INTERNATIONAL JOURNAL OF CLIMATOLOGY
*Int. J. Climatol.* **0**: 000–000 (2014)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3995

Royal Meteorological Society

# Short Communication

# The climate of Myanmar: evidence for effects of the Pacific Decadal Oscillation

Rosanne D'Arrigo[a]* and Caroline C. Ummenhofer[b]
[a] *Tree-Ring Laboratory, Lamont-Doherty Earth Observatory, Palisades, NY, USA*
[b] *Department of Physical Oceanography, Woods Hole Oceanographic Institution, Woods Hole, MA, USA*



**ABSTRACT:** We show evidence for the influence of the Pacific Decadal Oscillation (PDO) on Myanmar's monsoonal hydroclimate using both instrumental and 20th century reanalysis data, and a tree-ring width chronology from Myanmar's central Dry Zone. The 'regime shifts' identified in the instrumental PDO for the past century are clearly evident in the Myanmar teak. The teak record and PDO index correlate most significantly and positively during December–May, at $r = 0.41$ (0.002, $n = 109$). We generated composite climate anomalies for southern Asia and adjacent ocean areas during negative and positive PDO phases and above/below average teak growth for the May–September wet monsoon season. They show that negative (positive) PDO phases correspond to dry (wet) conditions, due to reduced (enhanced) moisture flux into central Myanmar. Multitaper Method (MTM) and Singular Spectrum Analysis (SSA) spectral analyses reveal considerable multidecadal variability over the past several centuries of the teak chronology, consistent with the PDO.

KEY WORDS

*Received 15 July 2013; Revised 11 February 2014; Accepted 4 March 2014*

## 1. Introduction

AQ1 Myanmar • is at considerable risk from environmental extremes and climatic change (droughts and floods), due to its agricultural economy, low coping ability, and historical isolation (Wheeler, 2011). Myanmar's hydroclimate is spatially complex, with varied topography and multiple environmental influences (Sen Roy and Kaur, 2000; Sen Roy and Sen Roy, 2011; Wang and Gillies, 2012). It lies directly under the eastern arm of the Indian summer monsoon, abutting the Bay of Bengal (BOB), yet also experiences the effects of the East Asian Western North Pacific (EAWNP) monsoon, and winter southeast Asian monsoon (R. Robinson, University of St. Andrews, personal communication, 2013). Myanmar represents a crucial link in our understanding of these overlapping monsoon systems (Xu *et al.*, 2012). Myanmar monsoon rainfall is also modulated by the El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole mode (IOD), the latter a quasi-periodic fluctuation in SST phase-locked to the September–November season (Kumar *et al.*, 1999; Saji *et al.*, 1999; Ashok *et al.*, 2010). Although the sign of these relationships varies with space and topography (Sen Roy and Sen Roy, 2011, R. Robinson, personal communication, 2013), these phenomena are linked to significant anomalies in rainfall, temperature and atmospheric circulation across Myanmar and south Asia (Ummenhofer *et al.*, 2013a).

Sen Roy and Kaur (2000) were among the first to investigate the instrumental climatology of Myanmar, identifying five homogenous regions using a 30-year station data set (1947–1979). Sen Roy and Sen Roy (2011) explored the potential link between the Pacific Decadal Oscillation (PDO, the dominant mode of Pacific sea surface temperatures (SST) poleward of 20°N on decadal timescales (Mantua *et al.*, 1997), ENSO, and Myanmar's summer monsoon precipitation using the CRU 52-year gridded dataset (1951–2002). Some contend that the primary driver of Pacific Decadal Variability (PDV) lies in the North Pacific (Barnett *et al.*, 1999); others that the PDO may be a reddened response to ENSO, originating in the tropics (Shakun and Shaman, 2009). Sen Roy and Sen Roy (2011) found that the PDO modulates precipitation during ENSO events across Myanmar, with drought during El Niños being more intense during the warm PDO phase, and the reverse for La Niñas, perhaps tied to the sensitivity of the Aleutian Low. Similar relationships between monsoon rainfall and the PDO were described for India (Krishnan and Sugi, 2003; Sen Roy, 2006). Using 306 rain gauge station records (1871–2002), Krishnan and Sugi (2003) concluded that the PDO could amplify Indian climate related to ENSO and might be useful in long-term forecasting across south Asia. Buckley *et al.* (2010a) observed a strong positive signal between the growth of Vietnam conifers and

*Correspondence to: R. D'Arrigo, Tree-Ring Laboratory, Lamont-Doherty Earth Observatory, Palisades, NY 10964, USA.
E-mail: rdd@ldeo.columbia.edu

the Interdecadal Pacific Oscillation (IPO), closely related to the PDO (Folland *et al.*, 2002, AQ2 •Meehl and Hu, 2006). Detailed understanding of the climate of this region is constrained by the shortness of the instrumental records, which are typically not of sufficient length to fully assess PDO-like (decadal to multidecadal) variability.

We further investigate the variability of monsoon precipitation in Myanmar using both instrumental/reanalysis climatic records and tree-ring data, with an emphasis on decadal to multidecadal time scales. Paleoclimatic studies are few for Myanmar and vicinity, but are essential for deducing longer-term variations exceeding those that can be resolved from the instrumental record, that covers only the past few decades to century.

D'Arrigo *et al.* (2011) described one of the first tree-ring chronologies for Myanmar, developed from the wood of living teak (*Tectona grandis*) trees in the Maingtha Reserve, in the so-called 'Dry Zone' in the center of the country (23°20 N, 96°20 E; 1613–2009). This chronology is used in the analyses below. It is based on ring-width measurements from 38 individual core samples of wood from 20 living trees. These data were standardized using the ARSTAN method (Cook and Kairiukstis, 1990, arstan chronology), using the Friedman super smoother, a data-adaptive smoothing technique (Friedman, 1984). Additional details are indicated in D'Arrigo *et al.* (2011). The mean and median segment length are 278 years. The Maingtha chronology was used to show that the late 18th century megadrought, identified in Thailand and elsewhere in Asia (Buckley *et al.*, 2007, 2010b; Cook *et al.*, 2010), also impacted Myanmar. The lowest ring-width index value in this teak record coincides with drought during the so-called 'El Niño of the Century' of the late 1990s. The greater context of the climate of monsoon Asia over the past millennium (based on the Palmer Drought Severity Index) is described in a tree-ring data network known as the Monsoon Asia Drought Atlas or MADA, although its original version did not include coverage over Myanmar and vicinity (Cook *et al.*, 2010; Ummenhofer *et al.*, 2013a).

## 2. Data, analysis and results

As noted, modulating effects from the PDO have been demonstrated on monsoon climate across Myanmar (Sen Roy and Sen Roy, 2011). Sen Roy and Sen Roy (2011) concluded that the 'role of the PDO on prevailing precipitation was mostly positive during both its cold and warm phases', focusing mainly on the PDO's modulation of ENSO's impact on rainfall. To further examine relationships between Myanmar hydroclimate and larger-scale dynamics, we analysed the instrumental record and 20th century reanalysis data, along with the Myanmar teak, to assess the large-scale climate patterns (precipitation, winds, moisture fluxes, monsoon indices) over Myanmar and adjacent southeast Asia during cold and warm phases of the PDO.

Annual time-series and 5-year running averages of the Maingtha teak chronology and instrumental PDO

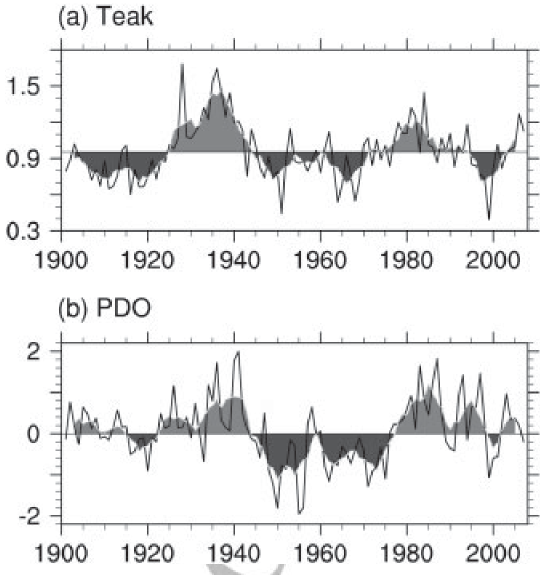





Figure 1. Annual time-series (black) and 5-year running average (green) of (a) Maingtha teak ring-width chronology and (b) PDO for the period 1901 to 2007, indicating that the teak record shows major regime shifts observed in the instrumental PDO index during the 20th century. Extended positive (red) and negative (blue) phases in the teak record and the PDO, based on the 5-year running averages, are indicated. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

index (Mantua *et al.*, 1997) are plotted for 1901 to 2007 (Figure 1). The so-called abrupt climatic 'regime shifts' in the instrumental PDO for the past century (Mantua *et al.*, 1997) are clearly evident in the Myanmar teak series, suggestive of the PDO's impact on Myanmar's monsoon hydroclimate. Overall, the teak record and the PDO correlate most significantly and positively with each other during the boreal cold season (December–May), at $r = 0.41$ (0.002, $n = 109$, based on the annual tree-ring/PDO time series).

Interestingly, mean Dec–Jan–Feb temperatures for Anchorage, Alaska (within the Gulf of Alaska region of peak PDO influences – Global Historical Climate Network (Peterson and Vose, 1997)) correlate with the PDO index at 0.66 (0.000, $n = 93$) and with the Myanmar teak at 0.30 (0.004, $n = 91$). Since 1940, Anchorage temperature correlations (for December–March) are even stronger, 0.81 (0.000, $n = 71$) with the PDO and 0.41 (0.001, $n = 69$) with the Myanmar teak. These relationships further indicate a significant link between the PDO and climate over south Asia. The closely related Oct – Dec IPO correlates with the Burma teak at $r = 0.43$ for 1950–2007; the signal with Vietnamese tree-ring data is even stronger (Nov–Feb IPO 1950–2007, $r = 0.66$, Buckley *et al.*, 2010a).

We next generated composite climate anomalies over southern Asia and adjacent ocean areas during negative and positive PDO phases and below/above average teak growth (cf. periods highlighted in blue/red in Figure 1) for the May–September months of the wet monsoon season (1901–2007; Figure 2). Data include monthly gridded fields from the Global Precipitation Climatology Centre (GPCC) precipitation, version 4 (Fuchs and Rudolf, 2007), moisture fluxes (as the product of specific humidity and



Color Figure - Online only

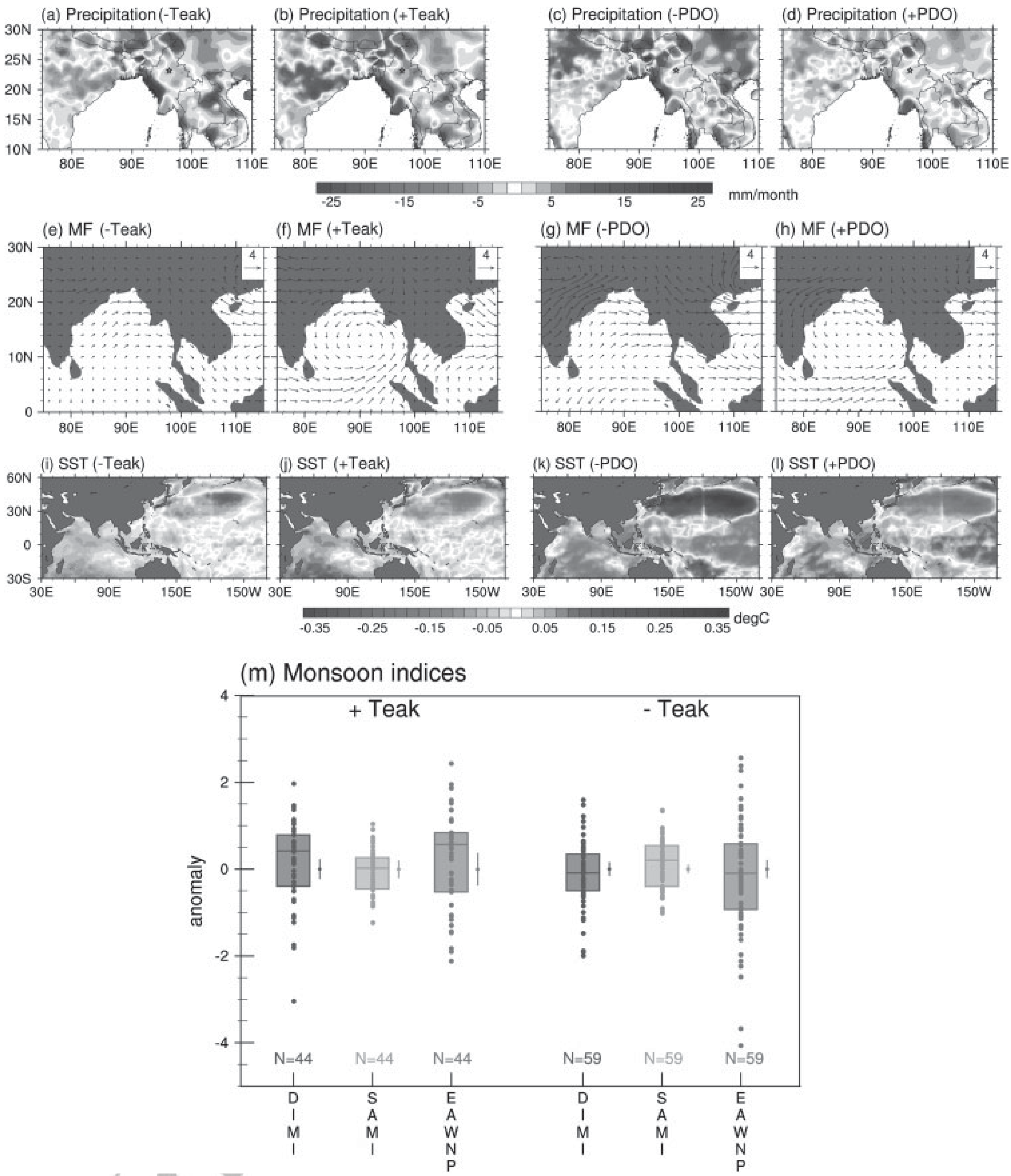



Figure 2. Composite of climate anomalies during sustained negative and positive phases of the teak and PDO time-series (cf. periods highlighted in Figure 1) for (a–d) precipitation anomalies, (e–h) moisture fluxes at the 850 hPa level, and (i–l) SST. (m) Anomalies in the monsoon indices shown as dots during sustained positive and negative phases in the teak record: coloured boxes are delimited by upper and lower quartiles, with the middle bar denoting the median in the respective index. Error bars indicate the value needed to be exceeded for the median to differ significantly from 0 (at the 95% confidence level, as estimated by Monte Carlo testing) for the different indices/categories. The number of years (N) is indicated below. All analyses for the May–September months for the period 1901–2007. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

zonal and meridional winds) at the 850 hPa level from the Twentieth Century reanalysis (Compo *et al.*, 2011), and SST from the Hadley Centre's HadISST product at 1° resolution (Rayner *et al.*, 2003). The composites show that negative phases in the teak record correspond to anomalous dry conditions in central Myanmar (Figure 2(a)) due to reduced moisture flux (Figure 2(e)). Enhanced westerly moisture flux is associated with wetter conditions along Myanmar's west coast from the anomalously warm BOB and strengthened easterly flow from the EAWNP monsoon, with increased precipitation in northern Vietnam (Figure 2(a), (e), and (i)). Conditions are reversed during positive teak phases (Figure 2(b), (f), and (j)). A similar composite of precipitation anomalies during sustained negative and positive PDO phases is shown in Figure 2(c) and (d). These composites generally reveal similar spatial patterns between the PDO (with opposing relationships for cold and warm phases), large-scale climate anomalies and the regional manifestation in precipitation and the Myanmar teak record. The SST composite anomalies during negative/positive teak periods show large-scale Indo-Pacific SST anomaly patterns strongly reminiscent of those during the negative/positive PDO phases, respectively (Figure 2(i)–(l)).

Anomalies in monsoon circulation as inferred from the Myanmar teak can be deduced from comparison with indices representative of subsystems of the Asian monsoon (Figure 2(m)), such as the Dynamic Indian Monsoon Index (DIMI; Wang and Fan, 1999), South Asian Monsoon Index (SAMI; Goswami *et al.*, 1999), and East Asia-Western North Pacific Index (EAWNPI; Wang *et al.*, 2008) (Fig. 6, in Ummenhofer *et al.*, 2013a). During sustained periods of positive teak growth, both the DIMI and EAWNP indices are anomalously strong, while the SAMI is unusually strong during prolonged negative teak phases (Figure 2(m)), consistent with enhanced onshore moisture flux and wet conditions along the Myanmar coast (Figure 2(a) and (e)).

## 3. Spectral modes of variability in Myanmar teak

To identify the dominant modes of variability in the teak record on interannual to decadal and longer time scales, we evaluated its main spectral properties over the past four centuries using multitaper analysis (MTM, Mann and Lees, 1996) and Singular Spectrum Analysis (SSA, Vautard and Ghil, 1989) (Figure 3).

MTM: The most pronounced spectral peak over 1630–2009 for the Myanmar chronology using MTM is observed at 38–68 years (significant, 99% level), with secondary peaks at ∼27 years (95% level), and 2–4 years (99% level) (Figure 3). Previous studies, based on instrumental Myanmar rainfall data for shorter intervals (decades-past century), similarly noted 2–6 year periodicities indicative of ENSO and the quasi-biennial oscillation (R. Robinson, personal communication, 2013), typical of the Asian monsoon system (Kumar *et al.*, 1999; Allan, 2000).

*SSA*: Waveforms were extracted from the Maingtha chronology using SSA (Figure 3, Vautard and Ghil, 1989). These reconstructed waveforms, consistent with the MTM results, reveal considerable decadal to multidecadal variability over the past several centuries of this chronology (1630–2009). The top four modes, extracted using a 100-lag covariance matrix, were identified at 47.62 years (EV1-2, 22.6% variance), 25 years (EV3-4, 8.7%), 18.87 years (EV 5-6, 4.5%), and 14.93 years (EV7-8, 3.6%). The 18.87 and 14.93 years modes have the greatest amplitude modulation over time, both with attenuation after around the middle to later 1800s. SSA of the annual PDO index of Mantua *et al.* (1997; using a 56-lag autocovariance matrix, high-pass filtered below 60 years, EV1, 3-4; 1900–2011) indicates a dominant mode at 51 years, accounting for ∼46% of the overall variance. For this same period (1900–2009), the dominant mode in the teak record is similar, at ∼48 years. Their stability over time and space, and possible interactions of these modes and their causes, are complex and require further investigation.

## 4. Discussion and conclusions

Paleoclimatic studies on the impact of the PDO in Asia are few compared to those for western North America, where the climatic effect is stronger (D'Arrigo *et al.*, 2001; Wilson *et al.*, 2007). For Asia, Shen *et al.* (2006) observed that the spatiotemporal variability of summer rainfall over eastern China is correlated with the PDO, using a drought/flood index to reconstruct the annual PDO index since 1470 AD, finding quasi-centennial (75- to 115-years) and pentadecadal (50- to 70-years) oscillations. D'Arrigo and Wilson (2006) generated a preliminary tree-ring reconstruction of the Asian expression of the PDO. The PDO has also been linked to instrumental and paleoclimatic records for north Asia, including Japan and the Russian Far East (Mantua *et al.*, 1997; Jacoby *et al.*, 2004). Deng *et al.* (2013) investigated variations in the PDO as inferred from a coral record since 1853 from the northern South China Sea, and Grove *et al.* (2013) from the Indian Ocean (Madagascar). In South Asia, as noted, PDO-related linkages with climate and ENSO have been found for India (Krishnan and Sugi, 2003) and Myanmar (Sen Roy and Sen Roy, 2011).

Results highlight the presence of coherent interbasin decadal variability in the Indo-Pacific region (Krishnan and Sugi, 2003), with the North Pacific signal likely transmitted to Southeast Asia via an atmospheric bridge, with impacts similar to ENSO (Mantua and Hare, 2002). It is also important to note that ENSO-related decadal variability may also be linked to the PDO and tropical climate (Allan, 2000). On decadal timescales, oceanic transmission of anomalous Pacific variability through the Indonesian Throughflow (Shi *et al.*, 2007) could also contribute to Indian Ocean warming during negative PDO phases (Figure 2(k)). Through interannual covariability in thermocline depth in the Western Pacific and eastern Indian Ocean (Ummenhofer *et al.*, 2013b), remote decadal Pacific signals reflected in Western Pacific thermocline depth and attributed to PDO forcing (Williams and Grottoli, 2010) could modulate Indian Ocean temperatures and consequently the region's monsoon circulation.

We confirm that there are significant decadal to multidecadal modes of variability linked to monsoon rainfall in both instrumental/reanalysis data and the longer teak tree-ring data from Myanmar, which appear to reflect the remote influence of the PDO and related regime shifts, and their impact on monsoon rainfall. The boreal winter PDO may precondition tree growth at the onset of the wet season over south Asia, via its impact on the Asian monsoon system. Our spectral teak analyses revealed modes

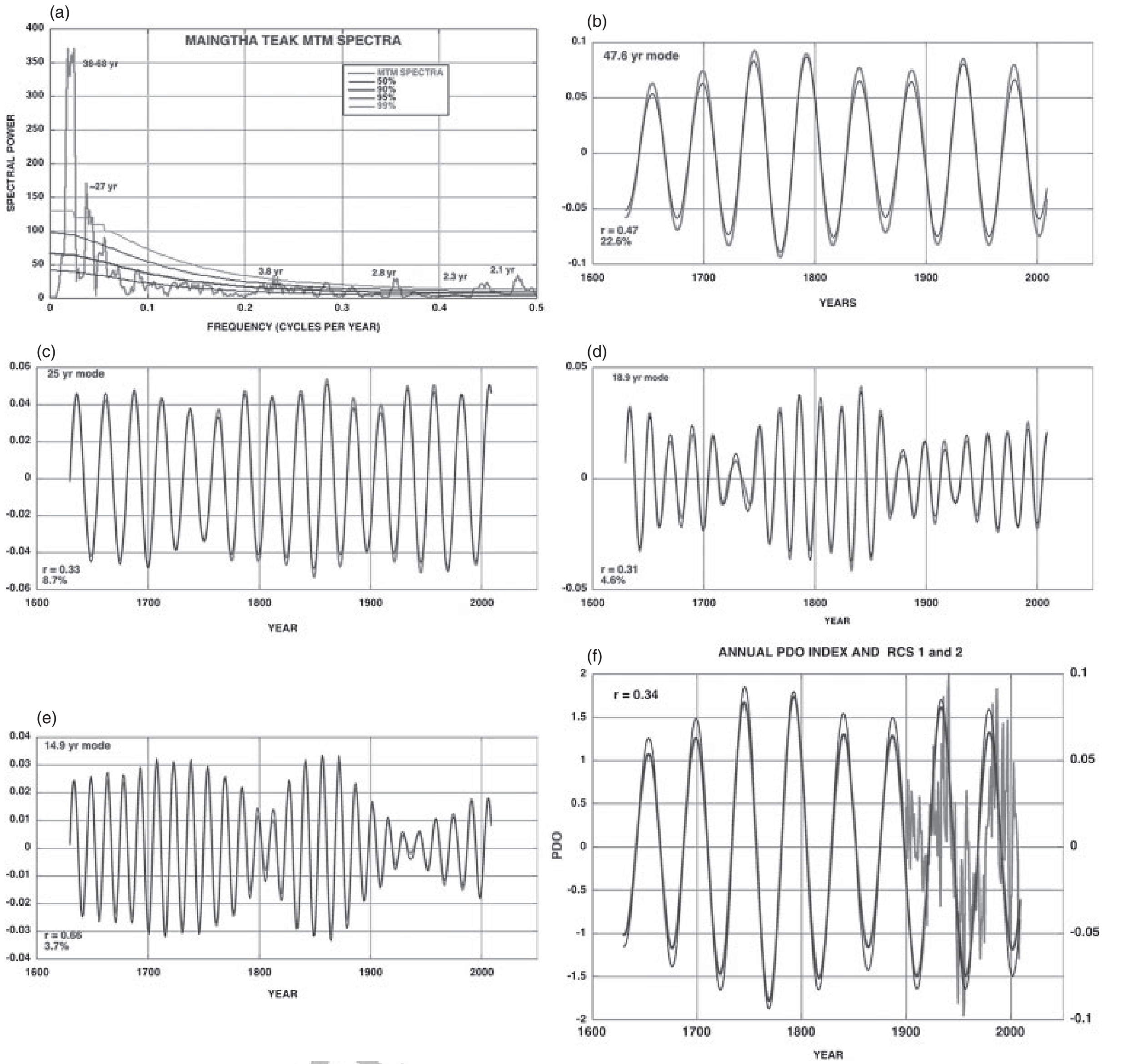



Figure 3. Spectral Analyses. (a) MTM spectral analysis of Maingtha teak ring width record for 1630–2009. Note significant peaks at interannual (within classical ENSO bandwidth) and multidecadal time scales (38–68, and 27 years, broadly consistent with the PDO). (b–e) Dominant waveforms extracted from Maingtha teak chronology over its length from 1630–2009, isolated using singular spectrum analysis or SSA. Dominant oscillatory modes are identified with periods of ~48 years, ~25 years, 18.9 and 14.9 years. Percentages of the original variance contributed by these waveforms are indicated on the lower left hand corner of each figure, along with the correlation with the teak series. Lowermost plot (f) shows comparison of the first RC pair for the ~48 years mode with the instrumental annual PDO. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

similar to those identified for the PDO and other long instrumental series of North Pacific variability. A ~48-year mode is also evident in teak from northwestern Thailand, shown to reflect decadal Pacific variability (Buckley *et al.*, 2007, 2010b). The ~27 years mode in the teak record is similar to that observed in a tree-ring reconstruction of Upper Indus, Pakistan streamflow over the past millennium (Cook *et al.*, 2013). An ~18 years mode, observed in the Maingtha teak, has been associated with lunar-tidal forcing in some North Pacific tree-ring records (Wilson *et al.*, 2007). A ~14–15 years mode corresponds to bandwidths associated with lower-frequency ENSO variability (Allan, 2000), and the PDO (Krishnan and Sugi, 2003). Amplitudes of the latter two modes vary considerably over time, and all these modes may interact and are likely modulated by various climatic forcings and synoptic phenomena.

We had discussed evidence for sustained megadroughts in the Maingtha teak from Myanmar (D'Arrigo *et al.*, 2011). Low growth (1756–1768) overlaps the so-called 'Strange Parallels' drought, one of the most important drought periods in the MADA (Buckley *et al.*, 2007, 2010b; Sano *et al.*, 2009; Cook *et al.*, 2010). Myanmar teak growth was below average during the late Victorian Great Drought, associated with a major ENSO warm event (1876–1878), perhaps the most spatially pervasive and severe drought in the MADA (Cook *et al.*, 2010). Some of these sustained megadroughts and other decadal features might be linked to regime-type shifts in the PDO prior to the instrumental era.

## Acknowledgements

This project was funded by the National Science Foundation Paleoclimate and P2C2 programmes (Grants AGS-1304245, AGS-1303976; AGS-1159430) and DOE DE-SC0006616. C. C. U. acknowledges support from the Penzance and John P. Chase Memorial Endowed Funds at WHOI. We thank Nyi Nyi Kyaw, Jonathan Palmer and Paul Krusic for their valuable participation in this research. We also gratefully acknowledge the cooperation of our colleagues at the Forest Research Institute, Yezin, Myanmar. We thank Z. Myint for assistance with fieldwork, and P. Fenwick for processing of tree-ring data. We acknowledge use of NOAA 20th Century reanalysis and GPCC Precipitation data, NOAA/OAR/ESRL PSD, Boulder, Colorado (http://www.esrl.noaa.gov/psd/) and HadISST by the UK Met Office. LDEO Contribution No. 0000.

## References

Allan RJ. 2000. ENSO and climatic variability in the past 150 years. In *ENSO: Multiscale Variability and Global and Regional Impacts*, Diaz HF, Markgraf V (eds). Cambridge University Press: New York, NY; 3–55.

Ashok K, Guan Z, Saji N, Yamagata T. 2010. Individual and combined influences of ENSO and the Indian Ocean dipole on the Indian summer monsoon. *J. Climate* **17**: 3141–3155.

Barnett TP, Pierce D, Saravanan R, Schneider N, Dommenget D, Latif M. 1999. Origins of the midlatitude Pacific decadal variability. *Geophys. Res. Lett.* **26**: 1453–1456, DOI: 10.1029/1999GL900278.

Buckley BM, Palakit K, Duangsathaporn K, Sanguantham P, Prasomsin P. 2007. Decadal scale droughts over northwestern Thailand over the past 450 years and links to the tropical Pacific. *Clim. Dyn.*, DOI: 10.1007/s00382-007-0225-1.

Buckley B, Sano M, Anchukaitis K, Nam L. 2010a. A millennial perspective on the climate of Southeast Asia from tree rings, First Asia 2 k Workshop, 26–28 August, Nagoya, Japan.

Buckley BM, Anchukaitis K, Cook E, Penny D, Sano M, Nam L, Hong T, Minh T. 2010b. Climate as a contributing factor in the demise of Angkor. *Proc. Natl. Acad. Sci. U. S. A.* **107**: 6748–6752.

Compo GP, Whitaker JS, Sardeshmukh PD, Matsui N, Allan RJ, Yin X, Gleason BE, Vose RS, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel RI, Grant AN, Groisman PY, Jones PD, Kruk MC, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Nordli Ø, Ross TF, Trigo RM, Wang XL, Woodruff SD, Worley SJ. 2011. The twentieth century reanalysis project. *Q. J. R. Meteorol. Soc.* **137**: 1–28, DOI: 10.1002/qj.776.

Cook E, Kairiukstis L. 1990. *Methods of Dendrochronology*. Kluwer: Dordrecht, the Netherlands.

Cook E, Anchukaitis K, Buckley B, D'Arrigo R, Jacoby G, Wright W. 2010. Asian monsoon failure and megadrought during the last millennium. *Science* **328**: 486–489, DOI: 10.1126/science.1185188.

Cook E, Palmer J, Ahmed M, Woodhouse C, Fenwick P, Zafar M, Wahab M, Khan N. 2013. Five centuries of upper Indus River flow from tree rings. *J. Hydrol.* **486**: 365–375.

D'Arrigo R, Wilson R. 2006. On the Asian expression of the PDO. *Int. J. Climatol.* **26**: 1607–1617.

D'Arrigo R, Villalba R, Wiles G. 2001. Tree-ring estimates of Pacific decadal climate variability. *Clim. Dyn.* **18**: 219–224.

D'Arrigo R, Palmer J, Ummenhofer C, Kyaw N, Krusic P. 2011. Three centuries of Myanmar monsoon climate variability inferred from teak tree rings. *Geophys. Res. Lett.* **38**: L24705, DOI: 10.1029/2011GL049927.

Dai A, Trenberth K, Qian T. 2004. A global data set of Palmer Drought Severity Index for 1870–2002: Relationship with soil moisture and effects of surface warming. *J. Hydrometeorol.* **5**: 1117–1130, DOI: 10.1175/JHM-386.1. •

AQ3

Deng W, Wei G, Xie L, Ke T, Wang Z, Zeng T, Liu Y. 2013. Variations in the Pacific Decadal Oscillation since 1853 in a coral record from the northern South China Sea. *J. Geophy. Res. Oceans*, DOI: 10.1002/jgrc.20180.

Folland C, Renwick J, Salinger M, Mullan A. 2002. Relative influences of the Interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone. *Geophys. Res. Lett.* **2**: 211–214, DOI: 10.1029/2001GL014201.

Friedman, J. 1984. A variable span smoother, Tech. Rep. LCS5, Department of 402 Statistics, Stanford University, Stanford, CA.

Fuchs T. and B. Rudolf. 2007. Global precipitation analysis products of the GPCC. Technical Report, Global Precipitation Climatology Centre (GPCC), Deutscher Wetterdienst, Offenbach a. M., Germany, 10 pp.

Goswami B, Krishnamurthy B, Annamalai H. 1999. A broad-scale circulation index for interannual variability of the Indian summer monsoon. *Q. J. R. Meteorol. Soc.* **125**: 611–633.

Grove C, Zinke J, Peeters F, Park W, Scheufen T, Kasper S, Randriamanantsoa B, McCulloch M, Brummer G. 2013. Madagascar corals reveal a multidecadal signature of rainfall and river runoff since 1708. *Clim. Past* **9**: 641–656.

Jacoby G, Solomina O, Frank D, Eremenko N, D'Arrigo R. 2004. Kunashir (Kuriles) oak 400-year reconstruction of temperature and relation to the Pacific Decadal Oscillation. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **209**: 303–311.

Krishnan R, Sugi M. 2003. Pacific Decadal oscillation and variability of the Indian summer monsoon rainfall. *Clim. Dyn.* **21**: 233–242.

Kumar K, Rajagopalan B, Cane M. 1999. On the weakening relationship between the Indian Monsoon and ENSO. *Science* **284**: 2156–2159.

Mann ME, Lees J. 1996. Robust estimation of background noise and signal detection in climatic time series. *Clim. Change* **33**: 409–445.

Mantua NJ, Hare S. 2002. The Pacific Decadal Oscillation. *J. Oceanogr.* **58**: 35–44.

Mantua N, Hare S, Zhang Y, Wallace J, Francis R. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. *Bull. Am. Meteorol. Soc.* **78**: 1069–1080.

Peterson T, Vose R. 1997. An overview of the Global Historical Climatology Network Temperature Database. *Bull. Am. Meteorol. Soc.* **78**: 2837–2849.

Rayner N, Parker D, Horton E, Folland C, Alexander L, Rowell D. 2003. Global analyses of SST, sea ice and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* **108**, DOI: 10.1029/2002JD002670.

Saji NH, Goswami B, Vinayachandran P, Yamagata T. 1999. A dipole mode in the tropical Indian Ocean. *Nature* **401**: 360–363.

Sano M, Buckley B, Sweda T. 2009. Tree-ring based hydroclimate reconstruction over northern Vietnam from *Fokienia hodginsii*: eighteenth century mega-drought and tropical Pacific influence. *Clim. Dyn.* **33**: 331–340, DOI: 10.1007/s00382-008-0454-y.

Sen Roy S. 2006. The impacts of ENSO, PDO, and local SSTs on winter precipitation in India. *Phys. Geogr.* **5**: 464–474.

Sen Roy, N., Kaur S. 2000. Climatology of monsoon rains of Myanmar (Burma), *Int. J. Climatol.*, **20**: 913–928, DOI:10.1002/1097, 0088(20000630)20:8913::AID-JOC485 -3.0.CO;2-U.

Sen Roy S, Sen Roy N. 2011. Influence of Pacific Decadal Oscillation and El Niño-Southern Oscillation on the summer monsoon precipitation in Myanmar. *Int. J. Climatol.* **31**: 14–21, DOI: 10.1002/joc.2065.

Shakun J, Shaman J. 2009. Tropical origins of north and south Pacific decadal variability. *Geophys. Res. Lett.* **36**: L19711, DOI: 10.1029/2009GL040313.

Shen C, Wang W, Gong W, Hao Z. 2006. A Pacific Decadal Oscillation record since 1470 AD reconstructed from proxy data of summer rainfall over eastern China. *Geophys. Res. Lett.* **33**, DOI: 10.1029/2005GL024804.

Shi G, Ribbe J, Cai W, Cowan T. 2007. Multidecadal variability in the transmission of ENSO signals to the Indian Ocean. *Geophys. Res. Lett.* **34**: L09706, DOI: 10.1029/2007GL029528.

Ummenhofer CC, D'Arrigo R, Anchukaitis K, Buckley B, Cook E. 2013a. Links between Indo-Pacific variability and drought in monsoon Asia in the MADA. *Clim. Dyn.* **40**: 1319–1334.

Ummenhofer CC, Schwarzkopf F, Meyers G, Behrens E, Biastoch A, Böning C. 2013b. Pacific Ocean contribution to the asymmetry in Eastern Indian Ocean variability. *J. Clim.* **26**: 1152–1171.

Vautard R, Ghil M. 1989. Singular spectrum analysis in nonlinear dynamics, with applications to paleoclimatic time series. *Physica D* **35D**: 395–424.

Wang B, Fan Z. 1999. Choice of south Asian summer monsoon indices. *Bull. Am. Meteorol. Soc.* **80**: 629–638.



Wang S-Y, Gillies R. 2012. Influence of the Pacific quasi-decadal oscillation on the monsoon precipitation in Nepal. *Clim. Dyn.* **40**: 95–107, DOI: 10.1007/s00382-012-1376-2.

Wang B, Wu Z, Liu J, Chang C-P, Ding Y, Wu G. 2008. How to measure the strength of the East Asian summer monsoon. *J. Clim.* **21**: 4449–4463.

Wheeler D. 2011. Quantifying vulnerability to climate change: implications for adaptation assistance. Working Paper 240, January 2011, Center for Global Development.

Williams B, Grottoli A. 2010. Recent shoaling of the nutricline and thermocline in the western tropical Pacific. *Geophys. Res. Lett.* **37**: L22601, DOI: 10.1029/2010GL044867.

Wilson R, Wiles G, D'Arrigo R, Zweck C. 2007. Cycles and shifts: 1300 years of multi-decadal temperature variability in the Gulf of Alaska. *Clim. Dyn.* **28**: 425–440, DOI: 10.1007/s00382-006-0194-9.

Xu H, Hong Y, Hong B. 2012. Decreasing Indian summer monsoon intensity after 1860 AD in the global warming epoch. *Clim. Dyn.* **39**: 2079–2088.



**QUERIES TO BE ANSWERED BY AUTHOR**

**IMPORTANT NOTE: Please mark your corrections and answers to these queries directly onto the proof at the relevant place. DO NOT mark your corrections on this query sheet.**

**Queries from the Copyeditor:**

**AQ1.** Please provide keywords.

**AQ2.** "Meehl and Hu 2006" is cited in text but not given in the reference list. Please provide details in the list or delete the citation from the text.

**AQ3.** Reference "Dai et al. (2004)" has not been cited in the text. Please indicate where it should be cited; or delete from the reference list.

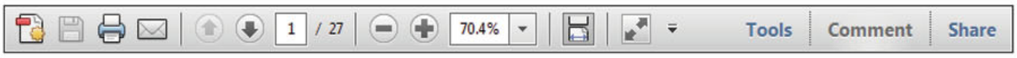
**AQ4.** These figure(s) 1–3 has been supplied in color. There is a charge to print the figure(s) in color, however figure(s) will be published in color online free of cost. The first color printed page will be £250 and each color printed page thereafter will be £150 (per page). Please confirm if this figure is to be reproduced in (a) color in print, (b) color online only if suitable (at no charge to author) or (c) black and white in both cases (please provide new figure). Color will be invoiced when the article is published in print. For the options (b) and (c), could you kindly identify and make any necessary text amendments that may need to be made in the caption or text with regard to this change.

**WILEY-BLACKWELL**

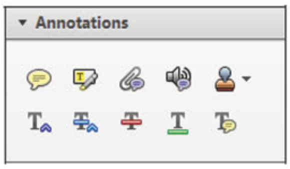
## USING e-ANNOTATION TOOLS FOR ELECTRONIC PROOF CORRECTION

**Required software to e-Annotate PDFs: Adobe Acrobat Professional or Adobe Reader (version 7.0 or above). (Note that this document uses screenshots from Adobe Reader X)**
**The latest version of Acrobat Reader can be downloaded for free at: http://get.adobe.com/uk/reader/**

Once you have Acrobat Reader open on your computer, click on the Comment tab at the right of the toolbar:




This will open up a panel down the right side of the document. The majority of tools you will use for annotating your proof will be in the Annotations section, pictured opposite. We've picked out some of these tools below:

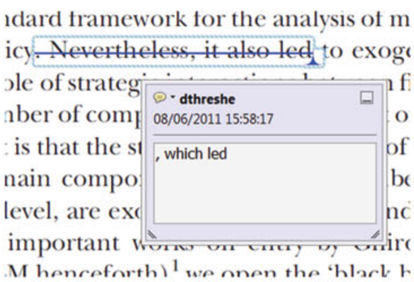



**1. Replace (Ins) Tool – for replacing text.**

Strikes a line through text and opens up a text box where replacement text can be entered.

**How to use it**

- Highlight a word or sentence.
- Click on the Replace (Ins) icon in the Annotations section.
- Type the replacement text into the blue box that appears.

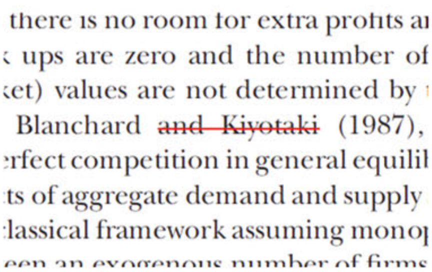



**2. Strikethrough (Del) Tool – for deleting text.**

Strikes a red line through text that is to be deleted.

**How to use it**

- Highlight a word or sentence.
- Click on the Strikethrough (Del) icon in the Annotations section.

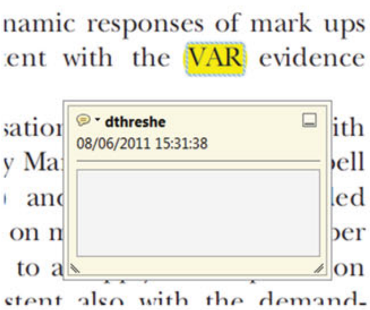


**3. Add note to text Tool – for highlighting a section to be changed to bold or italic.**

Highlights text in yellow and opens up a text box where comments can be entered.

**How to use it**

- Highlight the relevant section of text.
- Click on the Add note to text icon in the Annotations section.
- Type instruction on what should be changed regarding the text into the yellow box that appears.

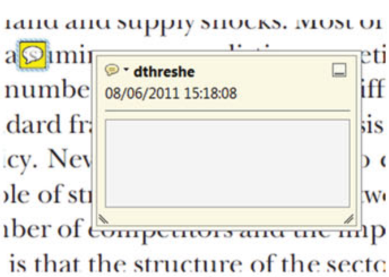



**4. Add sticky note Tool – for making notes at specific points in the text.**

Marks a point in the proof where a comment needs to be highlighted.

**How to use it**

- Click on the Add sticky note icon in the Annotations section.
- Click at the point in the proof where the comment should be inserted.
- Type the comment into the yellow box that appears.



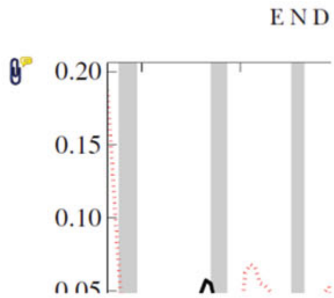
## USING e-ANNOTATION TOOLS FOR ELECTRONIC PROOF CORRECTION

**5. Attach File Tool – for inserting large amounts of text or replacement figures.**

Inserts an icon linking to the attached file in the appropriate pace in the text.

**How to use it**

- Click on the Attach File icon in the Annotations section.
- Click on the proof to where you'd like the attached file to be linked.
- Select the file to be attached from your computer or network.
- Select the colour and type of icon that will appear in the proof. Click OK.

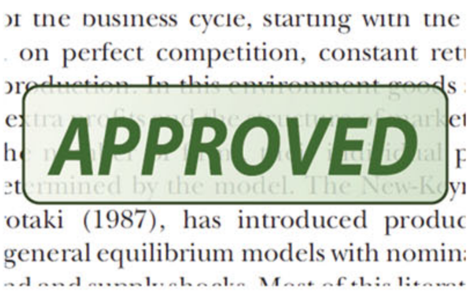


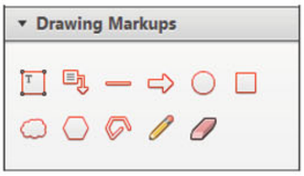

**6. Add stamp Tool – for approving a proof if no corrections are required.**

Inserts a selected stamp onto an appropriate place in the proof.

**How to use it**

- Click on the Add stamp icon in the Annotations section.
- Select the stamp you want to use. (The Approved stamp is usually available directly in the menu that appears).
- Click on the proof where you'd like the stamp to appear. (Where a proof is to be approved as it is, this would normally be on the first page).



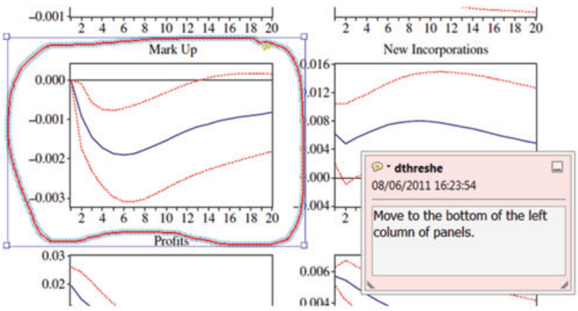




**7. Drawing Markups Tools – for drawing shapes, lines and freeform annotations on proofs and commenting on these marks.**

Allows shapes, lines and freeform annotations to be drawn on proofs and for comment to be made on these marks..

**How to use it**

- Click on one of the shapes in the Drawing Markups section.
- Click on the proof at the relevant point and draw the selected shape with the cursor.
- To add a comment to the drawn shape, move the cursor over the shape until an arrowhead appears.
- Double click on the shape and type any text in the red box that appears.




**For further information on how to annotate proofs, click on the Help menu to reveal a list of further options:**