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The role of poleward energy transport in Arctic temperature evolution

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[1] The observed evolution of Arctic troposphere temperature is the combined effect of many processes including the poleward transport of atmospheric energy. In this study we quantify the relationship between poleward energy transport and decadal temperature variations in the Arctic free-troposphere. Time series of Arctic free-troposphere mean temperature show a decade of maximal cooling centered in the late eighties, followed by a decade of pronounced warming centered in the late nineties. We show that about 25% of the decadal cooling trend can be ascribed to decreasing poleward energy transport into the Arctic, and about 50% of the decadal warming trend was due to increasing poleward energy transport. These changes were reflected throughout the free-troposphere, were associated with changing intensity of the polar meridional circulation cell, and were dominant in the autumn and winter seasons. By contrast, the last decade has been fairly neutral in terms of temperature and energy transport change. **Citation:** Yang, X.-Y., J. C. Fyfe, and G. M. Flato (2010), The role of poleward energy transport in Arctic temperature evolution, *Geophys. Res. Lett.*, *37*, L14803, doi:10.1029/2010GL043934.

1. Introduction

[2] Near-surface temperatures over land north of 65°N have been rising more-or-less monotonically in recent decades in response to anthropogenic emissions of greenhouse gases and sulphate aerosols [*Gillett et al.*, 2008], and amplified through a feedback with snow/ice albedo [*Serreze et al.*, 2009; *Screen and Simmonds*, 2010]. By contrast, Arctic mean temperature in the free-troposphere (above 700–800 hPa) has been decidedly non-monotonic, and the influence of anthropogenic forcing far less obvious. This is seen in Figure 1 (bottom left) which shows decadal trends of temperature averaged over the Arctic and through the free-troposphere for one satellite and two reanalysis products. These data reflect a quasi-decadal variation, with a decade of maximal cooling centered in the late 1980s, followed by a decade of pronounced warming centered in the middle to late 1990s, and near neutral conditions over the last decade. Here we ask to what extent was poleward energy transport responsible for this decadal variation of Arctic troposphere temperature? This question is not only one of scientific importance but is also one of practical importance with respect to climate change detection and attribution.

[3] The issue of the impact of poleward energy transport on Arctic temperature trends, particularly associated with middle troposphere Arctic temperature amplification, was raised by *Graversen et al.* [2008a]. Using ERA-40 reanalyses they concluded that poleward energy transport accounted for a considerable fraction of the 1979 to 2001 warm season temperature trend pattern in latitude ($\phi \geq 30°$N) and pressure ($p \geq 100$ hPa). However, several recent studies have questioned these results based on the unreliability of long term trends in ERA-40 reanalyses [*Thorne*, 2008; *Bitz and Fu*, 2008; *Grant et al.*, 2008] – a criticism that *Graversen et al.* [2008b] defended against using a second reanalysis data set. Recently it has been established that diminishing sea ice, rather than poleward heat transport, plays the leading role in near-surface Arctic temperature amplification observed over recent decades [e.g., *Serreze et al.*, 2009; *Screen and Simmonds*, 2010].

[4] To be clear, our study differs substantively from these earlier studies in that our study concerns decadal time scale variation rather than long term multi-decadal change, and focuses on free-troposphere rather than near-surface temperature trends. Whereas multi-decadal change can be difficult to confirm in reanalyses given a time-varying mix and coverage of observations [*Thorne*, 2008], we show below (using multiple data sources) that short term decadal variations are more easily established.

2. Data and Methodology

[5] In this study we use monthly temperature for 1979 to 2008 obtained from the Microwave Sounding Unit (MSU) on the NOAA TIROS-N polar-orbiting satellites. These data were processed independently by the University of Alabama in Huntsville (UAH) [*Christy et al.*, 2000] and by Remote Sensing Systems (RSS) [*Mears et al.*, 2003] and we employ both versions in our study. We consider free-troposphere channel 2 temperature (T2) whose vertical weighting function $w_2(p)$ shown in Figure 1 (top) is maximal at $p = 595$ hPa.

[6] From ERA-40 (ERA) [*Uppala et al.*, 2005] and NCEP/NCAR (NRA) [*Kistler et al.*, 2001] reanalyses we use temperature T, horizontal velocity $\mathbf{u} = (u, v)$, vertical velocity ω, geopotential height z, and specific humidity q. These data are archived at daily resolution on 2.5° (longitude) by 2.5° (latitude) horizontal grids. The ERA data are for 1979 to 2001 and are on 23 pressure levels from 1000 hPa to 1 hPa. The NRA data are for 1979 to 2008 and are on 17 pressure levels from 1000 hPa to 10 hPa. To quantitatively compare the satellite and reanalysis temperatures, we weight the latter by $w_2(p)$ and average vertically over all available pressure levels.

[7] Using the daily reanalyses we compute atmospheric energy E in units of joules per kilogram (J kg^{-1}) on a given pressure level p as the sum of kinetic $\frac{1}{2}\mathbf{u} \cdot \mathbf{u}$, sensible c_pT, potential gz, and latent Lq energies; where c_p is specific heat at constant pressure, g is gravity, and L is specific heat of

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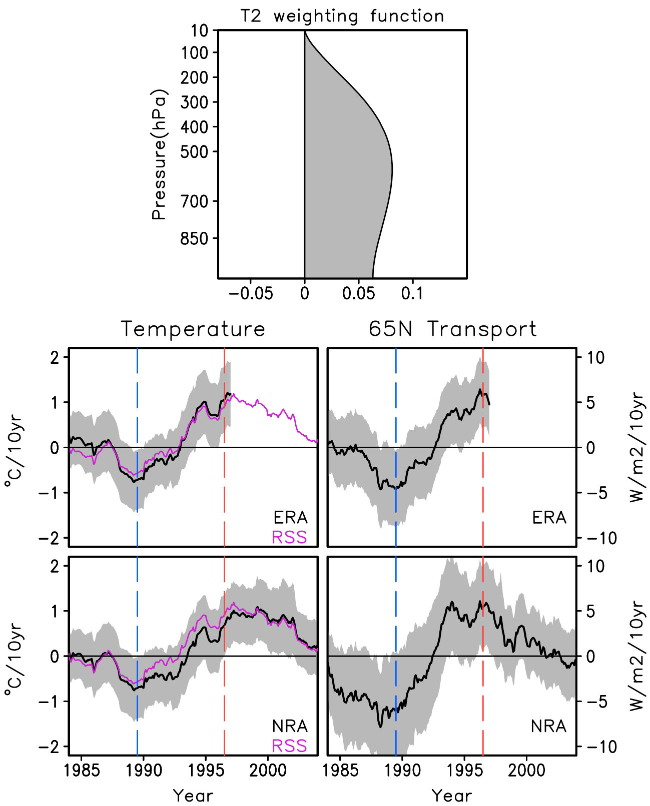

Figure 1. Decadal trends in monthly temperature averaged over (left) the Arctic and (right) poleward energy transport across 65°N. (top) Satellite data (RSS) are T2 temperatures with weighting function $w_2(p)$, and Arctic averages are from 60°N to 82.5°N. Reanalysis data are Arctic averages north of 65°N, and are weighted by $w_2(p)$ before averaging from 1000 hPa to 1 hPa (ERA) and to 10 hPa (NRA). Trends are centered on the indicated year (e.g. the trend at 1985 is based on data from 1980 to 1990).

condensation. The vertical integral of poleward energy transport across latitude ϕ_o in units of watts (W) is

$$\mathcal{F}_{\phi_o}(t) = g^{-1} \int_{p_{bot}}^{p_{top}} \int_{\phi_o} Ev\, a \cos\phi_o\, d\lambda\, dp, \qquad (1)$$

where a is earth's radius, λ is longitude, p_{bot} = 1000 hPa, p_{top} = 1 hPa for ERA and 10 hPa for NRA, and the longitudinal integration is along ϕ_o = 65°N. As with temperature we weight the integrand by $w_2(p)$, noting however that our results are anyways insensitive to this weighting. Finally, we divide the result by the area of the Arctic (i.e. $\phi \geq \phi_o$) to obtain units of W m^{-2}. These energy calculations use daily data and results are monthly averaged. All significance testing of decadal trends is at the 95% confidence level taking into account temporal autocorrelation [*Santer et al.*, 2000].

3. Results

3.1. Temporal Variation

[8] Figure 1 (bottom left) shows decadal trends in monthly Arctic area mean and vertical mean temperature $\mathcal{T}(t)$ for the ERA, NRA, and RSS data sets. The UAH trends are not shown as they are indistinguishable from the RSS trends.

[9] While some differences exist between the data sets they strongly agree on a decade of maximal cooling centered in the late eighties, of pronounced warming centered in the middle to late nineties, and near neutrality over the last decade. The ERA Arctic troposphere temperature trends for the cooling decade (centered on 1989), warming decade (centered on 1996), and all decades (from 1979 to 2001) are about −0.72 ± 0.67°C decade^{-1}, +1.06 ± 0.72°C decade^{-1}, and +0.18 ± 0.20°C/decade, respectively. The individual decadal trends are large and statistically significant, while the long term (1979 to 2001) trend is small and statistically insignificant.

[10] Figure 1 (bottom right) shows decadal trends in $\mathcal{F}_{\phi_o}(t)$ (ϕ_o = 65°N) for the ERA and NRA data. (Note that climatologically speaking $\mathcal{F}_{\phi_o}(t) > 0$ in all calendar months). The decades of maximal cooling and pronounced warming in the Arctic troposphere correspond to decades of decreasing and increasing vertically-integrated poleward energy transport into the Arctic, respectively. On time scales of a few days

$$\rho c_p \nu\, d\mathcal{T}/dt \sim \mathcal{F}_{\phi_o} + F_r + F_s \qquad (2)$$

where ρ is air density, ν is Arctic atmosphere volume, F_r is net radiative heat flux at the top of the polar cap, and F_s is net heat flux at the bottom of the polar cap. However, for time scales of a month or more, $d\mathcal{T}/dt$ is small and balances arise between the right-hand-side terms, each of which depends on $\mathcal{T}$. As a result, $\mathcal{T}$ should depend on the energy transport itself for long time scales. Figure 1 confirms this, indicating a linear relationship between decadal trends in $\mathcal{T}(t)$ and $\mathcal{F}_{\phi_o}(t)$.

[11] In ERA data the cooling decade, warming decade, and long term trends correspond to $\mathcal{F}_{\phi_o}(t)$ trends of about −4.63 ± 4.24 W m^{-2} decade^{-1}, 5.90 ± 3.61 W m^{-2} decade^{-1}, 0.32 ± 1.09 W m^{-2} decade^{-1}, respectively. As with temperature the individual decadal trends are large and statistically significant, while the long term trend is near zero and statistically insignificant. We now proceed using the ERA data set alone since differences with the NRA data set are slight.

3.2. Spatial Patterns

[12] Figure 2 (top) shows decadal trends in vertical mean vertically-weighted temperature for the cooling (left) and warming (right) decade. The cooling decade is characterized by Arctic wide cooling (largest on the Siberian side) and mid-latitude warming at most longitudes. The warming decade is an approximate mirror image with Arctic wide warming (largest on the North American side) and mid-latitude cooling at most longitudes. These patterns of north-south dipolar temperature change are consistent with decreasing vertically-integrated poleward energy transport into the Arctic in the cooling decade and increasing energy transport into the Arctic in the warming decade. To confirm this we compute the transport congruent temperature trend pattern as $\alpha R(\phi, \lambda)$ where α is the (cooling or warming) decadal trend in $\mathcal{F}_{\phi_o}(t)$ and

$$R(\phi, \lambda) = \overline{\mathcal{F}'_{\phi_o}(t)\; T'(\phi, \lambda, t)} / \overline{\mathcal{F}'_{\phi_o}(t)^2}, \qquad (3)$$

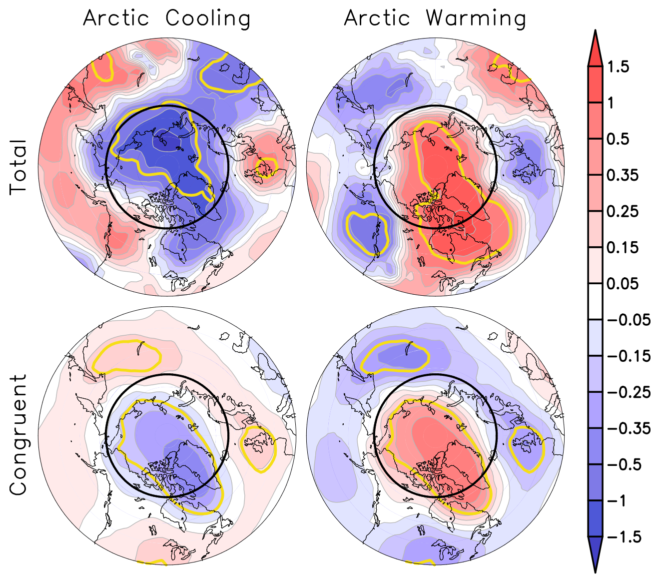

Figure 2. Decadal trends in (top) monthly vertical mean vertically-weighted temperature and (bottom) transport congruent temperature in units of °C/decade. The Arctic cooling decade is centered on 1989 and the Arctic warming decade is centered on 1996. The thick black circles delimit the Arctic region as defined in this study, and the yellow curves show the 95% confidence limit. Here, and in what follows, a small hemispheric mean value has been removed to help visually accentuate the regional pattern of change.

computed from 1979 to 2001. Here an overbar denotes a time-mean and a prime denotes deviations from a time-mean after removing all linear trends. Note that $T'(\phi, \lambda, t)$ refers to anomalous vertical mean vertically-weighted temperature.

[13] Figure 2 (bottom) shows the transport congruent temperature trend pattern for the cooling (left) and warming (right) decade. Take note that these congruence patterns are identical by construction except for differing scaling factors α. For both periods there is a clear correspondence between the total and transport congruent trend patterns. In terms of pattern correspondence, the spatial correlation between the total and transport congruent pattern (over the plotted domain) is about 0.65 for the cooling decade and 0.79 for the warming decade. In terms of magnitude correspondence, about 23.2% of the Arctic mean cooling trend and 46.7% of the Arctic mean warming trend is explained by decreasing and increasing vertically-integrated poleward energy transport, respectively. The components of sensible and potential energy transport dominate these change in about equal measure (not shown).

[14] Figure 3 (top) shows decadal trends in zonal mean vertically-weighted temperature for the cooling (left) and warming (right) decade. The cooling decade is characterized by middle latitude warming (largest in the middle troposphere) and high latitude cooling (largest in the lower and upper troposphere). Figure 3 (top) also shows decadal trends in the vertically-weighted meridional and vertical energy transports. These transport trends indicate a spinning down and spinning up of the polar meridional circulation cell (which is climatologically anti-clockwise) during the Arctic

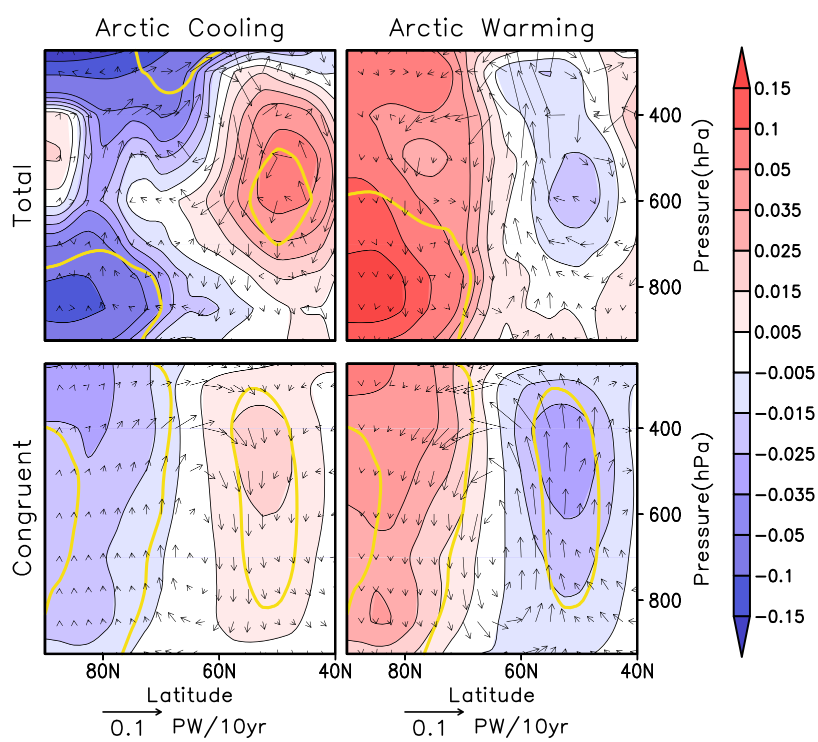

Figure 3. Decadal trends in (top) monthly zonal mean and vertically-weighted temperature and (bottom) transport congruent temperature in units of °C/decade. Also shown are decadal trends in zonally integrated meridional and vertical components of energy transport $A_\phi(\phi, p, t) = (\Delta p/g) \int Ev\, a \cos \phi\, d\lambda$ and $A_p(\phi, p, t) = (a\, \Delta\phi/g) \int E\omega\, a \cos \phi\, d\lambda$, respectively, where Δp is pressure increment, and $\Delta\phi$ is latitude increment. Note that $A_\phi(\phi, p, t)$ and $A_p(\phi, p, t)$ have been weighted by $w_2(p)$.

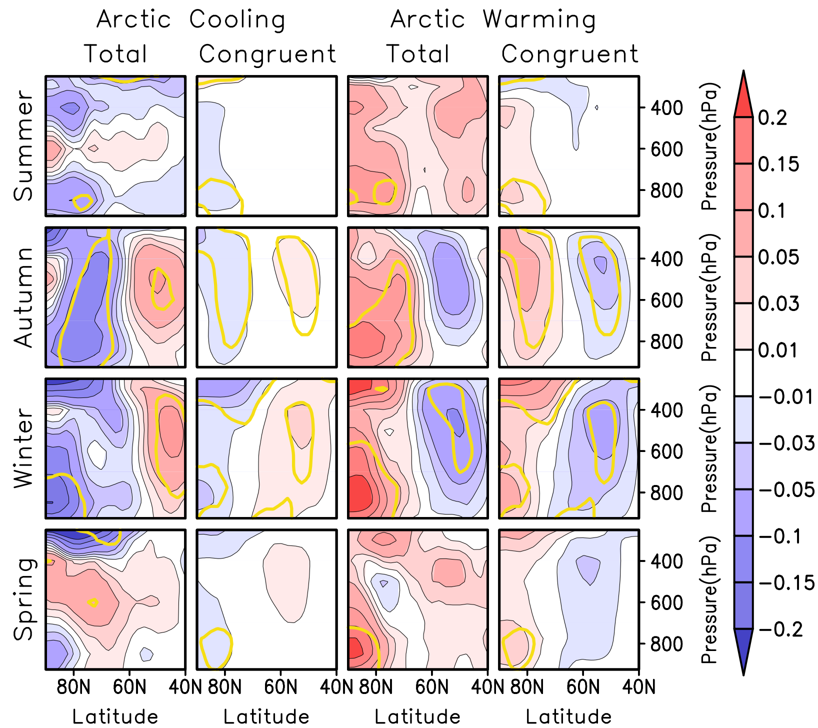

Figure 4. As in Figure 3 but for seasonal means.

cooling and warming decades, respectively. In Figure 3 we also see that the decadal trends in net (i.e. vertically integrated) poleward energy transport across 65°N reflect a delicate balance between large opposing values in the upper and lower troposphere.

[15] Figure 3 (bottom) shows the transport congruent temperature and transport trends for the cooling (left) and warming (right) decade. Again we see a clear correspondence between the total and transport congruent trends. The spatial correlations between the total and transport congruent temperature trends (over the plotted domain) are about 0.75 for the cooling decade and 0.72 for the warming decade. Take note that the region of greatest difference between the total and transport congruent patterns is in the Arctic lower troposphere where we assume that surface heat fluxes are important. In summary, energy transport plays an important role in free-troposphere Arctic temperature change, and involves changing intensity of the polar meridional circulation cell.

[16] Our calculations so far have been based on monthly data for all months of the year. To establish the seasonality of the temperature and energy transport co-variation we repeat our calculations using seasonal mean data. Figure 4 shows decadal trends in zonal mean vertically-weighted temperature for each of the traditional seasons. In terms of the total trend patterns we see that the autumn and winter patterns best reflect the all-month patterns shown in Figure 3. The transport congruent trend patterns similarly show this, and are particularly explanatory of the total trends in the winter season when temperature gradients and meridional flows are strong. For the winter season the spatial correlation between the total and transport congruent pattern is about 0.74 for the cooling decade and 0.76 for the warming decade. Further, in winter about 37.9% of the Arctic mean cooling trend and 71.1% of the Arctic mean warming trend is explained by changing vertically-integrated poleward energy transport.

4. Conclusions and Discussion

[17] This investigation, using satellite and reanalysis based observations over the last thirty years, has led us to conclude that the decadal time scale variation of Arctic free-troposphere temperature is heavily influenced by changing poleward transport of atmospheric energy. The transport induced component of the decadal time-scale temperature variation observed during this period: 1) was dominated by sensible and potential energy components; 2) was reflected throughout the middle to high latitude troposphere; 3) was associated with changing intensity of the polar meridional circulation cell; and 4) was dominant in the autumn and winter seasons. Transport induced changes are least important near the surface where the powerful snow/ice albedo feedback mechanism produces near-surface Arctic temperature amplification [*Serreze et al.*, 2009; *Screen and Simmonds*, 2010].

[18] A logical next question to ask is whether the transport induced temperature changes identified here are linked to any particular aspect of Northern Hemisphere atmospheric circulation change? To assess this we computed the temporal correlation between anomalies in energy transport $\mathcal{F}_{\phi_o}(t)$ and the leading principal component time series of hemispheric 500 hPa geopotential height – commonly referred to as the Arctic Oscillation [*Thompson and Wallace*, 1998]. Not surprisingly, there is a significant degree of anti-correlation between these two indices (i.e. $r \approx -0.53$), indicating that the transport of energy into and away from the Arctic is related to month-to-month annular-type fluc-

tuations in the Northern Hemisphere atmospheric circulation. This relationship is also reflected in that both the AO index and $\mathcal{F}_{\phi_o}(t)$ show large opposing trends during the cooling and warming decades, and near neutral conditions over the last decade.

[19] As mentioned earlier near-surface Arctic land temperatures have been rising fairly monotonically in recent decades in response to anthropogenic emissions of greenhouse gases and sulphate aerosols [*Gillett et al.*, 2008], and presumably amplified through a feedback with snow albedo [*Screen and Simmonds*, 2010]. However, free-troposphere temperature changes over the Arctic have been decidedly non-monotonic indicating much less, if any, anthropogenic influence. Our results show that large amplitude internal fluctuations in atmospheric transport are certain to make the exercise of climate change attribution and detection for the Arctic troposphere a significant challenge, even though the anthropogenic signal is clear near the surface.

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