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Interactive comment on "Mechanism of Seasonal Arctic Sea Ice Evolution and Arctic Amplification" *by* K.-Y. Kim et al.

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Anonymous Referee #3 Received and published: 15 June 2016

The authors have examined the mechanisms by which declining sea ice in the Arctic is contributing to Arctic amplification of climate change. They focused on the differential changes in the Barents-Kara, Laptev and Chukchi seas and identified a unique pattern of change in the Barents and Kara seas associated with turbulent transport of heat from open water in the winter. The authors make a useful contribution to our understanding of the surface energy budget under conditions of reduced sea ice in the Arctic. I have a few general recommendations and some specific edits recommended:

General comments

Comment1(C1): The authors often talk about sea ice "melt" when they are referring to the trend toward reduced sea ice concentration. In some cases, "melt" may be the appropriate term, but in most cases it would be better to refer to reduced sea ice concentration and/or extent.

Response1(R1): Thank you for pointing this. We replaced "sea ice melting" by "sea ice loss" or "sea ice reduction" except when we really meant "melting". [Corrections are scattered throughout the manuscript.]

C2: The authors discuss the increase in 850hPa temperatures over the Barents and Kara seas of less than 0.1K, which they indicate leads to a âĹij1 W/m2 in downwelling longwave, which leads to two questions (see p. 8, l. 25-34). a. How can the authors be certain that the change in 850hPa temperature is due to the reduced sea ice concentration? b. I did some back of the envelope calculations, and it appears the magnitude of the downwelling longwave change is too large to be fully explained by the 850hPa temperature increase. Perhaps increased atmospheric moisture is playing a role in the increased downwelling longwave? The authors briefly discuss (p. 9, l. 20- 23) and cite the recent Park et al. paper (p. 12, l. 21-23), but perhaps this issue should be further explored/discussed.

R2a: As can be seen in Figure 10 (new Figure 9), the anomaly pattern of sea ice loss and those of turbulent heat flux, 2 m air temperature, upward longwave radiation, downward longwave radiation, and 850 hPa air temperature have common centers of action. These patterns share the same PC time series (Figure 2b). It seems reasonable to assume that these patterns share an identical source of variability. Figure R1 shows the loading vectors of the Arctic warming mode derived from the daily ERA-Interim data in winter (Dec. 1-Feb. 28; 90 days); the loading vectors are averaged over the Barents-Kara Seas. As can be seen in the figure, sea ice reduction is clearly seen throughout the winter (Figure R1a). The loading vector of turbulent heat flux has a positive mean and is generally positive throughout the winter because of the sea ice reduction in the area (Figure R1b; red curve)). The 850 hPa air temperature anomaly is also positive with a mean value of ∼1.26 K (Figure R1b; black curve). Finally, the loading vector of specific humidity has a mean value of ∼0.15 g kg-1, and is highly correlated with the 850 hPa air temperature; correlation is 0.91 (Figure R1b; blue curve). The specific humidity is moderately correlated with moisture convergence (corr = 0.54). Turbulent heat flux is negatively correlated with 850 hPa air temperature and specific humidity. This negative correlation seems to indicate that turbulent heat flux decreases as air temperature increases and specific humidity increases and reflects the bulk formulas for latent and sensible heat flux. It should be noted that all the variables have significant positive means. This positive mean is due to sea ice reduction throughout the winter. On top of the increased turbulent heat flux through the open surface of the ocean, the release of the turbulent heat flux is affected by the atmospheric condition (such as air temperature and humidity) as well as horizontal moisture transport.

Figure R2 shows the winter average pattern of moisture transport and convergence for the Arctic warming mode. This pattern is similar to Figure 5 in Park et al. (2015). There is a sign of moisture convergence in the Barents-Kara Seas. On the other hand, the daily time series over the Barents-Kara Seas (Figure R1c) indicates that the sign of moisture convergence fluctuates around zero. Thus, it is difficult to explain the non-zero mean of specific humidity in Figure R1b in terms of the moisture transport and convergence.

Thus, we think that the loss of sea ice leads to increased turbulent heat flux, which not only warms the atmospheric column but also increases specific humidity. Saturation specific humidity also increases as the atmospheric column warms up. The increased air temperature and specific humidity both contribute to the increased downward long-wave radiation. This discussion is difficult to include in the revision, since it requires new analysis based on daily ERA-Interim reanalysis data. [no corrective action]

R2b: According to the first law of thermodynamics, we have

$c_p \partial T/\partial t$ = - Del · F , (1)

where is the density of air, c_p is specific heat at constant pressure, T is temperature, and F âČŮ is heat flux. In a one-dimensional column model, (1) can be rewritten as

$c_p \partial T/\partial t = -\partial/\partial z (F_{up}-F_{down}) = -\partial/\partial z(F_{net})$. (2)

By integrating (2) with respect z from level z_1 to z_2, we have

$c_p \partial/\partial t$ (Integral_(z_1)-(z_2) T dz) = $-F_{net}(z_2)+F_{net}(z_1)$. (3)

Let $z_1=\varepsilon$ is the level at which radiative transfer is zero (say, slightly below the surface). Then, we can show that

$c_p \partial/\partial t$ (Integral_ε-(z_2) T dz) = $-F_{net}(z_2) = F_{down}(z_2)-F_{up}(z_2)$. (4)

If z_2 represents a vertical level slightly above the surface, the temperature near the surface is determined by downward and upward flux at level $z=z_2$. According to Figure 9, downward flux is larger than upward flux at the surface. Henceforth, surface temperature should increase. Likewise, we can let be the 850 hPa level and determine net heat flux for a temperature change integrated from 850 hPa to surface. Nonetheless, we cannot calculate upward flux and downward flux separately; we can only calculate net flux. Therefore, we cannot show what the downward flux from the 850 hPa level. In short, it is not the downward flux but the net flux that is related to the temperature change at the 850 hPa level (0.07 K). Of course, we do not have flux information at all vertical levels and we cannot verify theoretically that the downward flux 0.97 W m-2 is due to temperature change. [We eliminated Figure 9 together with the text associated with it.]

3. I appreciated that the authors added a schematic to explain the processes involved in the Barents and Kara seas (Fig. 9). Unfortunately, I was still left somewhat confused by the figure. For example, the "Increase T 0.07K" does not indicate at what level. The arrows leave me wondering if this is all happening concurrently or if there is a time associated with each process. I think this schematic is a good idea but could benefit

from some additional thought.

As explained in the method section, regression in CSEOF space allows us to write data in the form:

Data(r,t)=$\sum\_n\{B\_n(r,t), C\_reg\_n(r,t), D\_reg\_n(r,t), E\_reg\_n(r,t),\}T\_n(t),$

where the terms in curly braces for each n represents a physical process as reflected in different variables (say, temperature, sea ice concentration, 850 hPa air temperature, upward longwave radiation, etc.). The terms in curly braces are physically consistent with each other. For example, Figure R3 below shows the daily evolution associated with the Arctic Amplification mode. CSEOF analysis was conducted on the daily ERA-Interim data during winter (Dec. 1-Feb. 28), and the first CSEOF mode represents Arctic Amplification as in the present analysis. Shown in Figure R3 are the terms in curly braces for five different variables averaged over the Barents-Kara Seas [21°-79.5°E $\times$ 75°-79.5°N]. As can be seen in the figure, loss of sea ice is reflected in the positive values of anomalous 2 m air temperature, 850 hPa temperature, upward longwave radiation, and downward longwave radiation. Daily variations of atmospheric variables are highly correlated with each other, suggesting that they have a common cause (see Figure R4). Specifically, the impact of synoptic disturbance is conspicuous with significant fluctuations on synoptic time scales.

Further, CSEOF analysis indicates that these variations are amplifying in time as reflected in the PC time series. The mechanism described in Figure 9 (old) is the winter average picture of the mechnism which is similar to that shown in Figure R3. We can average the CSLVs during winter to estimate the relative magnitude of change in heat flux or atmospheric variables as sea ice loss continues. Whatever the cause of sea ice reduction is, a 1% loss of sea ice results in the changes in other variables as described in Figure 9. Further, the lagged correlation analysis among these variables indicates that turbulent heat flux preceeds 850 hPa warming, which, in turn, is followed by increased downward longwave radiation (see Figure R4). Ultimately, surface air

temperature increases due to increased downward longwave radiation.

On the other hand, the mechanism addressed above cannot be demonstrated in CSEOF analysis of monthly data. The cause-and-effect relationship among the variables in Figure R4 can only be appreciated when we analyze 3-hourly data. Therefore, we remove the entire discussion associated with Figure 9. Hopefully, we will address this mechanism in a new paper where 3-hourly data is employed for CSEOF analysis. [Removed the text associated with Figure 9.]

Minor comments

C1: p. 1, l. 10: “Arctic” misspelled, article missing

R1: Thank you. Corrected. [P1 L10]

C2: p. 1, l. 14: remove “to be”

R2: Corrected. [P1 L14]

C3: p. 2, l. 4: “Serreze” misspelled

R3: Corrected. [P2 L5]

C4: p. 2, l. 7: “in the earlier period” please be specific

R4: The cited references differ in terms of “earlier” and “later” periods. Therefore, we cannot be specific about the definition of earlier period. [no corrective action]

C5. p. 2, l. 29: “remains to be melted” is awkward

R5: We rephrased it as “sea surface remains to be ice free”. [P2 L29]

C6: p. 2, l. 32: “While summer sea ice melting is clearly seen. . .” Does this mean decreased summer sea ice concentrations? P. 3, l. 2: “winter sea ice melting” Is sea ice really melting during the winter? Please see general comment #1 above.

R6: We would like to keep the wording “sea ice melting” here, since it is sea ice melting.

In winter, however, it is not “melting” but “reduction”. Therefore, we changed it to “sea ice loss in winter”. [P3 L1]

C7: p. 3, l. 12-13: “each term in the feedback” is repeated

R7: We changed the sentence as follows: “. . . in order to clarify their relative importance in the feedback.” [P3 L13]

C8: p. 3, l. 22: add “and” before “2 m temperature”

R8: Thank you. Complied. [P4 L4]

C9: p. 5, l. 4: “extract physically meaningful consistent evolutions from these variables” I was confused by this statement, perhaps because of the use of the word “evolutions”

R9: We used the word “evolution”, since we are dealing with temporal variation of spatial patterns. We changed the wording as follows: “. . . extract physically consistent space-time evolution patterns from these variables.” [P7 L5] We also changed the “method of analysis” section significantly so that the concept of CSEOF analysis can be more easily conveyed.

C10: p. 5, l. 9: “volatile” is not the word choice I would have expected

C10: We changed the word to “sensitive”. [P7 L10]

C11: p. 6, l. 2: should be “increases” (agr)

R11: Thank you. Corrected. [P8 L5]

C12: p. 7, l. 21-22: “It is noted that” and “It is also worthy of remark that” are not necessary

R12: Complied. [P9 L26-28: Both the downward and upward radiation at the surface is maximized in winter (specifically February) with very small values in summer (Fig. 7b). Turbulent heat flux is maximized when 850 hPa temperature is minimum in March and November (Fig. 7c).]

C13: p. 8, l. 2: “is maintaining sea ice stay melted” is confusing

R13: We changed it as follows: “delayed warming is not so effective in sustaining the ice-free condition in winter in the . . .” [P10 L6]

C14: p. 9, l. 21: “trapping” is not a good description of this process

R14: We changed “trapping” to “absorbing”. [P11 L21]

C15: Figure 3 (and others): Some of the contours are difficult to follow, particularly on the JJA panel. If you chose not to label some of the contours, you may want to indicate the contour interval in the captions.

R15: We modified the contouring intervals to make the map readable. [See Figures 3-5 and Figure captions.]

* Figure Captions

Figure R1. The Daily patterns of variability over the region of sea ice loss (21°-79.5°E × 75°-79.5°N): (a) sea ice concentration, (b) 850 hPa air temperature (black), turbulent flux (red), and specific humidity (blue)×10, and (c) specific humidity (blue) and moisture convergence (red).

Figure R2. The winter average pattern of moisture transport and convergence for the Arctic warming mode. This pattern is obtained by averaging daily patterns over DJF.

Figure R3. Daily patterns of variability over the region of sea ice loss (21°-79.5°E × 75°-79.5°N): (a) sea ice concentration, (b) 2 m air temperature (red), 850 hPa air temperature×2 (black), and upward longwave radiation (blue), and (c) same as (b) except for the regressed downward longwave radiation (blue). Correlation of upward and downward longwave radiations with 2 m air temperature is respectively 0.90 and 0.95, whereas with 850 hPa air temperature is 0.60 and 0.86. (d) Corresponding PC time series.

Figure R4. Correlation of upward (solid lines) and downward (dotted lines) longwave radiations with 2 m air temperature (blue), 850 hPa temperature (red), and sea ice concentration (black). Longwave radiation lags the other variable for a positive lag. Lagged correlation between 2 m air temperature and 850 hPa air temperature (black dashed line); 2 m air temperature leads 850 hPa temperature for a positive lag.

** The combined response file including a marked-up manuscript is attached.

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/tc-2016-69/tc-2016-69-AC3-supplement.pdf

Interactive comment on The Cryosphere Discuss., doi:10.5194/tc-2016-69, 2016.

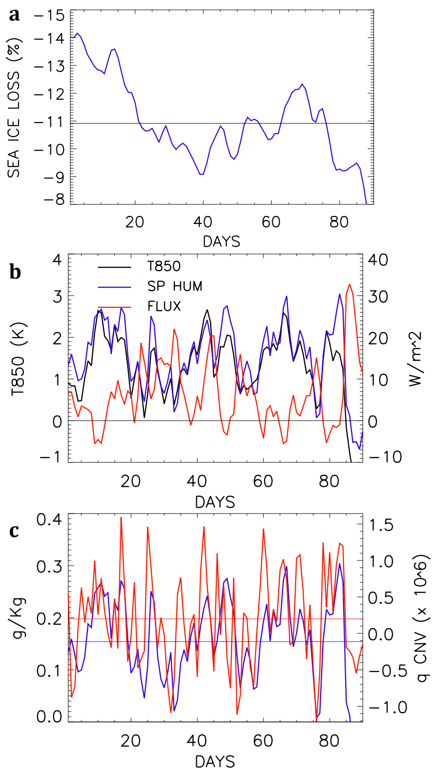

Fig. 1. The Daily patterns of variability over the region of sea ice loss (21°-79.5°E × 75°-79.5°N): (a) sea ice concentration, (b) 850 hPa air temperature (black), turbulent flux (red), and specific humidity

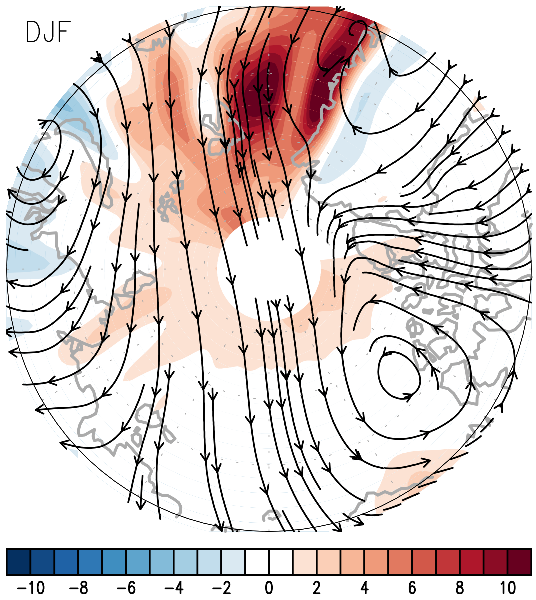

Fig. 2. The winter average pattern of moisture transport and convergence for the Arctic warming mode. This pattern is obtained by averaging daily patterns over DJF.

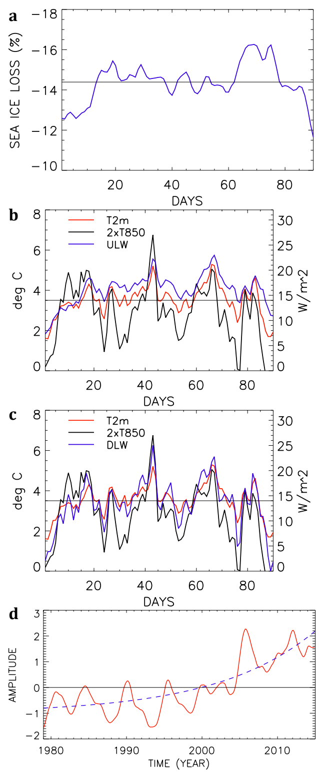

Fig. 3. Daily patterns of variability over the region of sea ice loss (21°-79.5°E × 75°-79.5°N): (a) sea ice concentration, (b) 2 m air temperature (red), 850 hPa air temperature×2 (black), and upward longwav

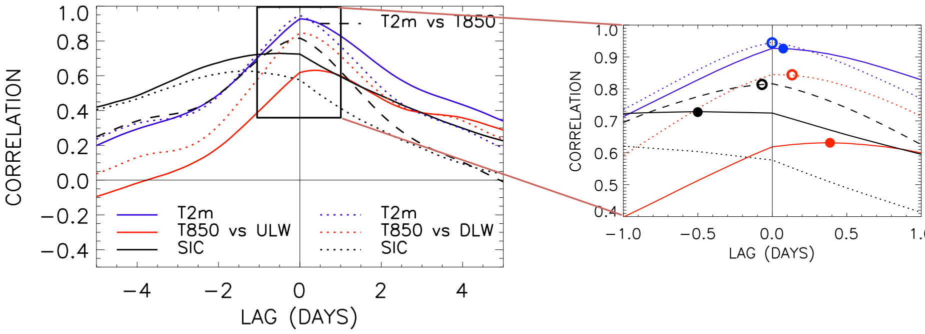

Fig. 4. Correlation of upward (solid lines) and downward (dotted lines) longwave radiations with 2 m air temperature (blue), 850 hPa temperature (red), and sea ice concentration (black). Longwave radiation