Representation of Arctic Moist Intrusions in CMIP5 Models and Implications for Winter Climate Biases

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ABSTRACT

This paper examines the wintertime northward moisture flux at 70°N from 1981–2005 in 31 of the CMIP5 models compared with the ERA-Interim reanalysis product. The models' total zonally integrated northward moisture flux is found to agree reasonably well with the reanalysis, but with large compensating regional biases. Specifically, the models systematically underpredict the moisture flux in the Atlantic sector and overpredict it in the Pacific sector. The biases are predominantly due to misrepresentation of extreme moisture flux events, which are known to exert a significant control on Arctic climate. Biases in these high-intensity fluxes are almost entirely contributed by biases in the meridional velocity, suggesting a link with biases in storm-track activity at lower latitudes. The extent to which the deficit of moisture intrusions in the Atlantic sector and excess in the Pacific sector may account for biases in the climate of the respective sectors is assessed. Biases in the frequency of moisture intrusions explain roughly 17% of surface temperature and 24% of surface downward longwave radiation biases in the Atlantic sector, and about 14% and 16% of the gradient in these respective biases between the two sectors. The predicted bias gradients, while small in amplitude, are very highly correlated with the true bias gradients in the models, suggesting that the temperature bias directly induced by misrepresented intrusion statistics may be strongly amplified by sea ice feedback.

1. Introduction

Observations show that the surface temperature has increased at almost every location on Earth over the past few decades (Hartmann et al. 2013). In the Northern Hemisphere, the warming has a strong latitudinal dependence, with the greatest warming having occurred in the Arctic during winter (Cohen et al. 2014). This phenomenon is commonly referred to as “Arctic amplification” in the literature (Serreze and Barry 2011). Positive local feedbacks and changes in the meridional heat transport are thought to be responsible for the amplified Arctic response to global warming. Changes in sea ice

volume and the associated ice-albedo feedback (Serreze and Francis 2006; Serreze et al. 2009; Kwok et al. 2009; Screen and Simmonds 2010), increased ocean heat transport (Spielhagen et al. 2011; Sato et al. 2014), and increased downwelling longwave radiation (Francis and Hunter 2006; Graversen and Wang 2009; Bintanja et al. 2011; Kapsch et al. 2013; D. Park et al. 2015; H. Park et al. 2015a; Woods and Caballero 2016; Graversen and Burtu 2016) have all contributed to observed Arctic warming, but the precise underlying mechanisms and their relative contributions remain incompletely understood.

In recent work (Woods and Caballero 2016), we showed that approximately 45% of the recent surface temperature and 35% of the observed sea ice concentration changes in the Barents and Kara Seas during winter can be attributed to increased downwelling longwave radiation associated with an increased frequency of moisture intrusion events—filamentary intrusions of anomalously moist, warm air akin to atmospheric rivers (Gimeno et al. 2014) that cross the entire Arctic basin. These events are typically initiated within the northward-advecting branches of cyclones held in place by blocking highs to the east, sustaining extreme moisture

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fluxes into the Arctic cap over the course of several days (Woods et al. 2013; Liu and Barnes 2015). The resulting warm, moist air mass can intrude deep within the Arctic region, inducing significant thermodynamic perturbations at the surface (Woods et al. 2013; Doyle et al. 2011; Raddatz et al. 2013; H. Park et al. 2015b; Woods and Caballero 2016; Cullather et al. 2016). For clarification throughout this paper we refer to the initial injection of moisture sustained at the Arctic boundary (taken here as the 70°N latitude line) as a *moisture injection*, while the subsequent path followed by the moist air mass across the Arctic basin is referred to as a *moisture intrusion*.

Previously (Woods et al. 2013), we reported on the significant influence these moisture intrusion events exert on the interannual variability of the Arctic winter climate. Despite its significant impact on Arctic climate, only about 30% of the total northward moisture flux at 70°N is contributed by injection events. We also demonstrated that the remaining 70% of the northward moisture flux (which is made up of instantaneous fluxes too weak to qualify as injection events) has no significant climatic impacts, highlighting the disproportionate role these extreme moisture transport events play in climate variability and climate change at high latitudes.

In this study, we assess the representation and climatic impacts of these atmospheric phenomena within 31 models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) by comparing their present-day historical simulations against reanalysis data. Understanding the limitations of these models in the present-day period is key to building confidence in their future climate projections. The models suffer from well-known biases in midlatitude cyclones (Zappa et al. 2013), clouds (Karlsson and Svensson 2013), surface fluxes (Svensson and Karlsson 2011), and ocean heat transport (Wang et al. 2014). Our aim here is to determine the biases in the representation of individual intrusion events and their statistics, and understanding their possible impacts on Arctic climate.

The paper outline is as follows. In section 2 we describe the model and reanalysis data used in this study, as well as the methods used in our analysis. In section 3 we present and discuss biases in the CMIP5 models for some key dynamical and thermodynamical fields, including the northward moisture flux. In section 4 we discuss the representation of intense moisture injection events in the CMIP5 models. In section 5 we track these moist air masses within the Arctic region and discuss the discrepancies in CMIP5 with respect to reanalysis data. In section 6 we discuss the vertical structure of temperature perturbations induced by intrusions in the deep Arctic in the CMIP5 models and ERA-Interim. In section 7 we

quantify climatic biases in the Arctic region caused by biases in the statistics of intense moisture intrusions. Our conclusions are summarized in section 8.

2. Data and methods

a. CMIP5 and reanalysis data

We use the present-day historical simulations performed with 31 of the CMIP5 models (see Table 1). Our choice of models represents the largest available ensemble that satisfied all our data requirements (i.e., containing all the necessary variables and with a high temporal frequency). No model has been given preference in the selection process. The data are daily mean on eight pressure levels between 1000 and 10 hPa. The horizontal resolution of the data varies between the models, from 0.5° to 3.5°. Details of the operational atmospheric grids used by each model, as well as more general information, can be found in Table 1. We use the European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis dataset (Dee et al. 2011) as a control for evaluating the performance of the CMIP5 models. The data are daily mean on 16 pressure levels between 1000 and 30 hPa, with a horizontal resolution of 1° × 1°. The ERA-Interim reanalysis has been shown to rank highly among other reanalyses in terms of Arctic performance (Lindsay et al. 2014). Prior to our analysis, all CMIP5 model and reanalysis data were linearly interpolated to same horizontal and vertical grid between 30 and 1000 hPa, respectively. All our results are based on the December–February (DJF) winter season from 1981 to 2005 in both the CMIP5 models and ERA-Interim reanalysis datasets. We use the convention that the winter of 1990 ends in February 1990. Parts of the analysis specifically focus on three longitudinal sectors: the Labrador sector, 80°–30°W; the Atlantic sector, 30°W–105°E, and the Pacific sector, 105°E–80°W.

b. Moisture flux

The instantaneous column-integrated fluxes of moisture and mass, and the instantaneous column-averaged specific humidity, which are functions of longitude λ and time t at a given latitude, are defined respectively as

$$f(\lambda, t) = \frac{1}{g} \int_{p_t}^{p_s} vq \, dp, \quad (1)$$

$$m(\lambda, t) = \frac{1}{g} \int_{p_t}^{p_s} v \, dp, \quad \text{and} \quad (2)$$

$$r(\lambda, t) = \frac{1}{\Delta p} \int_{p_t}^{p_s} q \, dp, \quad (3)$$

where v is the meridional velocity, q is the specific humidity, $p_s = 1000$ hPa is the surface pressure, p_t is the

pressure level at the top of the column, g is the acceleration due to gravity, and $\Delta p = p_s - p_t$. Vertical integrals are computed using the trapezoidal rule described in [Simmonds et al. \(1999\)](#).

As in [Woods et al. \(2013\)](#) we employ the Heaviside function $H(\cdot)$ to select northward moisture fluxes. The Heaviside function is a discontinuous function whose value is 0 and 1 for negative and positive arguments, respectively. In discrete form, it can be expressed as

$$H(x) = \begin{cases} 1, & x > 0 \\ 0, & x \leq 0 \end{cases} \quad (4)$$

Here, we further include a threshold $f_{\min} \geq 0$ allowing for computation of the portion of the time-mean northward moisture and mass transports contributed during instances when $f > f_{\min}$. Thus the component of time-mean northward moisture and mass transport contributed by moisture fluxes greater than $f_{\min}$, as well as the mean column averaged specific humidity when $f > f_{\min}$, are respectively defined as

$$\bar{F}(\lambda, f_{\min}) = \frac{\int H(f - f_{\min}) f dt}{\int dt}, \quad (5)$$

$$\bar{m}(\lambda, f_{\min}) = \frac{\int H(f - f_{\min}) m dt}{\int dt}, \quad \text{and} \quad (6)$$

$$\bar{r}(\lambda, f_{\min}) = \frac{\int H(f - f_{\min}) r dt}{\int H(f - f_{\min}) dt}, \quad (7)$$

where $dt = 1$ day. For $f_{\min} = 0$, the quantities $\bar{F}$ and $\bar{m}$ are identical to the total climatological northward moisture transport and mass transport respectively, while $\bar{r}$ is the mean humidity of northward-moving air. In [section 3c](#), we discuss how the nature of the northward moisture flux biases in the 31 CMIP5 models depends critically on the value of $f_{\min}$.

c. Bandpass filtered sea level pressure

We apply a Butterworth bandpass filter of order 6 to the daily-mean sea level pressure data to select variability with time scales of 2–6 days, corresponding to the typical time scales of synoptic-scale systems. The standard deviation of the filtered sea level pressure field is used to identify storm tracks ([Zappa et al. 2013](#)).

d. Moisture injections

In this study, moisture injection events are detected at 70°N using an algorithm previously outlined in [Woods](#)

[et al. \(2013\)](#). In [Woods et al. \(2013\)](#) and [Woods and Caballero \(2016\)](#) we defined intense moisture injections, using 6-hourly data, as events in which f (integrated between 30 and 1000 hPa) at 70°N sustains values in excess of $200 \text{ Tg day}^{-1} \text{ deg}^{-1}$ for at least of 1.5 days at every point within a sector of at least 9° zonal extent. Furthermore, [Woods et al. \(2013\)](#) and [Woods and Caballero \(2016\)](#) also computed forward trajectories (discussed in the next section) at every time step and grid point that each injection event satisfied the detection criteria. Injection events with less than 40% of their representative forward trajectory ensemble members reaching 80°N over 5 days were then rejected from the dataset. It is worth noting that moisture transport across 70°N has important contributions from mesoscale waves (~ 200 km), which may not be fully resolved features in the CMIP5 and ERA-Interim models. As such, the full longitudinal extent of detected moisture intrusions may be underestimated. This may lead to overestimation of the thermodynamic impacts of moisture intrusions over the Arctic region for given quantity of moisture transport computed at 70°N. However, as we are primarily focusing on transports of moisture that cross the entire Arctic basin (~ 4000 km), this is likely a small contribution.

In the present study we use daily mean data and therefore slightly modified detection criteria; a moisture injection is an event in which f (integrated between 30 and 1000 hPa) at 70°N exceeds $240 \text{ Tg day}^{-1} \text{ deg}^{-1}$ for a minimum duration of 2 days at every point within a sector of at least 9° zonal extent. We find that the relative increase in magnitude of the duration and minimum flux intensity criteria in this study reproduces well the moisture injection statistics reported in [Woods et al. \(2013\)](#)—without the need to reject injection events using forward trajectories and a minimum latitude criteria ([Table 2](#)). Approximately 13 injection events are detected during each DJF season in both ERA-Interim reanalysis and the CMIP5 multimodel mean in this study, which compares well with the 14 reported in [Woods et al. \(2013\)](#).

e. Moisture intrusions

Forward trajectories are computed for each moisture injection event using the methodology of [Woods and Caballero \(2016\)](#). The three-dimensional velocity fields are integrated over 5 days using a forward Euler scheme:

$$\mathbf{x}(t + \Delta t) = \mathbf{x}(t) + \mathbf{u}(\mathbf{x}, t) \Delta t, \quad (8)$$

where $\mathbf{x}$ and $\mathbf{u}$ are the three-dimensional position and velocity vector fields, using pressure as a vertical coordinate. Prior to computing the trajectories we linearly

TABLE 1. The model and reanalysis data used in this study. (Expansions of acronyms are available online at <http://www.ametsoc.org/PubsAcronymList>.)

No.	Model index	Institution	Model version	Country	Atm. resolution	Reference
1	ACCESS1.0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology	Australian Community Climate and Earth System Simulator (ACCESS), version 1.0	Australia	192×144 , L38	Bi et al. (2013)
2	ACCESS1.3		ACCESS, version 1.3			Bi et al. (2013)
3	BCC-CSM1.1	Beijing Climate Center (BCC), China Meteorological Administration	BCC Climate System Model, version 1.1	China	128×64 (T42), L26	Li et al. (2014)
4	BCC-CSM1.1-m		BCC Climate System Model, version 1.1m		320×160 (T106), L26	Li et al. (2014)
5	BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University (BNU)	BNU Earth System Model (ESM), version 1	China	128×64 (T42), L26	Ji et al. (2014)
6	CanESM2	Canadian Climate Centre for Modeling and Analysis	Second Generation Canadian ESM	Canada	128×64 (T63), L35	Chylek et al. (2011)
7	CCSM4	National Center for Atmospheric Research	Community Climate System Model, version 4	United States	288×192 , L27	Gent et al. (2011)
8	CMCC-CESM	Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC)	CMCC Carbon ESM	Italy	96×48 (T31), L39	Fogli et al. (2009)
9	CMCC-CM		CMCC Climate Model		480×240 (T159), L31	Scoccimarro et al. (2011)
10	CMCC-CMS		CMCC Climate Model with a resolved stratosphere		192×96 (T63), L95	
11	CNRM-CM5	Centre National de Recherches Météorologiques (CNRM) and Centre Européen de Recherche et de Formation Avancées en Calcul Scientifique	CNRM coupled global climate model, version 5	France	256×128 (T127), L31	Voldoire et al. (2013)
12	CSIRO-Mk3.6.0	CSIRO and the Queensland Climate Change Centre of Excellence	CSIRO Mark, version 3.6.0	Australia	192×96 (T63), L18	Rotstayn et al. (2010)
13	EC-Earth	Swedish Meteorological and Hydrological Institute (SMHI) and Meteorological Institutionen, Stockholm University (MISU)	EC-Earth consortium, version 2.3	Europe	320×160 (T159), L62	Hazeleger et al. (2012)
14	FGOALS-g2	State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics	Flexible Global Ocean–Atmosphere–Land System model gridpoint, version 2	China	128×60 , L26	Li et al. (2013)
15	GFDL-CM3	Geophysical Fluid Dynamics Laboratory (GFDL)	GFDL Climate Model, version 3	United States	144×90 (C48), L48	Donner et al. (2011)

TABLE 1. (Continued)

No.	Model index	Institution	Model version	Country	Atm. resolution	Reference
16	GFDL-ESM2G		GFDL ESM with Generalized Ocean Layer Dynamics component		144 × 90, L24	Dunne et al. (2012)
17	GFDL-ESM2M		GFDL ESM with Modular Ocean Model component		144 × 90, L24	Dunne et al. (2012)
18	INM-CM4	Institute for Numerical Mathematics (INM)	INM Coupled Model, version 4	Russia	180 × 120, L21	Volodin et al. (2010)
19	IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace (IPSL)	IPSL Coupled Model, version 5, coupled with the Nucleus for European Modeling of the Ocean (NEMO), low resolution	France	96 × 96, L39	Hourdin et al. (2013a)
20	IPSL-CM5A-MR		IPSL Coupled Model, version 5, coupled with NEMO, mid resolution		144 × 143, L39	Hourdin et al. (2013a)
21	IPSL-CM5B-LR		IPSL Coupled Model, version 5, coupled with NEMO, new atmospheric physics, low resolution		96 × 96, L39	Hourdin et al. (2013b)
22	MIROC-ESM	National Institute for Environmental Studies	Model for Interdisciplinary Research on Climate (MIROC) ESM		128 × 64 (T42), L80	Watanabe et al. (2011)
23	MIROC-ESM-CHEM		MIROC ESM, coupled with a chemical model for the troposphere (CHASER 4.1)		128 × 64 (T42), L80	Watanabe et al. (2011)
24	MIROC4h		MIROC, version 4, high resolution	Japan	640 × 320 (T213), L56	Sakamoto et al. (2012)
25	MIROC5		MIROC, version 5		256 × 128 (T85), L40	Watanabe et al. (2010)
26	MPI-ESM-LR	Max Planck Institute for Meteorology (MPI)	MPI ESM, low resolution	Germany	192 × 96 (T63), L47	Giorgetta et al. (2013)
27	MPI-ESM-MR		MPI ESM, medium resolution		192 × 96 (T63), L95	Stevens et al. (2013)
28	MPI-ESM-P		MPI ESM, low resolution, paleo mode		192 × 96 (T63), L47	Giorgetta et al. (2013)
29	MRI-CGCM3	Meteorological Research Institute (MRI)	MRI coupled atmosphere–ocean general circulation model, version 3	Japan	320 × 160 (T159), L48	Yukimoto et al. (2012)
30	MRI-ESM1		MRI ESM, version 1		320 × 160 (T159), L48	Adachi et al. (2013)
31	NorESM1-M	Norwegian Climate Centre	Norwegian ESM, version 1, medium resolution	Norway	144 × 96, L26	Bentsen et al. (2013)
32	ERA-Interim	European Centre for Medium-Range Weather Forecasts (ECMWF)	ECMWF Integrated Forecast System, cycle 31r2	Europe	480 × 240 T(255), L60	Dee et al. (2011)

TABLE 2. Statistics of northward moisture flux and moisture injection events for the 31 CMIP5 models and ERA-Interim reanalysis. Quantities are shown for the Arctic (-180° to 180° E), Labrador (-80° to -30° E), Atlantic (-30° to 105° E), and Pacific sectors (105° to -80° E). The term $\bar{F}$ is the zonally integrated climatology of DJF northward moisture flux at 70° N in Pg day^{-1} ; the contribution to this quantity from vertically integrated moisture fluxes in excess of the injection detection threshold ($f = 240 \text{ Tg day}^{-1} \text{ deg}^{-1}$) is shown, for the whole domain, in parentheses. Also, N is the mean number of injection events originating within the various sectors each DJF season; σ_N and σ_L are the standard deviations of the DJF injection frequency and mean surface downward longwave radiation north of 70° N; and dL/dN is the detrended regression coefficient between the number of injections events and the DJF mean surface downward longwave radiation north of 70° N (units of W m^{-2} per injection). The terms r_{inj} and r_{res} are the correlation coefficients between DJF mean surface downward longwave radiation north of 70° N and the northward moisture flux contributed by injection events and the bulk residual moisture flux not contributed by injection events, respectively. Regression and correlation coefficients significant at the 2% level are highlighted in boldface. The symbols $[\bar{x}]$ and $[\sigma]$ indicate the CMIP5 multimodel mean and intermodel standard deviation of the various quantities, respectively. The $^+$ and $*$ symbols denote models that best represent the thermodynamic impacts and spatial distribution of moisture intrusion events, respectively.

Model index	Arctic							Labrador			Atlantic			Pacific		
	$\bar{F}$	N	σ_N	σ_L	$\frac{dL}{dN}$	r_{inj}	r_{res}	$\bar{F}$	N	σ_N	$\bar{F}$	N	σ_N	$\bar{F}$	N	σ_N
ACCESS1.0 ^{+,*}	12.7 (4.7)	10.2	2.63	3.13	0.57	0.48	0.28	1.84	1.1	1.08	7.94	8.1	1.62	2.98	1.0	1.31
ACCESS1.3 [*]	14.7 (5.8)	12.1	2.18	2.63	-0.03	0.35	-0.15	2.17	1.8	1.49	8.98	8.6	1.69	3.62	1.7	1.42
BCC-CSM1.1	14.2 (5.2)	13.2	2.10	3.45	0.36	0.26	0.16	1.63	0.8	0.96	6.66	6.3	1.91	6.00	6.0	1.75
BCC-CSM1.1-M	18.7 (8.6)	17.8	3.17	4.56	0.56	0.56	0.10	1.40	0.9	0.98	8.78	8.6	2.72	8.52	8.3	1.97
BNU-ESM ⁺	14.5 (4.8)	13.9	3.13	4.27	0.75	0.68	0.32	2.37	2.2	1.51	6.50	7.1	2.66	5.67	4.6	1.85
CanESM2 [*]	11.3 (3.7)	9.3	2.60	4.53	0.78	0.61	0.72	1.14	0.6	0.57	6.51	6.4	1.77	3.71	2.3	1.66
CCSM4 ⁺	19.0 (8.5)	19.0	3.34	4.46	0.72	0.67	0.03	1.93	1.5	1.10	9.45	10.3	2.78	7.73	7.2	2.18
CMCC-CESM	13.1 (4.4)	11.7	3.47	5.34	0.76	0.60	0.54	1.87	1.4	1.05	6.68	6.8	2.91	4.57	3.5	1.56
CMCC-CM ⁺	13.7 (4.5)	11.3	2.54	2.92	0.62	0.65	0.37	1.76	1.0	1.11	6.68	6.6	1.99	5.26	3.8	1.58
CMCC-CMS	14.4 (5.3)	13.3	3.28	2.97	0.18	0.31	0.20	1.81	1.3	1.40	7.15	7.5	2.40	5.53	4.5	2.21
CNRM-CM5 [*]	10.7 (3.1)	8.6	2.42	5.11	0.78	0.58	0.26	1.73	1.3	1.27	5.65	5.5	1.69	3.33	1.8	1.34
CSIRO-Mk3.6.0 ⁺	11.3 (3.4)	9.9	2.95	3.37	0.58	0.54	0.41	2.13	2.2	1.66	4.65	4.2	2.17	4.60	3.5	1.39
EC-Earth [*]	12.3 (4.0)	9.2	2.42	4.65	1.03	0.70	0.45	1.32	0.5	0.57	7.22	6.7	2.48	3.76	2.0	1.19
FGOALS-g2	13.0 (4.5)	12.2	2.22	2.89	-0.09	-0.15	0.56	3.56	4.3	1.80	4.67	4.4	1.80	4.89	3.5	1.39
GFDL-CM3	15.0 (5.6)	12.9	2.57	4.29	0.18	0.46	-0.11	1.81	1.3	1.40	8.49	8.3	1.58	4.78	3.4	1.55
GFDL-ESM2G	11.5 (3.5)	10.0	2.74	2.90	0.24	0.58	0.48	1.33	0.6	0.78	5.58	5.2	2.16	4.65	4.2	1.73
GFDL-ESM2M	12.1 (3.8)	10.8	3.93	5.48	0.77	0.62	0.68	1.76	1.6	1.45	5.56	5.4	2.82	4.88	3.8	2.32
INM-CM4	14.0 (3.8)	11.0	3.69	4.82	0.53	0.65	0.36	2.57	2.5	1.36	5.95	5.1	1.91	5.50	3.4	2.18
IPSL-CM5A-LR ⁺	12.0 (3.2)	9.2	2.63	4.06	0.94	0.53	0.36	2.05	1.4	1.05	5.22	3.6	1.96	4.82	4.1	1.58
IPSL-CM5A-MR	13.7 (4.4)	11.3	3.36	3.63	0.41	0.75	0.19	1.89	1.1	1.14	6.48	5.9	1.88	5.40	4.3	2.11
IPSL-CM5B-LR	12.4 (3.4)	10.7	2.44	2.92	0.14	0.33	0.79	2.44	2.4	1.06	5.15	4.1	1.80	4.91	4.3	1.77
MIROC-ESM ⁺	18.6 (7.8)	19.8	3.25	3.87	0.68	0.72	0.07	4.53	5.8	1.89	7.09	7.3	2.76	7.04	6.6	2.20
MIROC-ESM-CHEM ⁺	18.7 (7.8)	19.2	3.38	4.05	0.56	0.63	-0.06	4.70	5.6	1.80	6.93	7.6	1.94	7.15	6.0	2.47
MIROC4h	15.1 (5.6)	13.6	2.45	3.15	0.31	0.40	0.42	2.37	1.9	1.14	6.88	7.0	2.46	5.93	4.7	1.66
MIROC5	14.0 (4.7)	13.0	3.11	3.62	0.17	0.08	0.38	2.68	2.7	1.65	5.66	5.7	2.05	5.78	4.6	2.14
MPI-ESM-LR ⁺	16.2 (6.6)	15.7	3.42	4.71	1.04	0.63	-0.03	2.31	2.2	1.43	8.51	9.1	2.61	5.47	4.4	2.21
MPI-ESM-MR ⁺	16.1 (6.4)	15.5	2.93	4.44	0.77	0.47	0.21	2.57	2.4	1.24	8.05	8.6	2.42	5.52	4.4	1.83
MPI-ESM-P	16.3 (6.5)	14.8	2.69	3.34	0.58	0.30	-0.01	2.33	2.1	1.45	8.44	8.5	2.25	5.58	4.2	1.72
MRI-CGCM3 ⁺	15.5 (6.0)	13.3	3.13	4.82	0.75	0.43	0.37	1.14	0.5	0.79	8.33	8.3	2.65	6.09	4.4	2.16
MRI-ESM1 ⁺	16.1 (6.3)	14.3	3.26	5.35	0.86	0.68	0.18	1.42	0.9	0.84	8.28	8.4	2.64	6.42	5.0	2.12
NorESM1-M	18.4 (8.1)	18.1	2.76	4.27	0.24	0.60	0.47	2.19	1.7	1.82	9.19	10.0	2.32	7.05	6.4	1.36
CMIP5 $[\bar{x}]$	14.5 (5.3)	13.1	2.91	4.00	0.54	0.51	0.29	2.15	1.9	1.25	7.01	6.9	2.22	5.39	4.3	1.80
CMIP5 $[\sigma]$	2.4 (1.6)	3.1	0.46	0.83				0.82	1.3	0.35	1.36	1.7	0.40	1.25	1.6	0.35
ERA-Interim	14.3 (5.2)	12.8	2.92	4.95	0.76	0.50	0.16	2.07	1.5	1.12	8.25	9.3	2.37	4.01	2.0	1.38

interpolate the daily mean velocity data in the CMIP5 model and reanalysis data to a 6-hourly time resolution. An ensemble of 5-day forward trajectories are then computed for each injection event, using a time step of 6 h; the trajectories are initiated at 70° N and 900 hPa at each time step and grid point for which the injection criteria were satisfied. The 900-hPa level is where the time mean wintertime northward moisture transport is maximum (Woods et al. 2013).

For each injection event, we compute centroid trajectories by averaging the concurrent coordinates of the trajectories initiated at each time step for which the injection existed. These centroid trajectories allow us to represent each moist air mass intrusion into the Arctic with a set of n trajectories, where n is the number of days the injection event was sustained. We discuss the representation of these moist air intrusions in CMIP5 in section 4.

f. Missing fields

Some variables were unavailable for several of the CMIP5 models evaluated during the course of this study. These include sea ice concentration for models 5 and 13, precipitable water for model 14, and the vertical component of the wind velocity for model 18. Moisture intrusion trajectories were therefore not computed for model 18. (As such, Figs. 4, 5, and 6 are representative of the 30 other CMIP5 models listed in Table 1.)

3. CMIP5 biases

a. Surface climatology biases

Figure 1 shows the multimodel mean biases of some key fields for the CMIP5 models. We first note that the biases in the standard deviation of the 2–6-day bandpass filtered sea level pressure have a dipole pattern centered over the North Pole, with negative biases from the Labrador to the Barents/Kara Seas and positive biases from Alaska to Siberia. The negative biases in the North Atlantic have been reported on before and are generally attributed to overly zonal and southward-shifted storm tracks in the CMIP5 models (Zappa et al. 2013). As can be seen in Fig. 1c, a similar dipole pattern is also apparent in the surface temperature bias, with warm biases in Siberia and Alaska and cold biases from Greenland to the Barents/Kara Seas. Comparison with Fig. 1b shows that the peak cold biases are closely aligned with areas of excessive sea ice concentration, which also correlate with areas of negative bias in downward longwave radiation (Fig. 1d).

In the Pacific sector, positive biases in synoptic wave activity are displaced farther south than their North Atlantic counterparts and predominantly occur over land. Warm surface temperature biases tend to be lower in amplitude and more spatially heterogeneous than in the Atlantic sector. The largest thermodynamic biases in the Pacific sector occur over eastern Siberia, and may be also be related to poorly represented orography there.

Dry biases (Fig. 1f) predominantly occur in the North Atlantic, especially along the Norwegian coast and the southeastern coast of Greenland. There is also a robust moist bias in the Hudson Bay, associated with negative sea ice concentration and warm temperature biases there. Surface temperature biases tend to be of the same sign and larger in magnitude than those aloft over regions with low orography (Figs. 1c,e), indicating that the strength of the temperature inversion is generally too large in cold-biased regions and too weak in warm-biased regions. In section 6 we attempt to quantify the contribution to the surface temperature and surface downward longwave radiation biases arising

from misrepresentation of moisture intrusion events in the CMIP5 models.

b. Climatological moisture flux biases

The total zonally integrated time-mean northward moisture transport during DJF 1981–2005 [i.e., the zonal integral of $\bar{F}(\lambda, 0)$] in ERA-Interim is approximately 14.3 Pg day^{-1} . The corresponding values for each of the 31 CMIP5 models are reported in Table 2. There is a reasonably close agreement between the CMIP5 models and ERA-Interim, with a multimodel mean of 14.5 Pg day^{-1} and an intermodel variability on the order of 15% of the mean. For perspective, the corresponding southward quantities in ERA-Interim and the CMIP5 multimodel mean are -9 and -8.6 Pg day^{-1} , respectively.

In ERA-Interim, the contribution to the total zonally integrated northward moisture flux from events with flux intensities greater than the threshold used in our detection algorithm, $\bar{F}(\lambda, 240)$, is approximately 5.2 Pg day^{-1} or roughly 37% of the total. This partitioning is well represented in the CMIP5 models; about 36% of the total moisture flux is contributed by fluxes in excess of our threshold in the multimodel average, with an intermodel standard deviation of about 5%. The value of $f = 240 \text{ Tg day}^{-1} \text{ deg}^{-1}$ (equivalent to $73 \text{ kg s}^{-1} \text{ m}^{-1}$) also corresponds to the 93rd percentile of all vertically integrated northward moisture fluxes over all longitudes at 70°N in the ERA-Interim reanalysis. Liu and Barnes (2015) reported, in a similar analysis to Woods et al. (2013), that approximately 38% of the total northward moisture transport at 60°N is contributed by fluxes in excess of the 90th percentile, leading to a mean moisture flux of approximately $100 \text{ kg s}^{-1} \text{ m}^{-1}$ in injection events at 60°N . These numbers highlight the importance of extreme events in the climatology of moisture transport at 70°N .

The zonally resolved total northward moisture flux $\bar{F}(\lambda, 0)$ is shown in Fig. 2. As has been reported before (Woods et al. 2013), the bulk of the moisture flux into the Arctic occurs through the Atlantic sector, with subsidiary peaks in the Pacific and Labrador sectors. Substantial systematic biases in the spatial distribution of the fluxes are apparent in the CMIP5 models, with a tendency for underestimation in the Atlantic and overestimation in the Pacific sector (Fig. 2b and Table 2). These biases tend to compensate in the zonal mean, leading to the small net bias of only about 0.23 Pg day^{-1} noted above. The intermodel variability is on the same order as the mean bias, as evidenced by the contours of standard deviation in Fig. 2b. Nonetheless, over 80% of the models agree on the sign of the bias in the Atlantic and Pacific sectors. Furthermore, the moisture transport

FIG. 1. Mean DJF biases (1981–2005) in CMIP5 models for (a) standard deviation of the 2–6-day bandpass filtered sea level pressure, (b) sea ice concentration, excluding models 5 and 13, (c) surface temperature, (d) surface downward longwave radiation, (e) 850-hPa temperature, and (f) precipitable water, excluding model 14. The solid contour in (b) encloses the region with mean DJF sea ice concentration greater than 15% in ERA-Interim. Stippling denotes mean biases where at least 80% of the CMIP5 models agree on the sign of the bias. Dotted lines indicate the 70° and 80°N parallels. Green, red, and blue lines in (f) highlight the longitudinal extent of our objectively defined sectors.

biases are predominantly contributed by the higher-intensity fluxes ($f > 240 \text{ Tg day}^{-1} \text{ deg}^{-1}$), which are known to exert a significant control on climate in reanalysis datasets (Woods et al. 2013).

One may wonder about the sensitivity of these northward moisture flux biases to the choice of reanalysis dataset used as a control. The relative paucity of observations at high latitudes leads to a large reliance of

reanalysis datasets on their model derived output. As such, discrepancies between reanalysis datasets themselves may also constitute an important source of the moisture flux biases demonstrated in Fig. 2b. Figure S1 in the online supplemental material attempts to quantify the sensitivity of these biases to the choice of reanalysis dataset. The reanalyses examined include the National Centers for Environmental Prediction–National

FIG. 2. Shown as functions of the daily mean vertically integrated moisture flux intensity between 30 and 1000 hPa [f , see Eq. (1)] and longitude: (a) climatological northward moisture transport across 70°N in the ERA-Interim reanalysis during DJF 1981–2005 and (b) mean bias of the climatological northward moisture transport across 70°N in the 31 CMIP5 models during DJF 1981–2005. The quantities in (a) and (b) are summed into 75 Tg day^{−1} deg^{−1} by 10° longitude bins. Contours in (b) show the standard deviation of the intermodel biases. Dashed lines indicate the threshold value $f_{\min} = 240$ Tg day^{−1} deg^{−1} used in the injection detection algorithm. Stippling denotes mean biases where at least 80% of the CMIP5 models agree on the sign of the bias. Solid black lines in (a) highlight the longitudinal extent of our objectively defined sectors.

Center for Atmospheric Research Reanalysis 1 (NCEP1) and NCEP–U.S. Department of Energy Reanalysis 2 (NCEP2), ECMWF’s ERA-40, and NASA’s Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2). Figures S1b–e show that, in all cases, the dipole structure demonstrated in Fig. 2b is a robust feature of the CMIP5 models. The intermodel variance in CMIP5 (contours in Fig. 2b) is about double that of the inter-reanalysis variance (Fig. S1a), meaning that disagreements between CMIP5 models are typically twice as large as those between the reanalyses. Generally, the ECMWF reanalyses have less

northward moisture flux than their NASA and NCEP counterparts. These discrepancies are relatively homogeneous in ERA-Interim and the other reanalyses, displaying very little of the dipole structure seen in Fig. 2b. This strengthens our argument that the biases in Fig. 2b are a result of systematic biases in the CMIP5 models themselves. As we will see, dynamical biases play a key role in the emergence of this dipole structure.

c. Role of v and q

The large-scale structure of the northward moisture flux bias (Fig. 2b) is consistent with the biases in synoptic eddy activity and humidity shown in Fig. 1: given weaker eddy activity and lower humidity in the Atlantic we might expect fewer injection events and a negative bias in the moisture flux there, and vice versa for the Pacific. Here, we quantify how much of the bias in the moisture flux is due to biases in the meridional velocity and specific humidity fields, respectively.

We address this issue by first noting that the layer between 600 and 1000 hPa contains, on average, 81% of the total northward moisture transport $\bar{F}$ integrated through the full depth of the column in both the CMIP5 models and the reanalysis data. The results in Fig. 2 remain qualitatively unchanged when integrating the moisture flux between 600 and 1000 hPa, with the same robust and compensating biases between the Atlantic and Pacific sectors. It turns out that $\bar{F}$ for the 600–1000-hPa layer can be closely approximated by the product of the time mean northward mass flux $\bar{m}$ and the time-mean specific humidity $\bar{r}$, defined in (6) and (7) respectively, in the same layer:

$$\bar{F} \approx \bar{m} \bar{r}. \quad (9)$$

The average relative error of this expression, $|\bar{m} \bar{r} - \bar{F}|/\bar{F}$, averaged over all longitudes in the ERA-Interim reanalysis and CMIP5 model datasets is approximately 11% for $f_{\min} = 0$ and 4% for $f_{\min} = 240$ Tg day^{−1} deg^{−1}. Note that although $\bar{m}$ is a climatological mean, it is not the same as the mass flux carried by the climatological flow (i.e., the sum of the stationary waves and the zonal-mean overturning cell): because of the Heaviside function in (6), it actually contains contributions from northward motion on all time scales, including synoptic time scales.

For a given CMIP5 model, the terms in (9) may in turn be expressed as sums of the reanalysis climatology and the model bias:

$$\bar{F}^R + \bar{F}' \approx (\bar{m}^R + \bar{m}')(\bar{r}^R + \bar{r}'), \quad (10)$$

where the superscript R and the prime ($'$) refer to the reanalysis climatology and the model bias, respectively.

FIG. 3. The terms in (11) averaged over all 31 CMIP5 models for (a) $f_{\min} = 0$ and (b) $f_{\min} = 240 \text{ Tg day}^{-1} \text{ deg}^{-1}$. Magenta shading shows the intermodel standard deviation of $\bar{F}'$.

Expansion of the right-hand side of (10) allows us to write the moisture flux bias for a given model as

$$\bar{F}' = \bar{r}^R \bar{m}' + \bar{m}^R \bar{r}' + \epsilon, \quad (11)$$

where $\bar{F}'$ is the true bias in northward moisture flux and is equivalent to the integration of Fig. 2b along the y axis where $f > f_{\min}$. The terms $\bar{r}^R \bar{m}'$ and $\bar{m}^R \bar{r}'$ represent the contribution to $\bar{F}'$ from biases in v and q , respectively. The last term, ϵ , contains the error due to our initial assumption (9) and also the effect of cross-correlation between $\bar{m}'$ and $\bar{r}'$, which will be shown below to be small.

The terms in (11) averaged over all the 31 CMIP5 models are shown in Fig. 3 for $f_{\min} = 0$ and $240 \text{ Tg day}^{-1} \text{ deg}^{-1}$. In the $f_{\min} = 0$ case (Fig. 3a), the total moisture flux bias has

contributions of similar size from v and q , with the former having a slightly larger contribution than the latter, and ϵ being small. In the Barents Sea ($\sim 10^\circ\text{--}60^\circ\text{E}$), positive biases in the meridional velocity are largely compensated by negative biases in the specific humidity, leading to a small net moisture flux bias in the region, and the opposite behavior occurs over a small region east of Greenland. Elsewhere, biases in v and q contributions have the same sign.

For the more intense fluxes with $f_{\min} = 240 \text{ Tg day}^{-1} \text{ deg}^{-1}$ (Fig. 3b) the moisture flux bias is overwhelmingly dominated by biases in v at all longitudes. Over the Atlantic sector there are some small negative contributions from the specific humidity biases. This implies that dynamical biases in the models are the dominant source of climatically important moisture flux biases at high latitudes.

4. Moisture injections at 70°N

In Table 2 we present the statistics of moisture injection events from the CMIP5 models and ERA-Interim reanalysis. Moisture injection events are detected for each DJF season from 1981 to 2005 using the algorithm described in section 2d. Over the whole domain, the mean number of injections N detected each season in CMIP5 models is very close to that in ERA-Interim, with approximately 13 events per season. The compensating biases in $\bar{F}$ between the Atlantic and Pacific sectors lead to a similar pattern in the biases of moisture injection frequency between the two respective sectors. In the Atlantic sector an average of seven events per season occur in the CMIP5 models, compared to around nine in ERA-Interim, whereas in the Pacific sector approximately four events occur each season in the CMIP5 model mean, compared to about two in ERA-Interim. Biases in $\bar{F}$ and N in the Labrador sector are very small, as is the contribution to the total flux. Shown also for each of the sectors is the interannual standard deviation of injection frequency, σ_N . The mean variability in moisture injection frequency over all CMIP5 models is very close to that observed in the ERA-Interim reanalysis ($\sigma_N \approx 3$ injections per season).

We also examine the impacts of moisture injections on the variability of surface downward longwave radiation averaged over the Arctic region. The term σ_L denotes the standard deviation of the DJF-mean surface downward longwave radiation north of 70°N for the 1981–2005 period. On average, the CMIP5 models underestimate the interannual variability by about 1 W m^{-2} , or 20%. The regression coefficient, obtained by regressing the detrended time series of moisture injection frequencies N each winter onto the seasonal mean surface downward

longwave radiation north of 70°N, is denoted by dL/dN . This quantity differs significantly between the ERA-Interim reanalysis and CMIP5 model mean, with the average model exhibiting weaker seasonal surface impacts due to intrusions. An anomaly of +1 injection in a given season corresponds to an increase in the seasonally averaged surface downward longwave flux north of 70°N of about 0.75 and 0.5 W m^{-2} in the ERA-Interim and CMIP5 model mean, respectively. Note that the ERA-Interim value is itself likely an underestimate of the real value because of the misrepresentation of mixed-phase clouds in the reanalysis (Engström et al. 2014).

Thus, intrusions in the CMIP5 models show about 33% weaker surface downward longwave radiation impacts due to moisture intrusions than in ERA-Interim. This underestimation may be due in part to the cold bias in the majority of the models (Figs. 1c,e). For a given temperature perturbation ΔT induced by an intrusion, the resulting downward longwave radiation perturbation crudely estimated from the Stefan–Boltzmann law, $\Delta F \sim 4\sigma T^3 \Delta T$, depends partially on the background temperature T (the background humidity is also an equally important factor that can contribute to this bias). Thus, models with cold-biased Arctic climates will have a tendency to underestimate the radiative perturbations associated with moisture intrusions.

As shown in Woods et al. (2013), in ERA-Interim the minority of the total northward moisture flux that is contributed by intrusions exerts a significant control on the interannual variability of surface downward longwave radiation north of 70°N, while the remaining bulk of the northward moisture flux exerts no significant control. We also assess this feature in the CMIP5 models. The term r_{inj} denotes the correlation coefficient computed for the 1981–2005 period between the detrended time series of the total northward moisture transport contributed by the injection events each season and the seasonal mean surface downward longwave radiation averaged over the region north of 70°N. The same correlation, but with respect to the bulk residual of the northward moisture transport (that which is not contributed by the injection events), is denoted by r_{res} . Correlations significant at the 2% level are shown in boldface. Overall, 17 of the 31 models exhibit the same qualitative behavior as in the ERA-Interim reanalysis, with significant and insignificant correlations in r_{inj} and r_{res} , respectively. Models with significant correlations and regression coefficients in r_{inj} and dL/dN , respectively, and with insignificant correlations for r_{res} are denoted by a superscript plus sign (+) in Table 2. Models in which the ratio of the combined number of intrusions originating in the Labrador and Atlantic sectors to the number of intrusion originating in the Pacific sector is greater than 3 [i.e., $[(N_{\text{lab}} + N_{\text{atl}})/N_{\text{pac}}] > 3$] are

denoted by an asterisk (*). In ERA-Interim this ratio is approximately 5.5.

5. Moisture intrusions into the Arctic

We now turn our attention to tracking intrusions through the Arctic region from their initial point of injection at 70°N. As described in section 2d, forward trajectories are computed for each injection event in the CMIP5 models and ERA-Interim reanalysis. Figure 4 shows the climatological densities of centroid trajectories, computed by dividing the region north of 70°N into 400 km × 400 km grid boxes, and counting at each grid box the number of injection events in which at least one representative centroid trajectory passed through the grid box. We also separately examine intrusions originating in the Atlantic and Pacific sectors (Figs. 4d–i). We do not show results for the Labrador sector due to the relatively small number of injection events and low biases exhibited in the region.

The results for ERA-Interim (Fig. 4b) show a great deal of similarity with those reported in Woods and Caballero (2016, their Fig. 3). The arrows indicate that intrusions entering through the Atlantic (Figs. 4d,e) and Pacific sectors (Figs. 4g,h) turn cyclonically as they propagate through the Arctic basin, following very similar mean trajectories in both the CMIP5 models and ERA-Interim reanalysis.

As expected, the sectoral biases in injection frequency (Table 2) lead to complementary intrusion density biases within the Arctic region (Fig. 4, right column). In the CMIP5 models, we note higher intrusion densities in the Pacific sector and lower intrusion densities in the Atlantic sector on average. It is clear that the intrusion density bias in the Atlantic sector is entirely due to the bias in injections emanating from the Atlantic sector itself, with the same being true for the Pacific sector. The total bias in intrusion density in each sector is almost entirely contributed by the respective biases in the Atlantic and Pacific sectors (i.e., Fig. 4c is approximately a combination of Figs. 4f,i).

The overall patterns of intrusion densities compare very well between the CMIP5 models and ERA-Interim. Biases in intrusion densities in the Atlantic and Pacific sectors emerge principally due to overestimation and underestimation of the pattern amplitude, respectively. As such, dynamical biases related to the position of the storm tracks are likely the main source of intrusion density biases in the CMIP5 models.

6. Vertical structure of temperature perturbations induced by intrusions

We compute composites of temperature anomalies associated with the passage of an intrusion north of 80°N

FIG. 4. (a) Mean climatological intrusion trajectory density during DJF 1981–2005 for all intrusions in 30 of the CMIP5 models (model 18 not included). (b) As in 9a), but for the ERA-Interim reanalysis. (c) Mean intrusion density bias in the CMIP5 models. Arrows show the mean tangent vector at each point; a value of 1 [shown in upper left of (a)] implies all trajectories passing a certain point move in the same direction. (d)–(f) As in (a)–(c), but for the subset of intrusions originating from the Atlantic sector. (g)–(i), As in (a)–(c), but for the subset of intrusions originating from the Pacific sector. Stippling denotes mean biases where at least 80% of the CMIP5 models agree on the sign of the bias. Dotted lines indicate the 70° and 80°N parallels.

in the CMIP5 models and ERA-Interim as follows. The region is first divided into $200 \text{ km} \times 200 \text{ km}$ grid boxes. Each centroid trajectory from the CMIP5 model or ERA-Interim dataset is then sampled at 24-hourly time

steps beginning from the injection point at 70°N; for each sample point northward of 80°N we extract a 9-day time series of vertical temperature profiles centered on the time when the trajectory arrives at the grid point. We subtract

the 1981–2005 DJF mean temperature for the given CMIP5 model or reanalysis and average over all events.

The vertical structure of temperature perturbations induced by intrusions is compared between ERA-Interim and the CMIP5 models in Fig. 5. The CMIP5 models capture the amplitude and structure of the temperature perturbations reasonably well on average; intrusions are associated with warm anomalies in the troposphere and cold anomalies in the stratosphere on average (Figs. 5a,b). The effects of an intrusion begin to be felt around 4 days before the arrival of the centroid trajectory at the grid point. CMIP5 models tend to underestimate the persistence of the surface-based anomalies, however, leading to more vertically uniform perturbations compared to ERA-Interim in the days following the passage of an intrusion. The structure of these anomalies in ERA-Interim has been reported on in more detail by Woods and Caballero (2016). We note here an interesting and previously unreported feature: intrusions originating in the Atlantic sector tend to be accompanied by stratospheric cooling (Figs. 5c,d), whereas intrusions originating in the Pacific sector tend to be accompanied by stratospheric warming (Figs. 5e,f). From this, one may conclude that the stratospheric signature of intrusions in the deep Arctic is not primarily determined by thermodynamic impacts of the troposphere on the stratosphere. Rather, this pattern suggests a possible link with the heat flux in the stratosphere, which is itself associated with vertical wave coupling between the stratosphere to the troposphere (Shaw and Perlwitz 2013). We do not consider the issue further here, but it remains an interesting avenue for further research.

7. Impacts on surface temperature and surface downward longwave radiation biases

The large-scale pattern of biases in intrusion density (Fig. 4c) are robust, and match closely with the systematic biases in some of the key dynamical and thermodynamical fields (Fig. 1). In Woods and Caballero (2016) we reported that moisture intrusions have significant seasonal-mean warming impacts over the Arctic region, particularly in the marginal sea ice zones. As such, the systematic misrepresentation of intrusion densities in the CMIP5 models may be a proximate cause for the surface climatic biases in these regions.

In this section we attempt to estimate the proportion of the surface downward longwave radiation and surface temperature biases contributed by biases in moisture intrusion density over the Arctic region. Our method follows previous work (Woods and Caballero 2016) in which we estimated Arctic winter climate change using detrended regressions between intrusion centroid trajectory

density and seasonal mean fields at each grid point north of 70°N. These regressions quantify the association between interannual variability in intrusion density and surface fields. We compute these detrended regressions for each of the CMIP5 models. Averaging over all CMIP5 models, detrended regressions show significant impacts by intrusions on seasonal-mean surface temperature (Fig. 6a) and surface downward longwave radiation (Fig. 6g). As in ERA-Interim, the largest impacts occur in the marginal sea ice zones of the Labrador, Barents, Kara, and Chukchi Seas (Woods and Caballero 2016). We note that the largest amplitude signals are displaced southward in CMIP5 relative to ERA-Interim. This is most likely due to the positive sea ice concentration biases (Fig. 1b), which displace marginal sea ice zones to the south.

As in Fig. 4, we partition the injections by their sectors of origin. Figures 6b,c show the mean CMIP5 detrended regressions between intrusion density and seasonal mean surface temperature, computed using only the subset of intrusions originating within the Atlantic and Pacific sectors, respectively. We note that intrusions tend to have significant warming impacts in their sectors of origin and cooling impacts (albeit statistically insignificant) over the sectors on the opposite side of the Arctic basin. This leads us to a conceptual picture whereby intrusions entering the Arctic initially have a strong warming effect in the immediate marginal sea ice zones. It is important to note that the formation of clouds is very important in the emergence of this surface-based warming. Clouds, on account of their high emissivity, absorb and reemit a large portion of the longwave radiation originating from the surface. As the cloud continues to reemit this radiation downward, the surface temperature increases. As such, the surface and cloud tend toward a state of radiative equilibrium in which the cloud base and surface temperatures are approximately equal. Considering that the climatological temperature profiles are characterized by inversions during winter, a transition to an isothermal profile due to the formation of a cloud would cause large temperature anomalies at the surface. As the warm moist air mass propagates farther northward, the surface warming impacts begin to diminish as the air becomes cooler and drier (e.g., Pithan et al. 2016). The air mass eventually equilibrates with the Arctic winter state somewhere near the North Pole, corresponding to a relaxation time scale of about 4–5 days. As the air mass continues to be advected toward the south, dry cold air leads to seasonal cooling impacts at the surface. The cooling impacts are statistically insignificant on average in the CMIP5 models, possibly due to forward trajectories decorrelating over their latter part. The cooling effects we have noted lead to an underestimation of the warming impacts when computing detrended regressions using

FIG. 5. Composite anomalies showing the temperature perturbation associated with the passage of an intrusion over grid points north of 80°N in the (left) CMIP5 multimodel mean and (right) ERA-Interim reanalysis. Composites are computed for intrusions originating in (a),(b) all sectors, (c),(d) the Atlantic sector, and (e),(f) the Pacific sector. Stippling denotes mean anomalies where at least 80% of the CMIP5 models agree on the sign of the anomaly.

FIG. 6. Detrended regression coefficients averaged over 30 of the CMIP5 models (model 18 not included) of DJF intrusion density at each grid box onto DJF mean surface temperature at the same grid box for intrusions originating from (a) all sectors, (b) the Atlantic sector, and (c) the Pacific sector. (e) The contribution of the Atlantic sector intrusions to the true bias in surface temperature, obtained by averaging the product of the regression field and respective intrusion density bias field over all models. (f) As in (e), but for intrusions originating in the Pacific sector. (d) The mean predicted bias in surface temperature for all intrusions over the 30 CMIP5 models; obtained by averaging the sum of the predicted biases from the Labrador (not shown), Atlantic and Pacific sector intrusions, respectively [i.e., (d) $\approx$ (e) + (f)]. (g)–(l) As in (a)–(f), but for the surface downward longwave radiation. Solid black contours enclose regions where the CMIP5 model regressions were significant at the 10% level on average. Regions enclosed by solid (70° – 90° N, -30° – 90° E) and dashed (70° – 80° N, 180° – 230° E) black lines in (d) and (j) show the regions used for computing the gradients in Figs. 7a and 7b, respectively. Dotted lines show the 70° and 80° N parallels.

all injections together (Figs. 6a,g), as significant warming impacts are compensated by smaller cooling impacts in the time mean. The same qualitative behavior is noted when using the surface downward longwave radiation (Figs. 6h,i), with the significant impacts occurring over a slightly larger area on average.

Statistically predicted biases of the surface temperature field are computed for each model by taking the product of the intrusion density bias field and the detrended regression coefficient field. This method is

conceptually similar to that used by Woods and Caballero (2016). Figures 6e and 6f show this predicted bias, averaged over all CMIP5 models, for injections originating in the Atlantic and Pacific sectors, respectively. As can be seen, the negative bias in injections originating in the Atlantic sector leads to a predicted negative bias in the surface temperature. In the Pacific sector, the positive bias in intrusion densities leads to average predicted biases that are positive. The total predicted surface temperature bias due to all injection biases—the sum of the biases predicted for each of the sectors—is shown in

FIG. 7. Regressions of the true and predicted bias gradients in 30 of the CMIP5 models (model 18 not included), computed between the regions enclosed by solid and dashed black lines in Figs. 6d,j, for (a) surface temperature and (b) surface downward longwave radiation. Both regressions are significant at the 0.002% level. Thick dashed lines show the linear regression curve (equation in lower right of each panel) between the quantities. Label numbers refer to the models outlined in Table 1. Label colors indicate the sea ice area bias for each model, integrated over the region enclosed by solid black lines in Fig. 6d. Sea ice concentration data were not available for models 5 and 13 (colored in black). Sea ice area bias is calculated at each grid point as the product of the sea ice concentration bias and grid box area.

Fig. 6d. The negative bias in surface temperature in the Atlantic sector is almost entirely contributed by the negative bias in Atlantic injection frequencies, with the converse being true in the Pacific sector. We also compute predicted biases of the surface downward longwave radiation using the same methodology (Figs. 6j–l), which show very similar patterns.

The large-scale patterns of predicted biases in Figs. 6d,j compare well with those presented in Figs. 1c,d. Over the Atlantic sector (region enclosed by solid black lines in Figs. 6d,j), our predicted biases explain approximately 17% and 24% of the total biases in surface temperature and surface downward longwave radiation, respectively. Clearly, processes other than northward moisture transport also play an important role in biasing the Arctic winter climate in this sector. Processes such as ocean heat transport and heat flux through sea ice presumably exhibit biases of their own, but quantifying them is outside the scope of this study. Biases in the cloud fields and cloud properties may also be an important contributing factor. Reanalysis datasets have relatively large discrepancies in their climatological cloud fields and cloud properties, however (Lindsay et al. 2014; Engström et al. 2014). Quantifying the biases in CMIP5 contributed by biases in the cloud data is therefore difficult, as the results are likely to be quite sensitive to the choice of reanalysis dataset used as a control. As such, we do not consider the explicit role of clouds in this paper but rather choose to focus on the bulk thermodynamic impacts of the intrusions at the surface, which certainly contain important contributions from clouds. Recall also that the seasonal impacts of

thermodynamic perturbations associated with moisture intrusions are themselves too weak in CMIP5 (section 4). This point is confirmed by the significantly larger amplitude of regressions observed in reanalysis data; compare Figs. 9a,c in Woods and Caballero (2016) with Figs. 6a,g in the present study.

In the Pacific sector (region enclosed by dashed black lines in Fig. 6d) our methodology predicts mean biases of 0.8 K and 3.5 W m^{-2} . These are qualitatively different from the true biases in the region (Figs. 1c,d), which are -2.2 K and -2.45 W m^{-2} , respectively. Thus, biases in intrusion density induce a relative warming of the Pacific region, in contrast to the cooling observed. Other processes such as ocean heat transport (Wang et al. 2014) induce a near-uniform cold bias across the Arctic. Background biases of about -3 K and -6 W m^{-2} , due to other processes, would be sufficient to translate our predicted biases of surface temperature and surface downward longwave radiation much closer to those observed.

As we have noted, the gradients of biases across the Arctic basin are also a feature of interest. Figures 7a,b show the true and predicted gradients in surface temperature and surface downward longwave radiation biases. These gradients are estimated as the difference between the respective fields averaged over the boxes shown in Fig. 6d. The boundaries for the area averaging were chosen to best represent the regions with significant regression coefficients (solid black contours in Figs. 6b,c,h,i). The gradient is taken going from the Atlantic region to the Pacific region, and is positive in most models.

Regression coefficients in Figs. 7a and 7b indicate that our methodology explains only about 14% and 16% of

the gradients of surface temperature and surface downward longwave radiation biases between the regions, respectively. However, there is a high degree of skill associated with the prediction, with a p value less than 0.002% in both cases. Thus, while our method may only predict a small amplitude, it is highly correlated with the true bias gradients. Furthermore, the bias is underpredicted largely as a result of the excessive sea ice concentration biases in the Atlantic sector, which are associated with similarly large biases in the surface temperature and surface downward longwave radiation fields. Label coloring in Figs. 7a,b indicates that the models with the largest gradients are invariably the models with the most excessive amount of sea ice in the Atlantic. The fact that our method is so highly correlated with the true bias gradients in the models, but predicts only a small amplitude pattern, suggests that strong positive feedbacks may exist between intense moisture transport at 70°N and sea ice extent in the Atlantic sector. Intrusion biases appear to play an important role in the emergence of these gradients across the Arctic basin. The effect of excessive sea ice concentration in the Atlantic is clearly an important factor in amplifying these bias gradients.

The ERA-Interim reanalysis assimilates observed sea ice concentration data, and as such reflects what may be considered as the true response of sea ice to intrusions in the marginal zones. We suspect that the modeled sea ice dynamics in the CMIP5 models may be too slow in these marginal zones. If the sea ice does not react quickly enough to the relatively short-lived thermodynamic and dynamic perturbations induced by intrusions, the long-lasting impacts due to sea ice loss captured in the reanalysis (Woods and Caballero 2016) will not be reproduced. Limitations in sea ice modeling in climate models (Rampal et al. 2011) may therefore lead to the weaker seasonal impacts of intrusions in the marginal zones we have noted, and may also explain how sea ice concentration biases in the Atlantic region of around 40% can be associated with an injection discrepancy of only 25% in the same region. Excessive sea ice concentration in the Atlantic region will also lead to enhanced drying and cooling of intrusions as they travel northward. All else being equal, a positive sea ice concentration anomaly in the Atlantic sector would cause moist intrusions to have weaker thermodynamic impacts at a given point downstream of their point of origin. Given that the climatology at a given point in the Arctic region is partly dependent on the frequency and intensity of intrusions that reach there, adding the sea ice would tend to induce indirect cooling downstream of the sea ice anomaly, along the climatological moisture intrusion flow (Fig. 4e). This cooling could reinforce and induce further positive sea ice concentration

anomalies downstream, leading to more sea ice growth, and further downstream cooling, etc. This effect could contribute to the weaker seasonal impacts of intrusions in the interior that we have noted (Table 2).

8. Summary and conclusions

We have studied biases in some key meteorological fields during December to February in 31 of the CMIP5 models. Biases in surface temperature and synoptic activity over the Arctic region are characterized by a robust dipole pattern centered over the North Pole. One lobe of this dipole consists of a strong cold bias in the Atlantic sector associated with excessive sea ice concentration and a dry bias there. We examine how these dynamic and thermodynamic biases are related to the northward moisture flux at 70°N in the CMIP5 models. We find that robust biases exist in the mean northward moisture flux at 70°N. Underestimation of the northward moisture flux in the Atlantic sector is largely compensated by overestimation of the transport through the Pacific sector, leading to a mean bias close to zero when integrating over the whole domain. These regional biases of moisture flux are predominantly due to biases in the most intense moisture fluxes, in excess of the 93rd percentile of all moisture fluxes ($f > 240 \text{ Tg day}^{-1} \text{ deg}^{-1}$). These extreme moisture fluxes are known to have significant climatic impacts during winter (Woods et al. 2013; Woods and Caballero 2016), although such events only occur about once per week on average. The relative roles of the meridional velocity and specific humidity in the emergence of moisture flux biases were also examined and it was found that, for the most intense fluxes, the biases are due by mostly to biases in the meridional velocity field.

Biases in the northward moisture transport in CMIP5 lead to complementary biases in the frequency of moisture injection events at 70°N. In previous work (Woods et al. 2013) we showed that moisture injection events contribute approximately 30% of the total northward moisture flux, yet drive a significant amount of the interannual variability in winter surface temperature and surface downward longwave radiation north of 70°N. We further demonstrated that the residual 70% of the northward moisture transport exerts no significant control on the Arctic winter climate variability. We find that a majority of the CMIP5 models exhibit this same behavior. The impact of a single injection event on the seasonal-mean surface downward longwave radiation is estimated for each CMIP5 model and ERA-Interim by means of detrended linear regressions. CMIP5 models tend to underestimate the seasonal mean impacts of moisture injection events by about 33% compared to ERA-Interim, possibly due to systematic cold biases north of 70°N.

In more recent work (Woods and Caballero 2016) we followed the trajectories of these moist air masses through the Arctic region and showed that approximately 45% of recent surface warming and 35% of recent sea ice loss in the Barents and Kara Seas during DJF 1990–2012 can be explained by an increase in the frequency of moisture intrusion events being advected over the region. In this study, we have followed the methodology of Woods and Caballero (2016) and followed the moisture intrusions through the Arctic region in the CMIP5 models. We find qualitatively similar results to Woods and Caballero (2016) for the density of intrusion events north of 70°N; intrusions in CMIP5 predominantly originate in the Atlantic sector and curve cyclonically, over a period of 5 days, between their points of initial injection and exit region.

Biases in injection frequency in CMIP5 lead to negative intrusion density biases in the Atlantic sector and positive biases in the Pacific sector. We used a statistical prediction technique to quantify the contribution of intrusion biases to the biases in surface temperature and surface downward longwave radiation north of 70°N in the CMIP5 models. In the Atlantic sector, approximately 17% and 24% of the biases of these fields are explained by biases in intrusion density. Approximately 14% and 16% of the gradients in surface temperature and surface downward longwave radiation biases, between the Atlantic and Pacific sectors, are explained by the biases in intrusion densities over the Arctic region. One may speculate on the sensitivity of these results to the choice flux threshold ($f_{\min}$) used in the moisture injection detection algorithm (section 2d). To address this we have recomputed the quantities shown in Figs. 6 and 7, but using values of $f_{\min} = 150$ and $400 \text{ Tg day}^{-1} \text{ deg}^{-1}$ in the detection algorithm, respectively. Results are shown in the accompanying supplementary material (Figs. S2–S5). Overall, our main results are not qualitatively changed by the choice of $f_{\min}$. We find that using the lower threshold of $f_{\min} = 150 \text{ Tg day}^{-1} \text{ deg}^{-1}$ increases the proportion of the bias gradients that we predict by about 4%–5% with respect to Fig. 7 (Fig. S4), with about a 65% increase in the frequency of moisture intrusion events—approximately 21 per DJF season in ERA-Interim. When using the higher flux intensity threshold of $f_{\min} = 400 \text{ Tg day}^{-1} \text{ deg}^{-1}$, we find that our prediction of the bias gradients is reduced by about 6% with respect to Fig. 7 (Fig. S5), implying that important moisture injections are likely being left out at this higher threshold. Note that the regions of significance in Fig. S3 are much smaller on account of the very small number of intrusions making up the composites (~5 per DJF season, roughly a 60% decrease in the frequency of intrusion events in ERA-Interim). In all the flux threshold cases we see a similar pattern; a high significance in the

regression, which explains only a small proportion of the true signal: between 10% and 20% depending on the choice of threshold. Furthermore, Figs. S1b–e indicate that the use of ERA-Interim as control leads to a dipole bias that is actually underestimated with respect to the majority of the other reanalyses. MERRA and the NCEP reanalyses suggest that the dipole structure in the northward moisture flux bias at 70°N is stronger than ERA-Interim would suggest. These larger moisture flux biases from MERRA and NCEP would likely translate into complementary moisture intrusion events biases; all else being equal, one would expect an even greater disparity between the Atlantic and Pacific sectors in terms of moisture intrusion frequency when using these reanalyses as control. The choice to use ERA-Interim as a control may therefore lead us to underestimate the impacts of moisture intrusion biases on Arctic climate biases. In either case, the highly significant correlation between our predicted bias gradients and the true bias gradients suggests that strong feedbacks may exist between intense moisture transport at 70°N and sea ice extent. Excessive sea ice concentration in the Greenland, Barents, and Kara Seas appears to be closely linked to the emergence of these gradients. Our results indicate that additional biases of approximately -3 K and -6 W m^{-2} are likely being contributed by processes other than moisture intrusions.

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