We present a new Lagrangian diagnostic for identifying the sources of water vapor for precipitation. Unlike previous studies, the method allows for a quantitative demarcation of evaporative moisture sources. This is achieved by taking into account the temporal sequence of evaporation into and precipitation from an air parcel during transport, as well as information on its proximity to the boundary layer. The moisture source region diagnostic was applied to trace the origin of water vapor for winter precipitation over the Greenland ice sheet for 30 selected months with pronounced positive, negative, and neutral North Atlantic Oscillation (NAO) index, using the European Centre for Medium-Range Weather Forecasts’ ERA-40 reanalysis data. The North Atlantic and the Nordic seas proved to be the by far dominant moisture sources for Greenland. The location of the identified moisture sources in the North Atlantic basin strongly varied with the NAO phase. More specifically, the method diagnosed a shift from sources north of Iceland during NAO positive months to a maximum in the southeastern North Atlantic for NAO negative months, qualitatively consistent with changes in the concurrent large-scale mean flow. More long-range moisture transport was identified during the NAO negative phase, leading to the advection of moisture from more southerly locations. Different regions of the Greenland ice sheet experience differing changes in the average moisture source locations; variability was largest in the north and west of Greenland. The strong moisture source variability for Greenland winter precipitation with the NAO found here can have a large impact on the stable isotope composition of Greenland precipitation and hence can be important for the interpretation of stable isotope data from ice cores. In a companion paper, the implications of the present results are further explored in that respect.

archives [Hurrell et al., 2003]. This is also the case for ice
cores from the Greenland ice sheet. Via snow accumulation
or stable water isotopes, these can provide proxy records of
the past behavior of the NAO [e.g., Appenzeller et al., 1998;
Vinther et al., 2003].

The variability of the general circulation associated
with different climate modes in turn offers the opportunity,
for example by means of atmospheric reanalysis data, to
study key aspects of the present-day atmospheric water
cycle. One such important question concerns the source
regions of precipitation. Past studies have aimed at inferring
moisture sources of Greenland from the stable isotope
signal in ice cores [e.g., Johnsen et al., 1989; Barlow et al.,
1993]. However, such approaches have remained limited,
as they required many assumptions which so far could
only be partly constrained. In a Lagrangian framework, air
parcel back trajectories can provide a link between the
evaporative sources of water vapor and the precipitation
elsewhere. Thereby it is possible to study the effect of
source region variability on the isotopic composition of
precipitation in Greenland.

Several previous studies have aimed at attaining
information on the sources of moisture in a Lagrangian
framework. Thereby, air parcels are traced as they are
transported in the atmosphere and, to a first-order approxi-

mation, change their specific humidity due to precipitation
and evaporation processes. Wernli [1997] and later Eckhardt
et al. [2004] derived quantitative precipitation estimates
from back trajectories, but did not address the question of
moisture origin. Massacand et al. [1998] inferred a Medi-
terranean moisture source for heavy precipitation on the
Alpine south side from examining the specific humidity
traced along back trajectories. Wernli et al. [2002] made
first qualitative attempts to identify links between evapora-
tion from an area of anomalously warm SSTs and a severe
winter storm with back trajectories. A first, more complete
Lagrangian moisture source diagnostic was developed by
Dirmeyer and Brubaker [1999]. These authors used quasi-
isentropic back trajectories in combination with model-
derived surface fluxes to determine evaporation sources
along back trajectories. The same method was later applied
by Brubaker et al. [2001], Reale et al. [2001], and Dirmeyer
and Brubaker [2006]. It is however limited by methodo-
logical (no kinematic trajectories) and conceptual (large
vertical distance between evaporation sources and air parcel
locations) shortcomings. James et al. [2004] diagnosed net
water changes along a large number of back trajectories to
infer the moisture sources for the Elbe flood in August
methodology to a Lagrangian particle model, again to study
the Elbe flood, and in a second step to determine the
moisture budgets of large river basins. In their method, all
changes of specific humidity in an air parcel are diagnosed,
irrespective of additional criteria, such as an air parcel’s
altitude.

All Lagrangian approaches applied so far are limited
with respect to the definite demarcation of moisture sources.
Here we therefore introduce a new Lagrangian methodology
for the identification of the sources of water vapor for
precipitation. By considering the temporal sequence of
evaporation and precipitation in an air parcel during trans-
port, as well as information about the boundary layer height,
the method allows for a quantitative demarcation of evap-
orative moisture sources. Such a Lagrangian moisture
diagnostic is complementary to Eulerian methods with
water vapor tracers, and can therefore be compared to the
results from these other approaches. Being based on reanal-
ysis data, this diagnostic approach avoids problems which
are often inherent to studies based on General Circulation
Model (GCM) simulations, namely that the differing syn-
optic evolution does not permit a direct comparison to
observational data.

Hence, in Part 1 of this two-part paper, the Lagrangian
moisture source diagnostic is introduced and applied to
examine the NAO variability of the moisture sources for
winter precipitation over the Greenland plateau. In Part 2
(H. Sodemann et al., Interannual variability of Greenland
winter precipitation sources: 2. Effects of North Atlantic
Oscillation variability on stable isotopes in precipitation,
submitted to Journal of Geophysical Research, 2007, here-
inafter referred to as Part 2), the moisture transport con-
ditions are diagnosed in more detail, and used as input data
for calculations of the stable isotope composition of Green-
land precipitation based upon a well-established isotope
fractionation model. These results are then compared to
stable isotope observations from Greenland ice cores.

2. A Lagrangian Moisture Source Diagnostic

In a Lagrangian framework, the movement of air
parcels through space and time can be described by trajec-
tories. The changes in specific humidity of such an air
parcel along its trajectory will predominantly reflect the
effects of precipitation and evaporation processes. Thereby
we assume the “integrity” of these air parcels over several
days, and neglect the effects of mixing with neighboring
parcels. Adopting this basic concept, we pursue two aims:
(1) to identify where moisture enters an air parcel and (2) to
estimate which moisture sources contribute how much to
the precipitation falling from an air parcel at a specific target
area. The latter is achieved by taking into account the
temporal sequence of evaporation into and precipitation
from the air parcel during transport from the source to the
target area.

2.1. Identification of Moisture Uptake

Moisture changes in an air parcel during a certain
time interval \( \frac{\Delta q}{\Delta t} \) are generally the net result of evap-
oration \( E \) into and precipitation \( P \) from the air parcel
[James et al., 2004; Stohl and James, 2004]:

\[
\frac{Dq}{Dt} \approx \frac{\Delta q}{\Delta t} = E - P \left( \text{g kg}^{-1} (6 \text{ h})^{-1} \right). \tag{1}
\]

As all changes are evaluated over a 6 h time interval, in
the following the denominator \( \Delta t \) is dropped for simplicity.
Under the assumption that during a particular 6 h time
interval either precipitation or evaporation dominates, the
sign of \( \Delta q \) for a given part of a trajectory allows
determination of locations of evaporation or precipitation
[James et al., 2004]. Figure 1 shows a sketch of an air
parcel trajectory from the Atlantic ocean to Greenland.
Corresponding to the order of the backward calculation, the
arrival point of the trajectory over Greenland is in the
following referred to as the start point \((t = 0 \text{ h})\), while the earliest point is called end point \((t = -54 \text{ h in this example})\). The dashed blue line gives the evolution of the air parcel’s specific humidity \((q)\). The \(\Delta q^0\) bars above the thin blue line denote moisture increase \((\Delta q^0 > 0)\), and below a moisture decrease \((\Delta q^0 < 0)\) during a 6 h time interval:

\[
\Delta q^0(t) = q(\bar{x}(t)) - q(\bar{x}(t - 6 \text{ h})),
\]

where the superscript \(^0\) indicates that this is a total diagnosed moisture change at a source region (as compared to a weighted value, see section 2.2 below), and \(\bar{x}(t)\) denotes the parcel position at time \(t\). It is assumed that when an air parcel enters the boundary layer, turbulent fluxes can exchange moisture between the air parcel and the surrounding boundary layer air. Hence, if a Lagrangian moisture increase occurs inside the atmospheric boundary layer (BL), an evaporative moisture source (or moisture uptake point) is identified at this location (Figure 1, label 1). In terms of objective selection criteria, a moisture uptake event is identified along a trajectory if a moisture increase occurs \((\Delta q^0 > 0)\), and the air parcel’s altitude is below the approximate BL height. If moisture increase is diagnosed above the BL, it is not possible to assign this moisture to an evaporation source at the surface (Figure 1, label 2). It must then be assumed that other physical or numerical processes caused the moisture increase in the traced air parcel, such as convection, evaporation of precipitating hydrometeors, subgrid-scale turbulent fluxes, numerical diffusion, numerical errors associated with the trajectory calculation, or physical inconsistencies between two ECMWF analysis time steps (see section 5).

As the interest here is to identify the origin of water that leads to precipitation in a specific target area, only air parcels which precipitate at \(t = 0\) are traced backward in time (Figure 1, label 4). In rough agreement with the parameterizations of the ECMWF model, it is assumed that clouds exist and precipitation falls whenever a relative humidity threshold of 80% is exceeded. The amount of precipitation at the target area is diagnosed from the decrease in \(\Delta q^0\) during the last 6 h time interval, and then projected to the trajectory’s starting point. This follows the approach of Wernli [1997], and has been applied in several other Lagrangian studies [e.g., James et al., 2004; Sodemann et al., 2006].

In order to derive a Lagrangian estimate of the precipitation at sufficiently high spatial resolution, the air mass over the target area (target volume) is discretized vertically and horizontally into a large number of air parcels (see section 2.3). Under the simplifying assumptions that (1) in case of \(\Delta q^0 < 0\) all moisture decrease is due to precipitation and (2) that this precipitation falls immediately, the precipitation at the surface \(P_{\text{sfc}}\) is then given by the total moisture decrease over a column of air parcels:

\[
P_{\text{sfc}} = -\frac{1}{g} \sum_{k=1}^{k_{\text{max}}} \Delta q^0_k(t = 0) \cdot 10^{-3} \cdot \Delta p_k (\text{mm} \text{ h}^{-1}),
\]

where \(g\) is the acceleration due to gravity, \(k\) is the vertical index of the trajectory starting grid (see section 2.3), \(\Delta q^0_k(t = 0)\) is the moisture decrease in an air parcel at the start location (in g/kg), and \(\Delta p\) is the vertical extent of an air parcel (in hPa).

In summary, the six steps taken for the identification of moisture sources are:

1. Consider all air parcels that are precipitating \((\text{RH} > 80\%)\) at \(t = 0\).
2. Calculate a precipitation estimate for the start location of the backward trajectory according to equation (3).
3. Trace the air parcel backward until a positive $\Delta q^0$ larger than a threshold $\Delta q^0 = 0.2 \text{ g kg}^{-1}$ is detected. This threshold suppresses spurious uptakes due to numerical noise and keeps the analysis computationally feasible (see section 5).

4. Check if the moisture increase is within the BL. This is the case when the estimated altitude a.s.l. of the air parcel smaller than the boundary layer height (BLH, in m) from the ECMWF model. Since the ECMWF model and the trajectory calculations use pressure as the vertical coordinate, a US standard atmosphere is assumed to convert from the air parcel’s pressure $p$ to an altitude:

$$1.5 \cdot \text{BLH} \geq 8000 \cdot \ln(1014/p)/(\text{m}) \ldots (4)$$

The factor 1.5 was adopted to account for the considerable small-scale variability of the marine BLH, and the tendency of parameterizations in NWP models to underestimate the marine BLH [Zeng et al., 2004]. This ensures that moisture which is detrained at the boundary layer top is considered by the methodology as originating from the surface below. In the ECMWF model, the BLH is calculated from a combined Richardson number and parcel rise method [Troen and Mahrt, 1986]. To take into account spatial and temporal variability of this field, the BLH and the air parcel altitude at the mean air parcel location during $t$ and $t - 6 \text{ h}$ are averaged before applying equation (4).

5. If equation (4) applies, a moisture uptake location is identified at the intermediate parcel position for the time interval $[t - 6 \text{ h}, t]$. $\Delta q^0$ is stored, and several other meteorological parameters are extracted at this location which are important for the further analysis. If however the moisture increase occurs clearly above the BL, no specific moisture uptake location can be identified. The location and amount of the above-BL moisture increase are then stored for method evaluation purposes (section 3).

6. The identification of moisture uptake locations is continued backward in time, either until the trajectory falls almost dry because of rain-out ($q \leq 0.05 \text{ g kg}^{-1}$), or the end point of the trajectory is reached. One backward trajectory can therefore be associated with several moisture uptake locations.

### Table 1. Attribution of Moisture Sources to the Target Area Precipitation Along the Trajectory in Figure 1

<table>
<thead>
<tr>
<th>Time, h</th>
<th>$q$, g kg$^{-1}$</th>
<th>$\Delta q^0$, g kg$^{-1}$ 6 h$^{-1}$</th>
<th>$\Delta q$</th>
<th>$e$</th>
<th>$f$</th>
<th>$d_{\text{tot}}$</th>
<th>$e_{\text{tot}}$</th>
<th>$f_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.1</td>
<td>-0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.08</td>
<td>0.11</td>
<td>0.81</td>
</tr>
<tr>
<td>-6</td>
<td>2.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.08</td>
<td>0.11</td>
<td>0.81</td>
</tr>
<tr>
<td>-12</td>
<td>2.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.08</td>
<td>0.11</td>
<td>0.81</td>
</tr>
<tr>
<td>-18</td>
<td>2.6</td>
<td>0.3</td>
<td>0.3</td>
<td>0.11</td>
<td>-</td>
<td>0.08</td>
<td>0.11</td>
<td>0.81</td>
</tr>
<tr>
<td>-24</td>
<td>2.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.08</td>
<td>0.00</td>
<td>0.92</td>
</tr>
<tr>
<td>-30</td>
<td>2.3</td>
<td>-0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.08</td>
<td>0.00</td>
<td>0.92</td>
</tr>
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<td>2.5</td>
<td>1.5</td>
<td>1.5, 1.380$^b$</td>
<td>-</td>
<td>0.6, 0.53$^c$</td>
<td>0.08</td>
<td>0.00</td>
<td>0.92</td>
</tr>
<tr>
<td>-42</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.20</td>
<td>0.00</td>
<td>0.80</td>
</tr>
<tr>
<td>-48</td>
<td>1.0</td>
<td>0.8</td>
<td>0.8, 0.736$^b$</td>
<td>-</td>
<td>0.8, 0.32$^d$, 0.28$^e$</td>
<td>0.20</td>
<td>0.00</td>
<td>0.80</td>
</tr>
<tr>
<td>-54</td>
<td>0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

$^a$ $q$, specific humidity of the air parcel; $\Delta q^0$, unweighted change in specific humidity during 6 h; $\Delta q$, change in specific humidity weighted by the rain-out during transport; $e$, above-boundary layer uptake fraction; $f$, attributed fraction; $d_{\text{tot}}$, total unknown fraction; $e_{\text{tot}}$, total above-boundary layer uptake fraction; $f_{\text{tot}}$, total attributed fraction.

$^b$Discounted after precipitation at $t = -30$.
$^c$Updated after uptake above the boundary layer at $t = -18$.
$^d$Updated after uptake at $t = -6$.

#### 2.2. Moisture Source Attribution

[20] Over the course of several days, an air parcel may undergo multiple cycles of evaporation and precipitation. Because of precipitation en route, earlier evaporative sources of moisture will contribute less and less to the precipitation at the arrival site. Hence the precipitation at the target area is a weighted sum of the previous uptakes. In this section, we introduce a source attribution method to calculate the contribution (and therefrom the weight) of each evaporation location along a trajectory to the precipitation at the target location.

[21] An example of this procedure is provided in Table 1 and Figure 1. With the approach described in section 2.1, two moisture sources were identified within the BL (−36 h and −48 h), and one above the BL (−18 h) for this example trajectory. The moisture source attribution algorithm proceeds then along the following three steps:

1. Initialize all moisture increases at the uptake locations with their unweighted contribution $\Delta q = \Delta q^0$ where $\Delta q^0$ is calculated from equation (2) (0.8 g kg$^{-1}$ at −48 h and 1.5 g kg$^{-1}$ at −36 h in the example, see Table 1).

2. Evaluate, proceeding forward in time from the end to start point of the backward trajectory: At an uptake location $n$ inside the BL, calculate the fractional contribution $f_n$ of the uptake amount $\Delta q_n$ to the moisture in the air parcel $q_n$ as

$$f_n = \frac{\Delta q_n}{q_n} \ldots (5)$$

Since a new uptake reduces the importance of previous uptakes, the fractional contributions of all moisture uptakes at previous times $m$ with respect to the new specific humidity are recalculated:

$$f_m = \frac{\Delta q_m}{q_n}, \quad m > n \ldots (6)$$

In the example, the second uptake at −36 h reduces the contribution of the uptake at −48 h to the air parcel’s specific humidity from 80% to 32%. The total attributed fraction $f_{\text{tot}, n} = \sum_{m\geq n} f_m$ at −36 h amounts then to 92%
equation (7) are then discounted according to moisture sources at previous times to the Greenland regression, and boxes denote group means. Dashed line is a linear Hurrell methodology, plotted against the monthly mean NAO

In the example, at a precipitation location, all previous contributions to the moisture in the air parcel in proportion to the precipitation amount \( \Delta q^m_n \) are discounted:

\[
\Delta q^m_n = \Delta q^m_n + \Delta q^0_n \cdot f_m \text{ for all } m > n.
\]

In the example, at \(-30 \text{ h}, -0.2 \text{ g kg}^{-1}\) of moisture precipitate from the air parcel. The contributions \( \Delta q \) of the moisture sources at previous times to the Greenland precipitation \( t = 0 \) are then discounted according to equation (7) \((-0.064 \text{ g kg}^{-1} \) for \(-48 \text{ h} \) and \(-0.12 \text{ g kg}^{-1} \) for \(-36 \text{ h}, \) see Table 1\). The fractions \( f_m \) remain unchanged. At an uptake location above the BL, the same steps as for an uptake inside the BL are performed. The only difference is that the moisture increase stems from unidentified sources above the BL. This could for instance be due to evaporating precipitation, or vertical moisture transport due to convection. In the example, at \(-18 \text{ h}, 0.3 \text{ g kg}^{-1}\) of moisture enter the air parcel at a location above the BL (Figure 1, label 2). The above-BL contribution fraction is labeled \( e \) and amounts to 0.11, and the previous BL uptakes at \(-36 \text{ h} \) and \(-48 \text{ h} \) are discounted according to equation (6) to \( f = 0.53 \) and \( f = 0.28 \), respectively (Table 1).

At the start point, \( f_{tot} \), the sum of the latest fractional contributions of all uptake points in the BL, gives the fraction of the total precipitation to which sources can be attributed. In the example, \( f_{tot} \) amounts to 81%, 11% originate from increases above the BL (Table 1, \( e_{tot} \)), the remaining 8% of water vapor have no moisture source that can be identified with our method (Table 1, \( d_{tot} \)). This moisture was either present in the air parcel before the earliest uptake identified \( t \leq 54 \text{ h} \) in the example), or may be due to small uptakes with \( \Delta q^0 < \Delta q^m \). The fractions \( d_{tot}, e_{tot}, \) and \( f_{tot} \) can hence be used for evaluating the representativeness of the moisture source attribution.

In summary, the combined methods of moisture source identification (section 2.1) and attribution (section 2.2) provide information on (1) to what extent moisture sources can be demarcated and (2) what relevance each of these source regions has for precipitation at the start point. This is also an important prerequisite to estimate the influence of other parameters on the isotopic composition of the transported moisture (see Part 2). Some uncertainties of the method are discussed in section 5.

2.3. Setup of the Calculations

The calculations were set up in a way that allowed for identifying the variability of moisture transport to Greenland corresponding to different NAO phases. The two main requirements of such a setup are that (1) NAO variability clearly be present in the selected calculation period and (2) the spatial resolution of the calculations be sufficiently high to identify regional differences in moisture transport to the Greenland plateau.

As the NAO atmospheric variability pattern mainly occurs in Northern Hemisphere winter, we selected 30 winter months from the time period 1958–2002. Ten months each were chosen with strongly positive NAO indices [Hurrell, 1995], \((3.89 \pm 0.64, \text{NAO}+)\), strongly negative \((-5.00 \pm 0.88, \text{NAO}–)\), and neutral \((0.01 \pm 0.31, \text{NAO}0)\) indices, respectively (Figure 2). The selected months were not the most positive and negative ones, but subsets at about 2 standard deviations from the mean, and about equally distributed over the ERA-40 period.

An increasing tendency of the monthly mean precipitation over the Greenland ice sheet (estimated from the Lagrangian methodology at the points in Figure 3, see below) with decreasing NAO index is obvious from Figure 2, a relation that has also been noted by Bromwich et al. [1999]. The selection of months shows a consistent picture, and no outliers in terms of precipitation are obvious.

As the NAO atmospheric variability pattern mainly occurs in Northern Hemisphere winter, we selected 30 winter months from the time period 1958–2002. Ten months each were chosen with strongly positive NAO indices [Hurrell, 1995], \((3.89 \pm 0.64, \text{NAO}+)\), strongly negative \((-5.00 \pm 0.88, \text{NAO}–)\), and neutral \((0.01 \pm 0.31, \text{NAO}0)\) indices, respectively (Figure 2). The selected months were not the most positive and negative ones, but subsets at about 2 standard deviations from the mean, and about equally distributed over the ERA-40 period.

In order to achieve a spatially detailed picture of the moisture transport to Greenland, the atmosphere above the ice sheet was discretized horizontally \((60 \times 60 \text{ km})\) and vertically \((\Delta p_h = 30 \text{ hPa})\) from the surface to 480 hPa into air parcels of equal mass. In comparison to a high-resolution digital elevation model, the orographic representation of Greenland in the ERA-40 model is generally within \(\pm100 \text{ m}\) over most of the plateau region. Near the flanks, deviations can reach several hundred meters [Hanna et al., 2005]. For our study however exact agreement is less relevant than for instance for mass balance models that require accurate surface temperatures. Nevertheless, starting points for the backward calculation of trajectories were only selected over the Greenland plateau, which we defined as the region above 2000 m altitude in a \(10^6 \times 10^6 \text{ resolution orography data set}\) (Figure 3). 88% of the starting points exceeded 2000 m altitude in the ERA-40 orography as well. The maximal number of starting points above the 284 surface locations was 5964 per 6 h time interval.
For each of the 30 months, every 6 h, 20-d kinematic backward trajectories were calculated from each selected starting point. Starting points were selected if the relative humidity (RH) at the location in (latitude, longitude, pressure)-space was $\geq 80\%$. On average $2.66 \pm 0.64$ air parcels per atmospheric column contributed to precipitation during a 6 h precipitation event. Trajectories were calculated with the LAGRANTO model [Wernli and Davies, 1997], using ECMWF’s three-dimensional 6 hourly reanalysis (ERA-40) wind fields ($u$, $v$, $w$) interpolated onto a regular $1^\circ \times 1^\circ$ grid. Along each trajectory, latitude, longitude, pressure, potential temperature, and specific humidity were interpolated and stored at a 6 h interval. Infrequently, calculations were halted when an air parcel left the calculation domain (i.e., the Northern Hemisphere). When air parcels intersected with the orography, they were displaced a few hPa above the surface, so that calculations could be resumed.

With this setup, $\sim 7000 – 42,000$ trajectories were calculated for every month, less for dry than for wet months in Greenland. More than 95% of the trajectories precipitating during arrival were associated with at least one moisture uptake location [Sodemann, 2006].

3. Performance of the Method
3.1. Precipitation Estimate

First, we check the quality of the column precipitation over Greenland, derived from the Lagrangian methodology (equation (3)). This precipitation estimate is compared to the 6-hourly prognostic precipitation from the ERA-40 data set. To this end, ERA-40 precipitation was calculated as differences of the accumulated 12–6 h or 18–12 h forecasts that were initiated every 12 h. Because of model spin-up effects, these differences are believed to be superior to the 6 h forecast steps. In terms of the geographical pattern, which we consider the most relevant aspect for the present study, the correspondence between the two precipitation estimates is generally high (Figure 4). For both estimates, precipitation is limited to the eastern part of the plateau during NAO+ months, and shifts to the northwest with an overall increase of precipitation magnitude during NAO− months. The arithmetic mean for all NAO= months (NAO= phase mean) exhibits a pattern similar to NAO−, but of smaller amplitude (not shown).

When considering individual grid points, the Lagrangian precipitation estimate is systematically higher than the one from ERA-40 forecasts. This is particularly the case for areas where the phase mean precipitation exceeds 25 mm. In the NAO− phase, this positive bias reaches values of 20–40% in the regions of high precipitation at the southeastern slope of Greenland [Sodemann, 2006]. In the drier regions of the ice sheet, the precipitation shows no systematic bias, but considerable scatter of $\sim 10–20\%$ (further discussion in section 5). Despite these limitations, the correspondence to the ERA-40 forecasts is close enough for considering the Lagrangian precipitation estimate a valid approximation, in particular over the drier interior of Greenland.

A comparison of the model predicted precipitation with observational records is less straightforward, since reliable precipitation measurements are difficult to obtain for Greenland. Bromwich et al. [1999] retrieved precipitation over Greenland by the method of Chen et al. [1997] from ECMWF analysis data, and found precipitation patterns for NAO+ and NAO− means that closely resemble Figure 4a. Validating the variation of snow accumulation in Greenland from ECMWF forecasts against ice core data, Hanna et al. [2001] found, despite a 20–30% low bias, reasonable first-order agreement. Studying the NAO variability of Greenland precipitation, Appenzeller et al. [1998] found good correspondence between ERA-15 precipitation and ice accumulation data, with higher accumulation along the east coast (west coast) during the NAO+ (NAO−) phase. Recently, Hanna et al. [2006] provided a similar comparison of modeled accumulation over the Greenland ice sheet using ERA-40 data, and a range of ice core data. They note a 10–30% dry bias in the northern to central parts of the plateau, and a wet bias of locally up to 50% in SE Greenland. This agrees also with the findings from a thorough evaluation of the ERA-40 hydrological cycle [Hagemann et al., 2005].

3.2. Moisture Source Attribution

The representativeness of the moisture source identification method can be evaluated from the three different uptake fractions defined in section 2.2. From our methodology, $\sim 66\%$ of the precipitation in the target area can be attributed to specific evaporative moisture sources. About 20% are incorporated into air parcels above the BL, while the remaining $\sim 14\%$ originate from moisture sources that cannot be identified with our approach.
As the three fractions are very similar for all three NAO phases, the mean histograms for all months are shown in Figure 5. Considering every single trajectory, the fraction of precipitation which can be attributed to specific source regions inside the BL (\(f_{\text{tot}}\)), weighted by the respective precipitation amount of each corresponding trajectory, has a median of \(\sim 70\%\) attribution. About 10\% of the precipitation events reach more than 90\% attribution, while \(\sim 5\%\) have \(\leq 10\%\) attribution.

The fraction of moisture increase that was identified above the BL, \(e_{\text{tot}}\), (Figure 5, solid line) shows that about 55\% of the trajectories are associated with above-BL uptakes of \(\geq 10\%\). More than 80\% of the precipitating air parcels have less than 30\% of above-BL moisture in their final precipitation sample. This fraction is to some extent sensitive to the BL height threshold applied in equation (4). The fraction from unknown moisture sources, \(d_{\text{tot}}\) (Figure 5, dotted line), only rarely exceeds 20\% for individual trajectories. The moisture increase threshold \(\Delta q^0_c\) largely determines the fraction of this moisture from unknown sources. Thus, despite some (unavoidable) noise, the method provides sufficient information for further analysis.

4. Diagnosed Moisture Sources and Transport

First, the identified moisture source patterns for winter precipitation on the Greenland plateau and their variability with the NAO are presented. Comparisons are then made to previous estimates of the moisture source regions for Greenland from GCM simulations. We proceed with an examination of the moisture source variability for different regions of the Greenland ice sheet. Finally, atmospheric transport patterns associated with the identified

![Figure 4](image_url)  
**Figure 4.** NAO phase mean monthly accumulated precipitation over Greenland, gridded according to the starting points of the trajectory calculations. (a) ERA-40 precipitation and (b) Lagrangian precipitation estimate. Points with \(\leq 5\) arriving trajectories are left blank in both panels.

![Figure 5](image_url)  
**Figure 5.** Method validation histogram for all trajectories that transport moisture to the Greenland plateau. Shaded bars indicate attributed boundary layer fraction \(f_{\text{tot}}\), solid line indicates above-boundary layer uptake fraction \(e_{\text{tot}}\), and dotted line indicates unknown sources fraction \(d_{\text{tot}}\).
Moisture source regions are exemplified by means of two illustrative examples, and an attempt is made to identify typical transport patterns that lead to the evaporation of water vapor into air masses on their way to Greenland during winter.

4.1. Moisture Source NAO Variability

Figure 6 shows the mean moisture source distributions for Greenland precipitation (in mm of precipitation contribution) which were derived with the Lagrangian methodology for the three NAO phases. Individual moisture uptake locations where weighted by their contribution to the precipitation in Greenland, gridded onto a 1° × 1° latitude-longitude grid, and then corrected for convergence of the meridians with latitude. The source regions look strikingly different for the three NAO phases. While during the NAO+ phase uptake locations are confined to areas of the Atlantic north of 40°N (Figure 6a), a southward extension beyond 30°N can be observed for NAO= (Figure 6b) and in particular NAO− months (Figure 6c). In addition, a large patch of moisture sources with a maximum to the west of the British Isles appears during NAO− months, which is not present for the NAO+ phase. Moisture uptakes during NAO= months (Figure 6b) exhibit a transitional pattern. For all NAO phases, almost all moisture uptakes are located over the North Atlantic.

Recall that these moisture sources are a subset of the total evaporation at the sea surface that occurs during these
months, and only the evaporative contribution to the precipitation over the Greenland plateau is displayed. The pattern can hence be interpreted as a Lagrangian backward projection of the NAO phase mean winter precipitation in Greenland onto its respective source areas. It is therefore no surprise that the mean surface evaporation in the North Atlantic for the same months exhibits a substantially different pattern (not shown).

Maps of the phase mean SLP give a first indication of the circulation features that are associated with the identified moisture sources (Figure 7). The mean SLP for the NAO positive winters shows a clear pressure minimum centered over Iceland and a broad high-pressure area centered over the Azores (Figure 7a). The pronounced mean Icelandic low, which is related to cyclones traveling to the northeast along a storm track confined to the north, is strongly reminiscent of the mean SLP pattern during the NAO+ phase derived for longer time intervals [e.g., Hurrell et al., 2003]. The mean SLP map for the NAO negative months shows a reversed pressure gradient between Iceland and the Azores (Figure 7b), again similar to the findings from more climatological studies. The respective moisture source areas in Figures 6a and 6c are consistent with the mean circulation during the NAO phases. This is however only the case if the months are stratified according to the corresponding NAO indices. In addition, from the inspection of the SLP maps alone it is not possible to derive a quantitative estimate of the moisture source areas, as is provided from this study, because SLP implies circulation patterns, but not evaporation into (or precipitation out of) the moving air.

Another view of the NAO influence on moisture source areas is provided by subdividing the Northern Hemisphere source areas into source sectors, as is indicated in Figure 8a. The ocean sources are divided into four North Atlantic sectors (NE, NW, SE, SW), an Arctic sector (A), which mainly contains the GIN (Greenland, Icelandic, Norwegian) seas, the Mediterranean (M), and the Pacific (P). Furthermore, moisture uptakes over land are distinguished. The relative contribution of the various moisture sources changes strongly for the three NAO phases (Figure 8b). The southeastward shift from NAO+ to
NAO—months is evident from the decrease of GIN seas uptakes from 44.9% to 14.7%, along with an increase of the NW and NE Atlantic contribution (24.7% → 30.0% and 21.9% → 25.8%) and the SW and SE Atlantic contributions (2.9% → 7.3% and 1.0% → 9.6%). Contributions from the Pacific, the Mediterranean and other sources are low. Also, all land sources jointly contribute only ~3–4% to the winter precipitation in Greenland. This underlines the solitary role played by the North Atlantic ocean for the moisture supply to the Greenland ice sheet during winter.

The Greenland moisture sources presented here are the first which are diagnosed from reanalysis data, and show some notable differences to previous studies. In a conceptual isotope model study on annual mean moisture transport to Greenland, Johnsen et al. [1989] found best agreement with ice core data from Greenland when a fixed subtropical moisture source was assumed, located between 30–40°N in the western North Atlantic. White et al. [1997] assumed an annual mean moisture origin at a latitude band of 20–30°N, while Barlow et al. [1997] argued for more northerly moisture sources. Even though our results only cover the winter season, we diagnose a latitudinal and longitudinal variability of Greenland’s moisture sources with the NAO that was not captured by these previous studies (see also Part 2).

Greenland’s moisture sources have also been derived from GCM simulations with water vapor tracers. During the winter period of a present-day climate simulation using the GISS GCM, Charles et al. [1994] found 23% contribution from the GIN seas and the Norwegian-Greenland Sea to Greenland precipitation. This corresponds reasonably well with the contribution from the Arctic sector of this study (average over all NAO phases 33%; no distinction was made between NAO phases by Charles et al. [1994]). Their North Atlantic sector (30°–50°N) contributed 31%, which is only about half the total moisture derived from the NW and NE sectors here (53% for all NAO phases). This may be partly due to the more southerly location of their North Atlantic sector. Charles et al.’s [1994] tropical Atlantic source (30°N–30°S) contributed 11%, again corresponding reasonably to our combined SW and SE sectors (12% for all NAO phases). In their study, 16% of moisture originated from the Pacific, compared to 0% here. In a similar combined isotope/tagging study with the ECHAM model (with T30, i.e., ~3.75° × 3.75° resolution), Werner et al. [2001] generally confirmed the findings of Charles et al. [1994]. In these simulations, average winter precipitation for Greenland consisted of 25% Arctic, 40% North Atlantic, 15% tropical Atlantic, 18% Pacific, and 6% continental moisture. Note however that both GCM simulations did not investigate the strong variability of the moisture sources with the NAO. The second difference of the GCM results to this study concerns the contribution of Pacific moisture. The relatively large influence of the Pacific moisture source in the GCM simulations could be due to their coarse spatial resolution. This leads to a smoothing and lowering of orographic barriers, such as the Rocky Mountains and could enable unrealistically large long-range moisture transport. Nevertheless, correspondence between the Lagrangian diagnostic and the fundamentally different GCM approach is reasonable.

4.2. Regional Moisture Sources

The high spatial discretization of the air mass above Greenland allows for a detailed view on the moisture sources for different regions of the Greenland ice sheet. Figure 9 displays the mean source longitude and latitude of the moisture, and its transport time, weighted by the fraction f, and projected forward onto the respective arrival location over Greenland. Figure 9 shows that the strong source longitude gradient of 50°W–10°E apparent during the NAO+ phase shifts to a smoother gradient of 45–20°W during the NAO− phase (Figure 9a). Note that the moisture origin for individual events can deviate strongly from the mean picture shown in Figure 9. The mean longitude changes of the moisture sources with the NAO are most obvious in the northeast of the Greenland ice sheet (Figure 9a, right). In contrast, the southern part of the ice sheet has similar mean source longitudes for the two NAO phases.

[46] Latitudinal shifts of the uptake regions also vary spatially over the Greenland ice sheet (Figure 9b). In both NAO phases, parts of the ice sheet closer to the coast are fed by more northerly source regions, while the (higher) interior of the ice sheet receives its moisture from locations which are on average ~8° latitude further south. This highlights the orographic influence on the moisture supply for different regions of the ice sheet. The largest source region latitude shifts occur in the northeast and southeast. Here, sources shift up to ~16° latitude to the north for NAO+ months compared to the NAO− (Figure 9b, right).

[47] The transport time of moisture is calculated as the time between moisture uptake in the BL and the arrival of the corresponding precipitating air parcel over Greenland. The spatial pattern of the mean transport time gives an indication of the transport processes of moisture (Figure 9c). During the NAO+ phase, moisture transport to Greenland takes on average 3–4 d. Areas close to the east coast of Greenland have somewhat shorter transport times. This agrees with the moisture sources being on average located at higher latitudes for these regions. During the NAO− phase, a N-S oriented transport time gradient is apparent. While the southeastern part of Greenland is also associated with a transport time of 3–4 d, transport to central Greenland takes on average 4–5 d. A region in the northeast is associated with significantly longer transport times (~7–9 d). This suggests a tendency toward more long-range instead of local moisture transport during NAO− months.

[48] In order to obtain a regional view of the identified moisture source regions, the ice sheet was subdivided into 5 arrival sectors (Figure 3), following Bromwich et al. [1999]. The moisture sources of the different regions are shown for the NAO+ and NAO− phases in Figure 10. Note that since each panel is scaled to the maximum uptake value of the respective region and NAO phase (Nmax), no direct quantitative comparison is possible from Figure 10. It demonstrates, however, the spatial variability of the moisture sources for the five subdomains, and their variation with the NAO. A very pronounced shift of moisture sources with the NAO from the northeast to the south of Greenland is apparent in the northern sector (Figure 10a). In contrast, the central-west sector shows less spatial variability of the moisture source, but an almost complete shutoff of moisture transport during the NAO+ phase (Figure 10b, note values of Nmax). The central and central-east sectors (Figures 10c
and 10d) both show a strong southward shift of the moisture sources in the NAO− phase, with the central sector having somewhat more southerly contributions. While the central sector in addition experiences increased moisture transport during the NAO− phase, the reverse applies for the central-east sector. The spatial shifts for the southern sector appear similar to the central and central-east sectors, but absolute changes are of smaller magnitude (Figure 10e). In the sectors with small Nmax (<0.1, i.e., regions N, C-W), single events could be dominating the observed pattern.

The regional view of the moisture source regions of the Greenland plateau can be highly insightful for other studies as well. Rogers et al. [1998] for example stressed the difference between east and west Greenland in terms of the stable isotope composition and its correlation with SLP patterns. Hence the findings presented here underline the particular relevance of moisture transport diagnostics for interpreting stable isotope variability in Greenland [Masson-Delmotte et al., 2005], and for reconstructing NAO signals from snow accumulation records [Vinther et al., 2003]. They may also prove useful for the finding new potential drilling sites for NAO reconstructions from ice core proxies. This is further explored in Part 2.

4.3. Moisture Transport Processes

The results presented so far suggest that moisture transport processes to Greenland undergo significant changes with the NAO. To illustrate the flow patterns associated with some of the identified source regions, two characteristic months are examined in more detail. February 1997 has been chosen to represent the NAO+ phase, February 1965 for the NAO− phase. Monthly mean SLP maps for the two months approximately correspond to the NAO phase mean SLP patterns shown in Figure 7. In addition, during February 1965 a blocking anticyclone resided over Ireland, a constellation that is known to be more frequent during the NAO− phase [Scherrer et al., 2006].

Figure 9. Averaged (a) longitude and (b) latitude of moisture source locations and (c) transport time of moisture that contributes to precipitation at a given location on the Greenland plateau. Shown are Lagrangian forward projections of the moisture uptake conditions, projected onto the start grid over Greenland. (left) NAO+ phase mean, (middle) NAO− phase mean, and (right) the difference between the NAO− and NAO+ phase. Individual values from the uptake locations are weighted by the respective contribution to the phase mean precipitation at each arrival location.
In February 1997, two main regions of moisture uptake for Greenland precipitation are apparent, one along the Norwegian coast, and the other off southeastern Greenland (Figure 11a), closely resembling the mean NAO+ pattern (Figure 6a). Two coherent trajectory clusters were extracted from a Ward’s clustering based on the normalized 6-hourly trajectory coordinates of the air parcels arriving at 0000 UTC 19 February 1997 [Sodemann, 2006]. Ward’s algorithm minimizes within-cluster variance using a Euclidean distance measure [Moody and Galloway, 1988]. For clarity, only a 5 d section of the 20-d backward trajectories is shown (Figure 11c). A cyclonically curved cluster of trajectories represents air parcels that originated over eastern Canada, descended to the sea surface, increased in specific humidity at about −96 h south of Greenland, and precipitated while rapidly ascending from 850–900 hPa onto the Greenland plateau (650–500 hPa). The second sample cluster represents air parcels that moved from the Arctic.
at various midtropospheric altitudes in southeasterly directions (Figure 11c), until at \(-48\) h they sharply changed direction, descended westward to the coast of Norway, increased their specific humidity over the Norwegian Sea, and delivered it as precipitation to eastern Greenland the following day at \(750–600\) hPa. During the arrival of the two clusters, a midlatitude cyclone was present east of Greenland (not shown).

Of the months considered in this study, February 1965 has the second-largest monthly mean precipitation on the plateau (Figure 2). In that month, a particularly strong moisture contribution from the east Atlantic is apparent (Figure 11b). Using the same clustering methodology as for the previous case, a coherent trajectory cluster arriving at 1200 UTC 15 February 1965 was extracted (Figure 11d). The trajectory cluster originated in the middle troposphere (400–600 hPa) over the GIN sea and slowly descended anticyclonically toward Spain. Five days before arrival over Greenland, the specific humidity of the air parcels increased by \(4\) g kg\(^{-1}\) over the eastern North Atlantic. This corresponds to the southeastern maximum in moisture uptake locations in Figure 11b. The air parcels then moved in northwesterly direction at low altitudes and ascended from southerly directions onto the Greenland plateau within \(\sim 24\) h.

Studying a 2-year period, Chen et al. [1997] found cyclonic systems to provide most precipitation to Greenland, and highlighted differences between cyclone tracks to the east and west of the ice shield. Hanna et al. [2006] pointed to the need for better understanding of the synoptic influences on the Greenland ice sheet. In this context, the selected transport patterns of the two example months studied here provide insight into the significant regional variability of moisture uptake and transport to the Greenland plateau which is apparent in Figure 9, and stress the important role of synoptic systems for transporting moisture. During the NAO\(^+\) phase, southeasterly arrivals along the southeast coast of Greenland could correspond to transport similar to the Canadian cluster, while northeasterly arrivals would correspond to transport more alike to the Norwegian cluster (Figure 11c). For the NAO\(^-\) phase, the increasing transport time toward northern parts of the Greenland plateau is in line with the S-N oriented long-range moisture transport as suggested by the trajectory cluster in February 1965 (Figure 11d).

### 4.4. Preevaporation Air Transport

A further interesting aspect of this Lagrangian analysis is to investigate the flow conditions leading to moisture uptakes near the surface. Evaporation of surface water into an air parcel is driven by the saturation pressure deficit and the wind velocity near the surface. The preevaporation transport history of air masses is defined here as the motion of an air parcel before it first experiences significant moistening. Note that this refers only to the air parcels that eventually precipitate over Greenland, that this moisture can
be lost later because of precipitation during transport, and that only a 20-d transport history is examined. As we are concerned here with the processes leading to evaporation, in this section only the unweighted moisture increases during a 6 h time interval are considered.

The first (earliest) location of moisture uptake along the 20-d back trajectories, and the locations 1, 3, and 5 d earlier were identified from the Lagrangian diagnostic. (In the example in Figure 1, this would correspond to the locations at −48 h, −72 h, −120 h, and −168 h). The NAO dependency of this preevaporation transport history is depicted in Figure 12. During the NAO+ phase, the areas of first uptake are distributed along the North American east coast, and in the northern Norwegian Sea (Figure 12a, blue shading). With decreasing NAO index, areas of first moisture uptake also gradually appear along the European west coast, and northwestern Africa (Figures 12b and 12c). One day before the first uptake, the air parcels are for the most part located over the continents (Figure 12, solid contour). This impression further increases for the locations at 3 and 5 d before the first uptake (Figure 12, dashed and dash-dotted contours).

It is interesting to note that the continental origin is a common feature of the preevaporation transport, both near the American east coast and the European west coast. The outflow areas of continental air identified here are only consistent with the climatological mean flow if data are stratified according to the NAO index. Along the east coast of Greenland, a consistent feature in the locations 1 d before moisture uptake indicates a possible importance of cold and dry katabatic outflow for evaporation at the sea-ice boundary in the GIN (Greenland, Icelandic, Norwegian) seas. Finally, it is noteworthy that during the NAO− phase preevaporation locations are detected over northwestern Africa, which could indicate that subsiding warm and dry desert air contributes to the eastern North Atlantic moisture source maximum (see Figure 6c).

Grotjahn and Wang [1989] studied the transformation of air masses that were incorporated into frontal cyclones developing in the northwestern Pacific during winter. They describe a two-stage mechanism that involves moistening of air masses from continental cold-air outbreaks over the Pacific ocean due to evaporation, and subsequent incorporation of the transformed air into the warm sector of a cyclone following upstream. From examining movies of the diagnosed moisture transport to Greenland for February 1997 and February 1965 (not shown), it can be conjectured that similar processes are taking place here. However, it currently remains an open question to what degree the increased winter precipitation in Greenland during the NAO− phase is due to generally warmer air temperatures, longer over-ocean fetch of the advected air masses, or more frequent advection of cyclones onto the ice sheet.

5. Evaluation of the Lagrangian Diagnostic

The Lagrangian moisture source diagnostic revealed new insights into the processes of moisture transport to Greenland and its interannual variability. However, there is a need to reconsider some of the assumptions, limitations and caveats of this new method, and to compare it with previous Lagrangian moisture source diagnostics.

5.1. Precipitation Estimate

The Lagrangian precipitation estimate agrees qualitatively with the ERA-40 precipitation forecast. There is good quantitative agreement in the drier regions of the ice sheet, but a ~20–40% positive bias in the regions of high precipitation. One major simplification is that microphysical processes are neglected in our precipitation estimate: decreased specific humidity in an air parcel is directly

![Figure 12. Air parcel positions before the first moisture uptake during (a) NAO+, (b) NAO−, and (c) NAO− months for air parcels precipitating onto Greenland. Shading indicates first moisture uptake location, and contours are 1, 3, and 5 d before first uptake. Contours are drawn at 20% of the maximum value of the respective frequency distribution.](image-url)
assumed to produce surface precipitation. This is quite different to the precipitation parameterization in the ECMWF model, where condensing moisture takes the pathway via liquid and/or ice clouds to precipitation. Other studies using the same or more detailed Lagrangian precipitation estimates also found a general positive bias [Wernli, 1997; Eckhardt et al., 2004; James et al., 2004; Stohl and James, 2004]. Part of the positive bias is also due to the assumption that the $\Delta q^0$ during the last 6 h before the start point is completely precipitated over the arrival location, instead of distributing it over the area crossed by the air parcel during a 6 h period. With southerly (easterly) winds, this may lead to a northward (westward) displacement of the estimated precipitation.

5.2. Parameter Choice

[60] The minimal positive moisture increase required to diagnose a moisture uptake event ($\Delta q^0$) is an arbitrary threshold that we have included in our method. The presently used threshold value has been chosen as a trade-off between the identification of the dominant moisture sources and the exclusion of spurious moisture uptakes. Choosing a smaller $\Delta q^0$ only led to a slight increase of $f_{tot}$ compared to the current values, while larger $\Delta q^0$ up to 1.0 g kg$^{-1}$ reduced the diagnosed moisture sources roughly uniformly (not shown). Still, some subjectivity remains in choosing this parameter, and other study areas or seasons may require a different parameter choice.

5.3. Transport Errors

[61] It is known that for trajectory calculations beyond 10 d, the coherency of an air mass decreases significantly, and wind field errors can lead to large deviations from the actual movement of air parcels [Stohl and Seibert, 1998]. For a backward calculation time of 20 d, as was applied here, the influence of calculation errors can become unacceptably large. However, virtually all relevant moisture uptakes and transport processes take place on shorter timescales ($\leq 7$ d), and hence the increasing uncertainty for trajectory lengths beyond 10 d is not expected to affect the present results. A posteriori it appears that such long calculation times were in fact not required to apply the moisture source diagnostic for Greenland.

5.4. Lagrangian Methodology

[62] Comparing this method with previous Lagrangian moisture source diagnostics, several similarities and differences can be noted. The moisture diagnostic of Dirmeyer and Brubaker [1999] has two characteristics that prompt further discussion. First, they use quasi-isentropic backward trajectories, which can have severe limitations when diabatic processes are important. Second, in their method surface fluxes contribute to the moisture increase along trajectories, even when these are clearly above the boundary layer. The method proposed here instead relies on three-dimensional kinematic trajectories, and requires moisture increases to be inside the BL. The Lagrangian moisture source identification of James et al. [2004] and Stohl and James [2004, 2005], similar to the method developed here, shows a qualitatively good but quantitatively overestimated precipitation estimate in comparison with ERA-40 forecasts. Again, the major difference between our approach and that of James et al. [2004] and Stohl and James [2004, 2005] is the introduction of a BL criterion for uptakes and a quantitative attribution of moisture sources. These two innovations allow for a clearer determination of moisture sources compared to previous approaches. In particular, the source attribution limits the amount of the identified moisture uptake to that of the precipitation estimate, and avoids the up to 7-fold overestimations found by Stohl and James [2004].

5.5. Limitations

[63] A number of moisture transport processes had to be neglected in the current Lagrangian framework. This includes moisture changes due to convection, turbulence, numerical diffusion, and rainwater evaporation, which all could contribute to unattributable or unidentified moisture increments. For wintertime moisture transport to Greenland, convective activity should be generally low, even though it may play a role over more southerly ocean areas, and in strong fronts and synoptic systems. Convection or evaporation from land surfaces could, however, introduce additional uncertainties when the method is applied to summer conditions. Lagrangian particle dispersion models include parameterizations for turbulence and diffusion. Incorporating our methodology into such a model could greatly increase its applicability, e.g., to situations where convection is important.

[64] Analysis errors, which are due to uncertainties in observations or the data assimilation technique, can lead to spurious fluctuations of specific humidity in an air parcel [Stohl et al., 2004]. Large analysis errors leading to spurious fluctuations larger than the threshold $\Delta q^0$ could bias the diagnosed moisture sources toward later uptakes.

[65] While the net effect of moisture changes in an air parcel actually reflects P-E (equation (1)), only one of the processes at a time is assumed to cause the identified $\Delta q^0$. In agreement with Stohl and James [2004], the results found here also suggest validity of this assumption. However, a rigorous check would require a comparison with trajectory calculations with a higher output frequency (e.g., 1 h) and on a finer spatial scale, e.g., from a regional model simulation. Even more powerful could be a direct comparison with an Eulerian method with water vapor tracers, since such a method would also take into account the moisture transport processes omitted here. These aspects will be explored in a forthcoming study.

6. Summary and Conclusions

[66] In this study, a new Lagrangian method is presented which is able to diagnose and quantify the sources and transport paths of water vapor from three-dimensional kinematic back trajectories. The method considers the full transport history of an air parcel. Evaporation and subsequent precipitation en route are taken into account. The contribution of each uptake location to the diagnosed precipitation at the arrival location was thereby determined. For the first time, a diagnostic picture of the effective moisture source regions for Greenland winter precipitation could be obtained. The moisture source diagnostic allows direct attribution of $\sim 66\%$ of the diagnosed precipitation to moisture sources in the BL. Including the above-BL uptake
of moisture, the fraction of attributable precipitation increases to ~86%. The remaining ~14% are either incorporated into air parcels before the 20 d analysis period, or increments are too small to be distinguished from numerical noise.

[67] The Lagrangian diagnostic can be readily applied to other hydrological settings. In addition to the moisture sources, the transport conditions of the water vapor (e.g., altitudes or air temperatures) can be identified, and give insight into the evaporation conditions and the synoptic influences during large-scale transport for particular precipitation events. As the method is applicable to reanalysis data, comparisons to actual synoptic developments and observational data are possible. This is particularly important for examining interannual variability of moisture transport, for instance the influence of the NAO. Further evaluation of the method will include an analysis of the impacts of spatial and temporal resolution, and of different seasons or latitudes.

[68] The Lagrangian analysis of precipitation origin for the Greenland plateau during selected winter months identified the North Atlantic and the GIN seas as the by far dominant moisture sources. Uptakes in further remote source areas, such as the Pacific and the Gulf of Mexico, are strongly discounted by considering the consecutive precipitation of moisture during transport. The reduced importance of remote sources agrees with expectations from the timescale of tropospheric water transport, and is a notable difference to GCM studies of moisture transport to Greenland. Source regions of moisture were found to vary strongly with the NAO: A shift from sources in the north and west of Iceland during NAO positive months to a maximum in the southeastern North Atlantic for NAO negative months was consistent with concurrent changes in the mean large-scale flow. Moisture sources for higher elevations of Greenland were shown to have more southerly moisture sources, and vice versa. In addition, more long-range moisture transport occurs during the NAO− phase. Interannual variability was found to be spatially nonuniform for different sectors of the Greenland plateau.

[69] These findings constitute a new aspect of the influences that large-scale climate modes can impose on the hydrological regime of the Greenland ice sheet. They are of fundamental importance for understanding annual accumulation and stable isotope records in ice cores from the Greenland ice sheet. In the companion paper to this study, the Lagrangian method is further exploited in that respect.

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