Response to Reviews os-2015-84

On behalf of my co-authors and myself, I wish to submit a revised manuscript for consideration for publication as an article.

The Reviewers identified points primarily around strengthening the discussion. We have responded to each of the reviewer's points as detailed below. This has resulted in two new figures and many improvements in the text, for which we thank the Reviewers. We are very aware of the time and effort involved in this process and thank yourself and reviewers. We look forward to hearing from you in due course.

Sincerely

Craig Stevens

Response to Referee #1   osd-12-C1452-2016

Reviewer Summary: This manuscript reports observations of turbulent ocean heat fluxes in supercooled waters under sea ice, in a setting that may promote platelet ice growth. Time series of ocean current, temperature, and salinity are described alongside turbulent flux measurements in the boundary layer over the course of several tidal periods. The observed turbulent fluxes are shown to be well characterised using standard bulk formulae, based on the observed supercooling and the inferred friction velocity at the ice base. The friction velocities are used to argue that the platelet ice has a greater roughness length than alternative settings for heat transfer under sea ice.

The manuscript is clearly written, subject to a few technical clarifications. In my opinion the article provides useful observational data and constraints on bulk heat transfer correlations for settings with platelet ice growth, that are worthy of publication. One concern is that whilst the supposition in the title and last sentence of the abstract that the turbulent heat transfer controls platelet ice growth seems plausible, I would argue it is not yet firmly supported by the analysis in the present version of the manuscript. The results demonstrate turbulent heat transfer consistent with interaction with a freezing boundary, but have not yet shown that this flux is as significant, or more significant than other potential sources of heat transfer as detailed below. This conclusion needs to be either better supported by some further analysis/information, or else the discussion modified accordingly. Some suggestions for how to better evaluate this hypothesis follow below, along with a few other requests for technical clarification.

Author Response: We thank the Reviewer for their useful comments and we are pleased that that they found "useful observational data and constraints on bulk heat transfer correlations for settings with platelet ice growth, that are worthy of publication". We are presented with something of a conundrum in that Reviewer #2 recommends that we actually strengthen the language around our results and conclusions. The Reviewer raises several issues which we address in the following material. We have now modified the Discussion as requested and separated out our conclusions into a separate section and strengthened our justification for the conclusions with several new references that target points made by the Reviewer.

Specific comments:

Reviewer Comment 1. The title, last sentence of the abstract, and comment on page 2818, line 16-17 suggest that this manuscript has demonstrated that the ocean heat flux is providing a strong control on sea ice growth in this location. However, the present version of the manuscript arguably only demonstrates that the ocean turbulent flux is consistent with transfer between a boundary at the insitu freezing point, and a supercooled bulk fluid. It is less clear how significant this flux is as an overall driver of sea ice growth. Is there any evidence to demonstrate that this is indeed a strong control on the sea ice growth at this location, in comparison to other potential heat fluxes due to some combination of conduction up through the ice interior, lateral advection in the surface ocean, and relief of supercooling in the surface ocean over time by ice growth? If there were independent estimates of ice growth rate, these might be usefully compared to the ice growth expected if all of the downward ocean heat flux were used to remove latent heat of solidification. It may also be possible to produce scaling estimates for the heat flux conducted up through the sea ice if ice thickness and the upper and lower ice surface temperatures could be estimated.

Author Response: It would appear Reviewers 1 and 2 are opposed on this point. We view it as a likely hypothesis that needs more investigation. We lacked measurements for viable estimates of conductive heat flux in the ice column. Still, in agreement with Rev 2, if the product of ustar x deltaT limits (1-d) heat transfer away from the horizontal ice base, it provides an important limit on platelet growth. It seems that crystals grew more readily on objects suspended in the supercooled water because the heat can be diffused and advected away continuously in all directions. Our experience with time series of ice temperature profiles suggests that thermal memory in the ice precludes using upper and lower temperatures to estimate conductive flux on time scales as short as here. We have therefore modified the discussion significantly by rewriting the paragraph indicated above (page 2818, lines 11-18) and also paragraph that was on page 2817, lines 7-16. In page 2818 paragraph, we now reference Purdie et al. (2006) and Gough et al. (2012) who performed the calculations for sea ice growth as suggested by the reviewer here and obtained estimates of the amount of ice growth through negative oceanic heat flux. We did not have a thermistor probe installed at the site of our measurements, so cannot repeat the method of those authors, but since this is a similar location and with similar ice, this is sufficient in our view.

Reviewer Comment 2. The authors make several references to ice nucleation on the moorings and masts, and in particular that they have carefully discarded any of the ADV measurements that may have been contaminated by freezing. Based off your observations, is it possible to rule out any freezing onto instruments also impacting the temperature and salinity measurements, or whether such artificially induced freezing might have played a significant role in the heat budget for the region of the water column that is being measured?

Author Response: Yes this can have an effect on the measurements and this issue is addressed in McPhee et al., JGR 2013. The text is modified to clarify this and now states “This can affect both ADVs and conductivity sensors. We used the criteria identified in McPhee et al. (2013) to remove affected data”.

Reviewer Comment 3. Estimate of z_0 between equations (7) to (8). Some of the details of this calculation were not clear to me - can you provide further details? In particular, at what value of z is U(z) evaluated when estimating z_0? Also, taking log(z_0) in equation (8) needs a more consistent treatment of the physical units - has there been some non-dimensionalisation here? Minor clarifications/suggestions on presentation:

Author Response: We have added a qualifier "for U measured at 1 m" which addresses this (i.e. log 1 = 0).

Reviewer Comment 4. I didn’t find definitions of the directions of u_0, v_0 and w_0 before first use in equation (1), or an explicit definition of the turbulent dissipation rate above equation (2).

Author Response: The text has been amended so that it now states …” currents averaged over each realization were rotated into a reference frame such that mean vertical and cross-stream horizontal components vanished, from which the velocity perturbation components were resolved (u', v' and w'). Linear trends were then removed, then “area-preserving” (weighted) spectra were calculated…”. Reference to ε is now made in the opening paragraph of section 2.2.

Reviewer Comment 5. It might be worth providing a background reference(s) for the justification of equations (2), (3) and (7), for readers less familiar with the relevant parts of turbulence theory.

Author Response: We now reference the landmark text Tennekes and Lumley 1972.

Reviewer Comment 6. The scaling estimate in equation (3) assumes that buoyancy-driven convective turbulence is not significant in modifying the boundary layer structure. It might be useful to mention this here, but then note later (e.g. near to p.2815, lines 10-15) that the very good comparison between the two estimates of turbulent eddy length-scales in figure 5b provides support for your hypothesis of a shear-dominated boundary layer.

Author Response: The assumption that buoyancy is not influencing production of turbulence is implicit in the existing text which said “then TKE production rate by current shear is…”. The text has now been amended to say – “it is possible that buoyancy effects are also contributing to the turbulence and this can be examined by comparing production and dissipation rates.” Further below, where the two terms are compared the text now states - “This supports the hypothesis that buoyancy-induced turbulence is minimal in the present conditions.”

Reviewer Comment 7. Is there a typo in equation (4)? If I equate the production in equation (3) to the dissipation rate so that _ _ u$_3$_=(_ jzj) and substitute for _ jzj _ _ = c_=k$_{max}$, I end up with u_ _ (_c_=k$_{max}$)$_{1=3}$.

Author Response: We thank the Reviewer for spotting this – we're not sure what went wrong in the drafting but the equation got restructured somehow. It has now been corrected.

Reviewer Comment 8. p2816, line 8/9 "negatively increasing". Would "decreasing" be easier to read?

Author Response: Possibly, but the wording was chosen to emphasize that the thermal forcing increases in a negative sense. As a compromise the text now says "(Fig. 6a and c). The departure from the freezing point temperature also exhibits the trend of becoming larger (i.e., increasingly negative) with time during the observation period."

Reviewer Comment 9. p2816, line 11. Can you give a standard error (or other error bar) on the estimated value of c_H to allow a better estimate of it's similarity or difference to the other values? Also, I think there is a typo here as c changes from lower to upper case between lines.

Author Response: This could potentially be achieved by adding and subtracting the std dev error bars associated with the measured quantities, but this might be misleading for a record this short. The data from 2 tidal cycles are suggestive, not definitive.

Reviewer Comment 10. p2817, lines 8-16; discussion of congelation vs platelet ice growth. Could this be reworded to more clearly emphasise that the key difference between congelation and platelet ice growth is that a supercooled ocean allows a significant part of the released latent heat to also be removed into the cooler ocean in the case of platelet ice growth, whereas congelation growth cannot conduct heat into the ocean when the ocean is warmer than the freezing temperature at the ice-ocean boundary.

Author Response: This paragraph is now changed to read: "The ocean turbulent heat flux was negative (downward) throughout the entire measurement period (Fig. 6a). Sea ice in this region is typically forms as congelation ice early in the growth season, then incorporated platelet ice towards the end of the growth season (e.g., Smith et al., 2001). Congelation ice grows when the latent heat released during phase change is conducted from the relatively warm ocean to the relatively cold atmosphere. In this context, relatively cold means below the freezing point temperature of seawater. Platelet ice formation occurs in supercooled seawater and when this occurs near the ice/ocean boundary, the latent heat released can either be conducted upwards through the main ice column or transported downwards by turbulent heat flux into the ocean boundary layer. The latter process of negative oceanic heat flux does not occur for congelation ice because the ocean in that case is warmer than the freezing point temperature at the ice-ocean boundary."

Reviewer Comment 11. p2817, lines 11 and 12 "congelation growth in water at freezing temperature requires a small upward ocean heat flux to compensate for salt release" Can you provide a reference, or more detailed justification to support this statement? It isn't immediately clear to me that such a heat flux is always required (especially if salt were segregated into the pore space within the sea-ice interior during congelation growth, rather than being rejected at the sea ice interface with the ocean, and there is some delay in the subsequent drainage of brine out of the ice back into the ocean).

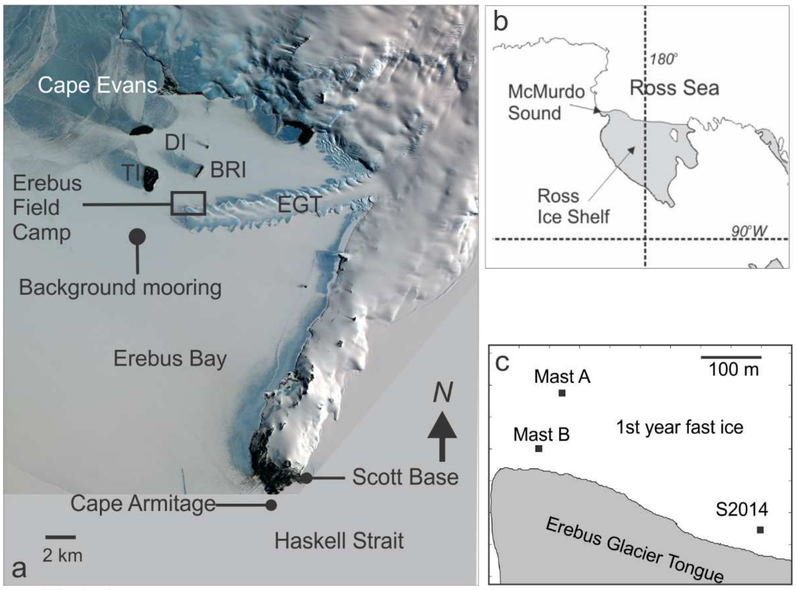
Author Response: The reviewer identifies an important aspect of the data. The appropriate reference is McPhee, Morison, Nilsen 2008. In order to keep the mixed layer at freezing as salt is added requires heat extraction. The argument does neglect the "mushy layer" concept but it is worth noting such layers are not always present. An example of this with a small upward heat flux consistent with downward salt flux is seen in Fig 6.14, McPhee (2008).

Reviewer Comment 12. p2818, line 25-26. “u_ will be modulated primarily by tides”. Is this universally true, rather than flows induced by ocean currents or wind-driven ice motion? Worth adding a qualifier?

Author Response: Agreed, the text now says “u_* will be modulated primarily by tides as direct wind forcing is effectively absent in the present fast ice situation.”

Reviewer Comment 13. Figure 2. The labels are small and hard to read in panel (c).

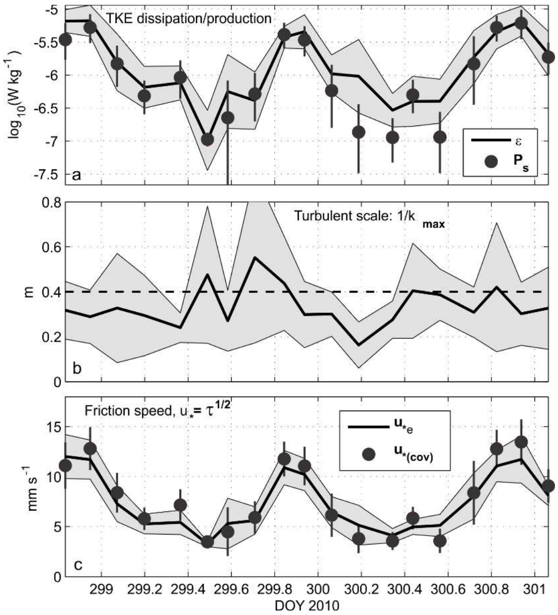
Author Response: The figure has been modified in response to this and to Reviewer Two’s comments.



Modified Figure 2

Reviewer Comment 14. Figure 5(c). What is t in the label at the top left? I’m presuming it is proportional to a turbulent stress, but it should be defined before use.

Author response: Again we thank the Reviewer for spotting this - a font change had been lost in the editing – it is τ and defined previously. It is corrected. Thanks.



Corrected Figure 5

Response to Referee #2 osd-12-C1459-2016

This paper presents a nice data set of turbulence under fast ice in Antarctic waters. In contrast to "the normal" situation in polar waters the heat flux is downward into the water below the ice. The unique data set and the clear way it is presented makes this a valuable contribution. The changes suggested before publications are minor in my view.

I have one substantial scientific comment, regarding the conclusions, consistent with the other reviewer. Contradictory to the other reviewer I think you could make stronger conclusions based on your results though. At least we agree that a conclusion section should be added. The conclusions given in the discussion are very modestly formulated in my view. Perhaps my view is guided by my experience and that I thus find the proposed hypothesis likely. Given the conclusive data set and that the first author is one of the most experienced researchers in this field, I would suggest that more firm conclusions should be stated. Given the very similar C_H values found here and in other studies, I think it is appropriate to fully conclude that the process has been explained, and that you can go beyond "hypothesizing" and "postulating".

Author Response: It is not clear to us that Reviewer #1 was actually asking for a separate conclusions section to be added. However, we see the Reviewer's point about strengthening the impact of the work and have done so. This mainly separates out the last few paragraphs of the text. Our reticence to be overly expansive in the generality of our conclusions lies in the small and focused nature of the results in a relatively unique macro-scale environment. However, saying this, the Reviewer is correct, at the boundary-layer scale it is a nice dataset and does have general applicability. We have used this as support for our strengthening of the language.

Minor comments:

Abstract: Line 9-10: You hypothesize that platelet growth is rate limited by turbulent heat transfer. It seems to me that you should you be able to answer this question fully.
Author Response: We have made minor, but key, changes that strengthen the definitiveness of our statements. Changes include "The data show that turbulent heat exchange at the ocean-ice boundary is….. Platelet ice growth appears to increase the hydraulic roughness (drag) of fast ice compared with un-deformed fast ice without platelets. … Platelet growth in supercool water under thick ice appears to be rate-limited by turbulent …"

Introduction: On the Weddell side large ice crystals were detected quite deep down in the water column (Dieckmann et al 1986), but at a location where super cooled Ice Shelf Water was present. This appears to be the same type of crystals as the platelets. My point is that large crystals have been found elsewhere outside the Ross sector, and that that given presence of super cooled water such crystals have been found a few decades back. The process studied here is thus more general than what the introduction appears to describe, and this should be included somehow.
Author Response: The Reviewer makes a good point and it wasn't intentional to suggest either that this process is only seen in McMurdo and/or that our group were the only people working on the topic. The text has now been amended with "The appearance of these supercooling-induced crystals is not limited to the western margin of the Ross Ice Shelf, with observations made in most cold-cavity systems sampled to date (Dieckmann et al. 1986; Craven et al. 2014; Hoppmann et al. 2015)."

Methods:
Page 6, line 19. "nonsensical" is new to me, I guess you mean "erroneous" or "invalid" or "wrong"?
Author Response: We have modified the text and replaced the word with "incorrect".

Results:
Page 7, line 19. What data do you mean here? I think it would be better to say "The presented data comes from spring tide: : :." But you also present data over several days (Figure 4,5,6 three days). So I think you need to re-write this part a little.
Author Response: We use spring tide here in the sense of being a period of larger tides rather than a single tidal period. The text has been amended to state "The present data come from springs phase of the tide…"

Page 8, line 4: How do you know the water column was isothermal down to 40 m? Did you do CTD casts – if so you should state this. It would be OK to do this without showing the figure if this will be used in a different paper. Also the statement for a super-cooled water column down to 15 m depth needs to be supported by either data or a citation.
Author Response: Good point. Profiles made with the mobile TIC mast B indicated that the water column was isothermal to about 40 m. In addition data described in

Stevens et al (2014) from the same campaign support the content that to within +/- 5mK the upper 40 m was isothermal. The text has now been modified to reflect these points.

Page 8, line 12. Please define DOY when it is used the first time.
Author Response: done

Page 8, line 16 – 18. Ok here comes the part explaining why you focus on the spring tide, so this should somehow be blended with the initial text on page 7, line 21.
Author Response: I think we made this overly confusing, our point simply was by working during the larger spring tides we get a wider range of velocities. The text now says: "The present data come from springs phase of the tide (Figure 3a) in order to experience the widest range of flow speeds, although the tidal effect is only weakly manifest in the far-field thermal structure (Figure 3b)."

Page 8, line 23. YD should be DOY? Also the section break here seems wrong because the section above and this one cover the same.
Author Response: OK we corrected the DOY and removed the paragraph break.

Page 8, line 25. I have not seen "slack water" before. Perhaps my tidal vocabulary is limited, but it also sounds very American. Is there a better and more precise term to use in a European English journal?
Author Response: We discussed this amongst ourselves and it appears that it has an Anglo provenance. We expanded the text to make it clear that it referred to periods of near-zero bulk flow at, or around, high and low water.

Page 9, line 7. Delete "with". Discussion:
Response: done

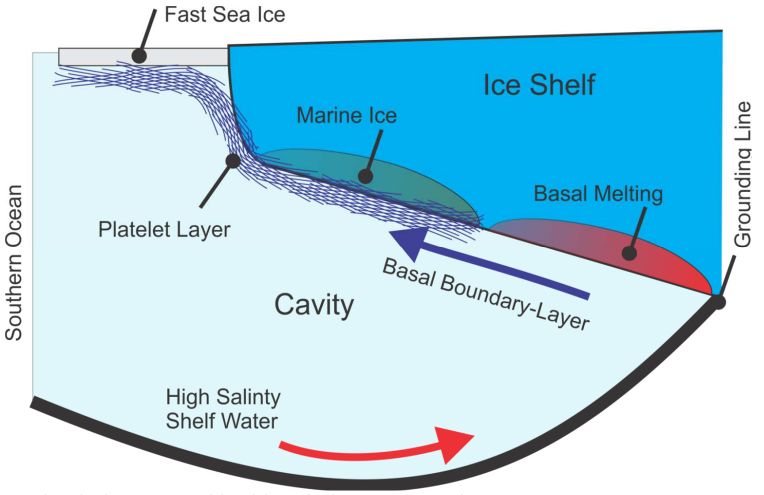
Page 11, line 11-12. "congelation : : :. release" This sentence is not meaningful to me. Ice growth leads to salt release, but in what way is an ocean heat flux required? Probably some text is missing here?

Author Response: We worked on this paragraph in conjunction with the other Reviewer's points. It now states "There is supercooled Ice Shelf Water water below the crystals, and these large crystals could not appear from the smaller ISW plume, because such large crystals would be bouyant enough to leave the ISW plume (Jenkins and Bombusch 1995; Smedsrud and Jenkins 2004). They need further heat loss in situ to grow to the large sizes observed, but yet the heat flux through the thick fast ice must be small. The ocean turbulent heat flux was negative (downward) throughout the entire measurement period (Fig. 6a). Sea ice in this region is typically forms as congelation ice early in the growth season, then incorporated platelet ice towards the end of the growth season (e.g., Smith et al., 2001). Congelation ice grows when the latent heat released during phase change is conducted from the relatively warm ocean to the relatively cold atmosphere. In this context, relatively cold means below the freezing point temperature of seawater. Platelet ice formation occurs in supercooled seawater and when this occurs near the ice/ocean boundary, the latent heat released can either be conducted upwards through the main ice column or transported downwards by turbulent heat flux into the ocean boundary layer. The latter process of negative oceanic heat flux does not occur for congelation ice because the ocean in that case is warmer than the freezing point temperature at the ice-ocean boundary."

Page 12, line 14 – 16. Again you draw conclusions extremely carefully. What else than delta T and friction velocity could contribute to the heat flux? I understand the difference in time scale between variation in u_* and the heat flux, but still think that you can pose proper conclusions based on your observations. If you can't state that this has been explained "well enough" then who can? There is supercooled Ice Shelf Water (ISW) water below the crystals, and these large crystals could not appear from the smaller ISW plume, because such large crystals would be bouyant enough to leave the ISW plume (Jenkins 1995, Smedsrud 2004). So they need further heat loss in situ to grow that large, and the heat flux through the thick fast ice must be small as stated in the cited work. Some more reasoning around this issue could perhaps convince the other reviewer, that might be less familiar with the physical setting here, but probably has a better grasp of the turbulent heat transfer.
Author Response: This is a nice summary and we have taken the liberty of paraphrasing some of it, including the suggested and relevant references. Our on-going work is looking at the deep-water supply of the crystals, exploring some of the points that follow from this and the Dieckmann observations identified elsewhere by this Reviewer.

Figures:

Figure 1: I think it is much better to NOT use abbreviations in a figure, because people might look at it independently. There is plenty of room in the figure. Abbreviations could be given in the figure caption if needed.
Author Response: OK, we have amended the Figure.

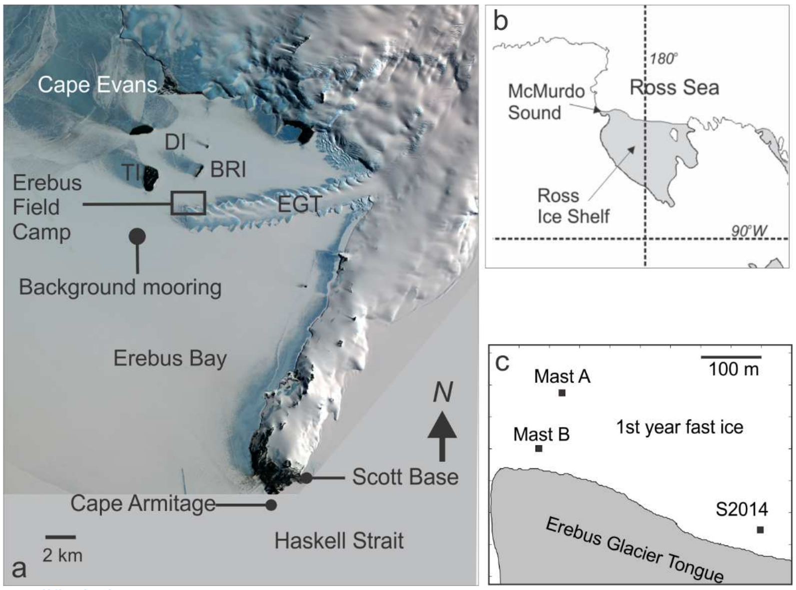


Revised Fig 1 now with abbreviations removed

Figure 2: This figure is definitely too small. It is not possible to see the names and features in the image. The middle image should be larger, and the two insets could

be placed inside this one. With a larger figure the names can be spelled out properly as well. Also the square box in the upper figure seems to have no purpose.

Author Response: The figure has been restructured, largely as suggested, with the superfluous box removed. The smaller images could not reasonably be placed as insets and still be meaningful. A couple of the abbreviations had to remain but most were removed. But if this is a full width figure this will work well.



Modified Figure 2

New references:

Dieckmann, G., G. Rohardt, H. Hellmer, and J. Kipfstuhl (1986), The occurrence of ice platelets at 250 m depth near the Filchner Ice Shelf and its significance for sea ice biology, Deep Sea Res., Part A, 33, 141–148.

Jenkins, A., and A. Bombosch (1995), Modeling the effects of frazil ice crystals on the dynamics and thermodynamics of the ice shelf water plumes, J. Geophys. Res., 100, 6967–6981.

Smedsrud, L. H., and A. Jenkins (2004), Frazil ice formation in an ice shelf water plume, J. Geophys. Res., 109, C03025, doi:10.1029/2003JC001851.

Tracked Changes Version

Turbulent heat transfer as a control of platelet ice growth in ~~supercool~~supercooled under-ice ocean boundary-layers

M.G. McPhee[1], C.L. Stevens[2,3], I.J. Smith[4] and N.J. Robinson[2]

[1] McPhee Research Company, Naches Washington, USA.

[2] National Institute for Water and Atmospheric Research~~,~~ (NIWA), Greta Point Wellington, New Zealand.

[3] Department of Physics, University of Auckland, ~~Dept. Physics~~Auckland, New Zealand

[4] Department of Physics, University of Otago, ~~Dept. Physics~~Dunedin, New Zealand.

Correspondence to: C.L. Stevens NIWA, 301 Evans Bay Pde, Kilbirnie PO Box 14-901, 6021, New Zealand (c.stevens@niwa.co.nz)

Abstract

~~L~~ate winter measurements of turbulent quantities in tidally modulated flow under land-fast sea ice near the Erebus Glacier Tongue, McMurdo Sound, Antarctica, identified processes that influence growth at the interface of an ice surface in contact with ~~supercool~~supercooled seawater. The data ~~suggest~~show that turbulent heat exchange at the ocean-ice boundary is characterized by the product of friction velocity and (negative) water temperature departure from freezing, analogous to similar results for moderate melting rates in seawater above freezing. Platelet ice growth appears to increase the hydraulic roughness (drag) of fast ice compared with undeformed fast ice without platelets. ~~We hypothesize that platelet~~Platelet growth in ~~supercool~~supercooled water under thick ice ~~is~~appears to be rate-limited by turbulent heat transfer and that this is a significant factor to be considered in mass transfer at the under-side of ice shelves and sea ice in the vicinity of ice shelves.

Introduction

In addition to seaward advection, calving and basal melting, the distribution of mass in ice shelves depends on the so-called ice pump (Lewis and Perkin, 1986). By this mechanism, water warmer than the in situ freezing point temperature, typically High Salinity Shelf Water entering the under-shelf cavity, encounters glacial ice at~~ high pressures, e.g.,~~, or near, the grounding line~~, where it is cooled~~. The local cooling and ~~freshened~~freshening by basal melting (~~BM, ~~Figure 1) of the ice shelf underside happens at high local pressure. The resultant buoyant water circulates to lower pressure regions as the glacier base thins toward the terminus, and in the process may become ~~supercool~~supercooled relative to its in situ pressure (Foldvik and Kvinge, 1974).

~~Supercool~~Supercooled water can then deposit ice by direct growth of ice crystals attached at the ice underside, or by upward migration of frazil crystals suspended by turbulence in the water~~.~~ (Dieckmann et al. 1986). In this way, fresh glacial ice near the grounding line ~~transforms~~can be transformed to marine ice (Langhorne 2008). Evidence from icebergs (Kipfstuhl et al., 1992), borehole (Craven, et al., 2005) and radar studies (Engelhardt and Determann, 1987; Robin et al., 1983; Holland~~,~~ et al., 2009) indicate that marine ice can reach appreciable thicknesses, and that the ice pump is active under shelves where the water entering the cavity is near freezing.

Formation of marine ice ~~(MI, ~~(Figure 1) under ice shelves is difficult to observe directly (Craven et al. ~~2015~~2005), but similar effects are readily observed beneath nearby sea ice where it is called platelet ice (e.g. Robinson et al., 2014; Hughes et al., 2014; Hoppmann et al~~.~~., 2015; Langhorne et al~~. 2015; Hughes et al.~~., 2015). For example in McMurdo Sound, Antarctica, sea ice crystals that have formed in ~~supercool~~supercooled water have been observed and reported since the British National Antarctic (Discovery) Expedition of 1901–04 (Hodgson, 1907) and the British Antarctic (Terra Nova) Expedition of 1910-1913 (Wright and Priestley, 1922). Crystals observed in McMurdo Sound have reported to be up to 250 mm in diameter (Robinson et al~~,~~., 2014; Smith et al., 2001). In part because of their size and aspect ratio, and that turbulent suspension is not a direct driver, these crystals are ~~now known~~identified as “platelet ice”. They have been observed attached to the underside of sea ice (Gow et al., 1998), often forming layers 2-3 m thick (Dayton et al., 1969) and in some places as much as 8 m thick (Hughes et al~~.~~., 2014). Platelet ice crystals have been observed to become incorporated into the sea ice by subsequent congelation growth (Jeffries et al., 1993).

The presence of ~~supercool~~supercooled water measured below sea ice (Lewis and Perkin, 1985; Smith et al., 2001~~)~~), and the abundance of platelet ice, has been linked to locations of observed supercooling (Crocker and Wadhams, 1989) and to the ocean currents from beneath the ice shelf (Leonard et al., 2011; Fer et al. 2012). Evidence of this link is provided by the thicker accumulations of platelet ice (i.e. a sub-ice platelet layer~~ PL~~ Figure 1) found on the western side of McMurdo Sound (Dempsey et al., 2010; Hughes et al., 2014; Robinson et al., 2014~~) than~~), compared to that on the east (Gow et al., 1998; Jeffries et al., 1993~~,~~; Dempsey et al., 2010) where platelet ice only starts to form in late winter (Paige, 1966). Leonard et al. (2006) and Mahoney et al. (2011) reported acoustic and video evidence that platelet ice crystals begin as small crystals (2-20 mm) that become larger once attached to the sea ice cover above.

Based on heat and mass balance measurements within the ice column, the residual oceanic heat flux associated with incorporated platelet ice has been reported as negative (i.e., heat moves downwards into the ocean) by several authors (Gough et al., 2012; Purdie et al., 2006; Smith et al., 2012; 2015) with values ~~as large as~~of -30 W m^{-2} or more reported ~~elsewhere~~ (Purdie et al., 2006; Smith et al., 2001; Langhorne et al., 2015). Smith et al. (2001) noted that forced convection was needed to account for the amount of platelet ice observed in McMurdo Sound, and Smith et al. (2001) and Stevens et al. (2009) estimated kinematic eddy viscosities of 2×10^{-5} m^2 s^{-1} and 5×10^{-4} m^2 s^{-1}, respectively, in ~~supercool~~supercooled water in McMurdo Sound. Smith et al. (2012) observed episodic growth of individual platelet ice crystals, with periods of growth at least an order of magnitude faster than the growth of the bulk sea ice. They suggested that variable currents were responsible for the episodic nature of the crystal growth. The appearance of these supercooling-induced crystals is not limited to the western margin of the Ross Ice Shelf, with observations made in other cold-cavity systems sampled to date (Dieckmann et al., 1986; Craven et al., 2014; Hoppmann et al., 2015; Langhorne et al., 2015).

~~This~~The present work seeks to answer the questions (i) if and how the growth of platelet ice at a ~~supercool~~supercooled ice-ocean interface impacts the physical characteristics of the interface, including hydraulic roughness and the rate of heat transfer in the water column, and (ii) what feedbacks might exist. Direct turbulence measurements make this possible by enabling characterisation of the boundary-layer and direct measurement of heat fluxes. This facilitates improved parameterization of exchange processes in terms of mean quantities and will enhance the modeling of the ice-pump deposition phase in ice shelf cavities (Gwyther et al., 2015) as well as estimation of the spatial envelope of sea ice growth influenced by these cavities (Langhorne et al~~.~~., 2015).

Methods

Field camp and instrumentation

In October and November, 2010, the New Zealand National Institute Water and Atmospheric Research (NIWA) established a temporary station (Erebus Field Camp -- EFC) on fast (immobile) sea ice near Erebus Glacier Tongue (EGT) in McMurdo Sound, Antarctica. The general layout of EFC and its location relative to nearby geographic features is described by Stevens et al. ~~(2014) (Figure 2).~~(2014; 2011) and shown in Figure 2. The experiments took place prior to the 2012 calving that substantially reduced the length of the glacier tongue (Stevens et al. 2014). Included in the deployment was instrumentation designed to accurately measure current, temperature, and salinity in tidal flow beneath the stationary sea ice, at a resolution sufficiently small to enable turbulent fluxes of momentum, heat, and salt to be quantified.

A top-mounted mooring was deployed in 350 m of water, 2.5 km to the SW of the EFC at 77° 42.7730 S, 166° 21.4350 E, spanning the period in question. This mooring contained three Aanderaa RCM-9 units coupled with SBE 37 Microcat temperature, salinity, and pressure recorders (Seabird Electronics, USA). The current meter/Microcat pairs were located at depths of 50, 150, and 300 m. Upon recovery of the mooring it was found that the line had lifted sufficiently so that the top 10 m had frozen into the growing ~~subice~~sub-ice platelet layer. This has been encountered previously on instrument deployments when the buoyancy force from platelet accretion on mooring lines had overwhelmed the mooring ballast. The remote nature of the field camp meant it was not possible to deploy very heavy ballast blocks.

Flux measurements near the ice/ocean interface were made with turbulence instrument clusters (TICs), each comprising an acoustic-Doppler velocimeter (Sontek ADVOcean, 5 MHz), mounted with its fixed sample volume in the same plane as a nearby Sea-Bird Electronics temperature (SBE 3F)/conductivity (SBE 4) pair. Conductivity measurements were supplemented by a dual electrode microstructure conductivity instrument (SBE 7). The velocity sensors have a resolution of 0.1 cm s^{-1} and an accuracy of ±1% of measured velocity. The dynamic range of the conductivity signal is typically large relative to instrument sensitivity with an initial accuracy of ± 0.0003 S m^{-1}. The thermometers have an initial accuracy of ± 0.001 °C and a stability 0.002 °C per year typically along with a self-heating error <0.0001 °C in still water. Here we assume a working accuracy for the temperature sensors of 5 mK. TICs configured as above have been deployed under ice during several previous projects (McPhee, 2008a; McPhee et al., 2008; McPhee et al., 2013; Sirevaag et al.,

2010) and shown to measure well into the inertial subrange of the turbulent kinetic energy spectrum, hence adequately capturing the covariance of vector and scalar variables in turbulent flows.

The TICs were deployed on separate suspended masts (Figure 2) under fast sea ice ~~about~~with 2.15 m in initial ice thickness (start day of year, DOY 298) and a thin layer (~10 cm, think compared to observations described elsewhere, e.g. Robinson et al. 2014) of platelets. Mast A included two TICs mounted 1 and 3 m below the ice on a fixed mast suspended through a 1 m diameter hole, located about 140 m from the edge of EGT. Mast B, located closer (40 m) to the glacier tongue, included two TICs mounted 4 m apart on a rigid mast that could be lowered by cable to depths up to 70 m.

Turbulence analysis

Time series of three velocity components, temperature, and salinity derived from temperature and conductivity were segmented into 15-min realizations for calculating turbulence statistics, including the rate of dissipation of turbulent kinetic energy ε, following the method described by McPhee (2008a). Currents averaged over each realization were rotated into a reference frame such that mean vertical and cross-stream horizontal components vanished, ~~linear trends were~~from which the velocity perturbation components were resolved (u', v' and w'). Linear trends were then removed, then "area-preserving" (weighted) spectra were calculated, and transformed to the wave-number (spatial) domain under the frozen field hypothesis. Ice nucleation on instruments immersed in ~~supercool~~supercooled water significantly degraded their performance after just a few tidal cycles. This can affect both ADVs and conductivity sensors. We used the criteria identified in McPhee et al. (2013) to remove affected data. Ice accreting on the ADV hydrophones increased noise at higher frequencies, eventually leading to ~~nonsensical~~incorrect velocities. Consequently, we placed added emphasis on ensuring that turbulent spectra exhibited key elements including a peak in the area-preserving spectrum of vertical velocity variance and a reasonable fall-off to the -2/3 slope in the log-log representation of the area-preserving spectrum (McPhee, 1994; 2008a). Each 15 minute spectrum was evaluated for a discernible peak in the area- preserving vertical velocity variance spectrum, and if found to be viable, was included in a three-hour grouping of realizations to determine mean statistics.

Friction speed, u_*, (the square root of kinematic Reynolds stress magnitude) was estimated by averaging covariance statistics, i.e.,

~~$u_* = \left(\langle u'w'\rangle^2 + \langle v'w'\rangle^2\right)^{1/4}$~~

$$u_* = \left(\langle u'w'\rangle^2 + \langle v'w'\rangle^2\right)^{1/4} \qquad (1)$$

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where we have invoked Taylor's frozen field hypothesis linking measurements in the time domain at a single location to ensemble statistics. After identifying the peak in each spectrum, a high-order polynomial was fitted to wavenumbers in its vicinity, which was then analyzed to determine the wavenumber where the negative slope reached or exceeded 2/3, taken as signifying spectral levels in the inertial subrange. The turbulent kinetic energy (TKE) dissipation rate was estimated from (see e.g. Tennekes and Lumley, 1972)

~~$\varepsilon^{2/3} = \frac{3}{4\alpha_\varepsilon} S_{ww}(k) k^{5/3}$~~

$$\varepsilon^{2/3} = \frac{3}{4\alpha_\varepsilon} S_{ww}(k) k^{5/3} \qquad (2)$$

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where S_{ww} is the spectral density evaluated at angular wave number k, in the inertial subrange, and α_ε is the Kolmogorov constant for the along-stream spectrum (0.51).

By assuming that flow within 1 m of the boundary lies within the so-called surface layer, where stress is nearly constant and the velocity profile is logarithmic, then TKE production rate by current shear is

$$\cancel{P_s = \tau \frac{\partial u}{\partial z} = \frac{u_*^3}{\kappa |z|}} \; P_s = \tau \frac{\partial u}{\partial z} = \frac{u_*^3}{\kappa |z|} \qquad (3)$$

where κ is Kàrmàn's constant (0.4). It is possible that buoyancy effects are also contributing to the turbulence and this is examined by comparing production and dissipation rates.

Results

The present data come from the "springs" period of the spring~~ tide~~-neap tidal cycle (Figure 3a) in order to experience the widest range of flow speeds, although the tidal ~~flow~~effect is only weakly manifest in the far-field thermal structure (Figure 3b). No data were retrieved from this far-field mooring at depths shallower than 50 m due to platelet growth effects. Indeed, as well as the incorporation of the upper 10 m of the instrumented mooring line into the growing sea ice, the mooring line itself was subject to ice accumuation-driven buoyancy-driven rise of 8 m in a 50 day period although the lift was only around 1 m during the collection of the data in (Figure 3). The 50 m data remain around -1.91 to -1.92 ° C.

At the mast site, during the measurement period, profiles made with the mobile TIC mast B indicated that the water column was isothermal to about 40 m~~ depth, with~~. In addition data described in Stevens et al. (2014) from the same campaign support the contention that, to within ±5 mK, the upper 40 m was isothermal. The upper 15 m exhibited temperatures below the pressure-dependent freezing temperature, i.e., in-situ

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~~supercool, down to about 15 m~~supercooled. The growth of ice on the far-field mooring was corroborated by platelet growth on the cable suspending Mast B. At Mast A (TICs at 1 and 3 m below the ice undersurface) ice accretion on the instruments limited the duration of acceptable measurements to about two diurnal cycles (~60 h) ending early (~~UT~~UTC) on DOY (day of year) 301. Shortly afterwards, Mast A was recovered, and thereafter Mast B was generally stationed below the ~~supercool~~supercooled zone at depths ranging from 18 to 62 m, so as to minimize ice accretion. Here we emphasize data from Mast A to address conditions near the horizontal fast ice/ocean interface.

S~~pring tide data~~Data recorded during spring tides provide the largest velocity range and also the largest horizontal advection of different water masses. Currents measured 1 m below the ice/water boundary at Mast A from late on 25 Oct 2010 (DOY 298) to early on 28 Oct (Figure 4a) show a significant tidal signal resulting in speeds up to around 0.15 m s^{-1}. This is superimposed upon a steadier westward flow strong enough to prevent current reversal (Figure 4b) either through flow rectification or regional circulation (Stevens et al~~.~~., 2011, 2014).

This was confirmed over a 10-day period beginning ~~with YD300~~on DOY300, where currents measured in the upper 60 m of the water column at the Mast B site ranged from 0.03 to 0.28 m s^{-1} westward (Stevens et al~~.~~., 2014). Salinity shows a slowly increasing trend of around 0.0075 PSU/day that is interrupted briefly ~~at~~ during low flows (“slack water”) at high and low tide (Fig. 4c).   In near-freezing waters, salinity dominates~~ influence on~~ buoyancy and so these perturbations are likely some form of propagating feature in the density structure. Certainly, the features in salinity at DOY 299.3-299.5 coincide with the directional change in Fig. 4b. Temperature measurements (Fig. 4d) on the other hand do not have obvious signatures connected to the flow. This is not uncommon at these temperatures where there is almost no thermal

Formatted: Normal, Indent: First line: 1.27 cm, Space Before: 5.75 pt, After: 5.75 pt, Line spacing: Double, No widow/orphan control, Don't hyphenate contribution to density. The record shows that water 1 m below the ice remained, on average, 8.7 mK below freezing. The salinity trend's influence on the freezing point is apparent in Figure 4d. This trend is largely mirrored in the measured temperature.

Consideration of the turbulent properties in the measurement volume indicates that the three-hour-average estimates of rate of dissipation of turbulent kinetic energy ε compares closely to ~~with~~ the production P_s (Figure 5a). The only departure from this is for a slack-water low flow period (DOY 300.2-300.6) when the production estimate drops significantly below the dissipation rate estimate. Under-ice measurements have shown close correspondence between the dominant turbulence length scale and the inverse of the angular wavenumber at the peak of the vertical velocity variance spectrum, i.e., ~~$\lambda = c_\lambda / k_{\max}$~~ $\lambda = c_\lambda / k_{\max}$, where c_λ is a constant of order unity (McPhee, 2008a; McPhee and Martinson, 1994). A time series of λ is compared with the geometric (surface layer) scale $\kappa|z|$ in Figure 5b which one would expect to be a limiting scale on the turbulent eddies. The inverse peak wavenumber turbulence lengthscale sits mostly beneath the geometric scale.

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When TKE production and dissipation rates are comparable, as suggested by Figure 5a, the steady, horizontally homogeneous TKE equation provides an independent estimate of friction speed based exclusively on characteristics of the vertical velocity variance spectrum

~~$u_{*\varepsilon} = (k_{\max}\varepsilon / c_\lambda)^{1/3}$~~

$$u_*^3 = \lambda\epsilon = \frac{c_\lambda}{k_{max}}\epsilon \qquad (4)$$

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The virtually-independent estimates of friction speed (Figure 5c) agree well. This supports the hypothesis that buoyancy-induced turbulence is minimal in the present conditions.

The vertical turbulent heat flux can be estimated from

~~$H_f = \rho c_p \langle w'T' \rangle$~~

$$H_f = \rho c_p \langle w'T' \rangle \qquad (5)$$

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where ρ is water density and c_p is specific heat of seawater at constant pressure (Figure 6a). Heat flux measurements derived in such a way (Figure 6a) remain entirely negative with the standard deviation being around half the mean value. The heat flux follows a weakly diurnal pattern with broad similarity to u_* (Fig. 5c). The implication then is that a bulk description may be useful as employed for moderate melt rates in water above freezing, so that

~~$H_f = \rho c_p c_H u_* \Delta T$~~

$$H_f = \rho c_p c_H u_* \Delta T \qquad (6)$$

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~~w~~here $\Delta T = T - T_f(S, p)$ is the departure from the freezing temperature. The ΔT (Figure 6b), is semidiurnal in structure and so not particularly coupled with the diurnal cycle seen in the calculated and measured heat fluxes (~~Figure~~Fig. 6a~~,c),~~ and ~~has a negatively increasing trend. Unlike~~c). The departure from the ~~heat flux estimate,~~freezing point temperature also exhibits the ~~variability around~~trend of becoming larger (i.e., increasingly negative) with time during the ~~mean is reduced.~~observation period. The ~~relationsip~~relationship can be restructured to solve for the transfer coefficient c_H. ~~Averageing~~Averaging the ratio from each of the acceptable 3-hour averages results in $c_H = 0.0085$. Applying this average bulk transfer coefficient and comparing with the measured (Figure 6C) indicates that the bulk approach does ~~reasonable~~reasonably well. Notably, the diurnal cycle, while not apparent in the semidiurnal ΔT, is sufficiently

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Discussion

The questions posed in the introduction relate to how the supercooling and the modified roughness associated with the resulting crystals influence the heat flux. Equation (6) indicates that the problem, for a given temperature difference, can be reduced to a combination of the turbulent heat transfer coefficient c_H and the turbulent velocity scale. The c_H value found here (0.0085) is not far different from values reported for basal heat exchange in above freezing water: e.g., c_H = 0.0057 for the year-long SHEBA project in the western Arctic (McPhee, 2008a); 0.0056 for first-year ice in the Weddell Gyre (McPhee et al., 1999). Furthermore, it almost matches the c_H =0.0084 determined for rapid melting in the eastern Arctic (Sirevaag, 2009). This suggests any different behaviour in heat flux is due to the velocity structure induced by the roughness.

As identified by Gwyther et al. (2015), the roughness of the boundary affects growth in two ways. First, it influences heat transfer at the ice-ocean interface and second it alters the mixing within, and entrainment into, the basal boundary-layer ~~(BaBL, ~~(Figure 1). While these authors note that sea ice is different to the underside of an ice shelf, it is likely that, at the boundary-layer scale~~ that,~~ the presence of ~~supercool~~supercooled water and ~~platelets~~platelet ice crystals will generate similar effects in the two systems.

~~The~~There is supercooled Ice Shelf Water (ISW) water below the crystals, and these large crystals could not appear from the smaller ISW plume, because such large crystals would be sufficiently buoyant to leave the ISW plume (Jenkins and Bombusch

1995; Smedsrud and Jenkins 2004). The crystals require further in situ heat-loss to grow to the large sizes observed. As the heat flux through the thick fast ice is small it indicates the ocean heat flux is the major driver of growth. This is supported here as the ocean turbulent heat flux was negative (downward) throughout the entire measurement period ~~(Figure 6a).~~(Fig. 6a). Sea ice in this region typically ~~grows in water near or slightly above freezing, where~~forms as congelation ice early in the growth season, then forms incorporated platelet ice towards the end of the growth season (e.g., Smith et al., 2001). Congelation ice grows when the latent heat released during phase change is ~~balanced by upward conduction driven by air temperatures lower than the freezing~~ conducted from the relatively warm ocean to the relatively cold atmosphere. In this context, relatively cold means below the freezing point temperature of seawater. ~~In the absence of horizontal advection, congelation growth in water at freezing temperature requires a small upward ocean heat flux to compensate for salt release. In contrast, platelet nucleation~~Platelet ice crystal formation occurs in supercooled seawater and when this occurs near the ice/ocean boundary ~~releases~~, the latent heat ~~that must be conducted~~released can either ~~upward in~~be conducted upwards through the main ice column ~~(perhaps against the temperature gradient within the platelet layer, PL Figure 1) or downward~~ or transported downwards by turbulent heat flux ~~in~~into the ocean boundary layer. –The latter process of negative oceanic heat flux does not occur for congelation ice because the ocean in that case is warmer than the freezing point temperature at the ice-ocean boundary.

There is a growing awareness of the ubiquity of such downward heat flux conditions in the vicinity of ice shelves (Robinson et al~~.~~., 2014; Craven et al., 2015; Hoppmann et al., 2015). The resistance then imposed by a stationary ice cover influenced by such crystal growth on underlying boundary-layer flow depends on the

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Formatted: Font: Do not check spelling or grammar undersurface *hydraulic roughness, z₀*. For the conditions found at EGT (i.e. $P_s \approx \varepsilon$, undeformed, relatively uniform underice surface), we expect the flow 1 m below the interface to follow the dimensionless shear equation

$$\cancel{\frac{\kappa|z|}{u_*}\frac{\partial u}{\partial z}-1}\;\frac{\kappa|z|}{u_*}\frac{\partial u}{\partial z}=1 \tag{7}$$

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~~w~~here U is mean current speed. The integral of (7) yields a logarithmic velocity profile (the "law of the wall") where the integration constant is ~~$\log z_0 = -\kappa U/u_*$.~~ $\log z_0 = -\kappa U/u_*$. For slow currents, the law of the wall is not necessarily valid at 1 m (McPhee, 2008b), so we evaluated $\log z_0$ for 3-hour averages with current speeds >= 0.05 m s^{-1}. ~~The~~ For U measured at 1 m (i.e. log 1 = 0) the average with standard deviation of the acceptable 3-hour samples was

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$$\cancel{\langle \log(z_0)\rangle = -3.95 \pm 0.30}$$

$$\langle \log(z_0)\rangle = -3.95 \pm 0.30 \tag{8}$$

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The expected value for z_0 is thus about 19 mm.

The observed z_0 identified here is larger than values obtained previously from measurements under undeformed fast ice without platelet accumulation, typically found to be nearly hydraulically smooth, with z_0 ~ ~~10^{-5} m~~0.01 mm (Crawford et al., 1999; McPhee et al., 2008; McPhee et al., 2013). It is comparable to values inferred for drifting, multiyear pack ice in the Arctic and western Weddell Sea: ~40 mm (McPhee, 2008b; Shaw et al., 2009) and is considerably larger than first-year, drifting ice near the center of the Weddell Gyre, ~1 mm (McPhee et al., 1999).

~~We postulate~~

Conclusions

Our data show that ~~this~~ turbulence-enhanced transfer of ~~supercool~~supercooled seawater ~~is~~can be the source of the negative heat flux measured within the ocean boundary layer ~~during~~dring the present observations. Our results thus complement the negative ocean heat flux inferred from ice measurements by, e.g., Smith et al. (2012). In addition, Purdie et al. (2006) and Gough et al. (2012) estimated of the amount of ice growth through negative oceanic heat flux (Figure 7), which provides additional support for our contention. Furthermore, the downward ocean heat flux, which this work suggests depends on the product of friction speed and ΔT, imposes a strong constraint on the rate of ice growth under stationary ice in ~~supercool~~supercooled water. This has significant implications for parametrization of basal boundary-layers beneath both ice shelves and sea ice (Gwyther et al., 2015).

It is instructive to consider the heat flux distribution as a function of the u_* and ΔT drivers (Figure 7) as there is growing evidence that the presence of ice shelves produces values for both that are outside present expectations. The heat flux contours enable contextualisation of existing results obtained either as measurements of u_* and ΔT pairs or as a heat flux for a particular temperature condition. Parameterisation in terms of u_* suggests timescale is important. While heat flux is typically considered over daily, or longer, timescales so as to compare with seasonal ice growth, u_* will be modulated primarily by tides~~.~~ as direct wind forcing is effectively absent in the present fast ice situation. This is especially important if there is some non-linearity in the growth of more ice as the form of platelets influences u_*.

While the present short period of data saw around a factor of 6 variablity in H_f (Figure 6c) as the two drivers are largely de-coupled, the contours (Figure 7)

~~suggest~~show that, depending on the local turbulence conditions and degree of supercooling, this variability ~~might approach~~approaches two orders of magnitude. Extending this idea, Gwyther et al. (2015) presents a sensitivity analysis that suggest that the variability in u_* through platelet modification of C_d might be as much as an order of magnitude. Future work to address this issue needs to ~~enhance our understanding of~~focus on quantifying the combined influence of turbulence, thermally-induced roughness and heat transfer.

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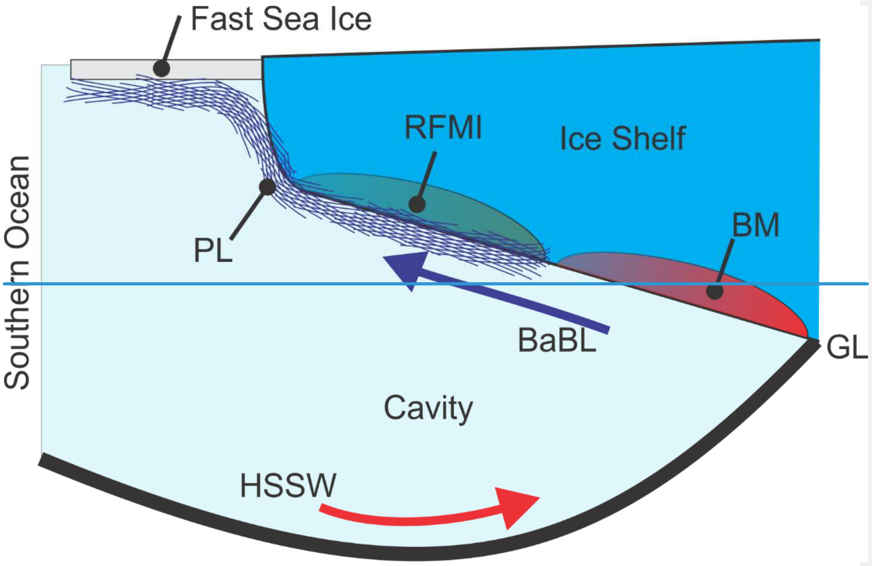


Figures

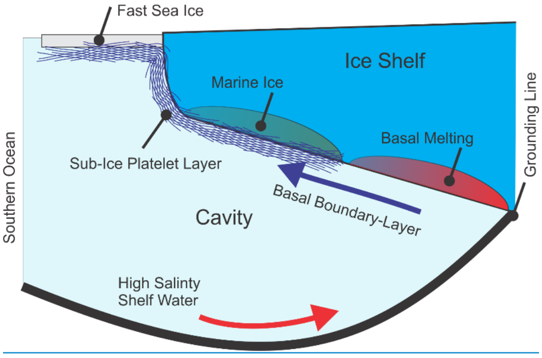
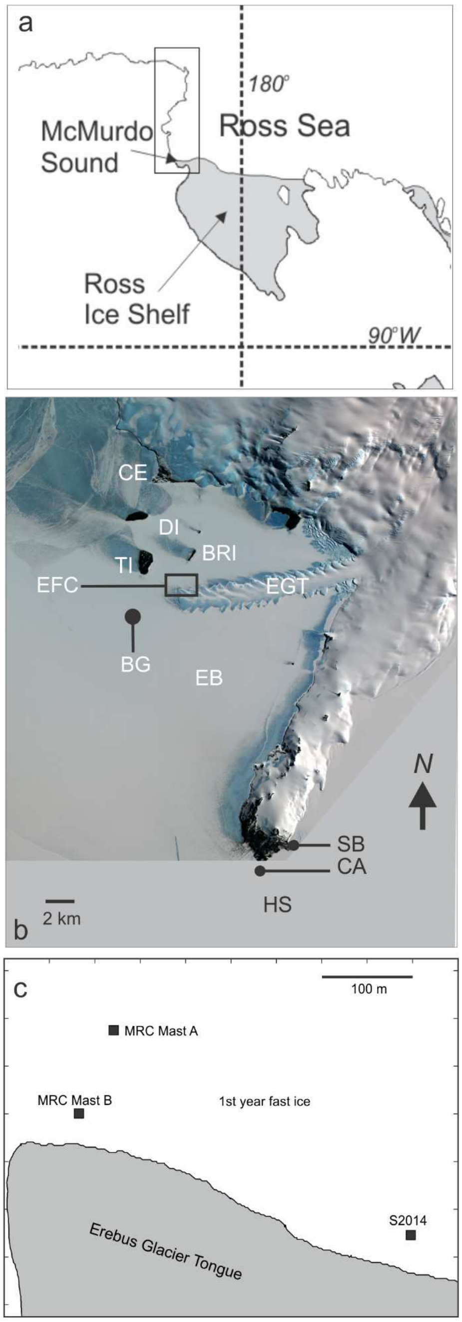


Figure 1 Ice pump showing high salinity shelf water (HSSW) flowing in at the base of an ice shelf cavity, commencing basal melting ~~(BM)~~ at, or around, the grounding line ~~(GL).~~. This buoyant meltwater flows upwards and outwards in a basal boundary-layer ~~(BaBL).~~. An associated sub-ice platelet~~-forming~~ layer ~~(PL)~~ supports ice growth through freezing into marine ice ~~(MI)~~ and ~~PL~~sub-ice platelet layer beneath fast sea ice.


a
180°
Ross Sea
McMurdo Sound
Ross Ice Shelf
90°W
CE
DI
BRI
TI
EFC
EGT
BG
EB
N
SB
CA
HS
2 km
b
c
100 m
MRC Mast A
MRC Mast B
1st year fast ice
Erebus Glacier Tongue
S2014

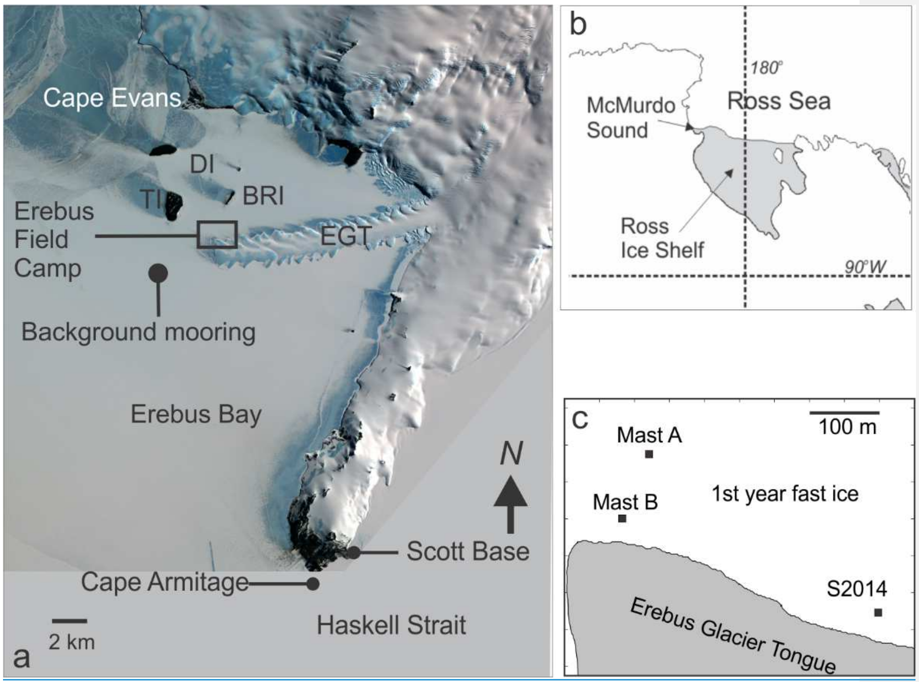
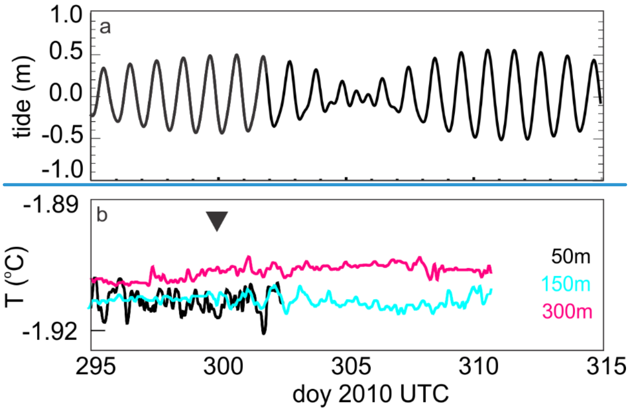


Figure 2 (a~~) McMurdo Sound, Antarctica, in the context of the Ross Ice Shelf and the Ross Sea, (b~~) SW McMurdo Sound image from ASTER (Advanced Space borne Thermal Emission and Reflection Radiometer) satellite image of south east McMurdo Sound including the Erebus glacier tongue (EGT), the Dellbridge Islands (DI), Erebus Bay ~~(EB),~~, Cape Evans~~ (CE),~~, Cape Armitage~~ (CA),~~, Haskell Strait~~ (HS),~~, Scott Base ~~(SB),~~, background ~~mooring (BG) and~~mooringand the Erebus field camp~~ (EFC).~~. The Dellbridge Islands include Tent Island (TI) and Big Razorback Island (BRI). (b) The McMurdo Sound region, Antarctica, in the context of the Ross Ice Shelf and the Ross Sea, (c) Erebus Field Camp locale showing the turbulence mast locations relative to the edge of EGT.



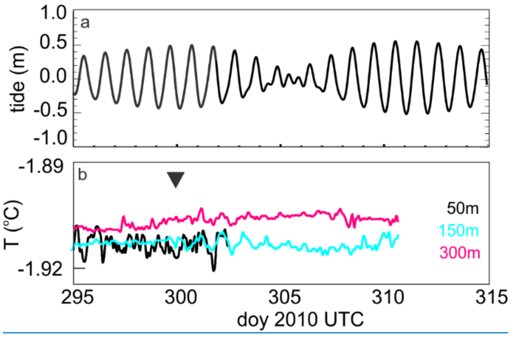
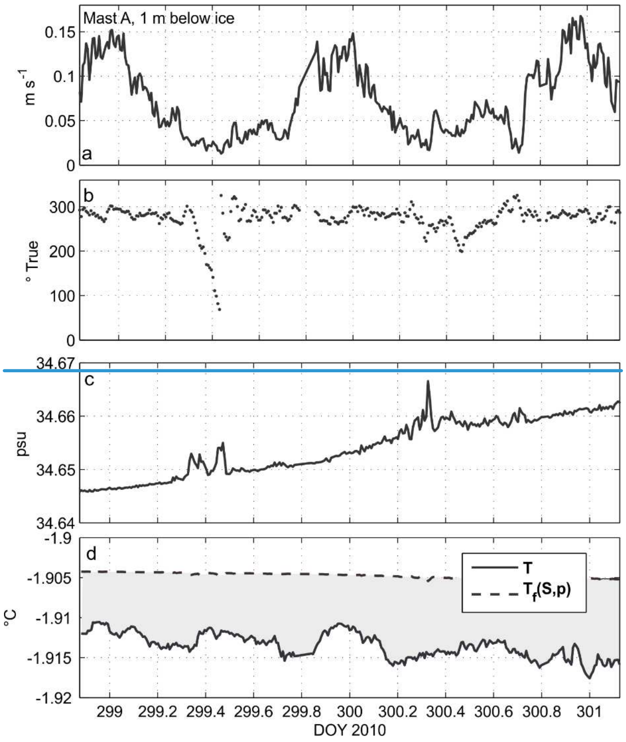


Figure 3 (a) tidal elevation and (b) in situ temperatures from background mooring (~~BG~~shown in Figure 2). The time of the present detailed observations are marked with the triangle in (b). The sensor at 50 m stopped early due to battery exhaustion.


Mast A, 1 m below ice
a
b
c
d
m s^{-1}
° True
psu
°C
T
T_f(S,p)
0.15
0.1
0.05
0
300
200
100
0
34.67
34.66
34.65
34.64
-1.9
-1.905
-1.91
-1.915
-1.92
299
299.2
299.4
299.6
299.8
300
300.2
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300.6
300.8
301
DOY 2010

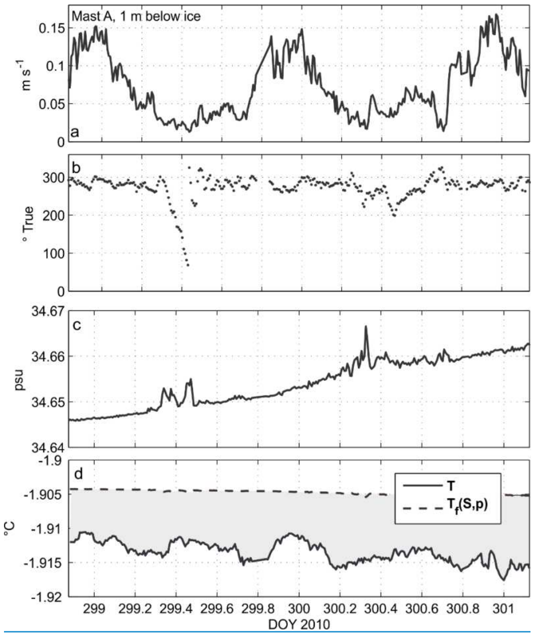
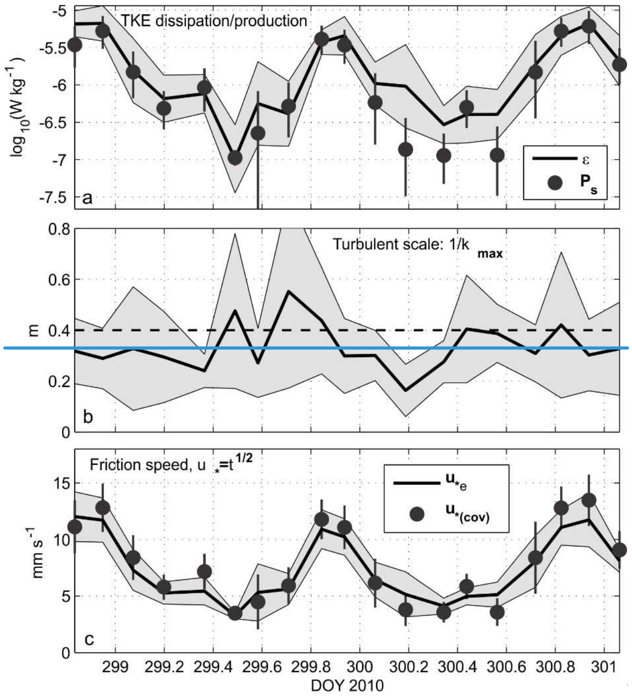


Figure 4 (a) Current speed at 1 m below the ice/ocean boundary from Mast A. (b) Current direction (bearing from true north). (c) Salinity (~~practical salinity scale~~Practical Salinity Scalei). (d) Water temperature (solid) and water freezing temperature at 2 m depth (dashed).



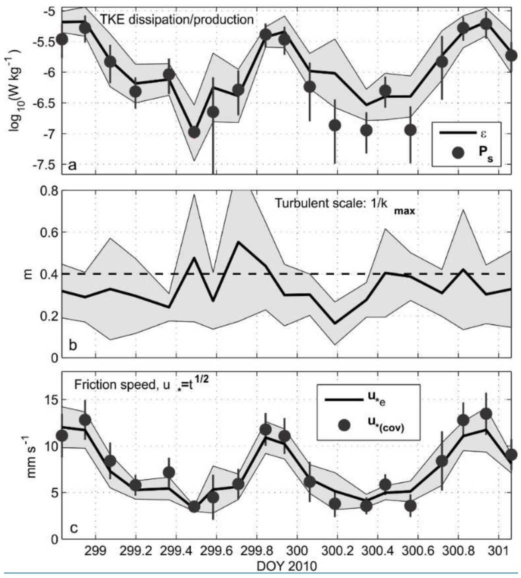
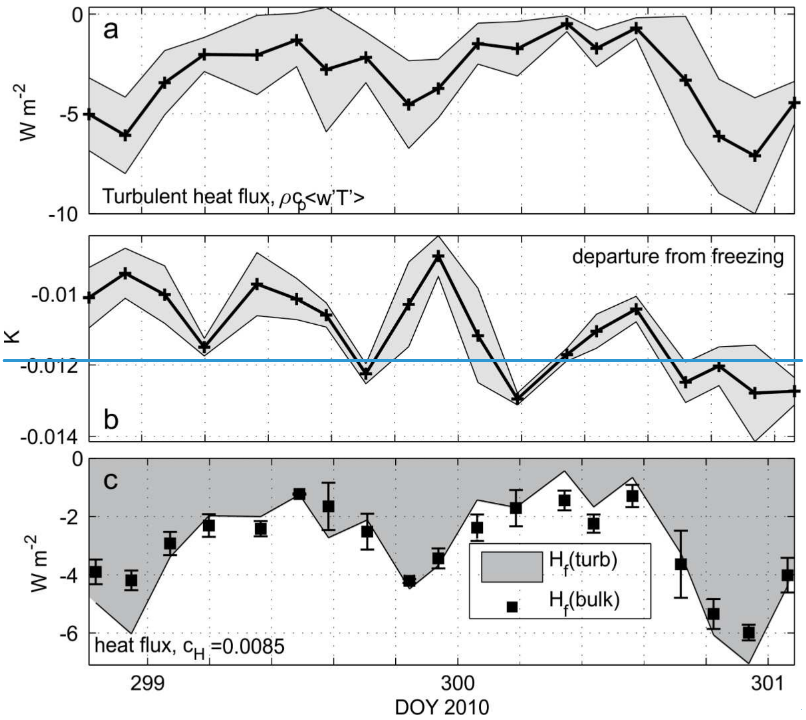


Figure 5 (a) Three-hour averages of turbulent kinetic energy dissipation rate (solid with shading showing ±1 std. deviation of the 15-min realizations in each average) and TKE production by shear (circles with std. deviation). (b) Turbulent length scale from the inverse wavenumber at w variance spectral peaks. Dashed line indicates the "geometric" surface layer scale, $\kappa|z|$. (c) Independent estimates from of friction speed from w variance spectra (solid with shading) and from covariance statistics (circles with std. deviation bars).



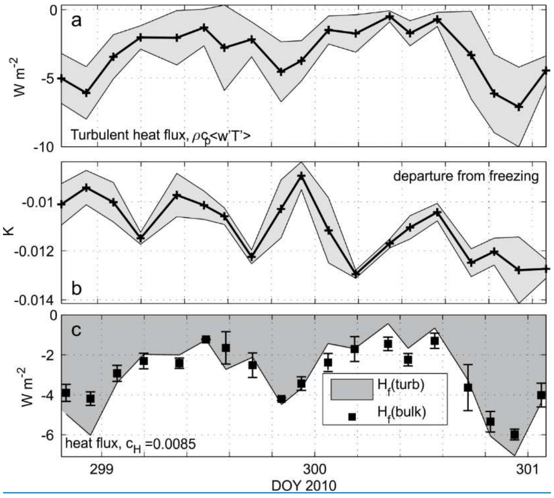
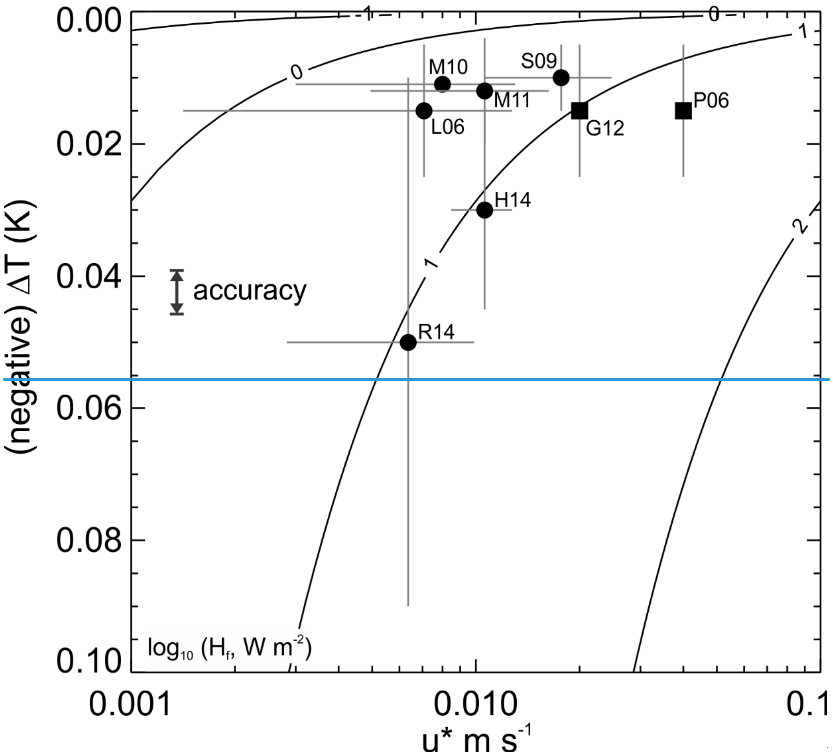


Figure 6 (a) Three-hour averages of turbulent heat flux, solid with std. deviation shading. (b) Departure of temperature from in situ freezing point temperature. (c) Comparison showing measured heat flux (shaded) with bulk estimates based on the product of u_* and ΔT using the transfer coefficient identified using equation (6).



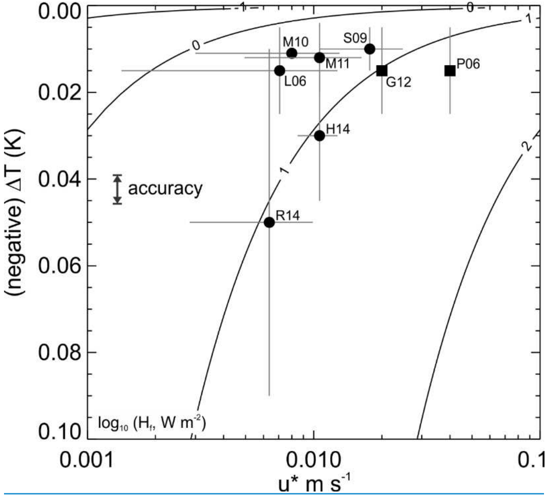


Figure 7 Contours of log$_{10}$ of heat flux H_f, as a function of friction speed u* and thermal driving ΔT, for present c_H estimate. Contours describe equation (6). Circles

are from measurements of u* and ΔT, (L06 Leonard et al 2006; S09 Stevens et al. 2009; M11 Mahoney et al. 2011; H14 Hughes et al. 2014; R14 Robinson et al. 2014 and M10 this study). The “error-bars” represent degree of variability. The u* were either directly measured (i.e. M10) or infered from flow U using a drag coefficient whereby $u^*=(C_d)^{1/2}U$. The squares are from observations inferring heat flux so that a u* is inferred given the observed ΔT (P06 Purdie et al. 2006; G12 Gough et al. 2012).