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The 2015 Borneo fires: What have we learned from the 1997 and 2006 El Niños?

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Abstract

Fire activity in Indonesia is strongly linked with El Niño events, whose sea surface temperature (SST) patterns can weaken the Walker circulation to induce drought conditions in the region. Here we show via case analyses and idealized climate model simulations that it is the central location of the SST anomalies associated with El Niño, rather than its strength, that is mostly linked with the fire occurrence. During our study period of 1997–2015, Eastern Pacific (EP) El Niño events produced the largest fire events in southern Borneo (i.e., in 1997, 2006, and 2015), while Central Pacific (CP) El Niño events consistently produced minor fire events. The EP El Niño is found to be more capable than the CP El Niño of weakening the Walker circulation that acts to prolong Borneo's drought condition from September to October. The extended dry conditions in October potentially increase the occurrence of fires during EP El Niño years. The 2015 fire event owes its occurrence to the location of the 2015 El Niño but not necessarily its 'Godzilla' strength in affecting the fire episodes over southern Borneo. Projecting the location of El Niño events might be more important than projecting their strength for fire management in southern Borneo.

1. Introduction

Fire in Indonesia is known to be strongly linked with El Niño events (Field and Shen 2008, van der Werf *et al* 2008, Field *et al* 2009, Reid *et al* 2012), and has critical impacts on the global carbon budget, tropical biodiversity, ecosystem health, global energy supplies, as well as air quality and human health (Sodhi *et al* 2004, Danielsen *et al* 2009, van der Werf *et al* 2010, Marlier 2012). The year of 2015, the fire situation in this region is exceptionally severe (Voiland 2015). In fact, 2015 has become the largest fire year since 1997 (van der Werf 2015) and surpasses the second largest year (2006). Often, fires are set for agricultural purposes, legally or illegally, during the dry season in Indonesia (Hendon 2003). In remote areas, there is little means to contain the burning except to wait for the onset of the wet season (Page *et al* 2002). During drought years, fire can evade this control and burn a substantial acreage beyond what was intended of, as in the 2015 fire episode in Indonesian Sumatra and southern Borneo.

Drought events in Indonesia are strongly associated with El Niño events that occur roughly every 2 to 7 years. Coupling of large fire events and El Niño events is well known and greatly acknowledged (van der Werf *et al* 2008, 2010). Studies across various tropical and subtropical regions have proved that fire forecast relies at least partially on seasonal El Niño forecasts (Chen *et al* 2011, Wooster *et al* 2012). El Niño characteristics vary from event to event and successive El Niño events are not identical (Capotondi and Sardeshmukh 2015). The interannual variability of fire activity is related to the details of the sea surface temperature (SST) patterns associated with the El Niño events (Reid *et al* 2012). From the prospect of pre-warning and effective fire management in the region that has a global impact, it is crucial to be able to identify the key features of the El Niño SST pattern that matter to the magnitude of fire activity and to understand the physical linkages between them.

Here we use a number of datasets to demonstrate a mechanism through which the El Niño type, characterized by the central location of the associated SST pattern, can impact the magnitude of fire season in Indonesia. The datasets used are: National Oceanic and Atmospheric Administration (NOAA)'s Precipitation Reconstruction over Land (PREC/L) (Chen *et al* 2002), Advanced Along Track Scanning Radiometer ([A]ATSR) fire thermal anomaly detections from the European Space Agency (ESA) (Arino *et al* 2012), Monthly velocity potential (VP) from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset (Kalnay *et al* 1996), and Extended Reconstructed Sea Surface Temperature (ERSST) dataset from the International Comprehensive Ocean–Atmosphere Dataset (ICOADS) (Huang *et al* 2015, Liu *et al* 2015).

2. Methods and datasets

2.1. Precipitation

Our rainfall data are from NOAA's PREC/L (Chen *et al* 2002). The product reports monthly average rainfall over land reconstructed from global gauge station observations. In a parallel analysis, we used a TRMM dataset (TMPA 3B43) (Liu *et al* 2012) for comparison.

2.2. Fire activity in Borneo

The ESA [A]ATSR on board various ESA satellites reported (globally) nighttime surface thermal anomalies in the 3.7 μm mid-infrared channel from 1995 to 2012 (Arino *et al* 2012). We used the ATSR World Fire Atlas (WFA) Algorithm 1 as our primary analysis dataset. We rebinned monthly latitude–longitude records from ATSR to a $0.5^\circ \times 0.5^\circ$ resolution raster file for comparison with the precipitation data. Fire generally shows a strong diurnal cycle (Giglio 2007). Therefore, we performed a parallel analysis using MODIS Terra products (MOD14CMH) (Giglio *et al* 2006) with an overpass time in the late morning. The result from MODIS Terra is similar to that from ATSR products, except for a difference in scales for fire pixel count that is expected (supplementary figure 2).

2.3. Velocity potential

Monthly VP data were obtained from the NCEP/NCAR reanalysis dataset (Kalnay *et al* 1996). The reanalysis product is available as monthly means with T62 horizontal resolution. We analyzed the temporal evolution and spatial distribution of the VP on the 0.2582 sigma level (approximately 250 hPa) over the equatorial Pacific and the Maritime Continent.

2.4. Sea surface temperature

We examined variations of SST using the ERSST dataset version 4 derived from the ICOADS (Huang *et al* 2015, Liu *et al* 2015). The product contains monthly mean SSTs with a spatial resolution of $2^\circ \times 2^\circ$. As in the analysis performed on the VP, we analyzed the temporal evolution and spatial distribution of SST over the equatorial Pacific.

2.5. Bootstrap method

We calculated confidence intervals for precipitation mean based on 1000 bootstrap replicates (Mooney and Duval 1993). The bootstrap replicate is derived by calculating the mean of the bootstrap sample. For each bootstrap sample, we randomly draw with replacement items from actual years and keep the number of randomly selected years equal to the number of actual years. By repeating this process 1000 times, we could obtain 1000 bootstrap replicates, and then the 99% confidence intervals, for example, is derived by taking the 5th and 995th largest of the 1000 replicates.

2.6. Model simulations

We conducted ensemble experiments for the Eastern Pacific (EP) and Central Pacific (CP) El Niño episodes using NCAR Community Atmosphere Model (CAM4) with a T42 Euler spectral resolution. Each ensemble experiment consists of 10 members, and each member is forced with 22 month long SSTs associated with EP/CP El Niño (including El Niño developing phase, peak phase, and decaying phase). These SSTs (following Yu *et al* 2012) are made by adding together climatological SSTs and the typical SST anomalies of the EP or CP El Niño. The typical SST anomalies are constructed by a regression between tropical Pacific SST anomalies and EP/CP El Niño indices and then scaling them to typical El Niño intensities (Yu *et al* 2012).

3. Results

We searched for fire hotspot detections during the period 1997–2015 in southern Borneo (109 °E–118 °E, 4.5 °S–1 °S), roughly Central and South Kalimantan in Indonesia (figure 1(a)), because fire activity in this region is the most variable annually and represents approximately 60% of the fire hotspots in Borneo from 1997 to 2012. Forest and peatland are widely burned to clear land for oil palm plantation in southern Borneo during the dry season, releasing large amounts of greenhouse gases into the atmosphere (van der Werf *et al* 2010, Page *et al* 2011). The regular dry season in southern Borneo generally lasts from June to September, during which the average rainfall drops 36%–160 mm month^{-1}. Typically, rains return in October and quickly reach 220 mm month^{-1} by the onset of the wet season in November (figure 1(b)).

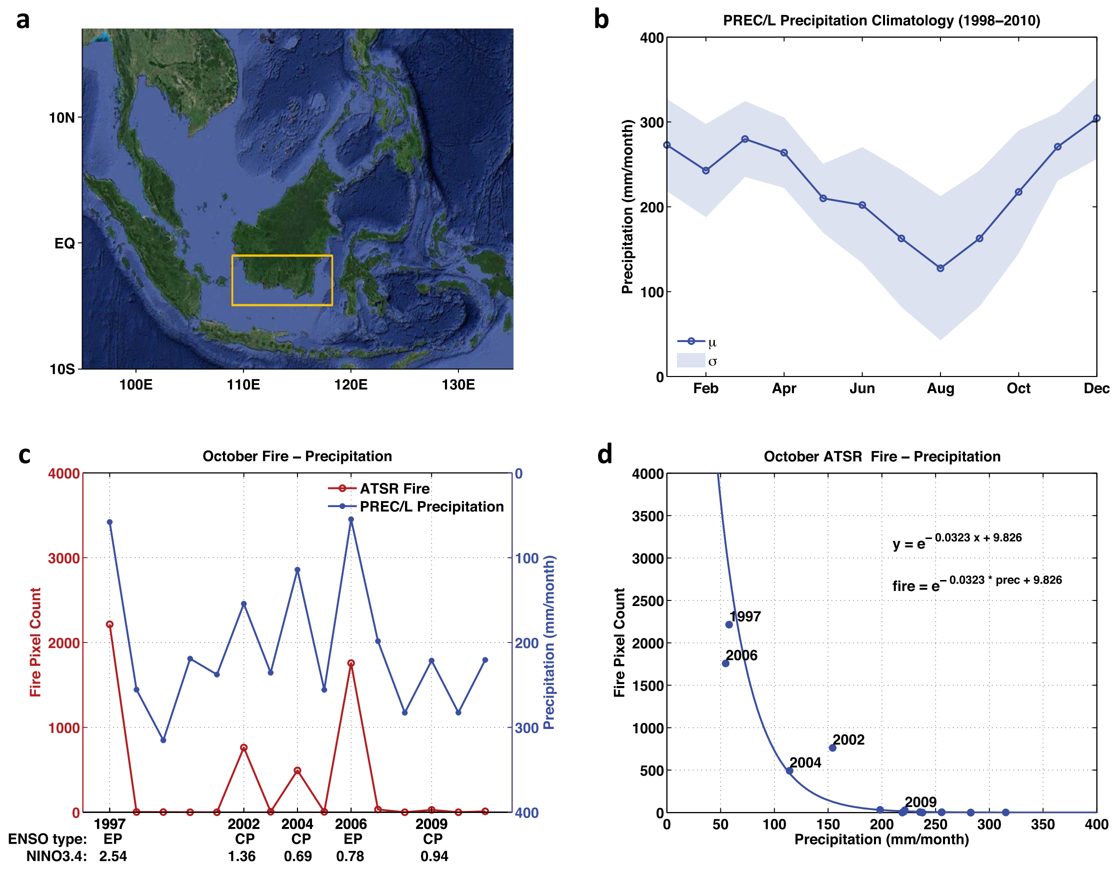

Figure 1. (a) Satellite image of the Maritime Continent and Borneo with area studied delineated by the yellow box (Map created using a Google Maps: Imagery ©2016 TerraMetrics; Map data ©2016 Google). (b) The climatological precipitation in southern Borneo averaged from 1998 to 2010. The shaded area represents the region within one standard deviation of the climatology. (c) Interannual evolution of the southern Borneo fire pixel count and precipitation in October. Types of El Niño events and intensities (based on Niño3.4 in October) are indicated at the bottom of the figure. (d) Relationship between southern Borneo fire pixel count and precipitation in October. The blue curve shows an exponential relationship with $r^2 = 0.93, p < 0.001$.

A prolonged dry season, characterized by below normal October precipitation, was observed during the six El Niño years (1997, 2002, 2004, 2006, 2009, and 2015) in our study period (supplementary figure 1). During these years, the concurrent increases in fire occurrence in October reflect a typical link between biomass burning and drought, as well as drainage of peatland water tables (Page *et al* 2011, Kettridge *et al* 2015). However, fire activity does not increase with El Niño strength in every case. For example, 2006 was a very active fire year in spite of the fact that this El Niño event was relatively weak, as the Niño3.4 SST index reached a maximum of only 0.78 °C in October. Here, Niño3.4 is an index popularly used to gauge the strength of an El Niño and is defined as the averaged SST departure from the climatological value in a specific equatorial Pacific region (120 °W–170 °W, 5 °N–5 °S). The 2009 event was stronger with a Niño3.4 index of 0.94 °C in October, yet the fire activity during October was only moderate in southern Borneo. Interestingly, we find that the October fire occurrence in southern Borneo is more closely linked with the El Niño type than with its strength (figure 1(c)). In our study period, major fire episodes occurred during the years of EP type of El Niño, whose maximum surface ocean warming is in the tropical EP (i.e., 1997, 2006, and 2015), while minor ones occurred during years of the CP type of El Niño, whose maximum surface ocean warming is in the tropical CP (i.e., 2002, 2004, and 2009). Past studies have already identified the type for all major El Niño (Fu *et al* 1986, Ashok *et al* 2007, Hong *et al* 2008, Kao and Yu 2009) events. The most striking difference between these two types of El Niño is the central location of their SST anomalies in the tropical Pacific. When these anomalies are centered in the tropical EP the event is defined as an EP El Niño, while an event where anomalies are centered in the tropical CP is defined as a CP El Niño (Yu and Kao 2007).

The October fire activity during the EP El Niño years (i.e., 1997, 2006, and 2015) stands out by almost an order of magnitude in southern Borneo (figures 1(c) and (d), the complementary analysis in supplementary figure 2(b) also indicates the larger October fire activity in 2015 than in 2006). Fires during the 2002 and 2004 CP El Niño years are not as abundant, although still higher than in neutral years. Despite the occurrence of a relatively strong CP El

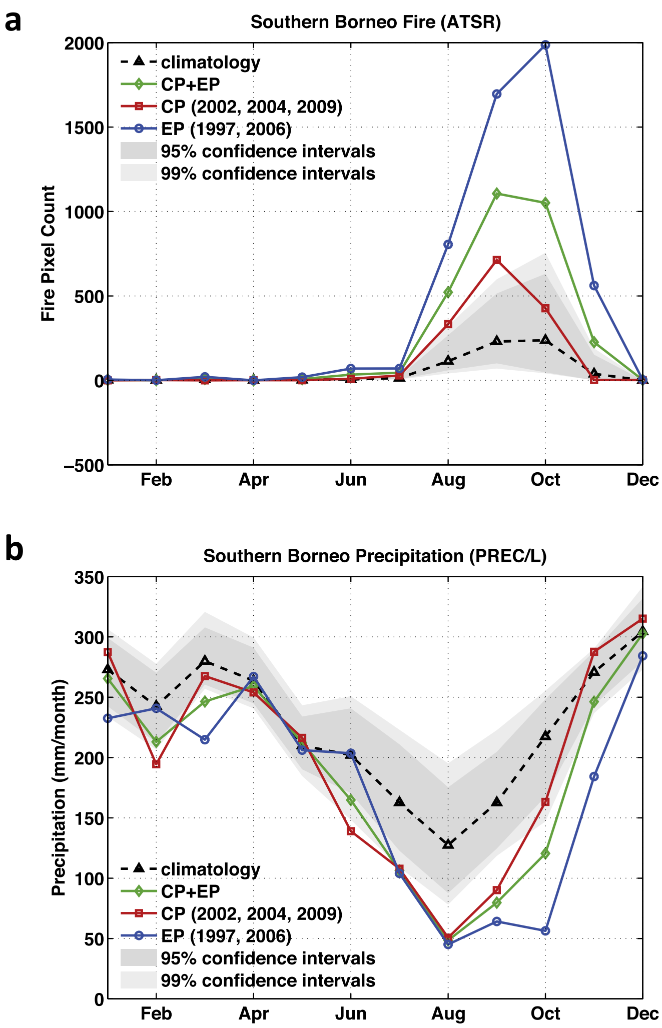

Figure 2. (a) Seasonality of the fire pixel count over southern Borneo. The climatology shown by the black dashed line is calculated using data for the period 1998 to 2010. All El Niño composites are shown by the green line, while the red line is for the CP El Niño composite (2002, 2004, and 2009), and the blue line is for EP El Niño composite (1997 and 2006). The shaded area represents the region within 95% (dark gray) and 99% (light gray) confidence intervals for monthly mean. (b) Same as (a), but for monthly precipitation.

Niño event, fire occurrence in 2009 is unusually low. Fire occurrence in October is also found highly correlated with precipitation ($r^2 = 0.93$, $p < 0.001$, $n = 11$) (figure 1(d)).

This raises the following question: What makes the EP El Niño more capable than the CP El Niño of increasing fire occurrence in southern Borneo? We find a key to the fire occurrence is the unusually low precipitation rates in October during EP El Niño (supplementary figures 1 and 2). During EP El Niño events, the fire season extends beyond November and its peak month shifts from September to October (figure 2(a), supplementary figure 2(a)). During CP El Niño episodes, on the other hand, fire seasonality remains similar to the climatology: fire activity peaks in September and mostly ends in November. This significant difference in fire seasonality between the EP and CP El Niño is not observed if all El Niño events are combined regardless of the type (figure 2(a), green line).

Fire season usually lags the dry season by 1–3 months because fuel humidity is a cumulative effect (Turetsky *et al* 2015). Additionally, precipitation is generally a better predictor for the magnitude of fire activity than SST or soil moisture parameters (Field and Shen 2008, Chen *et al* 2011). This is important particularly for peat fires common in southern Borneo. Peat fires usually go underground and last for months during drought when the water table is depleted (Page *et al* 2011, Kettridge *et al* 2015). Fires are often set for agricultural purposes, but a lower precipitation which significantly departures from the climatological mean in October in southern Borneo (figure 2(b), departures exceed 99% confidence intervals) will lower the fuel humidity and water table, which can indirectly cause the fire expansion and prolong the fire season. Therefore, the anomalously low precipitation in October acts as a major cause for a longer and more severe fire seasons during EP El Niño events.

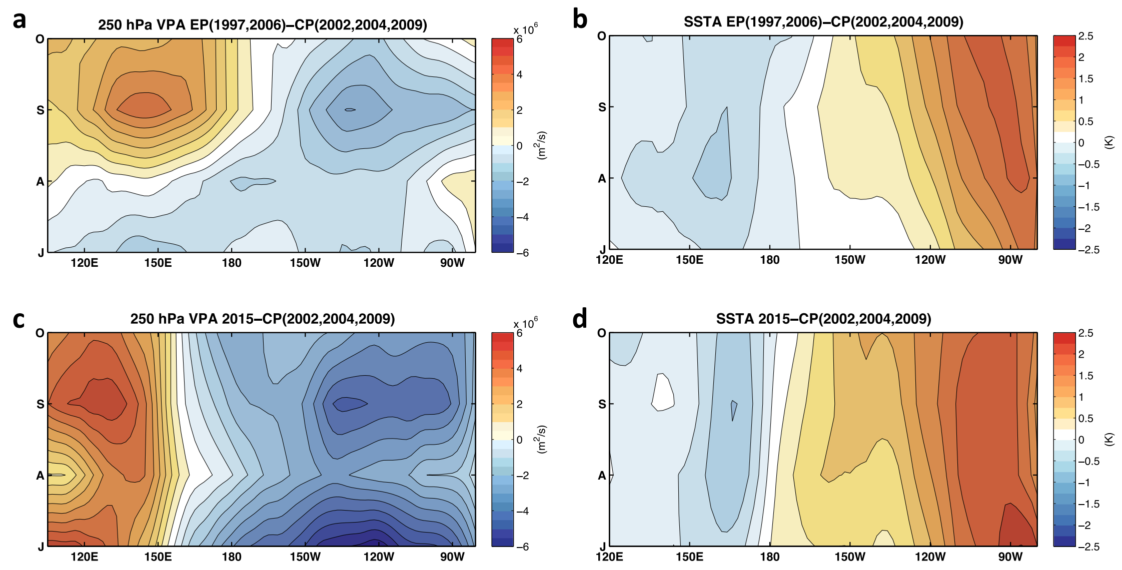

Figure 3. (a) Longitude-time evolution of 250 hPa velocity potential difference between the EP El Niño composite and the CP El Niño composite averaged between 5 °N and 5 °S from July to October. (b) Same as (a), but for sea surface temperature. (c) Longitude-time evolution of the 250 hPa velocity potential difference between 2015 and CP El Niño composite averaged between 5 °N and 5 °S from July to October. (d) Same as (c), but for sea surface temperature.

The greater reduction in precipitation in October during the EP El Niños than during the CP El Niños is associated with the subsidence differences over Borneo between these two El Niño types, which can be seen from the 250 hPa VP differences (figure 3(a), mean of the two EP events minus mean of the three CP events). The VP differences indicate that the EP El Niño induces a stronger upper-level convergence over the western Pacific (including Borneo) from August to October and a stronger upper-level divergence over the EP. This upper-level difference pattern represents a stronger weakening effect of the Walker circulation by the EP El Niño than the CP El Niño and the anomalous subsidence over the western equatorial Pacific, which can result in the reduction of Borneo precipitation (supplementary figures 3). This weakening effect of the Walker circulation is related to the warmer SST anomalies of the EP El Niño in the tropical EP and colder SST anomalies in the tropical western Pacific than during the CP El Niño (figure 3(b)). Apparently, the more eastward-located warm anomalies during the EP El Niño are more effective in weakening the Walker circulation than the more westward-located warm anomalies characteristic of the CP El Niño (Zou *et al* 2014).

4. Model simulations

We further performed idealized climate model experiments to demonstrate the eastward-located warm SST anomalies and the associated apparent subsidence anomalies over the Maritime Continent regions during the EP El Niño. We conducted ensemble experiments for the EP and CP El Niño episodes using NCAR Community Atmosphere Model (CAM4) with a T42 Euler spectral resolution. Each ensemble experiment consists of 10 members, and each member is forced with 22 month long SSTs associated with EP/CP El Niño (including El Niño developing phase, peak phase, and decaying phase), following Yu *et al* (2012). Technically, the model resolution (2.8° × 2.8°) is not high enough to capture the exact location of maximum VP difference; thus, may not overlap exactly with Borneo. However, results from the model simulations clearly indicate that during EP El Niño SST in the EP is warmer and subsidence in the western Pacific is stronger (figure 4).

5. Conclusions

The 2015 El Niño has been confirmed to be the first EP El Niño in the tropical Pacific since 2006. Figures 3(c) and (d) show that the evolution of its upper-level VP and SST anomalies from August to October are similar to the evolution during the two previous EP El Niño events. Moreover, fire occurrence in 2015 in Borneo and surrounding regions of Indonesia such as Sumatra and Papua are remarkably similar to what were observed in 1997 and 2006. Fire season in 2015 extends well into November, although heavy rains have been reported on October 26th in Kalimantan, and substantially lowers the number of satellite active fire detections (van der Werf 2015). While the general community relies mostly on the strength of the 2015 El Niño to explain the associated anomalous fire activity, we suggest that it is the central location of the SST anomalies associated with this El Niño event that should be emphasized for the 2015 Borneo fire event.

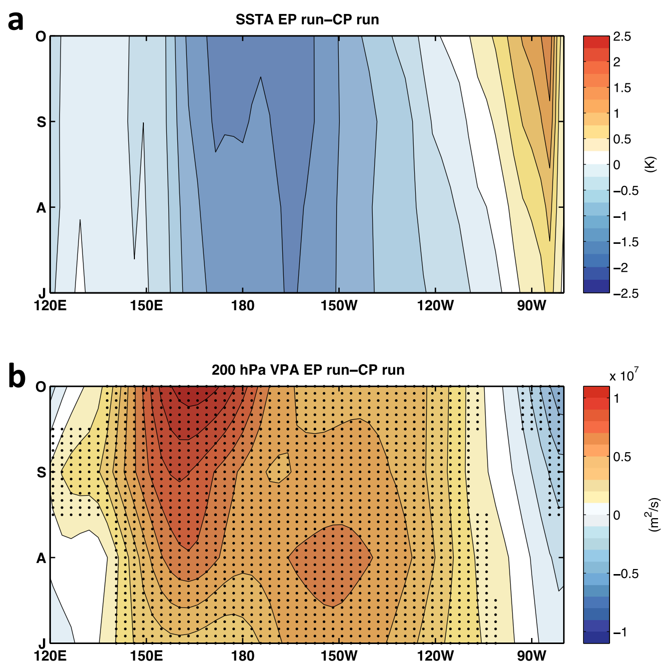

Figure 4. (a) Longitude-time evolution of sea surface temperature difference between the EP El Niño simulations composite and the CP El Niño simulations composite averaged between 5 °N and 5 °S from July to October. (b) Same as (a), but for the 200 hPa velocity potential. Dotted areas indicate significance at the 95% confidence level.

Thus, projecting the location of El Niño events might be more important than projecting their strength for fire management in southern Borneo since there is a tendency for large Borneo fires to occur during the EP than CP type of El Niño events.

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