

# Robust Atmospheric River Response to Global Warming in Idealized and Comprehensive Climate Models

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**ABSTRACT:** Atmospheric rivers (ARs), narrow intense moisture transport, account for much of the poleward moisture transport in midlatitudes. While studies have characterized AR features and the associated hydrological impacts in a warming climate in observations and comprehensive climate models, the fundamental dynamics for changes in AR statistics (e.g., frequency, length, width) are not well understood. Here we investigate AR response to global warming with a combination of idealized and comprehensive climate models. To that end, we developed an idealized atmospheric GCM with Earth-like global circulation and hydrological cycle, in which water vapor and clouds are modeled as passive tracers with simple cloud microphysics and precipitation processes. Despite the simplicity of the model physics, it reasonably reproduces observed dynamical structures for individual ARs, statistical characteristics of ARs, and spatial distributions of AR climatology. Under climate warming, the idealized model produces robust AR changes similar to CESM large ensemble simulations under RCP8.5, including AR size expansion, intensified landfall moisture transport, and an increased AR frequency, corroborating previously reported AR changes under global warming by climate models. In addition, the latitude of AR frequency maximum shifts poleward with climate warming. Further analysis suggests that the thermodynamic effect (i.e., an increase in water vapor) dominates the AR statistics and frequency changes while both the dynamic and thermodynamic effects contribute to the AR poleward shift. These results demonstrate that AR changes in a warming climate can be understood as passive water vapor and cloud tracers regulated by large-scale atmospheric circulation, whereas convection and latent heat feedback are of secondary importance.

**KEYWORDS:** Atmospheric river; Climate change; Extratropics; Idealized models; Transport; Water vapor

## 1. Introduction

Atmospheric rivers (ARs) are long, narrow corridors of synoptic horizontal water vapor transport in the midlatitude lower troposphere, accompanied with low-level jet streams ahead of the cold front of extratropical cyclones (e.g., [Zhu and Newell 1998](#); [Ralph et al. 2004](#); [Neiman et al. 2008](#); [Cordeira et al. 2013](#); [Guan and Waliser 2015](#)). These narrow corridors of concentrated moisture transport often originate from tropical oceans and carry large amounts of water vapor to the high latitudes, contributing 30%–60% of the annual total precipitation to the west coasts of continents (e.g., [Guan et al. 2010](#); [Dettinger et al. 2011](#); [Guan et al. 2012](#); [Rutz and Steenburgh 2012](#); [Viale et al. 2018](#)). Too many, too strong, and/or long-lasting ARs, as well as a favorable antecedent soil moisture condition, bring extreme rainfall and floods to these regions (e.g., [Dettinger 2006](#); [Ralph et al. 2006](#); [Stohl et al. 2008](#); [Lavers et al. 2011](#); [Neiman et al. 2011](#); [Ralph et al. 2013](#); [Konrad and Dettinger 2017](#); [Paltan et al. 2017](#); [Corringham et al. 2019](#); [Ralph et al. 2019](#)). ARs also breed snow accumulation and snowmelt events over both the Arctic and Antarctic ([Gorodetskaya et al. 2014](#); [Baggett et al. 2016](#); [Hegyi and Taylor 2018](#); [Mattingly et al. 2018](#); [Wille et al. 2019](#)), modulating the hydrological cycle in polar regions ([Nash et al. 2018](#)). An improved understanding of

ARs in a warming climate is critical for predicting regional weather and hydrological extremes. In recent decades observations indicate that there are more landfalling ARs along with warming over the North Pacific ([Gershunov et al. 2017](#)). Under future warming, it is expected that ARs will become longer, wider, and wetter (e.g., [Espinoza et al. 2018](#)). Both the intensity and the number of landfalling ARs and resultant heavy rainfall will increase in accordance with the projected warming ([Lavers et al. 2015](#); [Hagos et al. 2016](#); [Curry et al. 2019](#); [Gershunov et al. 2019](#); [Huang et al. 2020](#); [Ma et al. 2020b](#)).

Given that integrated water vapor transport (IVT) consists of moisture and horizontal wind, the mechanisms for these AR changes in a warming climate can be roughly divided into two interrelated aspects [see review by [Payne et al. \(2020\)](#)]. The first mechanism is focused on the effects of robust thermodynamic characteristics of greenhouse gas increases on moisture. The Clausius–Clapeyron (CC) equation implies that the water-holding capability of the atmosphere increases with global warming. This is supported by many model studies, suggesting that the future changes of ARs are generally dominated by a uniform increase in atmospheric moisture and therefore the enhanced IVT in a warming climate (e.g., [Gao et al. 2015, 2016](#); [Lavers et al. 2015](#); [Payne and Magnusdottir 2015](#); [Warner et al. 2015](#)). The other perspective is centered on the latitude of ARs due to the circulation response to global warming, termed dynamic change. A poleward shift of ARs as the westerly jet shifts in a changing climate is found over the North Atlantic

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and Southern Hemisphere (e.g., Gao et al. 2016; Ma et al. 2020a) while a small but robust reduction in IVT magnitude and an equatorward shift of ARs due to wind changes are found over the North Pacific (e.g., Payne and Magnusdottir 2015; Gao et al. 2015; Shields and Kiehl 2016). In addition, ARs tend to occur with the extratropical cyclone development (Eiras-Barca et al. 2018; Zhang et al. 2019), which may be impeded by the reduction in the low-level baroclinic instability in a warmer climate, further increasing the complexity of AR response to global warming. Thus, the large uncertainty in midlatitude circulation changes, especially in comprehensive model simulation, can obfuscate a simple explanation of the AR dynamical response to global warming.

Climate models to date represent observed statistics of ARs relatively well while large regional biases still exist [e.g., Payne and Magnusdottir 2015; Guan and Waliser 2017; see also the review by Waliser and Cordeira (2020)]. While the earlier studies have characterized the AR features and associated hydrological impacts in a warming climate using comprehensive climate models, the fundamental dynamics (e.g., temperature gradient, baroclinic instability, eddy momentum flux, and eddy heat flux) for changes in AR statistics (e.g., frequency, length, width) are not well understood. Although simulating ARs as accurately as possible is vital to pursue robust projections of AR changes, the large uncertainty and complexity in the comprehensive climate model make it difficult to understand the fundamental dynamical processes in the AR response to a warming climate.

In this study, we take a different approach and examine the AR change in a warming climate using a combination of idealized and comprehensive climate models. Many idealized models have no explicit hydrological cycle [e.g., the dry dynamical core in Held and Suarez (1994)] or unrealistic boundary conditions [e.g., the aquaplanet model in Neale and Hoskins (2000)] and thus cannot simulate realistic spatial distributions of ARs. We developed a new idealized GCM with Earth-like global circulation with simple water vapor processes. Despite the simplicity of model physics, the idealized model produces robust AR changes under climate warming similar to a comprehensive model, improving our confidence in atmospheric moisture transport and the fundamentals of AR dynamics in a warming climate.

The paper is organized as follows. Section 2 describes the model setup of this new idealized model. The datasets used for model evaluation are also introduced in section 2. Section 3 evaluates the performance of the idealized model in simulating the observed general circulation and hydrological cycle. The modeled ARs in the control run are evaluated with observations in section 4. The circulation and AR responses to a warmer climate in the idealized model and CESM LENS are presented in section 5.

## 2. Model setup and datasets

### a. Model setup

In this study, a simple GCM is constructed to simulate reasonably accurate ARs and their changes in a warming climate. Unlike the comprehensive GCMs designed to model every

observed detail as much as possible, simple models are designed to capture the fundamental physical processes only, and thus are valuable for understanding nature and are suitable for our goal. To simulate the ARs in a GCM with relatively simple physics but with atmospheric circulations close to the real atmosphere, we set up a dry atmospheric dynamical core by introducing Newtonian relaxation of temperature toward an equilibrium temperature that helps reproduce the observed climatology, and water vapor and cloud are implemented into the dry dynamical core as passive tracers, as described below.

We begin with the GFDL dry dynamical core (Held and Suarez 1994), which relaxes the temperature to a three-dimensional radiative equilibrium temperature field  $T_{\text{eq}}$  by Newtonian relaxation to mimic diabatic heating in the form of  $(\partial T/\partial t) = -(T - T_{\text{eq}})/\tau$ , where  $T$  is temperature and  $\tau$  is a prescribed relaxation time scale given in the appendix of Jucker et al. (2014). The  $T_{\text{eq}}$  fields are determined individually for each month of the year and then linearly interpolated to daily values. To create a more Earth-like atmospheric circulation in the model, we employ the zonal asymmetric relaxation temperature field  $T_{\text{eq}}$  generated based on the mean state of the observation following (Wu and Reichler 2018), which was achieved through the iterative procedure described in Chang (2006). We simply describe the algorithm in the appendix. The effect of seasonal variations in the mean state is examined by individually calculating for each month. While only the mean climate is the target of the iteration process, transient eddies are created internally by the baroclinically unstable atmosphere. Eddy fluxes of momentum and energy highly resemble the observations with some slight differences in magnitude (Chang 2006; Wu and Reichler 2018), likely due to the close relationship between eddy statistics and mean climate. The actual Earth topography is employed in the model to further generate realistic planetary waves. There is no explicit boundary layer parameterization. The wind fields are damped by Rayleigh friction near the surface. With the above setting, an Earth-like atmospheric general circulation, including the stratospheric circulation and stationary planetary waves (Wu and Reichler 2018), is produced in this idealized model.

Given that the object of this study is ARs, which involves hydrological processes including moisture transport and precipitation as mentioned in the introduction, a feasible technique to model the hydrological cycle is required. We achieve this by adopting a simple cloud physics in which the water vapor and cloud fraction are modeled as passive tracers, following Ming and Held (2018, hereafter MH18). Here we simply summarize this cloud physics and describe a few technical differences of our work from MH18. In this simple cloud physics, there is no convective parameterization. Water vapor and cloud fraction are modeled as passive tracers, and thus they do not affect the flow. There are three water tracers advected: specific humidity, liquid, and ice condensates. Surface evaporation is mimicked by nudging RH at the bottom layer to 100% with a time scale of 30 min (as compared to RH below 850 hPa being nudged in MH18). As in the GFDL HiRAM (Zhao et al. 2009), the large-scale cloud scheme diagnoses cloud fraction and condensation from grid-mean total water (water vapor and cloud condensates) using an

assumed subgrid-scale distribution, which takes the form of a beta distribution with its width controlled by the grid-mean total water multiplied by a width parameter, defined in [Tompkins \(2002\)](#). The beta distribution parameters are the same as [MH18](#). We adopt a single-moment cloud microphysics developed by [Rotstayn \(1997\)](#) and [Rotstayn et al. \(2000\)](#), which has been successfully applied in GFDL AM2 and AM3. The main pathways for transformation between cloud condensates, precipitation formation, and re-evaporation of condensates and precipitation are involved. As in [MH18](#), this scheme assumes that condensation (re-evaporation) does not generate condensational heating (cooling) and thus does not affect flow. No water vapor and cloud radiative effect is involved in this scheme either. Thus, water vapor and cloud are completely passive.

Since the model uses a spectral core, a finite-volume grid-point advection scheme, applicable to the Gaussian grid, is used to advect the model's passive tracers. The horizontal tracer transport is computed using the finite-volume formulation ([Lin and Rood 1996](#)). This formulation has been examined by a study of tracer transport in baroclinic life cycle ([Polvani and Esler 2007](#)), an investigation of subtropical water vapor source ([Galewsky et al. 2005](#)), and isentropic mixing of tracers by large-scale atmospheric circulation ([Chen and Plumb 2014](#)). The reader is referred to [MH18](#) for a more detailed exposition for the tracer advection algorithm.

Our model has 40 levels in the vertical. A sponge layer is employed near the model cap. The horizontal resolution is T42, with a resolution of about  $2.8^\circ \times 2.8^\circ$ . We investigate the sensitivity of parameters for the calculation of cloud fraction and condensation, such as the width parameter for the tracer distribution that has been tested in [MH18](#). The sensitivities in the vertical structure simulation of water vapor are reasonable and consistent with that in [MH18](#) with a zonally symmetric circulation (figure not shown). More model evaluations for the simulations of cloud fraction, cloud water, and cloud ice will be presented in [section 3](#).

### *b. Datasets, method, and statistics*

To evaluate the simulated circulation, hydrological cycle, and ARs, we compare the control (Ctrl) run with ERA-Interim (ERA-I) reanalysis ([Dee et al. 2011](#)). The variables from ERA-I have a horizontal resolution of  $1.5^\circ \times 1.5^\circ$  and 37 levels in vertical. The daily data and the long-term mean of 1979–2018 are used.

The outputs of 40 ensembles in the large ensemble simulation (LENS) based on CESM, a comprehensive fully coupled climate model from NCAR, are employed ([Kay et al. 2015](#)). Every member was under identical historical forcing before 2005 and RCP8.5 forcing after that. We collect the daily data during 1979–2005 (27 years) in historical runs (Hist hereafter) and during 2074–2100 (27 years) in RCP8.5 runs (RCP8.5 hereafter). The projected AR changes in CESM simulations are used to assess the AR response to climate warming in the idealized model simulations.

The analysis in this study is based on the climatology of annual mean if no specific statement. The pattern correlation coefficient (PCC) is employed to measure the pattern similarity

between the Ctrl run and observations. Vertical and latitudinal weights are considered, and the global mean is removed before the calculation of PCC.

### **3. Atmospheric circulation and hydrological cycle**

It is important to verify that this simple model is able to achieve a realistic atmospheric circulation and hydrological cycle. We first conduct a control simulation (Ctrl run) based on the model setup described above. The Ctrl run is integrated for 36 model years and the outputs from the last 30 years are analyzed.

Starting with the zonal mean circulation, [Fig. 1a](#) presents the zonal mean zonal wind (color) and temperature (contour) in the Ctrl run. As expected, the modeled temperature field highly resembles the ERA-I as shown in [Fig. 1b](#), including the spatial pattern and the magnitude, since the  $T_{eq}$  used to drive this model is produced to reproduce observations by an iterative approach as described in [section 2a](#). Specifically, the pattern correlation coefficient between the Ctrl and the ERA-I is effectively 1.0, indicating the model recovers the spatial pattern of temperature through the iterative process. Correspondingly, the zonal mean zonal wind is well reproduced in this idealized model. The correlation coefficient for the zonal mean zonal wind reaches 0.97. The westerly jet positions and their nonsymmetric pattern in two hemispheres, even in the stratosphere, are very close to that in the ERA-I. These well-reproduced zonal mean zonal wind patterns are mainly determined by the well-simulated temperature field, especially over the extratropics where the thermal wind balance is dominant. [Figures 1c and 1d](#) compare the mean meridional circulation and relative humidity in the simple model and ERA-I. In the tropics, the lack of convective scheme in our model leads to an underestimation of the tropical convection in the simulation (determined by the prescribed  $T_{eq}$ ), and thus a weaker Hadley cell (tropical convection) is produced in comparison with the observation. However, the spatial pattern of the Hadley cell is well captured in the simple model (PCC = 0.93). Therefore, the vertical structure of the relative humidity, such as the dry subtropics and wet high latitudes, shares similarity with that in observation (PCC = 0.91). It should be noted that the simulated relative humidity is generally higher than that in ERA-I, since we simply nudge the relative humidity to 100% at the bottom level of the idealized model which exaggerates the wetness over the land area. In addition, due to the lack of convection scheme and thus the weak vertical motions in the deep tropics, the model bias also lies in the vertical structure of RH ([Figs. 1c,d](#)). In the real atmosphere, the large values of low-level humidity and associated CAPE will trigger convective instability, which is generally treated by subgrid convective parameterizations in a comprehensive climate model, including the release of CAPE and mixing with drier environmental air. This setting prevents the excessive accumulation of moisture at the low level and the disappearance of the RH vertical gradient in the mid-to-upper troposphere in the tropics ([Figs. 1c,d](#)). Nevertheless, this simplification does not affect the simulation in the overall picture of the zonal mean structure of relative humidity, which is controlled by the moisture transport associated with large-scale atmospheric circulation ([Galewsky et al. 2005](#)).

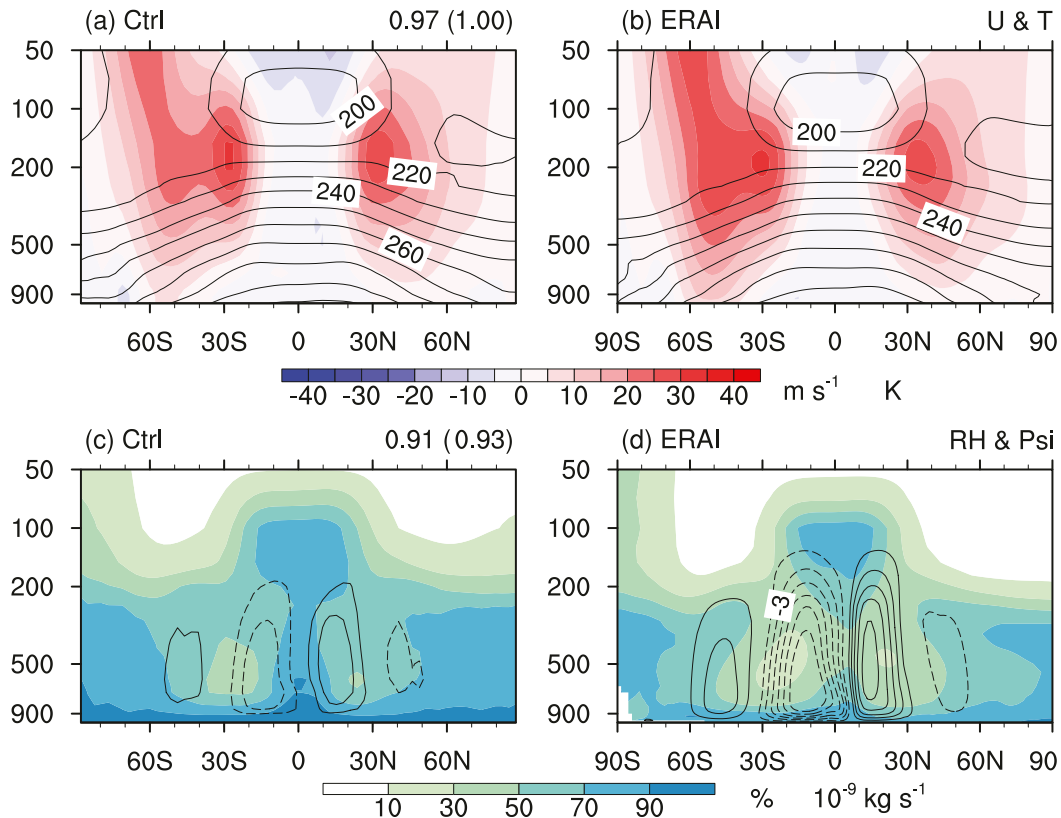


FIG. 1. Zonal mean zonal wind, temperature, relative humidity, and mean meridional circulation in the idealized model and observations. (a),(b) Zonal mean zonal wind (color shading;  $\text{m s}^{-1}$ ) and temperature (contour; K) in the Ctrl run and ERAI. (c),(d) Zonal mean relative humidity (%) and meridional streamfunction (interval is  $1.5 \times 10^{-9} \text{ kg s}^{-1}$ ) simulated in the Ctrl run and ERAI. The value 0.97 ( $\sim 1.0$ ) at the upper right of (a) is the pattern correlation coefficients between Ctrl and ERAI for zonal mean zonal wind (zonal mean temperature). The value 0.91 (0.93) in (c) is that for RH (meridional streamfunction) between Ctrl and ERAI.

The moisture transport budget is  $P - E = \nabla \cdot \mathbf{V}q$  diagnosed in Fig. 2 to assess the simulation of the hydrological cycle in the idealized model. The modeled precipitation minus evaporation ( $P - E$ ) is balanced by the moisture transport  $-\nabla \cdot \mathbf{V}q$ . Compared to ERAI, while the moisture transport over the tropics and the subtropics of the South Hemisphere in the model is weaker due to the biases in the magnitude of the tropical convection, the water cycle over extratropical regions where most ARs occur is very close to the reanalysis data. The good simulation of the extratropical water vapor balance facilitates a reasonable simulation of ARs in this model (as will be discussed later).

Figure 3 depicts the simulated cloud fields (cloud fraction, cloud liquid, and cloud ice) in the Ctrl run and ERAI reanalysis. The simulated clouds in the middle and lower troposphere in the tropics are unrealistic due to the lack of a convection scheme, as we mentioned earlier. Thus, we consider that the relevance of this model for the real atmosphere is confined to the extratropics. Similar to MH18, the model is capable of qualitatively simulating some familiar aspects of the highly inhomogeneous cloud distribution over the tropical upper troposphere and extratropics compared with ERAI.

Cloud fraction generally extends vertically through almost the entire troposphere in the extratropics, especially over the storm tracks where ARs occur frequently. The cloud fraction in the subtropical dry zones is also well reproduced in the model.

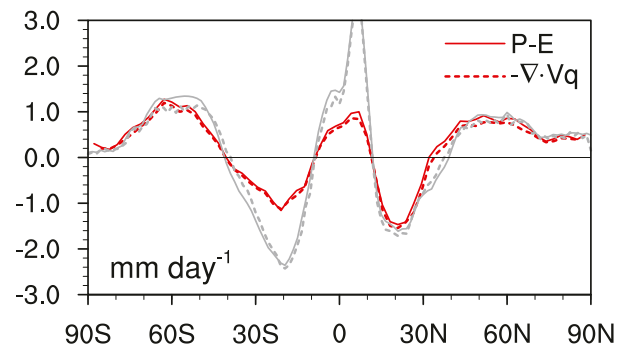


FIG. 2. Hydrological cycle in the idealized model and observations. Zonal mean  $P - E$  (precipitation minus evaporation; solid line;  $\text{mm day}^{-1}$ ) and horizontal convergence of moisture transport (dotted line;  $\text{mm day}^{-1}$ ) in the Ctrl run (red lines) and ERAI (gray lines) are shown.

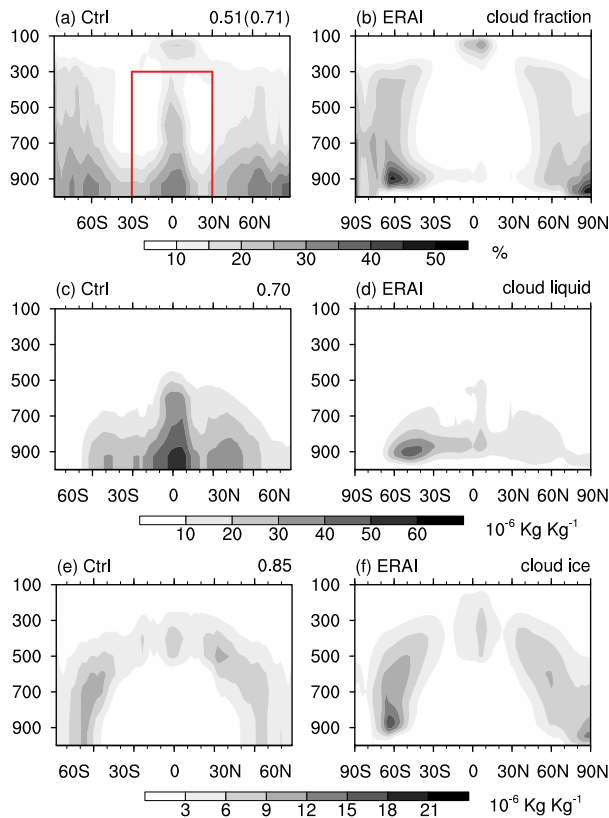


FIG. 3. Clouds in the idealized model and observations. (a),(b) Cloud fraction (%), (c),(d) cloud liquid ( $10^{-6} \text{ kg kg}^{-1}$ ), and (e),(f) cloud ice ( $10^{-6} \text{ kg kg}^{-1}$ ) simulated in the control run and that in ERA-I. Weighted centered pattern correlation coefficients between Ctrl and ERA-I are shown at the top right of (a), (c), and (e) for corresponding variables. The red box in (a) marks the tropical middle- to low-level clouds produced in this idealized model due to the lack of convection parameterization. The correlation coefficient in the parentheses in (a) shows the pattern correlation with the exclusion of the red box region.

Similar to ERA-I, the transition from cloud liquid to ice in the Ctrl run follows the freezing line (Figs. 3c–f).

#### 4. Characteristics of atmospheric rivers

According to the above evaluation, the simple model used here is capable of reasonably modeling the realistic large-scale circulation and moisture transport, especially over the extratropical regions. We next further verify that this model is able to simulate ARs, including their fine-scale dynamical structure and climatological distribution. The AR detection method in Guan and Waliser (2015) is employed in this study. This AR detection algorithm is based on integrated water vapor transport (IVT) derived from specific humidity and wind fields at the pressure levels between 1000 and 300 hPa inclusive for the idealized model and ERA-I. For CESM LENS, IVT is calculated by vertically integrated specific humidity and horizontal winds from near the surface to 200 hPa because data at 1000 and 100 hPa are not archived. The 85th percentile of

IVT strength or  $100 \text{ kg m}^{-1} \text{ s}^{-1}$ , whichever is greater, is chosen as the threshold for AR detection at each grid for each month. Since the 85th percentile IVT is used as a threshold most of the time, any bias in the IVT calculation will be implicitly accounted for when detecting ARs. Therefore, this AR detection algorithm is not sensitive to the ways how IVT is derived. Only objects with its meridional component of mean IVT greater than  $50 \text{ kg m}^{-1} \text{ s}^{-1}$  are considered, given the notion that ARs transport water vapor from low to high latitudes. For the detected object to be considered as an AR, there should be fewer than half of the grid cells that have IVT deviating more than  $45^\circ$  from the object's mean IVT direction. In addition, the direction of mean IVT deviates from the overall orientation should be less than  $45^\circ$ . The overall orientation here is defined as the mean azimuth of the arc connecting the two end grid cells of the AR's axis with the maximum great circle distance following Guan and Waliser (2015). In this algorithm, an AR should be longer than 2000 km and with a length to width ratio of at least 2:1.

Figure 4 gives the spatial structure of a specific AR in the model and in the ERA-I, respectively. We compose this figure following Ralph et al. (2017) and one can see that the modeled AR captures the key AR characteristics: a narrow, elongated, synoptic-scale jet of water vapor extending thousands of kilometers in length and an order of magnitude less in width. As shown in the vertical cross section of ERA-I (Fig. 4d), the low-level moisture transport is concentrated in the bottom 3 km of the atmosphere. While the low-level jet ahead of the cold front carries the vast majority of the horizontal water vapor transport, the cold upper-jet advects dry air aloft. Despite the coarse resolution and simple moist scheme, this coherent spatial structure is well reproduced in the idealized model (Fig. 4c), indicating a major role of large-scale atmospheric circulation in the development of ARs through isentropic mixing of air mass and moisture (Chen and Plumb 2014).

The AR climatology simulated in this idealized model is further assessed. Figure 5 presents the climatologies of IVT and AR frequency. The strong moisture transport mainly occurs over the tropical trade wind belts (i.e., ITCZ), monsoon regions, and midlatitude oceanic basins (Fig. 5b). Since there is no convective parameterization in the model, the ITCZ is hardly simulated, while the water vapor transport over the Asian monsoon region can be reproduced mainly due to the topography effect. In contrast, the pattern of moisture transport over the extratropics, especially over the midlatitude oceanic basins, where the storm tracks and ARs are active, is well reproduced ( $\text{PCC}_{\text{extratropics}} = 0.82$ ), except that the values are lower than the observation again due to the lack of convection scheme and thus no condensational heating feedback in the model. In addition, the coarse resolution could contribute to this underestimation as well. Given that ARs are defined with the threshold of 85th percentile IVT, and thus not sensitive to the climatological magnitude of IVT, the pattern of AR frequency is well simulated in the model ( $\text{PCC} = 0.95$ ). In addition, the magnitude of the AR frequency over the midlatitude ocean is in good agreement with that in the observation (8%–14%).

Given that the ARs are active at the midlatitudes as shown above, we calculate the zonally integrated meridional IVT

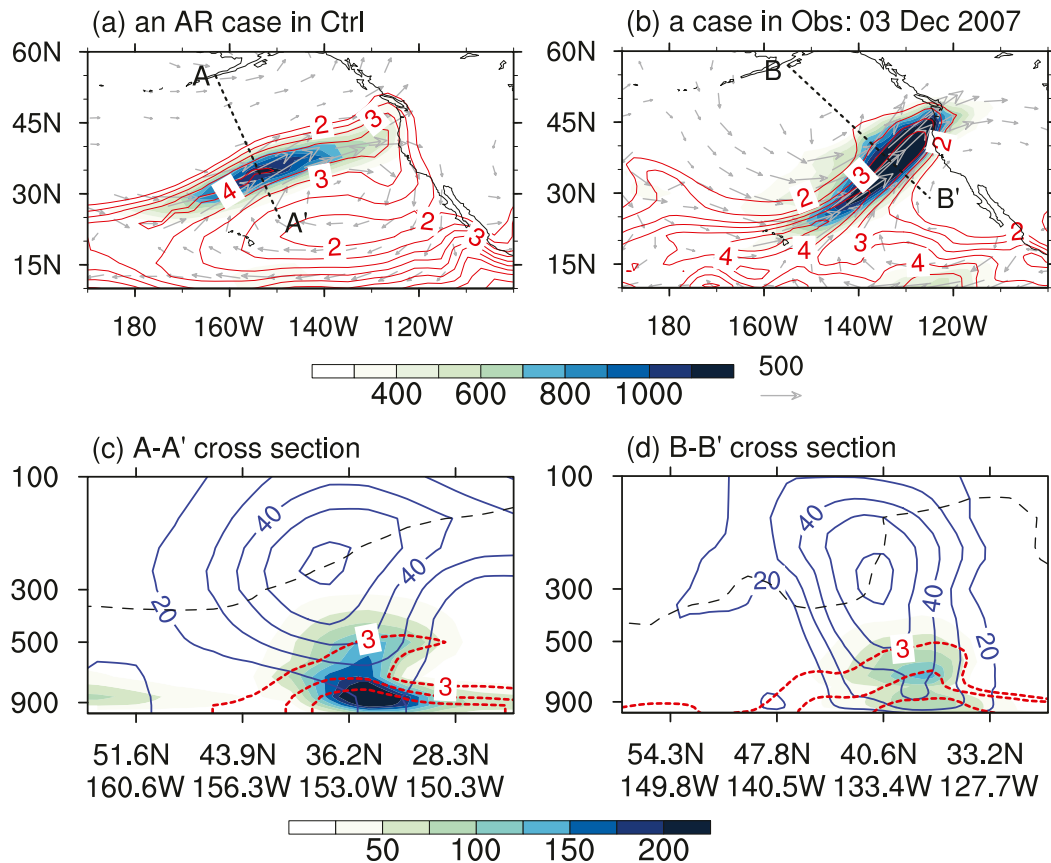


FIG. 4. An AR case simulated in the Ctrl run and a case in observation (ERA-Interim), respectively. Integrated water vapor transport (IVT;  $\text{kg m}^{-1} \text{s}^{-1}$ ) vectors (gray arrows; not shown if the magnitude is smaller than  $100 \text{ kg m}^{-1} \text{s}^{-1}$ ) and its magnitude (color shading), and integrated water vapor (IWV; red contours; cm) in (a) Ctrl and (b) ERA-Interim. The position of the cross sections shown in (c) and (d) is denoted by the dotted lines A-A' in (a) and B-B' in (b), respectively. Also shown is the vertical cross-section perspective, including the core of the water vapor transport in the atmospheric river (color shading), water vapor mixing ratio (red dotted lines;  $\text{g kg}^{-1}$ ), and cross-section isotachs (blue contours;  $\text{m s}^{-1}$ ) in (c) Ctrl and (d) ERA-Interim. The tropopause is denoted by the black dashed line in (c) and (d).

associated with AR transport and the AR zonal scale over  $30^{\circ}$ – $50^{\circ}\text{N/S}$  following Guan and Waliser (2015). The results show that the ARs account for 81% (82%) of the total meridional IVT and 9% (11%) of the zonal circumference over  $30^{\circ}$ – $50^{\circ}$  in the Northern (Southern) Hemisphere in the Ctrl run. The AR fractional IVT is slightly lower than that in the observations, 85% (89%) of total meridional IVT, which could be due to the idealized setting of excessive surface moisture over the land where the AR activity is much less. The AR fractional zonal scale in the idealized model matches the observation, 8% (11%) of the zonal circumference, indicating that the idealized model relatively well captures the key characteristic of ARs found in early studies that estimated ARs, while covering  $\sim 10\%$  of Earth's circumference at midlatitudes, accounting for the majority of the total poleward water vapor transport at these latitudes (e.g., Zhu and Newell 1998; Newman et al. 2012; Guan and Waliser 2015).

Figure 6 shows the probability density function (PDF) of AR basic characteristics in Ctrl run and ERA-Interim, including size (length and width), meridional range (lowest latitude and

highest latitudes), direction of mean IVT and coherence of IVT direction, mean magnitude of IVT, and landfall magnitude. Here, the coherence of the IVT direction of an AR event is measured by the fraction of AR grid cells with IVT directed within  $45^{\circ}$  of the mean AR IVT (Guan and Waliser 2015). For the AR size, the distribution of AR length is well reproduced in the idealized simulation, while the AR width in Ctrl is about 200 km wider than that in the observation (Figs. 6a,b). This biased PDF shift in the simulated AR width is likely due to the coarser spatial grids in the idealized model compared to  $1.5^{\circ} \times 1.5^{\circ}$  in ERA-Interim, since the coarse horizontal resolution of the model cannot capture the filamentation aspect of the ARs well (Guan and Waliser 2015). The PDFs of the highest and lowest latitude of ARs in each hemisphere, which measure the meridional range of AR activities, also match the observations (Figs. 6c,d). The PDFs of the direction of mean IVT and its coherence in the Ctrl run are well in agreement with the observation in both hemispheres (Figs. 6e,f). For the magnitude of landfall IVT and the mean magnitude of IVT, although bias is found in

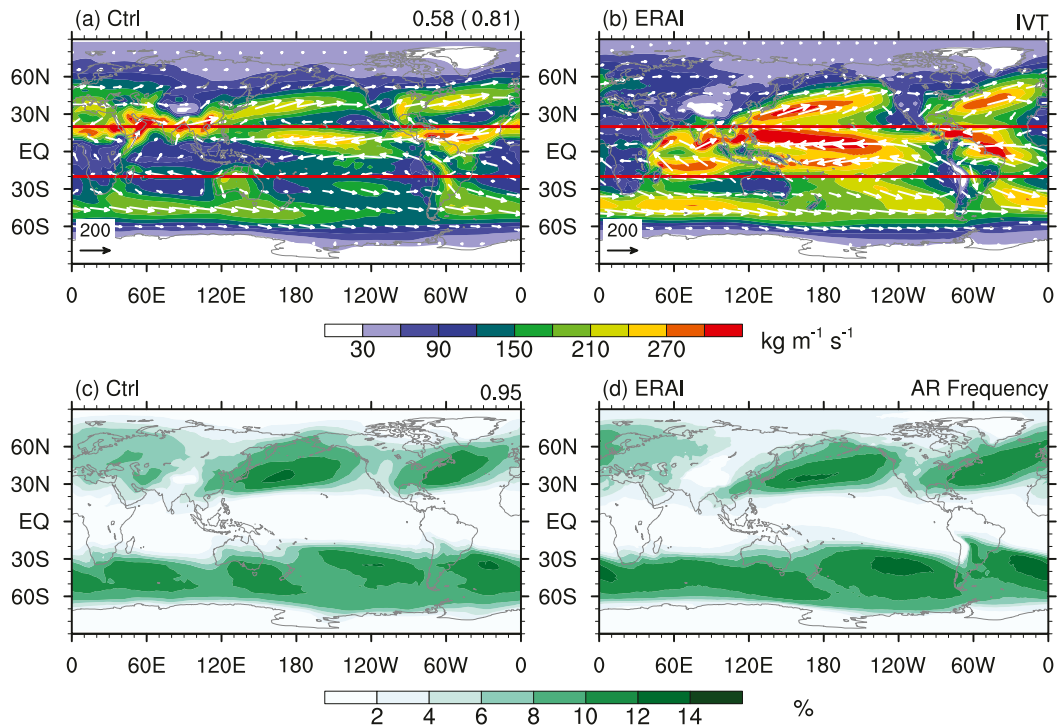


FIG. 5. Mean integrated water vapor transport (IVT;  $\text{kg m}^{-1} \text{s}^{-1}$ ) vector (white arrows) in (a) Ctrl and (b) ERAI. (c),(d) As in (a) and (b), but for atmospheric river (AR) frequency (%). Weighted centered pattern correlation coefficients between Ctrl and ERAI are shown at the top right of (a) and (c) for corresponding variables. The correlation coefficient in the parentheses in (a) shows the pattern correlation excluding the tropical region ( $20^{\circ}\text{S}$ – $20^{\circ}\text{N}$ ; denoted by the red lines).

the simulated PDFs, the basic shapes of the distribution are captured by the idealized model (Figs. 6g,h). The too strong landfalling ARs in the idealized simulation are probably due to the setting of humidity in the model, in which the relative humidity is simply nudged to 100% at the lowest level without the moisture limitation over land. Overall, besides some biases in quantitative values of width and magnitude, the general AR characteristics are well simulated in the idealized model, further corroborating that the AR dynamics is dominated by large-scale atmospheric circulation and associated moisture transport.

In summary, the simple model used in this study is capable of simulating not only the large-scale circulation and hydrological cycle but also the 3D spatial structure and statistical characteristics of the ARs with some quantitative biases. These results demonstrate the basic dynamics of ARs can be understood through the transport of passive water vapor and cloud tracers, indicating the important role of large-scale circulation and advection in the simulation of IVT and thus the AR activity.

## 5. AR response to global warming

### a. Experimental design and the mean state response to climate warming

Since this idealized model is reliable for AR simulation as evaluated in the last section, we next explore the response of

ARs to a changing climate in this simple model. A series of experiments with idealized warming (or cooling) forcing is conducted. The forcing employed in this study is a uniform temperature perturbation in the troposphere and a schematic diagram (Fig. 7a) shows the design for the vertical profile of the uniform (4 K for example) tropospheric warming (Trop4K), which is comparable to a  $\sim 4.4$ -K warming on average by the end of the twenty-first century in the RCP8.5 scenario in CESM LENS simulations. Compared to the Ctrl run, a 4-K warming is prescribed in  $T_{\text{eq}}$  fields at each grid below the tropopause (red segment). A linear transition zone is taken into account near the tropopause to mimic an uplifting tropopause induced by tropospheric warming with no change to tropospheric lapse rate. For each temperature profile for Trop4K forcing, the lapse rate in the transition zone is determined by the averaged lapse rate in the three layers below the tropopause in the Ctrl run, and thus the thickness may vary from profile to profile. A similar approach was used in Lorenz and DeWeaver (2007) for a raised tropopause. The dotted green line in Fig. 7a denotes the new tropopause for 4-K warming. The actual temperature change for the 4-K warming experiment is shown in Fig. 7b (color shading). More experiments demonstrate that the results are not sensitive to the choice of the parameters to set up the transition zone (not shown). Such a thermal forcing is designed to mimic the thermal effect of uniform SST increase in aquaplanet simulations (e.g., Chen et al. 2013), with the effect of changes in lapse rate excluded.

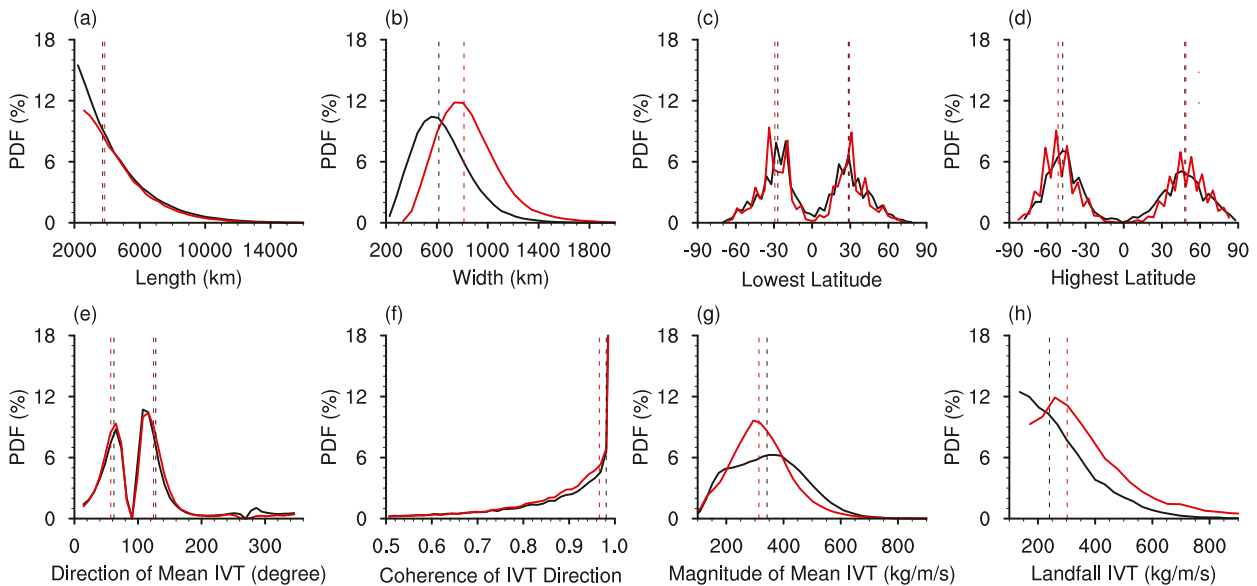


FIG. 6. PDFs of the basic characteristics of ARs in Ctrl run (red) and ERAI (black). (a) Length of ARs. (b) Width of ARs. (c) Latitude of equatorward tip. (d) Latitude of poleward tip. (e) Direction of mean IVT. (f) Coherence of IVT Direction. (g) Magnitude of mean IVT. (h) Magnitude of landfall IVT. The dashed vertical lines in each panel denote the median (in case of one red line and one black line) or the median in each hemisphere (in case of two red lines and two black lines) in Ctrl and ERAI, respectively.

Similarly, a series of experiments with a range of forcing, 2-K tropospheric warming and 2-K and 4-K tropospheric cooling, are conducted to explore the AR changes over a range of climates (see Table 1). The transition zone for the tropospheric cooling forcing is determined similarly as that in the warming forcing, except that the transition zone and the new tropopause are below the tropopause in the Ctrl run. These perturbation experiments have been run for 36 model years, respectively, and the last 30-yr outputs are used for analysis, same as the Ctrl run. The response is defined as the differences between the perturbation run and the Ctrl run. The same IVT threshold, the 85th percentile of IVT in the reference state, is used for AR detection in the perturbation scenarios.

We first show the responses of the zonal mean circulation to the tropospheric 4-K warming experiment (Trop4K) in Fig. 8 (left column). The results are approximately opposite in sign for the tropospheric 4-K cooling experiments (Trop-4K) and thus are not shown here. To further verify the model is able to simulate a reasonable response to tropospheric 4-K warming, we compared the responses in the idealized model to that in the comprehensive model simulations, CESM LENS (right column of Fig. 8). The zonal mean results are also similar to the atmospheric responses to 4-K uniform SST increase in aquaplanet models (e.g., Chen et al. 2013), which have an intermediate complexity in model physics between the idealized model and CESM. The response in LENS/CESM is defined as the difference between the climatologies of 2074–2100 in RCP8.5 and 1979–2005 in Hist. Compared to the tropospheric 4-K warming in the idealized simulation, the global tropospheric temperature response is about 4.4 K in LENS/CESM. As a result of the uniform tropospheric 4-K warming forcing, a warmer troposphere can be seen in Fig. 8a. However, the

pattern of temperature response is not totally uniform, especially over the extratropics, indicating the impact of the circulation feedback. Although the projected deep tropical warming and polar amplification cannot be fully represented, the uniform tropospheric warming still creates a temperature gradient increasing at the upper troposphere over the subtropics to midlatitudes due to the slope in the tropopause. Accordingly, consistent with the temperature changes and thermal wind balance, the responses in the zonal mean zonal wind are characterized by a poleward shift in the midlatitude westerly jet (more obvious in the Southern Hemisphere), with a large acceleration near the subtropical tropopause (Figs. 8a,c), resembling the zonal mean zonal wind responses in the LENS/CESM (Figs. 8b,d). The temperature gradient changes and jet shifts could influence the Hadley cell as well [see the review by Vallis et al. (2015)]. The response of the mean meridional circulation to Trop4K warming shows a weaker Hadley cell, with a poleward expansion in the Hadley cell and a poleward shift in the Ferrel cell (Fig. 8e) due to the decrease of baroclinic instability and the eddy feedback, displaying the classic pattern of the meridional circulation response to a warming climate that has been found in the comprehensive models (Fig. 8f) in many previous studies. This shift in atmospheric circulation in response to uniform tropospheric warming in the presence of a sloping tropopause is consistent with a recent study that quantifies a high sensitivity of the zonal jet to changes to the upper-tropospheric temperature gradient (Chen et al. 2020).

Changes in zonal mean circulation certainly lead to distinct changes in water vapor and the hydrological cycle. The responses of relative humidity are characterized by wetness in the stratosphere and dryness in the tropospheric extratropics (Fig. 8g). The former is likely the result of increased water



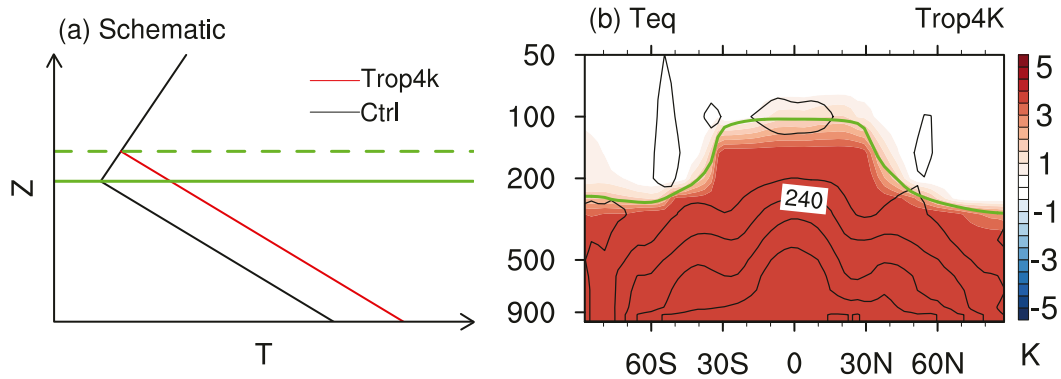


FIG. 7. Design of uniform tropospheric warming forcing. (a) Schematic diagram for the changes to the vertical profile of tropospheric temperature due to global warming. The black line is an idealized profile of temperature in the troposphere and lower stratosphere. The red line denotes a uniform warming in the troposphere. Solid and dashed green lines in (a) denote the tropopause and its elevation due to the tropospheric warming forcing. (b) Equilibrium temperature ( $T_{eq}$ ; K) in Ctrl (contour) and the 4-K uniform tropospheric warming in  $T_{eq}$  for the Trop4K run (color shading). Green line shows the position of the tropopause in Ctrl. The forcings for Trop2K, Trop-2K, and Trop-4K experiments were implemented in the model in a similar way.

vapor entering the stratosphere in response to tropospheric warming and the latter indicates a larger increase in the saturation vapor pressure than the vapor pressure in a warming climate. These responses in relative humidity are generally in agreement with that in the RCP8.5/LENS except the differences over the upper tropical troposphere likely due to the lack of convective scheme (Fig. 8h). Previous studies (Wright et al. 2010) suggested that the spatial distribution of zonal mean relative humidity responses is largely dependent on circulation and transport changes, such as the poleward expansion of the Hadley cell, poleward shift of the extratropical jets, and increase in the height of the tropopause as illustrated in previous sections. The tropospheric warming effects are also reflected in changes of precipitation minus evaporation ( $P - E$ ; Fig. 9), a measure of the global water vapor budget. The responses roughly show a drying effect in the subtropical regions where mean  $P - E < 0$  and a wetting effect in the extratropics and tropics where mean  $P - E > 0$  (Fig. 9), a well-known thermodynamic mechanism for the hydrological cycle response to global warming (e.g., Chou and Neelin 2004; Held and Soden 2006). In addition, the magnitude of  $P - E$  changes over the extratropics in the idealized simulation is close to that in CESM LENS.

### b. Response of ARs in climate warming

As discussed above, the changes of atmospheric circulation and hydrological cycle in the idealized model experiments resemble that in the comprehensive model simulations, paving the way to explore the response of ARs under a warming climate with a combination of the idealized and comprehensive model. Here we present the response of AR frequency in the Trop4K run in Fig. 10a. The AR frequency increases over the mid- to high-latitude regions in response to the tropospheric 4-K warming, especially over the poleward side of its climatological maximum in the South Hemisphere in the Ctrl run. These more frequent AR activities in a warmer climate are highly consistent with those in the RCP8.5/CESM simulations (Fig. 10b) and many previous studies [see the review by Payne

et al. (2020)], confirming that the idealized model design is capable of simulating the AR response to global warming.

To explore the mechanisms of changes in ARs, we employ a simple scaling method developed in Ma et al. (2020a) to separate the AR response due to the moisture change with climate warming (thermodynamic effect; i.e., the Clausius–Clapeyron relation), and that due to the dynamical effect (wind changes). Note that our method rescales daily IVT in a warming climate by the change in climatological mean moisture, and then the same threshold can be used to compare different scenarios. We create two hypothetical scenarios of daily IVT for each perturbation run by a scaling method applying to specific humidity, given the moisture changes are expected to scale in line with CC. In the first scenario for the ARs with dynamic effect, the specific humidity at each time step, each pressure level, and each grid cell in the perturbation run is scaled with a factor of  $q_c/q_p$ , where  $q_c$  ( $q_p$ ) is the climatological specific humidity in the Ctrl (perturbation) run at the level and grid cell to which this factor applies. By scaling the data this way, the AR response due to specific humidity changes is removed in the hypothetical scenario. Then, the dynamic effect is isolated by contrasting this scaled case against the Ctrl run. Similarly, for the second hypothetical scenario of thermodynamic effect, the wind and specific humidity in Ctrl are used but the specific humidity in the Ctrl run is scaled with a factor of  $q_p/q_c$  so as to remove the dynamic response. The thermodynamic effect is the difference between the second hypothetical scenario and the Ctrl run. These two components are linearly additive (see Fig. 11e), indicating that the covariance of the two components is negligible.

Additionally, we also analyze the sensitivity of the thermodynamic component to local temperature changes (thermo\_Local) versus global temperature changes (thermo\_GlobalMean). This separates the nonlinear moisture dependence on temperature. That is, while the increase of saturation vapor pressure with temperature is commonly referred to as  $7\% \text{ K}^{-1}$  warming, this rate is larger at lower temperatures (e.g., polar

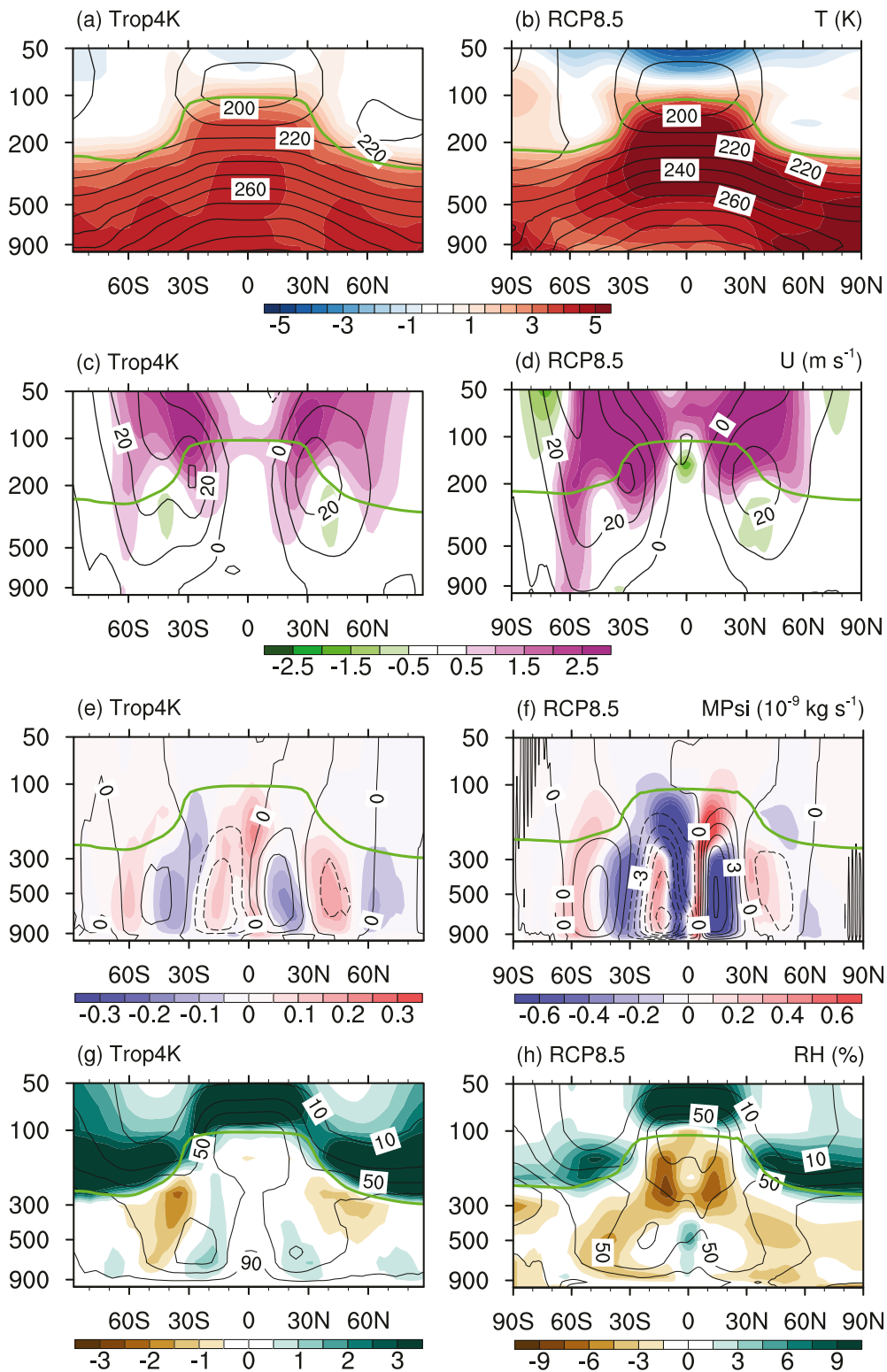


FIG. 8. Response of zonal mean temperature, zonal wind, meridional streamfunction, and relative humidity in (left) the Trop4K run and (right) RCP8.5 in CESM LENS. The contours denote the corresponding variables in the Ctrl run (at left) and historical simulations in CESM LENS (at right). Green lines denote the tropopause in their reference states, respectively.

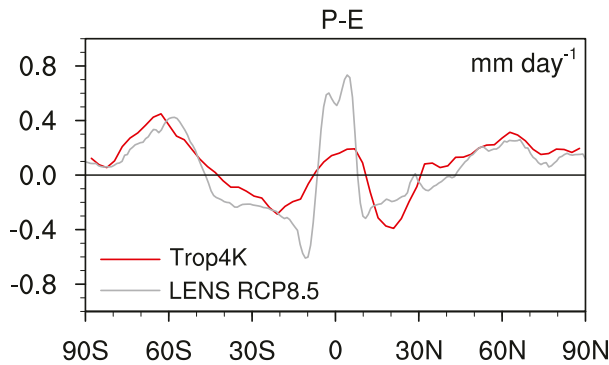


FIG. 9. Responses of  $P - E$  in the Trop4K run (red line) and CESM LENS RCP8.5 (gray line).

regions). Specifically, for the additional hypothetical scenario of thermo\_GlobalMean, the wind and specific humidity in the Ctrl run are used but the specific humidity in the Ctrl run is scaled by a factor of  $[q_p]/[q_c]$ , where the square brackets denote the global mean, and therefore the ARs with the thermodynamic effect due to the global mean change are detected. The difference between the thermodynamic effect and the Thermo\_GlobalMean can be regarded as the thermo\_Local effect.

The AR frequency increases are mainly attributed to the thermodynamic effect (Fig. 11a), namely the moisture changes in line with CC, in which the thermo\_GlobalMean dominates the magnitude changes over the midlatitudes (Fig. 11c). In contrast, the thermo\_Local and dynamic effects contribute to the AR poleward shift (Figs. 11b,d). The thermo\_Local is also characterized by a dipole structure in the midlatitude oceans (Fig. 11d), which is likely the imprint of the storm track shift in the tracer field of water vapor. We further quantify the contribution of dynamic and thermo\_Local effects in Fig. 11f by presenting the zonal mean AR frequency. The dynamic effect leads to an AR decrease over the midlatitude and increase over the high latitudes, contributing to the poleward shift of ARs. The contribution of thermo\_Local to the AR increases in high latitudes is comparable to or even larger than the dynamic effect. This thermo\_Local effect on a global scale has not been

studied yet while most previous studies attribute the AR poleward shift only to the wind changes focusing on region of interest. In addition, the dynamic effect also results in an AR increase over the subtropics of the North Hemisphere, suggesting the topographic effect in the asymmetric responses of two hemispheres.

Next, we check the responses in the basic characteristics of ARs in Fig. 6. Robust responses are found in length, width, coherence of direction, and landfall magnitude, as illustrated in Fig. 12. In response to the uniform tropospheric 4-K warming, the ARs become longer and wider, indicating that larger ARs are expected under global warming according to the same detection threshold (Figs. 12a,c). It is worth noting that the coherence of IVT direction decreases along with the size increasing (Fig. 12e), given that the detected ARs are larger according to the same threshold and thus presenting a less organized feature. The intensity of landfalling ARs is enhanced in a warmer climate (Fig. 12g), consistent with previous studies (e.g., Lavers et al. 2015; Hagos et al. 2016; Espinoza et al. 2018; Curry et al. 2019; Gershunov et al. 2019; Huang et al. 2020). These results in the idealized model are in agreement with the responses in the RCP8.5 scenario in CESM LENS simulations with  $\sim 4.4$ -K warming on average (Fig. 12, right column). The consistency in the responses of AR characteristics between the idealized model and comprehensive model further indicates that, although there are some biases in the simulation of AR characteristics (e.g., width in Fig. 6b), the idealized model is able to simulate the AR changes in a warming climate. The simplicity of model physics in the idealized model demonstrates that the projected AR changes under global warming can be understood as passive water vapor and cloud tracers without explicit consideration of convections and associated latent heating feedback, and thus are not particularly sensitive to details of model physics. In other words, the dominant physical mechanism for atmospheric rivers is the mixing of air mass and moisture along isentropic surfaces associated with large-scale tropospheric weather systems (Chen and Plumb 2014), which also play a major role in the humidity structure of the atmosphere (Galewsky et al. 2005; Wright et al. 2010).

One advantage of the idealized model over the comprehensive model is to test the sensitivity of the response to climate

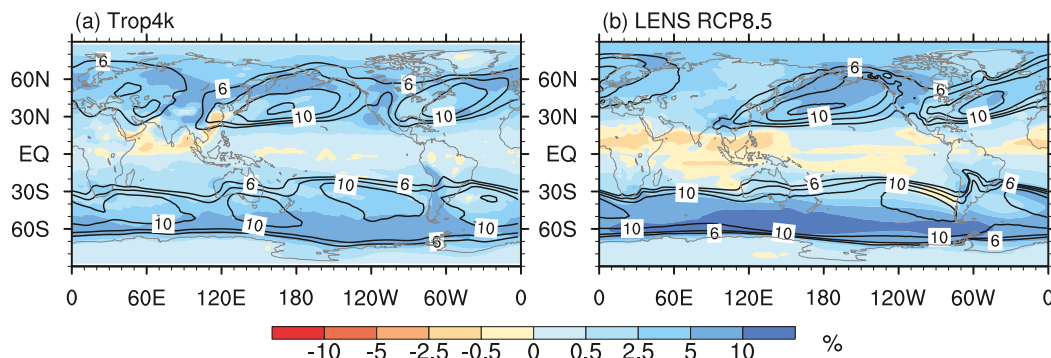


FIG. 10. Frequency changes of atmospheric rivers in response to global warming. (a) AR frequency (%) in Ctrl (contour) and its response (Trop4k-Ctrl) in Trop4K run (color shading). (b) AR frequency in historical runs of CESM LENS during 1979–2005 (contour) and its response in RCP8.5 runs during 2074–2100 (color shading).

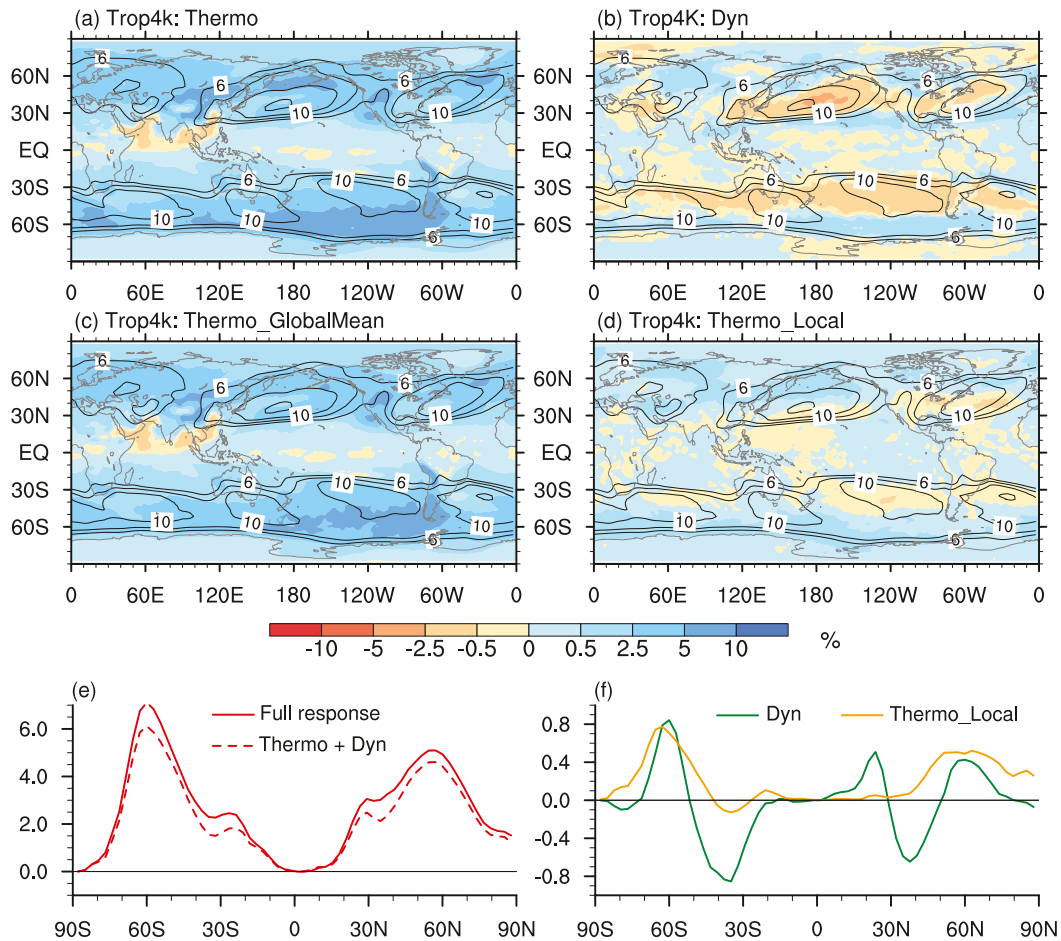


FIG. 11. Decomposition of the response in AR frequency in Trop4K simulation. (a) Thermodynamic effect. (b) Dynamic effect. (c) Thermodynamic effect due to global mean warming. (d) Thermodynamic response due to local effect. (e) Full response and the sum of the thermodynamic and dynamic effects in zonal mean AR frequency. (f) Thermo\_Local and dynamic effects in zonal mean AR frequency.

forcing. Here we further investigate the AR changes among a range of climates ( $-4$ ,  $-2$ ,  $0$ ,  $2$ , and  $4$ -K temperature forcing; see Table 1). The zonal means of the AR frequency in a series of experiments are shown in Fig. 13a. The AR activities gradually become more frequent along linearly with the tropospheric temperature changes, while a clear poleward shift is found in the latitude of the AR frequency maximum, especially over the Southern Hemisphere. The increase of AR frequency over the Southern Hemisphere along with warming is larger than that in the Northern Hemisphere. This hemispheric asymmetry is enhanced along with the forcing magnitude. The poleward shift of the ARs and its hemispheric asymmetry in a warming climate is in agreement with that in the RCP8.5/CESM simulations (Fig. 13b). Observations also witnessed a poleward shift in AR in recent decades, with important implications for moisture transport into the Antarctic (Ma et al. 2020a). Interestingly, the increase of AR frequency in the Trop4K run is 48.1%, while a 50% increase is found in the RCP8.5/CESM simulation with a tropospheric 4.4-K warming on average. Thus, we conclude that the shift and intensification

of AR frequency in response to global warming in the idealized model experiments are comparable to those in the CESM simulation.

For the statistics of the basic characteristics of ARs, the PDFs present a monotonic change among a range of climates (Fig. 14). The PDFs of AR size tend to shift to the longer and wider sides in a warming world and to shift to the shorter and narrower sides in a cooling world according to the same detection threshold (Figs. 14a,b). Along with the AR size expansion due to the monotonic temperature increases, the coherence of ARs is weakened monotonically (Fig. 14c). The PDF of the magnitude of landfalling IVT tends to shift to the more intense side gradually along with temperature increases, indicating the amplified influence on the coastal region following further warming in the future. The line chart in each subplot of Fig. 14 explicitly shows the shifts of medians (gray line with colored stars) to their reference state (the median in Ctrl or Hist). Similar to the response in AR frequency, the change of the medians in simple model simulation Trop4K are quantitatively close to that in CESM LENS RCP8.5 with a

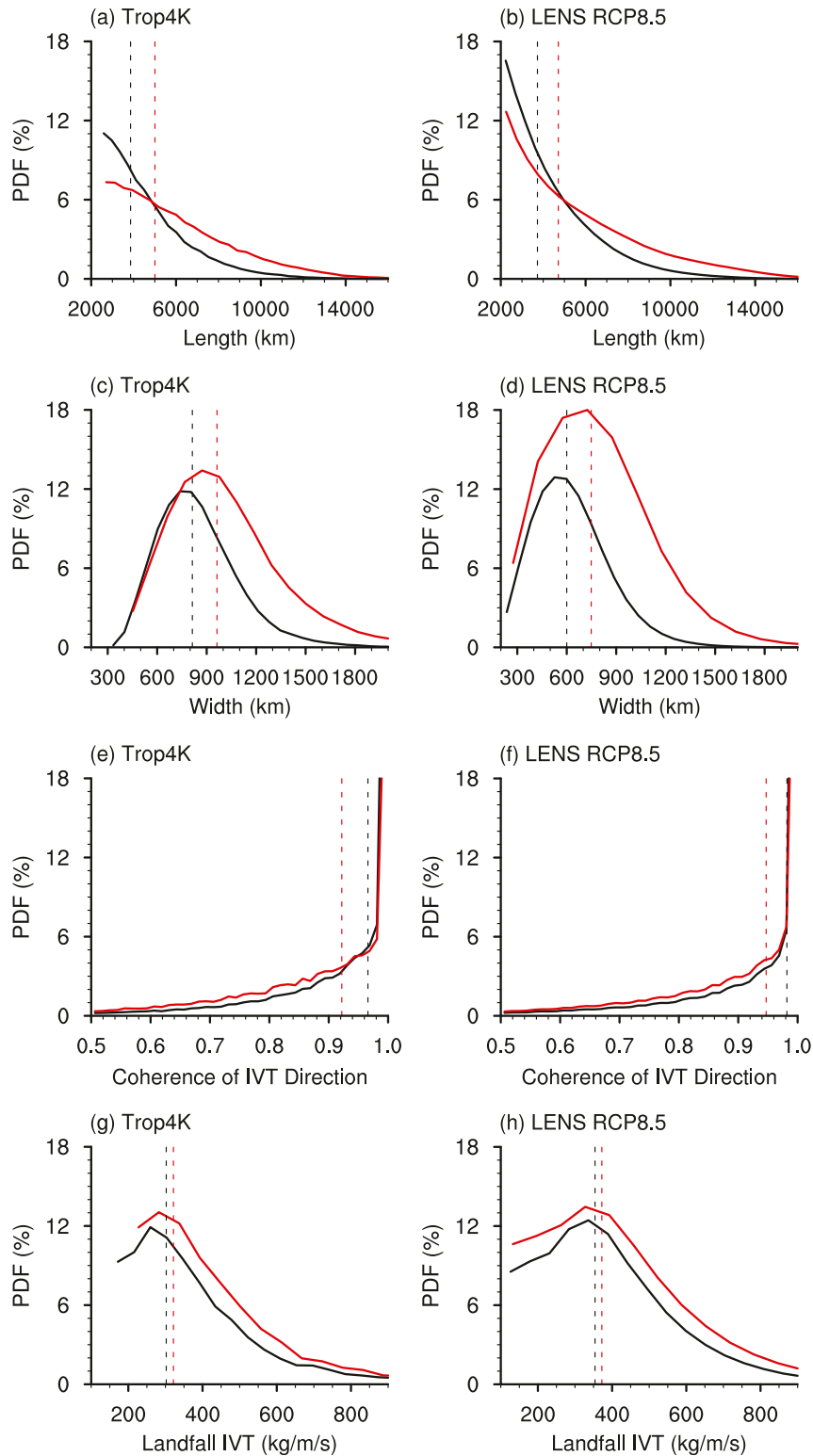


FIG. 12. Responses in the PDFs of AR characteristics to global warming in (left) idealized model experiments and (right) CESM LENS outputs. (a),(b) Length of ARs. (c),(d) Width of ARs. (e),(f) Coherence of IVT direction of ARs. (g),(h) Magnitude of IVT at the landfalling point. Black indicates the reference state (Ctrl or Hist) and red indicates the warmer climate (Trop4K or RCP8.5). The two dashed vertical lines in each panel denote the median.

TABLE 1. Model experiments conducted in this study.

Expt name	Description
1 Trop4K	Forced by an additional uniform 4-K warming in the troposphere
2 Trop2K	Same as Trop4K but with a 2-K forcing
3 Ctrl	Control run
4 Trop-2K	Same as Trop4K but with a -2-K forcing
5 Trop-4K	Same as Trop4K but with a -4-K forcing

tropospheric 4.4-K warming on average (cf. the red star and solid circle in each line chart in Fig. 14). The above results demonstrate that the responses of ARs in a warming climate, albeit with some biases, can be understood as passive water vapor and cloud tracers in a changing circulation. This simple physical setup helps to boost our confidence in the model projections of ARs in a warmer climate. Further, the contributions of dynamic and thermodynamic to the changes in AR characteristics are also shown in the line chart in each subplot (green and orange lines, respectively). It is clear that the thermodynamic response is dominant, and the dynamic response can be ignored. These analyses indicate that the AR structure changes (e.g., larger size) in a warmer climate are mainly due to the higher moisture in a warmer climate that leads to more grids fulfilling the same detection threshold, while the response in the wind field contributes little to the AR structure changes. For the response of landfall IVT (Fig. 14d), the dynamic effect even weakens the landfalling ARs (i.e., the weaker velocity of midlatitude storms in a warmer climate; e.g., Caballero and Hanley 2012), while the moisture carried by landfalling ARs predominantly increases in a warming climate, and thus their total effect enhances the landfalling ARs.

## 6. Conclusions

In this study, we have presented the statistics of atmospheric river response to global warming in idealized and comprehensive climate models. In particular, we developed a new idealized GCM with Earth-like global circulation and hydrological cycle to simulate the spatial distribution of the ARs and their response to a warming climate. In this idealized model, the mean temperature resembles the observations through relaxation to prescribed equilibrium temperature with an iterative method (Chang 2006; Wu and Reichler 2018), and water vapor and clouds are modeled as passive tracers with cloud microphysics and precipitation processes but without cloud radiative effects or latent heat release (MH18). Despite the simplicity of model physics, this idealized GCM produces qualitatively similar global moisture transport,  $P - E$ , and cloud distributions as compared with observations; especially over the extratropics, the model produces remarkable simulations in the dynamical structure of individual ARs, the basic statistical characteristics of ARs and the realistic spatial distributions of AR climatology. This idealized model under uniform tropospheric warming projects robust AR changes in response to global warming similar to the CESM LENS

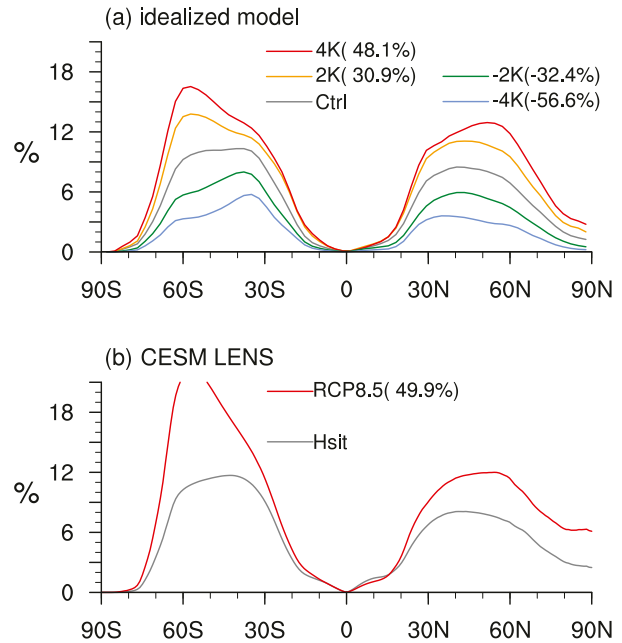


FIG. 13. (a) Zonal mean of AR frequency (%) among a range of climates in idealized simulations. The AR frequency changes relative to the Ctrl run are shown in legend (the percentages, calculated as changes divided by reference state). (b) As in (a), but for that in CESM LENS. For the tropospheric temperature response in CESM LENS, there is about 4.4-K warming in 2074–2100 in RCP8.5 runs compared to 1979–2005 in historical runs.

simulations under RCP8.5, including the AR size expansion according to the same detection threshold, intensified landfall moisture transport magnitude, and an increase in AR frequency, which is mainly attributed to the higher moisture with warmer climate (i.e., thermodynamic effect), further improving our confidence in previously reported AR changes under global warming (e.g., Lavers et al. 2015; Payne and Magnusdottir 2015; Warner et al. 2015; Gao et al. 2016; Hagos et al. 2016; Gershunov et al. 2017; Espinoza et al. 2018; Curry et al. 2019). In addition, the AR frequency shifts poleward with uniform tropospheric warming. We further suggest that this poleward shift is attributed not only to the dynamic effect but also to the thermodynamic effect due to the nonlinear moisture dependence on temperature, with a larger increase in saturation vapor pressure with warming at lower temperatures (e.g., polar regions). The contribution of the local nonlinear effect to the poleward shift in ARs has not been studied yet. This poleward shift is more notable in the Southern Hemisphere, where observations saw a poleward shift in AR in recent decades, with important implications for the moisture transport into the Antarctic (Ma et al. 2020a).

These results demonstrate, despite their fine-scale structures, that the basic dynamics of ARs in a warming climate can be understood as passive water vapor and cloud tracers without explicit consideration of convections and associated latent heat feedback. In other words, the dominant physical mechanism for atmospheric rivers is the mixing of air mass and moisture along isentropic surfaces associated with

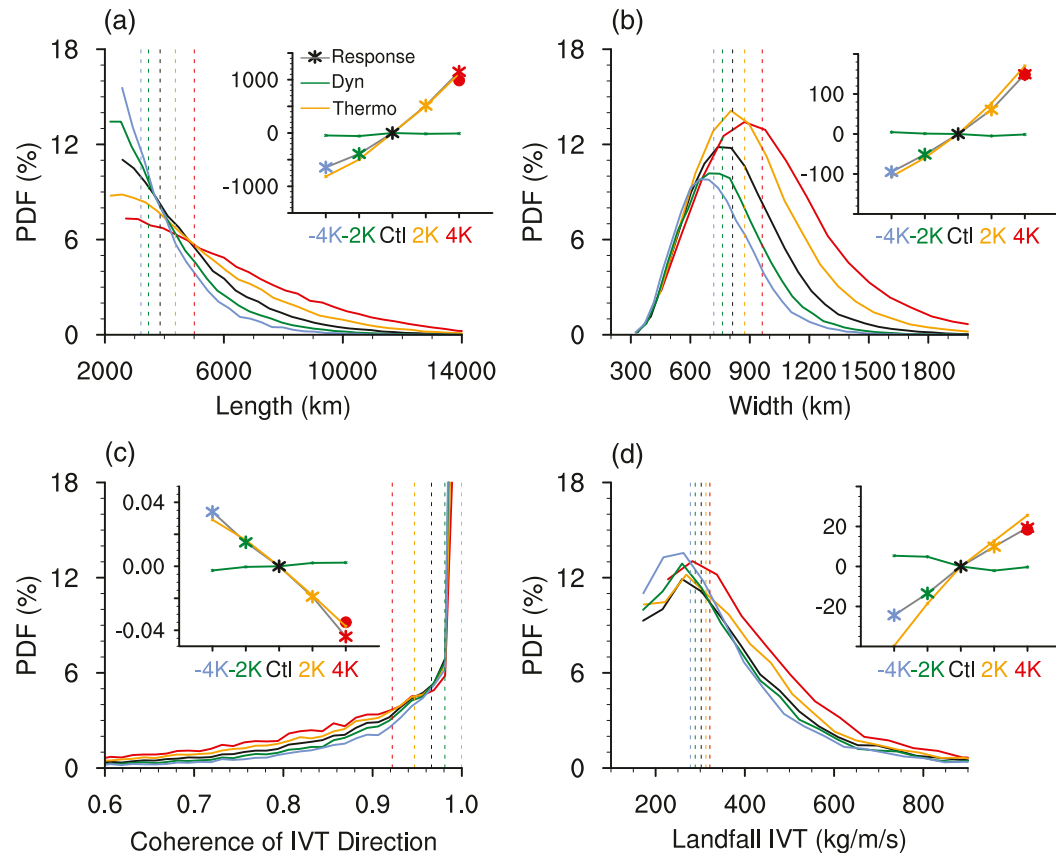


FIG. 14. As in Fig. 11, but for that in Trop-4K (blue), Trop-2K (green), Ctrl (black), Trop2K (orange), and Trop4K (red) experiments. The line with colored stars in the line charts in every panel shows the median changes in sensitivity experiments, respectively. The green line and orange line in the line charts in each panel show the median changes in dynamic response and thermodynamic response, respectively. The median changes for each variable are defined as the differences between the medians in the 5 experiments and the Ctrl. The median changes with a 4.4-K warming in RCP8.5 compared to HIST in CESM LENS are marked as red solid circles in the line charts.

large-scale tropospheric weather systems (Chen and Plumb 2014), which also play a major role in the humidity structure of the atmosphere (Galewsky et al. 2005; Wright et al. 2010). This may be a little counterintuitive as latent heat release is often considered as a major source of energy that reinforces the synoptic storm associated with an AR. This may be explained by a recent study on midlatitude extreme precipitation, in which the latent heat feedback is largely canceled by the increased stratification in a warming climate (Li and O’Gorman 2020).

Although the idealized model simulates the ARs and their responses in changing climate well, care must be taken in generalizing this simple model to some studies of ARs in the real climate. For example, given that some tropical factors, such as the Madden–Julian oscillation (MJO) and El Niño–Southern Oscillation (ENSO), could influence extratropical ARs through atmospheric teleconnections (Guan et al. 2012; Guan and Waliser 2015; Mundhenk et al. 2016), the biased simulation over the tropics in the idealized model may limit its capability to model the variability of ARs. In addition, the modeled landfalling ARs are too strong as compared to observations because of the excessive moisture over the land simulated

by the model in which the relative humidity is simply nudged to 100% at the lowest model level. A more realistic evaporation scheme with realistic land–sea contrast is warranted to describe better the landfalling ARs and their impact on the coastal regions.

Finally, this idealized model provides a new tool for understanding Earth-like global circulation and hydrological cycle on regional scales. Our study has demonstrated that the idealized model can capture many features of atmospheric general circulation, midlatitude storms, and moisture transport in a warming climate. Many idealized models have no explicit hydrological cycle (e.g., Held and Suarez 1994) or unrealistic boundary conditions (e.g., Neale and Hoskins 2000) and thus cannot simulate realistic spatial distributions of ARs. The new idealized model developed in this study overcomes these limitations and reproduces individual ARs and their climatology well, and thus helps improve our confidence in regional atmospheric moisture transport and AR dynamics in a warming climate.

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## APPENDIX

### Iteration Algorithm

The model is supposed to reproduce a temperature field similar to a given reference temperature climatology  $T_R$ . Here,  $T_R$  is the mean state of the MERRA2 in 1980–2015 (Wu and Reichler 2018). For an iteration step ( $i$ ), a model run forced with a  $T_{\text{eq}}(i)$  produces a time-mean output temperature field  $\bar{T}(i)$ . Then we calculate the difference between  $\bar{T}(i)$  and  $T_R$  and define  $T_{\text{eq}}(i + 1)$  as

$$T_{\text{eq}}(i + 1) = T_{\text{eq}}(i) - \alpha[\bar{T}(i) - T_R] \quad (\text{A1})$$

to yield  $\bar{T}(i + 1)$  closer to  $T_R$ . Note that  $\alpha = 2/3$  is used here following Chang (2006) to avoid overshooting the optimal  $T_{\text{eq}}$ . Equation (A1) is then iterated until  $T_{\text{eq}}(n)$  that yields a  $\bar{T}(n)$  sufficiently close to  $T_R$  is generated.

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