Interactive comment on “Latitude and bathymetry modify lake warming under ice” by Cintia L. Ramón et al.

Response to Referee #1

Received and published: 18 November 2020

In this paper the authors consider how late winter solar radiation driven convection may be controlled by the relative strength of Coriolis force. As many as half the lakes in the world freeze and are located at high latitudes where Coriolis forces could be important. However it is very hard to do field work under these lakes, and while the process of solar driven convection is somewhat well known, how Coriolis forces interact with lateral temperature gradients to drive basin wide circulation is not well known. This paper represents an important first step to address some of these issues. The paper is well written, and my comments below are mainly about putting this new work into context of existing literature of Coriolis effects on convection. Addressing these comments does not require any changes to figures, rather just some careful thought to some of text so should be somewhat straight forward and will make the paper stronger.

We thank Referee #1 for his/her encouragement and very interesting suggestions on how to improve the manuscript. We present below how we will implement the changes suggested by Referee #1.

1) I think it would be very helpful for authors to emphasize some caveats and qualifications to the generality of their study. What might happen in the many lakes that are long and narrow? Do you expect multiple gyres? Could the authors comment on whether the Rossby number is time dependant in a real lakes, due to increases in buoyancy forcing as the length of the day increases? This might mean change in sense of circulation patterns over the end of winter . How typical is the strong stratification that is as warm as 4C at bottom? Many large but relatively shallow lakes are less stratified and maybe be 2C or 3C at base (see https://aslopubs.onlinelibrary.wiley.com/doi/abs/10.1002/lno.11543 as one example). In these less stratified lakes you are much more likely to see gravity currents going to base of lake, so are circulation patterns are possibly different?

AR (Authors’ response) 1: The objective of this work is to provide a general characterization of the respective contribution of lake bathymetry and rotation on the warming of lakes under the ice. But the reviewer raises an important point regarding the basin's shape and the background stratification.

The study sites, Kilpisjärvi and Pavilion lakes, that we included in the discussion section, and where gyres were detected in the field, cannot be described as bowl-shape lakes. Pavilion Lake for example is an elongated lake and a gyre was measured at one of the regions where the lake widens. As far as we know, AUV transects were only conducted in this region of the lake (Forrest et al., 2013), so the presence of other gyres in other regions in this lake remains unknown. We think that not only the shape (surface and perimetral geometry), but the bathymetry itself will define the number of gyres that form (e.g, Akitomo et al., 2004). Especially relevant would be the presence of constrictions and/or shallow areas not only close to the lake shore but in the lake interior creating different “sub-basins”. The modeling work by Huttula et al (2010) in Lake Pääjärvi suggests that indeed multiple gyres could form in more complex bathymetries. The role of the bathymetry in gyre formation would be definitely worth exploring in future work.

As the reviewer suggests, the effective buoyancy flux is expected to increase as the radiative forcing increases. In our numerical experiments, the effective buoyancy flux decays in time. In the field, however, the variations in solar radiation might lead to phases where the effective buoyancy flux is actually increasing in time, before reaching a point at which it starts decreasing due to the minimum in thermal expansivity. Thus, potentially yes, a lake initially in the geostrophic regime could move to the ageostrophic regime in the course of the Winter II period.

There are examples in the literature of lakes reaching temperatures close to T_{MD} (or even higher) near the bottom (e.g., Bengtsson and Svensson,1996 (doi:10.2166/nh.1996.0018); Malm et al., (1998) (doi: 10.4319/lo.1998.43.7.1669); Cortés and McIntyre, 2019 (doi: 10.1002/lno.11296); Forrest et al., 2013). But, as the reviewer pointed out, many other lakes reach temperatures of only 2-3 degrees at the bottom of the lake. Certainly, the strength of the initial stratification (dρ/dz) at the start of the Winter II period (e.g., Jang et al., 2020) would affect the rate of deepening of the CML. For a given radiative flux and forcing time, a weaker background stratification would lead to deeper CMLs. The CML could potentially reach the base of the lake before the ice melts and then gravity currents would also flow downslope until the base of the lake. We do not see, though, why, there should be a change in the circulation pattern if the rotation regime remains the same.

We propose to expand the discussion section where we present the limitation of our approach with existing site-specific studies. We propose that the new text in the Discussion section reads: "*The numerical experiments described herein intend to provide a general characterization of the respective contribution of lake bathymetry and rotation on the warming of lakes under the ice; however, site-specific conditions will determine the actual response of a given lake. For example, although basin or sub-basin scale gyre formation has been reported to occur in lakes with bathymetries departing from the bowl-shaped one used in this study (e.g., Forrest et al, 2013; Kirillin et al., 2015), bathymetric effects could prevent gyre formation, or, by contrast, lead to the development of more complicated patterns (for example, multiple horizontal gyres, as in Huttula et al. (2010)). Also, the initial conditions could vary among lakes (e.g., Yang et al. 2020a). Although there are examples in the literature of lakes reaching values close to* T_{MD} *near the lake bottom (e.g., Bengtsson and Svensson, 1996; Cortés and McIntyre, 2020; Forrest et al., 2013; Malm et al., 1998), other lakes reach temperatures of only 2-3 degrees at the bottom of the lake (e.g., Bouffard et al., 2016; Yang et al., 2020b). The radiative forcing conditions could also depart from those in this study, where a spatially-uniform radiative flux (e.g., Malm et al., 1997) or a steady daily radiative cycle (e.g., Bouffard et al., 2016) have been prescribed. The initial and forcing conditions (magnitude and time evolution) will influence the deepening rate of the CML, and/or the strength of differential heating and density currents, and will also determine the magnitude of Ro.*"

Akitomo, K., Kurogi, M. and Kumagai, M.: Numerical study of a thermally induced gyre system in Lake Biwa, Limnology, 5(2), 103–114, doi:10.1007/s10201-004-0122-9, 2004.

Bengtsson, L. and Svensson, T.: Thermal regime of ice covered Swedish lakes, Nord. Hydrol., 27(1–2), 39–56, doi:10.2166/nh.1996.0018, 1996.

Bouffard, D., Zdorovennov, R. E., Zdorovennova, G. E., Pasche, N., Wüest, A. and Terzhevik, A. Y.: Ice-covered Lake Onega: effects of radiation on convection and internal waves, Hydrobiologia, 780(1), 21–36, doi:10.1007/s10750-016-2915-3, 2016.

Malm, J., Terzhevik, A., Bengtsson, L., Boyarinov, P., Glinsky, A., Palshin, N. and Petrov, M.: Temperature and salt content regimes in three shallow ice-covered lakes: 1. Temperature, salt content, and density structure, Nord. Hydrol., 28(2), 99–128, doi:10.2166/nh.1997.0007, 1997.

Malm, J., Bengtsson, L., Terzhevik, A., Boyarinov, P., Glinsky, A., Palshin, N. and Petrov, M.: Field study on currents in a shallow, ice-covered lake, Limnol. Oceanogr., 43(7), 1669–1679, doi:10.4319/lo.1998.43.7.1669, 1998.

Yang, B., Wells, M. G., Li, J. and Young, J.: Mixing, stratification, and plankton under lake-ice during winter in a large lake: Implications for spring dissolved oxygen levels, Limnol. Oceanogr., lno.11543, doi:10.1002/lno.11543, 2020a.

Yang, B., Wells, M. G., McMeans, B. C., Dugan, H. A., Rusak, J. A., Weyhenmeyer, G. A., Brentrup, J. A., Hrycik, A. R., Laas, A., Pilla, R. M., Austin, J. A., Blanchfield, P. J., Carey, C. C., Guzzo, M. M., Lottig, N. R., Mackay, M. D., Middel, T. A., Pierson, D. C., Wang, J. and Young, J. D.: A New Thermal Categorization of Ice-covered Lakes, Geophys. Res. Lett., doi:10.1029/2020GL091374, 2020b.

2) I was also wondering if the title might be slightly qualified? Rather than "Latitude an geometry", I'd suggest order be "geometry and latitude", as I think geometry is more important. You find the vast majority of dimictic lakes from about 40 to 70oN (Northern America and Northern Europe) where f varies from 0.935 to 1.367 10-4sˆ-1. So most of the variation in Rossby number between lakes is not primarily due to latitude, but rather their scale (and possibly magnitude of radiation which is indirectly also related to latitude).

AR2: The reviewer is right. *Ro* is changing primarily due to *L*. We will modify the order of the words in the title as suggested: "*Bathymetry and latitude modify lake warming under the ice*". However, we believe that the term bathymetry is more appropriate than geometry. The term geometry could be interpreted by the reader only in terms of lake dimensions and shape; however, *L* depends also on the width and depth of the shallow region, and so, on the topography of a given lake.

3) I think you need to qualify that statement on line 20 that "Yet, as we move from planetary to smaller-scale systems, the importance of rotation in affecting convective processes remains overlooked. This is the case in lakes." I think you want to change or qualify the word "overlooked". In terms of convection there have many studies of the "spring thermal bar" where heating of lakes that are below 4oC drives a radial geostrophic flow near the shore, (https://en.wikipedia.org/wiki/Thermal_bar). This seems to be very closely related physics, so It would be worth reminding the reader of the connection between your study and this well known process in larger lakes (which is probably at low Ro end of your simulations). This is a well known example of Coriolis limiting heat transfer from edges to interior.

What I am confused about is that all observations and models thermal bar suggest you'd get an anti-clockwise flow (cyclonic) near the shore in Northern Hemisphere. I think this is opposite however to what is shown in low Rossby number case for Figure 3. There are many theoretical papers from 1970s on thermal bar, one example is https://doi.org/10.1080/03091927208236071 Huang, Joseph Chi Kan. "The thermal bar."Â˘aGeophysical Fluid DynamicsÂ˘a3, no. 1 (1972): 1-25. This article mentions that "The results show a dominant meridional cyclonic flow along the perimetric edge of the lake and an anticyclonic flow in the middle portion of the lake. Â˘a" I am confused what is the key difference between that classic field observation and your simulations for low Rossby number? I may be confused here, but if the sense of circulation is fundamentally different it would be useful to explain what is the key difference in setting up your simulations.

AR3: The reviewer is correct. However, we believe that if we present the thermal bar in the introduction, this could lead the reader to think that this is a process covered in this study. Instead, in the introduction we propose to tone down our statement. We will change the text: *"Yet, as we move from planetary to smaller-scale systems, the importance of rotation in affecting convective processes* ***has drawn, comparatively, less attention****. This is the case in lakes".*

If the littoral region heats above T_{MD} while the lake interior remains below T_{MD} a thermal bar would form separating the two regions. The radial circulation in this case would be different to that in our ageostrophic regime. In our cross-section, we would see two thermal bars and four recirculating cells in the radial direction (one per littoral region and two at the lake interior). The water from both littoral regions, which is lighter than the water in the thermal bar (~T_{MD}), will move close to the surface towards the thermal bar and a return flow would form near the bottom. This is opposite to the radial circulation in the differential heating case under ice, where littoral waters are denser than pelagic waters. In the lake interior, water is also lighter than the water at the thermal bar region, so there would be a flow from the lake center towards the thermal bar near the surface and a return flow at deeper depths.

An opposite radial circulation would explain a different pattern in the azimuthal circulation. As the effect of rotation intensifies the water moving from the littoral region towards the thermal bar will be deflected at the surface towards the right, leading to the formation of a cyclonic gyre. In the lake interior, however, the flow at the surface is from the lake center towards the thermal bar, so when deflected to the right, it would lead to the formation of an anticyclonic gyre (e.g., Huang, 1972). This is opposite to the pattern described in this study. The pressure in our simulations is decreasing towards the littoral region, so, in the geostrophic regime an anticyclonic gyre develops in the lake.

We will include some lines in the discussion section. We propose that the text now reads: "*To our knowledge, this circulation has not been reported in the field at times of under-ice radiatively-driven convection. The lake-wide anticyclonic circulation in Fig. 5b would be consistent with the inferred lake-wide anticyclonic gyre reported by Rizk et al (2014) at a time when circulation in lake Pääjäarvi was dominated by a lateral gradient in the heat flux from the sediment and Ro was O(10^{-3}-10^{-2}) [...].* ***Due to a different distribution of the pressure field (decreasing towards the littoral region in the under-ice differential heating case), the sense of the azimuthal circulation in Figs. 3g,h and Fig. 3k,l is, for example, opposite to that observed inshore of thermal bars (ice-free period), where a cyclonic gyre develops (e.g., Huang et al., 1972; Malm et al., 1993)***".

Joseph Chi Kan Huang (1972) The thermal bar, Geophysical Fluid Dynamics, 3:1, 1-25, DOI: 10.1080/03091927208236071

Malm, J., Grahn, L., Mironov, D. and Terzhevik, A.: Field investigation of the thermal bar in Lake Ladoga, spring 1991, Nord. Hydrol., 24(5), 339–358, doi:10.2166/nh.1993.12, 1993.

4) There is a recent paper by Jazi Davarpanah et al. (2020) on rotating gravity currents using the Coriolis facility in Grenoble that goes into great detail on Rossby number effects and is a better reference than Wells, 2009 on line 32 https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JC015284 This study would also qualify your statement on line 149-150 that "When R/U > f gravity currents are affected by Earths rotation" - rather the large Grenoble experiments found that there is a gradual transition in gravity current dynamics that starts at Rossby number greater than 1,

AR4: Thanks. We will include this reference on both lines.

5) A number of studies in last 40 years have studied convection in rapidly rotating "dishes" - as an analog to understanding zonal jets in gas giants like Jupiter. Physically one might expect that these should have same or similar circulation patterns as your low Rossby number simulations (although they lack stratification). Hence it would be worth briefly commenting to what degree the circulation *patterns look similar or different to your Figure 3. I appreciate the experiments below are not stratified, but for many physicists these would be the rotating experiments they are familiar with. One recent example from Grenoble os*

Read, P.L., Jacoby, T.N.L., Rogberg, P.H.T., Wordsworth, R.D., Yamazaki, Y.H., Miki-Yamazaki, K., Young, R.M., Sommeria, J., Didelle, H. and Viboud, S., 2015. An experimental study of multiple zonal jet formation in rotating, thermally driven convective flows on a topographic beta-plane.Â˘aPhysics of Fluids,Â˘a27(8), p.085111.

Before computer simulations were easier this type of system was also used in some high profile papers in 1980-1990s, see figure 2 in

Condie, Scott A., and Peter B. Rhines. "A convective model for the zonal jets in the atmospheres of Jupiter and Saturn."Â˘aNatureÂ˘a367, no. 6465 (1994): 711-713.

Sommeria, J., Meyers, S.D. and Swinney, H.L., 1989. Laboratory model of a planetary eastward jet.Â ˘aNature,Â˘a337(6202), pp.58-61.

also used to think about the modes of convection driven circulation under sloping geometry of Lake Vostok - see for instance the change from differential heating to columnar vortices in https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2007GL032162

AR5: We thank the reviewer for sharing these references. In our discussion section we already compared our circulation with the work by Fultz et al. (1959), which was conducted in a rotating cylinder and aimed at explaining the atmospheric large-scale circulation. We discussed there about the circulation patterns that we see in our simulations being analogue to those described by Fultz et al. (1959). In the discussion about the geostrophic regime, we specified that Fultz's work is conducted in laboratory rotating tanks ("The anticyclonic gyre circulation is also consistent with the Rossby wave regime reported in laboratory studies (rotating cylinder and annulus) mimicking the mid-to-high-latitude atmospheric circulation (Fultz et al., 1959)."). We will clarify also in the ageostrophic regime that this is a lab-scale work in the text and we will add other references.

In the discussion about the ageostrophic regime, we propose that the text now reads "*When Ro $\gtrsim 10^{-1}$, the horizontal heat transport is then accomplished by the ageostrophic components of the flow (downslope gravity currents). This cross-shore circulation might be considered analogue to the atmospheric Hadley cells,* ***as reproduced in laboratory rotating-tank experiments (e.g., Fultz et al., 1959)***".

In the discussion about the geostrophic regime, we propose that the text reads "*The basin-scale anticyclonic gyre circulation is consistent with the Rossby wave regime reported in laboratory studies (rotating cylinder and annulus) mimicking the mid-to-high-latitude atmospheric circulation (e.g., Fultz et al., 1959; Sommeria et al., 1989 Condie and Rhines, 1994). The sense of rotation of the gyres in Figs. 3g,h and Fig. 3k,l is also consistent with these studies. Water temperature in the rotating tanks is above T_{MD} and the sense of the gyre rotation is anticyclonic when the heating and cooling sources are provided at the center and the tank rim, respectively. The sense of rotation is reversed (cyclonic gyre) when the heating and cooling sources are exchanged. Within the Rossby regime, vortices and waves traveling cyclonically develop (Fig. 3h) and as Ro decreases, the wave lengths decrease and the gyre circulation is concentrated into jets that meander in the radial direction and could finally break (Condie and Rhines, 1994; Smith et al., 2014; Read et al., 2015). The presence of waves and/or vortices as in the scenario with Ro $O(10^{-2})$ (Fig. 3h) is typical of transitional regimes (Fultz et al., 1959) and when they develop, the center of the anticyclonic gyre is not static in time but fluctuates laterally (video S1).*"

6) There are a few more key studies on ice covered lakes that can be compared directly to the simulations. In particular in old studies on Tub lake, the scale and geometry looks like about exactly

scale as in the present student study. The lake is symmetric and has a profile from 0-4C, so is probably as similar as you could find, so a good question is whether the sense of circulation in studies by Likens is the same? They inferred basal heating was very important (as have other under ice studies during winter I.) but I feel this should be somewhat similar to radial differences in temperature gradients in winter II.
LIKENS, G. E., AND A. D. HASLER. 1962. Movements of radiosodium (NaZ4) within an ice-covered lake. Limnol. Oceansgr. 7: 48-56.
LIKENS, G. E., AND R. A. WACOTZKIE. 1965. Vertical water motions in a small icecovered lake. B. Geophys. Res. 70: 2333-2344.

Likens, G.E. and Ragotzkie, R.A., 1966. Rotary circulation of water in an ice-covered lake: With 6 figures and 1 table in the text. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, 16(1), pp.126-133.

Another old paper shows possible sinking near boundaries, consistent with your observations Welch, HE, & Bergmann, MA (1985). Water circulation in small arctic lakes in winter. Canadian Journal of Fisheries and Aquatic Sciences , 42 (3), 506-520.

AR6: Thanks for sharing these key references. Indeed, by injecting radioactive tracers near the center and in the littoral region in Tub lake (45°N) in January 1962, Likens and Ragotzkie (1966) were able to detect the presence of a double-gyre circulation in the lake, with a cyclonic gyre in the lake interior (their Fig. 2), surrounded by an anticyclonic gyre in the littoral region (their Fig. 3). The azimuthal circulation pattern seems to be recurrent during the ice-on season, since Likens and Hasler (1962) already had detected the interior cyclonic circulation in January 1960.

They reported horizontal velocities of 30-35 m/day (3.5 x 10^{-4}-4 x 10^{-4} m/s). For *L* ~ 50 m (the radius of bowl-shape Tub Lake), and *f* = 1.028 x 10^{-4} s^{-1} (45°N), the Rossby number, *Ro*, is ~ 0.07-0.08. This range lies within the values of Ro in our simulation in the ageostrophic regime and is consistent with the predicted circulation pattern. As the reviewer highlighted, in this case, and due to the snow cover on the lake, the circulation in the lake was thought to be driven by the input of heat from the sediment (Winter I).

Welch and Bergmann (1985) certainly identified the presence of density currents by adding dye (rhodamine) near the bottom of the littoral region (~ 4-m depth) in Methane Lake (63°N) during the Winter I period. They estimated through fluorometry that the approximate advance of the density current was ~10 m/day (=1 x 10^{-4} m/s). However, if we use this velocity value, and for *L* ~ 100 m and *f* = 1.3 x 10^{-4} s^{-1} (63°N), the Rossby number should be ~0.009 and the system should be in the transitional or geostrophic regimes. The authors reported that they "*were unable to detect the dye laterally more than a few meters on either side of a line between the addition site and the center of the lake*", suggesting no sign of the presence of a gyre in the lake. This mismatch between the expected and observed regime would suggest that other processes could play a role during Winter I period. Another possibility for the mismatch, is the uncertainty in their reported velocity estimates. The authors through the manuscript recurrently refer to "approximate" distances or "approximate limits of detectability". Given that lake horizontal currents are of O(10^{-4}-10^{-3}) m/s during the Winter I period, there is probably a non-negligible error associated with the method used. Both Likens and Ragotzkie (1966) and Welch and Bergmann (1985) used indirect methods to estimate current velocities. This range of velocities were already a limitation for later studies using direct measurements. For example, Malm et al. (1998) (doi: 10.4319/lo.1998.43.7.1669) used an acoustic current meter to directly measure horizontal velocities under ice and they reported a threshold limit for the device of 0.2 mm/s, resolution of 0.2 mm/s and ± 40% accuracy of reading.

In any case, we will include both studies in the subsection "*Conceptual model for lake circulation*" in the Discussion section. We propose that the text there now reads: "*A double-gyre circulation was also reproduced in numerical simulations (Huttula et al., 2010) of early winter conditions in Lake Pääjäarvi (61° N), when under-ice circulation was dominated by the input of heat* *from the sediment instead of by radiatively-driven convection. Also, when the input of heat from the sediment dominated lake circulation, Likens and Ragotzkie (1966) injected radioactive tracers near the center and in the littoral region in Tub Lake (45° N, R~50 m and $A_{total} = 8.4 \times 10^{-3}$ km^2) and detected the presence of a double-gyre circulation when Ro ~0.1 (calculated with their indirect estimates of horizontal velocities of 3.5×10^{-4}-4×10^{-4} m s^{-1}). The central cyclonic circulation had already been detected in this same lake by Likens and Hasler (1962) in a previous winter, suggesting that this azimuthal circulation pattern is recurrent during the ice-on season in the lake* ". In the discussion of the geostrophic regime, we propose that the text now reads: "*The lake-wide anticyclonic circulation in Fig. 5b would be consistent with the inferred lake-wide anticyclonic gyre reported by Rizk et al (2014) at a time when circulation in lake Pääjäarvi was dominated by a lateral gradient in the heat flux from the sediment (Winter I period) and Ro was O(10^{-3}-10^{-2}). Nonetheless, Welch and Bergman (1985), reported radial velocities of 1×10^{-4} m s^{-1} during the Winter I period in Methane Lake (63°N, R ~100 m, and $A_{total} < 0.1$ km^2) that would lead to estimates for Ro of O(10^{-3}-10^{-2}). By adding a dye (rhodamine) in a point in the littoral region and close to the lake bed, they detected the presence of density currents flowing offshore and no sign of gyre formation. This would be contrary to the expected radiatively-driven lake circulation in the geostrophic regime as presented in this study, and suggests that (1) other processes could be at play during Winter I or that (2) the radial velocity magnitude, and thus Ro, was underestimated by the authors. The latter is possible given that Welch and Bergman (1985) used dye concentrations to indirectly estimate O (10^{-4}) m s^{-1} radial velocities in the lake.*"

I hope all these comments are helpful in providing some more context to your interesting simulations.

We are grateful for this very helpful review.