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

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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 (± 0.010) °C per degree] than in Asia [-0.046 (± 0.011) °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

S Online supplementary data available from stacks.iop.org/ERL/9/034002/mmedia

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_2 (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_2 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 ΔT 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_2 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)). 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

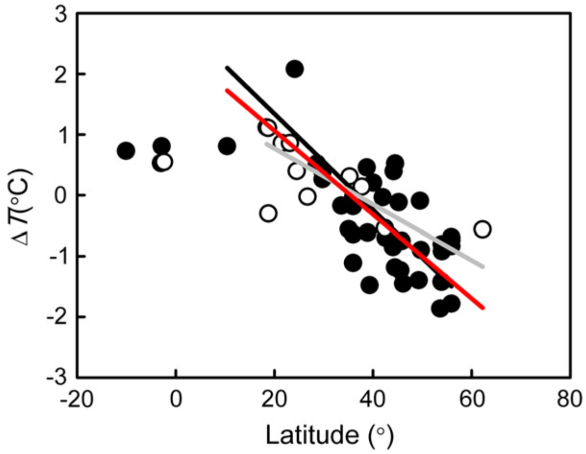

Figure 2. Annual mean temperature difference ΔT (open land minus forest) as a function of latitude. Black solid circles and open circles denote weather station/forest site pairs in Americas and in Asia, respectively. The black solid line indicates the linear regression for Americas (latitude >10°N: $y = -0.079\ (\pm 0.010)x + 2.923(\pm 0.424)$, $n = 38$, $R^2 = 0.44$, $P < 0.0001$), the gray solid line indicates the linear regression for Asia (latitude >10°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°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 (ΔT) 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 °C km^{-1}. According to the North American Reanalysis, local lapse rate varies between 4 and 9 °C km^{-1} among the North American sites (Lee *et al* 2011). If we used these extreme values, the mean ΔT of the tropical site pairs in the latitude span of 15°S–20°N would change from 0.67 to 1.01 and 0.33 °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 ΔT

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

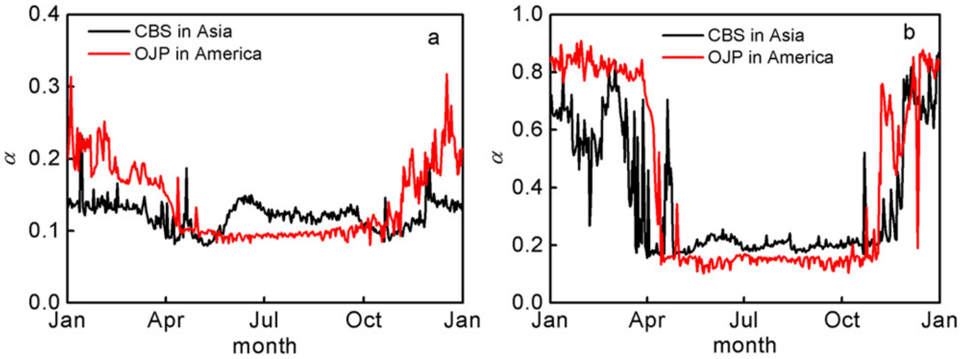

Figure 3. Seasonal dynamic of albedo (α) in the Changbaishan temperate mixed forest site pair (CBS) (42.4°N, 128.08°E) in Asia and the Saskatchewan BERMS old jack pine site pair (OJP) in America (53.92°N, 104.69°W). (a) Albedo of open land; (b) albedo of forest.

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 ΔT latitudinal trend in latitudes north of 10°N was similar between the two continents, the regression slope of ΔT versus latitude was more negative for Americas than for Eastern Asia. The rate of ΔT decrease with increase in latitude was −0.079 (±0.010) °C per degree in Americas, but was −0.046 (±0.011) °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 ΔT decrease with increasing latitude (latitudes north of 10°N) was −0.067 (±0.018) °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 ΔT. Baldocchi and Ma (2013) reported that ΔT 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 °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_{max} and T_{min} in forested and open land in four latitudinal zones. To remove site-to-site variations, here we computed the mean T_{max} and T_{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_{max} and T_{min} were different among these zones:

(1) In latitudes higher than 45°N, T_{max} in the open land was almost the same to that in the forested land. However, T_{min} in the open land was about 2 °C lower than that in the forested land (figure 4(a)). The mean temperature difference (open land minus forest land) was -0.95 ± 0.51 °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_{max} of the open land was much higher (by about 2.4 °C) than that of the forested land, and T_{min} of the open land was almost identical to that of the forested land. The mean temperature difference was 0.67 ± 0.45 °C ($n = 8$).

(3) The zone between 35°N and 45°N shows transitional behaviors. T_{max} of the open land was higher (by about 1.2 °C) than that of the forested land, and T_{min} of the open land was lower (by about 1.9 °C) than that of the forested land (figure 4(b)). The mean temperature difference was -0.35 ± 0.60 °C ($n = 18$).

(4) The zone 20°N–35°N is also transitional. The open land had 1.3 °C higher T_{max} and 0.3 °C higher T_{min} than the forest land (figure 4(c)). The mean temperature difference was 0.58 ± 0.66 °C ($n = 9$).

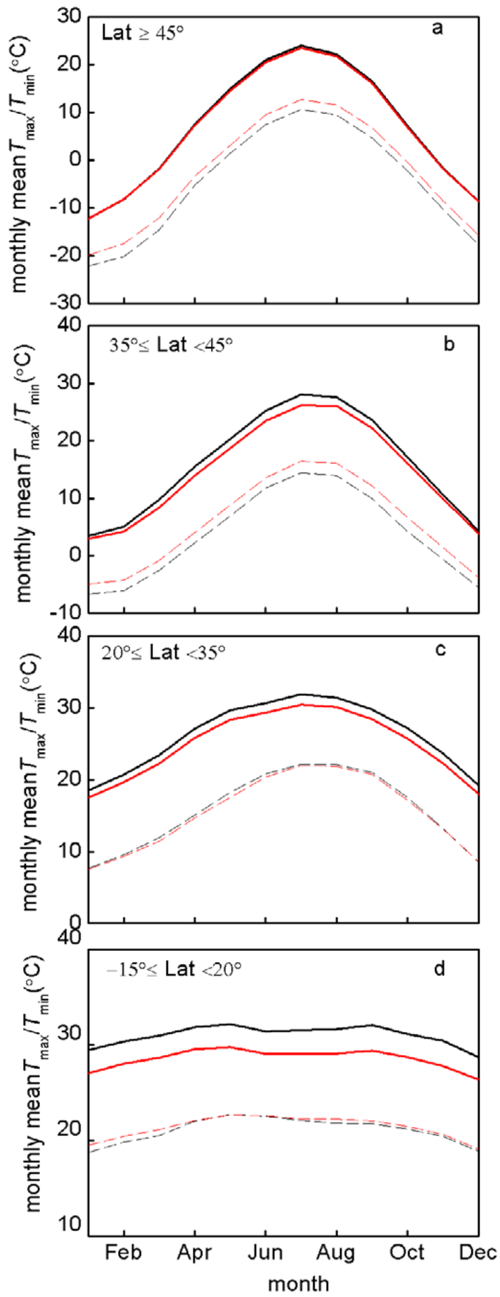

Figure 4. Comparison of seasonal variation of daily maximum and minimum air temperature in four latitudinal ranges. The black and red solid lines indicate T_{max} of open and forested land, respectively. The black and red dashed lines indicate T_{min} of open and forested land, respectively.

These diurnal temperature patterns indicate that in the boreal zone (>45°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

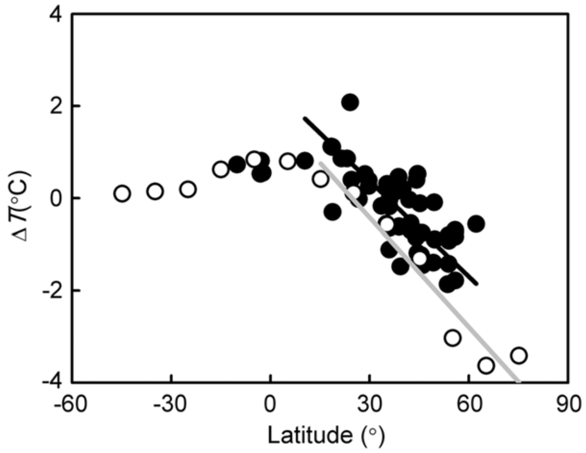

Figure 5. Comparison of measured and modeled latitudinal patterns of the annual mean temperature difference ΔT. Black solid circles are observations and open circles are zonal mean values simulated by the climate model of a fully coupled land–ocean–atmosphere GCM (Davin and de Noblet-Ducoudré 2010). 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 ΔT (latitude >10°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°S–20°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)). 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 ΔT 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°N, the cooling signal we observed in our comparison is weaker, by about 2 °C, than the model prediction. For example, according to

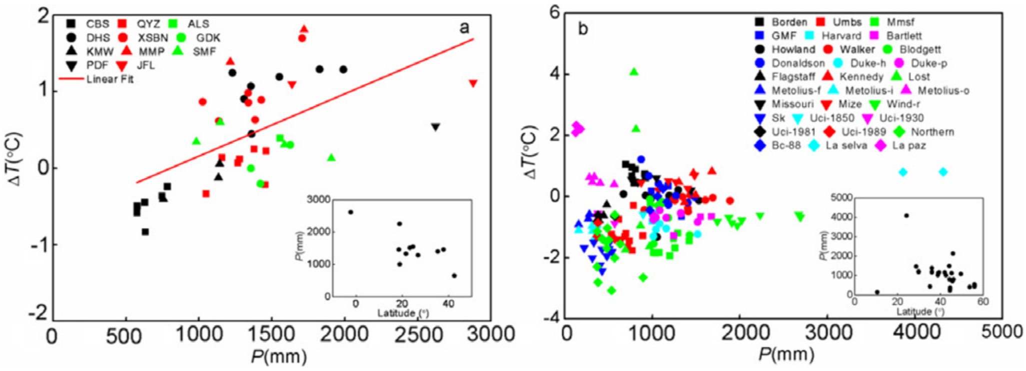

Figure 6. Relationship between annual mean temperature difference ΔT and annual precipitation for (a) Asia and (b) Americas. The insets to (a) and (b) show the site mean precipitation as a function of latitude. The line in panel a is linear regression of the individual site-year data [$y = 0.00081\ (\pm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

the model results, deforestation causes a cooling of 3.0 °C at 55°N; at the same latitude, the observational data indicates a cooling signal of ∼1.0 °C. The rate of simulated ΔT decrease with latitude is 0.079 °C per degree, slightly larger than the observed value (0.069 °C per degree). In the observational study, the land clearing occurred at scales too small to have measurable influence on the atmospheric CO_2. Nor should it trigger the large-scale dynamic feedbacks described above. In other words, the observed ΔT is a measure of the intrinsic biophysical mechanisms without the contributions of the large-scale feedbacks and the CO_2 radiative forcing. Perhaps the difference between the observed ΔT and the modeled ΔT 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°N.

Interestingly, in the latitudinal interval from 15°S to 10°N, the modeled and observed results show nearly the same ΔT. 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 ΔT variations

Annual precipitation P appears to be a driver of interannual variations of the deforestation signal in Asia (figure 6(a)). Generally, ΔT 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 ΔT 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 ΔT and P among the individual site-year data points. The linear correlation coefficient between ΔT and P was 0.58 (p value < 0.001). The ΔT increased with P at a rate of 0.81 (±0.18) °C per 1000 mm. That precipitation decreases with increasing altitude (inset to figure 6(a)) implies that the ΔT 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 ΔT 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 ΔT 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 ΔT (open land minus forest) due to land clearing was dependent on latitude in these continents. North of 10°N, the observed latitudinal dependency was greater in magnitude for Americas (−0.079 (±0.010) °C per degree latitude) than for Asia (−0.046 (±0.011) °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 ± 0.45 °C (number of site pairs $n = 8$) in tropical and subtropical latitudes (15°S–20°N) and cooled the surface air by 0.95 ± 0.51 °C ($n = 17$) in boreal latitudes (≥45°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°N, the observed cooling signal was weaker, by about 2 °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 ΔT and annual precipitation P for the Asian site pairs, suggesting that precipitation was a driver of the ΔT interannual variability and its latitudinal dependence. In comparison, the correlation between ΔT and P was much weaker in Americas.

Acknowledgments

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