

A Link between the Hiatus in Global Warming and North American Drought

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ABSTRACT

Portions of western North America have experienced prolonged drought over the last decade. This drought has occurred at the same time as the global warming hiatus—a decadal period with little increase in global mean surface temperature. Climate models and observational analyses are used to clarify the dual role of recent tropical Pacific changes in driving both the global warming hiatus and North American drought. When observed tropical Pacific wind stress anomalies are inserted into coupled models, the simulations produce persistent negative sea surface temperature anomalies in the eastern tropical Pacific, a hiatus in global warming, and drought over North America driven by SST-induced atmospheric circulation anomalies. In the simulations herein the tropical wind anomalies account for 92% of the simulated North American drought during the recent decade, with 8% from anthropogenic radiative forcing changes. This suggests that anthropogenic radiative forcing is not the dominant driver of the current drought, unless the wind changes themselves are driven by anthropogenic radiative forcing. The anomalous tropical winds could also originate from coupled interactions in the tropical Pacific or from forcing outside the tropical Pacific. The model experiments suggest that if the tropical winds were to return to climatological conditions, then the recent tendency toward North American drought would diminish. Alternatively, if the anomalous tropical winds were to persist, then the impact on North American drought would continue; however, the impact of the enhanced Pacific easterlies on global temperature diminishes after a decade or two due to a surface re-emergence of warmer water that was initially subducted into the ocean interior.

1. Introduction

There has been a prolonged drought over portions of western North America since around the year 2000 (Stahle et al. 2009; Cayan et al. 2010; Seager and Hoerling 2014), encompassing regions from the western Great Plains to the U.S. West Coast. This decadal-scale drought has created substantial impacts in many societal sectors, including agriculture and wildfires (Dennison et al. 2014). The underlying causes of the drought are not

well established in terms of the role of natural variability versus human-induced radiative forcing changes, such as from increasing greenhouse gases. Recent work focusing on California drought during the shorter 2011–14 period has suggested that internal variability is likely responsible (Wang and Schubert 2014a; Funk et al. 2014; Seager et al. 2015, manuscript submitted to *J. Climate*), although aspects of the atmospheric circulation associated with that drought could have some relationship to climate change (Swain et al. 2014). The causes of the larger-scale decadal drought over western North America are less clear. This decadal-scale drought has occurred at the same time as the so-called global warming hiatus (Easterling and Wehner 2009; Bindoff et al. 2014; Hawkins et al. 2014), a decadal period with

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little increase in global mean surface temperature. In this study we find a clear link between the hiatus and recent decadal-scale drought over portions of North America via enhanced easterly winds in the tropical Pacific and their association with decadal changes in local sea surface temperature.

There are a number of factors that could have contributed to the recent observed hiatus in global warming (Clement and DiNezio 2014), including natural radiative forcing, anthropogenic radiative forcing, and internal variability of the climate system. Potential natural radiative forcing factors include volcanic activity (Santer et al. 2014) and a persistently low level of solar irradiance in the most recent solar cycle, in addition to changes in stratospheric water vapor (Solomon et al. 2010). An altered vertical distribution of heating within the ocean could have also contributed to the hiatus (Trenberth and Fasullo 2013; Katsman and van Oldenborgh 2011; Balmaseda et al. 2013). The hiatus could also have substantial contributions from internal variability of the coupled system, linked to phenomena such as ENSO and the Pacific decadal oscillation (Meehl et al. 2011, 2013; Vecchi and Wittenberg 2010; Ogata et al. 2013) or the Atlantic multidecadal oscillation (Tung and Zhou 2013). It has also been suggested that incomplete coverage in observing systems (Cowtan and Way 2014) could have led to underestimation of the true warming trend.

Recent work has highlighted the importance of observed changes in the tropical Pacific for explaining the hiatus in global warming. Kosaka and Xie (2013) were able to simulate the hiatus using a global climate model when sea surface temperatures (SSTs) over the eastern near-equatorial Pacific were strongly damped toward observed SSTs. England et al. (2014) extended this work by first noting that the hiatus period has exhibited unusually intense easterly winds in the tropical Pacific. They then showed that these enhanced easterly winds in the Pacific lead a climate model to replicate many aspects of the observed hiatus, including global mean surface air temperature and the patterns of upper ocean heat content change. Taken together, Kosaka and Xie (2013) and England et al. (2014) indicate that much of the hiatus may be connected to tropical Pacific SST and wind stress changes. Recent work has suggested that the enhanced tropical Pacific easterly winds could be partly driven from regions outside the Pacific, whether from the Indian Ocean (Luo et al. 2012) or the Atlantic (McGregor et al. 2014).

In the current study we use numerical modeling experiments to explore the relationships between enhanced tropical Pacific easterly winds and global climate. The results of our experiments, done with a suite of different models, independently confirm the results of England et al. (2014) and support the

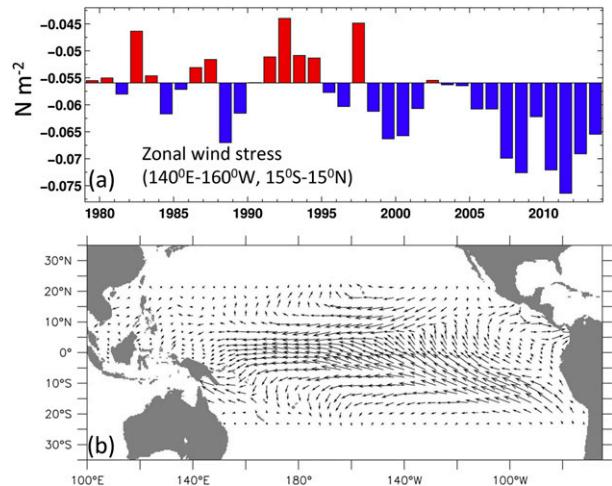


FIG. 1. (a) Time series of annual mean zonal wind stress (N m^{-2}) applied to the model ocean in the ALLFORC_STRESS experiment averaged over 15°S – 15°N , 140°E – 160°W . As discussed in the main text, the stress anomalies are from ERA-Interim. (b) Spatial pattern of stress anomalies applied to the model in the ALLFORC_STRESS experiment for the period 2002–12 relative to the period 1979–2000.

conclusions of Kosaka and Xie (2013). Further, we show a strong connection between these same tropical Pacific wind stress changes and drought over North America. Our results suggest that the observed drought over portions of western North America over the last decade is not likely to be a direct response of the climate system to radiative forcing changes, unless the wind stress changes themselves are induced by radiative forcing changes. We also show, using idealized experiments, that the impact of constant easterly tropical Pacific wind anomalies on simulated global mean temperature appears to be transient, diminishing after a decade or two.

2. Model, simulations, and observational data

a. Model and simulations

We use targeted numerical experiments with multiple comprehensive climate models in concert with observational analyses. We use three models: 1) the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model (Delworth et al. 2006; Wittenberg et al. 2006), hereinafter CM2.1; 2) the GFDL Forecast-Oriented Low Ocean Resolution version of CM2.5 (CM2.5_FLOR) model (Vecchi et al. 2014), hereinafter FLOR; and 3) the GFDL flux adjusted CM2.5_FLOR (CM2.5_FLOR_FA) model (Vecchi et al. 2014), hereinafter FLOR_FA. All three models share many aspects of their physics and have very similar ocean models, but they differ in atmospheric resolution. The CM2.1 model has an atmospheric horizontal

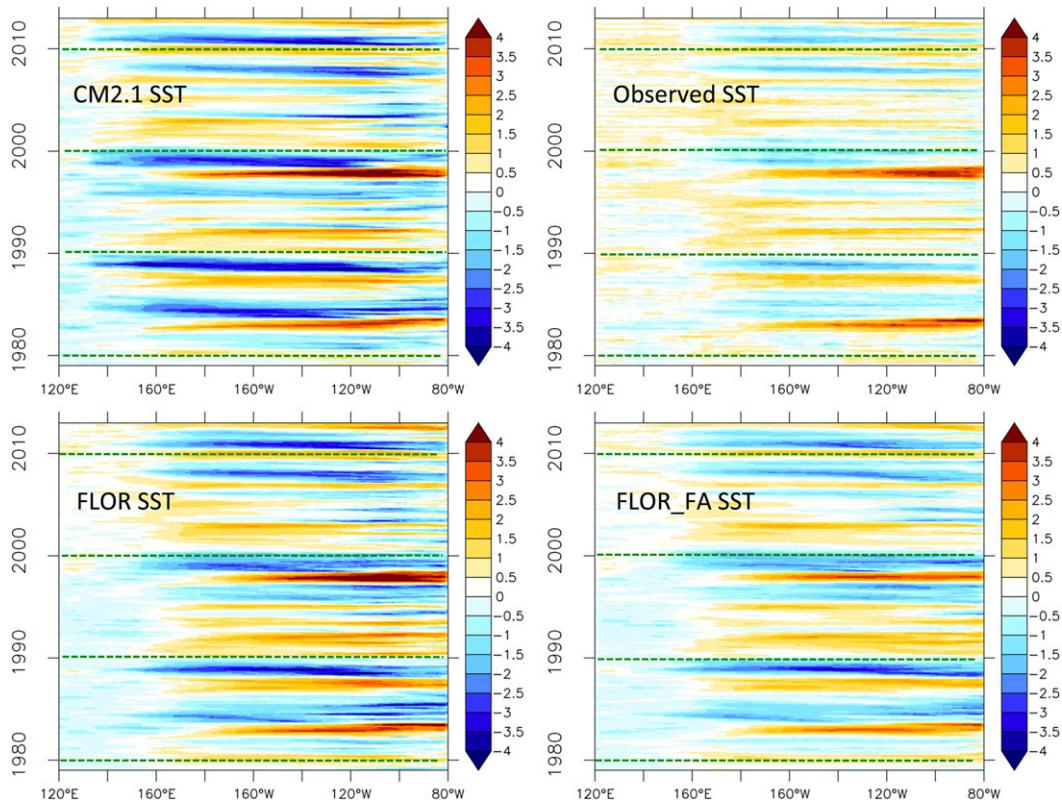


FIG. 2. Time-longitude plots of monthly SST anomalies (K) for observations from (top right) the HadISST dataset (Rayner et al. 2003) and models (CM2.1, FLOR, and FLOR_FA). SST values are averaged between 5°S and 5°N. For visual perspective, dashed green horizontal lines are drawn every 10 years.

grid spacing of approximately 200 km, with 24 vertical levels. The FLOR and FLOR_FA models derive from the GFDL CM2.5 model (Delworth et al. 2012), and have atmospheric grid spacing of approximately 50 km in the horizontal, with 32 levels in the vertical, and a more sophisticated land model than the CM2.1 model. The FLOR_FA model differs from FLOR through the use of flux adjustments (Magnusson et al. 2013) as a numerical technique to reduce climatological model biases, while allowing the model to generate internal variability and respond to radiative forcing. The CM2.1 and FLOR models are used in routine seasonal prediction as part of the North American Multimodel Ensemble (Kirtman et al. 2014).

We use several types of experiments. Experiments using CM2.1 are 10-member ensembles, while experiments using FLOR and FLOR_FA are 5-member ensembles.

- 1) CONTROL simulations use concentrations of greenhouse gases and other radiative forcing components that are constant at preindustrial conditions (approximately calendar year 1860).
- 2) CONTROL_STRESS simulations are conducted as departures from the CONTROL simulation, but

in which a uniform zonal wind stress anomaly (-0.008 N m^{-2}) over a rectangular domain in the tropical Pacific is added to the momentum flux into the ocean calculated by the coupled model from air-sea gradients. The domain for the stress addition extends from 15°S to 15°N, with a 10° buffer zone on the northern and southern sides where the stress anomalies taper linearly to zero at $\pm 25^\circ$ latitude; in longitude the domain extends from 150°E to the coast of South America, with a 10° buffer zone from 140° to 150°E. These simulations are 100-yr long.

- 3) ALLFORC simulations cover the period from 1861 to 2040, using estimates of the observed changes in radiative forcing over the 1861–2005 period, and with estimated changes in radiative forcing for 2006–40 based on the representative concentration pathway 4.5 (RCP4.5) scenario (see <http://cmip-pcmdi.llnl.gov/cmip5/forcing.html> for details).
- 4) ALLFORC_STRESS simulations are identical to ALLFORC, except that the model calculated wind stress anomalies that the ocean feels are replaced over the tropical Pacific (region shown in Fig. 1b) with stress anomalies derived from European

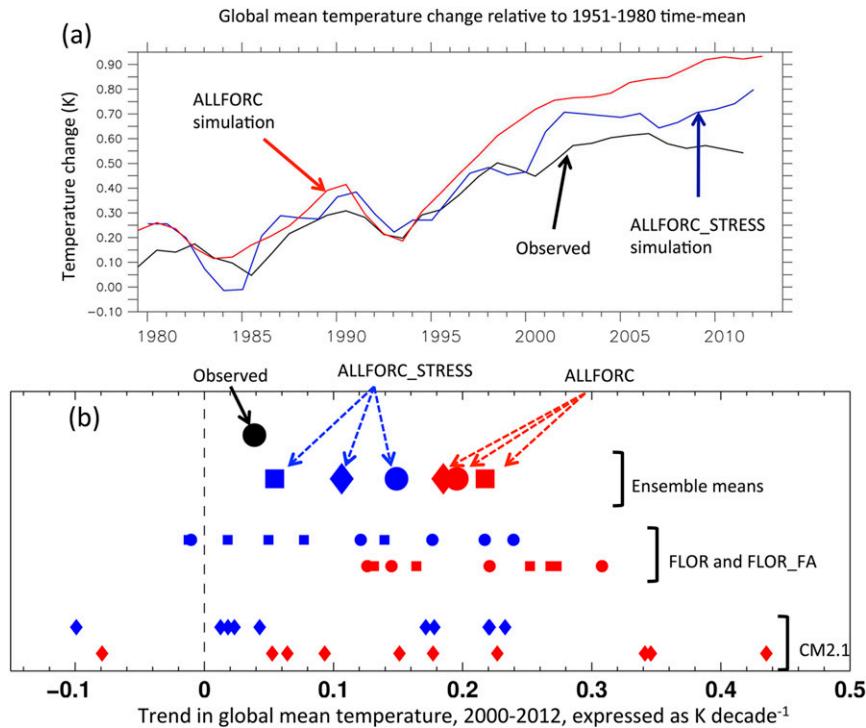


FIG. 3. (a) Time series of anomalies in global mean, annual mean surface air temperature relative to the time mean over the period 1951–80 (K). Black line denotes observations from the CRU of the University of East Anglia. Red (blue) line corresponds to the ensemble mean of the CM2.1 ALLFORC (ALLFORC_STRESS) experiments. A 3-yr running mean was applied to all time series. (b) Trends in global mean surface air temperature over the period 2000–12 (K decade^{-1}). Red (blue) symbols indicate ALLFORC (ALLFORC_STRESS) experiments. Large symbols are ensemble mean, and small symbols are individual ensemble members. Experiments using models CM2.1, FLOR, and FLOR_FA are indicated by diamonds, squares and circles respectively.

Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (Dee et al. 2011) on a month by month basis over the period 1979–2013. This replacement occurs only over the tropical Pacific, and only affects the momentum flux. The differences between ALLFORC_STRESS and ALLFORC experiments represent the impacts on the global climate system of the momentum flux into the ocean from observed tropical Pacific wind stress anomalies over the period 1979–2013.

More specifically, we replace the model-calculated wind stress at each time step with a stress value from an imposed wind stress time series. This time series is composed of three parts: 1) daily wind stress values from the ALLFORC simulation that have been filtered to retain only time scales shorter than 30 days, 2) a repeating seasonal cycle of wind stress calculated from the ALLFORC experiment, and 3) monthly wind stress perturbations derived from the ECMWF interim

reanalysis (ERA-Interim; Dee et al. 2011). These perturbations are calculated as the anomalies from their climatological seasonal cycle computed over the 1979–2013 period; this ensures that the time mean of the reanalysis wind stress anomalies applied to the CM2.1 model is zero over the 1979–2013 period. The above construction conserves the time mean of the wind stress time series from the original coupled model, so as not to induce a model drift, but still allows the model to feel interannual wind stress variations similar to observational estimates over this period. For the Pacific there is a complete replacement of the wind stress in the deep tropics (15°S – 15°N); within 25° – 15°S and 15° – 25°N the wind stress is a mixture of the model's calculated wind stress and the replacement time series, with a linear taper such that the replacement effect goes to zero at 25°S and 25°N . Poleward of 25° the model stresses are computed entirely by the model based on air–sea gradients and then passed to the ocean component. In this process we only alter the flux of momentum through the stress field; the wind effects on

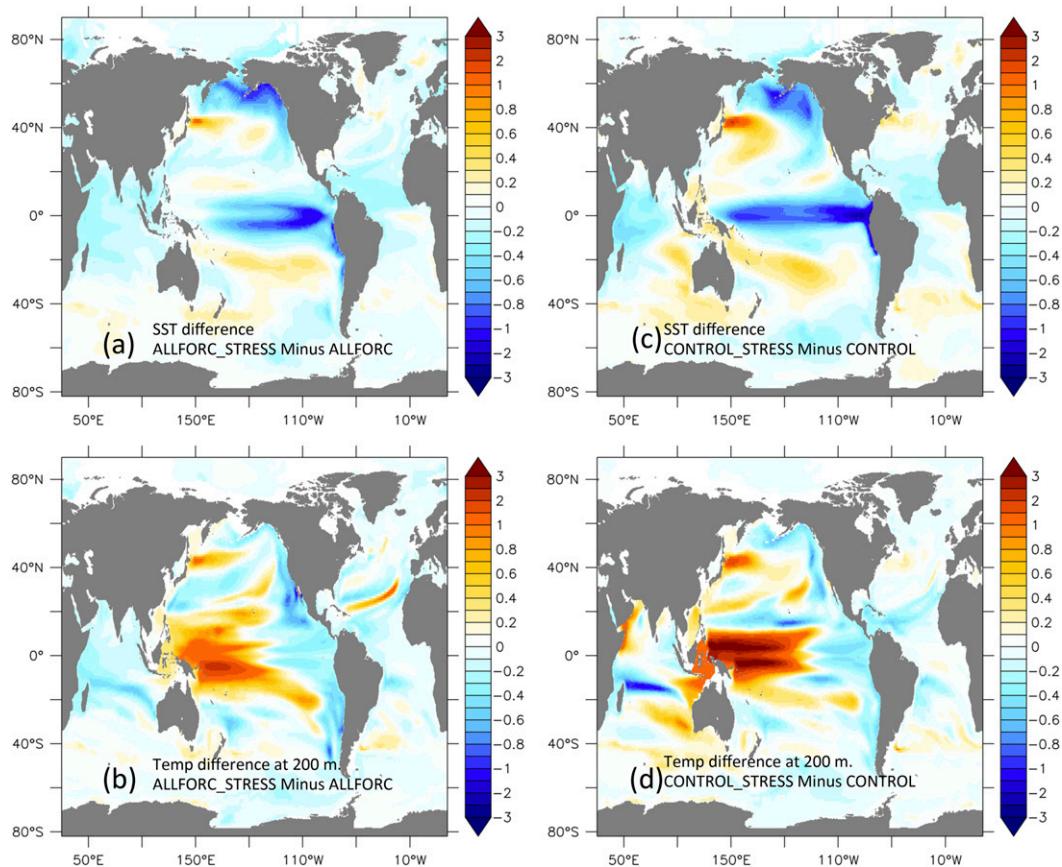


FIG. 4. (a) Spatial pattern of the SST response to imposed wind stress forcing (K), calculated as the time mean over 2002–12 in ALLFORC_STRESS minus ALLFORC. (b) As in (a), but for temperature at 200 m (K). (c), (d) As in (a), (b), but for experiment CONTROL_STRESS minus CONTROL.

latent and sensible heat fluxes are unaltered, and are computed based on the model's internal physics.

We show the time series (Fig. 1a) and spatial pattern (Fig. 1b) of the tropical Pacific wind stress anomalies imposed in the ALLFORC_STRESS experiments. The primary characteristic is an enhancement of the easterly winds from the late 1990s onward. The ALLFORC_STRESS simulations are able to largely replicate the observed timings of El Niño and La Niña events (Fig. 2) in response to the imposed wind stress anomalies, although the simulated amplitude of SST variations is larger than observed. The simulation of ENSO in FLOR_FA is notably more realistic than in FLOR (Vecchi et al. 2014), with a more realistic amplitude and seasonal phase locking than in FLOR or CM2.1.

We note that within the tropical Pacific, the zonal wind stress is tightly coupled to the zonal SST gradient and zonal thermocline slope. Thus in the above experiments, the wind stress can be viewed as a proxy for the state of the tropical Pacific Ocean and atmosphere. Prescribing the wind stress anomalies in this region is

one method to prescribe the full decadal state of the tropical Pacific, which then permits an assessment of the Pacific's downstream impacts on the rest of the globe.

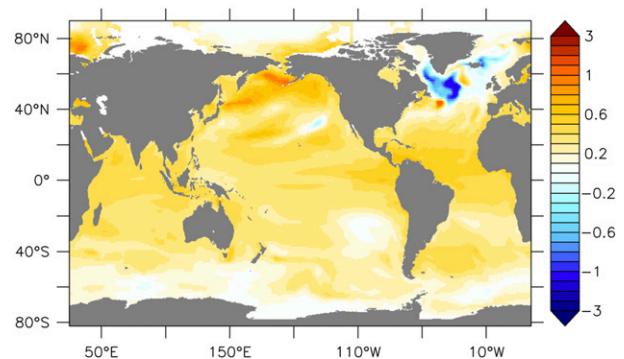


FIG. 5. Estimate of SST response (K) to radiative forcing change using the ALLFORC experiment with the CM2.1 model. The estimate is calculated as the 10-member ensemble mean SST for the 2002–12 period minus the 10-member ensemble mean SST for the 1979–2000 period. The negative values in the subpolar North Atlantic are associated with a weakening of the Atlantic meridional overturning circulation.

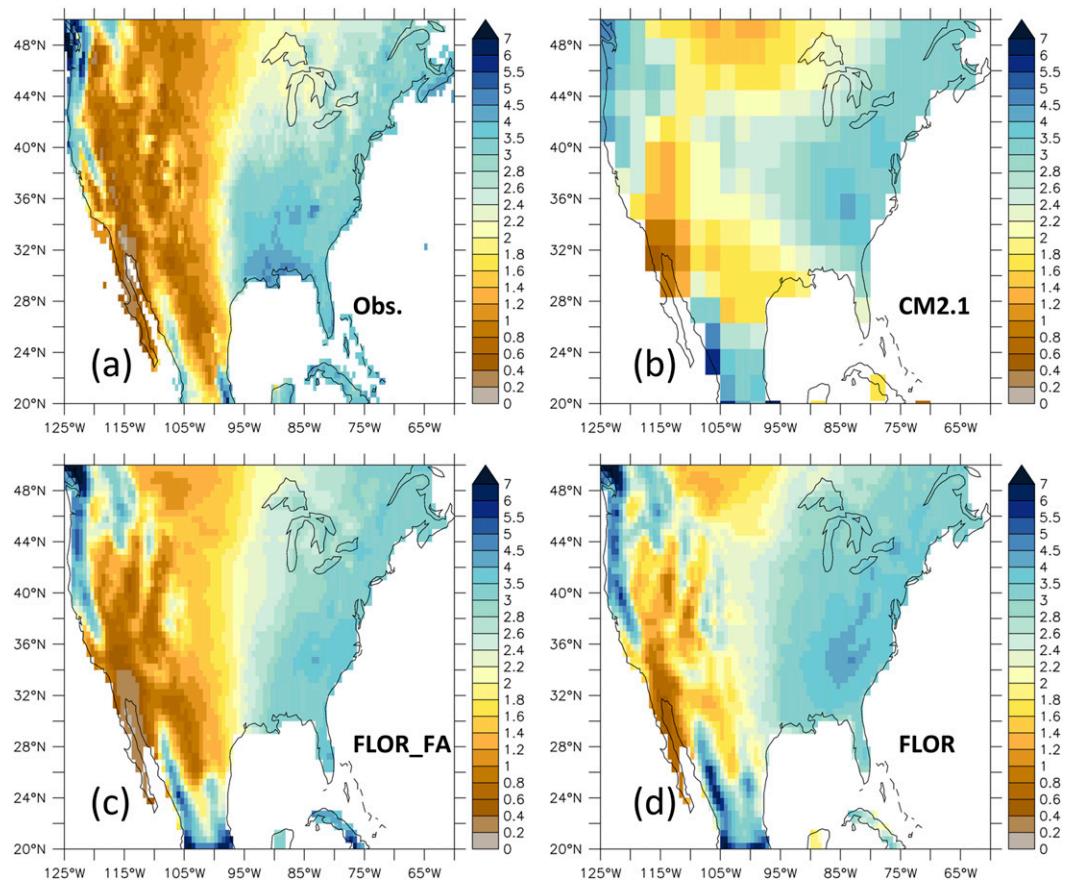


FIG. 6. Precipitation climatology from observations and the models. Annual mean precipitation (mm day^{-1}) is shown for (a) observations from the CRU of the University of East Anglia, (b) CM2.1 model, (c) FLOR_FA model, and (d) FLOR model.

b. Observational data

The observed monthly precipitation data (Harris et al. 2014) come from the Climatic Research Unit (CRU) of the University of East Anglia. The data are global on a 0.5° grid, extending from 1901 through 2012. The observed monthly surface air temperature (HadCRUT4; Jones et al. 2012) also comes from CRU and is on a 5° grid, extending from 1850 to the present. The surface wind stresses come from ERA-Interim (Dee et al. 2011).

3. Results

a. Temperature response

The simulations are able to capture many aspects of the hiatus in response to the tropical Pacific wind stress anomalies (Fig. 3a). The observed record shows the 2002–13 hiatus period with little trend in global mean surface air temperature. The ALLFORC ensemble continues warming throughout the period. In contrast, the ALLFORC_STRESS ensemble has considerably

reduced warming after the year 2002, demonstrating that it has replicated aspects of the observed hiatus in response to the strengthening of the tropical Pacific easterly winds, similar to England et al. (2014). While the ALLFORC_STRESS ensemble mean warming trend is still larger than the observations (for CM2.1 and FLOR), the decadal temperature trends in the ALLFORC_STRESS ensemble members using the three models are systematically smaller than in the corresponding ALLFORC ensembles (Fig. 3b). In particular, the observed trend lies near the center of the distribution of trends from the ALLFORC_STRESS runs using FLOR_FA.

We show in Fig. 4 the patterns of surface and subsurface ocean temperature change in response to the imposed wind stress changes using the CM2.1 model for the ALLFORC_STRESS and CONTROL_STRESS experiments (we obtain similar results using the FLOR and FLOR_FA models; not shown). By increasing upwelling and vertical mixing and strengthening the zonal tilt of the equatorial thermocline, the enhanced easterly winds force cold subsurface water in the eastern tropical

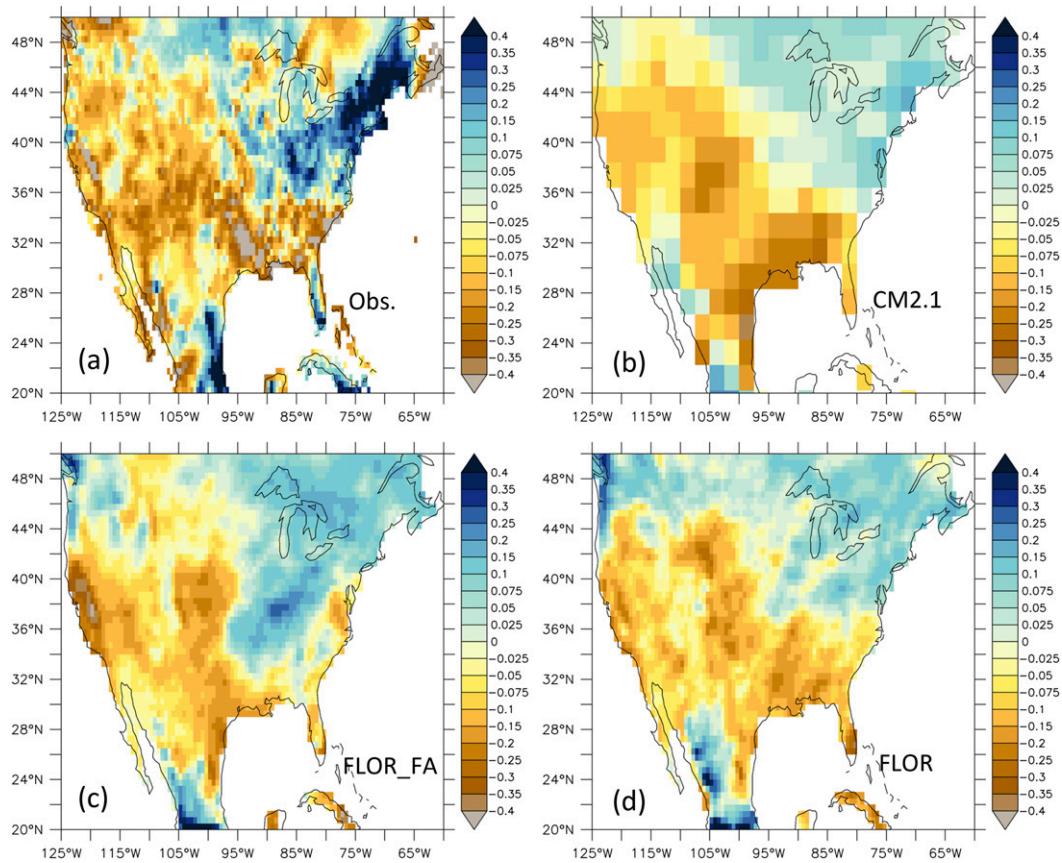


FIG. 7. (a) Difference in observed annual mean precipitation for the period 2002–12 minus 1979–2000 (mm day^{-1}). Observations are from the CRU of the University of East Anglia. (b) As in (a), but using model results from CM2.1 ALLFORC_STRESS, showing the combined effects of wind stress and radiative forcing changes. (c) As in (b), but using FLOR_FA. (d) As in (b), but using FLOR.

Pacific to the surface. The enhanced winds also depress the thermocline in the western tropical Pacific and force warm near-surface water in the tropical western Pacific to subduct into the ocean interior; this leads to positive subsurface temperature anomalies in the western tropical Pacific (Figs. 4b,d). The exposure of the cold water to the atmosphere in the eastern Pacific, combined with the movement of warmer surface water into the subsurface ocean in the western Pacific, contributes to the hiatus. In contrast, the pattern of SST change that occurs solely in response to radiative forcing changes (Fig. 5) is much more uniform.

b. Precipitation response

How are these enhanced easterlies and the hiatus connected to North American drought? It has been known for some time that SST in the Pacific can influence precipitation over North America (Ropelewski and Halpert 1986; Trenberth et al. 1988; Hoerling 2003; Seager et al. 2005; Schubert et al. 2004, 2009; Findell and

Delworth 2010; Seager and Hoerling 2014; Wang and Schubert 2014b). In particular, cold ocean temperature anomalies in the eastern tropical Pacific have been linked with anomalously dry conditions over parts of North America. We therefore examine whether these stress-induced Pacific SST changes induce precipitation anomalies over North America.

We first examine (Fig. 6) the ability of the models to simulate annual mean climatological precipitation over North America. The higher-resolution models (FLOR and FLOR_FA) simulate a more realistic spatial pattern and magnitude of annual mean precipitation than the lower-resolution CM2.1 model. In addition, the model using flux adjustments (FLOR_FA) has the most realistic simulation of annual mean precipitation among the models, including a more realistic depiction of the east–west precipitation gradients from Texas through the Great Plains. Biases in the model’s simulation of ocean temperature contribute to the biases in continental precipitation over North America (and for other continents; not shown).

We show in Fig. 7 changes in annual mean precipitation (2002–12 minus 1979–2000) for the observations (Fig. 7a) and for the ALLFORC_STRESS simulations (Figs. 7b–d). The observed tendency for reduced precipitation in western North America (Fig. 7a) is reproduced in the ALLFORC_STRESS experiments with each model (Figs. 7b–d). Averaged over the region 30° – 42° N, 130° – 95° W, the reduction in observed precipitation is $0.137 \text{ mm day}^{-1}$. For models CM2.1, FLOR, and FLOR_FA the simulated reductions over this region (land only) are 0.102, 0.095, and $0.117 \text{ mm day}^{-1}$, respectively. Since these experiments contain both radiative forcing changes and wind stress changes, we ask whether the tendency for reduced precipitation is due to radiative forcing changes or to the effects of tropical Pacific wind stress changes. We estimate the wind-forced component as the difference in precipitation between the ALLFORC_STRESS and ALLFORC experiments for the 2002–12 period. We also estimate the radiatively forced component as the precipitation in ALLFORC for the 2002–12 period minus the 1979–2000 period. Combining the results of all three models, the wind stress forcing accounts for 92% of the reduction in simulated annual mean precipitation, with the radiatively forced component accounting for 8%. A number of model-based studies (see, e.g., Seager et al. 2007; Cayan et al. 2010) have shown that aridity may increase over southwestern North America in response to increasing greenhouse gases and the resultant warming of the planet and from associated factors such as the expansion of the Hadley cell (Lu et al. 2007). However, the current results suggest that such factors were not primary drivers of the recent drought, consistent with earlier results (Hoerling et al. 2010; Seager and Naik 2012).

The tropical SST anomaly pattern creates a tendency for an atmospheric circulation pattern that is conducive to drought, but atmospheric internal dynamics also influence whether or not a drought occurs. Given this important role for atmospheric internal variability, we evaluate the likelihood of a change in precipitation in a more probabilistic framework. We first note that for the period 1979–2000 we have 220 individual years for the CM2.1 ALLFORC ensemble ($22 \text{ yr} \times 10$ ensemble members) and 220 total years for the ALLFORC ensembles using both FLOR and FLOR_FA ($22 \text{ yr} \times 5$ ensemble members $\times 2$ models). For each model precipitation time series we compute an areal mean over the region 30° – 42° N, 130° – 95° W (land only). We consider all of the model output for the period 1979–2000 to be one “population” (440 points). We then randomly sample this population, drawing 11 samples at a time and then computing an 11-yr mean (the same length as the 2002–12 period). We repeat this process 10 000 times to form a distribution of decadal mean precipitation

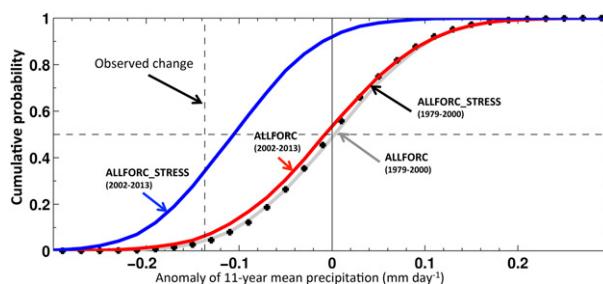


FIG. 8. Cumulative probability distribution of 11-yr mean precipitation anomalies (mm day^{-1}) averaged over 30° – 42° N, 130° – 95° W, land only. Gray curve (black crosses) indicates results using model values from the period 1979–2000 from experiment ALLFORC (ALLFORC_STRESS) using all three models (CM2.1, FLOR, and FLOR_FA). Red (blue) curve denotes values from ALLFORC (ALLFORC_STRESS) over the period 2002–12. The distributions are generated by resampling all ensemble members from each model (CM2.1, FLOR, and FLOR_FA) for the experiment and period indicated. For example, for the gray curve we use output from all 10 ensemble members of experiment ALLFORC, as well as 5 ensemble members each from FLOR and FLOR_FA models, over the period 1979–2000 (440 total points, based on 22 yr and 10 ensemble members from CM2.1 and 5 ensemble members for 22 yr from FLOR and FLOR_FA, respectively). We randomly pick 11 different values from among this pool of 440 values, and then average those to form an 11-yr mean, and then subtract from that the ensemble mean value over the period 1979–2000. We repeat this process 10 000 times to form a distribution of 11-yr mean anomalies, and plot that as a cumulative probability distribution function. We repeat this process using years 1979–2000 from ALLFORC_STRESS, years 2002–12 from ALLFORC, and years 2002–12 from ALLFORC_STRESS.

anomalies consistent with the 1979–2000 period for these models, and show that in Fig. 8 as a cumulative distribution function. We do the same with output from the ALLFORC_STRESS ensembles over this same period. These two distributions are very similar, indicating similar likelihoods of dry and wet decades from the ALLFORC and ALLFORC_STRESS ensembles for the 1979–2000 period. We then repeat this process using output for the period 2002–12 from the ALLFORC ensemble. We see (Fig. 8) that the distribution for 2002–12 from the ALLFORC ensemble has been displaced slightly to the left, indicating a small increased likelihood of negative decadal mean precipitation anomalies in response to radiative forcing changes. We next repeat this process for the ALLFORC_STRESS output from 2002 to 2012. We find a much larger movement of the distribution to the left, indicating a substantial increase in the likelihood of dry decades in response to enhanced tropical easterly winds. It is still quite possible to have a decade with above average precipitation in the ALLFORC_STRESS simulations, but the likelihood of such a decade has dropped substantially. These model results therefore suggest that

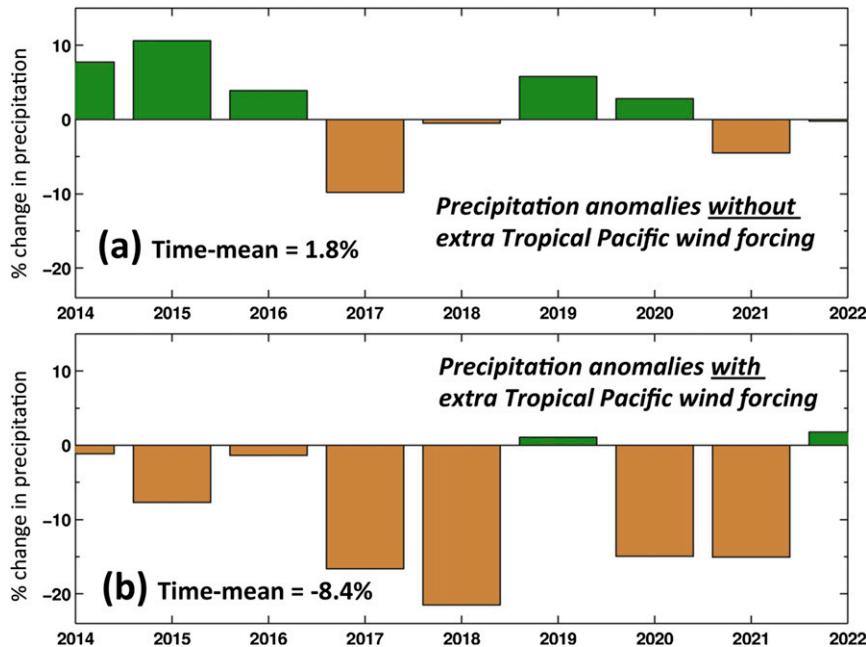


FIG. 9. Time series of simulated percentage change in annual mean precipitation relative to the 1979–2000 time mean, spatially averaged over 30° – 42° N, 130° – 90° W (land only). The simulations used the CM2.1 model, were 10-member ensembles, and started from identical initial conditions at the end of experiment ALLFORC_STRESS. (a) Precipitation change with no wind forcing anomaly in tropical Pacific. (b) Precipitation change when observed wind stress anomalies over the period 2005–13 are applied to the model over the period 2014–22.

the sustained easterly wind anomalies over the tropical Pacific, through their relationship with local sea surface temperature, created conditions that greatly increased the likelihood of drought over parts of western North America over the last decade, with an additional smaller role for radiative forcing changes in these models.

We find through examination of multimillennial control simulations that the magnitude and duration of the easterly wind stress anomaly seen over the last decade in the tropical Pacific is unprecedented based on this model's control run internal variability, consistent with England et al. (2014). This suggests several possibilities: (i) the models do not simulate sufficient decadal-scale internal variability, (ii) the observed event over the last decade is so rare that longer model simulations would be needed to realize such an event, or (iii) the easterly wind stress anomaly has some contribution from radiative forcing that is not dominant in these models (Clement et al. 1996; Compo and Sardeshmukh 2010; Solomon and Newman 2012).

4. Discussion and potential future changes

The strong connection between the intensification of Pacific trades and the drying in western North America observed over the past decade suggests that this drying

cannot be connected in a straightforward fashion to greenhouse gas increases. In most coupled GCM simulations anthropogenic forcing produces a long-term weakening of the Walker circulation and tropical Pacific trade winds but with substantial intrinsically generated variability on decadal scales (Vecchi et al. 2006). Therefore, unless it can be shown that the strengthened trade winds are a result of either natural or human-induced radiative forcing changes, the model results suggest that the observed drying over the western United States over the last decade may be primarily due to natural variability, and therefore not necessarily a harbinger of a secular drying trend (Hoerling et al. 2010; Seager and Naik 2012). These results highlight how vulnerable western North America is to severe decadal swings in hydroclimate arising from internal variations of the climate system. Recent results suggest that temperature variations in either the Indian Ocean (Luo et al. 2012) or the Atlantic Ocean (McGregor et al. 2014) could act as external drivers of, or feedbacks for, the Pacific trade wind changes. It is also possible that the wind changes are due solely to coupled processes in the tropical Pacific.

To illustrate possible changes in drought over the next decade we conduct two additional experiments for the period 2014–22 using CM2.1, both starting from the end of the ALLFORC_STRESS experiment. In the first

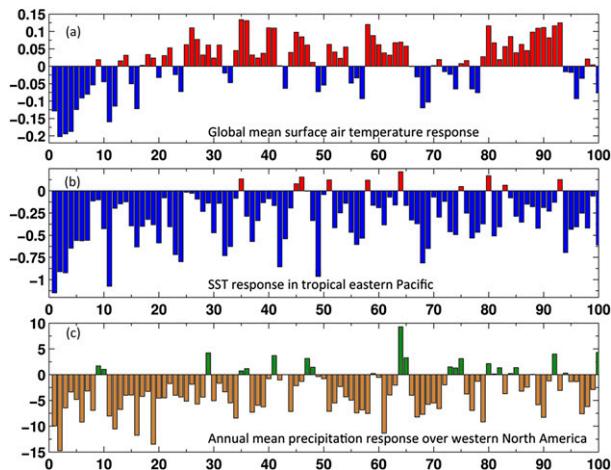


FIG. 10. Response of temperature and precipitation to sustained addition of anomalous easterly wind stress in the tropical Pacific for experiment CONTROL_STRESS. (a) Time series of global mean surface air temperature response (K) calculated as global mean temperature in CONTROL_STRESS minus CONTROL. (b) As in (a), but for SST (K) averaged over a portion of the tropical eastern Pacific (10°S – 10°N , 170° – 100°W). (c) As in (a), but for annual mean rainfall averaged over 30° – 42°N , 130° – 90°W , land areas only, expressed as percentage change from long-term mean.

experiment we do not impose wind stress anomalies, and the model computes its own wind stresses for the 2014–22 period. In the second experiment the model experiences the same sequence of wind stress anomalies that was experienced over 2005–13 (i.e., with unusually strong easterly winds). In the first experiment (Fig. 9a) precipitation is much closer to its climatological normal, with interannual deviations around the long-term mean. In the second experiment (Fig. 9b) there is a tendency for continued negative precipitation anomalies over the western United States in response to the continued easterly wind stress anomalies in the tropical Pacific. Therefore, a significant factor over the coming decade

for western U.S. water resources, and for the water managers dealing with variations in water supply, is the behavior of the winds in the tropical Pacific. Although prediction of such decadal-scale variations is challenging (Wittenberg et al. 2014), it is important to improve our understanding of the factors responsible for the wind stress anomalies observed over 2002–13 (McGregor et al. 2014). This may allow us to better characterize potential future trajectories for western U.S. water resources.

We further assess future prospects for the hiatus and North American drought using the idealized experiment CONTROL_STRESS. In this experiment we maintain the idealized zonal wind stress forcing anomaly for 100 years, and assess the evolution of the climate system. We see (Fig. 10a) that the global cooling in response to the enhanced tropical easterlies is a transient feature, persisting in these models for only a decade or two. In these simulations the initial cooling is associated with upwelling of cold subsurface water and subduction of warmer surface water into the interior. We find that after a decade or two some of this warmer water that was sequestered in the ocean interior makes its way back to the surface (Fig. 11), offsetting the cooling associated with upwelling in the eastern tropical Pacific, and therefore eliminating the global cooling signal. There is in fact a small tendency for positive global temperature anomalies, likely associated with enhanced oceanic heat uptake during the first decade or two of these simulations. In contrast, eastern tropical Pacific SST anomalies remain negative, although with somewhat reduced amplitude. These results suggest that if the hiatus in global warming is generated solely by enhanced tropical wind stress, then the duration of the hiatus is limited to the order of a decade or two (at least according to this model). This time scale is determined by the processes by which positive heat anomalies that were sequestered in the upper tropical ocean can reemerge at the surface.

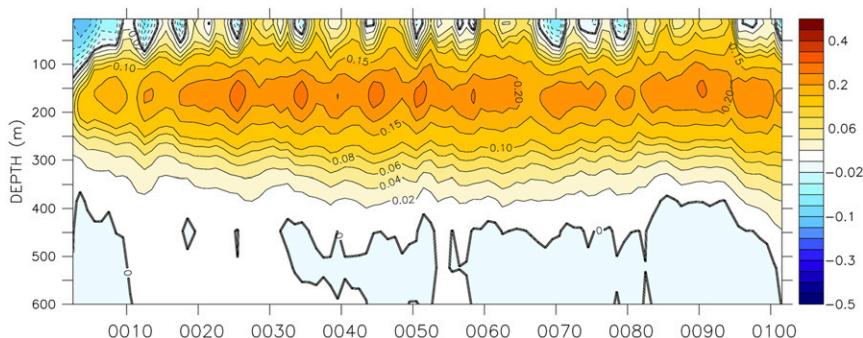


FIG. 11. Response of global mean ocean temperature to sustained addition of anomalous easterly wind stress in the tropical Pacific, calculated as CONTROL_STRESS minus CONTROL. Positive values indicate a warming of the ocean in response to the anomalous easterlies.

However, despite the elimination of the global cooling, negative temperature anomalies persist in the eastern tropical Pacific (Fig. 10b) and therefore continue to create conditions conducive to drought over western North America (Fig. 10c), although with diminishing amplitude. This suggests that the drought would persist in response to a continued surface cooling in the eastern tropical Pacific, despite the cessation of the hiatus in global warming.

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