The open ocean sensible heat flux and its significance for Arctic boundary layer mixing during early fall

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Abstract. The increasing ice-free area during late summer has transformed the Arctic to a climate system with more dynamic boundary layer clouds and seasonal sea ice growth. The open ocean sensible heat flux, a crucial mechanism of excessive ocean heat loss to the atmosphere during the fall freeze season, is speculated to play an important role in the recently observed cloud cover increase and boundary layer (BL) instability. However, lack of observations and understanding of the resilience of the proposed mechanisms, especially in relation to meteorological and interannual variability, has left a poorly constrained BL parameterization scheme in Arctic climate models. In this study, we use multi-year Japanese cruise ship observations from R/V Mirai over the open Arctic Ocean to characterize the surface sensible heat flux (SSHF) during early fall and investigate its contribution to BL turbulence. It is found that mixing by SSHF is favored during episodes of high surface wind speed, and is also influenced by the prevailing cloud regime. The maximum ocean-atmosphere temperature difference is observed during cold air advection (associated with the stratocumulus regime), yet, contrary to previous speculation, the efficiency of sensible heat exchange is low. On the other hand, the SSHF contributes significantly to BL mixing during the uplift (low-pressure) followed by the highly stable (stratus) regime. Overall, it can explain ~10% of the open ocean BL height variability, whereas cloud (moisture and radiative) driven mechanisms appear to be the other dominant sources of convective turbulence. Nevertheless, there is strong interannual variability in the relationship between the SSHF and the BL height which can be intensified by the changing occurrence of Arctic climate patterns, such as positive surface wind speed anomalies and more frequent conditions of uplift. This study highlights the need for comprehensive boundary layer observations such as the R/V Mirai for better understanding and predicting the dynamic nature of the Arctic climate.

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1 Introduction

The recent decline of the Arctic sea ice during late summer (Aug-Sep) has raised several questions for the new climate system, for example, the response of boundary layer clouds and the feedback to sea ice recovery. Turbulent heat fluxes over the ice-free ocean are expected to play an important role under these circumstances. The aim of this study is to provide a better understanding of the role of surface sensible heat flux in the formation of oceanic boundary layer and dissipating ocean heat to the atmosphere during late summer and early fall.

Model simulations of the 21st century climate have suggested that even if the Arctic Ocean were to become completely ice-free in summer, the loss of excess heat to the atmosphere through enhanced ocean (sensible and latent) heat fluxes during October-December months would enable the recovery of sea ice (Tietsche et al. 2011). Ship-based observations during the fall of 2010 have similarly indicated the importance of the ocean sensible heat flux for the onset of the annual freeze cycle (Inoue and Hori 2011). The authors suggested that the cold air outbreak in the wake of cyclogenesis enabled significant cooling of the upper ocean (and freeze onset; Inoue and Hori 2011). Presently, however, there is limited observational guidance for the open ocean heat fluxes and the efficiency of turbulent heat exchange during such events.

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The rapid sea-ice retreat in recent years has also raised speculation that the increased air-sea temperature gradients may contribute to reduced boundary layer stability and associated cloud changes (Kay and Gettelman 2009; Schweiger et al. 2008). For example, observations from satellites (Kay and Gettelman 2009; Wu and Lee 2012;) and ground stations (Eastman and Warren 2010) suggest a general increase in the low cloud cover over the ice-free Arctic Ocean during fall, especially in regions of reduced atmospheric stability (Kay and Gettelman 2009). Studies have also shown an increase in the mid-level cloud cover (and simultaneous decrease in low clouds) indicating a deepening of the Arctic boundary layer (Sato et al. 2012; Schweiger et al. 2008; Palm et al. 2010). This has also been attributed mainly to the enhanced air-sea temperature difference and resulting upward sensible heat flux (Sato et al. 2012; Schweiger et al. 2008). Despite the observed cloud changes, no direct measurements have been made to quantify the open ocean surface fluxes or its influence on boundary layer mixing. As this area continues to increase in a warmer climate, it becomes more important to fully understand and characterize the changes in cloud cover and the underlying boundary layer processes.

Observations over sea ice show that mixing in the Arctic boundary layer is primarily driven by clouds and cloud top radiative cooling (Tjernstrom et al. 2004; Inoue et al. 2005; Morrison et al. 2011; Shupe et al. 2013), which can be more significant than surface turbulent fluxes (Curry et al. 2000; Morrison et al. 2012; Shupe et al. 2013; Nicholls and Leighton 1986). Such a BL represents the situation arising from strongly insulating sea ice that prevents efficient turbulent heat exchange at the surface. Over the open ocean, the air-sea interaction can be more pronounced. For example, it has been suggested that surface heat and moisture fluxes lead to boundary layer "roll" clouds during cold air outbreak events over the open Arctic Ocean (Klein et al. 2009). In this study, using multi-year ship-based observations, we investigate the variability of the open ocean sensible heat flux, and more importantly its contribution to boundary layer mixing (and turbulent heat exchange) under varying weather (and cloud) regimes.

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2 Datasets

Surface and upper-air meteorological data from the ice-strengthened research vessel (R/V Mirai) operated by the Japan Agency for Marine-Earth Science and Technology are analyzed in this study. The vessel surveyed the ice-free regions mainly in the vicinity of Beaufort and Chukchi seas (from 125° W - 175° E longitude and between 60° - 80° N latitude). Data were collected during September and early October of the years 2002 (Fujiyoshi and Shimada 2002), 2004 (Fujiyoshi and Shimada 2004), 2008 (Kurita and Yoneyama 2008), 2009 (Inoue and Yoneyama 2009), 2010 (Inoue 2010) and 2013 (Inoue 2013). On account of the retreating sea ice, recent observations were collected in more northern latitudes compared to earlier years (Fig. 1; Sato et al. 2012; Inoue and Hori 2011). The year 2013, however, is an exception when observations were primarily collected at a fixed point (72.75 °N and 168.25 °W) as part of the Arctic Research Collaboration for the Radiosonde Observing System (ARCROSE) experiment (Inoue et al. 2015; Kawaguchi et al. 2015). The radiosonde data include profiles of temperature, pressure, winds, and relative humidity, typically sampled at 3 to 12 hour intervals with vertical resolution ranging from 40 m in the lower levels to around 70 m in the mid-troposphere. In order to exclude the near-surface contamination due to warming and cooling of the ship body, a minimum height threshold of 100 m is imposed to ensure quality data of the atmospheric profiles.

Also used in the R/V Mirai data analysis are independent, quality controlled observations of surface meteorological variables, viz., 10-minute average values of sea surface temperature (SST), surface air temperature (SAT), surface pressure, and surface horizontal wind speed (V_{surf}). The SAT and V_{surf} are measured at 21 m and 25 m above sea level, respectively. These measurements are used to estimate the surface sensible heat flux (SSHF) at the time of radiosonde launches. A total of 876 contemporaneous samples of boundary layer structure and SSHF (excluding missing data) are analyzed from all cruises. Thus, this dataset provides a unique and valuable survey of Arctic boundary layer properties over the open ocean (Fig. 1), complementing other observational efforts carried out mainly on the central polar ice pack (Tjernstrom et al. 2004; Shupe et al. 2013) and coastal/continental Arctic regions (Eastman and Warren 2010).

3 Methods

3.1 Estimation of surface sensible heat flux

The product of the wind speed, and the temperature difference between the sea surface and overlying air (ΔT), is a common estimate of the SSHF (Fairall et al. 1996; Bourassa et al. 2010; Inoue et al. 2011). In this study, the SSHF is calculated using the following equation,

$$\mathrm{SSHF} = \rho C_p C_H V_{surf} (\Delta T), \tag{1}$$

where $\Delta T = SST - SAT$, °C,

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V_{surf} = surface horizontal wind speed, m s^{-1}

ρ = air density, kg m^{-3}

C_p = specific heat capacity of air, J kg^{-1} K^{-1}

C_H = transfer coefficient for SSHF (based on winds measured at 20 m height)

The values of the constants ρ, C_p, and C_H, are adopted from Inoue et al. (2011). Based on Eq. 1, positive values of SSHF will indicate upward surface sensible heat flux (from the ocean to the atmosphere).

3.2 Determination of boundary layer height

The height of the well-mixed boundary layer is calculated using the parcel-based method, as illustrated in Fig. 2. In this method, a surface parcel is assumed to ascend along a dry adiabat up to the lifting condensation level (LCL), and along a moist adiabat thereafter (denoted by red dashed line in Fig. 2). There is no striking difference in the slopes of the dry and moist adiabats in Fig. 2, as they are nearly parallel in a cold environment. The height of the boundary layer (BL) is computed as the level where the parcel temperature falls below the environment temperature by a value of 0.6 °K or more. For most soundings, this level is coincident with the cloud top or the base of the temperature inversion (as shown in Fig. 2). To comprehend the complex Arctic BL processes, we also examine the influence of BL clouds as described in the following subsection.

The boundary layer over the open Arctic Ocean is found to be mixed or neutral (>90% of the time), in agreement with Sato et al. (2012). The wind speed variance in the BL is typically less than 30% of the mean, suggesting negligible mechanical turbulence for most cases. The Arctic BLs, thus, appear to be primarily mixed by convective fluxes. In a well-mixed BL, the surface turbulent fluxes decrease linearly with height (Holton 2004). Hence, we examine the correlation between the SSHF and the BL height on a profile-by-profile basis. A good correlation implies that the SSHF controls the convective turbulence in the BL. In the case of a poor correlation, factors such as cloud or moisture driven turbulence may influence the BL height (Morrison et al. 2012; Shupe et al. 2013). We investigate the BL cloud statistics as described below. Note that a *bottom-up* approach is used to identify the boundary layer top, which ensures that clouds identified within the BL are always coupled to the *surface*.

3.3 Estimation of boundary layer cloud thickness ratio

Based on past studies over sea ice, the Arctic is found to be mostly cloudy, and the cloud-driven turbulence is known to control the BL height variability (Tjernstrom et al. 2004; Shupe et al. 2013). Low clouds coupled to the boundary layer may generate convective turbulence from above (Curry et al. 2000; Morrison et al. 2012; Shupe et al. 2013), thereby weakening the correlation between the SSHF and BL height. It is therefore important to consider the effect of boundary layer clouds in

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this study. For this purpose, the BL cloud thickness ratio is calculated as the percentage ratio of cloud layer within the BL. The cloud-base is defined as the first layer above the surface where the relative humidity (RH) equals 90% or more (as in Sato et al. 2012), and the cloud layer is calculated as the vertical integral of all layers within the boundary layer that exceed 90% RH. As an example, for the profile shown in Fig. 2 (inset), the cloud-base and BL heights are calculated as 580 m and 1180 m respectively, and the BL cloud thickness ratio is estimated to be ~50%.

4 Results

4.1 Characteristics of SSHF over the open Arctic Ocean

Figure 3 shows the distribution of the SSHF, the temperature gradient between sea surface and air (ΔT), and the surface wind speeds (V_{surf}), based on multi-year observations. The lack of meaningful differences in the yearly SSHF median values suggests that its interannual variability is not significant at the 95% confidence level. The correlation between SSHF and ΔT (*correlation coefficient* = 0.77) is found to be higher than that of SSHF and V_{surf} (*correlation coefficient* = 0.45). The distribution in Fig. 3 (a) indicates that more positive SSHF values, and a heavier tail (barring outliers), occur in recent years (2009, 2010, 2013). It appears that more negative SAT values (not shown) may contribute to the broader ΔT and SSHF distributions observed during 2009 and 2010 (Figs. 3 (a) and (b)). (In general, the ΔT appears to be more strongly influenced by SAT rather than SST).

As the SSHF can be sensitive to the ΔT variability during fall, it is particularly interesting to explore its relationship with negative SATs. In model simulations, the occurrence of cold air advection (CAA) events and increased ΔT, is known to release copious amounts of ocean heat flux and trigger the seasonal recovery of sea ice (Deser et al. 2010; Kolstad and Bracegirdle 2008). Models also project that future occurrences of CAA may spread further poleward along the retreating sea ice margin (Kolstad and Bracegirdle 2008). In spite of recent observations and modeling efforts (Inoue and Hori 2011; Klein et al. 2009), there are limited measurements of actual surface fluxes during such events. In the following sections, using ship-based measurements, we investigate the instantaneous relationship between the surface sensible heat flux and the boundary layer height, which qualitatively represents the efficiency of turbulent heat exchange between the ocean and the atmosphere.

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4.2 The SSHF contribution to boundary layer mixing

Figure 4 (a) shows that a weak positive relationship exists between the SSHF and BL height, which can explain up to 10% of the BL height variability. Contrary to expectations, this relationship is not found to depend on the ocean-atmosphere temperature gradient (ΔT). Instead, the correlation coefficient (*r*) is sensitive to the surface wind speeds (V_{surf}; Fig. 4 (b)) suggesting that the surface-generated turbulent mixing is favored during episodes of strong winds, and is independent of the ΔTs.

Additionally, low-level clouds, which are known to generate turbulence in the Arctic BL, may influence the correlation. Therefore, we closely inspect the behavior of the correlation coefficient (*r*) under varying cloud regimes in the following subsection.

4.2.1 Effects of cloud regime

In the Arctic, large-scale atmospheric processes are mainly responsible for the occurrence and sustenance of low cloud cover (Herman and Goody 1976; Morrison et al., 2012; Solomon et al., 2014). Barton et al. (2012) recently classified Arctic clouds based on the background dynamic and thermodynamic state of the lower troposphere. They identified four robust meteorological regimes based on the lower tropospheric stability or the potential temperature difference between the surface and 700 mb (θ_{700} - θ_{surf}), and the 500 mb pressure vertical velocity (ω_{500}). The first three regimes have positive ω_{500} values indicating weak subsidence, and differ only in their lower tropospheric stability (θ_{700} - θ_{surf}; Barton et al. 2012). The fourth atmospheric state comprises the uplift regime (characterized by rising motion or negative ω_{500} values), which is only found to occur 10-15% of the time (Barton et al. 2012; Taylor et al. 2015). The subsidence regimes typically have cloud bases within the boundary layer, and are characterized by increasing cloud-top/BL height with decreasing stability (Barton et al. 2012). During the uplift regime, on the other hand, the cloud fraction peaks in the free troposphere above the boundary layer (Barton et al. 2012). In our study, the focus is on the boundary layer height variability therefore we will not be studying clouds with cloud-base above the BL. Moreover, in lieu of the pressure vertical velocity (ω_{500}), we examine the surface pressure to distinguish between the uplift and subsidence regimes.

The bottom panel of Figure 5 (a) shows the frequency distribution of BL cloud thickness ratio during fall. Three distinct BL cloud types emerge, with cloud ratios peaking at 5%, 65%, and 95% (Fig. 5 (a)). Consequently, the observations are divided into three groups consisting of low (<20%), medium (20-80%), and high (>80%) BL cloud thickness ratios, respectively. Note that threshold pairs other than 20-80% (such as 10-90% and 25-75%) were tested for classification purposes, and the results were found to remain robust. Table 1 shows the occurrence frequency, mean surface pressure, and the lower tropospheric stability (θ_{700} - θ_{surf}) associated with each group, while Figs. 5 (b)-(d) show the average temperature and moisture profiles. Significantly lower pressure conditions (99% confidence level) are associated with the low BL cloud thickness group, which occurs roughly 15% of the time. While upper level clouds may be present, a vast majority of the cases do not have boundary layer clouds (Fig. 5 (b)). Therefore this group is synonymous with the uplift regime described by Barton et al. (2012). On the other hand, the top panel of Figure 5 (a) suggests that BL clouds are favored in a subsiding environment (high-pressure conditions), consistent with Barton et al. (2012).

For the group with high BL cloud thickness (greater than 80%), the relatively strong lower tropospheric stability (Table 1) and shallow BL height (Fig. 5 (d)) indicate that it belongs to the very highly stable/highly stable regime (Barton et al. 2012). Figure 5 (c) on the other hand shows a deeper boundary layer with moderate stability suggesting that the group with medium cloud thickness (20 to 80%) is similar to the stable regime described by Barton et al. 2012. Note that the

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occurrence frequency of these two groups (Table 1) also aligns with that of the respective regimes observed during fall (Barton et al. 2012).

A comparison of the lower tropospheric stability and BL (cloud-top) height between both groups (Table 1 and Figs. 5 (c), (d)) reveal that they are in fact analogous to the stratocumulus and stratus cloud types. The stable, shallow, and cloudy boundary layer in Fig. 5 (d) is characteristic of the stratus cloud regime, whereas the deeper well-mixed BL with higher cloud top (Fig. 5 (c)) represents the stratocumulus-topped boundary layer. Similar distinctions between stratus and stratocumulus Arctic clouds were noted in previous studies as well (Sato et al. 2012). Thus, the low, medium, and high BL cloud thickness groups identified in Table 1, are henceforth referred to as the uplift, stratocumulus, and stratus regimes, respectively. Figure 6 compares the lower tropospheric structure of temperature and moisture for stratus and stratocumulus regimes. Consistent with Sato et al. (2012), it is evident that CAA is mainly responsible for the occurrence of stratocumulus clouds (Fig. 6 (a)) whereas warm and moist air advection (or subsidence) leads to the formation of stratus clouds in the Arctic (Fig. 6).

Table 1 shows the average wind speed, ΔT, and the correlation coefficient (*r*) between SSHF and BL height for the three regimes. The wind speeds are comparable, but the ΔT is significantly higher for the stratocumulus regime (99% confidence level). In the past, there has been speculation that the surface-generated turbulence is enhanced due to strong air-sea temperature gradients associated with cold air advection over open water (Sato et al. 2012; Kay and Gettelman 2009). Yet, the weak correlation coefficient (*r*) for the stratocumulus regime in Table 1 suggests that despite the enhanced ΔT, the surface sensible heat flux appears to contribute very little to the formation of the deep well-mixed boundary layer (Table 1). Figure 6 (a) shows that the temperature anomaly in this regime is maximized between 0.3 to 1.5 km altitudes, indicating that cold air advection occurs *above* the surface where stratocumulus clouds likely form by the release of latent heat of vaporization. In such a case, the unstable lapse rate is perhaps more strongly driven by cloud condensational processes rather than the SSHF. This will be further explored in Section 4.4.

On the other hand, the surface contribution to boundary layer mixing is significant during the uplift regime, as well as in the presence of stratus clouds occurring within a (warm and wet) subsiding environment (*r* in Table 1). Other studies have also noted that the influence of surface type (sea ice vs. open water) is more significant for shallow boundary layer clouds occurring in the highly stable (stratus) regime compared to the stable (stratocumulus) regime (Barton et al. 2012; Taylor et al. 2015). In the following subsection, we will more closely examine the relationship between the SSHF and BL height in the uplift and stratus regimes.

4.2.2 Influence of surface winds

Figure 7 (a) shows that the SSHF can explain a substantial amount of the BL height variability in the uplift regime (up to 37%). For the stratus cloud regime, the correlation between SSHF and BL height is already significant (Table 1) but improves substantially during episodes of high (> 9.8 ms^{-1}) surface wind speed (Fig. 7 (b)). For the deep, stratocumulus-

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topped boundary layer, the relationship between SSHF and BL height becomes weakly positive (r = 0.14) during high surface wind speeds but remains insignificant. Thus, apart from other factors, surface winds are clearly important for generating turbulent heat exchange in the stable Arctic boundary layer.

Altogether, based on the linear relationships between SSHF and BL height and the frequency of occurrence of the uplift (~15%) and stratus cloud regimes (~41%), the surface-generated turbulence may explain up to 10% of the Arctic BL height variability during fall. Whereas the in-cloud moist and radiative processes that are responsible for formation of mixed layers over sea ice (Tjernstrom et al. 2004; Shupe et al. 2013; Morrison et al. 2012) are likely to be dominant over the open ocean as well. In the following subsection, we examine the interannual variability in the BL height and its relationship to the SSHF.

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4.3 Interannual variability

As discussed in the previous section (4.2.3), the height of the well-mixed Arctic BL is likely controlled by the cloud-generated turbulence rather than the SSHF. Figure 8 shows the yearly distribution of BL height, BL cloud thickness ratio, and surface pressure, for the period of the cruise. Compared to the SSHF (Fig. 3 (a)), the BL height has more interannual variability (Fig. 8 (a)) as suggested by the significantly shallow boundary layer observed during 2002 (95% confidence level). The large-scale circulation (sea level pressure distribution) appears to be different during this year (Fig. 8 (c)). The circulation anomaly may have a significant influence on the BL cloud distribution (Fig. 8 (b)), which may consequently impact the BL height variability (Fig. 8 (a)). (This will be discussed in the following subsection).

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The interannual variability in the correlation coefficient (r; Table 2) suggests that the SSHF and BL height relationship is most significant for the years 2002 and 2010 (99% confidence level). The time-series of both quantities indeed confirms the dominant role of surface fluxes in the evolution of the Arctic BL (Fig. 9). The reasons for the same are explored below.

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As described in section 4.2, both cloud-type and wind speeds may influence the SSHF contribution to BL mixing. The frequency distribution of different cloud regimes and the corresponding surface wind speed anomalies (positive only) are shown for each year in Fig. 10. For the years with positive Arctic Oscillation (Table 2), it is evident that the stratus and stratocumulus regimes dominate the climate. The regime distribution is quite different during 2002 and 2013 (both years with negative AO index). The year 2002 is governed by anomalously low surface pressure or the uplift regime, whereas the year 2013 is accompanied by greater than usual occurrence of stratocumulus clouds (bottom panel of Fig. 10). Sampling inconsistency due to spatially restricted (fixed point) observations can also contribute to the anomalous cloud regime distribution observed during 2013. From Fig.10, it appears that a lower stratocumulus cloud fraction (bottom panel) coupled with higher surface wind speeds in the stratus regime (top panel), contribute to the better correlation between SSHF and BL height during 2002 and 2010 (Table 2).

Thus, although the SSHF presently controls only 10% of the BL height variability, the relationship can become stronger under more frequent occurrences of the uplift regime and/or high surface wind speeds associated with the stratus regime. As a result, the changing patterns of future Arctic climate, such as more frequent storms and greater wind stress (Hakkinen et al. 2008; Smedsrud et al. 2011), may act to enhance the ocean-atmosphere coupling. In the following section, we will further evaluate the relative roles of SSHF and clouds in atmospheric mixing based on boundary layer thermodynamics.

4.4 Boundary layer thermodynamics over the open Arctic Ocean

The role of SSHF for BL mixing is better understood by examining the thermodynamic equation (Eq. 2).

$$\underbrace{\int_0^{BL}\frac{\partial T}{\partial t}}_{(A)} + \underbrace{\int_0^{BL}\bar{V}\nabla T}_{(B)} + \underbrace{\int_0^{BL}(\Gamma_{adiabat}-\Gamma_{env})w}_{(C)} = \underbrace{\int_0^{BL}\frac{Q}{c_p}}_{(D)}$$

where A = time-rate of change in local temperature

B = horizontal temperature advection in the BL

C = product of the vertical velocity and the difference between the adiabatic and environment lapse-rates

D = diabatic heating/cooling that can be caused by surface turbulent fluxes, cloud (condensational/evaporative) processes, and radiative mechanisms.

The explanation of various terms in Eq. (2) can be found in Holton (2004). The measure of the atmospheric stability (Term C) is zero, by definition, for a well-mixed boundary layer because the environmental lapse-rate (Γ_{env}) equals the dry/moist adiabatic lapse-rate ($\Gamma_{adiabat}$; see Section 3.2). We inspect processes (sources of vertical motions) that are necessary to make Γ_{env} equal to the $\Gamma_{adiabat}$. If we assume that horizontal thermal advection (term B) is homogenous leading to uniform changes in the local temperature profile (term A), then it may not influence the atmospheric stability (Γ_{env}). However, Γ_{env} can change in response to diabatic heating in the Arctic atmosphere (term D), which includes two main sources viz., surface (sensible and latent) heat fluxes and clouds.

The largely positive temperature gradient (ΔT) during early fall (Fig. 3 (b)) is favourable for episodes of upward sensible heat flux and rising air parcels which can make Γ_{env} more unstable. (Note that although the surface latent heat fluxes

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are not measured here, they are typically proportional to the SSHF). Similarly, Arctic clouds which form due to large-scale processes (Herman and Goody 1976; Morrison et al., 2012; Solomon et al., 2014) can generate vertical mixing due to a combination of condensational warming and cloud-top radiative cooling. Now, in the absence of low-clouds, the surface fluxes will be the main factor to control Γ_{env} and the BL mixing. This is consistent with our results which basically show a good correlation between the SSHF and BL height for the cases with near-zero BL cloud thickness (uplift regime in Table 1 and Fig. 7 (a)). On the other hand, when low-clouds are observed in the vicinity of well-mixed layers (stratus and stratocumulus regimes in Table 1), a weaker relationship is found to exist between the SSHF and BL height, as condensational warming may enhance the height of the surface mixed layer. The shallow BL observed in 2002 is likely due to the lack of occurrence of low-clouds during that year (Fig. 8 (a),(b)).

Now, let us consider the large-scale environment associated with cloudy Arctic BLs. It appears that CAA leads to stratocumulus cloud formation, whereas stratus clouds occur in a warm, subsiding environment (Figs. 5 and 6; Sato et al. 2012). One might expect greater cloud-generated BL turbulence in the latter as they have a lower cloud base and a larger cloud fraction within the well-mixed layer (Table 1 and Fig. 5). Conversely, the SSHF contribution is speculated to be much higher during the stratocumulus regime due to the larger ΔT associated with CAA (Table 1). But, we find no significant relationship between the BL height and ΔT as explained in section 4.2. During CAA, it appears that the SSHF contributes very little (if at all) to BL mixing, which suggests that condensational warming due to stratocumulus cloud formation is likely to be more significant. Contrary to our findings, a recent modelling study by Deser et al. (2010) showed that during cold months, CAA over the Arctic Ocean is nullified by the substantial release of surface heat fluxes with minimal contribution from cloud condensational warming. It is therefore important to re-evaluate the role of diabatic heating sources in Arctic climate models, especially their sensitivity to air-sea temperature gradients, by using observational guidance from campaigns like the R/V Mirai. Our study also indicates that the surface fluxes can control BL mixing under strong winds during the warmer stratus regime (Fig. 7(b)).

5 Discussions

5.1 Relationship between the declining sea ice and clouds

While it is clear that the early fall open Arctic Ocean has a deeper well-mixed boundary layer with more convective clouds compared to its ice-covered counterpart (Sato et al. 2012; Schweiger et al. 2008; Kay and Gettelman 2009), the role of surface heat fluxes remains debatable. Based on our analyses, the SSHF contributes to only 10% of the BL height variability. Moreover, the deepest and most convective BLs (stratocumulus cloud regime) appear to develop independently from the surface and are likely produced by a combination of in-cloud moist and radiative processes supported by large-scale CAA. It is expected that the changing frontal dynamics along the marginal sea ice zone (Kolstad and Bracegirdle 2008), as well as the reportedly enhanced moisture flux over the ice-free ocean (Boisvert and Stroeve 2015; Boisvert et al. 2015), may influence the formation of the deep, well-mixed stratocumulus boundary layer observed during early fall. If this is the case,

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then the retreating boundaries and the shrinking area of the summer Arctic sea ice, will have a direct influence on the open ocean cloud characteristics which in turn may have significant radiative feedbacks to the darker, ice-free Arctic Ocean. It is therefore imperative to study the changing nature of the large-scale circulation and cloud regimes in relation to the retreating sea ice.

Moreover, some model studies suggest that the surface turbulent fluxes dominate polar amplification during fall and early winter (Bekryaev et al. 2010; Serreze et al. 2009; Deser et al. 2010; Tietsche et al. 2011). Our results suggest that cloud condensational warming and radiative processes might be as important (if not more) for atmospheric warming

5.2 Implications for sea ice recovery mechanisms

During late summer and early fall, the turbulent heat loss from the ocean is considered important for initiating refreeze processes (Inoue and Hori 2011; Tietsche et al. 2011). Our study shows that the efficiency of turbulent heat exchange has not increased substantially over the regions that have recently experienced accelerated summer sea ice loss. Thus, we strongly recommend continuing the exploration of mechanisms that contribute to the cooling of the ocean and the recovery of the fast declining Arctic sea ice.

Model simulations may have a more optimistic representation of the ocean-atmosphere interactions in the dynamic new ice-free Arctic, which appears to be sensitive to the temperature gradient (ΔT) at the surface (Deser et al. 2010; Tietsche et al. 2011; Schweiger et al. 2008). For example, simulations show that the complete loss of summer ice over the Arctic Ocean will be reversed during the following cold season (fall and winter) due to enhanced heat flux from the ocean to the atmosphere during fall (Tietsche et al. 2011). However, more recent measurements have shown that the ocean heat gained during summer can be sustained over the period of fall and winter without being immediately dissipated to the atmosphere, thereby slowing the recovery of sea ice (Jackson et al. 2010; 2012). The chances of possibly irreversible and more permanent feedbacks of sea ice loss need to be seriously evaluated in models. Based on our results, it appears that conditions of uplift and high surface wind speeds may favour efficient heat dissipation by SSHF, whereas episodes of CAA may not. Nilsson et al. (2001) similarly found that the late summer/early fall turbulent heat fluxes over the Atlantic sector of the open Arctic Ocean can be sensitive to cyclone activity and cloud regimes. These dynamical triggers should be duly considered in BL

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parameterization schemes and surface layer schemes of climate models while evaluating future scenarios and sea ice recovery mechanisms for the Arctic.

6 Conclusions

For the rapidly evolving Arctic region, a comprehensive understanding of ocean-atmosphere interactions and underlying coupling processes is crucial for improving regional and global climate models and their predictability. Current models have significant differences in important physical processes such as the efficiency of turbulent heat transfer from the ocean to the atmosphere (Kolstad and Bracegirdle 2008; Grønas and Skeie 1999; Pagowski and Moore 2001). The primary goal of this study was to evaluate and quantify the role of open ocean sensible heat flux in Arctic BL turbulence based on multi-year ship-based observations acquired during early fall. The main conclusions are summarized as follows:

- The surface sensible heat flux during fall is mostly positive owing to the positive ocean-atmosphere temperature differences (ΔT) over the ice-free ocean. Yet, the instantaneous atmospheric response to enhanced fluxes only occurs during specific large-scale (cloud) regimes. It is favored during the uplift (low-pressure) regime (~ 15% of the cases) followed by the stratus cloud (warm subsidence) regime (~ 41% of the cases). Additionally, the ocean heat dissipation is more efficient during episodes of high surface wind speeds compared to increased ΔT.
- Stratus and stratocumulus clouds are frequently observed in the open Arctic boundary layer, prevalent roughly 85% of the time (Fig. 10). The year 2002 is an exception with low BL cloud fraction due to the anomalously low surface pressure conditions. In agreement with previous work (Sato et al. 2012), it is found that stratus clouds are associated with warm air advection and a shallow BL (high stability), whereas stratocumulus clouds result from CAA and have deeper, well-mixed BLs (low stability). Contrary to speculation, the surface generated turbulence is more strongly favored in the former compared to the latter. The instability associated with the stratocumulus-topped BL appears to be caused by cloud-related (moist adiabatic and radiative) processes rather than surface fluxes.
- Consistent with studies over late-summer sea ice (Tjernstrom et al. 2004; Shupe et al. 2013; Morrison et al. 2012), it is evident that the BL height variability in the open Arctic Ocean is also primarily controlled by the dynamical influence of the large-scale circulation and low-level clouds (Fig. 8). The surface sensible heat flux explains only up to 10% of the BL height variability for all cases observed by R/V Mirai. There is pronounced interannual variability in this relationship, which point towards an influence of surface wind speeds and cloud regimes that may act to weaken/strengthen the ocean-atmosphere coupling during early fall.

This study highlights the need for comprehensive in-situ observations to improve model physics for more reliable projections of the coupled Arctic climate and sea ice in the future. Using available surface and upper-air observations from ship cruises, we provide first-hand insights of the optimal conditions for the SSHF contribution to atmospheric mixing. The relevant

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coupling mechanisms identified in this study, especially the influence of large-scale circulation patterns (winds, cloud regimes), can be incorporated in current climate models to investigate the consequences of sea ice loss, and the possibility of irreversible effects on Arctic climate. The role of latent heat fluxes and cloud formation were evaluated using proxy measurements, nevertheless, it appears to be rather important for the Arctic BL stability. The regional and seasonal scale variability in SSHF and BL height warrants further investigation as well, which will be pursued in future studies.

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Acknowledgements

This work is supported by NASA Earth Science GNSS Remote Sensing and Interdisciplinary Research programs. Data used in this study were acquired during the MR02-K05 Leg 1, MR04-05, MR08-04, MR09-03 Leg 2, MR10-05 Leg 2, and MR13-06 Leg 1 cruises of R/V Mirai, Japan Agency for Marine-Earth Science and Technology. The Arctic Oscillation Index values were obtained from the National Oceanic and Atmospheric Administration's Climate Prediction Center using the following webpage: http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml.

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Tables

Table 1. The frequency of occurrence, mean surface pressure, mean lower tropospheric stability, mean boundary layer height, cloud regime, the correlation coefficient (*r*) between SSHF and BL height, mean temperature difference between ocean and air, and mean surface wind speed, observed for the three different groups of BL cloud thickness ratio (see text and Fig. 5 for explanation). Statistically significant values of *r* (99% confidence level) are highlighted in bold.

BL cloud thickness ratio (%)	≤ 20	20 to 80	≥ 80
Occurrence frequency	15	44	41

(%)			
Surface Pressure (mb)	1008	1015	1014
$\theta_{700} - \theta_{surf}$ (°C)	13.6	14.9	18.1
BL height (m)	646	997	508
Cloud Regime	Uplift	Stratocumulus (stable)	Stratus (very highly/highly stable)
r	**0.58**	-0.04	**0.33**
ΔT (°C)	1.76	3.41	1.71
V_{surf} ($m.s^{-1}$)	7.01	7.20	7.05

Table 2. The average Arctic Oscillation (AO) index observed during the period of the cruise, the correlation coefficient between SSHF and BL height (*r*), and the number of observations (*n*), for each cruise year. Statistically significant values of *r* (99% confidence level) are highlighted in bold.

Year	**2002**	**2004**	**2008**	**2009**	**2010**	**2013**
AO Index	-1.16	0.08	1.21	0.29	0.51	-1.50
r	**0.64**	0.15	0.18	0.16	**0.59**	-0.02
n	100	65	93	131	214	273

Figures

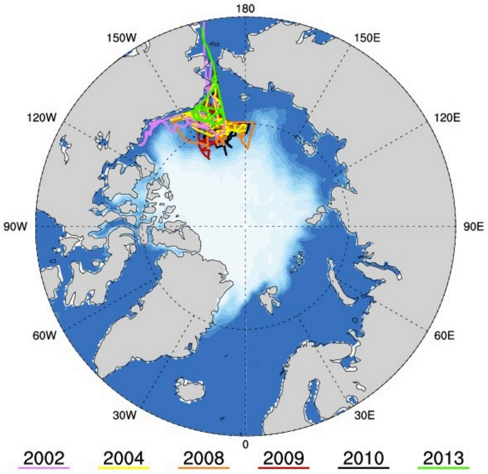

Figure 1: Ship tracks during multi-year cruises of the R/V Mirai indicated by solid colored lines. The average ice fraction (shaded white) at the time of cruise during 2008-2010 is also shown based on National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalyses project (Kalnay et al. 1996).

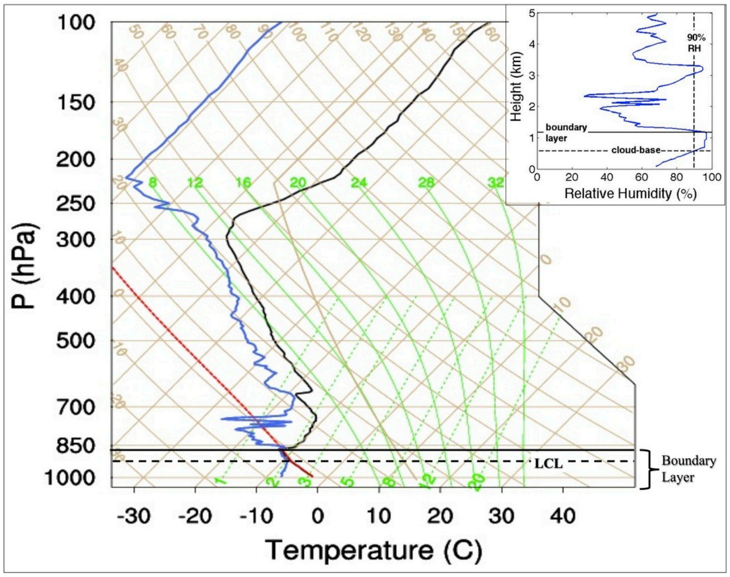

Figure 2: Skew T- log P diagram denoting the profiles of environmental temperature (black) and dew point temperature (blue) observed at 09Z September 21, 2013. The red dashed line represents the adiabatic ascent of a surface-based parcel. The solid horizontal black line is the boundary layer (BL) height determined using the parcel-based method, whereas the dashed horizontal black line represents the lifting condensation level or LCL; and (inset) a close examination of the relative humidity in the lowest 5 km, where the dashed vertical line represents the 90% RH threshold, the dashed horizontal line is the cloud-base, and the solid horizontal line represents the boundary layer. (For detailed description on the components of a skew T-log P chart, refer to the Air Weather Service technical report titled AWS/TR-79/006, *The Use of the Skew T, Log P Diagram in Analysis and Forecasting*, Dec.1979, revised March 1990).

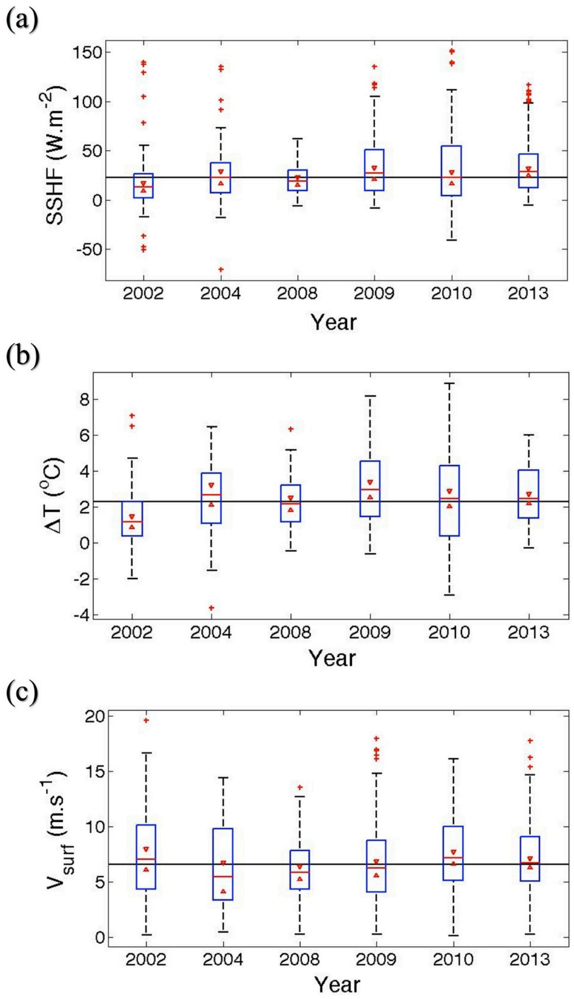

Figure 3: The interannual variability in the distribution of (a) the surface sensible heat flux (SSHF), (b) ocean-atmosphere temperature gradient (ΔT), and (c) surface wind speeds (V_{surf}). The solid horizontal black line represents the overall median value based on 6 years of ship data. The median for each year is represented by the horizontal red line within each boxplot, and the red notches represent the 95% confidence intervals around the same. Two medians are different at the 5% significance level if their intervals do not overlap.

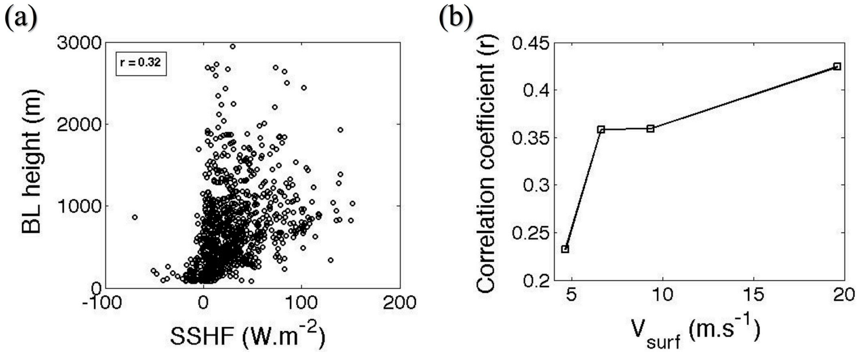

Figure 4: (a) Scatter plot of the SSHF and BL height using all observations based on 6 years of cruise-ship data. The correlation coefficient is denoted by *r*, and (b) *r* as a function of surface wind speed (V_{surf}). The data are binned based on the quartiles of V_{surf}, and *r* is calculated for each bin. The number of observations in each bin is equal to 219.

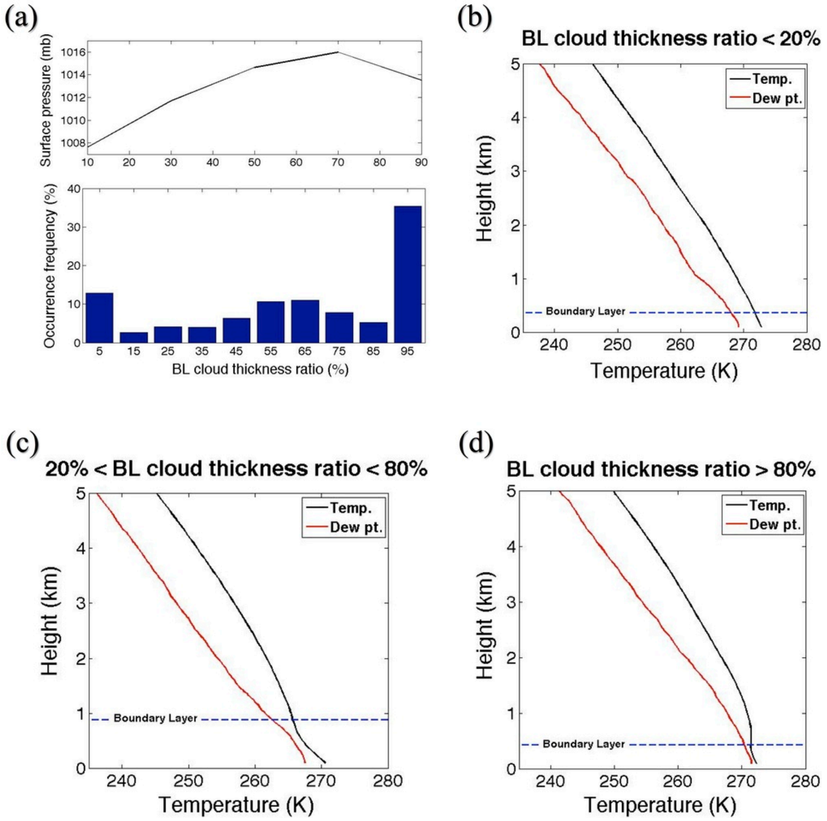

Figure 5: (a) The frequency distribution of BL cloud thickness ratio (bottom panel), and the mean surface pressure for 5 equally-spaced bins of the BL cloud thickness ratio (top panel), and (b) the profiles of mean temperature and dew point temperature observed for cases with BL cloud thickness ratio ≤ 20%, (c) same as (b) but for cases with 20% < BL cloud thickness ratio < 80%, and (d) same as (b) but for cases with BL cloud thickness ratio ≥ 80%.

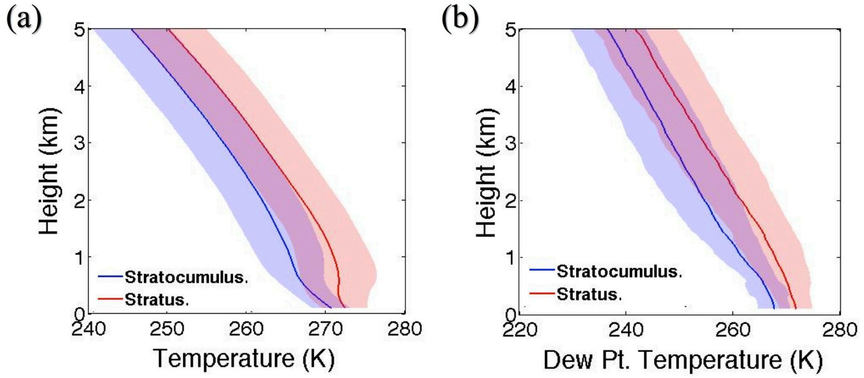

Figure 6: The atmospheric profile comparison between the stratocumulus and stratus regimes. The solid line represents the mean and the shaded area represents the standard deviation of (a) the temperature and (b) the dew point temperature.

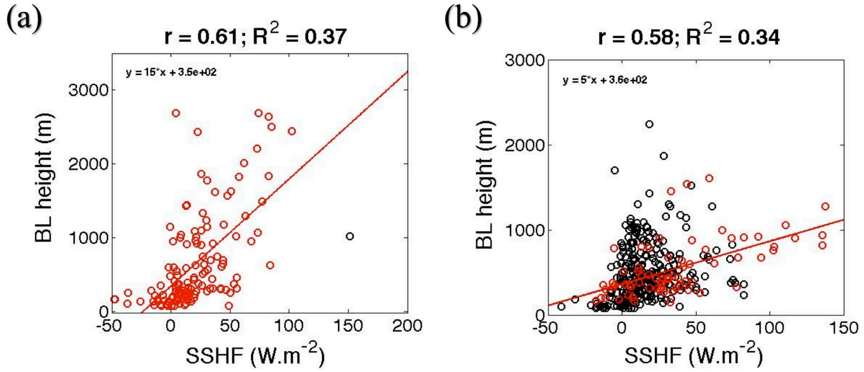

Figure 7: The scatter plot of SSHF and BL height during (a) the uplift regime, and (b) the stratus regime. The linear relationship between the SSHF and BL height derived using the least squares method of curve-fitting for (a) all cases except one outlier (indicated by black marker), and (b) cases with surface wind speeds exceeding 9.8 ms^{-1} (indicated by red markers). The correlation coefficient and the coefficient of multiple determination for each linear relationship is denoted by *r* and *R^2*, respectively.

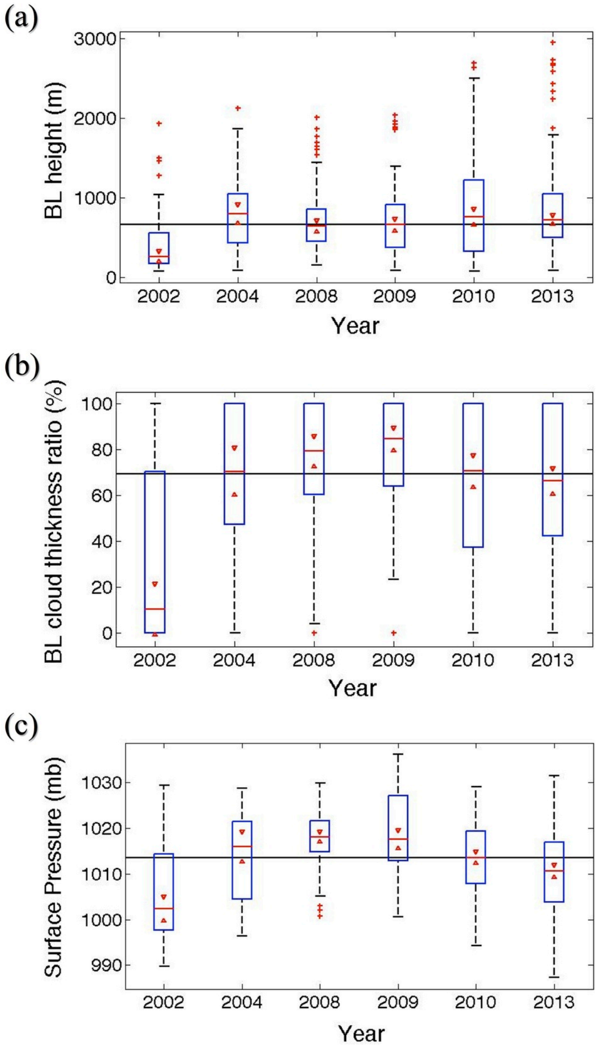

Figure 8: Same as Fig. 3 but for (a) boundary layer height, (b) boundary layer cloud thickness ratio, and (c) surface pressure.

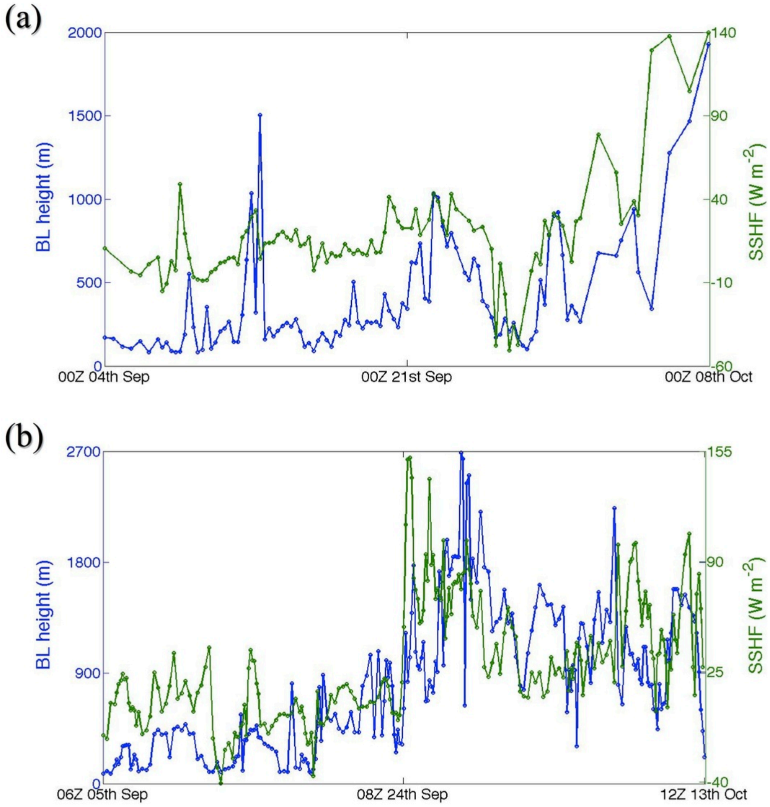

Figure 9: The time-series of the boundary layer height (blue line; left axis) and the surface sensible heat flux (green line; right axis) during the period of the cruise in (a) 2002 and (b) 2010. The dots represent the time instances of actual measurements.

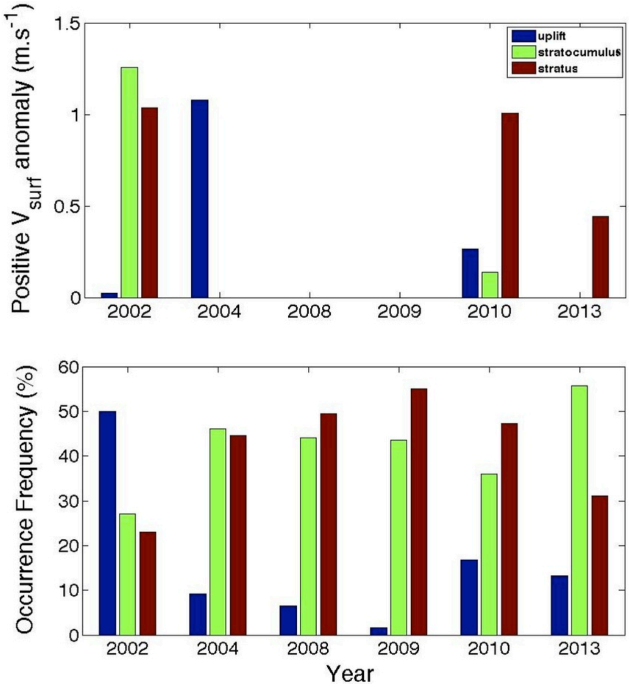

Figure 10: The distribution of occurrence frequency of the different cloud regimes within a given year (bottom panel), and the wind speed anomaly (positive only) for each year and each regime (top panel). Positive wind speed anomalies are calculated with respect to the mean wind speeds for the uplift, stratocumulus, and stratus regimes, which are 7, 7.2, and 7 ms^{-1}, respectively.

Response to Referee#1

Specific Comments:

Comment 1: The method to estimate the cloud fractions should be describe clearly.

Response: In the current manuscript, we have replaced the term “boundary layer cloud fraction” with “boundary layer cloud thickness ratio” which is defined in Section 3.3, as the percentage ratio of cloud layer within the BL. The cloud-base is defined as the first layer above the surface where the relative humidity (RH) equals 90% or more (as in Sato et al. 2012), and the cloud layer is calculated as the vertical integral of all layers within the boundary layer that exceed 90% RH. As an example, for the profile shown in Fig. 2 (inset) of the revised manuscript, the cloud-base and BL heights are calculated as 580 m and 1180 m respectively, and the BL cloud thickness ratio is estimated to be ~50%.

Comment 2: The definition of cloud regimes were unclear.

Response: The clouds are categorized based on the BL cloud thickness ratio as explained in Section 4.2.1 (Pg. 6, Lines 16-18) of the revised manuscript. Three distinct BL cloud types emerge, with thickness ratios peaking at 5%, 65%, and 95% (Fig. 5 (a)). Consequently, three categories are identified consisting of low (<20%), medium (20-80%), and high (>80%) BL cloud thickness ratios, respectively. Each category corresponds to one (or two) of the four regimes described by Barton et al. (2012). The low BL cloud thickness category (<20% ratio) corresponds to the “uplift regime”, the medium BL cloud thickness category (20-80% ratio) corresponds to the “stable” regime, and the high BL cloud thickness category (>80% ratio) corresponds to the “highly stable and very highly stable” regimes described by Barton et al. (2012). This is expressed in Table 1 of the revised manuscript.

Comment 3: The interpretation of the role of SLP on the surface sensible heat flux is questionable.

Response: We would like to stress that, in our study, we do not explicitly state that the SLP influences the surface sensible heat flux (SSHF). The SSHF depends on the surface winds and the air-sea temperature gradients as indicated by Eq. 1 of the revised manuscript. However, the efficiency of turbulent mixing might be favored within an unstable boundary layer which often accompanies cyclones or storms. There is some evidence for increased surface turbulent heat transfer during cyclonic activity in the Arctic Ocean (Nilsson et al. 2001, Brummer et al. 1994). Moreover, in the revised manuscript, we discuss the thermodynamic equation for the Arctic BL (Eq. 2) in order to better understand the factors favouring turbulent mixing.

It is possible that warm air advection (stratus regime) and **low-pressure** conditions (uplift regime) will favour rising motion/adiabatic cooling, which may lead to an unstable lapse-rate in the Arctic BL (term C in Eq. 2 of the revised manuscript). This may subsequently lead to a good correlation between the SSHF and BL height as turbulence is favoured in an unstable BL. Whereas **high-pressure** or cold air advection typically causes sinking motion in the BL, which may be responsible for the poor correlation between the SSHF and BL height during the stratocumulus regime. (The reader should be cautioned that this is purely speculative and we have not evaluated the relative contributions from thermal advection and compensatory adiabatic motions in the Arctic BL).

References:

Barton, N. P., S. A. Klein, J. S. Boyle, and Y. Y. Zhang, 2012: Arctic synoptic regimes: Comparing domain-wide Arctic cloud observations with CAM4 and CAM5 during similar dynamics, *J. Geophys. Res.*, 117, D15205, doi:10.1029/2012JD017589.

Brümmer, B., Busack, B., Hoeber, H., & Kruspe, G.,1994: Boundary-layer observations over water and Arctic sea-ice during on-ice air flow. *Boundary-Layer Meteorology, 68(1*- 2), 75-108.

Nilsson, E. D., Rannik, Ü., & Håkansson, M., 2001: Surface energy budget over the central Arctic Ocean during late summer and early freezeup. *Journal of Geophysical Research: Atmospheres (1984–2012), 106(D23),* 32187-32205.

Sato, K., J. Inoue, Y. M. Kodama, & J. E. Overland, 2012: Impact of Arctic sea-ice retreat on the recent change in cloud-base height during autumn.*Geophysical Research Letters*, *39*(10).

Specific Comments:

Comment 1: Page 3, line 19: What is the impact of the ship on these measurements?

Response: Unlike the radiosonde data, the surface meteorological measurements were checked for quality control before and after each cruise, as explained in individual cruise reports that are cited in Page 2; Lines 5-8 of the revised manuscript. The surface air temperature (SAT), in particular, was measured at two different locations (starboard and port sides) of the compass deck, thus minimizing negative effects from shadows and other local variations. Most importantly, all surface meteorological observations were compared with multiple instruments for quality and accuracy. Thus, we are sure that they are free from the impact of the ship, making them reliable for use in our study.

Comment 2: Section 3.2: I question how well the parcel-based method works when applied in conditions where there may be stratification. Given that the Arctic Ocean surface is open during the analysis times, these are likely times when this technique is generally acceptable. However, I would think that this would not be appropriate in cases where there is a surface inversion, for example, or in instances where clouds have worked to develop temperature structures and are not connected to the surface condition (as is pointed out to occur on occasion in the Arctic).

Response: Our goal is to identify the sources of convective mixing for the well-mixed Arctic BL, which is found to occur more than 90% of the time in the cruise ship observations used in our study. As the ocean is typically ice-free during this period, the Reviewer is correct in estimating that the conditions of stratification are rare (less than 10% frequency). Therefore, the use of the parcel-based method is generally acceptable. We understand that the reviewer is concerned about cases where the mixed layer is formed due to cloud-generated turbulence, and is decoupled from the surface. In the following paragraph, we will explain how and why such cases are excluded from our analysis.

We use a *bottom-up* parcel method to identify the boundary layer top, therefore we can safely assume that the well-mixed layers are, in fact, coupled to the *surface*. If the well-mixed layer does not include a cloud, only the surface fluxes are assumed to control the boundary layer development, as explained in Section 4.4 (Pg. 9, Line 25) of the revised manuscript. Whereas in cases where a cloud layer (e.g. stratus or stratocumulus) occurs within the boundary layer, the mixing can be caused due to both surface heat fluxes and cloud-generated turbulence. Even if the latter is dominant, the boundary layer will remain coupled to the surface. This is because the adiabatic temperature profile in the boundary layer, which is a pre-requisite for the parcel-based method, ensures free flow and exchange of heat and momentum with the surface. Thus, we are confident to use the bottom-up parcel-based method as it systematically excludes all decoupled cases while identifying the well-mixed boundary layer top.

Comment 3: Page 4, line 30: I struggle with the "boundary layer" terminology as applied. If the layer or cloud associated with it is decoupled, is it still a boundary layer? It seems that the layer may better be referred to as a "decoupled, cloud-driven mixed layer" or similar. I do understand that as defined, the "BL height" may still be located at the cloud height, but perhaps that is also justification for revisiting that definition.

Response: As explained in the previous response, we use a bottom-up parcel method and therefore only consider boundary layers that are coupled to the surface. The term "decoupled" was intended to convey the stronger influence of clouds on BL mixing compared to the surface. However, this term contradicts the very definition of a boundary layer which is assumed to always be coupled to the surface. Therefore, the sentence has been modified, and the use of the word "decoupled" is avoided here and elsewhere in the text. Thank you for bringing this misnomer to our attention.

Comment 4: Page 4, line 32: Again, are decoupled clouds really boundary layer clouds? Why would clouds at 1 km be any different than clouds at 3 km if both are decoupled?

Response: See response to Comments 2 and 3.

Comment 5: Page 5, line 2: In my experience, the near-surface humidity can often be 90% or more. Has an evaluation been completed of the impact of this definition on true cloud statistics? Doesn't the MIRAI also feature surface-based remote sensing? The frequent occurrence of BL cloud thickness ratios of 95% or greater in figure 5 is somewhat concerning. Perhaps it would be appropriate to evaluate the sensitivity of these metrics to the RH threshold chosen (for example, how does fig. 5 change if you choose 97% RH as the threshold?).

Response: Yes, the R/V Mirai does feature Doppler Radar and Ceilometer observations, but we use radiosonde profiles only to estimate boundary layer and cloud properties. As clouds can have large variability even at the microscale, we use a single source (radiosonde) dataset to study its relationship with BL height, mainly to avoid errors/inconsistencies in spatiotemporal sampling due to the use of multiple data sources.

A RH threshold of 90% is chosen in order to account for ice- or mixed phase clouds which often form under sub-saturated (RH < 100%) conditions in the cold Arctic region. The frequent occurrence of 95% BL cloud thickness in Fig. 5 (a) is not concerning as these cases are likely associated with the persistent stratus fog in the shallow Arctic BL (Nilsson and Bigg 1996). Nevertheless, we examined the sensitivity of the cloud characteristics in Fig. 5 against different RH thresholds (89,90,97%), and found that our results and analysis is robust.

As expected, the BL cloud occurrence frequency decreases when the RH threshold is increased beyond 90%, and vice-versa. The three distinct BL cloud thickness peaks shown in Fig. 5 (a) continue to exist at various RH thresholds (80,90,97%). The major difference is in the skewness of the distribution. For RH threshold of 97% (80%), this leads to a leftward (rightward) shift in the median, resulting in more positive (negative) skewness as compared to Fig. 5 (a). For example, when 97% RH threshold is used, the occurrence frequency of the maximum BL cloud thickness drops from 35 to 12%, whereas that of the minimum BL cloud thickness increases from 12 to 35%. While this does not affect the overall statistics of the stratus cloud regime, it appears to negatively impact the identification of stratocumulus clouds which typically form under colder air temperature conditions. Some cases of cold air advection, with RH > 90% but less than 97%, are (perhaps wrongly) classified as “dry” boundary layers with zero cloud layer thickness. The occurrence frequency of stratocumulus clouds reduces from 44% to ~30%, while that of “dry” BL conditions (uplift regime) increases from 15% to ~35%, which does not agree well with past studies cited in Section 4.2.1. On the other hand, the use of 90% RH threshold yields a reasonable distribution of cloudy vs. “dry” or cloud-free BLs, that agrees with past studies (Barton et al. 2012). Due to a better alignment of the occurrence frequency of cloud regimes with previous literature, and to account for ice or mixed-phase clouds that form under cold, sub-saturated conditions, we deem the use of 90% RH as the appropriate cut-off threshold in our study.

Comment 6: Page 5, line 13: I think that I understand this to mean that there were colder SATs observed in the recent years, is that correct? Otherwise can you explain how the variability of the SAT would result in increased surface sensible heat flux? Also, it might be informative to show the components that go into calculating deltaT. For example, how do the SSTs compare between years?

Response: Yes, this statement has been clarified to state that more negative SATs lead to the broader SSHF distribution observed in recent years (Pg. 5, Line 11). We didn’t include the figures showing the distribution of SSTs and SATs, as they are redundant, in our opinion. But these are shown here for your reference (Figs. 1 and 2).

Comment 7: Page 7, line 7-8: Interestingly, this is backwards from what I usually think about Arctic clouds (thick = frontal, thinner = stratocumulus, thinnest = decoupled stratus). I think it is important to remind the reader that this is cloud thickness within the boundary layer, and not total cloud thickness.

Response: Thank you for pointing this out. We have made sure to remind the reader that this is the boundary layer cloud thickness here (Pg. 7, Lines 3-5), and elsewhere in the text.

Comment 8: Page 7, line 13: This “(r)” should be positioned after “correlation coefficient”, not after “BL height”.

Response: The correction has been made (Pg. 7, Line 9). Thank you for your attention to the details.

Comment 9: Page 7, line 17-18: Yet as a whole, this regime does have deeper boundary layers than the two regimes with smaller deltaT.

Response: Yes, we have noted this in the text of the revised manuscript (Pg. 7, Lines 13-14).

Comment 10: Page 7, line 18-19: "indicating that stratocumulus clouds likely form by saturating to the significantly colder air mass that is advected above the surface" âĂŤ I'm not sure I follow what this means exactly. Suggest rewording for clarity.

Response: This sentence has been modified to read more clearly as follows:

"Figure 6 (a) shows that the temperature anomaly in this regime is maximized between 0.3 to 1.5 km altitudes, indicating that cold air advection occurs *above* the surface, where stratocumulus clouds likely form by the release of latent heat of vaporization". This is reflected in Pg. 7, Lines 15-17 in the new manuscript. Moreover, we have added a new section (Section 4.4) in which we use the thermodynamic equation to better explain how stratocumulus clouds may form during CAA over the open Arctic Ocean.

Comment 11: Page 7, line 25: More significant in what way? Page 7, line 31: More significant in what way?

Response: For the first case, we have replaced the word significant with the word evident (Pg. 7, Line 21). Studies supporting this sentence (Barton et al. 2012; Taylor et al. 2015) are cited in Pg. 7, Lines 22-23.

For the second case, we mean statistically significant at the 99% confidence level as indicated by Table 1. This has been explicitly mentioned in Pg. 7, Line 27 of the revised manuscript.

Comment 12: Page 8, line 17: Please redefine what "it" is in this sentence. I believe that you're referring to SSHF, but that should be explicitly stated in the text.

Response: "It" refers to the correlation coefficient (*r*) between the SSHF and the BL height. This has been explicitly stated in the revised manuscript (Pg. 8, Line 15).

Comment 13: Page 9, line 3: Is there a reason for thinking that the Arctic will see higher wind speeds in a future climate (or a reference which makes a case for this)?

Response: Some studies have reported that the Arctic will experience more frequent cyclonic conditions and higher wind stress in the future (Hakkinen et al. 2008; Higgins and Cassano 2009; Smedsrud et al. 2011). These have been duly cited in the text (Pg. 8, Line 32).

Comment 14: Section 5: I find this section to be less of a discussion, and more of a repetition of already stated findings.

Response: Section 5 has been re-written as a discussion of our present findings in context with previous literature. Relevant citations such as Boisvert and Stroeve (2015), Boisvert et al. (2015), Brümmer (1999), Brümmer and Pohlmann (2000), Hartmann et al. (1999), Deser et al. (2010), Higgins and Cassano (2009), Jackson et al. (2010; 2012), Nilsson et al. (2001), are now included in the revised manuscript.

Comment 15: Page 9, lines 24-25: I'm confused âĂŤ I thought that the higher wind speeds were shown to be a significant factor in the stratus regime, and not in the CAA/stratocumulus regime?

Response: Actually, the correlation coefficient '*r*' also improves with wind speeds in the CAA regime though it remains insignificant (Pg. 7, Lines 28-30). Nevertheless, we have removed this sentence as it was too speculative.

Comment 16: Page 10, lines 10-12: To what extent is this dependent upon the timing of the cruises? Does this number change under as the ocean advances towards refreezing in late October and early November, when air temperatures are colder? It might be nice to include information on the variability in observed SAT between the different years.

Response: We have carried out extensive analyses inspecting the spatial and temporal dependence of the SSHF-BL height relationship, and find that there is no sensitivity to the occurrence of negative SATs. Given that we have observations in October and September, we have looked at monthly differences and there is no evident seasonality. We are confident in our finding that the SSHF control of the BL height (~10%) is independent of the seasonal variations in ΔT. The interannual variability of observed SATs has been included here for your reference (Fig. 2).

Comment 17: Page 11, lines 7-9: I realize that this is supposed to be summarizing the previous text, but this has been stated many times already throughout the manuscript. I would have liked to see some more concrete discussion which synthesizes these results with other studies (without repeating the results of the current study over and over again).

Response: This entire section has been re-written (section 5 in the new manuscript), to include a more holistic discussion rather than repetition of our findings. New studies are cited (see response to Comment 14) to better synthesize our results with previous literature.

Comment 18: Section 6, bullet points: Again, I feel as though all of this has been stated many times already. I really don't see a need to repeat it a 3rd or 4th time.

Response: We have modified the section title to "Summary" as opposed to "Conclusions", and the bullet points now include only the key take-away points from our study.

Comment 19: Page 12, lines 12-13: What model physics need to be improved? The flux parameteri- zations? The cloud microphysics and radiation? Ocean dynamics and sea ice physics? More information on these questions would be more helpful than additional repetition of the results of the current study.

Response: In the revised manuscript, we have included a more comprehensive discussion of the implications of our results for model physics (Pg. 10, Lines 29-32, Pg. 11, Lines 1-2, and Pg. 11, Lines 15-21). This is provided below for your reference.

“Clouds, in turn, can have significant radiative feedbacks to the darker, ice-free ocean surface. Some model simulations of an ice-free Arctic Ocean suggest that the surface heat fluxes will dominate polar amplification during fall and early winter (Deser et al. 2010; Tietsche et al. 2011; Higgins and Cassano 2009). Our results suggest that both surface fluxes and clouds are sensitive to non-local large-scale factors, which influence their relative roles in diabatic heating of the Arctic atmosphere. This interaction between dynamic and thermodynamic variables must be duly incorporated in climate models for accurate projections of polar amplification”.

“Based on our results, it appears that conditions of uplift and high surface wind speeds may favour efficient heat dissipation by SSHF, whereas episodes of CAA may not. Nilsson et al. (2001) similarly found that the late summer/early fall turbulent heat fluxes over the Atlantic sector of the open Arctic Ocean can be sensitive to cyclone activity and cloud regimes. These dynamical triggers should be duly considered in BL parameterization schemes and surface layer schemes of climate models while evaluating future scenarios and sea ice recovery mechanisms for the Arctic. The chances of possible irreversible and more permanent feedbacks of sea ice loss also need to be seriously evaluated in models”.

Comment 20: Figure 1: I’m not sure that it’s necessary to show a map of the entire Arctic here. I think it would help to zoom in on the area of interest (say 60-90 N and 110W to 160 E).

Response: Figure 1 has been revised as per your recommendation. We have now zoomed in an area covering 120W to 150E for more clarity. Thank you for the suggestion. The new figure is included here for your reference (Fig. 3).

Comment 21: Figure 7: This caption is somewhat confusing. If I understand correctly: - The left hand figure is for uplift regime, and for all wind speeds, and the relationship is derived using all cases except the one outlier. How is this determined to be an outlier? Why are the cases with high BL height and very little SSHF not also outliers? - The right hand figure is for stratus cases, and is divided into two subsets âA ˇTˇ one for higher wind speeds (red) and one for lower (black). Why is there no relationship determined for the lower wind speeds? Please reword the caption for clarity.

Response: As explained in section 4.2 (Pg. 5, Lines 25-28), the ΔT has no influence on the correlation between SSHF and BL height (*r*), whereas surface wind speeds have a positive influence on ‘*r*’. For the observations of uplift regime shown in Fig. 7 (a), the point identified as an “outlier” has the maximum ΔT (6.77°C), which does not improve the linear relationship between SSHF and BL height. Whereas the red markers in Fig. 7 (b) are observations with maximum wind speeds, which has a positive influence on the linear relationship. For clarity, the caption has been modified to read as follows:

"Figure 7: The scatter plot of SSHF and BL height during (a) the uplift regime, and (b) the stratus regime. The linear relationship between the SSHF and BL height derived using the least squares method of curve-fitting for (a) all cases (except one outlier indicated by black marker), and (b) cases with surface wind speeds exceeding 9.8 ms^{-1} (indicated by red markers). The correlation coefficient and the coefficient of multiple determination for each linear relationship is denoted by r and R^2, respectively. Note that the outlier in the uplift regime is an observation point with maximum ΔT, which has no influence on r. Conversely, the red markers in the stratus regime are observations with maximum surface wind speeds, which have a positive influence on r. See section 4.2 for explanation."

References:

Barton, N. P., S. A. Klein, J. S. Boyle, and Y. Y. Zhang, 2012: Arctic synoptic regimes: Comparing domain-wide Arctic cloud observations with CAM4 and CAM5 during similar dynamics, *J. Geophys. Res.*, 117, D15205, doi:10.1029/2012JD017589

Boisvert, L. N., T. Markus, and T. Vihma, 2013: Moisture flux changes and trends for the entire Arctic in 2003–2011 derived from EOS Aqua data, *J. Geophys. Res. Oceans*, 118, 5829–5843, doi:10.1002/jgrc.20414.

Boisvert, L. N., and J. C. Stroeve, 2015: The Arctic is becoming warmer and wetter as revealed by the Atmospheric Infrared Sounder. *Geophys. Res. Lett.*, 42, 4439–4446. doi:10.1002/2015GL063775.

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Deser, C., R. Tomas, M. Alexander, and D. Lawrence, 2010: The seasonal atmospheric response to projected Arctic sea ice loss in the late twenty-first century. *Journal of Climate*, 23(2), 333-351.

Hakkinen, S., A. Proshutinsky, and I. Ashik, 2008: Sea ice drift in the Arctic since the 1950s. *Geophysical Research Letters*, 35(19).

Hartmann, J., et al., 1999: Arctic radiation and turbulence interaction study, *Polar Res. Rep.* 305, 81 pp., Alfred Wegener Inst. for Polar and Mar. Sci., Potsdam, Germany

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Hakkinen et al. 2008; Higgins and Cassano 2009; Smedsrud et al. 2011

Jackson, J. M., E. C. Carmack, F. A. McLaughlin, S. E. Allen, and R. G. Ingram, 2010: Identification, characterization, and change of the near-surface temperature maximum in the Canada Basin, 1993–2008. *Journal of Geophysical Research: Oceans*, 115(C5).

Jackson, J. M., W. J. Williams, and E. C. Carmack, 2012: Winter sea-ice melt in the Canada Basin, Arctic Ocean. *Geophysical Research Letters*, 39(3).

Nilsson, E. D., & Bigg, E. K. (1996). Influences on formation and dissipation of high arctic fogs during summer and autumn and their interaction with aerosol. *Tellus B*, *48*(2), 234-253.

Nilsson, E. D., Ü. Rannik, & M. Håkansson, 2001: Surface energy budget over the central Arctic Ocean during late summer and early freeze-up. *Journal of Geophysical Research: Atmospheres (1984–2012)*, *106*(D23), 32187-32205.

Smedsrud, L. H., A. Sirevaag, K. Kloster, A. Sorteberg, and S. Sandven, 2011: Recent wind driven high sea ice area export in the Fram Strait contributes to Arctic sea ice decline. *The Cryosphere*, 5(4), 821-829.

Taylor, P. C., S. Kato, K.-M. Xu, and M. Cai, 2015: Covariance between Arctic sea ice and clouds within atmospheric state regimes at the satellite footprint level, *J. Geophys. Res. Atmos.*, 120, 12,656–12,678, doi:10.1002/ 2015JD023520.

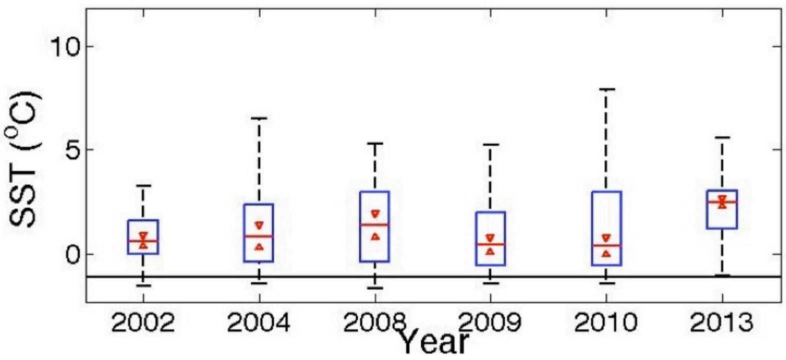

Fig. 1 The interannual variability in the distribution of the sea surface temperatures (SSTs). The solid horizontal black line represents the overall median value based on 6 years of ship data. The median for each year is represented by the horizontal red line within each boxplot, and the red notches represent the 95% confidence intervals around the same. Two medians are different at the 5% significance level if their intervals do not overlap.

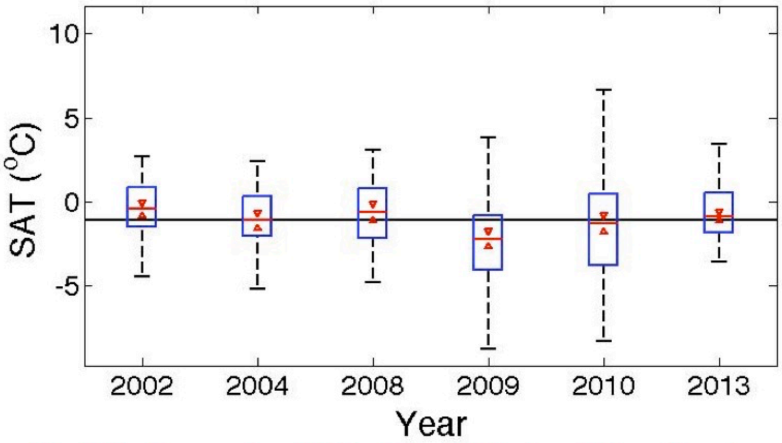

Fig. 2 The interannual variability in the distribution of the surface air temperatures (SATs). The solid horizontal black line represents the overall median value based on 6 years of ship data. The median for each year is represented by the horizontal red line within each boxplot, and the red notches represent the 95% confidence intervals around the same. Two medians are different at the 5% significance level if their intervals do not overlap.

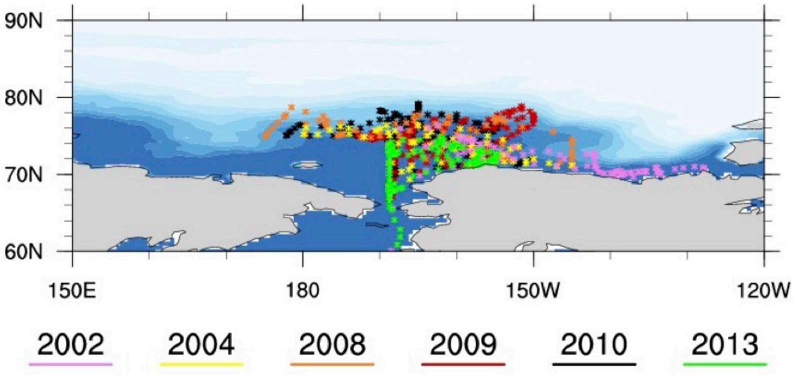

Fig. 3 Ship tracks during multi-year cruises of the R/V Mirai indicated by colored asterisk symbols. The average ice fraction (shaded white) at the time of cruise during 2008-2010 is also shown based on National Centers for Environmental Prediction/ National Center for Atmospheric Research (NCEP/NCAR) reanalyses project (Kalnay et al. 1996).