A Climatology of Tropospheric Humidity Inversions in Five Reanalyses

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Abstract

Specific humidity is generally thought to decrease with height in the troposphere. However, here we document the existence of specific humidity inversions in five reanalyses: the National Centers for Environmental Prediction (NCEP) second reanalysis (NCEP-2), the European Centre for Medium-Range Forecasts (ECMWF) 40-year reanalysis (ERA-40), the Modern Era Retrospective Analysis for Research Applications (MERRA), NCEP's Climate Forecast System Reanalysis (CFSR), and the ECMWF interim reanalysis (ERA-Interim). These inversions are most frequent in the polar regions. Inversions do occur elsewhere, most notably over the subtropical stratus regions, but are less frequent and likely overproduced depending on the location. Polar inversions are the most persistent in winter and the strongest (as defined by the humidity difference divided by the pressure difference across the inversion) in summer or autumn with low bases (at pressures > 900 hPa). Winter humidity inversions are lower, being near-surface, due to the persistence of low-level temperature inversions associated with these humidity inversions, while summer humidity inversions tend to be located near cloud top providing moisture to prevent the melt season stratus from evaporating. The most important contributions to affect humidity inversions in MERRA are dynamics, turbulence, and moist physics. However, local advection may not play as much of a role as regional humidity convergence. The subtropical stratus inversions are as thick as polar humidity inversions but with higher bases generally at pressures < 900 hPa. These inversions are confirmed by rawinsonde data, but there are discrepancies between the observed annual and diurnal cycle in inversion frequency and those portrayed in the reanalyses.

Keywords: specific humidity inversions; climatology; reanalyses; polar regions; subtropical stratus

1. Introduction

The vertical distribution of water vapor strongly affects radiative transfer as well as cloud and precipitation formation and hence plays a fundamental role in weather forecasting and climate studies. It is generally thought that specific humidity decreases with increasing height in the troposphere (e.g., Fig. 12.4 in Peixoto and Oort, 1992; Wagner et al., 1990; Johnsen and Rockel, 2001). On average, this is indeed the case as can be seen in the profile of the zonal mean of specific humidity from the National Aeronautics and Space Administration (NASA) Goddard Modeling and Assimilation Office (GMAO) Modern Era Retrospective Analysis for Research and Applications (MERRA) in Fig. 1.

However, in certain circumstances there can be specific humidity inversions, or layers in which specific humidity increases with height, in the troposphere. Fig. 2 presents the zonal mean of the vertical profiles of the difference in specific humidity Δq with height in MERRA for each season: (a) December-February or DJF, (b) March-May or MAM, (c) June-August or JJA, and (d) September-November or SON. This Δq is calculated at halfway between each pressure level in MERRA as the simple difference in specific humidity between pressure levels. Now, one can clearly see the areas of positive Δq , i.e. increasing humidity with height, as the blue shading in the polar regions. Over the Antarctic, positive Δq is only over the South Pole from austral autumn (MAM) to spring (SON). Over the Arctic, the largest area of positive Δq occurs in boreal winter (DJF). In boreal spring (MAM) and summer (JJA), there is no mean positive Δq , and the area of mean positive Δq redevelops in boreal autumn (SON). This seems to indicate that humidity inversions would be more numerous in the polar regions during the autumn and winter seasons but does not preclude the existence of humidity inversions in those regions in any

other season. Humidity inversions may be less numerous or not strong enough to withstand the averaging.

Previously, specific humidity inversions were observed periodically during the Arctic Ocean Experiment 2001 (Tjernström et al., 2004; Tjernström, 2005; Sedlar and Tjernström, 2009), and Gerding et al. (2004) documented the case of a moister layer above a near-surface dry layer observed by lidar on 28 February 2002 on the island of Spitsbergen in the Arctic. More recently, Vihma et al. (2011) investigated humidity inversions over two Svalbard fjords finding that they were connected to temperature inversions occurring simultaneously which was also found by Sedlar et al. (2011) from observations made during two field experiments over the Arctic Ocean. Arctic humidity inversions were also previously documented by Serreze et al. (1995) and modeled by Curry (1983).

These inversions are not limited to the Arctic. Near-surface humidity inversions can be seen from three years of summer and autumn radiosonde profiles over Dome C (Tomasi et al., 2006) and in ten years of radiosonde profiles at 11 coastal sites (Nygård et al. 2013a) in Antarctica. Additionally, Roberts et al. (2010) documented that specific humidity above 900 hPa tends to be higher than surface values over the northeastern Pacific Ocean in MERRA. Humidity inversions have also been observed over the Sichuan Basin (Jiang et al., 2012), the Tibetan Plateau (Liu et al., 2002), and associated with a radiative fog event in Nanjing, China (Liu et al., 2010). Humidity inversions outside of the polar regions may go by various other names. For instance, Kloesel and Albrecht (1989) called them “*q*-reversals.” They also may be found when looking at other phenomena, such as stratospheric air intrusions (Di Giralamo, 2009).

Such specific humidity inversions might have a radiative impact. Devasthale et al. (2011) implied that humidity inversions in the Arctic would impact longwave radiation

especially in winter since the inversion contributes as much as 50% to the total column precipitable water. Other radiative impacts may be associated with their effect on clouds. Sedlar and Tjernström (2009), Solomon et al. (2011), and Sedlar et al. (2011) documented instances of humidity inversions topping Arctic stratus in the summer, and Paluch et al. (1999) gave details of instances of higher free tropospheric specific humidity than in the boundary layer, or in other words, a humidity inversion, over the eastern Equatorial Pacific. All of these suggest that these humidity inversions prevent evaporation from cloud-top entrainment (induced by cloud-top radiative cooling), thus promoting continuity of the boundary layer cloud. Furthermore, such inversions would also impact the temperature-lapse rate feedback of the greenhouse effect, particularly at high latitudes where it is more important (Webb et al., 1993; Curry et al., 1995).

Given the possible implications of specific humidity inversions sometimes occurring in the troposphere, what are the temporal and spatial variabilities of such instances? Recently, Devasthale et al. (2011) produced a clear-sky climatology in the Arctic based on Atmospheric Infrared Sounder (AIRS) profiles. They found that Arctic humidity inversions were more prevalent in winter but strongest in summer. Our strategy is to do something similar but instead look at the all-sky climatology globally by using reanalyses. Similar work was done by Nygård et al. (2013b) for the Arctic and by Nygård et al. (2013a) in the Antarctic using radiosonde observations. However, by using radiosonde observations only, the results are rather localized, especially since these are only available regularly over land. A truly regional, and even global, perspective can only be reached by using reanalyses in which radiosonde data is assimilated. The reanalyses included here are two older generation reanalyses [the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year reanalysis (ERA-40) and the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental

Prediction (NCEP) reanalysis] and three current generation reanalyses (NASA MERRA, NOAA CFSR, and ECMWF ERA-Interim).

Recent studies have shown that some or all of these reanalyses have erroneous realizations of the low-level thermodynamics. For instance, Serreze et al. (2012) recently found that NCEP-1 (the predecessor to NCEP-2), ERA-40, the Japanese 25-year reanalysis (JRA-25), MERRA, CFSR, and ERA-Interim were biased warm and moist on average in comparison to radiosonde observations at nine locations across the Arctic Basin, thus preventing the realization of persistent temperature and humidity inversions. Similar warm and moist near-surface biases were found by Jakobson et al. (2012) in comparisons of tethersoundings taken at the drifting ice station Tara with the latest generation of reanalyses (MERRA, CFSR, ERA-Interim, and the Japanese Meteorological Agency Climate Data Assimilation). A warm near-surface bias was also found by Tjernström and Graversen (2009) in ERA-40 in comparison to soundings taken during the Surface Heat Balance of the Arctic (SHEBA) field experiment. de Boer et al. (2013) showed that such errors could be caused by errors in cloud occurrence and location in the models used to generate the reanalyses. Still, Fig. 3 shows the relative frequency of specific humidity inversions in the five reanalyses compared here, including two different versions of ERA-40 (ERA-40m and ERA-40p) which are defined below. Most reanalyses have humidity inversions in large portions of both polar regions in 100% (the light pink contour) of January means in the Northern Hemisphere and of July means in the Southern Hemisphere. This suggests that the humidity inversions in the reanalyses are strong and/or persistent enough to withstand the monthly averaging during these months.

The reanalyses are described in the next section, and the results are presented in section 3. In Section 4, we compare the reanalysis inversions to those in rawinsonde data, and in Section

5, we discuss the possible mechanisms for developing and maintaining such humidity inversions. Conclusions and further discussion are provided in Section 6.

2. Reanalyses

In this study, we use both the monthly mean and 6-hourly values from the second version of the NCEP reanalysis (hereafter, NCEP-2), ERA-40 (including three versions with varying horizontal and vertical resolutions), MERRA, CFSR, and ERA-Interim. A brief description of each reanalysis follows; more description can be found in the included references.

2.1. NCEP-2

NCEP-2 (also referred to as NCEP-DOE) was developed as a revision of the first reanalysis to correct errors discovered in the processing of the earlier version. NCEP-2 utilizes the same T62 spectral resolution model with 28 vertical layers as in the first version (NCEP-1) with some minor improvements to the model physics and data assimilation (Kanamitsu et al., 2002). Like in NCEP-1, data, which, for upper air, includes conventional sources from rawinsondes, dropsondes, pilot balloons (PIBALs), wind profilers, and aircraft measurements as well as satellite radiances from the Satellite Infrared Spectrometer (SIRS), the High Resolution Infrared Sounder (HIRS), the Vertical Temperature Profile Radiometer (VTPR), and TIROS Operational Vertical Sounder (TOVS) and upper-air winds from geostationary satellites, were assimilated using the spectral statistical interpolation (SSI) technique (Kalnay et al., 1996).

Here, we choose to use NCEP-2, because NCEP-1 had negative specific humidities in some parts of the polar regions. This seems to be one of the errors that has been corrected in NCEP-2. Both the monthly and 6-hourly data downloaded from the mass storage on the supercomputers at National Center for Atmospheric Research (NCAR) are on a regular $2.5^\circ \times 2.5^\circ$ grid with 17 standard pressure levels.

2.2. *ERA-40*

ERA-40 utilized the ECMWF atmospheric model with a spectral resolution of T159 and 60 vertical layers (Uppala et al., 2005). The model included improved parameterizations of deep convection and radiation and a new representation of sea ice (Uppala et al., 2005). Data assimilation was done by a 3D-Var system. Upper air observations from conventional sources were combined with satellite measurements from geostationary satellites, HIRS, the Microwave Sounding Unit (MSU), and the Advanced Microwave Sounding Unit A (AMSU-A) (Uppala et al., 2005).

Here, we use 6-hourly analyses and monthly means from three different versions that differ in terms of horizontal and vertical grids: the model original resolution both horizontally and vertically ($\sim 1.125^\circ \times 1.125^\circ$ and 60 vertical model sigma layers, hereafter referred to as ERA-40m), the data averaged vertically to 23 standard pressure levels but horizontally on the model grid (hereafter ERA-40p), and the data averaged horizontally to a regular horizontal grid of $2.5^\circ \times 2.5^\circ$ and vertically to 23 standard pressure levels (hereafter ERA-40g). ERA-40m and ERA-40p were downloaded from NCAR's Research Data Archive (RDA) web site (<http://rda.ucar.edu>), while ERA-40g was downloaded from the ECMWF website (<http://www.ecmwf.int>).

2.3. *MERRA*

MERRA is NASA GMAO's most recent reanalysis (Rienecker et al., 2010) using the Goddard Earth Observing System version 5 atmospheric general circulation model with a finite-volume dynamical core and a resolution of $1/2^\circ$ latitude $\times$ $2/3^\circ$ longitude and 72 vertical layers (Suarez et al., 2010). Assimilation is done by a three-dimensional variational analysis (Rienecker et al., 2010). To reduce shocks from the mass-wind analysis increments, the

incremental analysis update procedure (Bloom et al., 1996) is implemented (Rienecker et al., 2007). In this procedure, assimilation at the 6-h synoptic times is based upon 6 h of model predictions centered on the synoptic time. The analyzed correction, then, is applied at the previous 6 h, and the model is run for 12 h (Suarez et al., 2010).

MERRA assimilates upper-air data from conventional sources as well as from satellite measurements of upper air winds derived from geostationary satellites and the Moderate Resolution Imaging Spectroradiometer (MODIS), radiances from the Geostationary Operational Environmental Satellites (GOES) sounder, TOVS and Advanced TOVS (ATOVS) instruments, the Atmospheric Infrared Sounder (AIRS), MSU, and AMSU-A (Rienecker et al., 2010).

Used here are the three-dimensional analysis fields (inst6_3d_ana_Np) which are provided in the model horizontal resolution ($1/2^\circ$ latitude $\times$ $2/3^\circ$ longitude) in both the 6-h temporal resolution and the monthly means. These data were downloaded through the Goddard Earth Sciences Data and Information Services Center website (<http://data.sci.gsfc.nasa.gov>).

2.4. CFSR

CFSR is the latest NCEP reanalysis that utilizes a fully coupled atmosphere-ocean-sea ice-land model, the Climate Forecast System (CFS) (Saha et al., 2010). The atmospheric component is run at T382 spectral resolution with 64 vertical layers, while the ocean component is run at a horizontal resolution that varies between $1/4^\circ$ and $1/2^\circ$ latitude $\times$ $1/2^\circ$ longitude with 40 layers in the vertical of which the uppermost is 10 m thick. Similar upper air data to that of the other reanalyses plus radiances from GOES, AIRS, Advanced Microwave Sounding Radiometer-Earth Observing System (AMSRE), Infrared Atmospheric Sounding Interferometer (IASI), and Microwave Humidity Sounder (MHS) and radio occultation from the Challenging

Minisatellite Payload (CHAMP) and the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) are ingested into the CFSR.

Used here are the 6-hourly and monthly mean profiles gridded at 0.5° lat/lon on 37 pressure levels downloaded from NOAA/National Climatic Data Center's (NCDC) National Operational Model Archive and Distribution System (NOMADS) website (<http://nomads.ncdc.noaa.gov>).

2.5. *ERA-Interim*

ERA-Interim is the newest ECMWF reanalysis. The model used to produce ERA-Interim has a higher horizontal resolution of T255 and improved model physics from ERA-40. Instead of the 3D-Var assimilation used for ERA-40, ERA-Interim uses a 12-h 4D-Var assimilation system with improvements to the handling of data biases and of the background error constraint (Simmons et al., 2006; Dee et al., 2011). ERA-Interim uses the same data from ERA-40 plus clear-sky radiances from Meteosat-2, Global Ozone Monitoring Experiment (GOME) ozone profiles, CHAMP and COSMIC radio occultation (RO) measurements, the Gravity Recovery and Climate Experiment (GRACE), reprocessed ocean wave height data from ERS-1 and 2, and upper-level winds from Meteosat-2 (Simmons et al., 2006).

Used here are the 6-hourly and monthly mean analyses that have been interpolated to 37 pressure levels at the model horizontal resolution of $\sim 0.70^\circ \times 0.70^\circ$. These data were downloaded from the NCAR RDA web site (<http://rda.ucar.edu>).

3. The specific humidity inversion climatology in the reanalyses

To better understand the characteristics of humidity inversions, we define a humidity inversion strength QIS. For the vertical column of specific humidity in each grid box of a particular reanalysis, the pressure at the bottom of the lowest inversion layer above which

humidity begins to increase with height is $p_{\max}$, and the pressure at the top of that layer is $p_{\min}$.

Then,

$$\text{QIS} = \frac{q(p_{\min}) - q(p_{\max})}{|p_{\min} - p_{\max}|} \quad (1)$$

where $q(p_{\min})$ and $q(p_{\max})$ are the specific humidities (in g kg^{-1}) at the top and bottom of the inversion respectively. Thus if the pressures are given in hPa, QIS has units of $\text{g kg}^{-1} \text{ hPa}^{-1}$.

For the mean January profile in the Northern Hemisphere (in the middle of the season with the deepest and largest area of positive Δq over the Arctic), Fig. 4 shows that all reanalyses have humidity inversions in most of the areas poleward of 60°N as well as over much of mid-latitude Eurasia. NCEP-2 and MERRA also have inversions extending down over the North American continent east of the Rockies. Another area of inversions occurs along $\sim 15^\circ\text{N}$ from the northeastern Atlantic subtropical stratus region eastward into the southern Sahara and Sahel. MERRA additionally has some humidity inversions in January over the northeastern Pacific stratus region. The geographical extent varies between the different reanalyses in these regions. NCEP-2 has the smallest extent over the northeast Atlantic and the Sahara, whereas MERRA and CFSR have the most. There is also a difference between ERA-40m and ERA-40p in that humidity inversions cover less area over the northeast Atlantic and the Sahara in the latter. Even poleward of this, humidity inversions cover less area over the mid-latitudes in ERA-40p than in ERA-40m. The extent of humidity inversions in ERA-40g is very similar to ERA-40p (not shown).

Humidity inversions are weakest ($< 0.0025 \text{ g kg}^{-1} \text{ hPa}^{-1}$) over the Arctic and stronger over the subtropics (Fig. 4). The strongest inversions appear in NCEP-2 over the eastern Sahara (Fig. 4a) and in MERRA over the northeast Atlantic (Fig. 4j). The inversion bases over most of the Arctic and mid-latitudes are low to the ground ($> 900 \text{ hPa}$ except over high terrain) in all

reanalyses. They are mostly higher ($p_{\max} < 900$ hPa) in both ERA-40m, MERRA, and CFSR around $\sim 15^\circ\text{N}$ over the Sahara and the Northeast Atlantic (Fig. 4e,h,k), whereas the bases are still generally low (> 900 hPa) in these regions in NCEP-2, ERA-40p, and ERA-Interim (Fig. 4b,n). The inversions are generally thicker (> 150 hPa) in NCEP-2, ERA-40p, and CFSR (Fig. 4c,f,l) and thinner (< 150 hPa) in ERA-40m, MERRA and ERA-Interim over the Arctic.

The quantities based on the mean July profile in the Southern Hemisphere are shown in Fig. 5. As in the Northern Hemisphere winter, NCEP-2, ERA-40m, MERRA, CFSR, and ERA-Interim have mean inversions over most of Antarctica and some of the nearby ocean (Fig. 5a,d,j,m,p). MERRA also produces more inversions further out over the Southern Ocean than any of the other reanalyses (Fig. 5j). On the other hand, humidity inversions are lost over most of the Antarctic continent in ERA-40p, restricted to mainly the coast and nearby oceans (Fig. 5g). ERA-40g looks very similar to ERA-40p (not shown). Additionally, there are mean inversions over at least part of the subtropical stratus regions over both the southeast Atlantic and Pacific in NCEP-2, ERA-40m, MERRA, CFSR, and ERA-Interim (Fig. 5a,d,j,m,p). On the other hand, the humidity inversions have almost been lost over the subtropical stratus regions in ERA-40p, being limited to a very small area over the southeastern Atlantic stratus region (Fig. 5g). This is the same in ERA-40g (not shown). Interestingly, ERA-Interim with its higher horizontal resolution also has a limited amount of humidity inversions over the Southern Hemisphere subtropical stratus regions (Fig. 5p).

QIS is smallest over the polar region and higher over the subtropical stratus regions in all reanalyses (Fig. 5a,d,g,j,m,p). QIS is also higher in MERRA over the Southern Ocean (Fig. 5j). In fact, the highest QIS ($> 0.01 \text{ g kg}^{-1} \text{ hPa}^{-1}$) is from MERRA over the southeast Pacific and the Southern Ocean. In the Antarctic, the polar inversion bases are low to the ground following the

terrain to higher altitudes where there are humidity inversions in the interior of the continent (Fig. 5b,e,h,k,n,q). In the subtropical stratus regions, the inversions are generally the lowest near the coast ($p_{\max} > 900$ hPa) and are lifted higher ($600 < p_{\max} < 900$ hPa) away from the coast in NCEP-2, MERRA, and CFSR (Fig. 5b,h,n). Over the Antarctic, the humidity inversions are thicker in NCEP-2 than in ERA-40m, MERRA, CFSR, and ERA-Interim (Fig. 5c,f,l,o,r). Over the subtropical stratus, NCEP-2's inversions are thicker offshore, whereas there is no indication of this in ERA-40m, MERRA, or CFSR (Fig. 5c,f,l,o).

Figs. 4 and 5 are based on the humidity inversion in the climatological mean humidity profile. If, however, the humidity inversions are computed from each month's mean humidity profile, they also appear in varying degrees of frequency in most of the mid-latitudes and along a substantial fraction of a band along $\sim 15^\circ$ of both hemispheres in all reanalyses (Fig. 3). The frequency of occurrence in monthly mean humidity inversions is 100% (the light pink contour) over large fractions of the Arctic in all reanalyses (Fig. 3a,c,e,g,i,k) and of the Antarctic in NCEP-2, ERA-40m, MERRA, CFSR, and ERA-Interim (Fig. 3b,d,h,j,l); humidity inversions are still largely absent from most of the interior of Antarctica in ERA-40p (Fig. 3e,f). Humidity inversion frequency is $> 60\%$ over a large portion of the subtropical stratus regions except in the northeast Pacific (Fig. 3). Because of the low frequency of occurrence in this region, the humidity inversion is averaged out of the climatological mean profile in this region (Fig. 4).

Taking the mean of the quantities QIS, inversion base, and inversion thickness derived from each January's mean profile, the correlation in these quantities of NCEP-2 with ERA-40g, MERRA, CFSR, and ERA-Interim in the Northern Hemisphere is shown in Fig. 6. Here, we directly compare ERA-40g with the same resolution NCEP-2 product, whereas the other higher resolution reanalyses are regridded to the same $2.5^\circ \times 2.5^\circ$ resolution of NCEP-2. Note that

unshaded areas not only indicate areas where there are no humidity inversions but also areas where there is absolutely no variation in that quantity in either NCEP-2 or the other reanalysis or both. Fig. 6 shows that where there is variation in the QIS in both reanalyses, the correlation between the NCEP-2 and this quantity is weak as indicated by the light shading (Fig. 6a,d,g,j). In most areas, the other reanalyses are positively correlated, but there is more negative correlation over the Sahara and northeast Atlantic in all reanalyses. Also, MERRA is more negatively correlated over the mid-latitudes. On the other hand, the reanalyses are very strongly correlated to NCEP-2 in inversion base and thickness as indicated by the darkest shadings, mostly positively although again more negatively over the Sahara and northeast Atlantic (Fig. 6b,c,e,f,h,i,k,l). The same is true for the Southern Hemisphere in July (not shown).

The annual cycle in polar regional mean statistics are presented in Fig. 7. The top row presents the maximum percent total area possible to be covered by humidity inversions. As expected from Fig. 5, MERRA's inversion covers more area than the other reanalyses (Fig. 7a,b). In fact in boreal winter, almost 100% of the grids poleward of 60°N have inversions in the 1981-2000 mean. There is a minimum in all reanalyses in the areal extent in boreal summer (May in ERA-40p and ERA-40g with a secondary minimum in September; June in ERA-40m, MERRA and ERA-Interim; August in NCEP-2; and September in CFSR with a secondary minimum earlier in May). The secondary minimums in all versions of ERA-40, CFSR, and ERA-Interim are due to a slight increase in maximum possible areal extent reported by all of these in mid-summer. Also expected from Fig. 5, the vertical averaging done in ERA-40p and ERA-40g reduces maximum areal extent in these versions, most profoundly in boreal summer. In the Antarctic, the difference between the maximum possible areal extent of the inversion is more noticeable between MERRA and the other reanalyses (Fig. 7b). MERRA has a

minimum extent of ~75% in December and a maximum of > 95% in austral winter (July-September). On the other hand, NCEP-2, ERA-40m, ERA-40p, ERA-40g, CFSR, and ERA-Interim have a maximum of only ~40%, 40%, 22%, 22%, 30%, and 20%, respectively, in austral winter (Fig. 7b).

The remaining quantities reported in Fig. 7 are obtained from taking the regional mean of the quantities that have been averaged for each month over the 20-yr period 1981-2000. In the Arctic, MERRA has the highest QIS than any other reanalysis, but all reanalyses have a maximum in QIS in boreal summer (Fig. 7c). Over the Antarctic, all reanalyses have fairly constant mean inversion strength or a very weak annual cycle in this quantity (Fig. 7d).

As can be seen in Fig. 3, Arctic inversion bases from all five reanalyses are low (> 900 hPa) with very little variation throughout the year (Fig. 7e). Over the Antarctic, MERRA shows a weak annual cycle in base pressure with slightly lower bases in austral summer (December and January) and fairly constant pressures across most other months (Fig. 7f). Base pressures in all versions of ERA-40, CFSR, and ERA-Interim peak in austral spring (November and October, respectively). NCEP-2, on the other hand, has a very strong annual cycle in base pressure with much higher bases in January.

The annual cycle in both Arctic and Antarctic inversion thickness is fairly similar in NCEP-2, ERA-40m, MERRA, CFSR, and ERA-Interim with minimum thicknesses in summer and higher thicknesses in winter, but the thicknesses in NCEP-2, ERA-40p, and ERA-40g are higher than in the other three reanalyses (Fig. 7g,h). This is to be expected considering the lower vertical resolution of these latter products.

The monthly mean low cloud amount from the International Satellite Cloud Climatology Project (ISCCP) D2 product (Rossow and Schiffer, 1999; available from

<http://isccp.giss.nasa.gov>) is given in the bottommost panels in Fig. 7. In the Arctic (Fig. 7i), low cloud amount is smallest in winter and largest in summer with a maximum in June. This is also the season when humidity inversion strength is largest in this region (Fig. 7c). This suggests that humidity inversion characteristics may be influenced by clouds or vice versa in this region. This will be explored in more detail in Section 5. On the other hand in the Antarctic, the annual cycle in low cloud amount is small (Fig. 7j), coinciding with a similarly small annual cycle in humidity inversion strength (Fig. 7d).

A similar figure for the subtropical stratus regions is presented in Fig. 8. MERRA and CFSR generally have larger maximum possible inversion areal extent except for in the northeast Atlantic from June to November, while ERA-Interim generally has the lowest areal extents (Fig. 8a-d). On the other hand, NCEP-2 has the highest mean inversion strength in these regions (Fig. 8e-h). As deduced from Figs. 3 and 4, the mean inversion bases are lowest from NCEP-2 in all of these regions, whereas those in all versions of ERA-40, MERRA, CFSR, and ERA-Interim are generally about the same (Fig. 8i-l). Also as in Figs. 3 and 4, the reanalysis inversion thicknesses are similar from ERA-40m, MERRA, CFSR, and ERA-Interim, while NCEP-2, ERA-40p, and ERA-40g with reduced vertical resolutions have generally larger thicknesses in all four regions.

The monthly mean ISCCP low cloud amount for these subtropical stratus regions is also presented in the bottommost panels of Fig. 8. ISCCP low cloud amount is maximum in August in the northeast Pacific (Fig. 8q), January in the northeast Atlantic (Fig. 8r), and July in the southeast Pacific and Atlantic (Fig. 8s,t), while the cloud minimum occurs in November, August, and February over the northeast Pacific, northeast Atlantic, and southeast Pacific and Atlantic, respectively (Fig. 8q-t). These cloud fractions seem not to correspond as well to humidity

inversions characteristics as they do in the Arctic. For instance, the highest maximum possible coverage (Fig. 8a-d) and QIS (Fig. 8e-h) seem to occur when cloud cover is increased but not necessarily when cloud cover is at its maximum (Fig. 3q-t). This also varies from region to region and product to product.

4. Comparison to rawinsonde data

To verify the veracity of the humidity inversions in the reanalyses presented above, the reanalysis humidity profiles are compared to those of in situ rawinsonde data archived at the NOAA Earth System Research Laboratory (ESRL) (Schwartz and Govett, 1992). These data are also included in the Global Telecommunications System (GTS) that the reanalyses obtain their rawinsonde data from. The data from 1994 to 2001 were downloaded from the website <http://www.esrl.noaa.gov/raobs>. They have been processed using a hydrostatic error handling procedure to detect inconsistencies between observed temperatures and reported heights. Only data up to 300 hPa are used here. We selected a number of stations based upon whether or not they had a sufficient number of records (i.e., at least 20 days of at least one sounding per day for every month) in the database. From these, we selected nine stations in the Arctic and four in the Antarctic because of our focus on the polar regions plus another six from the mid-latitudes and subtropics and three from the tropics. Table 1 gives the locations of these 22 sites.

An example of the mean rawinsonde humidity profiles for January at the nine Arctic stations is shown in Fig. 9. At all stations except Ausiat, the observations indicate a mean near-surface humidity inversion of varying strength. For the reanalysis profiles, we take those from the 6-h values of the grid box that contains the station location interpolated to the rawinsonde vertical resolution. The reanalysis humidity profiles are generally smaller than the observed profile, whereas ERA-40's humidity profiles are higher than the observations at two stations

(Scoresbysund and Inuvik). There are inversions in the mean profiles from all reanalyses except NCEP-2 at all locations except Ausiat, while NCEP-2 produces inversions at all stations except Ausiat and Scoresbysund. The humidity profiles are not very different between ERA-40m and ERA-40g except at Barrow and Kotzebue.

Histograms of the frequency of inversions at these stations show that inversions occur throughout the year in both the observations and the reanalyses (Fig. 10). The highest observed frequencies ($> 80\%$) occur at Barrow (Fig. 10c), Alert (Fig. 10e), Eureka (Fig. 10f), Cambridge Bay (Fig. 10h), and Inuvik (Fig. 10i) in the winter and autumn. At these sites plus Kotzebue, there is a pronounced annual cycle with much more frequent inversions in winter than in summer or autumn. At the two Greenland stations (Ausiat and Scoresbysund, Fig. 10a,b), the observed annual cycle is much less pronounced, especially at Scoresbysund. At these sites, the reanalyses produce a larger annual cycle with MERRA, all versions of ERA-40, CFSR, and ERA-Interim overestimating the frequency of occurrence in the winter and autumn and underestimating in the summer and NCEP-2 underestimating all year long. At these Arctic locations, the different versions of ERA-40 are generally consistent.

The reanalyses are quite inconsistent over Antarctica (Fig. 11). At Casey (Fig. 11a), ERA-40m, ERA-40p, MERRA, CFSR, and ERA-Interim have a pronounced annual cycle with generally overestimated inversion frequencies throughout the year by MERRA, CFSR, and ERA-Interim and overestimated frequencies only in austral winter by ERA-40m and ERA-40p. On the other hand, NCEP-2 and ERA-40g have a small annual cycle, generally underestimating this. At Amundsen-Scott (Fig. 11b), the reanalyses produce inversions throughout the year, whereas there are practically none observed in austral winter (June-August) and only a few observed during the rest of the year. At Mawson (Fig. 11c), the reanalyses underestimate

inversion frequency throughout the year. ERA-40m, ERA-40p, MERRA, CFSR, and ERA-Interim have a small annual cycle, but NCEP-2 and ERA-40g have a pronounced annual cycle with frequencies approaching those observed from April to September. Finally at Dumont d'Urville (Fig. 11d), all reanalyses have a large annual cycle in inversion frequency. Like at Casey, ERA-40m, ERA-40p, MERRA, CFSR, and ERA-Interim generally overestimate frequencies, while NCEP-2 and ERA-40g generally underestimate. So at the Antarctic coastal sites (Fig. 11a,c,d), ERA-40g is more consistent with NCEP-2 with the same horizontal resolution than with ERA-40m and ERA-40p at the original model resolution.

At the six mid-latitude sites (see Table 1), observed humidity inversions at Legionowo, Durban, and Macquarie Island (Fig. 12a,c,f) do not have a pronounced annual cycle in inversion frequency. At Macquarie Island (Fig. 12f), the reanalyses do not have a strong annual cycle in humidity inversion frequency, while they produce a pronounced annual cycle with maxima in winter at Legionowo and Durban (in January and December and in June, respectively, Fig. 12a,c). At the other stations, there is a clear annual cycle in the observations (Fig. 12b,d,e) which all these reanalyses capture at San Clemente Island and Nashville (Fig. 12d,e). At Wuhan (Fig. 12b) though, there is a more pronounced annual cycle in humidity inversion frequency with the reanalyses generally overestimating throughout, less so in summer (July and August). At San Clemente Island underneath the Northeast Pacific stratus deck, the season of highest reanalysis inversion frequency coincides with the season in which the subtropical stratus is at its strongest (Klein and Hartmann, 1993 and Fig. 7q).

Some of the differences between the observed annual cycle and those in the reanalyses can also be seen in the diurnal cycle. Fig. 13 presents some examples of the frequencies in the periods from 18:00-6:00 LT (left) and 6:00-18:00 LT (right) for four stations (Eureka, Durban,

Nashville, and Hilo). At Eureka (Fig. 13a,b) and Nashville (Fig. 13e,f), all or most of the observed frequency occurs in the 6:00-18:00 LT period throughout the year, whereas the reanalyses distribute the frequency equally between the two periods. The same is also true at Resolute (not shown). At Durban, the frequency does not change much with season, with the reanalyses generally underestimating frequencies in both time periods. Finally, Hilo is an example where the reanalyses are consistent with the observed even distribution of humidity inversions throughout the day (Fig. 13g,h).

A final test on the accuracy of the humidity inversion frequencies in the reanalyses is shown in Table 2. All reanalyses have true positives, i.e., when the reanalysis correctly has a specific humidity inversion, in 38-52% of the total number of corresponding times with observations. True negatives, i.e., when the reanalyses and rawinsondes both do not have specific humidity inversions, occur ~25-30% of these occurrences. So, ERA-40g, ERA-40m, MERRA, CFSR, and ERA-Interim are correct in having or not having a specific humidity inversion in their profiles ~75% of the time, while NCEP-2 is correct a little less frequently. For the remaining percentage, the reanalyses either have a humidity inversion when it should not (false positives) or do not have one when it should (false negatives). The split between these depends on the reanalysis. MERRA has nearly equal frequencies of false positives and negatives, while NCEP-2, ERA-40, CFSR, and ERA-Interim have more false negatives than positives. Furthermore, the vertical and horizontal averaging in ERA-40g has the effect of increasing the frequency of false negatives and decreasing that of false positives slightly.

5. Discussion

Given that humidity inversions are quite frequent in the polar regions and less frequent elsewhere as shown in Section 3, under what conditions are humidity inversion formation

favorable? Temperature inversions, moist air advection, dry air advection, differential humidity advection, large-scale subsidence, condensation in the air and at the surface, and turbulence have all been hypothesized as contributing to the formation or continuance of polar humidity inversions (Nygård et al., 2013a; Curry, 1983). In its `tavg3_3d_qdt_Cp` dataset, MERRA provides the forecasted moisture tendencies due to dynamics; moist physics; turbulence; chemistry; and analysis, or the adjustment made by the assimilation. These quantities averaged over humidity inversions for winter and summer in both the Arctic and Antarctic as a function of the humidity difference across the inversion are presented in Fig. 14. As expected from the location in the lower troposphere, the chemical tendencies are zero. The dynamical (i.e., advective) tendency provides an overwhelming positive contribution on average to humidity inversions in both seasons and regions particularly as the humidity inversion gets stronger. Moist physics contributes a drying effect to humidity inversions that increases in magnitude with the strength of the humidity inversion. This effect is stronger for the strong inversions in winter than it is in summer in both hemispheres. Turbulence contributes a small moistening that is larger in the summer than in the winter in the Arctic. In the Antarctic, turbulence seems to have very little effect on humidity within inversions. Interestingly, analysis tendencies are low, producing a slight drying, but they have more of an effect in the Arctic summer. This suggests that humidity appears to get too high in humidity inversions in the Arctic, especially in summer.

Thus, dynamical, moist physics, and turbulent processes appear to be the most influential on humidity inversions in MERRA. The drying by moist physics would occur from condensation. This can occur within clouds or from cooling the air enough so that water vapor has to be removed, consistent with the Clausius-Clapeyron equation. The latter could occur in temperature inversions, and humidity inversions have long been recognized to be quite often

associated with temperature inversions in the Arctic (Devasthale et al., 2011; Sedlar et al., 2011; Vihma et al., 2011; Nygård et al., 2013a,b). Furthermore, specific humidity increasing with height would be consistent with the Clausius-Clapeyron equation within an increasing temperature profile (Nygård et al., 2013b) if the relative humidity is 100% with respect to ice. This is often the case near-surface in the Arctic (Andreas et al., 2002). Temperature inversions are slightly more frequent in Arctic winter (Serreze et al., 1992, 1995), and this is the season when the inversions are most prevalent (Fig. 7). In MERRA, humidity inversions are more prevalent when a temperature inversion is present (not shown). Fig. 15 shows the reanalysis humidity inversion strength as given by the humidity difference across the inversion as a function of the potential temperature difference across the humidity inversion in both polar regions. For most reanalyses, the humidity inversion is stronger when there is also a temperature inversion and as the temperature inversion strengthens. CFSR also has some very strong humidity inversions for unstable conditions that can even exceed the strongest humidity inversions for strongly stable conditions. This tends to occur over the oceans and in summer of both polar regions, suggesting that CFSR may have an even higher low-level moist bias than the other reanalyses.

Humidity inversions have also been recognized to be often coincident with clouds (Curry, 1986; Devasthale et al., 2011; Sedlar et al., 2011; Solomon et al., 2011). The annual cycle in monthly mean ISCCP low cloud amount is more pronounced in the Arctic (Fig. 7i) with some of the largest cloud amounts being in summer when humidity inversion strength is at its peak (Fig. 7c). In contrast in the Antarctic, the annual cycle in low cloud amount (Fig. 7j) and humidity inversion strength (Fig. 7d) are both correspondingly small. An example of a humidity inversion associated with a cloud deck was given by Solomon et al. (2011) at Barrow, Alaska where the

cloud top was situated in the middle of a humidity inversion in both the observations and a large eddy simulation. Similar conditions were also documented by Sedlar and Tjernström (2009) and Sedlar et al. (2011). In MERRA for 1994-2001 for instances of humidity inversions coinciding with a cloud over the Arctic when the surface pressure is above 1000 hPa (poleward of 60°N), the median cloud top (912.5 hPa) lies between the humidity inversion bottom (975.0 hPa) and top (900.0 hPa) in winter (December-February). This is also true in summer (June-August) with the three values being 887.5, 925.0, and 875.0 hPa, respectively.

Cloud-top humidity inversions that were reported by Sedlar and Tjernström (2009), Solomon et al. (2011), and Sedlar et al. (2011) were also coincident with a temperature inversion. Temperature inversions are indeed prevalent throughout the Arctic (Sverdrup, 1933; Kahl, 1990; Serreze et al., 1992), and humidity inversions are usually coincident with thermal inversions in both polar regions (not shown). Temperature inversions are prevalent throughout the year in the Arctic. However, surface-based inversions were found to be slightly more prevalent in winter and above-surface inversions more prevalent in summer during the Surface Heat Budget in the Arctic (SHEBA) experiment (Tjernström and Graversen, 2009). Polar humidity inversions may also follow this pattern. For example in MERRA during the winters of 1994-2001, the median humidity inversion top is lower when there is no cloud present (925.0 hPa) than when cloud is present (900.0 hPa) over the low-elevation Arctic (when the surface lies below 1000 hPa poleward of 60°N). This is also true over the Southern Ocean (poleward of 45°S) with the corresponding values being 825.0 and 750.0 hPa, respectively. These results suggest that the humidity inversions tend to be closer to the surface when clouds are less frequent in winter.

Thus, there appears to be two different humidity inversion regimes in the polar regions. The first is surface-based humidity inversions tied to surface-based temperature inversions. As the surface cools in the development of a surface temperature inversion, the humidity has to decrease adiabatically, because the air cannot hold as much water vapor as it cools (Devasthale et al., 2011). This type of humidity inversion would be more prevalent in the winter because of the prevalence of temperature inversions from the radiative cooling at the surface during the polar night. As clouds become more prevalent going into the summer melt season, a second regime in which humidity inversions capping clouds becomes more dominant. These are also coincidental with temperature inversions near the cloud top. Vowinckel and Orvig (1966) found that near-surface thermal inversions are more prevalent in winter when surface radiative cooling is dominant and upper level inversions are more prevalent in summer when clouds are more prevalent. However, cloud-topped temperature inversions are not necessarily absent from winter. Tjernström and Graversen (2009) found that, during SHEBA, about half of winter temperature inversions were surface-based with the remaining similar to the summer elevated inversions but at a lower height. These winter inversions rapidly moved between these two regimes.

For cloud-topped humidity inversions, Solomon et al. (2011) found from large eddy simulations that the downward flux of humidity inferred from the humidity inversion helps maintain stratus by keeping the cloud top air saturated even in the presence of entrainment. Downward moisture flux is also associated with surface-based inversions. This may explain the high frequency of hoarfrost, fog, and “diamond dust” observed in the Arctic (Sverdrup, 1933; Robinson and Ludwig, 1966; Andreas et al., 2002). Curry (1983) found that

falling frozen precipitation aids in the formation of humidity inversions by drying out the air as it falls.

Moist air advection, dry air advection, or differential humidity advection have been hypothesized as contributing to the formation or maintenance of humidity inversions (Nygård et al., 2013a). Devasthale et al. (2011) hypothesized that the increased stability of the temperature inversion would further focus moist air advection to the top or near the top of the inversion. Nygård et al. (2013a) suggested that differential humidity advection, i.e., moist air advection at or near the top of the inversion versus dry air advection, may be important. An example of the vertical profiles of the horizontal advective humidity fluxes ($-u \Delta q|_x$ for the zonal direction, thick red lines, and $-v \Delta q|_y$ for the meridional direction, thick blue lines, where u and v are the horizontal wind speeds in the respective directions and $\Delta q|_x$ and $\Delta q|_y$ are the horizontal humidity differences in those respective directions) from MERRA is given in Fig. 16 for five of the Arctic locations in Table 1. The mean humidity inversion bottom (solid red line across) and top (dashed red line across) at each site are also indicated in Fig. 16. Moist air advection at or near the inversion top would be indicated by a positive advective flux there, and this is evident at several locations (in zonal flux at Scoresbysund, Fig. 16a; in zonal flux at Barrow, Fig. 16b; in both fluxes at Kotzebue, Fig. 16c; and in meridional flux at Cambridge Bay, Fig. 16e). However, the highest meridional moist air advection occurs at the bottom of the mean humidity advection at Eureka in January (Fig. 16d) opposite to the dry air advection required by Nygård et al. (2013a). In July, there are increases in zonal humidity advection from negative to near-zero or positive across the humidity inversion only occurring at two locations (Barrow, Fig. 16g; Kotzebue, Fig. 16h). The moist advection is higher in the meridional direction and tends to decrease across the mean humidity inversion. These results may be affected by the combination

of humidity inversions at multiple layers, so it is inconclusive whether local humidity advection plays as much of a role in humidity inversions as previously believed. However, differential humidity advection may play a larger role in the Antarctic, especially at the coastal locations (not shown). This is not surprising considering the strong dry katabatic winds that often occur there (Nygård et al., 2013a).

Local humidity advection may not have as much of a role in humidity inversions, and it may be regional humidity convergence that might be more important, particularly in summer. This can be quantified by the column integrated horizontal humidity flux across a certain latitude like 60°N for the Arctic. Groves and Francis (2002), deriving such humidity fluxes from satellite-based moisture profiles combined with NCEP-1 winds, noted a net column-integrated (below 300 hPa) moisture flux between November and March into the Arctic mostly from the North Atlantic into Siberia and out through the Canadian Archipelago. The highest fluxes, though, occurred in boreal summer. An earlier study by Cullather et al. (2000) found similar summer maximum fluxes into the region using reanalysis data from ERA-40 and NCEP-1. Fig. 17 shows the mean annual cycle in total column integrated horizontal humidity flux from the MERRA dataset `tavg1_2d_int_Nx` across 60°N and 45°S. The Arctic annual humidity flux cycle here is comparable to that implied from the difference between regional mean precipitation and evaporation in Cullather and Bosilovich (2011). Most of this flux is due to transient eddies, or cyclones (Tietäväinen and Vihma, 2008; Jakobson and Vihma, 2010). Comparing this with the annual cycle in humidity inversion strength (Fig. 7c,d), the maximum humidity fluxes into the two polar regions correspond to the same months in which humidity inversions are the strongest (Fig. 17). The increased regional humidity fluxes provide more moisture for cloud formation which is also more frequent (Fig. 7i,j). In the Arctic in particular, the increased cloud cover

occurs during the melt season. The increased melt pond and open water coverage during this season is also an additional moisture source to the atmosphere.

Humidity inversions elsewhere likely play some different roles than in the polar regions. Similar to surface-based inversions in the Arctic regions, they probably affect the development and propagation of radiation fog events (Liu et al., 2011). Unlike in the Arctic, Paluch et al. (1999) found that radiational cooling is reduced from the top of eastern Equatorial Pacific clouds that were topped by humidity inversions. This is similar to the “*q*-reversals” that Kloesel and Albrecht (1989) found from observations of suppressed convective activity in the Tropics. These “*q*-reversals” were layers of increased specific humidity above a drier layer right above the top of the atmospheric boundary layer. These layers were hypothesized to have derived from deep convective detrainment. Similarly, the higher specific humidity observed by Paluch et al. (1999) over eastern Equatorial Pacific cloud-topped boundary layers was found to have originated from deep convection over the South American continent (Fuelberg et al., 1999). Table 3 presents the median humidity inversion tops and bottoms in MERRA for inversions coincident with clouds along with the median cloud tops for all four subtropical stratus regions presented in Fig. 7. Over the southeast Pacific and Atlantic, the humidity inversions do lie wholly above the cloud top like the “*q*-reversals” in Kloesel and Albrecht (1989). However, the cloud tops fall in the middle of the humidity inversions in the northeast Pacific like in the Arctic, and the humidity inversions lie wholly within the cloud in the northeast Atlantic.

Some of these contradicting characteristics of the subtropical stratus humidity inversions may be due to the reanalyses likely producing too many inversions outside of the polar regions. For the six mid-latitude sites in Fig. 12, the reanalysis performance varies from location

to location as the reanalyses produce reasonable annual cycles at three sites and unreasonable annual cycles at the other three sites. At one of these sites, San Clemente Island, Table 4 presents the frequencies of true and false positives and negatives in the reanalyses for 1994-2001 similar to what is presented in Table 2 for the Arctic. Most of the reanalyses correctly have many more true negative occurrences of humidity inversions than of true positive. However as suggested by Fig. 12d, there is a large amount of false positives. The effect of vertical and horizontal averaging is to increase the frequency of true negatives slightly by decreasing that of false positives, while the true positive frequency is reduced by increasing the false negative frequency.

6. Conclusions

We have documented the occurrence of humidity inversions, or layers in which specific humidity increases with height instead of decreasing, in five reanalyses (NCEP-2, ERA-40, MERRA, CFSR, and ERA-Interim), presenting the climatology of these occurrences and of their characteristics in the form of inversion strength, inversion base, and inversion thickness. In the Arctic, humidity inversions are the most prevalent in boreal winter, while the strongest inversions are in the summer melt season (Fig. 7) similar to what Devasthale et al. (2011) found for clear-sky Atmospheric Infrared Sounder (AIRS) satellite data for the Arctic. We have further shown that these five reanalyses produce humidity inversions in the Antarctic and in some other regions, most notably over the subtropical stratus regions. Even though Serreze et al. (2012) found that reanalyses had difficulty in producing humidity inversions over the Arctic, we find that humidity inversions still appear in 100% of the January (July) monthly means in a large portion of the north (some of the south) polar region and in excess of 60% of the January (July) monthly means in most of the subtropical stratus regions of the Northern (Southern) Hemisphere

(Fig. 3). There are some discrepancies between the reanalyses and rawinsonde observations at select sites in the Arctic (Fig. 10), Antarctic (Fig. 11), and mid-latitudes (Fig. 12). Since reanalyses provide data more than twice a day, we were able to compare the diurnal cycle of humidity inversions in the reanalyses to the rawinsonde observations here. Such a comparison reveals that the diurnal cycle is not captured correctly by reanalyses at some sites (Fig. 13).

Such discrepancies between reanalysis and rawinsonde observations in the polar regions might be due to a lack of rawinsonde data in these regions to constrain the model profiles. This may be especially true for NCEP-2 for which, as Groves and Francis (2002) pointed out, “moisture retrievals from NOAA’s operational TOVS processing system are not assimilated into the NCEP reanalysis over the Arctic, according to observation counts.” If so, the NCEP-2 humidity profiles in this region are actually that of the model and would suffer from the effects of model error. Such model error could arise from the model physics, i.e., the parameterizations of small-scale processes such as boundary layer turbulence and clouds. Furthermore, differences in weighting of the various observations and satellite measurements assimilated may also explain some of the differences in realization of humidity inversions between the reanalyses. Also as seen in the comparison of the three different versions of ERA-40, the horizontal and vertical resolution can impact somewhat how the humidity inversions are realized in a reanalysis. This appears to be most problematic in areas of steep topographic gradients and high topography such as over Antarctica (Figs. 4 and 11).

The use of reanalysis here allows for the investigation of the roles of various processes in the production of humidity inversions. MERRA provides humidity tendencies due to various processes including dynamics (i.e., advection), moist physics, turbulence, chemistry, and analysis (i.e., assimilation). Based on the mean tendencies across humidity inversions in the

polar regions, dynamics, turbulence, and moist physics are the most important (Fig. 14). Dynamics and turbulence moisten humidity inversions, while moist physics dries inversions. Moist, dry, and differential advection are a few dynamical processes proposed as being influential in triggering or maintaining humidity inversions (Nygård et al., 2013a). Based on mean profiles of advective fluxes of specific humidity (Fig. 16), it is inconclusive whether local advection plays such a strong role in the Arctic, but regional moisture convergence may be more important. The largest humidity fluxes into both polar regions (Fig. 17) are coincident with the season when humidity inversions are strongest (Fig. 7).

Moist physical processes can occur within clouds or from condensation due to cooling air until it gets saturated such as what may happen in temperature inversions. In the polar regions, humidity inversions are indeed more prevalent in the presence of a temperature inversion and becoming stronger as the temperature inversion becomes stronger (Fig. 15). However, the strongest humidity inversions occur in the summer melt season when clouds are the most prevalent (Fig. 7). The median summertime cloud tops are located within humidity inversions, creating a way to prevent the evaporation of cloud water by entrainment from the top (Solomon et al., 2011; Sedlar et al., 2011). This explains why stratus clouds are so prevalent in the polar regions during the summer melt season. In the winter, the humidity inversions tend to be lower, or in other words, surface-based. These humidity inversions are caused by the removal of moisture that is required when the surface is cooled to form a temperature inversion. This may help to explain why the surface is almost always near saturation with respect to ice in the Arctic (Andreas et al., 2002) leading to a high frequency of hoarfrost, fog, and “diamond dust” (Sverdrup 1933; Robinson and Ludwig, 1966; Curry, 1983; Andreas et al., 2002).

Outside of the polar regions, humidity inversions are still possible but less frequent and weaker (Fig. 8). In some regions, humidity inversions are tied to surface-based temperature inversions playing a role in the production and propagation of radiative fog events (Liu et al., 2011). Elsewhere, humidity inversions exist above clouds similar to what happens in the polar regions but may play different roles there than in the polar regions.

The work presented here helps to put previous hypotheses, particularly those made for Arctic humidity inversions, into context. Still, some questions remain. For instance, why do a small amount of humidity inversions in the polar regions still exist even when there is no temperature inversion present? Also, polar humidity inversions are unaffected by the phase of the Southern or Northern Annual Modes (not shown), even though one would expect so given the higher humidity fluxes into the polar regions during positive phases (Tietäväinen and Vihma, 2008; Jakobson and Vihma, 2010). Even though the reanalyses tend to form too many humidity inversions outside of the polar regions, they have been observed to form from time to time (e.g., Liu et al. 2002; Liu et al. 2010; Jiang et al. 2012). Back trajectory analysis of observed events would be extremely helpful here.

Reanalyses can be useful in further investigating this phenomenon even though their realization of humidity inversions may be problematic as discussed here and in Serreze et al. (2012). As seen here, averaging tends to wash out humidity inversions. Humidity inversions are the least robust in the climatological means. Also, horizontal resolution is important in not washing out humidity inversions, especially over high terrain. Furthermore, vertical resolution affects the realization of inversion statistics such as location and thickness. Thus, the current generation of reanalyses (MERRA, ERA-Interim, and CFSR) with this higher spatial resolution would be more useful in this regard. If process studies are warranted, MERRA includes a

myriad of additional quantities such as tendencies from dynamics and various parameterized processes and vertical integrals of fluxes which no other reanalysis includes so far.

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884 **Figure Captions**

885 **Fig. 1.** The zonal mean specific humidity (g kg^{-1}) from MERRA for 1981-2000. The black
886 areas indicate regions that are below ground.

887 **Fig. 2.** Zonal mean difference in specific humidity with height Δq (g kg^{-1}) averaged over 1981-
888 2000 for (a) December-February (DJF), (b) March-May (MAM), (c) June-August (JJA),
889 and (d) September-November (SON) from MERRA. This Δq is calculated at halfway
890 between each pressure level in MERRA as the difference between pressure levels. Blue
891 shading indicates positive Δq , and the black shading indicates areas below ground.

Fig. 3. The relative frequency of occurrence (%) of humidity inversions in the January (for the Northern Hemisphere, left column) and July (for the Southern Hemisphere, right column) monthly means in NCEP-2, ERA-40m, ERA-40p, MERRA, CFSR, and ERA-Interim. The light pink contour represents only 100% frequency of occurrence.

Fig. 4. Northern Hemisphere specific humidity inversion strength [QIS as defined in Eq. (1), $\text{g kg}^{-1} \text{ hPa}^{-1}$] (left column), inversion base pressure (p_{max} , hPa) (middle column), and inversion thickness ($|p_{\text{min}} - p_{\text{max}}|$, hPa) (right column) based on the January climatological mean profiles for 1981-2000 in NCEP-2, ERA-40m, ERA-40p, MERRA, CFSR, and ERA-Interim.

Fig. 5. Same as Fig. 4 except for July in the Southern Hemisphere.

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Fig. 7. (a,b) Maximum possible percentage of area covered by humidity inversions based upon the total area of all grids in which humidity inversions are possible every month plus area mean (c,d) inversion strength [QIS, Eq. (1)], (e,f) base pressure, and (g,h) thickness for only the grid cells that have an inversion poleward of 60°N (left column) and 45°S (right column). Also included is the area-mean low cloud fraction from the International Cloud Climatology Project (ISCCP) product (bottom row).

Fig. 8. Same as Fig. 7 except for the subtropical stratus deck regions in the northeast (NE) Pacific ($15^\circ\text{-}30^\circ\text{N}$, $110^\circ\text{-}140^\circ\text{W}$) (leftmost column), the NE Atlantic ($5^\circ\text{-}25^\circ\text{N}$, $20^\circ\text{-}40^\circ\text{W}$) (2nd column), the southeast (SE) Pacific ($25^\circ\text{S}\text{-}0^\circ$, $80^\circ\text{-}110^\circ\text{W}$) (3rd column), and the SE Atlantic ($25^\circ\text{S}\text{-}0^\circ$, $5^\circ\text{W}\text{-}5^\circ\text{E}$) (rightmost column).

914 **Fig. 9.** Climatological mean January specific humidity profiles for 1994-2001 from rawinsonde
915 observations and NCEP-2, ERA-40m, ERA-40g, MERRA, CFSR, and ERA-Interim at
916 nine stations over the Arctic.

917 **Fig. 10.** Relative frequency of occurrence of humidity inversions per month for each of the
918 Arctic stations in Fig. 9 in the rawinsonde data (obs.), NCEP-2, ERA-40m, ERA-40p,
919 ERA-40g, MERRA, CFSR, and ERA-Interim.

920 **Fig. 11.** Same as Fig. 10 except for the four Antarctic stations.

921 **Fig. 12.** Same as Fig. 10 except for the six mid-latitude stations.

922 **Fig. 13.** Same as Fig. 10 except for (a,b) Eureka, (c,d) Durban, (e,f) Nashville, and (g,h) Hilo
923 only split into earlier than 6:00 and later than 18:00 LT (left) and between 6:00 and 18:00
924 LT (right).

925 **Fig. 14.** The mean humidity tendencies due to dynamics (“dynamic”), moist physics (“moist”),
926 turbulence (“turbulent”), chemical processes (“chemical”), and assimilation (“analysis”)
927 for 0.05 g kg⁻¹ bins of the humidity difference across humidity inversions (Δq) in the
928 Arctic (top row, latitudes poleward of 60°N) and Antarctic (bottom row, latitudes
929 poleward of 45°S) in local winter (left column) and summer (right column).

930 **Fig. 15.** The mean humidity difference across humidity inversions (Δq) in the Arctic (top row,
931 latitudes poleward of 60°N) and Antarctic (bottom row, latitudes poleward of 45°S) for
932 2-K bins of potential temperature difference across humidity inversions ($\Delta \theta$) in local
933 winter (left column) and summer (right column).

934 **Fig. 16.** Climatological mean January (left column) and July (right column) profiles of
935 advective flux of specific humidity ($-u \Delta q|_x$ for the zonal direction, thick red lines, and $-v$
936 $\Delta q|_y$ for the meridional direction, thick blue lines, where u and v are the horizontal wind

speeds in the respective directions and $\Delta q|_x$ and $\Delta q|_y$ are the horizontal humidity differences in those respective directions) for 1994-2001 from MERRA at (a,f) Scoresbysund, (b,g) Barrow, (c,h) Kotzebue, (d,i) Eureka, and (e,j) Cambridge Bay. The mean humidity inversion bottom and top at each site are also indicated as the solid and dashed red lines, respectively, across.

Fig. 17. The 1981-2000 mean annual cycle in MERRA avg1_2d_int_Nx total column integrated specific humidity flux into the Arctic (across 60°N) and the Antarctic (across 45°S).

Table 1

The rawinsonde sites used in this study.

Station name	(Lat., Lon.)
<i>Arctic</i>	
Ausiat, Greenland	(68.7°N, 52.75°W)
Scoresbysund, Greenland	(70.5°N, 22°W)
Barrow, Alaska	(71.3°N, 146.8°W)
Kotzebue, Alaska	(66.9°N, 162.6°W)
Alert, Canada	(82.5°N, 62.3°W)
Eureka, Canada	(80°N, 85.9°W)
Resolute, Canada	(74.7°N, 95°W)
Cambridge Bay, Canada	(69.1°N, 105.1°W)
Inuvik, Canada	(68.3°N, 133.5°W)
<i>Antarctica</i>	
Casey, Antarctica	(66.3°N, 110.5°E)
Amundsen-Scott, Antarctica	(90°S, 0°E)
Mawson, Antarctica	(68.6°S, 62.9°E)
Dumont d'Urville, Antarctica	(66.7°S, 140°E)
<i>Mid-latitudes</i>	
Legionowo, Poland	(52.4°N, 21°E)
Wuhan, Hubei, China	(30.6°N, 114.1°E)
Durban, South Africa	(30°S, 31°E)
San Clemente Island, Calif.	(32.9°N, 117.2°W)
Nashville, Tennessee	(36.3°N, 86.6°W)
Macquarie Island, Australia	(54.5°S, 158.9°E)
<i>Tropics</i>	
Vishakhapatnam, India	(17.7°N, 83.3°E)
Hong Kong, China	(22.3°N, 114.2°E)
Hilo, Hawaii	(19.7°N, 155.1°W)

Table 2

The frequency of true positive and negative (when both the reanalysis and the rawinsonde have or do not have a specific humidity inversion, respectively) and false positive and negative (when the reanalysis has a humidity inversion but the rawinsonde does not or vice versa, respectively) humidity inversion occurrence relative to the rawinsonde observations for all nine Arctic stations.

Product	True positive	True negative	False positive	False negative
NCEP-2	38%	30%	7%	25%
ERA-40g	43%	29%	8%	20%
ERA-40m	46%	29%	8%	18%
MERRA	52%	26%	11%	11%
CFSR	49%	26%	11%	14%
ERA-Interim	46%	28%	9%	17%

Table 3

Median humidity inversion bottom and top and cloud top for instances of humidity inversions occurring with clouds over each of the subtropical stratus regions in Figure 7. Winter here in the Northern Hemisphere is December-January and is July-August in the Southern Hemisphere and vice versa for summer.

Season	Winter	Summer
<i>NE Pacific</i>		
Inversion top	750.0 hPa	775.0 hPa
Cloud top	837.5 hPa	862.5 hPa
Inversion bottom	850.0 hPa	875.0 hPa
<i>NE Atlantic</i>		
Inversion top	775.0 hPa	750.0 hPa
Cloud top	737.5 hPa	837.5 hPa
Inversion bottom	850.0 hPa	850.0 hPa
<i>SE Pacific</i>		
Inversion top	750.0 hPa	725.0 hPa
Cloud top	862.5 hPa	837.5 hPa
Inversion bottom	825.0 hPa	775.0 hPa
<i>SE Atlantic</i>		
Inversion top	800.0 hPa	775.0 hPa
Cloud top	887.5 hPa	862.5 hPa
Inversion bottom	875.0 hPa	850.0 hPa

1026 **Table 4**
 1027 Same as Table 2 except at San Clemente Island.

1028

		True	True	False	False
	Product	positive	negative	positive	negative
1031	NCEP-2	3%	64%	28%	6%
1032	ERA-40g	2%	76%	16%	6%
1033	ERA-40m	3%	72%	20%	5%
1034	MERRA	4%	55%	37%	4%
1035	CFSR	4%	58%	34%	4%
1036	ERA-Interim	2%	74%	18%	6%

1037

Fig. 1. The zonal mean specific humidity (g kg^{-1}) from MERRA for 1981-2000. The black areas indicate regions that are below ground.

Fig. 2. Zonal mean difference in specific humidity with height Δq (g kg⁻¹) averaged over 1981-2000 for (a) December-February (DJF), (b) March-May (MAM), (c) June-August (JJA), and (d) September-November (SON) from MERRA. This Δq is calculated at halfway between each pressure level in MERRA as the difference between pressure levels. Blue shading indicates positive Δq , and the black shading indicates areas below ground.

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