This paper analyses climate simulation results from a complex Earth system model to understand the influence of obliquity on low-latitude (thus tropical) climate. In detail, it is a more extensive (global) analysis of simulation results which are already described elsewhere, where previously the focus was more local (Africa, Mediterranean).

I found the described idea interesting. Thus, in principle this paper should be published in Climate of the Past. However, I believe some more details need to be shown and discussed before the idea is really convincing and supported by the paper. Thus, I have concerns about three major issues, (a) on the originality of the proposed idea, (b) on what the experiment is really telling us and (c) on a missing wider discussion.

(a) Originality of the proposed idea:
Right now the paper cites as original source of the Summer Inter Tropical Insolation Gradient (SITIG) hypothesis a paper by Lourens and Reichart (1996). It turns out that this is one chapter out of the PhD thesis of G.J. Reichart, which never made it in the peer-reviewed literature. While L. Lourens is coauthor of the present paper here, G.J. Reichart is not. Furthermore, from the given citation it was not possible to figure out who the overall author of the PhD thesis was. I found this proceeding questionable. Since this chapter by Lourens and Reichart (1996) was never published in peer-reviewed journals (for reasons we do not know), it needs to be considered unpublished. It is similar to a paper submitted to Climate of the Past Discussion, that is rejected: The paper is available online in submitted, but not in peer-reviewed form. I urgently suggest, this is not a reference, that should be used here. If any it might be mentioned in the discussion that some ideas on SITIG were proposed in the whole PhD thesis of GJ Reichart (then citing Reichart 1996, PhD thesis, not a single chapter). So one needs to acknowledge that the origin for any kind of low-latitude index on climate was the monsoon index proposed first by Rossignol-Strick (1983) (not cited by the authors, the authors cite another, later paper of this author). It was later changed to something similar as proposed here by Leuschner and Sirocko 2003. It might be worth investigating, which of the ideas is better, e.g. by revising Fig 6 and also including the other 2 indices here.

Author response:
Indeed the reference to Lourens and Reichart (1996) refers to a chapter on low latitude forcing of glacial cycles, which is part of the PhD thesis of G.J. Reichart. This thesis is available through the National Academic Research and Collaborations Information System: http://www.narcis.nl/publication/RecordID/oai%3A. We will make the citation clearer.

We will adapt part of our introduction (lines 23 p223 - 18 p224) and include a reference to Rossignol-Strick 1983 (indeed the first paper to mention the monsoon index), as well as remove the reference to the Reichart PhD thesis. The latter will be mentioned in the discussion. Furthermore we will refer to the paper of Mantzis et al 2014 (The response of large-scale circulation to obliquity-induced changes in meridional heating gradients, Journal of Climate). They discuss the effect of inter- and intra-hemispheric insolation gradients on the physics governing meridional overturning circulation such as the Hadley cell and ITCZ. They explain the main "SITIG" idea in their figure 11 and also show a stronger winter hemisphere Hadley cell during high obliquity. Our study adds more detail on moisture transport and precipitation as well as a link to the interpretation of proxy records.

The idea to incorporate the monsoon index of Rossignol-Strick (RS83) and that of Leuschner and Sirocko (LS03) into figure 6 (now figure 1) will be taken up, as it should provide a base on which to discuss and compare all the mechanisms proposed in these studies. The monsoon index of LS03 is very similar to SITIG, with a slight lag as the previous is defined using insolation on August 1st, while SITIG is based on June 21st. The power spectra of both show a peak both at precession and obliquity but the obliquity peak is much larger in the relative sense than it is in the monsoon index of RS83. The latter already has a stronger obliquity peak than insolation at a single latitude (23N, 65N) but by looking at the insolation difference between the tropics (SITIG, LS03) instead of the difference...
between the equator and a tropic (RS83) the influence of obliquity is stronger. Therefore SITIG (or LS03) shows a better match to for instance the sapropel record. In order to illustrate this, we've included sapropels (from core RC9-181, used by both Lourens & Reichart '96 and Rossignol '85) in the figure. Comparison to this record shows that insolation differences such as SITIG or ISMI (Indian Summer Monsoon Index, LS03) are a better match than 23N insolation or M (RS83).

Furthermore, it should be noted that the monsoon index M of RS83 is based on caloric half-year insolation, while SITIG is based on 21June (peak) insolation. Including insolation over a longer period such as RS83 introduces more obliquity variance - recreating M using 21June insolation has a smaller obliquity signal. This also indicates that SITIG is a better candidate to explain the orbital cyclicity in proxy records than M. Furthermore, the cross-equatorial moisture transport we see in our model results match better with the SITIG hypothesis than with M, as the latter only considers the gradient between the equator and the (northern) tropic. The importance of moisture transport in for instance the North African monsoon has been shown in Bosmans et al 2015 (Climate Dynamics). These points will be taken up in the discussion.

(b) What is the experiment really telling us:
Right now it is argued that with eccentricity switch off, and analysing the effects of changes in Earths tilt from minimum to maximum with an Earth system model without land ice it is analysed what the response of the low latitudes climate to these respective insolation changes is. I think this approach needs more evidence and information for the following reasons: The effect of land ice sheets on climate is (at least) twofold: First, higher surface albedo changes the radiative balance, second the height of the ice sheet changes in the atmospheric circulation and thus climate. The later was recently shown to be potentially the reason for abrupt climate change (Zhang et al., 2014), and this surely played no role here (no ice sheets in the model). The first however, still needs to be shown. Thus, the authors should analyse the difference in surface albedo in high latitudes. Maybe winter snow is not melting anymore in summer (probably not building an ice sheet, because of the short simulation time, and because the model might not be able to do so), thus having a similar effect on the radiative balance than an ice sheet. So in a first step, at least the albedo changes need to be described. If it turns out that albedo changes were still high (which I would suggest they are) it might be necessary to think about an additional simulation experiment, in which high latitude surface albedo is fixed in order to stick to the bold statements that high-latitude changes are not important for tropical climate change on obliquity time scales. It is up to the authors to decide here how to deal with sea ice.

Author's response:
Indeed we acknowledge that there is a strong effect of (land and sea) ice on climate. Here we investigate the effect of obliquity without changes in land ice, as multiple proxy studies have suggested that obliquity affects (tropical) climate at times without ice ages or with a lag that is too short to be explained by glacial cycles (see for instance lines 4-22, p223). Possible effects of obliquity including land ice changes are discussed in the Discussion section (mainly 4.3). In this part we will further clarify that the effect of obliquity is not only simply a change in the insolation gradient, but that this change may be intensified by albedo changes. Figure 2 (below) gives the albedo changes between the two obliquity experiments. As expected, albedo is reduced in polar areas where sea ice is reduced due to increased (summer) insolation during Tmax. This may indeed affect the meridional temperature gradient, which we will mention in the Discussion.

Of course ideally more experiments can be done with fixing albedo (or even insolation) at higher latitudes, but this is currently not feasible with the model. Also, it is not our aim to state that high-latitude changes are not important for tropical climate changes on obliquity time scales, our aim is to show that such climate changes can exist without high-latitude changes. In Section 4.3 we acknowledge that further research, for instance including ice sheets, is necessary to get a grip on the overall impact of obliquity on (meridional) temperature gradients and climate.

Furthermore, to be able to assess the impact of the chosen simulation scenarios a figure showing incoming radiation (insolation) as function of latitude and season (month) for both scenarios Tmax and Tmin and the difference of both is needed. All analysis (figures) are restricted to the latitudinal
band between 50°N and 50°S. Thus, it is impossible to judge, if changes in the high latitudes occur and potentially have an effect on tropical climate. I therefore suggest to change the figures to show results from 90°N to 90°S.

Author's response:
We will include a figure of the insolation changes per latitude and month. We previously left this out as this figure is given in other papers already, but for completeness we will include it in the re-submitted version.
We chose to show figures of 50N-50S as our focus is on the tropics. Showing global results would also distract from our main point and make the figures overall smaller.

(c) Missing wider discussion:
So far, it is proposed that the SITIG hypothesis is for the tropical regions an alternative to the Milankovitch hypothesis, which proposed that summer insolation changes at 65°N is responsible for climate change on orbital time scales. They furthermore mention that a similar idea to that of SITIG was proposed by Leuschner and Sirocko (2003) and some other ideas about monsoon strength. However, what I believe is missing here is how this idea is related to / or different from that of Laepple and Lohmann (2009), in which the local seasonal cycle in insolation and temperature are related. Laepple and Lohmann (2009) nicely show, that local insolation might be more important to local climate change on orbital time scales than the concept of explaining everything with incoming light in summer at 65°N. This idea seemed at least to be applicable to Antarctica (Laepple et al., 2011), but for the tropics the analysis are more diverse and less significant in Laepple and Lohmann (2009). So some comparisons and discussions are necessary here. There are other hypothesis on the obliquity forcing mainly on the idea how and why high-latitude ice sheets change, (e.g. integrated summer insolation by Huybers and Tziperman (2008)), so they might not be important here.

Author's response:
The study of Laepple and Lohmann (2009) applies the relationship between present-day temperature and insolation to the past, which gives overall a good indication of temperature changes in the past. Their conclusion that local insolation might be more important to local climate than 65°N insolation is similar to ours, but our study focusses on more than temperature and local insolation. We focus on changes in for instance precipitation or moisture transport through the interhemispheric insolation gradient that can help explain obliquity signals in for instance the sapropels. Furthermore, applying the relationship between present-day temperature and insolation to the Milankovitch cycles would result in a very weak obliquity signal in temperature over the tropics, as insolation over the tropics has very little obliquity variance (see Figure 6 of submitted paper, Figure 1 below). It can therefore not explain the obliquity patterns in low-latitude proxy records. The effect of obliquity on (local) polar climate and ice sheets is beyond the scope of our study - however there is a brief discussion of the effect of obliquity-induced changes in the intra-hemispheric insolation gradients on poleward heat and moisture transport in Section 4.3. Therefore we do not include the references to Leapple et al 2011 or Huybers and Tziperman 2008 (the latter discusses precession).

Minors:
• First cited figure is figure 6, so this should become figure 1.
This is indeed changed: figure 6 (now with more insolation indeces) becomes Figure 1.
• I found the acronym Tmin and Tmax for scenarios with low and high obliquity rather confusing. Typically in climate science T is the temperature. So I would suggest to use a different variable for obliquity. However, I also realized that in other papers of the same authors analysing the same simulations these acronyms were already introduced, so I have little hope here. The reviewer is correct that T is often for temperature, but since we already used T for tilt in previous studies (also those of Tuenter, 2003) we keep this acronym for comparability.
• Citation Bosmans et al 2014 in Climate Dynamics was published in 2015.
Indeed this is updated (it was accepted in 2014 but the actual article number etc was only given recently)
• Citation Leuschner and Siroko 2003 has an incomplete journal name. This will be corrected in the reference list of the revised paper.
• Please give a link to PhD thesis of GJ Reichart 1996 (available online at Utrecht University) and correct the citation Lourens and Reichart 1996 to Reichart 1996 (PhD thesis), if still cited in the discussion. The link is http://www.narcis.nl/publication/RecordID/oai%3Adspace.library.uu.nl%3A1874%2F274419/genre/d octoralthesis/uquery/Reichart/id/2/Language/NL. We will update the citation.
• Fig 6: Please use the same scaling for both left and right y-axis (both give insolation or insolation change in W m\(^{-2}\)) in subfigure 6a. Now left shows 140, right 100 W m\(^{-2}\), exaggerating the influence of SITIG. Please show curves in different colors in both subfigures. Include results for the other two hypothesis (monsoon index, index calculated by Leuschner and Sirocko 2003). We initially chose to plot different y-axis to compare the insolation patterns and amplitudes more easily (magnitudes vary so 1 y-axis would make the curves less easy to compare). However we have now changed the figure to include more indeces, each with its own y-axis.

References
Rossignol-Strick, M. (1983), AFRICAN MONSOONS, AN IMMEDIATE CLIMATE RESPONSE TO ORBITAL INSOLATION, NATURE, 304(5921), 46–49, doi:10.1038/304046a0.
Figure 1a. Insolation over the past 500 kyr. From top to bottom: insolation at 23N on June 21st (black), insolation at 65N on June 21st (red), monsoon index M (Rossignol-Strick 1983) on June 21st (blue), monsoon index M for the caloric summer half year (green), SITIG on June 21st (light blue) and ISMI (Leuschner and Sirocko, 2003) on August 1st (pink). The lowest part shows sapropels in marine core RC9-181 (Vergnaud-Grazzini, 1977, Rossignol-Strick 1985).
Figure 1b. Power spectra of the insolation curves shown in Figure 1a. The overall amplitude of SITIG and LS03 is smaller as they represent an insolation difference, but they have the largest (relative) obliquity peak.

Figure 1c, same as 1b but normalized (each curve is normalized by its peak power at ~0.045/kyr)
Figure 2: Difference in annual mean albedo between Tmax and Tmin. Overall, albedo is lower in polar regions where sea ice is reduced due to higher (summer) insolation during Tmax.
The authors performed two model experiments of obliquity extremes with the climate model EC-Earth. The results show a statistically significant climate response in the tropics. From analyzing the climate response and tropical circulation changes, they argue that the changes are caused by the changes in the cross-equatorial insolation gradient and propose that this gradient may be used to explain obliquity signals in tropical paleoclimate records.

The manuscript shows that even without considering ice-sheets, changing the obliquity results in changes in low-latitude climate. However, the mechanisms of these changes and the relevance of the simulated changes remain unclear. Thus I find the scientific value of the manuscript in its present version somehow limited and recommend major revisions.

My major concerns are the following:

Do the model experiments really prove that the orbital influence is via a low-latitude mechanism? From the presented results, the mechanism of the climate changes is unclear. The response could be caused locally caused or via teleconnections from the high latitudes etc. In principle a climate model could be used to determine this by e.g. running an experiment with changing only insolation in the tropics or in certain latitude bands but with the two simulations performed in this study, this is hard to tell. The conclusion that the simulations “suggest that these patterns arise from a direct response to changes in the cross-equatorial insolation gradient” is thus not well supported by the presented evidence.

Author's response:
Our aim is to show that obliquity-induced climate changes can occur without a lag on the orbital time scale and without any (land) ice changes. The changes that we see fit well with the SITIG hypothesis, better than with other ideas (i.e. we find no enhanced moisture transport from extratropical regions, see for instance figure 2a-d). We will change the line mentioned to "suggest that these patterns may arise..." as indeed an experiment with insolation changes only over the tropics would be needed to solidify this suggestion. Unfortunately this is not (yet) possible with the model (see also response to reviewer 1). We will suggest such an experiment in our Discussion. We will also add references stating that the present-day monsoon strength depends on the strength of the (winter hemisphere) Hadley cell (Lourens & Reichart 1996), also described as differential heating between for instance the Asian continent and the southern subtropical Indian Ocean (e.g. Clemens et al, 1996). This would strengthen the suggestion that such inter-hemispheric gradients drive monsoon strength on Milankovitch timescales as well.

Is the amplitude of the simulated changes relevant?
The relevance of the amplitude of the changes is unclear as no reference is given. Maybe changing the precession parameters would give an even stronger change (thus the problem of a stronger obliquity than precession signal would still be unsolved), or including an ice-sheet would lead to an obliquity caused climate change which is much stronger than the response found in this experiment?
Is the amplitude of the change found in the experiments relevant for proxy records? Maybe showing relative changes would help (e.g. relative precip and wind changes relative to the absolute precip amount / windspeed).

Author's response:
Concerning the amplitude of changes: it is true that the (seasonal) insolation amplitude introduced by precession is greater at the tropics, as expressed in the beginning of our introduction (lines 16-19, p 222). This is also observed in proxy records. The problem that we try to acknowledge in the beginning of our introduction is that while the precession signal in (tropical) proxy records is rather easily explained by the insolation at low latitudes, the obliquity signal is not. The latter does not show up in power spectra of tropical (summer) insolation.
Including an ice-sheet might indeed enhance the response to obliquity changes through an altered meridional temperature gradient (and thus poleward transport of heat and moisture), as discussed in the second part of Section 4.3 (see also response to reviewer 1). However such a response would be slower due to the slow response of ice sheets. The obliquity-induced changes are relative at the 95% (using a two-sided student t-test), but the relative changes were indeed not mentioned. We have checked the relative changes in precipitation and wind speed, which are given below (figures 1 and 2). Both precipitation and wind speed can change up to, and over, 100% in both summer and winter as well as in the annual mean. This will be mentioned in the revised version (and if required by the editor / reviewer these figures could be shown as supplementary material).

Detailed comments:
Introduction, page 222:
In the introduction about insolation is missing a discussion about the seasonality of the insolation: Precession results in strong changes when looking at single seasons (or single days) but has no effect on annual mean insolation. Obliquity in contrast is the only parameter having a significant influence on the annual mean. Therefore, it is well possible that a 100W/m² insolation anomaly only acting seasonally (and thus resetting every year) has a smaller influence than a 2W/m² annual mean change, which persists over thousands of years. Thus I’m not very surprised that some records, even in the tropics, only show obliquity.

Author's response:
Indeed precession and obliquity differ in their effect on annual mean insolation. We will mention this in the introduction. The annual-mean effect of obliquity has been used to explain climate changes through the intrahemispheric insolation (and temperature) gradient. However, some of the proxy records that show obliquity signals in the tropics capture a monsoon signal. Monsoonal precipitation falls mainly in summer so records showing obliquity in monsoonal precipitation must somehow be affected by summer insolation. The SITIG hypothesis presented in our study provides an explanation. Also, annual mean changes show a temperature drop and weaker circulation over the tropics during maximum obliquity, which cannot explain the enhanced precipitation. Furthermore the precession signal may result in annual mean temperature and precipitation changes because of feedbacks within the climate system or one season being more sensitive to insolation changes (Bosmans et al 2012, 2015 or Herold and Lohmann 2009).

Figures:
Figure quality is relatively poor and at least in my printouts it is hard to identify the axes labels. Please adapt the line thickness and size of axis annotations.
In Figure 6, it has to be clearly stated that these are all summer insolation values (June 21?). Maybe it would be useful to also show the spectra of annual mean insolation, which would give a completely different result.

Author's response:
When seen on A4 the figures look better; they appear smaller in CPD printouts.
Figure 6 indeed shows 21 June insolation values, which will be clarified. A new figure is now included (see comments to reviewer 1). Annual mean insolation would indeed show an obliquity peak and not a precession peak. Although this has been used to explain obliquity signals elsewhere (such as in glacial records, see Section 4.3), annual mean insolation cannot explain the full Milankovitch spectra found in (tropical) records (see remarks above). SITIG shows both a precession and obliquity peak, which fits nicely with for instance the sapropel record.
Figure 1a: relative change in summer (JJA) precipitation, percentage \(((\text{Tmax}-\text{Tmin})*100)/\text{Tmin}\).

Figure 1b: relative change in winter (DJF) precipitation, percentage

Figure 1c: relative changes in annual mean precipitation, percentage
Figure 2a: relative changes in wind speed in summer (JJA), percentage

Figure 2b: relative changes in wind speed in winter (DJF), percentage

Figure 2c: relative changes in annual mean wind speed, percentage
Obliquity forcing of low-latitude climate

J.H.C. Bosmans¹,²,*, F.J. Hilgen¹, E. Tuenter¹,²,*, and L.J. Lourens¹

¹Faculty of Geosciences, Utrecht University, the Netherlands
²Royal Netherlands Meteorological Institute (KNMI), the Netherlands
*J. Bosmans is now working exclusively at Utrecht University, E. Tuenter at KNMI

Correspondence to: J.H.C. Bosmans (J.H.C.Bosmans@UU.nl)

Abstract. The influence of obliquity, the tilt of the Earth’s rotational axis, on incoming solar radiation at low latitudes is small, yet many tropical and subtropical paleoclimate records reveal a clear obliquity signal. Several mechanisms have been proposed to explain this signal, such as the remote influence of high-latitude glacials, the remote effect of insolation changes at mid- to high latitudes independent of glacial cyclicity, shifts in the latitudinal extent of the tropics, and changes in latitudinal insolation gradients. Using a sophisticated coupled ocean-atmosphere global climate model, EC-Earth, without dynamical ice sheets, we performed two idealized experiments of obliquity extremes. Our results show that obliquity-induced changes in tropical climate can occur without high-latitude ice sheet fluctuations. Furthermore, the tropical circulation changes are consistent with obliquity-induced changes in the cross-equatorial insolation gradient, implying suggesting that this gradient may be used to explain obliquity signals in low-latitude paleoclimate records instead of the classic 65°N summer insolation curve.

1 Introduction

The influence of obliquity (axial tilt) on low-latitude insolation is very small; the difference over tropical latitudes between high and low obliquity is less than 10 W/m² in the summer or winter season, whereas precession-induced insolation changes reach (Figure 1). Precession induces much larger changes in seasonal insolation, up to 100 W/m² (Tuenter et al., 2003; Bosmans et al., 2015a). A power spectrum of Therefore, a times series of (summer) insolation at the tropics (23°N, roughly the Tropic of Cancer) shows a peak at reveals the periodicity of precession (~23 kyr), but not obliquity the periodicity obliquity is almost absent (~41 kyr) whereas insolation at 65°N shows a much larger influence of obliquity (Figure 2). The 65°N insolation curve also correlates better (see black
line at the top of Figure 2 and power spectra in Figure 3. Hence low-latitude insolation changes do
not correlate well with low-latitude paleoclimate records, such as the Mediterranean sapropels, than
cross to low-latitude paleoclimate records is with 65°N summer insolation, which has a stronger obliquity
signal than 23°N summer insolation (see red line in Figures 2 and 3). Many studies have therefore
attributed the relatively strong obliquity signal in low-latitude paleoclimate records to high-latitude
mechanisms. For instance, dust flux records from both the (sub-) tropical Atlantic and Arabian Sea
concur with obliquity-paced global climate cycles, suggesting a close link between changes in low-
latitude aridity and glacial variability (Bloemendal and deMenocal 1989; deMenocal et al. 1993
Tiedemann et al. 1994; deMenocal 1995). Several other proxy studies, however, find low-latitude
obliquity signals at times when glacial cycles were much smaller or even absent (Lourens et al. 1996
2001; Hilgen et al. 1995 2000; Sierro et al. 2000). In particular, obliquity-controlled interference
patterns in Mediterranean sapropels are not only present in the Pleistocene (Lourens et al. 1996), but
Sapropels are generally thought to be related to African monsoon strength through runoff from
African rivers into the Mediterranean (Rossignol-Strick 1983, 1985; Rossignol-Strick 1983, 1985), which
would indicate that monsoon intensity is affected by obliquity both before and after major Northern
Hemisphere (NH) glacial cycles determined global climate. Furthermore, in the late Pliocene and
Pleistocene, phase relations suggest that the obliquity influence on sapropel formation and North-
African aridity did not proceed indirectly via ice driven responses but more directly via summer
insolation (Lourens et al. 1996 2010). In addition, color changes associated with carbonate dilution
cycles in north-western Africa and Spain reveal precession-obliquity interference patterns similar
to those found in Mediterranean sapropels (Hilgen et al. 2000; Sierro et al. 2000). Also, others
have ruled out global ice volume as a primary forcing mechanism for the occurrence of obliquity-
related variability in Indian monsoon strength as inferred from sediment records of the Arabian Sea
(Clemens et al. 1991; Clemens and Prell 2003).

Hence the North-African and Indian monsoons may respond to obliquity independent of high-
latitude ice growth and decay. The driving mechanism of obliquity-induced climate change over
the tropics is yet poorly understood, since the influence of obliquity on low-latitude insolation
is small. Some studies have suggested that the obliquity signal in the tropics is related to a local
forcing mechanism. Rossignol-Strick (1983) introduced a monsoon index (M) based on the summer insolation difference between the tropic of Cancer and the equator,
recognising that the North-African monsoon depends on the strength of the Saharan heat trough
as well as on the pressure gradient between the heat trough and the equator (M, green line in Figures 2 and 3). The summer insolation difference between these two latitudes introduces an
obliquity signal, though too small to explain the characteristic obliquity interference patterns in the
Mediterranean sapropels (Lourens and Reichart, 1996) therefore introduced over the past 14 million years (Lourens et al., 1996; Hilgen et al., 1995; Zedden et al., 2014). Later, cross-equatorial (inter-hemispheric) insolation gradients have been introduced (e.g., Reichart, 1996; Leuschner and Sirocko, 2003), which acknowledge the role of cross-equatorial moisture transport (as part of the winter hemisphere Hadley cell) in monsoon strength both at present and on orbital time scales (e.g., Clemens et al., 1996; Mantsis et al., 2014; Bosmans et al., 2015). Here we focus on the Summer Inter Tropical Insolation Gradient (SITIG), $I_{23^\circ N} - I_{23^\circ S}$ at June 21st (Figure 2). Light blue line in Figures 2 and 3, which shows a better fit to the sapropel record. This gradient is based on the interhemispheric pressure gradient between the two limbs of the winter hemisphere Hadley cell, which drives monsoon winds into the summer hemisphere. At times of high obliquity, the insolation gradient over the tropics (SITIG) is stronger than during low obliquity. This also holds for SITIG in austral summer ($I_{23^\circ S} - I_{23^\circ N}$ at December 21st). A strong SITIG may result in than insolation at $23^\circ N$ or monsoon index M. A stronger inter-hemispheric insolation contrast drives a stronger (winter) Hadley circulation (Mantsis et al., 2014) and thus a stronger cross-equatorial winds and moisture transport into the summer hemisphere, associated with an intensified winter Hadley cell (Lourens and Reichart, 1996). SITIG. Inter-hemispheric insolation gradients can therefore explain the obliquity signal in the sapropels (through monsoonal runoff) as well as the Indian ocean proxy records without high-latitude mechanisms. The insolation curves and insolation gradients are discussed in more detail in Section 3.1. We note that obliquity may also affect climate through other insolation gradients (e.g., Lourens and Reichart, 1996; Leuschner and Sirocko, 2003; Raymo and Nisancioglu, 2003; Antico et al., 2010; Mantsis, 2011), which will be considered in the Discussion (Section 4).

Modelling results previously suggested that the influence of obliquity on the tropics resulted from high latitude forcing, i.e., consistent with the application of the $65^\circ N$ insolation curve. According to Tuenter et al. (2003), an increase in obliquity results in higher temperature and humidity at high latitudes. The resulting strengthening of southward moisture transport as well as a stronger Asian low pressure system act to strengthen the monsoons. This remote control (north of $30^\circ N$) accounts for 80-90% of the total obliquity signal in the North-African monsoon, without any changes in land ice (Tuenter et al., 2003). The model they used is EC-Bilt (Opsteegh et al., 1998), a quasi-geostrophic climate model of intermediate complexity. Due to simplifications in model physics as well as low resolution one can question its suitability for modelling tropical climate. Bosmans et al. (2015a) showed, using a state-of-the-art high resolution fully coupled ocean-atmosphere model, EC-Earth, that mechanisms behind the orbital forcing of the North-African monsoon are very different than previously established from the EC-Bilt model. From EC-Earth it emerged that while the effect of precession was larger, a clear obliquity signal appeared in the monsoon as well without high-latitude influences.

In this study we use the EC-Earth model to investigate the influence of obliquity signal on the entire tropics, without land ice changes. Specifically, we investigate whether our results are in line with the SITIG mechanism. The model and experimental set-up are described in Section 2. The
results in Section 3 describe insolation curves that are used in paleoclimate literature and describes the SITIG mechanism in greater detail. Section 3.2 describe EC-Earth model results such changes in atmospheric circulation that can help explain paleoclimate records, which usually reflect changes in precipitation (for example dust records or the sapropels) and/or wind (such as Arabian Sea records). The results are followed a discussion in Section 4 and a conclusion in Section 5. Figures of model results show the difference between high and low obliquity.

2 Model and experimental set-up

Here we use the new, state-of-the-art high resolution fully coupled ocean-atmosphere model, EC-Earth, to investigate influence of obliquity signal on the tropics. EC-Earth is used for the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Hazeleger et al. 2011) and was also used to perform the pre-industrial and Mid-Holocene experiments of the Paleoclimate Modelling Intercomparison Project (Bosmans et al. 2012). Following Tuenter et al. (2003), we performed two idealized obliquity experiments, one with a low obliquity (22.04°, Tmin) and one with a high obliquity (24.45°, Tmax). Eccentricity is set to zero, so the Earth’s orbit is perfectly round and there is no influence of precession. All other boundary conditions are fixed at pre-industrial levels, therefore there are no changes in land ice or in vegetation. The experiments were run for 100 years each, which is sufficient for atmospheric and surface variables, including sea surface temperature, to equilibrate to the insolation forcing. For more details see Bosmans et al. (2015a), where the same obliquity experiments are used to investigate the North African monsoon.

3 Results

3.1 Insolation curves

Obliquity-induced changes in insolation are shown in Figure 1. When obliquity is high (Tmax), insolation on the summer hemisphere is increased, especially near the poles. At the tropics, insolation changes are small. Therefore, time series of summer insolation at low latitudes (say 23°N, black line in Figures 2, 3) hardly shows variability on the ~41kyr timescale of obliquity, whereas 65°N summer insolation has a relatively strong obliquity signal (red line in Figures 2, 3). The latter therefore matches better with the sapropel record (sapropels from core RC9-181, as used by e.g. Rossignol-Strick 1983, 1985) are shown at the bottom of Figure 2. Although insolation peaks (precession minima) at 23°N match the occurrence of sapropels, 23°N summer insolation cannot explain the thick-thin alternations in the sapropel record related to obliquity (e.g. Lourens et al. 1996). 65°N shows a better match, for instance with thinner sapropels S4 and S7 matching lower insolation peaks.
The monsoon index (M) of Rosignol-Strick [1983] is given by $2^*I_{23^\circ N}-I_{10^\circ N}$ for the caloric summer half year (green line in Figure 2). By introducing the insolation difference between the northern tropic ($\sim 23^\circ N$) and the equator, an obliquity signal is present in M (Figure 3). Here we also show the monsoon index M for June 21st instead of the summer half year (dark blue line), in order to show that part of the obliquity signal in M originates from taking the half year insolation (Figure 3). Despite having a stronger obliquity signal than $23^\circ N$ insolation, M does not explain the thick-thin alternation in the sapropels (Figure 2).

Taking the insolation difference between two hemispheres, such as the Summer Inter Tropical Insolation Gradient (SITIG), $I_{23^\circ N}-I_{23^\circ S}$ at June 21st (light blue line in Figure 3), results in an insolation curve very similar to that of $65^\circ N$ at June 21st. In SITIG, the obliquity signal originates from the fact that, in contrast to precession, obliquity induces insolation increases on one hemisphere and, at the same time, insolation decreases on the other hemisphere (Figure 1). Therefore SITIG has a much stronger obliquity signal, relative to precession, than insolation at a single low latitude. At times of high obliquity (Tmax) the insolation gradient over the tropics (SITIG) is stronger than during low obliquity. This also holds for SITIG in austral summer ($I_{23^\circ S}-I_{23^\circ N}$ at December 21st). This strengthens the interhemispheric pressure gradient between the two limbs of the winter hemisphere Hadley cell, which drives monsoon winds into the summer hemisphere. A strong SITIG may therefore result in stronger cross-equatorial winds and moisture transport into the summer hemisphere, associated with an intensified winter Hadley cell [Rechard 1996]. A schematic overview of the effect of obliquity on the (winter) Hadley cell given in Figure 11 of Mantis et al. [2014].

Like insolation at $65^\circ N$ at June 21st, SITIG matches the sapropel record, including the obliquity-induced thick-thin alternations (Figure 4). An insolation gradient similar to SITIG was introduced by Leuschner and Sirocko [2003], the Indian Summer Monsoon Index ($I_{30^\circ N}-I_{10^\circ N}$ at August 1st). Despite a small lag (due to ISMI being defined on August 1st and SITIG on June 21st) they are rather similar and both have a relatively strong obliquity signal (Figure 3). $65^\circ N$ insolation is often used to interpret paleoclimatic record because of the matching patterns, but requires an explanation of how high-latitude insolation affects low-latitude climate. Here, we investigate whether changes in tropical climate and circulation patterns match the SITIG mechanism based on the EC-Earth experiments (next Section 3.2).

Note that we focus on (peak) summer insolation and climate, under the assumption that the paleoclimate proxies such as the sapropels are influenced by seasonal phenomenon such as monsoons. Changes in obliquity result in annual mean insolation changes (right side of Figure 1) per latitude as well as changes in the annual mean equator-to-pole insolation gradient. This is briefly discussed in Section 4.3.

### 3.2 EC-Earth obliquity experiments

EC-Earth shows statistically significant differences in net precipitation over the tropics between high (Tmax) and low obliquity (Tmin, Figure 4). Precipitation differences between Tmax and Tmin reach
up to and over 100%, for instance over the Sahara and South America (not shown). There is an overall intensification of the North African and Asian monsoons during boreal summer (June-July-August), with a redistribution of precipitation from ocean to land and stronger landward monsoon winds (Figure 3a, Bosmans et al. (2015a)). Differences in wind speed can also be as large as 100%, for instance in the areas of summer monsoon winds into North Africa and India (not shown). Over the equatorial and southern Pacific wind speed changes are small while winds around the North Pacific as well as the North Atlantic Highs are generally stronger. During austral summer (December-January-February) net precipitation and wind changes are smaller than during boreal summer, likely related to the smaller land mass and therefore weaker monsoons on the Southern Hemisphere (SH). The largest net precipitation increases occur over part of the South American and South African summer monsoon regions as well as the Atlantic and Indian Ocean, while net precipitation over the NH tropics is reduced (Figure 4b).

Our experiments indicate, in agreement with the SITIG mechanism, strengthened surface winds towards the summer hemisphere during Tmax (Figures 4a and 4b). The zonal mean cross-equatorial surface winds are northward and they are indeed stronger during boreal summer, extending slightly further into the NH (Figure 5a). With these stronger surface winds the moisture transport into the NH is strengthened as well during Tmax (Figure 5b). Moisture transport into the North-African and Asian monsoon areas is generally higher during boreal summer, with enhanced northward cross-equatorial transport mostly over the Indian Ocean (see Figure 7a). Changes over the Pacific are small, which could be related to the absence of land masses which have a stronger response to insolation changes.

During austral summer the zonal mean southward cross-equatorial surface winds are stronger when obliquity is high (Tmax), extending slightly further into the SH (Figure 5c). Therefore more moisture is transported southward across the tropics (Figure 5d). Most of this increased southward moisture transport occurs over the Indian Ocean (Figure 7b), where both wind and specific humidity are increased. Over the tropical Atlantic specific humidity is lower during Tmax, so moisture transport is not increased despite the increase in wind speed (Figure 4b).

The changes in surface winds and moisture transport can be related to changes in the (winter) Hadley cell. During boreal summer, the descending branch, centered at \(\sim 20^\circ\)S, is strengthened, mostly at the northern side, with a slight weakening at the southern side during Tmax (Figure 8a). The same holds for the ascending branch, centered at \(\sim 10^\circ\)N, so the winter Hadley cell is slightly stronger and extends further into the NH during boreal summer. During austral summer, the winter Hadley cell extends from a descending branch at \(\sim 20^\circ\)N to an ascending branch at \(\sim 10^\circ\)S (Figure 8b). The additional rising branch at 5-10\(^\circ\)N is most likely overestimated in the model due to a double-ITCZ over the Pacific, a feature that many models encounter (Lin [2007]). However, a strengthening of the winter Hadley cell can still be seen: both the descending and ascending branches are slightly stronger and extend further south during Tmax, in line with stronger southward surface winds.
While winds and moisture transport in the tropics are generally stronger during boreal and austral summer, they are weaker in the annual mean for Tmax (Figures 4c, 5f, 7c). This weakening can be related to the obliquity-induced redistribution of annual mean insolation from low to high latitudes during Tmax, resulting in weakening of the equator-to-pole insolation gradient. Therefore annual mean meridional winds and moisture transport as well as the annual mean Hadley circulation are weaker (Figure 8c). Annual mean precipitation changes resemble mostly the JJA changes over the continents, and reflect both JJA and DJF changes over the oceans (Figure 4c).

4 Discussion

We have shown that changes in low-latitude climate can arise as a direct result of obliquity-induced insolation changes, using the sophisticated model EC-Earth without land ice changes. Here we discuss that these changes support the previously proposed SITIG theory [Lourens and Reichart, 1996; Leuschner and Sirocko, 2003] SITIG theory [Reichart, 1996; Leuschner and Sirocko, 2003], what the implications are for the interpretation of obliquity signals in low-latitude paleoclimate records and how obliquity-induced gradients may influence global climate.

4.1 Model support for the SITIG theory

The simulated changes in winter Hadley cell strength during boreal and austral summer are in accordance with the SITIG theory [Lourens and Reichart, 1996; Leuschner and Sirocko, 2003] (Reichart, 1996; Leuschner and Sirocko, 2003) SITIG theory [Reichart, 1996; Leuschner and Sirocko, 2003]. The Summer Inter Tropical Insolation Gradient (SITIG, $I_{23^\circ N}$-$I_{23^\circ S}$ at June 21st) theory states that an increased SITIG during high obliquity (Tmax) is associated with an intensified winter Hadley cell and stronger cross-equatorial winds and moisture into the summer hemisphere. The winter Hadley cell is not entirely symmetric about the equator (as is assumed in the original SITIG hypothesis, [Lourens and Reichart, 1996], [Reichart, 1996]), nor are the changes in wind and moisture transport zonally invariant, likely due to differences in the land-sea distribution. Nonetheless, a stronger SITIG during high obliquity (Tmax) results in stronger zonal mean winds and moisture transport into the summer hemisphere and a stronger Hadley cell in our EC-Earth results. The Hadley cell as well as the meridional winds and moisture transport also extend farther into the summer hemisphere. This is in agreement with the poleward shift of the latitude of the tropics during Tmax (Rossignol-Strick, 1983; Larrasoña et al., 2003). In these studies, meridional shifts in the Hadley cell and the tropics are associated to changes in the equator-to-pole insolation gradient, which in summer has a strong obliquity component. These studies also suggest that the insolation gradient over the austral winter hemisphere causes temperature and trade wind changes that can influence the intensity and poleward penetration of the boreal summer monsoons. However, the winter (intrahemispheric) insolation gradient does not vary with obliquity, but with precession (Davis and Brewer, 2009), so changes in winter (intrahemispheric) hemisphere insolation gradients cannot be used to explain (low-latitude)
obliquity signals. Also, we suggest that while the Hadley cell, and thus precipitation patterns, might indeed shift on obliquity time scales due to changes the (summer) equator-to-pole gradient, such a shift does not explain the changes in precipitation amounts, the strength of the Hadley circulation and the strength of cross-equatorial winds and moisture transport that we identify in our obliquity experiments. Further sensitivity studies could shed more light on the relative roles of inter- and intra-hemispheric gradients (see Section 4.3).

4.2 Implications for the interpretation of paleoclimate records

Obliquity signals in low-latitude paleoclimate records are often interpreted using the 65°N 21st June insolation curve based on the matching precession-obliquity interference in the records and the 65°N insolation curve (Figure [2]). The model study of Tuenter et al. (2003), indicating that ~80-90% of the obliquity signal in the North-African monsoon is due to high latitude influences, supported the use of the 65°N insolation curve. Some studies, on the other hand, used a $P_{1/2}$T curve to interpret paleoclimate records (e.g. Lourens et al., 1996). This combination of the precession and obliquity parameters is very similar to the 65°N 21st June insolation curve, but by using $P_{1/2}$T no direct assumptions on climate mechanisms are made. Our results, based on a much more sophisticated (and realistic) model with fixed land ice, clearly suggest a low-latitude mechanism for obliquity patterns at low latitudes through a direct response to changes in the cross-equatorial insolation gradient. Furthermore, there is a strong resemblance between (boreal) SITIG and the 65°N 21st June insolation curve (Figure ??, Lourens and Reichart (1996), Leuschner and Sirocko (2003) as well as the $P_{1/2}$T curve (Lourens et al., 2001). Hence, the widely applied 65°N 21st June insolation curve (Tiedemann et al., 1994; Hilgen et al., 1995; Lourens et al., 1996, 2001; Hilgen et al., 2000; Sierro et al., 2000) needs to be reconsidered in favour of SITIG. SITIG instead of 65°N 21st June insolation relies on a physical basis as described by our model results rather than pattern matching, and explains the obliquity influence on tropical climate independently of glacial-interglacial variability. It thus provides an explanation for the obliquity influence in the sapropel record of the past 14 million years during both the recent glacial cycles as well as earlier warmer times.

We note that the original SITIG theory was based on the Mediterranean sapropels (Lourens and Reichart, 1996), which were originally linked to North African monsoon strength (e.g. Rossignol-Strick, 1985; Rudimman, 2007), but have recently also been attributed to changes in Mediterranean winter precipitation through changes in Atlantic storm track activity (e.g. Tzedakis, 2007; Brayshaw et al., 2011; Kutzbach et al., 2013). In our obliquity experiments, changes in Mediterranean winter precipitation are unrelated to the Atlantic storm tracks, but are of equal magnitude to summer monsoonal runoff into the Mediterranean. In terms of percentages, however, changes in monsoonal runoff are larger (Bosmans et al., 2015b). Another study stating the importance of cross-equatorial insolation gradients, (Leuschner and Sirocko, 2003), is based the insolation difference between 30°N and 30°S, which drives Indian summer monsoon strength through
pressure differences (pink line in Figure 2). Leuschner and Sirocko (2003) state that their record of continental dust transport (indicative of monsoon strength) responds immediately to changes in the cross-equatorial insolation gradient. This matches with our results, showing changes in Indian summer monsoon strength as well as cross-equatorial winds and moisture transport that are particularly strong over the Indian Ocean. Also, other paleoclimate records in the Arabian Sea have been used to rule out global ice volume as a primary forcing mechanism for the occurrence of obliquity-related variability in the Indian monsoon (Clemens et al., 1991; Clemens and Prell, 2003; Clemens and Prell, 2003; Clemens et al., 1991). Therefore we conclude that, despite the need to determine the relative role of (winter) precipitation over the Mediterranean in the formation of the sapropels, there is sufficient evidence from tropical and sub-tropical paleoclimate records suggesting a local, low-latitude, direct response to obliquity forcing.

4.3 Obliquity-induced gradients and their influence on global climate

Lourens and Reichart (1996) and Leuschner and Sirocko (2003), Leuschner and Sirocko (2003) and Reichart (1996) suggested that through monsoon-induced changes in atmospheric moisture content, a strong greenhouse gas, the Summer Inter Tropical Insolation Gradient (SITIG) may drive glacial-interglacial variability. Indeed we find a significant obliquity-induced change in cross-equatorial moisture transport (Figures 2b, 5b, 5d). However, whether changes in atmospheric moisture content resulting from changes in low-latitude atmospheric circulation on orbital time scales can indeed result in global climate change will need to be investigated with longer model experiments including dynamic ice sheets (not included in EC-Earth). Furthermore, despite having a relatively strong obliquity component, the precession component in SITIG is stronger (Figure 7). Precession, however, has an opposite effect on both hemispheres. Moisture changes during boreal summer may therefore be exactly opposite to moisture changes during austral summer, so the precession signal in atmospheric moisture content is canceled out. Lourens and Reichart (1996) suggest that in this case SITIG can account for the obliquity-dominated glacial variability between ~2.7 and 1 million years ago. Given the larger landmasses, and hence stronger monsoons, on the northern hemisphere we do not think that the precession effect cancels out, so SITIG will not result in a purely obliquity-paced signal. Furthermore, the role of precession-induced changes in moisture content would need to be assessed as well.

Another mechanism by which obliquity can affect high-latitude climate and glacial cycles through latitudinal insolation gradients has been proposed by Raymo and Nisancioglu (2003); Vettoretti and Peltier (2004); Antico et al. (2010); Mantis (2011). These studies suggest that the poleward transport of heat, moisture and latent energy is increased during minimum obliquity due to the intensified intrahemispheric (equator-to-pole) insolation and temperature gradient. The increased moisture transport towards the poles combined with low polar temperatures during low obliquity is favourable for ice growth. In our EC-Earth experiments we also find stronger poleward moisture transport out-
side the tropics during minimum obliquity (Tmin) during both boreal and austral summer as well as in the annual mean (not shown). The response to changes in the equator-to-pole insolation and temperature gradient can be further intensified by albedo changes. In our experiments land ice is fixed but sea ice at the poles responds to polar insolation changes (not shown). Furthermore, changes in poleward energy transport by ocean currents can play a role in obliquity’s effect on global climate (Khodri et al., 2001; Jochum et al., 2012; Khodri et al., 2001; Jochum et al., 2012; Mantsis et al., 2014). In order to determine the relative role of tropical circulation changes through interhemispheric insolation gradients (SITIG), compared to changes in poleward energy and moisture transport in both atmosphere and ocean through intrahemispheric gradients, further sensitivity experiments are necessary. Such experiments should include dynamic ice sheets and should be run longer for ice sheets and the (deep) ocean to equilibrate to the obliquity forcing. Also, experiments with insolation changes only over the tropics can be considered, to test the effect of inter- versus intrahemispheric insolation gradients. At this point such experiments are not yet feasible with the EC-Earth model.

Experiments testing the sensitivity to obliquity changes under different precession and / or greenhouse gas conditions should be considered as well (e.g. Rachmayani et al., 2015).

5 Conclusions

The low-latitude SITIG mechanism proposed here is fundamentally different from high-latitude mechanisms previously proposed to explain the obliquity patterns at low latitudes. Our results, based on the sophisticated model EC-Earth, suggest that these patterns may arise from a direct response to changes in the cross-equatorial insolation gradient, i.e. without any influence of ice sheets or other high-latitude mechanisms. Hence—Despite such mechanisms, related to ice sheets and / or equator-to-pole gradients, requiring further research, our results suggest that the widely applied 65°N 21st June insolation curve needs to be reconsidered in favour of SITIG.

Acknowledgements. The EC-Earth experiments were performed at KNMI using ECMWF facilities. This work was part of Joyce Bosmans’ PhD project, funded by a “Focus en Massa” grant at Utrecht University. We thank the editor and two anonymous reviewers for their constructive remarks, which helped improve this paper. Dr. M.L. Goudeau is acknowledged for her help with Figure 2.
References


Plio-Pleistocene astronomical timescale, Paleoclimatology, 11, 391–413, 1996.


Figure 1: Insolation difference between Tmax (24.45°) and Tmin (22.05°). On the left, insolation difference in W/m² is given per month on the x-axis and latitude on the y-axis. On the right, annual mean insolation difference is given, in W/m².
Figure 2: Insolation in W/m² over the past 500 kyr at 23°N (black) and 65°N (red) and insolation indices M (blue, green, Roussignol-Strick 1985), SITIG (light blue, Reichart 1996) and ISMI (pink, Leuschner and Sirocko 2003), based on the astronomical solution of Laskar et al. (2004), using Analyseries (Paillard et al. 1996). All are for June 21st, except M caloric (green) which is for the summer half year. The lowest part of the figure shows sapropels in core RC9-181 (Cita et al. 1977, Vergnaud-Grazzini et al. 1977). We note that the obliquity signal also appears in older parts of the insolation and sapropel records (e.g. Lourens et al. 1996, Hilgen et al. 1995, 2003, Zeeden et al. 2014).
Figure 3: Power spectra of insolation curves in Figure 2. (a) shows the power spectrum in absolute sense, (b) the normalized power spectrum. For (b), each curve is divided by its peak power at \( \sim 0.043 \text{ kyr}^{-1} \).
(a) June-July-August

(b) December-January-February

(c) Annual mean

Figure 4: Caption on page 18
Figure 4: Figure on page 17. Net precipitation differences and Tmax surface wind for JJA (a), DJF (b) and annual mean (c). For net precipitation (precipitation minus evaporation), the differences (Tmax minus Tmin) are shown in mm/day. Overlain are the wind vectors for Tmax in m/s. Purple vectors indicate larger windspeeds during Tmax than during Tmin. Cross-equatorial winds are stronger in JJA (a) and DJF (b), mostly over the Atlantic and Indian Ocean. Every 7th arrow in the x-direction is drawn and every 4th arrow in the y-direction. Results are only shown where the differences in net precipitation or windspeeds are statistically significant at 95% (based on a two-sided Student t-test). The full wind field is given in Figure 6.
Figure 5: Caption on page 24
Figure 5: Figure on page 19. Zonal mean meridional surface wind and moisture transport for JJA (a,b), DJF (c,d) and annual mean (e,f). The wind is given in m/s, moisture transport in kg/(ms) for both Tmax (black), Tmin (red) and the difference (blue, multiplied by 10 for clarity). Moisture transport is calculated as the mass-weighted vertical integral of specific humidity multiplied by horizontal wind. Positive values indicate northward wind or moisture transport, negative values southward. Wind and moisture transport into the summer hemisphere is stronger during Tmax for JJA (a,b) and DJF (c,d). Solid parts of the blue line indicate where the difference is statistically significant at 95% (based on a two-sided Student t-test). Note that the vertical scales are different.
Figure 6: Caption on page ??

21
Figure 6: Figure on page 21. Wind during Tmax in JJA (a), DJF (b) and the annual mean (c), in m/s. The colour scale indicates the difference in windspeed between Tmax and Tmin, in m/s. Note the different colour scale for the annual mean. Every 9th vector is shown in the x-direction, and every 5th in the y-direction.
Figure 7: Caption on page 24
Figure 7: Moisture transport in Tmax for JJA (a), DJF (b) and annual mean (c), vertically integrated, in kg/(ms). Purple vectors indicate larger moisture transport during Tmax than during Tmin. Every 7th arrow in the x-direction is drawn and every 4th arrow in the y-direction. Results are only shown where the differences are statistically significant at 95% (based on a two-sided Student t-test).
Figure 8: Caption on page 25
Figure 8: Zonal mean vertical velocity (omega, $10^{-2}$ Pa/s) during Tmax (contours) for JJA (a), DJF (b) and annual mean (c). Negative contours indicate upward motion (rising), positive contours indicate downward motion (sinking). The vertical scale (y-axis) denotes height in hPa. The colours indicate the differences between Tmax and Tmin, only shown where they are statistically significant at 95% (based on a two-sided Student t-test). The arrows indicate the direction of the air flow and are purple where the flow is stronger during Tmax compared to Tmin, which is the case for boreal and austral summer (a,b). Black arrows indicate where the flow is weaker during Tmax. Note the different colour scale for the annual mean.

Insolation over the past 500 kyr (a) at 23°N (solid line) and 65°N (dotted line) on the left y-axis and SITIG (insolation difference between 23°N and 23°S at June 21st, dashed line) on the right y-axis. (b) shows the power spectra of these three insolation curves, with peaks at 23 kyr (precession) and 41 kyr (obliquity), again the left y-axis is for 23°N and 65°N insolation, the right y-axis for SITIG.