warming-induced changes in the vertical structure of the atmosphere or ocean also produce opposite impacts on the Walker circulation.

So what's actually been going on over the past century? One issue for determination of trends in climate is that before 1979 (the start of the modern satellite era), virtually all tropical Pacific Ocean data were collected by ships that inadequately sampled in time and space[4–5]. Different datasets result when various techniques, either statistical or physics-based, are used to fill in regions with few observations. Changing methods of data collection must also be taken into account — for example, as ships have increased in size, their wind measurements are affected by the general increase of wind speed with height.

L'Heureux and co-workers address these concerns by focusing on surface pressure, rather than winds, and by restricting their 1900–2011 analysis to regions where relatively high data availability minimizes disagreement between the datasets.

By averaging sea-level pressure in two equatorial regions located in Indonesia and the eastern Pacific, they obtain a more reliable measure of the east–west pressure difference that drives the trade winds. They use this to investigate Walker circulation trends of varying lengths (from 10 to 40 years) throughout the twentieth century. Notably, although different time periods show trends of varying amplitude and sign, there is no obvious preferred direction of these trends since 1900 — demonstrating how fitting a tropical trend within a single multidecadal period can be problematic.

However, L'Heureux *et al.* do show a strengthening Walker circulation — associated with an eastern equatorial Pacific cooling trend — that coincides with the rapid increase of global temperatures beginning in the mid-1970s. Along with similar observational results[6–8], this apparently contradicts model simulations of the tropical response to global warming. Why? One possibility is that well-known modelling issues with correctly simulating both average tropical Pacific climate and ENSO variations[9–10] extend to longer timescales as well. For example, recent palaeoclimate reconstructions of tropical Pacific surface temperatures disagree with model simulations driven by historical solar variability and volcanic eruptions estimated for the last millennium[11].

Conversely, natural decadal tropical variability — both within the models and even from twentieth-century observations — may be significantly underestimated[12]. Furthermore, large and episodic ENSO events comprise a good-sized portion of tropical trends, even over many decades[2,8]. That is, strengthening might be a natural consequence of the recent dominance of cool ENSO events — just as earlier weakening estimates seem to be influenced by warm events in the 1990s[1] — and might reverse in the future even with continued global warming. The pronounced multidecadal strengthening of the Walker circulation shown by L'Heureux and colleagues is primarily linked to recent warming by association; they do not suggest a similar relationship to warming earlier in the century. Of course, this recent strengthening does not exactly support the case for warming-induced weakening either. In fact, this study allows for the possibility that no significant Walker circulation trend occurred over the twentieth century[13].

What seems likely is that the observational record is not sufficient to disprove opposing theories of global warming-induced changes to the Walker circulation, but is sufficient to cast doubt on model projections, leaving future tropical Pacific trends to remain uncertain. Moreover, the various mechanisms proposed for the tropical response to global warming may offset and/or interact in ways the models do not adequately simulate and we do not understand. L'Heureux and co-workers' study, by clarifying the history of recent tropical Pacific climate, leaves us with more questions than answers. ❐

Matthew Newman is at the Cooperative Institute for Research in Environmental Studies, University of Colorado and Physical Sciences Division/NOAA Earth System Research Laboratory, 325 Broadway, R/PSD1, Boulder, Colorado 80305-3328, USA.
e-mail: matt.newman@noaa.gov

References

1. Vecchi, G. A. *et al. Nature* **441,** 73–76 (2006).
2. L'Heureux, M., Lee, S. & Lyon,B. *Nature Clim. Change* **3,** 571–576 (2013).
3. Clement, A. C., Seager, R., Cane, M. A. & Zebiak, S. E. *J. Clim.* **9,** 2190–2196 (1996).
4. Tokinaga, H., Xie, S-P., Deser, C., Kosaka, Y. & Okumura, Y. M. *Nature* **491,** 439–443 (2012).
5. Deser, C., Phillips, A. S. & Alexander, M. A. *Geophys. Res. Lett.* **37,** L10701 (2010).
6. Wentz, F. J., Ricciardulli, L., Hilburn, K. A. & Mears, C. A. *Science* **317,** 233–235 (2007).
7. Merrifield, M. A. & Maltrud, M. E. *Geophys. Res. Lett.* **38,** L21605 (2011).
8. Cane, M. A. *et al. Science* **275,** 957–960 (1997).
9. Vanniere, B. *et al. Clim. Dynam.* **40,** 963–981 (2013).
10. Shin, S. I., Sardeshmukh, P. D. & Pegion, K. *J. Geophys. Res.* **115,** D21110 (2010).
11. Emile-Geay, J., Cobb, K. M., Mann, M. E. & Wittenberg, A. T. *J. Clim.* **26,** 2329–2352 (2013).
12. Ault, T. R. *et al. Geophys. Res. Lett.* **36,** L08602 (2009).
13. Compo, G. P. *et al. Q. J. R. Meteorol. Soc.* **137,** 1–28 (2011).

Corrected after print 31 May 2013

ARCTIC GREENING

Concerns over Arctic warming grow

Changes in the pattern of the seasons are implicated in observed Arctic greening.

Peter K. Snyder

A troubling transformation is taking place in the Arctic, and it has little to do with sea ice. Although record-breaking reductions in extent of sea ice in the Arctic Ocean drew the headlines in 2012, the more gradual and lesser-known changes to Arctic vegetation continued their inexorable march — with no less important implications for future planetary warming. Tundra and boreal forests are getting greener in response to changes in the Arctic climate. Writing in *Nature Climate Change*, Xu *et al.*[1] present compelling new evidence of these changes in vegetation, based on more than 30 years of satellite observations.

Increasing atmospheric greenhouse gas concentrations are having a particularly strong effect on the climate of the Northern Hemisphere at high latitudes, where warming is approximately twice that of the average for the planet as a whole[2]. Melting of snow and ice are primarily responsible for this extreme warming, because their absence allows more of the sun's energy to be absorbed by the less reflective underlying soil, vegetation and ocean surfaces[3,4]. In other words, the greenhouse gas-induced warming causes snow and ice melt, that further warms the land and ocean surfaces, contributing to more snow and ice melt — a

© 2013 Macmillan Publishers Limited. All rights reserved


© HEMERA TECHNOLOGIES/PHOTOS.COM/THINKSTOCK

Boreal forest in a snow-covered landscape. Boreal and Arctic vegetation are rapidly responding to widespread warming of the Northern Hemisphere. By analysing satellite data over the last 30 years, Xu and colleagues[1] show that a change in the seasonality of the climate is primarily responsible for increasing vegetation productivity over northern lands. These findings shed new light on the contribution of positive land surface feedbacks to amplifying high-latitude warming

vicious circle known as a positive feedback. This land and ocean feedback is expected to continue to increase winter temperatures over land throughout the remainder of this century[5].

Stronger winter warming — relative to the summer — means that the seasonality of temperature (the difference between summer and winter temperatures) is diminishing, leading to longer growing seasons for Arctic and boreal vegetation. Furthermore, warming has allowed some boreal forest and tundra species to thrive in locations that were recently too climatically harsh to support them. The vegetation in northern lands is greening up earlier, greening more and staying green for longer. All of this amplifies warming through strong, positive land surface feedbacks to the climate. Although a greener biosphere is likely to take up more atmospheric carbon dioxide through enhanced photosynthetic activity, observational and modelling evidence indicates that positive land surface feedbacks will, in general, exceed the moderating effects of greater carbon uptake by plants[6,7].

Using a new approach, Xu and colleagues examine more than 30 years of satellite data to confirm that the Arctic terrestrial biosphere is greening up in response to high-latitude warming. Assuming that this warming trend continues unabated, we can expect to see more greening of Arctic and boreal vegetation, and further warming because of the effectiveness of vegetation in absorbing the sun's energy. This analysis draws on several earlier studies that have also documented high-latitude greening[8–10], but Xu *et al.* focus specifically on the factors causing the increase in vegetation productivity.

At the heart of this approach is the identification of a strong relationship between temperature and vegetation seasonality. The latter is estimated from the satellite-derived normalized difference vegetation index (NDVI) — essentially a measure of vegetation greenness. They find that mean vegetation greening has increased dramatically (up to 41%) in Arctic and boreal vegetation over the three decades investigated. The greening trends are particularly pronounced in Eurasian forests, shrublands and tundra, eastern forests of North America and coastal tundra surrounding the Arctic Ocean. Perhaps most importantly, much of the Arctic and boreal vegetation undergoing change is located in environments where the growing season has been extended by more than three days per decade. One can infer from these findings that there is a strong coupling between vegetation and temperature seasonality, and that continued declines in the seasonality of temperature are likely to produce an additional increase in the productivity of Arctic and boreal forest vegetation. Climate models that do not represent this observed atmosphere–biosphere behaviour are probably underestimating the amount of warming that will occur by the end of this century.

Given that temperature seasonality generally increases with latitude because of the annual variation in solar radiation, it is reasonable to assume that as seasonality diminishes with warming, more northerly locations will begin to resemble the climate of regions to the south. In fact, Xu *et al.* found that between the early 1980s and late 2000s the seasonality of the warm-season temperature of the boreal and Arctic shifted by 5.2° and 4.0° of latitude, respectively, to resemble locations further to the south. Moreover, they found that the seasonality of boreal and Arctic vegetation (as determined by changes in NDVI) now resembles that of locations 6.3° and 7.1° of latitude, respectively, further south. This is a significant shift that has undoubtedly already led to considerable extra warming through strong positive land surface feedbacks.

In a region of the planet where land surface feedback mechanisms contribute most to the climate response, it is crucial that we continue to monitor landscape changes. Considering the inherent uncertainties associated with societal progress in reducing greenhouse gas emissions, and the challenges of accurately simulating the future climate with computer models, it is paramount that observational approaches remain the mainstay of efforts to understand how the climate is changing, and the factors responsible. In their timely new study, Xu *et al.* demonstrate the important role of satellite observations in understanding climate change. ❒

Peter K. Snyder is in the Department of Soil, Water, and Climate, University of Minnesota, USA.
e-mail: pksnyder@umn.edu

References

1. Xu, L. *et al. Nature Clim. Change* **3,** 581–586 (2013).
2. Trenberth, K. E. *et al.* in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) Ch. 3, 104 (Cambridge Univ. Press, 2007).
3. Chapin, F. S. *et al. Science* **310,** 657–660 (2005).
4. Serreze, M. C. & Barry, R. G. *Glob. Planet. Change* **77,** 85–96 (2011).
5. ACIA *Impact of a warming Arctic: Arctic Climate Impact Assessment* (Cambridge Univ. Press, 2004).
6. Bonan, G. B. *Science* **320,** 1444–1449 (2008).
7. Anderson, R. G. *et al. Front. Ecol. Environ.* **9,** 174–182 (2011).
8. Jia, G., Epstein, H. E. & Walker, D. A. *Geophys. Res. Lett.* **30,** 1029–1033 (2003).
9. Myneni, R. B., Keeling, C. D., Tucker, C. J., Asrar, G. & Nemani, R. R. *Nature* **386,** 698–702 (1997).
10. Tucker, C. J. *et al. Int. J. Biometeorol.* **45,** 184–190 (2001).

© 2013 Macmillan Publishers Limited. All rights reserved