Large-scale circulation associated with moisture intrusions into the Arctic during winter

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We examine the poleward transport of water vapor across 70°N during boreal winter in the ERA-Interim reanalysis product, focusing on intense moisture intrusion events. We analyze the large-scale circulation patterns associated with these intrusions and the impacts they have at the surface. A total of 298 events are identified between 1990 and 2010, an average of 14 per season, accounting for 28% of the total poleward transport of moisture across 70°N. They are concentrated over the main ocean basins at that latitude in the Labrador Sea, North Atlantic, Barents/Kara Sea, and Pacific. Composites of sea level pressure and potential temperature on the 2 potential vorticity unit surface during intrusions show a large-scale blocking pattern to the east of each basin, deflecting midlatitude cyclones and their associated moisture poleward. The interannual variability of intrusions is strongly correlated with variability in winter-mean surface downward longwave radiation and skin temperature averaged over the Arctic. Citation: Woods, C., R. Caballero, and G. Svensson (2013), Large-scale circulation associated with moisture intrusions into the Arctic during winter, Geophys. Res. Lett., 40, 4717–4721, doi:10.1002/grl.50912.

1. Introduction

Observations during recent decades show that there is greater surface warming occurring in the Arctic, particularly during winter, than at lower latitudes [Serreze et al., 2009; Serreze and Francis, 2006; Screen and Simmonds, 2010]. This disproportionate warming between high and low latitudes—known as “polar amplification”—is also a robust feature of global climate model simulations [Solomon et al., 2007]. Understanding the mechanisms controlling surface temperature in the Arctic is therefore an important priority in climate research.

The surface energy budget is a key proximate control on Arctic surface temperature. During winter, insolation is low or absent and the atmospheric boundary layer is typically very stable, limiting turbulent heat exchange, so that the surface energy budget is almost entirely governed by longwave radiation [Serreze et al., 2007]. The Surface Heat Budget of the Arctic Ocean (SHEBA) experiment [Uttal et al., 2002], a yearlong observational campaign which collected data at high temporal resolution at an ice-locked drifting site in the Beaufort Sea, showed that the net surface longwave radiation (NetLW) during the winter of 1997–1998 had a strikingly bimodal distribution: conditions oscillated between a “radiatively clear” state with rapid surface heat loss (NetLW ~ −40 W m−2) and a “moist cloudy” state with NetLW ~ 0 W m−2 [Stramler et al., 2011]. Each state can persist for days or weeks at a time, but transitions between them happen in a matter of hours. This distribution of NetLW has important implications for the Arctic climate, as even a small shift in the frequency of occupancy of each state would be enough to significantly affect the overall surface energy budget thus winter sea ice thickness [Morrison et al., 2011].

The clear and cloudy states typically occur during periods of relatively high and low surface pressure, respectively, suggesting a link with synoptic-scale dynamics [Stramler et al., 2011; Morrison et al., 2011]. This suggestion is consistent with previous studies indicating that the formation of low-level and midlevel clouds over the Arctic Ocean is typically associated with cyclonic activity and passing frontal systems [Curry et al., 1996]. More recent work [Doyle et al., 2011] has shown that intense filamentary moisture intrusion events are a common feature in the Arctic and can induce large episodic increases in the longwave radiation into the surface.

Our aim here is to better understand the statistical relationship between moisture intrusions into the Arctic, their associated large-scale dynamics, and their impacts on the surface energy budget. To motivate later developments, we present in Figure 1 a specific example of the type of event we are interested in. This is a moisture intrusion which occurred in 1998 and affected the SHEBA site. The event begins in the early hours of 1 January 1998 (this is the time when the intrusion is first detected by the objective search algorithm to be discussed below). At this time, a synoptic-scale low-pressure system is present over Iceland and persists in that position during the subsequent days. The upper-level flow, depicted here by the potential temperature on the 2 potential vorticity unit (PVU) surface (a good approximation to the tropopause for air originating poleward of about 25°N) (θ2PVU, see Thornicroft et al., 1993), shows an anticyclonic anomaly (high θ2PVU) over Europe; this blocking high persists for at least the following 2 days, impeding the eastward migration of the surface cyclone. The cyclone brings moist air toward the Arctic along its poleward branch; this moist air mass is subsequently ducted between a low-high pressure dipole straddling the Arctic basin, creating a thin intrusion which crosses the central Arctic in the subsequent days until it reaches the SHEBA site (indicated by a red dot in Figure 1). SHEBA NetLW observations show a sharp transition from clear to cloudy states coincident with the intrusion’s arrival at the site.

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Figure 1. Case study of an intrusion beginning at 00:00 UTC 1 January 1998 (+0 h) and followed for the subsequent 3 days. (top row) Potential temperature on the 2 PVU surface (color shading) and skin temperature anomaly over ocean (grey shading; light grey, 5–10 K; dark grey, 10–15 K; black, 15–20 K). (bottom row) Total column water over ocean (color shading) and sea level pressure (black contours every 16 hPa). The red dot denotes the approximate location of SHEBA at this time. Dotted circles show latitude lines at 70°N and 80°N.

[Stramler et al., 2011, Figure 2] (the transition occurs at Julian day 367.5). The radiative impact of the intrusion is in fact evident throughout its length, with skin temperature anomalies in excess of 15 K in the areas covered by the moist air mass.

[6] In section 2, we present an algorithm which systematically detects moisture intrusions of the type just discussed. We then compute composites of the surface and upper-level circulation fields to determine the flow structures associated with the intrusions (section 3); as in the case study above, we find that intrusions are typically enabled by a surface low held in place by a blocking high to its east. Section 4 explores the interannual variability of intrusions and their associated impact on the surface energy budget. Our conclusions are summarized in section 5.

2. Moisture Intrusions Into the Arctic

[7] Here we examine the statistical structure of poleward moisture fluxes across 70°N—which we define to be the boundary of the Arctic—seeking to establish objective criteria with which to select intense intrusion events of the type discussed above. We use the European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis data set [Dee et al., 2011] for the boreal winters (December–February) of the 21 years from 1990 to 2010 (with the convention that the winter of 1990 ends in February 1990). The data is 6-hourly on 16 pressure levels between 1000 and 30 hPa, with a horizontal resolution of 1°×1°.

[8] We define the instantaneous meridional moisture flux \( f \) at a given latitude as

\[
f(x, p, t) = vq \tag{1}
\]

where \( x \), \( p \), and \( t \) are, respectively, longitude, pressure, and time while \( v \) and \( q \) are, respectively, the instantaneous meridional velocity and specific humidity. As discussed in section 1, we are specifically focusing here on moisture injections into the polar cap from lower latitudes, so it is of interest to characterize the distribution of such northward-moving fluxes in the zonal-height plane. Figure 2a displays the climatology of northward moisture flux \( f_{+} = f_{\text{H}}(v) \), where \( f_{\text{H}}(\cdot) \) is the Heaviside function, across 70°N. The flux is concentrated in four sectors, which we label Labrador (90°W–30°W), Atlantic (30°W–25°E), Barents/Kara (25°E–90°E), and Pacific (145°E–130°E), respectively, accounting for about 15%, 35%, 23%, and 17% of the climatological zonally integrated poleward transport. Not surprisingly, these sectors correspond to the main oceanic passageways into the Arctic, with much weaker fluxes over land. The strongest fluxes occur at low levels in the Atlantic and Barents/Kara sectors, which are mostly free of sea ice at this latitude.

[9] Next, we investigate how the instantaneous fluxes are distributed around their climatological mean. Direct inspection of \( f \) snapshots at 70°N indicates that the fluxes are strongly coherent in the vertical, so that little information is lost by taking the vertical integral. For simplicity, we will therefore focus henceforth only on vertically integrated poleward moisture fluxes at a given latitude,

\[
F(x, t) = \frac{1}{g} \int_{p_s}^{p_0} f dp \tag{2}
\]

where \( p_s \) is the surface pressure and \( g \) is the gravitational acceleration; in practice, we extend the integral from the surface to 400 hPa, since there is negligible humidity above that level. We compute the integral using the trapezoidal rule as
the value fluxes in the 90th percentile. The red line in the plot marks the entire climatological flux at each longitude is due to flux of moisture fluxes, the distribution is almost identical if for positive $F$ longitude. (Note that we are only showing the distribution Figure 2b shows the quantity $FP$ during winter from 1990 to 2010. (b) The proportion of the total poleward moisture transport across 70°N from 1990 to 2010 contributed by vertically integrated moisture fluxes in 75 Tg d$^{-1}$ deg$^{-1}$ by 5° longitude bins. The dashed and solid black lines mark the 50th and 90th percentile values of vertically integrated poleward fluxes, respectively. The solid red line indicates the threshold value of flux used to detect intrusions in the algorithm.

outlined in Simmonds et al. [1999]. The climatology of $F$ can in turn be written

$$\mathcal{T} = \int F P(F) \, dF$$

where $P(F)$ is the probability distribution function of $F$. Figure 2b shows the quantity $FP(F)$, as well as the 50th and 90th percentiles of the probability distribution $F(P)$ at each longitude. (Note that we are only showing the distribution for positive $F$ here; because of the strong vertical coherence of moisture fluxes, the distribution is almost identical if $f_i$ is used in (2) instead of $f$.) The figure shows that almost the entire climatological flux at each longitude is due to flux events above the median, with the majority contributed by fluxes in the 90th percentile. The red line in the plot marks the value $F = 200$ Tg d$^{-1}$ deg$^{-1}$, which corresponds to the 90th percentile of all vertically integrated poleward moisture fluxes over all longitudes; roughly, 50% of the total zonally and vertically integrated poleward moisture transport is contributed by fluxes above this value. These results highlight the outsize role played by extreme events in poleward moisture transport, in agreement with previous findings at lower latitudes [Knippertz and Wernli, 2010; Messori and Czaja, 2013].

[10] We have also examined spatial and temporal autocorrelation functions of $F$ at 70°N. The zonal autocorrelation function decays roughly exponentially with a $\epsilon$-folding length of around 9° longitude ($\sim 340$ km), while the temporal autocorrelation function decays with a timescale of around 1.5 days; these numbers can be interpreted as the characteristic width and duration of a poleward moisture flux event.

[11] Based on the above results, we objectively define an intense moisture intrusion as an event in which $F$ at 70°N sustains values in excess of 200 Tg d$^{-1}$ deg$^{-1}$ for at least 1.5 consecutive days at every point within a sector of at least 9° zonal extent. Applying these criteria to the entire data set, we identify 413 intrusion events accounting for roughly 36% of the total poleward moisture transport. We further reduce this set of events by rejecting those that do not penetrate sufficiently deep into the Arctic. To do this, we compute forward Lagrangian trajectories using the horizontal and vertical velocity fields from the ERA-Interim reanalysis data set with linear interpolation [see Caballero and Hanley, 2012, for more details]. Trajectories are computed from each of the grid points enclosed by an event for 6 days starting from the time at which the event is first detected. We retain only those events where at least 40% of the trajectories crossed 80°N. The final data set contains 298 events accounting for about 28% of the total poleward moisture transport, of which 2%, 14%, 9%, and 3% come from the Labrador, Atlantic, Barents/Kara, and Pacific sectors, respectively. On average, there are 14 of these events per season, typically lasting 2–4 days but persisting for up to 10 days in some cases. The mass of water transported can be anywhere between 5×10$^3$ and 180×10$^3$ Tg, with an average value of 30×10$^3$ Tg per event.

3. Large-Scale Circulation Associated With Intrusions

[12] We now examine the large-scale circulation patterns which favor intense intrusions by computing composites of sea level pressure (SLP) and $\theta_{2PVU}$ at the time of maximum intensity for each of the intrusions identified as discussed above. To maintain spatial coherence, the composites are computed separately for intrusions occurring within each of the four compact sectors defined in section 2 (see Figure 1).

[13] Results are presented in Figure 3. A large-scale blocking pattern is apparent in the $\theta_{2PVU}$ composites (Figures 3a–3d) as a ridge of high $\theta_{2PVU}$—indicating an anticyclonic potential vorticity anomaly—on the eastern flank of each sector. Intrusions occur in the region of poleward flow to the west of the block, as indicated by the median position of the intrusions at maximum intensity (dashed black line). The SLP composites (Figures 3e–3h) show that a synoptic-scale low-pressure system is typically embedded in this region during an intrusion, feeding the low-level poleward flow of moisture. These features—closely matching those seen anecdotally in the case study presented in section 1—are common to all sectors, with some regional variations. The blocking ridge is most pronounced in the Pacific sector, where the associated surface high pressure extends all the way to the pole and plays an active role in the actual advection of moisture, as opposed to the apparently more passive blocking role in the Labrador and Atlantic sectors.
4. Statistics of Moisture Intrusions and Impact on Surface Energy Budget

[14] The final part of this study focuses on the interannual variability of the intrusions and their relation to variability in the surface energy budget. To do this, we define an annual index $E$ which is simply the total mass of water transported by all intrusions into the Arctic in a given winter, and can be written

$$E = NI$$  \hspace{1cm} (4)

where $N$ is the total number of intrusions occurring in a particular year and $I$ is the mean intensity of the intrusions, i.e., the average amount of water transported across 70°N by intrusions in that year. If $N$ and $I$ are weakly correlated, we can write

$$\frac{\Delta E}{E} \approx \frac{\Delta N}{N} + \frac{\Delta I}{I}$$  \hspace{1cm} (5)

where a hat denotes the climatology and $\Delta$ a departure therefrom. Each of the terms in (5) is plotted in Figure 4a. There is a statistically insignificant positive correlation ($r = 0.45$) between the number and average strength of intrusions, with each term explaining about half the total variance in $E$.

[15] Turning to the surface energy budget, we compute winter-mean anomalies of surface downward longwave radiation $R_L$ and skin temperature $T_s$ averaged over the region north of 70°N. These time series are shown in Figure 4b. As expected, there is an very tight correlation between $R_L$ and $T_s$. More interestingly, the intrusion index $E$ is positively correlated with $R_L$ ($r = 0.61$) and $T_s$ ($r = 0.54$), both of which are significant at the 1% level neglecting serial correlation (the correlations are significant at the 3% level if serial dependence is taken into account by assuming a reduced sample size $N(1-\rho_1)/(1+\rho_1)$, where $N = 21$ is the number of years and $\rho_1 = 0.2$ is the lag-1 autocorrelation of the predictor time series $E$). We find similarly significant correlations between $E$ and $R_L$ ($r = 0.56$) and $T_s$ ($r = 0.52$) if the fields are instead averaged over the area north of 80°N. These correlations are consistent with the physical picture whereby increases in the number and/or intensity of moisture intrusions drive increased downward radiation and higher surface temperatures. Recall, however, that $E$—the total water carried by intrusions—only accounts for around 28% of the total poleward moisture flux, and one may wonder about the impact of the remaining 72%. We find that the correlation between this remainder and $R_L$ is in fact negative ($r = -0.27$), albeit statistically insignificant. This result suggests a picture where much of the background moisture flux occurs in weak events which have little radiative impact, or fails to penetrate deeply into the Arctic, instead quickly exiting the 70°N boundary. It is only the deep, strong intrusions identified above that drive significant impacts on the surface energy budget.

[16] We note that a positive trend is apparent in $R_L$ and $T_s$, as well as a weaker one in $E$. These trends must be treated with some care, as artifacts related to observation system changes are always possible in reanalyses, especially in data-sparse regions such as the Arctic. We will not consider the issue further here, but it remains an interesting avenue for future research in light of recent work exploring trends in moisture transport to the Arctic [Zhang et al., 2013; Inoue et al., 2012]. In any event, removing linear trends from the respective time series results in correlations of $R_L$ and $T_s$ with $E$ of 0.65 and 0.64, respectively, so that the control of the surface energy budget by moisture intrusions is certainly robust on an interannual basis.
We have underscored the intimate connection between these relatively small-scale filamentary structures and the large-scale flow in which they are embedded; changes in Arctic climate may thus be related to dynamical changes occurring at lower latitudes [Screen and Simmonds, 2013; Screen et al., 2012]. These are promising avenues for future research.

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