The Role of Downward Infrared Radiation in the Recent Arctic Winter Warming Trend

TINGTING GONG
Institute of Oceanography, Chinese Academy of Sciences, and Laboratory for Ocean and Climate Dynamics, Qingdao National Laboratory for Marine Science and Technology, Qingdao, China

STEVEN FELDSTEIN
Department of Meteorology, The Pennsylvania State University, University Park, Pennsylvania

SUKYOUNG LEE
Department of Meteorology, The Pennsylvania State University, University Park, Pennsylvania, and School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea

(Manuscript received 26 February 2016, in final form 27 December 2016)

ABSTRACT
During the past three decades, the most rapid warming at the surface has occurred during the Arctic winter. By analyzing daily ERA-Interim data, it is found that the majority of the winter warming trend north of 70°N can be explained by the trend in the downward infrared radiation (IR). This downward IR trend can be attributed to an enhanced poleward flux of moisture and sensible heat into the Arctic by poleward-propagating Rossby waves, which increases the total column water and temperature within this region. This enhanced moisture flux is mostly due to changes in the planetary-scale atmospheric circulation rather than an increase in moisture in lower latitudes. The results of this study lead to the question of whether Arctic amplification has mostly arisen through changes in the Rossby wave response to greenhouse gas forcing and its impact on moisture transport into the Arctic.

1. Introduction
Geological evidence has shown that the surface air temperature (SAT; i.e., the temperature at approximately 2 m above the surface of the earth) has undergone large-amplitude fluctuations, with those fluctuations being greatest at high latitudes (Budyko and Izrael 1991). In the Northern Hemisphere, this phenomenon is known as Arctic amplification. The present warming also shows this amplification, predominantly during December–February (DJF). Even for the present warming, however, the primary underlying mechanism behind this important phenomenon is uncertain. Proposed theories include ice–albedo feedback (Budyko 1969; Sellers 1969; Stroeve et al. 2012a; Serreze and Barry 2011), poleward heat and moisture fluxes from outside of the Arctic (Cai 2005, 2006; Graversen 2006; Graversen et al. 2008; Lu and Cai 2010; Lee et al. 2011; Lee 2014; Ding et al. 2014; Krishnamurti et al. 2015), and water vapor and cloud feedbacks (Francis and Hunter 2006; Screen and Simmonds 2010a; Serreze et al. 2012; Ghatak and Miller 2013), although these processes are not necessarily mutually exclusive. The latest climate models still underestimate the rate of Arctic sea ice melting (Stroeve et al. 2012b) and the Arctic SAT increase (Koenigk et al. 2013), indicating that an important process is either missing or misrepresented by most models. Here, we present evidence that an increase in the downward infrared radiation (IR) associated with remote wave forcing is primarily responsible for the Arctic SAT trend and then investigate the processes that drive these changes in the downward IR.

2. Data
We utilize the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) data. While produced by a model, the
assimilation of observational data, especially that of satellite origin (since 1979), makes this global dataset well constrained by observations even for variables such as the Arctic downward IR. For example, a recent study showed that the ERA-Interim surface radiation data compare well with in situ measurements (Zib et al. 2012). We can also be reasonably confident of the viability of the Arctic downward IR data because, as we will see, regression with other variables, some involving independent datasets, yields physically consistent relationships. For the surface and radiative flux fields, we use daily accumulated ERA-Interim values at time steps 3 and 6 for both 0000 and 1200 UTC [step 3 (step 6) corresponds to a forecasted flux 3 h (6 h) after 0000 and 1200 UTC]. For both 0000 and 1200 UTC, the difference between the step 6 and step 3 forecasted values is calculated, and this difference is divided by the time interval in seconds. This calculation gives the step 3 to step 6 time average forecasted fluxes for 0000 and 1200 UTC. For each day, the 0000 and 1200 UTC forecasted flux averages are themselves averaged to give the surface and radiative flux values for that day. In this study, we follow the ERA-Interim sign convention that all downward radiative and surface heat fluxes are positive.

3. Results

a. Which of the surface energy balance terms dominate the SAT trend?

We investigate linear SAT trends (kelvin per DJF winter season) for 15 different 20-yr segments corresponding to the 1979–98 through 1993–2012 time periods (Fig. 1). This approach enables us to examine the acceleration of the Arctic warming during the latter part of the 1979–2012 time period. Over the Arctic Ocean, the first 5 segments of the earlier years exhibit a weak cooling trend, while the remaining 10 segments of the later years show an accelerated warming trend. During the earlier years, the Arctic cooling was accompanied by midlatitude warming, which was followed in later years by a large warming in the Arctic and over northeastern Canada.

To evaluate the contribution of different processes to the SAT trend, we first consider the surface energy balance, based on Eq. (2) of Lesins et al. (2012), which can be written as follows:

\[
G = I_d - \epsilon \sigma T_s^4 + F_{sh} + F_{lh} + C,
\]

where \(G\) is the storage, \(I_d\) is the downward IR at the surface, \(T_s\) is the skin temperature, \(F_{sh}\) and \(F_{lh}\) are the
surface sensible and latent heat fluxes, respectively, \( C \) is conduction from below Earth’s surface, \( \varepsilon \) the longwave emissivity, and \( \sigma \) the Stefan Boltzmann constant. During the Arctic winter, the solar irradiance can be neglected. The term \( \varepsilon \sigma T_s^4 \) in (1) corresponds to the upward IR. For a thin layer of air next to the surface, \( G \) can be written as follows:

\[
G = \int_0^{\delta z} \rho c_p \left( \frac{dT}{dt} \right) dz,
\]

where \( \rho \) is density, \( c_p \) the specific heat capacity at constant pressure per unit mass, \( T \) is temperature, \( t \) is time, and \( \delta z \) is a short distance above the surface. Because \( \delta z \) is very small for a thin layer of air next to the surface, \( G \) in (1) can be neglected. Following Lesins et al. (2012), taking the differential of (1), but with \( G \) still included, results in

\[
\Delta G = \Delta I_d - 4\varepsilon \sigma T_s^3 \Delta T_s + \Delta F_{sh} + \Delta F_{lh} + \Delta C,
\]

where \( \Delta \) is the differential operator. Solving for \( \Delta T_s \) then yields

\[
\Delta T_s = (\Delta I_d + \Delta F_{sh} + \Delta F_{lh} + \Delta C - \Delta G)/(4\varepsilon \sigma T_s^3).
\]

Neglecting \( \Delta G \) and \( \Delta C \) in (4) (\( \Delta C \) tends to be small during Arctic winter; Lesins et al. 2012), (4) implies that the trend in skin temperature is proportional to the trend in the downward IR and the sum of the surface sensible and latent heat fluxes. Noting that the skin temperature is highly correlated with the SAT during all seasons over the Arctic (e.g., Chen et al. 2002; \( r = 0.97 \)) and that horizontal temperature advection and adiabatic warming/cooling influence the SAT, the SAT trend should be proportional not only to the trend in downward IR and the surface heat flux, as in (4), but also to the trend in horizontal temperature advection and adiabatic warming or cooling.

We calculate the linear SAT trends associated with (i) downward IR, (ii) the surface heat flux, (iii) horizontal temperature advection, and (iv) adiabatic warming/cooling. [The latter two terms are determined following the method of Lee et al. (2011).] The SAT trends are obtained by regressing SAT against each of these four terms at every grid point. Mathematically, the SAT at each grid point is written as \( f \approx f(x_1, x_2, x_3, x_4) \), where \( f \) is SAT, \( x_1 \) is downward IR, \( x_2 \) is surface heat flux, \( x_3 \) is horizontal temperature advection, and \( x_4 \) is adiabatic warming/cooling. The 20-yr trends in \( f \) associated with each of the independent variables are expressed as \( \delta f/ \delta x_i \Delta x_i \), for \( i = 1, \ldots, 4 \), where \( \delta f/ \delta x_i \) is the change in SAT with respect to the change in \( x_i \) and is estimated by calculating the linear regression coefficient at each grid point between the predictand \( f \) and the predictor \( x_i \). An important aspect of this calculation is that we use daily, detrended (to be explained later) data for calculating \( \delta f/ \delta x_i \), while \( \Delta x_i \) is the 20-yr interdecadal trend in \( x_i \). Specifically, \( \delta f/ \delta x_i \), which we take to be the regression coefficient, is expressed as \( r \sigma \text{SAT}/\sigma(x_i) \), where \( r \) is the linear correlation between the SAT and the various \( x_i \), and \( \sigma \text{SAT} \) and \( \sigma(x_i) \) are the standard deviations of the SAT and \( x_i \), respectively. Prior to calculating the regression coefficient, the DJF mean values of the SAT and each \( x_i \) are subtracted separately for each winter. Therefore, the SAT trend is determined by the product of 1) the correlation between the SAT and the various \( x_i \), and 2) the trend in \( x_i \).

By calculating the regression coefficient \( \delta f/ \delta x_i \) using daily detrended data, we presume that the same process that drives intraseasonal variability in the SAT also plays a significant role in contributing to the long-term SAT trend. D.-S. R. Park et al. (2015) motivated this perspective by using El Niño influence on rains over California as an example: the root cause for the enhanced rain is the slowly evolving anomalies in the tropical Pacific SSTs, but their influence on the rains is realized through rapidly evolving weather systems. Similarly, Lee et al. (2011) showed, using cluster analysis, that the SAT trend between 1958 and 2001 was realized through changes in the frequency of occurrence of particular teleconnection patterns whose time scales are less than 10 days. As another example, Lee and Feldstein (2013) showed that the interdecadal Southern Hemisphere poleward jet shift is realized through changes in the frequency of occurrence of poleward shift events whose time scale is again less than 10 days. This view is consistent with Palmer (1993, 1999), who showed with idealized models that interannual variability in the atmosphere occurs through interannual changes in the frequency of occurrence of the dominant intraseasonal spatial patterns rather than through slow interannual changes in the structure of the spatial patterns.

The resulting calculations suggest that most of the SAT trend over the Arctic is driven by the downward IR (Fig. 2, which shows the trend calculations for three different 20-yr time periods). For the 1991–2010 time period, the primary exception to this relationship can be found over the Greenland, Barents, and Kara Seas, where the SAT trend resulting from the surface heat flux is comparable to or greater than that associated with downward IR. The dominance of the downward IR for the SAT trend is not surprising, since as stated above, horizontal temperature advection and adiabatic warming/cooling are small near the surface, and the strong temperature inversion over much of the Arctic during the
winter suppresses the surface heat flux (Lesins et al. 2012). Since solar radiation is absent during winter over the Arctic, to account for the winter warming, the ice–albedo feedback theory proposes that the Arctic Ocean warms during the summer through solar heating and then the heat is released to the atmosphere during the following autumn and winter (Stroeve et al. 2012a; Serreze and Barry 2011). However, because of the negligible role played by the surface heat fluxes over most of the Arctic, except over the Greenland, Barents, and Kara Seas, these results tell us that outside of these three seas this mechanism is likely unimportant, at least for the recent Arctic warming trends.

Additional insight to the SAT trends in Fig. 2 can be gained by illustrating the regression coefficient and the trend for each $x_i$. This is shown in Fig. 3 for the 1991–2010 time period. The product of the regression coefficient (Fig. 3, top) and the trend (Fig. 3, bottom) is equal to the corresponding trend in Fig. 2, bottom. We first examine the regression coefficients. If the change in SAT at a location is associated with a single process, then it would be expected that the sign of the correlation (and therefore the sign of the regression coefficient) between the SAT and the term corresponding to that process would be positive (except for the surface heat flux, as a negative correlation corresponds to an upward heat flux and an increase in the SAT). In contrast, if the change in SAT is associated with two or more processes that take place at the same time, the correlation between the SAT and a term corresponding to one of these processes could take on either sign. In Fig. 3 (top), the regression pattern that stands out is that for downward IR, which shows that SAT and downward IR are positively correlated at all grid
points. Similarly, the near-surface horizontal temperature advection is positive at most locations. However, the surface heat flux and adiabatic warming/cooling indicate more complex behavior, as although they are mostly positive throughout the Arctic, they do show some regions with negative correlations. The trends in the four terms being examined (Fig. 3, bottom) show widespread positive values over the Arctic only for the downward IR. Therefore, the dominance in the downward IR contribution to the interdecadal SAT trend can be understood as arising from both the close day-to-day linkage between the SAT and downward IR, as expressed by the positive regression coefficient, and the large positive interdecadal trend in the downward IR.

b. What drives the downward IR?

The above results imply that the question of what processes drive the SAT trend, to a large extent, can be relegated to the same question about the downward IR trend. What then drives the downward IR trend? Arctic station data indicate that the downward IR time scale (the time over which the lagged autocorrelation of downward IR decreases by a factor of e) is between 3 and 5 days (Flournoy et al. 2016). Thus, to address the question of mechanisms, we generate a daily IR index by projecting the daily downward IR field onto the downward IR trend pattern in Fig. 3. (The details of this projection are presented below.) The daily IR index has an e-folding time scale of about 10 days. Therefore, the IR index measures the day-to-day variation in the amplitude of the downward IR trend pattern at its intrinsic 10-day time scale.

Before discussing the benefit of using the daily IR index, we first note that the daily downward IR field can be separated into two parts. Following Feldstein (2003), we can write

$$\text{IR}(\lambda, \theta, t) = \text{IR}_{\text{index}}(t) \text{IR}_{\text{trend}}(\lambda, \theta) + \text{IR}_{\text{r}}(\lambda, \theta, t),$$  \hspace{1cm} (5)

where IR(\lambda, \theta, t) is the full daily downward IR field at longitude \(\lambda\), latitude \(\theta\), and time \(t\); IR_{\text{trend}}(\lambda, \theta) is the...
downward IR trend pattern in Fig. 3; \( IR_{\text{index}}(t) \) is the daily amplitude of \( IR_{\text{trend}}(\lambda, \theta) \), and \( IR_{r}(\lambda, \theta, t) \) is the downward IR that is spatially orthogonal to \( IR_{\text{trend}}(\lambda, \theta) \). As shown in Eq. (4) of Feldstein (2003), \( IR_{\text{trend}}(\lambda, \theta) \) and \( IR_{r}(\lambda, \theta, t) \) are spatially orthogonal to each other if \( IR_{\text{index}}(t) \) is specified to be equal to the following:

\[
IR_{\text{index}}(t) = \frac{\sum_{ij} IR(\lambda, \theta, t) IR_{\text{trend}}(\lambda, \theta) \cos \theta}{\sum_{ij} IR_{\text{trend}}(\lambda, \theta)^2 \cos \theta},
\]

where \( i \) and \( j \) correspond to longitudinal and latitudinal grid points, respectively. We define \( IR_{\text{index}}(t) \) to be our daily IR index. Another property of (6) is that the interdecadal trend in the downward IR field is equal to the interdecadal trend in the IR index multiplied by \( IR_{\text{trend}}(\lambda, \theta) \). The corresponding corollary is that the interdecadal trend in \( IR_{r}(\lambda, \theta, t) \) must be zero.

Focusing on the 1991–2010 time period, Fig. 3 reveals that the downward IR trend field for this time period has two separate maxima, one over the Arctic and the other outside of the Arctic over northeastern Canada. Therefore, two separate daily IR indices were generated, one over the Arctic and the other over 70\(^\circ\)–90\(^\circ\)N (region 1) and the other over 50\(^\circ\)–70\(^\circ\)N (region 2). For all variables to be examined, the summation of the region 1 and region 2 regressions are very similar to the separate regression against the index derived for the full 50\(^\circ\)–90\(^\circ\)N downward IR (not shown). Since the focus of the current study is on the Arctic warming, the region-1 daily IR index (IR1 index) is adopted in the following analysis. We also show the IR and IR1 indices in Fig. 4. As can be seen, these two time series are dominated by their intraseasonal variability, as to be expected from the 10-day e-folding time scale for the IR index. Furthermore, both indices show a steady upward trend over the 1991–2010 time period.

We hypothesize that moisture flux convergence, total column water, etc. are the main drivers of the Arctic downward IR at both its intrinsic 10-day time scale and for its interdecadal trend. For the trend, this hypothesis is examined by regressing the variables shown in Fig. 5 against the IR1 index. The regression equation is written as follows:

\[
\Delta(Y) = \frac{r \sigma(Y)}{\sigma(\text{IR1})} \Delta(\text{IR1}),
\]

where \( \Delta(Y) \) is the 20-yr interdecadal trend in \( Y \), the variable of interest, and \( \Delta(\text{IR1}) \) is the corresponding linear interdecadal trend in the DJF-mean values of the IR1 index. The quantity \( r \) is the linear correlation between the daily values of the variable of interest and the IR1 index, and \( \sigma(Y) \) and \( \sigma(\text{IR1}) \) are the standard deviations of \( Y \) and the IR1 index, respectively. The regression coefficient, which is calculated from daily data with the DJF mean values of \( Y \) and the IR1 index subtracted for each winter, expresses the relationship between \( Y \) and the IR1 index at the intraseasonal time scale. Therefore, \( \Delta(Y) \) in (7) is an estimate of the interdecadal trend in \( Y \) associated with the interdecadal trend in the Arctic downward IR field. With this approach, we are taking the perspective that to better understand the interdecadal trend of the Arctic downward IR it is necessary to examine the intraseasonal downward IR fluctuations at its intrinsic 10-day time scale.

Figure 5 shows linear trends of the vertically integrated moisture flux vector and its convergence (multiplied by the latent heat of vaporization \( L \)) as well as downward IR, calculated by regressing these fields against the IR1 index, for the 1980–99 and 1991–2010 time periods. The horizontal moisture flux is examined because the midlatitudes are the most likely source of the water vapor over the Arctic, given that the surface
Fluxes (hence local evaporation) are found to be small (Fig. 3). For both time periods, the regressed linear trend in the moisture flux convergence and downward IR show similar spatial patterns. Since the magnitude of the moisture flux convergence (multiplied by $L$) is about half that of the downward IR (e.g., the mean value of the downward IR trend averaged over the Arctic is about 0.8 W m$^{-2}$, whereas that of the moisture flux convergence multiplied by $L$ is about 0.4 W m$^{-2}$), these results suggest that the latent heat release arising from condensation is an important contributor to the increase in downward IR.

Further insight is attained by calculating the trends of low, medium, and high cloud fraction; total column water (liquid water plus ice); $\sigma T^4$, where $T$ is temperature; and the zonal-mean temperature. For the later time period, a positive trend in cloud fraction over the Arctic is found to occur for low ($1.0 > p/p_s > 0.8$), medium ($0.8 > p/p_s > 0.45$), and high ($p/p_s > 0.45$) layer clouds, with pressure $p$ and surface pressure $p_s$, with the positive trend for the lowest layer being slightly greater than that for the middle layer and much larger than that for the highest layer (not shown). Consistently, the trend in the total column water shows a spatial pattern that is very similar to that of the downward IR (Fig. 5). The regression of the zonal-mean temperature shows a trend that is positive throughout the troposphere poleward of 65°N, with largest values in the lower troposphere. The quantity $\sigma T^4$ is calculated for two reasons. First, we ask to what extent the trend in temperature within each layer explains the downward IR trend. To address this question, we compute the vertically averaged temperature for each layer, substitute the resulting value into $\sigma T^4$, and regress against the IR1 index. A positive trend in $\sigma T^4$ is found for all three layers, with the lowest-layer $\sigma T^4$ trend (Fig. 5) being largest. As can be seen, the spatial pattern and amplitude of the lowest-layer $\sigma T^4$ trend closely resembles that for the downward IR, which suggests that the warming of the lowest cloud layer makes a large contribution to the downward IR trend. Second, we estimate the contribution by the horizontal temperature advection trend to the downward IR trend. For this estimation, we calculate the vertically integrated horizontal temperature advection for the lowest layer at each grid point and then multiply the resulting value into $\sigma T^4$, and regress against the IR1 index. A positive trend in $\sigma T^4$ is found for all three layers, with the lowest-layer $\sigma T^4$ trend being largest. As can be seen, the spatial pattern and amplitude of the lowest-layer $\sigma T^4$ trend closely resembles that for the downward IR, which suggests that the warming of the lowest cloud layer makes a large contribution to the downward IR trend.

**Fig. 5.** The trends for different moist thermodynamic variables obtained by multiplying the regression coefficients (regression against the IR1 index) and the trend in the IR1 index. Trends are shown for (left) the vertically integrated moisture flux vectors and moisture flux convergence multiplied by $L$ ($L^*\text{MoisFluxconv}$), (left center) total column water (liquid water plus ice; TCIW + TCLW), (center) the lowest-layer $\sigma T^4$ ($\sigma T^4$), (right center) the lowest-layer $\sigma T^4$ (Advection), and (right) the downward IR. The trends are shown for the (top) 1980–99 and (bottom) 1991–2010 DJF time periods. The lag chosen in each panel is lag 0 days, except for (left), which shows the average of the lag day $-10$ through lag day 0 trends. The corresponding lag is shown above each column. The stippling indicates values that are statistically significant at the $p < 0.05$ level for the Student’s $t$ test.
convergence but with a smaller magnitude. These results suggest that the downward IR increase during the later time period is due to a warming of the atmosphere through both 1) latent heat release and 2) horizontal temperature advection, along with an increase in 3) water vapor and 4) clouds, both being excellent emitters of IR.

c. Which trend—circulation or moisture—dominates the moisture flux trend into the Arctic?

What then causes the moisture flux convergence to increase? Is it caused by changes in moisture, in wind, or in both variables? An increase in low-latitude moisture was proposed as an important driver of Arctic warming (Langen and Alexeev 2007). To address this question, we decompose the moisture flux trend into a wind-trend contribution, a moisture-trend contribution, and a contribution involving the trend of the transient eddy moisture flux. We express the moisture flux trend as

\[(vq)_T = [(v_c + v)(q_c + q')]_T, \tag{8}\]

where the subscript \(T\) indicates the linear trend over the 1991–2010 time period, the subscript \(c\) denotes the climatological time mean for the 1991–2010 time period, the prime indicates a deviation from the 1991–2010 climatological time mean values, \(v\) corresponds to the velocity vector, and \(q\) the specific humidity. Equation (8) can be rewritten as

\[(vq)_T = v'_T q_c + v q'_T + (v' q')_T. \tag{9}\]

By comparing the moisture flux vectors in Figs. 6a–d, it can be seen that the trend of the total moisture flux entering the Arctic (Fig. 6a) is dominated by its trend (\(v'_T q'_T\)) over the North Atlantic, Europe, and the Bering Sea (Fig. 6b), with the transient eddy moisture flux playing a secondary role (see the discussion below). This result indicates that the moisture flux trend associated with the trend in Arctic downward IR is determined primarily by the contribution from the trend in the wind field in these regions. Furthermore, since the trend in the sum of the surface latent and sensible heat fluxes is small (Fig. 3), and the trend in the moisture flux vector extends from the midlatitudes into the Arctic, these results suggest that the strengthening trend in the northward component of the wind is transporting water vapor from the midlatitudes into the Arctic. If we compare the wind-trend moisture flux (the product of the wind trend and the climatological specific humidity) convergence and the transient eddy moisture flux convergence (Figs. 6b,d), we see that the wind-trend contribution dominates east of Greenland and over the Arctic Ocean north of Scandinavia and western Siberia, and the transient eddy contribution dominates over the Arctic Ocean north of eastern Siberia. Furthermore, if we look at the trend of the moisture flux vectors, it can be seen that the wind-trend moisture flux convergence over eastern Greenland and north of Scandinavia and western Siberia is associated with a moisture transport from midlatitudes that extends over the North Atlantic and northern Europe. With regard to the transient eddy moisture flux convergence north of eastern Siberia, it can be seen that this moisture flux convergence is associated with moisture fluxes over far-eastern Siberia and the Bering Strait. Given the larger area of deep red shading for the wind-trend contribution (cf. Figs. 6b and 6d), it appears that the wind-trend contribution to the moisture transport into the Arctic is larger than the transient eddy contribution.

To obtain a more complete picture, the trend in the 250-hPa streamfunction field for the entire Northern Hemisphere is shown (Fig. 6e). As can be seen, the circulation trend is characterized by poleward-propagating planetary-scale Rossby wave trains that extend from the northeastern Pacific into the Arctic and from the North Atlantic into Siberia, as well as an equatorward-propagating wave train from Siberia to the subtropical northeastern Pacific. (The direction of wave propagation can be identified from the horizontal tilt of the anomalies, with a northwest–southeast-tilted orientation indicating poleward propagation, and vice versa.) Thus, it appears that the moisture flux trend into the Arctic is part of a much larger hemispheric-scale trend in the circulation. Given that a wave train resembling that shown in Fig. 6e over the North Pacific is often excited by tropical convection (Mori and Watanabe 2008; Johnson and Feldstein 2010; Moore et al. 2010; Lee et al. 2011), and the emerging evidence that a warmer Arctic can also excite Rossby waves that propagate toward midlatitudes (e.g., Deser et al. 2004, 2007; Honda et al. 2009), additional analyses are necessary to fully understand this wave train pattern.

d. Intraseasonal lead–lag relationships among moisture flux convergence, downward and upward IR, surface heat flux, total column water, and SAT

Next, we investigate the physical processes that drive the downward IR trend pattern on the intraseasonal time scale. These calculations are performed in two steps. First, we calculate the 1991–2010 trends in \(\Delta(Y)\), where \(Y\) corresponds to variables such as moisture flux convergence, total column water, downward and upward IR, surface heat flux, and SAT, by computing the lagged regression coefficient, \([r(\tau)Y/\sigma(IR1)]\), between \(Y\) and the IR1 index at time lag \(\tau\) and then multiplying the lagged regression coefficient by the linear
interdecadal trend in the IR1 index $\Delta$(IR1). The form of
this equation is identical to (7), except for the time lag. As in (7), the DJF mean values of $Y$ and the IR1 index are subtracted for each winter when calculating the regression coefficient. Then, we calculate the pattern correlations between $\Delta[Y(t)]$ and $Y_T$, where $Y_T$ is the trend in $Y$, for the domain poleward of 70°N over a range of lags (Fig. 7). By performing spatial correlations between $\Delta[Y(t)]$ and $Y_T$, we can identify the temporal evolution of $Y$ associated with the intraseasonal variation of the downward IR trend pattern. Implicit in this calculation is that a large portion of the trend in $Y$ is associated with the downward IR trend. The large pattern correlations in Fig. 7 show that this is indeed the case. Pattern correlations between $\Delta[Y(t)]$ and $\Delta[Y(0)]$ yield very similar results, which provides further support for the linkage between the trends in the downward IR and the variables in Fig. 7. We can see from Fig. 7 that the SAT warming is first initiated by moisture flux convergence into the Arctic, followed by an increase in total column water, downward and upward IR, and SAT, and then several days later by the surface heat flux.

This sequence of events takes place within about two weeks. Consistently, Woods et al. (2013) and Liu and
Barnes (2015) also showed that blocks, which evolve on a similar time scale, are associated with the transport of moisture from the midlatitudes into the Arctic during the winter. Furthermore, Woods et al. (2013), as well as Woods and Caballero (2016), showed that these moisture intrusions are accompanied by an enhanced downward IR and surface warming in the Arctic.

In our analysis of the relationship between the SAT and downward IR trends, we did not explicitly calculate the trend in upward IR. This was because the trend in upward IR in (3) was expressed as $4\sigma T_s^3 \Delta T_s$; that is, the upward IR trend simply expresses the trend in SAT. Nevertheless, further insight into the processes that take place at the surface can be gained by examining the daily evolution of the upward, downward, and total IR, as well as the surface heat flux and the SAT (Fig. 8). As can be seen, downward IR and upward IR are almost identical at all times (in spatial pattern, not sign), with the former being slightly greater than the latter from lag -9 to lag 0 days over much of the Arctic Ocean, but after lag +3 days, upward IR starts to exceed the downward IR, particularly over the Barents and Kara Seas where sea ice has been significantly declining (e.g., Screen and Simmonds 2010b; D.-S. R. Park et al. 2015). A consistent feature can be seen in Fig. 7, where it is shown that the downward IR and upward IR pattern correlations are similar at negative lags but that the latter is greater than the former at positive lags, indicating that the upward IR lingers longer. The picture that emerges from this analysis, and from the similar analysis by D.-S. R. Park et al. (2015), is that downward IR warming is almost instantaneously balanced by an upward IR response except over regions where thin sea ice melts and exposes warm ocean water to the atmosphere, as in marginal sea ice zones. [A consistent picture has been found by H.-S. Park et al. (2015), who showed that moisture intrusions into the Arctic with an accompanying increase in downward IR are associated with a melting of sea ice in the marginal ice zone within a period of about 10 days.]

As a result, upward IR (which in the first place is driven by downward IR warming) may exceed the downward IR over these marginal sea ice zones. In addition, in the Greenland, Barents, and Kara Seas, a strong upward surface heat flux is observed to take place at positive lags. By lag day +3, the surface heat flux over the Kara Sea has changed sign and become upward, followed by the surface heat flux becoming upward over the Barents Sea by lag day +6 and over the Greenland Sea by lag day +9. These results are consistent with the picture that downward IR melts sea ice and this is followed by a strong upward surface heat flux. Also, the SAT evolution shows a steady increase in the SAT from lag -6 to lag 0 days, peaking in the Kara Sea, followed by a steady decline over the following 9 days.

As discussed in the previous section, studies such as Stroeve et al. (2012a) and Serreze and Barry (2011) have proposed that an ice–albedo feedback during the preceding summer warms the upper parts of the ocean and that this heat is released to the atmosphere during the fall and winter. The results shown in Fig. 2 imply that this mechanism is unimportant for the recent warming over most of the Arctic except perhaps for the Greenland, Barents, and Kara Seas. Since the IR1 index fluctuates on a short 10-day time scale, much shorter than the seasonal time scale of the proposed ice–albedo feedback, and because the IR1 index expresses the downward IR trend for the Arctic as a whole, the regression method cannot fully address the question of whether the ice–albedo feedback does play a role locally in the Arctic, such as over the marginal sea ice areas of the Greenland, Barents, and Kara Seas. Nevertheless, the results from the regression calculation do allude to the ice–albedo feedback not being the dominant driver of the surface warming even over these three seas. This is because, for the Greenland, Barents, and Kara Seas, the regression of the surface heat flux against the IR1 index showed that an anomalous downward heat flux at negative lags is followed by an anomalous upward heat flux at positive lags. Therefore, even over the Greenland, Barents, and Kara...
FIG. 8. Lagged linear regression against the IR1 index for (left) downward IR, (left center) upward IR, (center) total IR, (right center) surface heat flux, and (right) SAT. The stippling indicates values that are statistically significant at the $p < 0.05$ level for the Student’s $t$ test.
Seas, it is plausible that the main driver of the surface warming is still an increase in downward IR, which melts sea ice, resulting in an increase in the surface heat flux and further warming of the atmosphere.

4. Conclusions

In this study, we show that the Arctic warming trend is overwhelmingly due to the trend in the downward IR, with this downward IR increase due to moisture influx and warm air advection from the midlatitudes caused by the trend in the hemispheric atmospheric circulation. Such a circulation-induced change is often attributed to internal variability (Yang et al. 2010; Wallace et al. 2012; Ding et al. 2014). However, it has been shown that much of the extratropical greenhouse gas (GHG)-driven surface warming is realized through warming of the tropical SST (Compo and Sardeshmukh 2009; Shin and Sardeshmukh 2011), possibly through poleward-propagating Rossby waves (Compo and Sardeshmukh 2009; Shin and Sardeshmukh 2011; Lee et al. 2011; Yoo et al. 2011). Therefore, the results of this study lead to the question of whether Arctic amplification has mostly arisen through the planetary-scale wave response to GHG forcing and its impact on moisture transport into the Arctic. This possibility is also consistent with the tropically excited Arctic warming (TEAM) mechanism, which states that Arctic amplification is sustained by planetary-scale waves that can be forcefully excited by tropical convection and do not rely on an elevated baroclinicity or zonal available potential energy (Lee 2014; Baggett and Lee 2015).

Acknowledgments. We thank all three anonymous reviewers for their helpful comments on this manuscript. This study was supported by the National Natural Science Foundation of China (41305048), the National Basic Research Program of China 2012CB417403, and the National Science Foundation Grants AGS-1455577, AGS-1036858, and AGS-1401220.

REFERENCES


