation changes such as ENSO-induced NAO-like response. Figure 20 15 shows the precipitation changes over the MENA region following strong El Niño and La Niña 21 forcing. The strong El Niño forcing causes enhanced precipitation over the Arabian Sea and 22 decreased precipitation over the Bay of Bengal. The structure of precipitation response is largely 23 consistent between the HiRAM and the CFS reanalysis. However, there exists slight variation over 24 the Indian Ocean following the La Niña forcing. Moreover, we noticed that the response of weak 25 ENSO forcing on the MENA region is much different and the HiRAM model gives a different 26 structure of 2-m surface air temperature over Europe and the Eurasian region (Figure 16), 27 suggesting that the weak ENSO forcing response is not well reproduced by HiARM model over the 28 MENA and Asia. The structure of precipitation response, especially over Europe, India including 29 the Arabian Sea is also different between the model and the reanalysis following weak La Niña 30 forcing in the winter season (Figure 17). Supplementary Figures S1 and S2 and associated 31 discussion regarding HiRAM response to circulation changes could account for discrepancies/biases 32 between HiRAM and CFSR. This supplementary analysis highlights the importance/need of air-sea 33 coupling (for better simulation of ENSO-induced thermal changes) and enhanced model top (to 34 better account for stratospheric processes, e.g., polar vortex changes and NAO-like teleconnection). 35 Therefore, systematic improvements in GCMs are needed to better simulate ENSO-induced 36 circulation changes and associated climatic impacts especially for MENA region, which being part of the Hadley cell, is sensitive to internal and external climate drivers (e.g., aerosol forcing or internal variability). Due to low model top, vertical variations of stratospheric dynamics and the impact of the stratospheric polar vortex are underestimated in HiRAM. Hence, by considering airsea coupling and increased model top in high-resolution AMIP-type simulations could improve the biases between the observations and simulation following strong and weak ENSO forcing.

6

7 4. Summary and Conclusions

8 The present study is an attempt to evaluate the role of ENSO intensity (i.e., strong and weak El 9 Niño/La Niña) in causing global and regional climate changes using a very high-resolution 10 atmospheric model (HiRAM), effectively at 25 km grid spacing. HiRAM simulated responses to 11 ENSO strength using 2m surface temperature, precipitation, geopotential height and vertical wind 12 composited anomaly pattern following El Nino/La Nina during the period 1979-2008 are compared 13 with a high-resolution CFS reanalysis, which is available at 38 km grid spacing.

14 Earlier studies suggest that the intensity and frequency of ENSO events have increased over the last 15 few decades resulting in a need to study the global and regional climatic impacts of ENSO strength. 16 Although, the main progress on the study of ENSO events and their climatic impacts was initially 17 made using climate models of intermediate complexity. However, these intermediate complexity 18 models have a coarse resolution, limiting them to have a detailed analysis of ENSO-induced 19 climatic responses, especially at the regional scale. Hence, to better understand ENSO-induced 20 climatic impacts at the global to regional scale, we used a high-resolution atmospheric model, 21 HiRAM, developed at GFDL, effectively at 25 km grid resolution. We have analyzed the impact of 22 El Niño/La Niña magnitude on 2m surface temperature, precipitation, sea level pressure, vertical 23 wind, and geopotential height at the global and regional scale focusing on the tropical and 24 extratropical regions.

25 The results obtained using HiRAM atmospheric model show that ENSO has a stronger impact over 26 the Inter-tropical Convergence Zone (ITCZ) region compared to extratropics and high-latitude 27 regions. These results are largely consistent with the findings of Zhao et al. (2016) who showed that 28 the ocean forcing from the ENSO is secondary and tend to be confined in the tropics. However, the 29 study of Zhao et al., 2016 did not categorize ENSO into strong and weak ENSO events. We further 30 noticed that the strong ENSO positive phase causes a significant weakening of rainfall over Africa, 31 South Asia whereas the La Niña phase of strong ENSO produces more rain over these regions. The 32 model results also reveal that ENSO has a stronger impact over South Asia particularly over the 33 Indian region because of its significant impact over the Indian Ocean focusing on the Arabian Sea, 34 the Bay of Bengal, and the Laccadive Sea through the Walker circulation. 35 Analysis of precipitation anomalies, zonal-mean vertical wind, and geopotential height changes at 36 850 and 200 hPa, reveal that the ENSO magnitude significantly impacts Hadley and Walker

37 circulation. Model-based configuration of Hadley cell following strong and weak El Niño (La Niña)

1 events emphasizes that the intensity of Hadley rising and sinking branches increased (decreased) 2 significantly exhibiting that Hadley circulation is very sensitive to the magnitude of ENSO forcing. 3 ENSO-induced changes in precipitation and vertical wind profile suggest that strong ENSO positive 4 phase (El Niño) can induce strengthening and equatorward shrinking to Hadley cell whereas the 5 negative phase of strong ENSO (La Niña) causes weakening of tropical Hadley cell. These AMIP-6 style HIRAM-based ENSO experiments further reveal that the strong El Niño (La Niña) induces 7 significant weakening (strengthening) to local Hadley cell covering MENA and Asian tropical 8 regions, which may cause weakening (strengthening) of Indian and African rainfall, indicating that 9 MENA and South Asian tropical regions are very sensitive to tropically excited SST changes. This 10 ENSO-induced strengthening and weakening of Hadley cell along with variations in Walker 11 circulation induce significant impact over tropical regions covering South and Southeast Asian and 12 African rain-belt regions. Our study reveals that strong El Niño (La Niña) episodes cause 13 strengthening (weakening) and equatorward (poleward) shift to jet streams.

14 Analysis of geopotential height (GH) changes suggests that ENSO-induced negative (positive) 15 NAO-like response and associated changes in Southern Europe and MENA region become 16 significantly strong following the increased intensity of El Niño (La Niña) in the northern 17 hemisphere in the boreal winter season. The HiRAM model reproduces the impact of ENSO over 18 the Pacific, North and South America, and African region quite well however it fails to accurately 19 produce ENSO teleconnection patterns and associated changes in temperature and precipitation 20 following weak ENSO events. One of the possible reasons for this disparity could be that the 21 ENSO-induced NAO-like response might be a key component that is not well reproduced by the 22 model.

23 Our study suggests that ENSO-induced changes in sea surface temperature over the tropical Indian 24 Ocean could play a significant role in governing teleconnections through changes in Walker 25 circulation that consequently induces changes in the meridional thermal gradient. This study further 26 concludes that SST forcing in the tropical Indian and the Pacific Ocean and their teleconnection 27 through large-scale zonal atmospheric overturning circulation is attributed to be a potentially 28 important driving condition for fully characterizing ENSO-induced climatic changes in South Asia. 29 In general ENSO-induced global and regional teleconnection patterns of surface temperature, 30 precipitation, sea level pressure (SLP) and geopotential height changes are consistent with CFSR as 31 well as with earlier studies, which indicates that the HiRAM model can be used effectively to better 32 understand ENSO-induced global and regional climatic responses.

The HiRAM model underestimated the cooling response following strong ENSO over the MENA region that could be accounted for by HiRAM weak response to ENSO-induced NAO-like teleconnection and associated regional impacts over MENA. We further find that the HIRAM model well reproduced the Matsuno-Gill pattern and horseshoe-like pattern following strong ENSO, however, these patterns are poorly reproduced following the weak ENSO phase resulting in varying 1 regional climatic impacts over the MENA, Eurasian, South, and Southeast Asian regions, 2 suggesting that HiRAM based ENSO results are sensitive to ENSO strength. The use of the air-sea 3 coupling and increased model top (to better reflect ENSO-induced polar vortex changes) in high-4 resolution AGCM simulations could improve these biases between observations and simulations

- 5 following strong and weak ENSO events.
- 6

7 Acknowledgements

8 We would like to thank the editor and two anonymous reviewers whose constructive suggestions 9 and comments significantly improved the manuscript. An updated description of the latest version 10 of the model used in this study as well as previous model versions is available at 11 https://www.gfdl.noaa.gov/atmospheric-model/.

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- 14 Figure Legends:

Figure 1: Composited mean spatial pattern of 2m surface air temperature (°C in top) and precipitation (mm/day in bottom) in winter season produced using CFSR (left panel) and HiRAM simulation (right panel). Wind vectors are also overlaid from CFSR (left bottom panel) and HiRAM (right bottom panel).

Figure 2: Composited mean 2m surface temperature anomaly pattern from HiRAM (left panel) and
 CFSR (right panel) following strong El Niño and La Niña forcing in winter (DJF) season.

Figure 3: Composited mean precipitation (mm/d) anomaly following strong El Niño and La Niña
forcing in winter (DJF) season.

Figure 4: Composited mean anomaly of zonal mean vertical velocity (Pa/s; in shaded colors) in the latitude pressure plane with overlaid zonal mean wind vectors (v; -100*omega) [m/s; 100*Pa/s] anomaly response following strong El Niño and La Niña forcing in winter (DJF) season. The length and direction of arrows depict the intensity (m/s) and direction of air movement in the latitude pressure plane respectively.

- Figure 5: Composited mean meridional-mean (20S-20N) anomaly of vertical velocity (Pa/s) in the
- 29 longitude pressure plane with overlaid meridional averaged (20°S-20°N) wind vectors (u; -

30 1000*omega) [m/s; 1000*Pa/s] anomaly response in HiRAM (left panel) and CFSR (right panel)

- 31 following strong El Niño and La Niña forcing in winter (DJF) season. The length and direction of
- 32 arrows depict the intensity (m/s) and direction of air movement in the longitude pressure plane.

Figure 6: Composited mean geopotential height anomaly at 850-hPa following strong El Niño and
La Niña forcing in winter (DJF) season.

Figure 7: Composited mean geopotential height anomaly at 200-hPa following strong El Niño and
 La Niña forcing in winter (DJF) season.

- 1 Figure 8: Composited mean 2m surface temperature anomaly pattern following weak El Niño and
- 2 La Niña forcing in winter (DJF) season.

Figure 9: Composited mean precipitation (mm/d) anomaly following weak El Niño and La Niña
forcing in winter (DJF) season.

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10 Figure 11: Composited mean meridional-mean (20°S-20°N) anomaly of vertical velocity (Pa/s) in

11 the longitude pressure plane with overlaid meridional averaged (20°S-20°N) wind vectors (u; -

12 1000*omega) [m/s; 1000*Pa/s] anomaly response following weak El Niño and La Niña forcing in

13 winter (DJF) season. The length and direction of arrows depict the intensity (m/s) and direction of

14 air movement in the longitude pressure plane.

15 Figure 12: Composited mean geopotential height anomaly at 850-hPa following weak El Niño and

16 La Niña forcing in winter (DJF) season.

17 Figure 13: Composited mean geopotential height anomaly at 200-hPa following weak El Niño and

- 18 La Niña forcing in winter (DJF) season.
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3 (right panel) following strong El Niño and La Niña forcing in winter (DJF) season.



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3 La Niña forcing in winter (DJF) season.

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2 Figure 14: Composited mean surface temperature anomaly following strong El Niño and La Niña

3 forcing over MENA region in winter (DJF) season.



2 Figure 15: Composited mean precipitation anomaly following strong El Niño and La Niña forcing

3 over MENA region in winter (DJF) season.

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2 Figure 16: Composited mean surface 2m temperature anomaly following weak El Niño and La

3 Niña forcing over MENA region in winter (DJF) season.



2 Figure 17: Composited mean precipitation anomaly following weak El Niño and La Niña forcing

3 over MENA region in winter (DJF) season.