

## Response of surface air temperature to small-scale land clearing across latitudes

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2014 Environ. Res. Lett. 9 034002

(<http://iopscience.iop.org/1748-9326/9/3/034002>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 128.36.9.53

This content was downloaded on 05/03/2014 at 16:32

Please note that [terms and conditions apply](#).

# Response of surface air temperature to small-scale land clearing across latitudes

Mi Zhang<sup>1</sup>, Xuhui Lee<sup>2</sup>, Guirui Yu<sup>3</sup>, Shijie Han<sup>4</sup>, Huimin Wang<sup>3</sup>, Junhua Yan<sup>5</sup>,  
Yiping Zhang<sup>6</sup>, Yide Li<sup>7</sup>, Takeshi Ohta<sup>8</sup>, Takashi Hirano<sup>9</sup>, Joon Kim<sup>10</sup>,  
Natsuko Yoshifuji<sup>11</sup> and Wei Wang<sup>1</sup>

<sup>1</sup> NUIST-Yale Center on Atmospheric Environment, Nanjing University of Information Science and Technology, Nanjing 210044, People's Republic of China

<sup>2</sup> School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511, USA

<sup>3</sup> Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, People's Republic of China

<sup>4</sup> Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, People's Republic of China

<sup>5</sup> South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, People's Republic of China

<sup>6</sup> Xishuangbanna Tropical 'Botanical' Garden, Chinese Academy of Sciences, Kunming 650223, People's Republic of China

<sup>7</sup> Research Institute of Tropical Forestry Chinese Academy of 'Forestry', Guangzhou 510650, People's Republic of China

<sup>8</sup> Graduate School of Bioagricultural Sciences, Nagoya University, Nagoya, 464-8601, Japan

<sup>9</sup> Graduate School of Agriculture, Hokkaido University, Sapporo 060-8589, Japan

<sup>10</sup> Department of Landscape Architecture and Rural Systems Engineering, Seoul National University, Seoul 151-742, Korea

<sup>11</sup> Graduate School of Agriculture, Kyoto University, Kyoto 606-8502, Japan

E-mail: [xuhui.lee@yale.edu](mailto:xuhui.lee@yale.edu)

Received 9 October 2013, revised 6 February 2014

Accepted for publication 7 February 2014

Published 4 March 2014

## Abstract

Climate models simulating continental scale deforestation suggest a warming effect of land clearing on the surface air temperature in the tropical zone and a cooling effect in the boreal zone due to different control of biogeochemical and biophysical processes. Ongoing land-use/cover changes mostly occur at local scales (hectares), and it is not clear whether the local-scale deforestation will generate temperature patterns consistent with the climate model results. Here we paired 40 and 12 flux sites with nearby weather stations in North and South America and in Eastern Asia, respectively, and quantified the temperature difference between these paired sites. Our goal was to investigate the response of the surface air temperature to local-scale (hectares) land clearing across latitudes using the surface weather stations as proxies for localized land clearing. The results show that north of 10°N, the annual mean temperature difference (open land minus forest) decreases with increasing latitude, but the temperature difference shrinks with latitude at a faster rate in the Americas [ $-0.079 (\pm 0.010) ^\circ\text{C}$  per degree] than in Asia [ $-0.046 (\pm 0.011) ^\circ\text{C}$  per degree]. Regression of the combined data suggests a transitional latitude of about 35.5°N that demarks deforestation warming to the south and cooling to the north. The warming in latitudes south of 35°N is associated with increase in the daily maximum temperature, with little change in the daily minimum temperature while the reverse is true in the boreal latitudes.

Keywords: deforestation, surface air temperature, diurnal temperature range, latitudinal pattern

 Online supplementary data available from [stacks.iop.org/ERL/9/034002/mmedia](http://stacks.iop.org/ERL/9/034002/mmedia)



Content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](http://creativecommons.org/licenses/by/3.0/). Any further

distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

## 1. Introduction

Deforestation is an important anthropogenic activity that can impact the climate system through biogeochemical and biophysical processes (Bonan 2008). Surface air temperature is a key variable for evaluating the effects of the deforestation impact (Hansen *et al* 2006, Pielke *et al* 2007, Mildrexler *et al* 2011). The biogeochemical process is related to the greenhouse effect of CO<sub>2</sub> (Bala *et al* 2007, Bonan 2008, Gotangco Castillo and Gurney 2013). Clearing of forests also alters biophysical processes, including reduction in evapotranspiration and in surface roughness (and hence turbulent exchange). These two biophysical changes can lead to increase in surface air temperature (Pielke *et al* 1998, Lean and Rowntree 1993, Betts *et al* 2007, Bonan 2008, Davin and de Noblet-Ducoudré 2010, Gotangco Castillo and Gurney 2013). According to these published studies, a third biophysical process associated with deforestation, the increase in surface albedo, will reduce the radiation forcing globally and locally, which will result in surface air temperature reduction. The overall impact of deforestation on the surface air temperature is determined by the balance of the four different processes.

The sign and magnitude of the surface air response to deforestation appear to be dependent on climate regime. According to the above climate model simulations, large (continental) scale deforestation in the tropics should produce a warming effect because cleared land can no longer sustain high rates of evapotranspiration as would be the case with forested land and because the land sink of CO<sub>2</sub> is greatly reduced. In the boreal zone, continental scale land clearing should lower the surface air temperature due to the drastic increase in surface albedo especially in the winter when snow cover is present and a land albedo–sea ice feedback. Some of the model results show that there exists a latitudinal asymmetry of the deforestation impact, in that the cooling effect of deforestation in high latitudes is much greater than the warming effect in low latitudes (Bala *et al* 2007, Betts *et al* 2007, Davin and de Noblet-Ducoudré 2010, Longobardi *et al* 2012).

Many ongoing land-use/cover changes occur at the local scale (hectares). Some of the climate model predictions have now been confirmed by the local-scale field observations in North America using a site-pair analysis. According to Lee *et al* (2011), the temperature difference  $\Delta T$  between forest sites and the adjacent open lands (temperature at open land minus that at forest land) is negative in mid- to high latitudes, with the cooling signal increasing linearly with increasing latitude. However, an outstanding question is whether such a latitudinal dependence also exists in Asia where climate regimes are markedly different from those in North America. For example, in eastern Asia, most of the annual precipitation occurs in the summer monsoon whereas in the boreal Canada precipitation is more even distributed throughout the year. It is possible that the snow albedo effect is less pronounced in northern Asia than in Canada.

It is useful to compare the observed latitudinal pattern of the deforestation effect with model simulation results. Simulations of large-scale land clearing in the boreal zone suggest that the ocean may exert a positive feedback which

amplifies the effect of land albedo changes through changes in the sea ice extent. The land albedo–sea ice feedback may increase the cooling effect of deforestation (Bonan *et al* 1992, Davin and de Noblet-Ducoudré 2010). In the tropical zone, the surface warming effect of deforestation may be reinforced by an evaporation–cloudiness feedback. The reduction in the land evaporation due to deforestation may result in more clear skies and less cloud cover. As a result, more solar radiation can reach the Earth's surface, causing the surface temperature to increase further (Dickinson and Henderson-Sellers 1998). The observation studies are typically performed at local scales (hectares) not large enough to trigger the above feedback mechanisms. Additionally, at the local scale the CO<sub>2</sub> biogeochemical effects are negligible. A comparison of small-scale observations and large-scale model results may provide insight into the strength of these feedback mechanisms.

In addition to the mean temperature, deforestation can influence the diurnal temperature variation. Diurnal temperature range (DTR, the difference between the daily maximum and minimum temperature) has been used to investigate surface climate variabilities (Easterling *et al* 1997, Wild *et al* 2007). In our previous study (Lee *et al* 2011), we found that deforestation decreases the daily minimum temperature in both the temperate and the boreal zones but increases the daily maximum temperature only in the temperate zone. It is unclear how the daily maximum and minimum temperature may shift in response to deforestation in subtropical and tropical latitudes.

Extending the study of Lee *et al* (2011), in this paper, we applied the site-pair analysis to observations in East Asia and Central and South America as well as North America. In the site-pair analysis, surface air temperature measured at a forest FLUXNET site is compared with that at a nearby standard weather station, using the latter as a proxy for small cleared land. By expanding the latitudinal coverage, we wish to investigate if the modeled latitudinal asymmetry also exists at scales of small land clearing. The other two objectives are: (1) to compare the deforestation effects between Americas and Eastern Asia, and (2) to quantify the effect of land clearing on the diurnal temperature range (DTR) in different latitudes.

## 2. Sites and data

Influenced by the eastern Asian monsoon, temperature and precipitation exhibit clear latitudinal gradients along Eastern Asia, between 73° and 145°E (Yu *et al* 2006, Piao *et al* 2012). A forest sequence exists along this longitudinal band including, from north to south, cold temperate coniferous forests, temperate mixed forests, warm temperate deciduous broadleaf forests, subtropical evergreen coniferous forests, evergreen broadleaf forests, and tropical rainforests (Yu *et al* 2008). The forest sequence is suitable for studying the effect of deforestation across latitudes.

In this study, we have identified 12 forest flux sites in Eastern Asia with appropriate matching weather stations in the nearby open land (figure 1; supplementary table S1



Figure 1. Site distribution.

(available at [stacks.iop.org/ERL/9/034002/mmedia](http://stacks.iop.org/ERL/9/034002/mmedia)). The furthest north site is a Siberia pine forest in Yakutsk, Russia (latitude 62.24°N) and the furthest south site is a rainforest in Palangkaraya, Indonesian (latitude 2.35°S). There are six sites in China, one site in Korea, one site in Japan, and two sites in Thailand. In each site pair, the chosen weather station is the one closest to the forest site. The average linear distance between the paired sites is 16 km. The largest distance is 48 km, which is located in China's Yunnan Province (Xishuangbanna site). The average elevation difference of the 12 site pairs is 161 m. The largest elevation difference is 1030 m, which is located in Thailand's Chiang Mai Province. Neither the horizontal distance nor the elevation difference is correlated with latitude (linear correlation for horizontal distance = 0.017, linear correlation for elevation difference = 0.014,  $n = 12$ ). These site pairs have continuous air temperature records for at least one complete year. Further details about these sites are given in the online supporting material.

The North/South American transect consists of 40 site pairs. This dataset is an expansion of the original 33 sites analyzed by Lee *et al* (2011), with improved coverage in low latitudes. Five of the seven new site pairs are distributed between 24°N and 11°S. The furthest south site is an evergreen broadleaf forest in Ji-Paraná, Brazil (latitude 10.08°S). There are three new site pairs in Brazil, one in Mexico, one in Costa Rica, one in the US, and one in Canada. The average linear distance between the North/South American paired sites is 27 km. The largest distance is 91 km, which is located in Saskatchewan Canada (Old Jack Pine site). The average elevation difference of the paired sites is 78 m. The largest elevation difference is 593 m, which is located in California, United State (Blodgett site). These differences are not correlated with latitude (linear correlation for horizontal distance = 0.05, linear correlation for elevation difference = 0.05,  $n = 40$ ). Same as with the East Asian transect, every forest site and its paired weather station have continuous air temperature records for at least one complete year.

We compared the surface air temperature measured on the forest eddy covariance tower with that in the adjacent surface weather station. According to the requirement of the World Meteorological Organization, the surface weather stations matching the flux sites were located in open grassy fields, and far away from urbanized land and waters. We used the surface weather stations as proxies for small cleared land. Air temperature was measured with shielded probes in all the

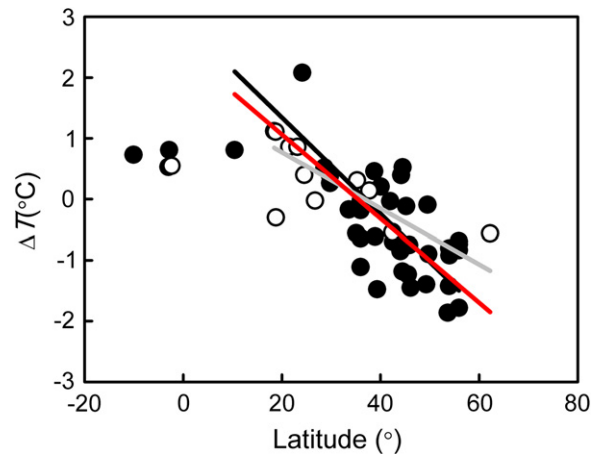


Figure 2. Annual mean temperature difference  $\Delta T$  (open land minus forest) as a function of latitude. Black solid circles and open circles denote weather station/forest site pairs in Americas and in Asia, respectively. The black solid line indicates the linear regression for Americas (latitude  $>10^\circ\text{N}$ ;  $y = -0.079 (\pm 0.010)x + 2.923 (\pm 0.424)$ ,  $n = 38$ ,  $R^2 = 0.44$ ,  $P < 0.0001$ ), the gray solid line indicates the linear regression for Asia (latitude  $>10^\circ\text{N}$ ;  $y = -0.046 (\pm 0.011)x + 1.692 (\pm 0.328)$ ,  $n = 11$ ,  $R^2 = 0.44$ ,  $P < 0.05$ ), and the red solid line indicates the linear regress for all the sites (latitude  $>10^\circ\text{N}$ ;  $y = -0.069 (\pm 0.007)x + 2.444 (\pm 0.280)$ ,  $n = 49$ ,  $R^2 = 0.51$ ,  $P < 0.0001$ ).

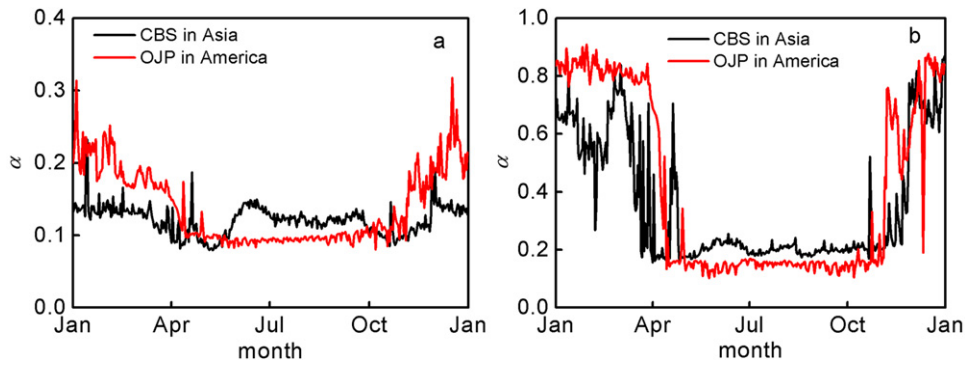
weather stations and the flux sites, although the model and make of the radiation shield may vary (Schmidt *et al* 2012). At the weather stations, air temperature was measured at the standard screen height of 1.5 m. Daily temperature data at the forests and the surface weather stations were used, including daily maximum ( $T_{\max}$ ), daily minimum ( $T_{\min}$ ), and daily mean air temperature ( $T$ ). The temperature difference ( $\Delta T$ ) for each site pair was calculated as air temperature at the surface weather station minus that recorded at the forest site. Diurnal temperature range was the difference between  $T_{\max}$  and  $T_{\min}$ .

Correction for altitude difference between the paired sites was made according to the lapse rate of  $6.5^\circ\text{C km}^{-1}$ . According to the North American Reanalysis, local lapse rate varies between 4 and  $9^\circ\text{C km}^{-1}$  among the North American sites (Lee *et al* 2011). If we used these extreme values, the mean  $\Delta T$  of the tropical site pairs in the latitude span of  $15^\circ\text{S}$ – $20^\circ\text{N}$  would change from 0.67 to 1.01 and  $0.33^\circ\text{C}$ . In other latitudinal zones, the lapse rate has little effect on the surface air temperature comparison.

### 3. Results and discussion

#### 3.1. Latitudinal variations in $\Delta T$

The annual mean  $\Delta T$  shows a clear latitudinal dependence across the transects in Eastern Asia and in Americas (figure 2). In the latitude range of  $15^\circ\text{S}$ – $10^\circ\text{N}$ , the annual mean  $\Delta T$  was positive at a roughly constant value of  $0.63^\circ\text{C}$ , indicating a warming effect of deforestation. In latitude north of  $10^\circ\text{N}$ ,  $\Delta T$  decreased linearly with increase in latitude at rate of  $-0.069^\circ\text{C per degree}$  if data from both transects were pooled together. The temperature difference  $\Delta T$  crosses zero at



**Figure 3.** Seasonal dynamic of albedo ( $\alpha$ ) in the Changbaishan temperate mixed forest site pair (CBS) (42.4°N, 128.08°E) in Asia and the Saskatchewan BERMS old jack pine site pair (OJP) in America (53.92°N, 104.69°W). (a) Albedo of open land; (b) albedo of forest.

35.5°N according to the linear regression. The results indicate that surface air temperature was higher in the open land than in forest in the tropical zone. There were weak warming effects of deforestation in the subtropical and the temperate zones. In the boreal zone, deforestation caused strong cooling.

Although the  $\Delta T$  latitudinal trend in latitudes north of 10°N was similar between the two continents, the regression slope of  $\Delta T$  versus latitude was more negative for Americas than for Eastern Asia. The rate of  $\Delta T$  decrease with increase in latitude was  $-0.079 (\pm 0.010)^\circ\text{C}$  per degree in Americas, but was  $-0.046 (\pm 0.011)^\circ\text{C}$  per degree in Asia (figure 2). Here the uncertainty range indicates the 95% confidence bound of the parameter estimate. The results suggest that the cooling effect of deforestation in high latitudes was stronger in North America than that in Eastern Asia. The phenomenon may be caused by different snow albedo effects in the two continents. Figure 3 compares the albedo contrast of the Changbaishan temperate mixed forest site pair (CBS, 42.4°N, 128.08°E) in Asia with that of the Saskatchewan BERMS old jack pine site pair in Canada (OJP, 53.92°N, 104.69°W). The albedo of the open land in OJP was higher than that in CBS during the winter (from November to April), because of higher winter precipitation in OJP. A characteristic of the Eastern Asia Monsoon is that precipitation mostly occurs in the form of rain in the warm season, and we expect less snowfall there in comparison to Canada and northern US. For example, the winter precipitation (from December to February) was 44 and 55 mm in CBS and in OJP, respectively, in the years from 2004 to 2006.

Some of the difference between the two continents may be caused by uneven site numbers. In the Asian transect, there is only one site, the Yakutsk Siberia pine forest site (YPF, latitude 62.24°N, longitude 129.65°E), in latitudes north of 50°N. When the YPF site was excluded, the rate of  $\Delta T$  decrease with increasing latitude (latitudes north of 10°N) was  $-0.067 (\pm 0.018)^\circ\text{C}$  per degree in Asia. This rate was still lower in magnitude than that in North America.

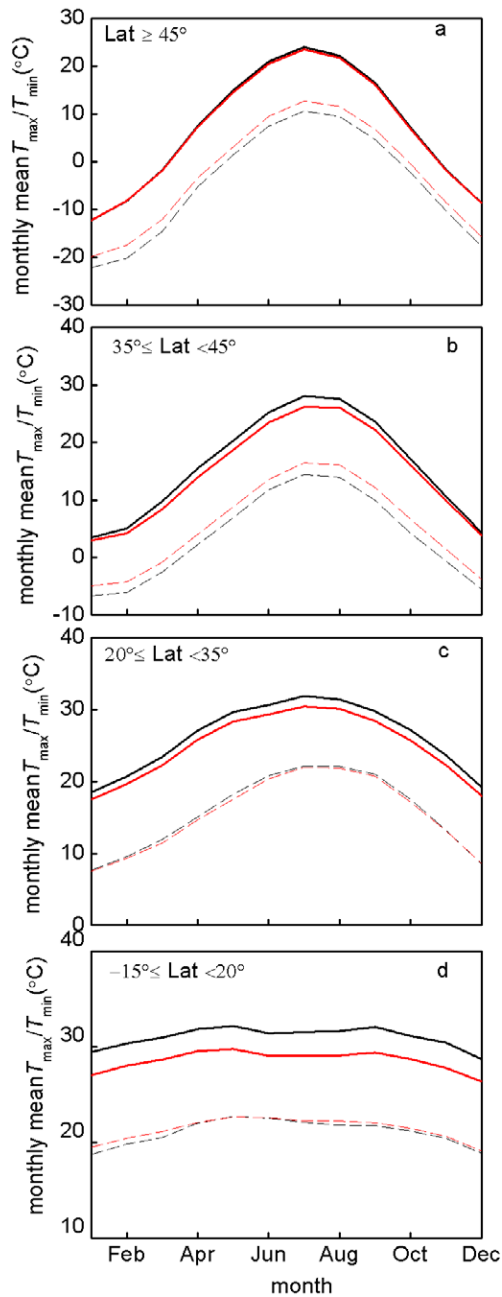
The above analysis focuses on the annual mean  $\Delta T$ . Baldocchi and Ma (2013) reported that  $\Delta T$  for a site pair consisting of an oak savanna (latitude 38.43°N, longitude 120.97°W) and an annual grassland in California, USA (latitude 38.41°N, longitude 120.95°W) has a strong seasonal

pattern. The annual grassland is 1.2 and  $-0.2^\circ\text{C}$  cooler than the oak savanna in the winter wet season and in the summer dry season, respectively. The authors attribute this seasonality to the opposite phases of evapotranspiration these two ecosystems have in this Mediterranean climate and the fact that the grassland has much higher albedo in the dry season than in the wet season.

### 3.2. Changes in diurnal temperature patterns

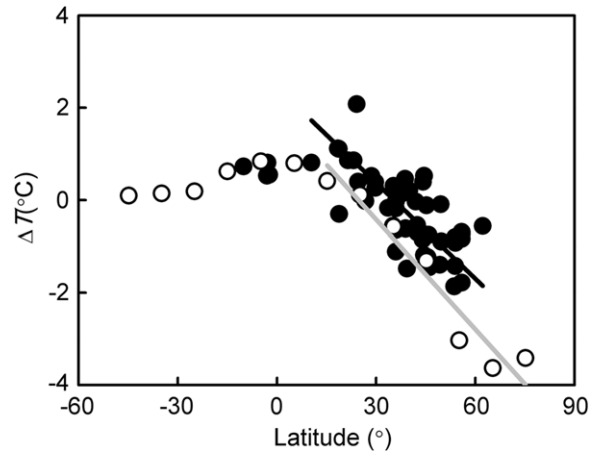
Figure 4 shows the seasonal variations of  $T_{\text{max}}$  and  $T_{\text{min}}$  in forested and open land in four latitudinal zones. To remove site-to-site variations, here we computed the mean  $T_{\text{max}}$  and  $T_{\text{min}}$  of forested and open land in every latitudinal zone using the site pairs from both transects. Generally, DTR was greater in the open land than in the forested land, but changes in  $T_{\text{max}}$  and  $T_{\text{min}}$  were different among these zones:

- (1) In latitudes higher than 45°N,  $T_{\text{max}}$  in the open land was almost the same to that in the forested land. However,  $T_{\text{min}}$  in the open land was about  $2^\circ\text{C}$  lower than that in the forested land (figure 4(a)). The mean temperature difference (open land minus forest land) was  $-0.95 \pm 0.51^\circ\text{C}$  (number of site pairs  $n = 17$ ).
- (2) The opposite was true in the latitudinal range from 15°S to 20°N (figure 4(d)) where  $T_{\text{max}}$  of the open land was much higher (by about  $2.4^\circ\text{C}$ ) than that of the forested land, and  $T_{\text{min}}$  of the open land was almost identical to that of the forested land. The mean temperature difference was  $0.67 \pm 0.45^\circ\text{C}$  ( $n = 8$ ).
- (3) The zone between 35°N and 45°N shows transitional behaviors.  $T_{\text{max}}$  of the open land was higher (by about  $1.2^\circ\text{C}$ ) than that of the forested land, and  $T_{\text{min}}$  of the open land was lower (by about  $1.9^\circ\text{C}$ ) than that of the forested land (figure 4(b)). The mean temperature difference was  $-0.35 \pm 0.60^\circ\text{C}$  ( $n = 18$ ).
- (4) The zone 20°N–35°N is also transitional. The open land had  $1.3^\circ\text{C}$  higher  $T_{\text{max}}$  and  $0.3^\circ\text{C}$  higher  $T_{\text{min}}$  than the forest land (figure 4(c)). The mean temperature difference was  $0.58 \pm 0.66^\circ\text{C}$  ( $n = 9$ ).



**Figure 4.** Comparison of seasonal variation of daily maximum and minimum air temperature in four latitudinal ranges. The black and red solid lines indicate  $T_{\max}$  of open and forested land, respectively. The black and red dashed lines indicate  $T_{\min}$  of open and forested land, respectively.

These diurnal temperature patterns indicate that in the boreal zone ( $>45^{\circ}\text{N}$ ), the increase in DTR due to land clearing was associated with the decrease in  $T_{\min}$ ; the decrease in  $T_{\min}$  resulted in the decrease in the daily mean surface air temperature. Lee *et al* (2011) postulate that the warmer nighttime temperature in the forested land is caused by the presence of tall trees. This is because the trees enhance turbulence which brings heat from aloft to the surface. A similar mechanism is proposed for wind farms (Zhou *et al* 2012): wind turbines in these farms can blend the upper warmer



**Figure 5.** Comparison of measured and modeled latitudinal patterns of the annual mean temperature difference  $\Delta T$ . Black solid circles are observations and open circles are zonal mean values simulated by the climate model of a fully coupled land–ocean–atmosphere GCM (Davin and de Noblet-Ducoudré 2010). The black solid line indicates the linear regression of the observations (figure 2), and the gray solid line indicates the linear regression for the modeled  $\Delta T$  (latitude  $>10^{\circ}\text{N}$ ;  $y = -0.079 (\pm 0.009)x + 1.948 (\pm 0.416)$ ,  $n = 7$ ,  $R^2 = 0.932$ ,  $P < 0.001$ ).

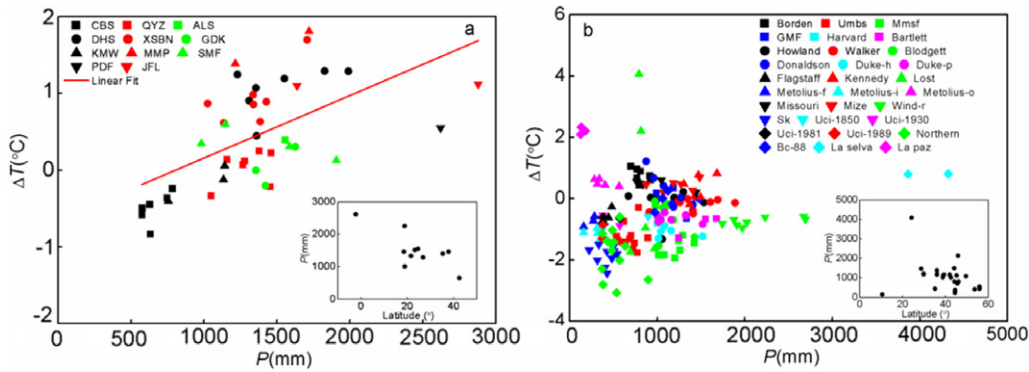
air with the lower cooler air at night, causing the surface air temperature to increase.

In low latitudes ( $15^{\circ}\text{S}–20^{\circ}\text{N}$ ), the increase in DTR due to deforestation was associated with the increase of  $T_{\max}$ , which also increased the daily mean air temperature. Here, the greatly decreased evapotranspiration in the open land was the main cause of the increased  $T_{\max}$ . Interestingly, the above nighttime ‘wind machine’ effect appeared absent in this latitudinal zone.

In addition, the standard lapse rate correction may not be accurate for correcting the elevation effect on  $T_{\max}$  and  $T_{\min}$ , because the lapse rate can change diurnally and seasonally (Pepin 2001). To avoid potential biases caused by large elevation mismatches between the paired sites, we have also compared the seasonal variations of  $T_{\max}$  and  $T_{\min}$  using only site pairs whose elevation difference is less than 100 m (supplementary figure S1 (also available at [stacks.iop.org/ERL/9/034002/mmedia](http://stacks.iop.org/ERL/9/034002/mmedia))). We found that the seasonal variations of  $T_{\max}$  and  $T_{\min}$  in the four latitudinal zones remain essentially unchanged.

### 3.3. Comparison with model results

The observed latitudinal pattern of  $\Delta T$  can be compared with that simulated by climate models of large-scale deforestation. In climate models, both larger scale feedback issues and the intrinsic biophysical mechanism are accounted for, whereas our observational study only considers the latter. Davin and de Noblet-Ducoudré (2010) applied a fully coupled land–ocean–atmosphere GCM to simulate the biophysical impact of global scale deforestation on the surface air temperature. Their results show a similar latitudinal pattern to our site-pair results (figure 5). In latitudes north of  $35^{\circ}\text{N}$ , the cooling signal we observed in our comparison is weaker, by about  $2^{\circ}\text{C}$ , than the model prediction. For example, according to



**Figure 6.** Relationship between annual mean temperature difference  $\Delta T$  and annual precipitation for (a) Asia and (b) Americas. The insets to (a) and (b) show the site mean precipitation as a function of latitude. The line in panel a is linear regression of the individual site-year data [ $y = 0.00081 (\pm 0.00018)x - 0.655 (\pm 0.251)$ ,  $n = 43$ ,  $R^2 = 0.34$ ,  $P < 0.0001$ ]. Site IDs are defined in the online supplement (available at [stacks.iop.org/ERL/9/034002/mmedia](http://stacks.iop.org/ERL/9/034002/mmedia)).

the model results, deforestation causes a cooling of  $3.0^\circ\text{C}$  at  $55^\circ\text{N}$ ; at the same latitude, the observational data indicates a cooling signal of  $\sim 1.0^\circ\text{C}$ . The rate of simulated  $\Delta T$  decrease with latitude is  $0.079^\circ\text{C}$  per degree, slightly larger than the observed value ( $0.069^\circ\text{C}$  per degree). In the observational study, the land clearing occurred at scales too small to have measurable influence on the atmospheric  $\text{CO}_2$ . Nor should it trigger the large-scale dynamic feedbacks described above. In other words, the observed  $\Delta T$  is a measure of the intrinsic biophysical mechanisms without the contributions of the large-scale feedbacks and the  $\text{CO}_2$  radiative forcing. Perhaps the difference between the observed  $\Delta T$  and the modeled  $\Delta T$  can be used to quantify these latter contributions. The modeling study by Davin and de Noblet-Ducoudré (2010) and Bonan *et al* (1992) show that without the land albedo–sea ice feedback, the deforestation cooling would be weakened by about 2–3 K at latitude  $60^\circ\text{N}$ .

Interestingly, in the latitudinal interval from  $15^\circ\text{S}$  to  $10^\circ\text{N}$ , the modeled and observed results show nearly the same  $\Delta T$ . We interpret this as evidence that the evaporation–cloudiness feedback may have been smaller than previously thought, although a more robust result should await additional observational data for the low latitudes.

### 3.4. Interannual $\Delta T$ variations

Annual precipitation  $P$  appears to be a driver of interannual variations of the deforestation signal in Asia (figure 6(a)). Generally,  $\Delta T$  had an increasing tendency with increasing  $P$ . For example, at the subtropical plantation site QYZ, one of the Asian sites with the longest record (7 years), the linear correlation coefficient between  $\Delta T$  and  $P$  was  $+0.41$ . At the northern temperate site CBS (6 years), the linear correlation coefficient was  $+0.64$ .

Furthermore, precipitation was a good predictor of inter-site variations in Asia, as shown by the strong linear correlation of  $\Delta T$  and  $P$  among the individual site-year data points. The linear correlation coefficient between  $\Delta T$  and  $P$  was  $0.58$  ( $p$  value  $< 0.001$ ). The  $\Delta T$  increased with  $P$  at a rate of  $0.81 (\pm 0.18)^\circ\text{C}$  per 1000 mm. That precipitation decreases with increasing altitude (inset to figure 6(a)) implies

that the  $\Delta T$  latitudinal dependence was driven at least in part by precipitation variations among the sites. In other words, deforestation has the tendency to increase the surface temperature in wet climate through reduction in surface evaporation.

In contrast, the correlation between  $\Delta T$  and  $P$  was less significant in Americas (linear correlation was  $0.15$ ,  $p = 0.04$ ; figure 6(b)). There the annual precipitation does not have a pronounced latitudinal pattern (inset to figure 6(b)). We suggest that the main driver of the latitudinal  $\Delta T$  variations in Americas was changes in surface albedo.

## 4. Conclusions

In this study, we examined the effects of small-scale deforestation on the surface air temperature using FLUXNET, AsiaFlux, ChinaFLUX, and Chinese Forest Ecosystem Research Network (CFERN) and paired surface station observations in North/South America and in Eastern Asia. Consistent with climate model predictions, the observed change in the surface temperature  $\Delta T$  (open land minus forest) due to land clearing was dependent on latitude in these continents. North of  $10^\circ\text{N}$ , the observed latitudinal dependency was greater in magnitude for Americas ( $-0.079 (\pm 0.010)^\circ\text{C}$  per degree latitude) than for Asia ( $-0.046 (\pm 0.011)^\circ\text{C}$  per degree), suggesting a stronger snow albedo effect in Canada than in northeast Asia. Using the combined datasets, we found that local deforestation warmed the surface air by  $0.67 \pm 0.45^\circ\text{C}$  (number of site pairs  $n = 8$ ) in tropical and subtropical latitudes ( $15^\circ\text{S}$ – $20^\circ\text{N}$ ) and cooled the surface air by  $0.95 \pm 0.51^\circ\text{C}$  ( $n = 17$ ) in boreal latitudes ( $\geq 45^\circ\text{N}$ ). The warming in the low latitudes was associated with increase in the daily maximum temperature with little change in the daily minimum temperature, while the reverse was true in the boreal latitudes. In latitudes north of  $35^\circ\text{N}$ , the observed cooling signal was weaker, by about  $2^\circ\text{C}$ , than that simulated using a climate model of large-scale deforestation (Davin and de Noblet-Ducoudré 2010).

The individual site-year data shows a significant positive correlation between the annual mean  $\Delta T$  and annual precipitation  $P$  for the Asian site pairs, suggesting that precipitation

was a driver of the  $\Delta T$  interannual variability and its latitudinal dependence. In comparison, the correlation between  $\Delta T$  and  $P$  was much weaker in Americas.

## Acknowledgments

This research was supported by the Ministry of Education of China (grant PCSIRT), the Priority Academic Program Development of Jiangsu Higher Education Institutions (PARD), the National Basic Research Program of China (Grant No. 2010CB833504), and the National Natural Science Foundation of China (Grant No. 31200377). We also thank the researchers at all the eddy flux sites and the weather stations for providing the temperature data.

## References

- Bala G, Caldeira K, Wickett M, Phillips T J, Lobell D B, Delire C and Mirin A 2007 Combined climate and carbon cycle effects of large-scale deforestation *Proc. Natl Acad. Sci.* **104** 6550–5
- Baldocchi D D and Ma S 2013 How will land use affect air temperature in the surface boundary layer? Lessons learned from a comparative study on the energy balance of an oak savanna and annual grassland in California, USA *Tellus B* **65** 19994
- Betts R A 2000 Offset of the potential carbon sink from boreal forestation by decreases in surface albedo *Nature* **408** 187–90
- Betts R A, Falloon P D, Goldewijk K K and Ramankutty N 2007 Biogeophysical effects of land use on climate: model simulations of radiative forcing and large-scale temperature change *Agric. Forest Meteorol.* **142** 216–333
- Bonan G B 2008 Forests and climate change: forcings, feedbacks, and the climate benefits of forests *Science* **320** 1444–9
- Bonan G B, Pollard D and Thompson S L 1992 Effect of boreal forest vegetation on global climate *Nature* **359** 716–8
- Davin E L and de Noblet-Ducoudré N 2010 Climatic impact of global—scale deforestation: radiative versus nonradiative processes *J. Clim.* **23** 97–112
- Dickinson R E and Henderson-Sellers A 1998 Modelling tropical deforestation: a study of GCM land-surface parameterizations *Q. J. R. Meteorol. Soc.* **114** 439–62
- Douville H and Royer J F 1997 Influence of the temperate and boreal forests on the Northern Hemisphere climate in the Meteo-France climate model *Clim. Dyn.* **13** 57–74
- Easterling D R et al 1997 Maximum and minimum temperature trends for the globe *Science* **277** 364–7
- Gotangco Castillo C K and Gurney K B 2013 A sensitivity analysis of surface biophysical, carbon, and climate impacts of tropical deforestation rates in CCSM4-CNDV *J. Clim.* **26** 805–21
- Hansen J, Sato M, Ruedy R, Lo K, Lea D W and Medina-Elizade M 2006 Global temperature change *Proc. Natl Acad. Sci. USA* **103** 14288–93
- Lean J and Rowntree P R 1993 A GCM simulation of the impact of Amazonian deforestation on climate using an improved canopy representation *Q. J. R. Meteorol. Soc.* **119** 509–30
- Lean J and Rowntree P R 1997 Understanding the sensitivity of a GCM simulation of Amazonian deforestation to the specification of vegetation and soil characteristics *J. Clim.* **10** 1216–35
- Lee X H et al 2011 Observed increase in local cooling effect of deforestation at higher latitudes *Nature* **479** 384–7
- Longobardi P, Montenegro A, Beltrami H and Eby M 2012 Spatial scale dependency of the modeled climatic response to deforestation *Biogeosci. Discuss.* **9** 14639–87
- Mildrexler D J, Zhao M S and Running S W 2011 A global comparison between station air temperatures and MODIS land surface temperatures reveals the cooling role of forests *J. Geophys. Res.* **116** G03025
- Ollinger S V 2010 Source of variability in canopy reflectance and the convergent properties of plants *New Phytol.* **189** 375–94
- Pepin N 2001 Lapse rate changes in northern England *Theor. Appl. Climatol.* **68** 1–16
- Piao S L et al 2012 The carbon budget of terrestrial ecosystems in East Asia over the last two decades *Biogeosciences* **9** 3571–86
- Pielke R A, Avissar R, Raupach M, Dolman A J, Zeng X and Denning A S 1998 Interaction between the atmosphere and terrestrial ecosystems: influence on weather and climate *Global Change Biol.* **4** 461–75
- Pielke R A et al 2007 Unresolved issues with the assessment of multidecadal global land surface temperature trends *J. Geophys. Res.* **112** D24S08
- Schmidt A, Hanson C, Chan W S and Law B E 2012 Empirical assessment of uncertainties of meteorological parameters and turbulent fluxes in the AmeriFlux network *J. Geophys. Res.* **117** G04014
- Wild M, Ohmura A and Makowski K 2007 Impact of global dimming and brightening on global warming *Geophys. Res. Lett.* **34** L04702
- Yu G R et al 2008 Environmental controls over carbon exchange of three forest ecosystems in eastern China *Global Change Biol.* **14** 2555–71
- Yu G R, Wen X F, Sun X M, Tanner B D, Lee X H and Chen J Y 2006 Overview of ChinaFLUX and evaluation of its eddy covariance measurement *Agric. Forest Meteorol.* **137** 125–37
- Zhou L M, Tian Y H, Roy S B, Thorncroft C, Bosart L F and Hu Y L 2012 Impact of wind farms on land surface temperature *Nature Clim. Change* **2** 539–43