Greenland’s Pressure Drag and the Atlantic Storm Track

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ABSTRACT

Some effects of Greenland on the Northern Hemisphere wintertime circulation are discussed. Inviscid pressure drag on Greenland’s slopes, calculated from reanalysis data, is related to circulation patterns. Greenland lies north of the core of the tropospheric westerly winds. Yet strong standing waves, which extend well into the stratosphere, produce a trough/ridge system with jet stream lying close to Greenland, mean Icelandic low in its wake, and storm track that interacts strongly with its topography. In the lower troposphere, dynamic height anomalies associated with strongly easterly pressure drag on the atmosphere are quite localized in space and relatively short-lived compared to upper levels, yet they involve a hemispheric-scale dislocation of the stratospheric polar vortex. It is a two-scale problem, however; the high-pass time-filtered part of the height field, responsible for 73% of the pressure drag, is quite different, and expresses propagating cyclonic development in the Atlantic storm track. Eliassen–Palm flux (EP flux) analysis shows that the atmospheric response is (counterintuitively) an acceleration of the westerly winds. The hemispheric influence is consistent with the model results of Junge et al. suggesting that Greenland affects the stationary waves in winter.

This discussion shows that Greenland is not a simple “stirring rod” in the westerly circulation, yet involvement of Greenland’s topography with the shape, form, and intensity of the storm track is strong. Interaction of traveling storms, the jet stream, and the orographic wake frequently leads to increase of the lateral scale such that cyclonic system expands to the size of Greenland itself (~2500 km). Using the global ECMWF general circulation model, the authors explore the effect of model resolution on these circulations. Statistically, in two case studies, and in higher-resolution global models at T1255 to T799 resolution, intense tip jet, hydraulic downslope jet, and gravity wave radiation appear in strong flow events, in accord with the work of Doyle and Shapiro. Three-dimensional particle trajectories and vorticity maps show the nature and intensity of the summit-gap flow. Cyclonic systems in the lee of Greenland are strongly affected by the downslope jet. Penetration of the Arctic Basin by cyclonic systems arises from this source region, and the amplitude of the pressure drag is enhanced at high resolution. At the higher resolutions, storm-track analysis verifies the splitting of the storm track by Greenland with a substantial minority of storms moving northward through Baffin Bay. Finally, analysis of 20 winters of 40-yr ECMWF Re-Analysis (ERA-40) reforecasts shows little evidence that negative pressure-drag events are followed by anomalously large forecast errors over Europe, throughout the forecast. Forecast skill for the pressure drag is surprisingly good, with a correlation of 0.65 at 144 h.

1. Introduction

The Pacific and Atlantic maritime storm tracks represent amplification of transient cyclonic systems, shaped and guided by the stationary waves of the winter circulation. The earth’s orography, and the Atlantic and Pacific Ocean heat sources, both strongly influence the stationary waves (e.g., Held et al. 2002). Greenland, the largest island in the world, extends one-quarter of the distance between the North Pole and equator, or 2500 km. The solid earth is below sea level in much of Greenland, and its massive ice cap, a remnant of the last glaciation, is a monument to poleward atmospheric moisture flux, which is concentrated in the Atlantic sector at these latitudes. With a height averaging about 1.5 km and reaching greater than 3.5 km, roughly the 650-
hPa level, and with relatively high volume and steep southern termination, its potential effect on the general circulation is great. Yet, lying between 60° and 83°N latitude, it is north of the maximum zonally averaged westerly winds, and the mean wintertime circulation approaches it from the southwest. It is the most significant topography lying beneath the northern stratospheric polar vortex (SPV). Circulation past Greenland thus does not resemble basic idealized “westerly zonal flow past a mountain,’’ nor does it affect the hemispheric standing waves as directly as do the Rocky Mountains and Tibetan Plateau. Indeed, the zonally averaged angular-momentum balance shows at these latitudes the opposite orographic tendency (westerly force on the atmosphere; Brown 2004). This arises not from Greenland but from the Aleutian low and its interaction with the upslope of the Coast Range of Alaska. The global angular momentum of the atmosphere responds primarily to pressure torque from the Rocky Mountains, Andes, and Tibetan Plateau. Pressure-drag variability on these topographies is associated with distinct atmospheric response patterns (e.g., Lott et al. 2004a,b).

This paper explores Greenland’s effect on the development of transient cyclonic systems, using as a base time series the east–west pressure drag exerted on its topography. The pressure-, or “form,’’ drag is a key component of the zonal momentum balance, and also turns out to be a useful indicator of cyclonic development east of Greenland, in the northern flank of the Atlantic storm track. Egger and Hoinka (2006) have very recently used the covariance of Greenland’s pressure drag with various hemispheric fields, and related these to a barotropic idealization of the dynamics. They show that during westerly drag events (when high pressure sits east of Greenland) the zonally averaged flow at these high latitudes does not respond to Greenland’s drag in the expected way. Rather, transient poleward flux of vorticity (which is related to the forcing of the zonal momentum) balances the drag force, spreading it to adjacent latitudes. Such results, normally cast in the zonally averaged language of Eliassen–Palm fluxes, highlight the strongly advective nature of the storm track. Meridional transport across a large span of latitude carries cyclonic vorticity as far as the high Arctic, where otherwise anticyclonic vorticity would tend to dominate. (Either potential vorticity stirring by Rossby waves of remote origin or symmetric descent of air cooled by radiation will give an anticyclonic tendency unless opposed by topographic guideways.)

Several works have used numerical simulations to describe the effects of Greenland on the circulation. Kristjansson and McInnes (1999) find a weakening of cyclones by the Greenland barrier, which can block cold air outflow from the Canadian Arctic. Petersen et al. (2003, 2004) model the flow round idealized mountains, and explore the effect of removing Greenland’s high-profile topography. Junge et al. (2005) also model a world without Greenland. The hemispheric stationary waves are strengthened by Greenland in Junge et al. and are shifted in phase and perhaps weakened at 500-hPa level, in the Petersen et al. experiments. Small changes in the North Atlantic Oscillation (NAO) and Icelandic low pressure center are found in both works. The clear dependence of these results on model resolution indicates further study of resolution effects. But the dynamic blocking effect of Greenland, causing damming cold air on its western side and stimulating a tip jet at its southern end, represents strong local effects of the topography that recur in most models. Doyle and Shapiro (1999) model the flow with nested grid model using idealized and realistic topographies. They find realistic tip jets in which loss of Bernoulli function following the flow expresses turbulent/dissipative dynamics of the wake. A related, significant “upstream” condition for southern Greenland is the Nares Strait between Greenland and Baffin Island, which is possibly the longest “wind chute” on earth. Extending nearly 600 km, it is the site of frequent episodes of jetlike northerly flow below 850 hPa.

We want to develop the study of Atlantic cyclogenesis in several directions. Model resolution will be carried from T1195 to T11,799 (grid resolutions of roughly 210 to 25 km) using the global European Centre for Medium-Range Weather Forecasts (ECMWF) forecast model system. Forty-year ECMWF Re-Analysis (ERA-40) data (roughly equivalent to T11,159 resolution) will be compared with model simulations, looking at the life cycle of cyclone development associated with strong pressure-drag events. Vertical structure of the fields covarying with drag will be explored. Cyclogenesis will be examined as a function of model resolution. Forecast skill for Europe will be examined. Three-dimensional air parcel trajectories will be examined in two case studies of strong pressure drag. Nongeostrophic, intense flows over Greenland will be documented, following the work of Bromwich et al. (1996, 2001), Doyle and Shapiro (1999), and Klein and Heinemann (2002). This work has numerous contacts with basic dynamical studies: generation of gravity waves, vorticity, and potential vorticity (PV) in the wakes of mountains (see Schärf 2002 for a review); global angular momentum balance (which seasonally trades between atmosphere and solid earth through the action of pressure and frictional drag, leading to a 1-ms annual variation in the length of the day; e.g., Hide et al. 1997);
\[ D_x = - \int_{S_G} \frac{p_x}{\cos \phi} \frac{\partial h}{\partial \lambda} \, d\sigma. \] (1)

The surface pressure is given by \( p_x \) and \( h \) represents the height of the orography. The integration is carried out over the area \( S \) (see Fig. 1). The zonal pressure drag \( D_x \) is negative, for example, if relatively high surface pressure resides on the western flank of the mountain, tending to decelerate the westerlies. The pressure force on Greenland is \(-D_x\).

Time series of \( D_x \) for the winter of 2004/05 are shown in Fig. 2. The normalization was carried out with respect to all winters of the period 2000/01 to 2005/06. The time series shows variations on a wide range of frequencies. Large day-to-day fluctuations are evident, due the rapid passage of synoptic systems. Two cases associated with the strongest negative pressure-drag values (27 December 2004 and 17 January 2005) will be investigated in more detail below. The high-frequency variations are superimposed on low-frequency intraseasonal fluctuations. Strong negative zonal pressure-drag values, corresponding to an easterly force on the atmosphere, prevailed in December 2004, whereas close to neutral anomalies are found during March 2005. The above-mentioned spectral characteristics are consistent with the results of Egger and Hoinka (2006).

The NAO index, and the related Arctic Oscillation (AO) and Northern Hemisphere annular mode (NAM) all correspond to wide-spectrum (in time) variability of the storm track and mean wintertime Icelandic low. The NAO index, also plotted on Fig. 2, shows episodes where it is highly anticorrelated with the pressure-drag time series (e.g., second half of January to beginning of February 2005). However these are not dominant and the overall correlation of the two is small, amounting to \(-0.6\) for all winters of the period 1982–2006.

2) Atmospheric circulation and Greenland pressure drag

Here we relate the time series of the pressure drag across Greenland to the atmospheric circulation based on daily ERA-40 data (Uppala et al. 2005) for winters December–March (DJFM) 1982–2001. Composite analysis (e.g., von Storch and Zwiets 1999) is used, based on amplitude criterion of one standard deviation above mean, for the pressure drag. This process is effective in nonlinear flows, and like cluster analysis, distinguishes between the spatial structure of positive- and negative-drag events. A second composite reflects climatological conditions and was computed by averaging those cases that occurred 365 days prior to low pressure-drag events. This is our way of accounting for mean annual cycle.
Highly negative pressure drag composites of daily 1000-hPa (Z1000) geopotential height fields for six different time lags along with climatological mean fields show that 6 days prior to easterly drag events the near-surface flow in the central North Atlantic is anomalously blocked (Fig. 3). The anticyclone south of Greenland strengthens toward zero lag and decays slowly thereafter. In contrast, the evolution of the anomalous surface cyclone is more asymmetric with respect to zero time lag. No precursors are evident 6 days prior to the easterly (negative-) drag event and decay is rapid afterward.

The same analysis has been carried out for 250-hPa geopotential height (Z250) fields (Fig. 4). Unlike the near-surface circulation, precursors appear at −6 days in the troposphere over northeastern Canada and Baffin Bay, and similarly at 500 hPa (not shown). The anomalous trough increases in strength and propagates eastward from days −6 to 0, followed by rapid decay. Strong pressure-drag events are associated with an anomalously strong polar jet stream over the northern North Atlantic (Fig. 4). The strongest deepening of the anomalous near-surface cyclone at zero lag (Fig. 3d) occurs underneath the northern flank of the diffluent part of the polar jet stream, in a region where upper-level diffluence is associated with lower-level cyclogenesis. Eady-index maps (not shown) support this genesis. This multilevel figure shows the phase tilt frequently found between the surface and 250 hPa, which is consistent with cold advection from the Canadian Arctic, where the northwesterly climatological wintertime flow down the Labrador Sea meets the Atlantic storm track.
Atmospheric circulation anomalies associated with strong zonal pressure-drag events across Greenland are not confined to the troposphere. Prior to high pressure-drag events an anomalous trough is evident in the stratospheric polar vortex (Fig. 5) over the Canadian Archipelago and Baffin Bay. Following easterly (negative) pressure-drag events the stratospheric anomaly decays rapidly. The scale of the stratospheric response is large, representing a roughly 500-km dislocation of the polar vortex center toward west Greenland. Generally speaking, the stratospheric image of the Atlantic storm track often involves both dislocation and distortion of the polar vortex, in the spirit of barotropization seen in geostrophic turbulence (Rhines 1979). We also realize that orographic response can involve the equivalent-barotropic vertical mode, which has a direct and immediate stratospheric component, and upward propagating baroclinic Rossby waves subject the Charney–Drazin “filter,” which selects long east–west wavelength.

The height field corresponding to drag of the opposite sign (westerly, or positive zonal force on the atmosphere) for 1000 hPa (Fig. 6, shown for zero time lag only) has a different spatial structure than that in Fig. 3d. This illustrates the nonlinear nature of the orographic drag phenomenon, which is not described by the linear covariance fields described by Egger and Hoinka (2006). Here an east–west dipole of pressure develops with cyclonic sense in Baffin Bay, west of Greenland, and high pressure on the eastern slopes of Greenland. The corresponding patterns for nonzero lag are weakened versions of Fig. 6, with little evidence of spatial propagation.

So, where is the expected progression of low-pressure synoptic systems that characterizes the storm track? It turns out that these structures are active in the zonal pressure drag at Greenland and emerge when the pressure field is high-pass filtered (using a Lanczos filter with a half-power width at 10 days) in time before constructing the composite anomalies (Fig. 7). The 1000-hPa composite anomaly for strong easterly drag now exhibits strong propagation from the southwest. Easterly drag occurs when cyclones develop in the Irminger and Greenland Seas east of Greenland. This is by far the most frequently observed aspect of the winter-time Icelandic low region. The systems are associated with a strong trough in the upper troposphere and jet stream that evolves slowly, spawning low-level transient cyclones. These developing storms move rapidly northeastward and interact with and enhance the orographic flow distortion around Greenland. Note that they are first evident in Fig. 7 at lag −4 days. There are frequently multiple cyclonic centers, as suggested by the additional low pressure centers showing at lags +2 and +4 days.

The differing results (Figs. 3 and 7) for the full pressure field and the high-frequency transient eddies correspond to the great diversity of phenomena present in the high-latitude winter circulation. The hemispheric standing waves set the upstream flow, as a part of which the upper-tropospheric jet stream orients nearly north–south during strong easterly drag events. The orographically related wake and lee cyclone generation near Greenland represents yet another contributor to cyclonic development. The net result is that the rapidly moving transient cyclones are only a part of the story and contribute their part of the Greenland pressure drag: the high-pass transient eddies (periods less than 4 days) account for about 73% of the easterly pressure-drag variability (in terms of the standard deviation).

**EP fluxes**

Beyond the intense, local lee cyclone and neighboring high pressure ridge near Greenland there is a hemispheric signal in the momentum flux. This involves both teleconnections in the downstream development ducted along the jet stream and also in the nature of the hemispheric stationary wave field. Nonlocal effects be-
gin to appear at upper levels. The 250- and 50-hPa height patterns, for example, in Fig. 4 and 5, extend farther toward the Pacific sector at −6 and −4 day lags. The stratospheric signal is fully hemispheric.

This suggests that zonally averaged Eliassen–Palm (EP) flux analysis might have a signal covarying with Greenland pressure drag. EP fluxes calculated for the same high-easterly-drag composites (Fig. 8) show up-

Fig. 3. Geopotential height anomalies (units of dam in shading) at the 1000-hPa level associated with cases of strongly negative (easterly) zonal pressure drag on the atmosphere, across Greenland at various time lags: (a) −6, (b) −4, (c) −2, (d) 0, (e) 2, and (f) 4 days. Also shown is the mean climatological field (solid, contour interval is 5 dam) along with the mean negative pressure-drag composite (dashed, contour interval is 5 dam). A threshold of −1.5 std dev has been used for compositing. All results are based on ERA-40 data for winters (DJFM) of the period 1958–2001. The dominant low pressure east of Greenland is quite local in space and time.
ward EP vectors in the latitude band of Greenland (60°–83°N) expressing the easterly forcing of the upper troposphere by the topography. This is correlated with the pressure-drag events, and in fact the vertical momentum flux reverses 4 days later. The day-0 composite also shows strong equatorward flux centered at 300 hPa, following the tilted-trough pattern visible in Fig. 3 and with a dipole distribution of momentum flux convergence/divergence. This pattern would be consistent with equatorward radiation of Rossby waves excited by the topography but that is not the dominant synoptic-scale dynamics of the storm track. It appears to reflect
the strong northern excursion, and southwest–northeast orientation, of the jet stream over Greenland during strongly negative wave-drag events. It is striking that this leads to a visible zonally averaged PV/momentum flux. Egger and Hoinka (2006) show that meridional vorticity flux in positive-drag (i.e., high pressure east of Greenland) events is so strong that the pressure-drag events do not accelerate the westerly winds locally, but the meridional momentum flux instead carries the acceleration to adjacent latitudes. This is consistent with the present discussion of easterly drag events (i.e., storm-track-related cyclones east of Greenland) and argues for a transmission equatorward of the easterly “push” of the topographic drag. While many

Fig. 5. As in Fig. 3, but for the 50-hPa level. The contour interval (solid and dashed contours) is 15 dam.
investigations emphasize the primary role of Rocky Mountain orography in the North America/Atlantic stationary waves, we wonder whether “suction” on the lee slopes of Greenland may contribute to the mean climatology of the stationary waves in the Atlantic sector, in the mid- and upper troposphere. The EP fluxes shown here do not in themselves establish a causal link to Greenland’s orographic forcing. However, causality is suggested by Petersen et al. (2003) who, in their T106 Community Climate Model (CCM3) simulations with and without Greenland, find the Eulerian storm track to be shifted in the Atlantic, with increased activity to the west and south, and decreased activity to the east, of Greenland. Small increase in variability occurs over North America and Asia. This would suggest a Greenland “dynamic blocking and sheltering” effect with respect to the Nordic Seas and Europe, yet we will describe below how higher model resolution can yield more intense activity eastward, in the wake of Greenland.

This speculation is consistent with the Junge et al. (2005) model simulations with and without Greenland’s orography, finding that Greenland strongly amplifies the hemispheric standing waves in winter, but only at higher (T106L19 ECHAM model compared with T42L19) resolution. Their models show both the trough and ridge in the stationary waves at 500 hPa to be strengthened by the topography. Like Petersen et al. (2003) they attribute the changes not to standing Rossby wave generation but to damming of cold air in Baffin Bay, west of the ice mountain.

The upward component of EP flux, which corresponds to inviscid pressure drag, vertically transmitted across isentropic surfaces (Rhines and Holland 1979; Dunkerton 1980), is also anomalous, with respect to the “normal” climatology of deceleration of the SPV. During strong easterly-pressure-drag events, the EP analysis shows a positive, westerly acceleration of the vortex. This is consistent with ideas of barotropization, in which growing cyclonic activity in the lower atmosphere reaches upward via chaotic vortex stretching and infects the stratosphere, pulling the center of the SPV toward Baffin Bay.

b. Model results

SENSITIVITY OF EXTRATROPICAL CYCLONES NEAR GREENLAND TO HORIZONTAL RESOLUTION

If Greenland’s orography has a significant influence on extratropical cyclones and their genesis, then increasing horizontal resolution should lead to more realistic cyclone life cycles in the vicinity of Greenland because of a more realistic orography. The main dataset used to carry out this investigation is the same as that described in Jung et al. (2006b). The amplitude of the pressure drag on Greenland during strong events increases with resolution, typically by 25% from T95 to T255, and another 10% from T255 to T511. Parameterized gravity wave drag decreases greatly (typically by 80%) between T95 and T255, as gravity waves become explicitly resolved.

The number of cyclonic systems with a lifetime of more than 12 h is shown in Fig. 9 for the four different datasets. The number of simulated cyclones increases with increasing resolution. Four areas stand out as being particularly sensitive to horizontal resolution, that is, the Irminger Sea, the northeast North Atlantic (including the western Greenland Sea), Baffin Bay, and northeastern parts of Canada.

Splitting of the storm track occurs south of Greenland (Fig. 9a); although most extratropical cyclones propagate northeastward along the eastern side of Greenland, a substantial fraction migrate via the Labrador Sea to Baffin Bay (also Hsu 1987). The latter branch of the storm track is missing in the schematic compiled by Hoskins and Hodges (2002) despite the fact that they too carried out cyclone tracking on ERA-40 data. The most likely explanation for this difference is that Hoskins and Hodges focused on long-lived, migratory systems only, whereas in this study relatively short-lived and quasi-stationary systems, which are prevalent west of Greenland, were included. Visual inspection of weather maps for many winters (using ERA-40 data) and animations made with this reanalysis data indeed shows the existence of strong
synoptic systems reaching Baffin Bay from the northwest North Atlantic, usually when a deep trough is located over northeast Canada and a blocking anticyclone over the central North Atlantic, leading to a poleward deflection of the polar jet stream (along which cyclogenesis occurs). The existence of these cyclones may have profound implications for air–sea interaction and sea ice drift in the Labrador Sea. They suffer in comparison with the dominant storm-track cyclones east of Greenland, from the loss of the warm ocean

Fig. 7. As in Fig. 3, but for high-pass-filtered transient height field at 1000 hPa. The field corresponds to strong easterly pressure drag on the atmosphere at Greenland. This filtering, retaining variability from 2 to 10 days, isolates the rapidly moving cyclones in the storm track, in particular those that move into the wake east of Greenland and develop there. The figure emphasizes the multiple disturbances that tend to move along the storm track during energetic events.
surface found southeast of Greenland. Frequent northerly winds from the Arctic, ducted through Nares Strait, also inhibit the northward movement of cyclones in this region.

Surprisingly, the cyclone track along the western side of Greenland is absent in the T95L60 model (Fig. 9b). This may partly be a result of the smallness of the systems in Baffin Bay, which are difficult to represent at a relatively coarse resolution of T95L60. Increasing horizontal resolution leads to a more realistic representation; however, even at T95L255 the number of synoptic systems propagating into Baffin Bay is underestimated significantly (Fig. 9d). Figure 10 shows the number of long-lived (>2 days), stationary, and migratory extratropical cyclones that have been generated in the Irminger Sea (Figs. 10a–c) and the Greenland Sea (Figs. 10d–f) for ERA-40 and seasonal integrations at two different horizontal resolutions (T95L95 versus T95L255). All three datasets show that most cyclones being generated in the Irminger Sea do not propagate much farther than Iceland; that is, they are quasi-stationary (see also Harold et al. 1999). The more migratory systems, albeit less frequent, tend to propagate toward the Nordic Seas and northern Europe. Increasing horizontal resolution from T95L95 to T95L255, and therefore the realism of the representation of Greenland’s orography, increases the number of cyclones generated in the Irminger Sea almost by a factor of 2. A comparison with ERA-40 reveals that this increase in cyclogenesis in the Irminger Sea is realistic. Interestingly, only a small fraction of low pressure systems generated east of the southern part of Greenland directly impact Europe. Some of the migratory low pressure systems generated north of Iceland take a more northward path entering the Arctic through Fram Strait, whereas the others propagate as far as the Kara Sea. Penetration of the Arctic is largely...
absent at lower (T95) resolution, in accord with the underprediction of this important pathway found in global climate models. Cyclogenesis north of Iceland seems to be less sensitive to horizontal resolution, suggesting that Greenland’s orography is of secondary importance.

The number of cases of cyclogenesis of long-lived, migratory systems along the eastern side of Greenland shows surprisingly little sensitivity to horizontal resolution (not shown in figures). Four local maxima are observed near Greenland, at the southwest coast, east of the southern tip, Cape Farewell, in the southeast Greenland Sea and in the Arctic to the north. Baffin Bay cyclones often are guided by lows in the Labrador Sea, which themselves are likely affected by Greenland orography. The T95L60 model fails here, yet even at T255L40, Baffin Bay cyclones are underpredicted. Similar remarks hold for Arctic cyclones just north of Greenland. Both long-lived and migrating cyclones are underestimated in the Irminger Sea at T95L60, yet this model performs better in the Greenland Sea.

The genesis of quasi-stationary systems in the wake of Greenland, on the other hand, is much more sensitive to horizontal resolution. The T95L60 model, for example, generates only about 60% of the number of such cyclones in the Irminger Sea compared to T255L40. This is consistent with Kristjansson and McInnes (1999) and Skeie et al. (2006).

Important to the global impact of Greenland is the penetration of the Arctic by cyclones, mentioned in connection with Figs. 9 and 10. Zhang et al. (2004) describe the origins of Arctic cyclones, which are roughly correlated with the intensity of activity in the Atlantic storm track. In our study, the number of cyclonic systems reaching north of 80°N is underestimated at T95, but improves compared with ERA-40 at higher resolutions. Genesis of these systems is dominated by the Greenland Sea. There is a small downward trend in flux of cyclones to the Arctic from 1980 to 2000. Zhang et al. (2004) document an increase in Arctic cyclone activity during their analysis period (1948–2002), and corresponding change in storm track (both in summer and winter). The effects of cyclonic invasion of the Arctic lower troposphere are widespread, from strong anomalous advection of sea ice to the activity of the stratospheric polar vortex and its episodic breakup.
in sudden warmings. The Atlantic storm track is the largest source of Arctic cyclones though there are other important sources. Of a total 6763 cyclones originating south of 70°N in the dataset, they record (1306, 1128) (winter, summer) cyclones originating in the Atlantic, (688, 683) in the North Pacific, (895, 1332) in Eurasian continent, and (364, 378) from North America. Those generated north of 70°N amounted to (6860, 6026) in winter and summer. Cyclone life cycles are intricate, however, and a recurring feature is the downwind development of new cyclones spawned by earlier developing cyclones upwind (wave packets of baroclinic instability) (e.g., Chang 1993; Chang et al. 2002). Thus some of the cyclone generation in the Arctic Basin can be associated with propagation from farther south.

The net result, in which a cyclonic appendage of the Icelandic low reaches high into the Arctic and greatly affects winds, ice drift, and temperatures, is clear from many observations, for example, the remarkable through-cloud satellite image videos of Arctic sea ice, using passive longwave Advanced Microwave Scanning Radiometer for Earth Observing System (EOS) (AMSR-E) radiometry by Agnew et al. (2005).

c. Case studies

The pressure-drag events near Greenland singled out two differing aspects of the Northern Hemisphere circulation: the rapidly moving transient cyclones of the Atlantic storm track and the slowly developing quasi-stationary waves and large deflection of the eddy-
driven high-latitude jet stream. It is apparent that the high-drag situations involve intense cyclonic systems propagating along the Atlantic storm track, rather than a simpler textbook westerly flow past a mountain. Centering attention on the pressure drag is thus as much an intuitive device to single out intense development of the Icelandic low as a diagnostic aimed at zonal momentum balance. Here, the focus will be on two cases, 1200 UTC 27 December 2004 and 1200 UTC 17 January 2005. These cases had a zonal pressure-drag magnitude which was three standard deviations below the long-term mean (Fig. 2), and dominated that winter season.

1) DESCRIPTION OF THE SYNOPTIC SITUATION

The winter of 2004/05 exhibited a moderately high NAO index, the monthly index averaging about +1 for December–January, and peaking at values just over 1.5. The daily NAO index and pressure-drag time series (Fig. 2) are not particularly well correlated, though clearly the intense westerly winds at south Greenland are often a characteristic of positive NAO. The east Atlantic pattern (Wallace and Gutzler 1981) also takes on strongly negative values during this period. An upper-tropospheric trough over the western United States moves eastward, deepening and casting off lows that develop rapidly above the warm western Atlantic Ocean. The jet stream deflects far northward on the east side of this trough, cresting over south Greenland. Each of the two case studies during this winter involves more than a single cyclonic system. The familiar pattern (which we personally learned long ago from sea captains) shows rapidly moving lows being “captured” in the lee of Greenland. This is in accord with the storm-track analysis of Hoskins and Hodges (2002), who see the wake of south Greenland as a site of slowly moving storms, and both lysis and genesis.

Between 20 and 30 December three distinct storms follow this track, and with their successors, the accumulated activity produces a much larger depression in the wake of Greenland that remains intense until mid-February. The size of this long-lived cyclonic system grows to that of Greenland itself, which reaches 2500 km in north–south extent. The first case, Christmas 2004, has a striking pattern in tropopause maps of 0 on the PV2 surface (Fig. 11), which outline the activity of the jet stream and adjacent cold polar air masses. The low moving in on 24 December deflects northward through Baffin Bay, west of Greenland, then reforms in the lee east of Greenland. Once in place it generates a strong tip jet over the Labrador/Irminger Seas (26–27 December) and subsequently, strong downslope jet through the orographic gap between the two highest summits (27 December). Cold air at the tropopause high overhead is seen streaming through this gap. The surface winds and 700-hPa vertical vorticity for this case (Fig. 12) show the strong Baffin Bay cyclone fragmenting as it crosses Greenland, reminiscent of the PV banners seen in the lee of the Alps (Schär et al. 2003). As the lee cyclone develops and expands in lateral scale east of Greenland, the jet stream (visible roughly as the temperature front on the PV2 surface in Fig. 11) lies above the east Greenland coast, aligned northeast–southwest nearly parallel to it, and then deforms as the lower-level cyclone engages it via the barotropization process.

Following another strong sequence like this on 6 January 2005, the second case study (15–17 January 2005; Figs. 13 and 14) also involves several (three in the course of 10 days) depressions collecting to form a low as big as Greenland itself (2500 km in north–south extent). In this case the tip jet is particularly strong. Once again the vorticity (and PV) is fragmented into streamers that wrap round within the lee cyclone. In both case studies there are large and small cyclones west of Greenland that are rather short-lived. They become upwind precursors of stronger, longer-lasting cyclones east of Greenland.

The fate of these depressions is often to die away over the Greenland Sea, but as described above, a substantial number move northward into the Arctic Ocean (Zhang et al. 2004; McCabe et al. 2001). This forms the statistical invasion of the Arctic with cyclonic energy that occurs in high NAO/AO/NAM index winters.

The Atlantic storm track reaches so far northward (often extending from 30° to 80°N) that its interaction with the more zonally oriented upper-tropospheric winds is enhanced. Long-range downstream development is invoked to suggest propagation of synoptic energy eastward along the jet stream waveguide, from the Pacific all the way to Europe (Chang et al. 2002; Branstator 2002) and implicated in superstorms like “Lothar” in Europe in 1999. We argue below, however, that such events reaching Europe do so along more southern routes, and not via the storm track near Greenland. More locally, similar upwind precursors are evident in these case studies, when six distinct lows develop and reach Greenland in the two weeks following 10 January. Jet stream waveguide activity, modeled for example by Hoskins and Ambrizzi (1993), based on the broad climatological jet, takes on a somewhat different character with the narrow, instantaneous jet or even a sharp PV gradient at the tropopause (e.g., Schwierz et al. 2004). The upper-level jet stream ex-
tends far north over or aside Greenland, as part of a deep ridge/trough system during these high pressure-drag events. Hoskins and Ambrizzi (1993) argue that the jet stream is not a continuous waveguide in the manner of Branstator’s “circumpolar waveguide mode,” yet regardless of how continuous it is, around the entire hemisphere, jet stream disturbances clearly have considerable downwind influence.

The stratospheric circulation connected with high negative-pressure-drag events at Greenland has been
described through composite anomalies earlier. The SPV is actively correlated with these high-energy events beneath, and though it does not, in the composites, execute a full sudden-warming breakup, its center moves toward Baffin Bay. This movement accompanies barotropization of the energetic cyclonic activity and is strongly present in animations of these case studies. It is possible that Greenland is a “stirring rod,” which, when impacted by storm track/jet stream activity, can (through barotropization interactions) displace the ver-

Fig. 12. As in Fig. 11, but for surface winds on the lowest model level (m s$^{-1}$) and relative vorticity (10$^6$ s$^{-1}$) at about 700 hPa. The gap jet and tip jet are clearly visible.
What we see in the composites of Fig. 5, however, are precursors of strong surface pressure drag, some 6 days preceding the event. This is reminiscent of Baldwin and Dunkerton’s (2001) demonstration that in much stronger stratospheric sudden warming events, such precursors do exist though they may in fact have earlier tropospheric origin [as recently argued in the “T-S-T” coupling model of Reichler et al. (2005)].

2) THREE-DIMENSIONAL LAGRANGIAN TRAJECTORIES

Airmass back trajectories (see Wernli and Davis 1997) for the two case studies (Fig. 15) show the large
deviation in paths associated with the tip jet and downslope “gap jet.” Low-level air that climbs over Greenland is drawn from nearly 1000 km to the south (where it is also at low levels) and from the 500-hPa level farther north. Earlier (Fig. 13f) we saw that the gap flow was evident as high as the tropopause. Anticyclonic vorticity expected over Greenland from vortex tube squashing is evident here and in the Eulerian vorticity maps (Figs. 12 and 14). The strong cyclonic vorticity appearing after descent off the icecap is also clear. The altitude history of the air parcels (Figs. 15b,d) records this descent, with surface air being drawn from the 650-

Fig. 14. As in Fig. 13, except for surface winds on the lowest model level (m s$^{-1}$) and relative vorticity (10$^{6}$ s$^{-1}$) at about 700 hPa.
We showed in Fig. 11, for the 27 December 2004 case study, how ducting of cold air through the summit gap of Greenland can reach as high as the jet stream/tropopause level. This is a remarkable testament to vertical interaction, given that intense downslope jets are, at lower latitude, normally confined to the lowest kilometer or so of the troposphere.

Kristjánsson and McInnes (1999) argue that Greenland weakens cyclones by obstructing the cold front/cold sector air that normally feeds the release of available potential energy. However, the orography provides an additional source of relative vorticity and wake energy, and can lead to considerable local intensification of the circulation and its cyclonic development.

Petersen et al. (2003) suggest a weakening of the storm track due to the presence of Greenland, which occurs even in the presence of locally increased energy density. The vorticity develops along the Lagrangian trajectories (Figs. 15a,c) in a manner consistent with cyclogenesis in the immediate lee of Greenland. A fuller dynamic study of these events would show the relative importance of baroclinic development from the upper-tropospheric trough, on the one hand, and vortex stretching in the downslope orographic flow, on the other. Suffice it to say that purely barotropic models of flow past a mountain on a β plane show intensive lee cyclogenesis and formation of jets without any preexisting jet stream or baroclinity (e.g., Rhines 2007).
3) SENSITIVITY TO HORIZONTAL RESOLUTION

To investigate the sensitivity of short-range forecasts to horizontal resolution 1-day forecasts were carried out for the two cases described in the previous section, focusing on local processes that affect the forecast performance. The forecasts (T$_{L95}$, T$_{L255}$, and T$_{L799}$) used 60 levels and model cycle 29R1. One-day forecasts of sea level pressure (SLP) and turbulent surface heat started at 1200 UTC 26 December 2004 (Figs. 16a–c) show the resolution effect on the wake of the southern part of Greenland. We note that classical hydrodynamic wakes often contain sheltered regions of quiescent or reversed flow. However, rotating stratified flows can as often produce concentrated downslope jets (here, the “gap jet”) and cyclogenesis in the lee of topography. Increasing horizontal resolution leads to splitting of the low-level wake into two branches, the Greenland tip jet and downslope gap jet described earlier. Associated with these are large increases in simulated surface heat fields with resolution. These air–sea heat fluxes may have a crucial effect on meridional overturning in the ocean, since several of the important dense, deep waters of the global meridional overturning circulation are formed here (e.g., Pickart et al. 2003). Moreover, the improvement continues as resolution increases further, T$_{L255}$–T$_{L799}$. The surface heat flux in the northernmost maximum in the T$_{L799}$ version of the model is in excess of 1000 W m$^{-2}$. These values are substantially higher than those found in the center of the Greenland tip jet. Similar conclusions are obtained for 1-day forecasts started at 1200 UTC 16 January 2005 (Figs. 16d–f). The tip jet is captured at all horizontal resolutions. The magnitude, however, increases from about 700 W m$^{-2}$ at T$_{L95}$ to 1000 W m$^{-2}$ at T$_{L799}$. Moreover, two local SLP minima are simulated at the highest resolution whereas one single large-scale SLP minimum is forecast at T$_{L95}$. The other significant vorticity forcing effect (for both atmosphere and ocean) is the curl of the surface wind stress. This involves the northward gradient of eastward stress on the ocean surface, which is similarly amplified at high resolution. Direct support for these enhanced fluxes is found in scatterometer wind maps (not shown here), which characteristically show greatly elevated wind stress, wind stress curl, and air–sea heat flux (e.g., Dickson 2003).

Vertical sections of potential temperature across Greenland at 62°N (Fig. 17) for 1-day forecasts started...
at 1200 UTC on 25 December 2004 use the three different horizontal resolutions. The most striking feature is the mountain wave, which propagates into the stratosphere in the T<sub>799</sub> model. It is weaker in the T<sub>255</sub> simulation with little propagation into the stratosphere. The low-resolution model is not capable of simulating the gravity wave at all. The ability to resolve these non-geostrophic (yet hydrostatic) phenomena in a global forecasting system is noteworthy. The extensive discussion on the downslope winds in the lee of Greenland by Shapiro et al. (2002) and their relevance to Greenland Sea synoptic activity is one focus of The Observing System Research and Predictability Experiment (THORPEX) program (http://www.wmo.int/thorpex/). The implication is that the intensity of non-geostrophic downslope jets can spill out and intensify cyclonic activity (e.g., Aebyisher and Schär 1998). The 17 January 2005 case (Fig. 18) shows an intenser downslope jet, yet with much weaker gravity wave generation and upward propagation. In the typical life cycle, northward-moving cyclones first drive a tip jet followed by gap jet.

Again, we remark that the shallowness of downslope orographic jets, as well as their hydraulic nature, seems modified here by a considerable upward reach of both waves and advection at the tropopause level.

d. Predictability

Given that Greenland lies near one of the most populated areas in the world, Europe, it is natural to ask whether the interaction between Greenland and the atmosphere has an influence on the predictive skill of European weather in the medium range, 3 to 10 days. Reforecasts with the ECMWF model T<sub>159L60</sub> have been investigated for winters of the period 1980–2001; these reforecasts were carried out in the framework of the ERA-40 project (Uppala et al. 2005) using the same model cycle (for each day, one 10-day forecast was carried out and differences analyzed). The first set are forecasts started one day prior to negative pressure drag across Greenland (pressure-drag anomaly exceeding one standard deviation). The second set, for com-
parison, comprises all forecasts started 365 days earlier to remove the annual cycle. On average, 1-day forecasts, for which the atmosphere strongly interacts with Greenland, are less skillful in the Irminger Sea region than normal (Fig. 19a). However, already by day 3 this signal has disappeared completely (Fig. 19c); that is, the skill of forecasts started before negative drag events are indistinguishable from normal forecast errors. It appears, therefore, that on average medium-range forecast skill over Europe is not affected by strong interaction between Greenland and the overlying atmosphere during earlier stages of the forecast, at least during wintertime. This is consistent with Ferranti et al. (2002) who show that anomalously high errors over western Europe in 5-day forecasts are associated with anomalously low surface pressure just south of Iceland. Figure 3f shows that such flows are not on average present 4 days after pressure-drag events at Greenland.

Another valuable source of information encompasses so-called Daily Reports, which are routinely written by members of the Meteorological Operations section at ECMWF. In these reports, among others, possible sources of errors of recent operational forecasts are being investigated by experienced synopticians. We went through all reports of the last 7 yr and found only a very limited number of cases of forecast failure over Europe, which could be traced back to the Greenland area (an example being the forecasts started on 20 February 2006). Although analysis increments (the differences between the observations and the first guess used to construct the analysis) are relatively frequently reported in the Greenland region, they do not seem to lead to large inconsistencies between subsequent forecasts over Europe, suggesting that the growth of these increments throughout the subsequent forecast is rather small. The daily reports thus lend support to the idea that Greenland has a rather minor direct influence on weather forecasts for the European region.

Previous sections have revealed that low zonal pressure-drag events across Greenland tend to be associated with high-impact features such as lee cyclogenesis, severe downslope wind storms, tip jets, and mountain waves. How predictable is the zonal pressure drag (Fig. 2) across Greenland? It turns out that the skill of the ECMWF model in predicting the zonal pressure drag across Greenland is surprisingly high (Fig. 20). The 5-day forecasts, for example, shows a correlation of $r = 0.75$ with the verifying analyses; and even by 10 days the correlation still amounts to $r = 0.3$. The skill in the medium-range (beyond 3 days) seems to be quite high given that synoptic-scale features have to be forecast (usually most of the skill of 10-day forecasts of the mid-latitude atmospheric flow arises from the predictability of the long waves). However, the relatively high predictability of zonal pressure-drag events across Greenland is consistent with our notion that planetary wave propagation, which is relatively predictable, is crucial in determining synoptic-scale developments associated with the Greenland massif.

4. Discussion

We have used the zonal pressure drag time series on south Greenland as a tool to examine intense cyclonic development in the subpolar Atlantic storm track. Other indices could have been used, including the NAO index or tip-jet index of Pickart et al. (2003). Our choice reflects interest in the possible “stirring rod” role of Greenland. Composite anomaly maps of the height fields in the Atlantic sector showed strong
easterly and westerly pressure-drag events associated both with a large-scale, standing pattern that reaches to the stratosphere and increases in lateral scale with altitude. The dynamics are nonlinear in the sense that an east–west dipole of pressure dominates westerly pressure-drag events, while a north–south dipole dominates easterly events. Yet, the high-pass-filtered composite anomaly fields show instead the traveling cyclones,

**Fig. 19.** Difference in Z500 forecast error (%) between cases for which forecasts were started one day prior to a negative zonal pressure-drag event across Greenland and randomly selected forecasts (climatological forecast skill): (a) $D + 1$, (b) $D + 2$, (c) $D + 3$, (d) $D + 4$, (e) $D + 5$, and (f) $D + 6$. A threshold of $-1$ std dev has been used. Positive (negative) values indicate anomalously large (small) deterministic forecast error following negative drag events.
which are rapid and frequent, interacting with either side of Greenland. The climatological-mean wintertime surface lows in the Pacific and Atlantic in fact have an interesting zonally averaged zonal-momentum image; the mean pressure drag on the atmosphere north of 60°N, as shown by Brown (2004), is positive (eastward), with the intense Aleutian low exerting “suction” on the Alaska coast range; the time-averaged zonal pressure drag on the atmosphere by the Greenland sector is negative, as expected with the dominant low-pressure systems in its wake.

Two case studies from winter 2004/05 illustrate the life cycle of pressure-drag events. These typically involve northeastward-propagating cyclones related to a strong trough over the eastern North America, followed by secondary development in the Irminger/Greenland Seas. A tip jet at Cape Farewell is often followed by a downslope jet through the gap in the Greenland summit ridge, as the systems move north. Through the secondary development, small, rapidly traveling cyclones merge with the Greenland wake and often expand to mimic the size of Greenland itself (2500 km in north–south extent). The Icelandic low expresses the accumulation of cyclonic activity east of Greenland at a scale larger than that of rapidly moving transient cyclones. This larger-scale part of the life cycle of storm track events that contributes greatly to the unfiltered composite fields for high easterly pressure drag on Greenland’s slopes.

Research into the effects of Greenland on the atmospheric circulation is very active, in the light of the higher resolution now available in both models and observations. An example of this increasing acuity is the cyclonic activity in Baffin Bay, west of Greenland. Depressions passing northward often take this track and there is also genesis of systems there, which shows up in ERA-40 yet has been underrepresented in low-resolution models and de-emphasized in earlier storm track diagnoses (e.g., Hoskins and Hodges 2002).

A second benefit of increasing resolution is the representation of wake effects: vorticity “banners” east of Greenland, nongeostrophic wake effects, and gravity waves. The intense episodes of downslope jets and gravity waves accompanying strong pressure drag influence both the atmospheric boundary layer and the lee cyclones, and also radiate up to the stratosphere. This is much in accord with earlier works of Shapiro and collaborators (e.g., Shapiro et al. 2002). Three-dimensional model air parcel trajectories emphasize the diverse origins of air entering the tip jet and downslope jet and the intense vortex stretching in the lee of Greenland. This Lagrangian picture complements the familiar Eulerian time-averaged circulation maps, which, where the wintertime mean Icelandic low tilts westward with increasing height, are indicative of cold-outbreak advection above the oceanic heat source.

A third improvement involves vertical interactions, both upper-troposphere PV anomalies associated with high Eady index and northward-reaching jet stream, and communication between the slopes of Greenland and the stratospheric polar vortex: at synoptic scale, planetary wave scales, and in impulsive gravity wave generation. The stratospheric polar vortex center moves toward Baffin Bay during intense easterly pressure-drag events. Vertical influence described here, with the stratospheric polar vortex showing a coherent, early emerging covariance with Greenland surface pressure drag, is not necessarily a statement of cause and effect, which remains to be clarified. The early stratospheric precursors (at day −6) of these events is consistent with the Baldwin and Dunkerton (2001) discovery of major stratospheric sudden warming precursors of tropospheric annular mode events.

A fourth benefit is seen in better representation of the northward development of the storm track, and invasion of the Arctic Basin by cyclonic systems from the lee of Greenland, which varies greatly with NAO and exerts a major influence on Arctic sea ice movement and melting.

A fifth benefit involves air–sea interaction. At higher resolution, the air–sea heat flux is much enhanced and localized in the lee of Greenland, and the wind stress curl is increased and sharpened (suggestive of enhanced
Ekman pumping in both atmosphere and ocean). Scatterometer wind observations portray these finescale model predictions convincingly in the two case studies described here.

One of the most exciting questions to be explored is the interaction of upper-tropospheric jet stream waveguide and synoptic systems in this region. We have emphasized that Greenland has both local and hemispheric influence. From EP-flux analysis covariant with strong pressure-drag events we do see impact of the strong upper-tropospheric trough/ridge on the hemispheric zonal momentum balance. This supports the idea that the stationary waves in the Northern Hemisphere are influenced by Greenland, as argued from the rather extreme model simulations with and without Greenland by Junge et al. (2005).

The northward tracking of many of the cyclonic systems means that forecasts for northern Europe are not often heavily impacted by this region, in a direct sense. This is shown here quantitatively. However, if downstream waveguide effects aloft are as significant as they seem, then this pathway for influencing Europe may also be active. Forecast skill of the high pressure-drag events themselves is quite high, using the standard ECMWF forecast model.

The two case studies were based on operational ECMWF analysis. It is likely that many of the smallest-scale features owe their existence to the first-guess, short-range model forecast. Verification requires high-resolution observations, like the mountain-wave dropsonde measurements used by Shapiro et al. (2002). Scatterometer winds are, however, available over the ocean. Surface winds at nominal 50-km resolution for 27 December 2004 (not shown) clearly define the tip jet and downslope gap jet. They are separated by a region of slack winds (~20 kt, or ~10.3 m s⁻¹). The core velocity is about 40 kt. Moreover, the tip jet of 17 January 2005 exhibits speeds exceeding 50 kt over a large region. These observations support the high-resolution model results above [assimilation of Quick Scatterometer (QuikSCAT) winds into the analysis does occur, but not with sufficient strength to explain the similarity for 1-day forecasts]. In a related study Eden and Jung (2006) use the high-resolution ECMWF analysis to force an eddy-resolving North Atlantic Ocean model. They show that, before the QuikSCAT satellite was flying, the model was capable of simulating the small-scale wakes of Cape Verde and Canary Islands. It is questionable that a resolution of T₄159, which was used to produce ERA-40, can capture the fine scales in Greenland’s wake. At T₄255, the resolution used in the ECMWF interim reanalysis, this may be better achieved.

To our knowledge this is the first study addressing predictability of the circulation interacting with Greenland (in terms of negative drag events). Short-range forecast errors were clearly affected locally, yet for medium range the differences in forecast skill between negative drag and climatological cases largely disappeared for European forecasts. We have not here considered downstream upper-tropospheric development (e.g., Chang et al. 2002), yet we see the strong effect of the jet stream’s proximity to Greenland. Its activity through local Eady-index related instability, downwind propagation, and planetary wave breaking, will be interesting to investigate.

We had our introduction to Greenland’s intense weather in the fall of 2003, when the remains of three tropical hurricanes reached Greenland and, coming beneath the jet stream, were re-energized (one of these, Juan, was the first significant hurricane to hit Halifax, Nova Scotia, since 1893). On many occasions it was impossible to walk outside in these winds. Hurricanes/tropical cyclones provide a “Green function study” for the jet stream waveguide and broader extratropical atmosphere. For example, Supertyphoon (145-kt sustained winds) Lupit similarly reached high latitude in November 2003, and plausibly excited the jet stream around the entire hemisphere (M. Shapiro 2004, personal communication). We urge the reader to view multilevel animations of pressure, theta, and vorticity fields during these events. Some of these are currently posted online at http://www.ocean.washington.edu/research/gfd.

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