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Validation of the 1/12° Arctic Cap Nowcast/Forecast System (ACNFS)

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14. ABSTRACT

Naval Research Laboratory has compared sea ice hindcast for the Arctic Ocean derived from the latest coupled ice-ocean prediction system to observations. The system is based on the HYbrid Coordinate Ocean Model coupled via the Earth System Modeling Framework to the Los Alamos Community Ice CodE and tested using the Navy Coupled Ocean Data Assimilation system. The validation of the 1/12° Arctic Cap Nowcast/Forecast System (ACNFS) was accomplished by comparing hindcast fields to the current operational Polar Ice Prediction System (PIPS 2.0) as well as comparing to observations. Both the ACNFS and PIPS 2.0 output daily fields of ice thickness, ice concentration, and ice drift. The goal of the validation is to determine if the new ACNFS is an improvement over the existing PIPS 2.0 model and should be used, operationally, in its place. NRL validated hindcasts and forecasts of ice edge location, ice thickness, ice draft, and ice drift using observational data sets such as daily ice edge, ice mass balance buoys, ice thickness survey flight data, upward looking sonars data and Special Sensor Microwave/Imager ice concentration data. NRL evaluated the models against these data during the years 2007–2009 depending on the availability of the observations.

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Contents

1 Introduction

The Naval Research Laboratory (NRL) has developed a 1/12° Arctic Cap Nowcast/Forecast System (ACNFS). ACNFS is based on the HYbrid Coordinate Ocean Model (HYCOM) coupled via the Earth System Modeling Framework (ESMF) to the Los Alamos National Laboratory Community Ice CodE (CICE) and uses the Navy Coupled Ocean Data Assimilation (NCODA) system.

This Validation Test Report documents a series of comparison studies (i.e., ice edge location, ice thickness, ice draft and ice drift) performed using ACNFS. ACNFS is validated against *in situ*, satellite and derived observations. The validation also includes a comparison to the existing operational Polar Ice Prediction System version 2.0 (PIPS 2.0) sea ice fields. Both ACNFS and PIPS 2.0 output daily fields of ice thickness, ice concentration and ice drift. One goal of this validation study is to determine if the newly developed ACNFS is an improvement over the existing PIPS 2.0. The ACNFS will be the interim ice forecasting system until the 1/12° Global Ocean Forecasting System (GOFS) V3.1 (global 1/12° HYCOM/NCODA/CICE) is operational. This full global system is scheduled for delivery to the Naval Oceanographic Office (NAVOCEANO) by the end of 2011.

ACNFS fields of ice concentration, ice edge location, ice thickness, ice draft and ice drift are validated using observational data sets including Arctic drifting buoy data, ice mass balance buoys, airborne ice thickness survey data, upward looking sonars, daily ice edge locations from the National Ice Center (NIC) and Special Sensor

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Microwave/Imager (SSM/I) ice concentration data. The validation spans the period of July 2007- June 2009. Analyses during this time period are preformed on both hindcast and 24 hr forecast simulations. Daily and seasonal analyses of the ice edge location indicate that ACNFS has substantially lower ice edge error than PIPS 2.0. ACNFS is generally performing similarly to PIPS 2.0 in ice thickness, ice drift and ice draft.

2 Ice Nowcast/Forecast System Descriptions

2.1 Polar Ice Prediction System (v2.0) – PIPS 2.0

The current operational ice forecasting system run at NAVOCEANO is PIPS 2.0 (Preller and Posey, 1996). PIPS 2.0 is an ice-ocean model that couples the Hibler ice model (Hibler, 1979), reformulated into spherical coordinates (Cheng and Preller, 1996), to the Cox (1984) ocean model, also in spherical coordinates. Figure 1 contains a schematic of all components of PIPS 2.0. Information between ice and ocean models is exchanged by interfacing the top level of the ocean model with the ice model. Parameters exchanged at this interface include ice/ocean stresses, salinity, temperature and heat fluxes. The ocean model temperature and salinity fields are loosely constrained (Sarmiento and Bryan, 1982) to the Levitus (1982) climatological data set. The bathymetry used by the ocean model is derived from the Naval Digital Bathymetric Databases 5’ x 5’ (DBDB5) (Naval Oceanographic Office, 1997). Atmospheric forcing is obtained from the Navy Operational Global Atmospheric Prediction System (NOGAPS) (Hogan et al., 1991).

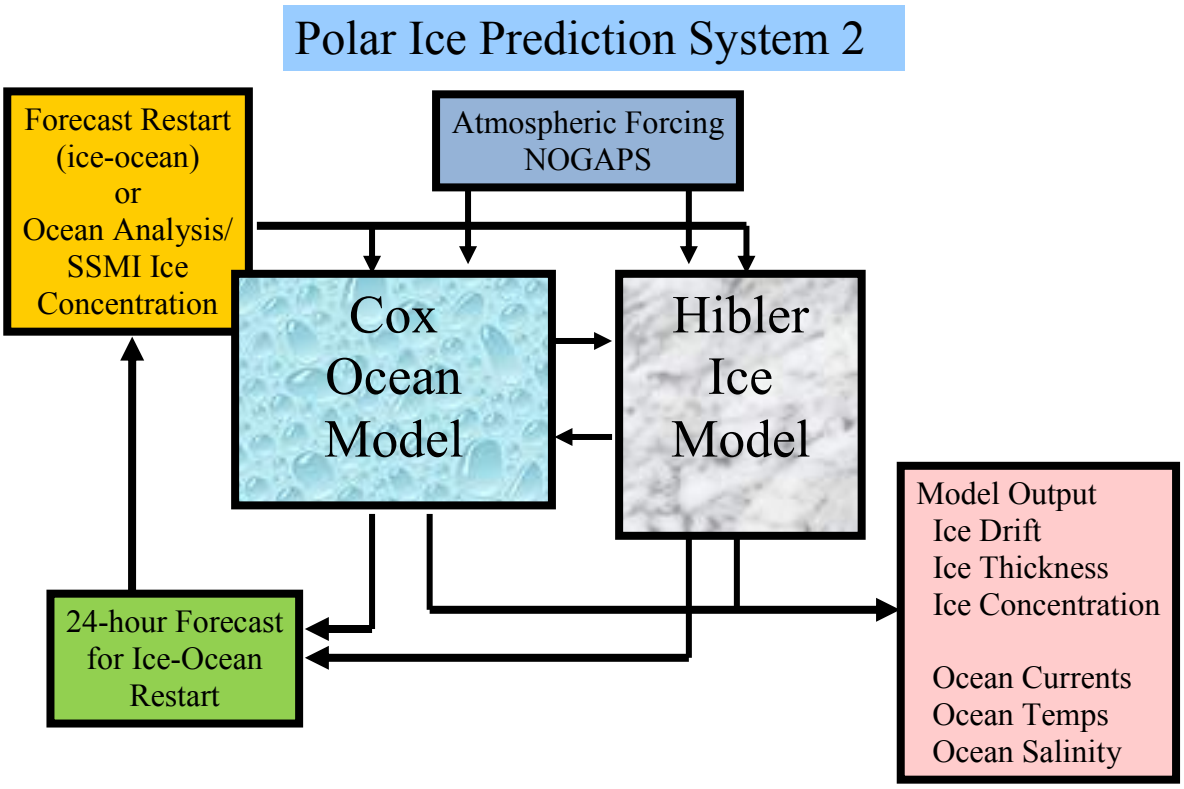

Figure 1. A schematic of the PIPS 2.0 sea ice forecast system.

PIPS 2.0 was developed to include all of the sea ice-covered regions in the Northern Hemisphere. The model domain extends from the North Pole to 30° N (Figure 2), and is designed to cover regions as far south as the Yellow Sea. The horizontal grid resolution of the model is 0.28° (17-33 km depending on the location within the spherical coordinate system). The ocean model uses 15 vertical levels. The top level is 30 m thick and increases with depth to a maximum thickness of 1025 m. PIPS 2.0 is currently run in serial mode on the Navy Department of Defense Supercomputing Resource Center (DSRC) IBM Power 6 (Davinci) at NAVOCEANO with a 2 hr time step for the ice model and a 30 min time step for the ocean model. All model boundaries are solid walls with zero flow conditions. The model boundaries are placed sufficiently far from the

main forecast locations to minimize any boundary effects on the forecasts. PIPS 2.0 output files include ice drift, ice thickness and ice concentration. Restart fields consisting of the model's 24 hr forecast are written to files to be used in the next forecast. If the model restart fields are not available a model derived climatology is used to restart the system.

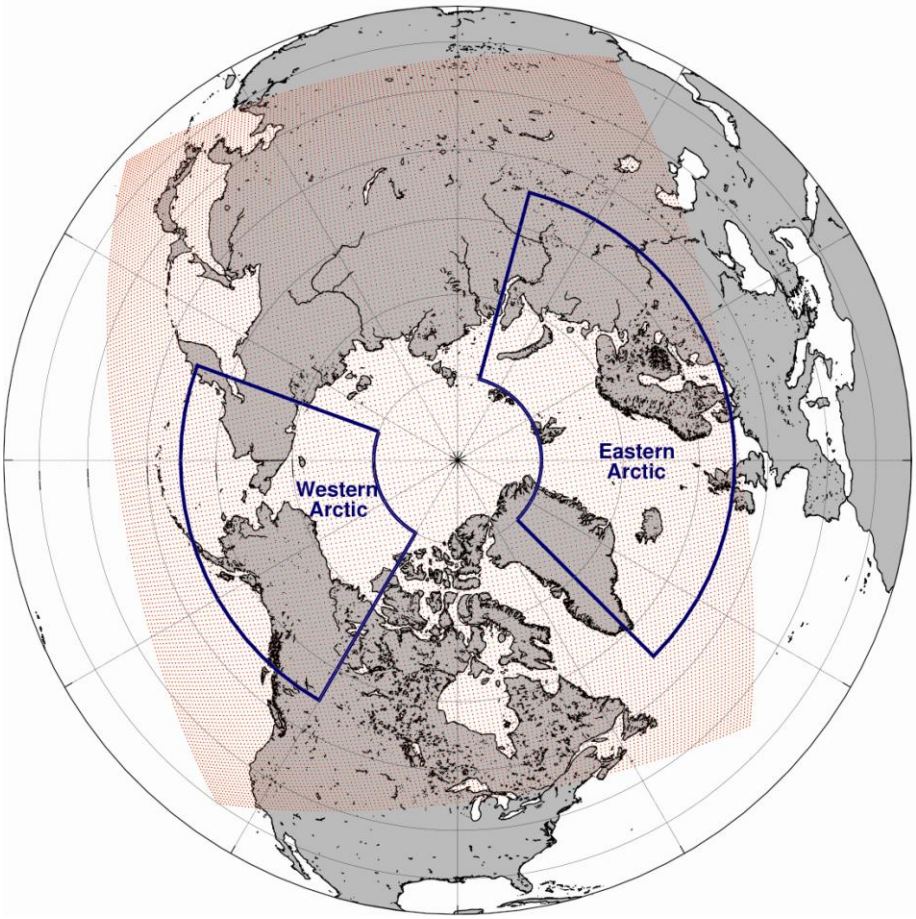

Figure 2. PIPS 2.0 model domain. Every other model grid point (red) is shown along with two regional validation areas (blue boxes) used in the comparison.

PIPS 2.0 uses ice concentration data from the Defense Meteorological Satellite Program (DMSP) SSM/I for daily initialization of the model's ice concentration field.

There are three factors which make the SSM/I data appealing as a source of initialization data: 1) the data are available in real time at the same site that the forecast systems are run, 2) the resolution of the data is similar to the resolution of PIPS 2.0 and 3) the data cover the entire model domain. In order to use SSM/I data it must first be converted into ice concentration data using the Navy's CAL-VAL algorithm (Hollinger et al., 1991). After PIPS 2.0 restart fields are read, the SSM/I data is then used to update ice edge location. Where PIPS 2.0 ice concentration is less than 15% and ice is shown in SSM/I data, ice is added to the PIPS 2.0 model. Conversely, where PIPS 2.0 ice concentration is less than 15% and ice is not shown in SSM/I data, ice is removed from PIPS 2.0. When adding or removing ice, the ice thickness and ocean temperature fields must be updated to be consistent with the data. For example, if the SSM/I data has ice concentration and the model does not, a small amount of ice (0.3-0.5 m) is added to the model ice thickness field and the sea surface temperature (SST) is set to 1.33°C so the ice won't immediately melt. If the model needs to remove ice (i.e., model has ice, SSM/I has none) then ice thickness is set to zero and the SST is set to 2°C in order to prevent immediate ice grow-back. PIPS 2.0 has been assimilating daily ice concentration data since 1996.

2.2 1/12° Arctic Cap Nowcast/Forecast System (ACNFS)

The 1/12° ACNFS is a coupled sea ice and ocean model that nowcasts and forecasts conditions in all sea ice covered areas in the northern hemisphere (poleward of 40° N). In ACNFS, CICE (Hunke and Lipscomb, 2008) is used as the ice model and is

coupled with HYCOM (Metzger et al., 2008, 2010). A schematic diagram of ACNFS is shown in Figure 3.

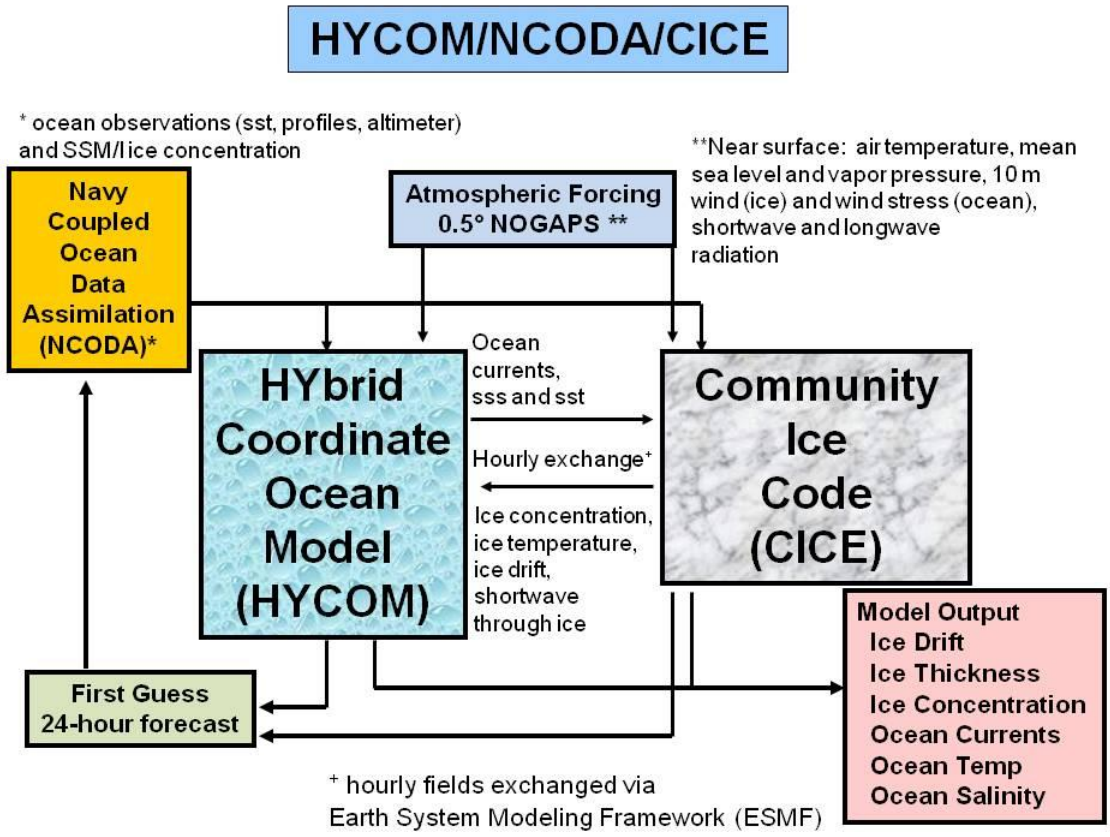

Figure 3. A schematic of the ACNFS sea ice forecast system.

The ice and ocean models are set up and coupled on the same 1/12^{o} horizontal grid. Resolution is approximately 3.5 km near the North Pole and 6.5 km near 40°N (Figure 4). Atmospheric forcing in ACNFS is obtained from the Fleet Numerical Meteorology and Oceanography Center 3 hrly 0.5° NOGAPS forcing. Forcing quantities include: air temperature at 2 m, surface specific humidity, net surface shortwave and longwave radiation, precipitation, ground/sea temperature, downward surface shortwave radiation, zonal and meridional wind velocities at 10 m, mean sea level pressure and

dewpoint temperature at 2 m. NOGAPS is run with a coarser horizontal resolution, T239 (aapproximately 0.5º Gaussian grid) and must first be interpolated to the finer horizontal resolution of the system. ACNFS assimilates observational data using NCODA (Cummings, 2005). NCODA is based on a 3-Dimensional VARiational analysis (3DVAR) scheme used to assimilate surface observations from satellites (altimeter data, SST and sea ice concentration) as well as *in situ* SST's and temperature and salinity profiles.

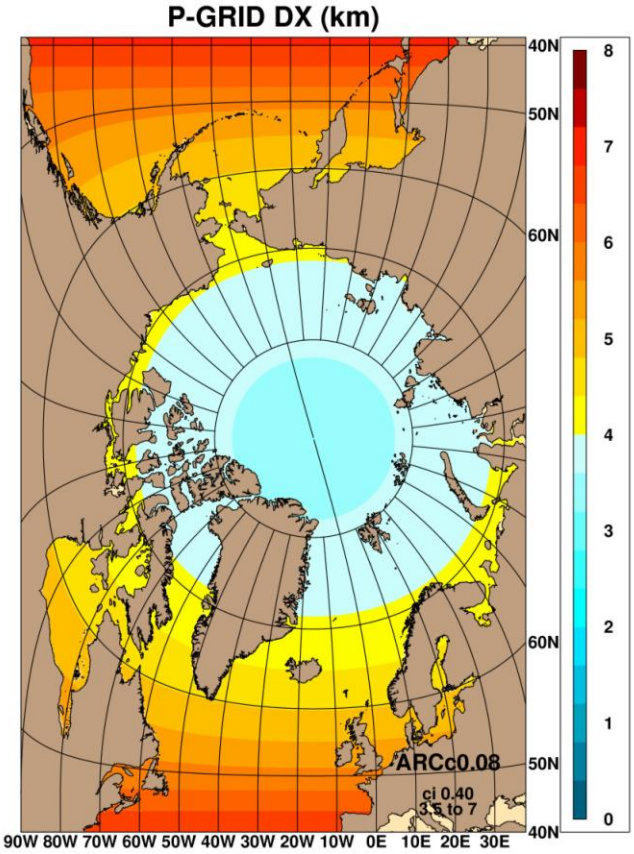

Figure 4. ACNFS model grid resolution (km).

In ACNFS, HYCOM provides surface ocean currents, salinity, SST, ocean mixed layer thickness, sea surface height and ocean heat flux fields to CICE, while CICE provides HYCOM with ice drift, ice stress, solar heat flux, ice freezing/melting heat and salt flux, ice net ocean flux, sea ice temperature, ice thickness and ice concentration fields. These fields are passed between the two models hourly using ESMF (Hill et al., 2004). ESMF is open source software for building climate, numerical weather prediction, data assimilation and other Earth sciences software applications. Each model calculates the same ice-ocean stress based on ocean currents and ice drift. CICE relaxes to HYCOM's SST and HYCOM relaxes to CICE's ice concentration both with an e-folding time of one day.

The sea ice component of ACNFS (CICE) was developed at the Los Alamos National Laboratory by Hunke and Lipscomb (2008) and is the result of an effort to develop a computationally efficient sea ice component for a fully coupled atmosphere-ice-ocean-land global climate model. CICE includes improvements in the ice thermodynamics over PIPS 2.0 such as multiple ice thickness layers, multiple snow layers and the capability to forecast multi-categories of ice thickness according to World Meteorological Organization definitions. In addition, CICE has several interacting components including a thermodynamic model that computes local growth rates of snow and ice due to snowfall; vertical conductive, radiative and turbulent fluxes; a model of ice dynamics that predicts the velocity field of the ice pack based on a model of the material strength of the ice; a transport model that describes advection of the areal concentration,

ice volumes and other state variables; and a ridging parameterization that transfers ice among thickness categories based on energetic balances and rates of strains.

HYCOM (Chassignet et al., 2003) was originally developed by the HYCOM Consortium through the National Ocean Partnership Program. It employs 32 hybrid vertical coordinates surfaces with potential density referenced to 2000 m and it includes the effects of thermobaricity. Vertical coordinates can be isopycnals (density tracking), often best in the deep stratified ocean; levels of equal pressure (nearly fixed depths), best used in the mixed layer and unstratified ocean; and σ-levels (terrain-following), often the best choice in shallow water. HYCOM combines all three approaches by choosing the optimal distribution at every time step. The model makes a dynamically smooth transition between coordinate types by using the layered continuity equation. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate circulation models toward shallow coastal seas and unstratified parts of the world ocean. It maintains the significant advantages of an isopycnal model in stratified regions while allowing more vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics. HYCOM is configured with options for a variety of mixed layer submodels (Halliwell, 2004). In the version of HYCOM used here, K-Profile Parameterization (KPP) (Large et al., 1994) is used to parameterize vertical mixing.

Data assimilation is essential for accurate ice/ocean predictions for many reasons. For example, many ocean phenomena are due to nonlinear processes (e.g., flow instabilities) and thus are not a deterministic response to atmospheric forcing. Errors in

the atmospheric forcing, limitations in numerical algorithms and grid resolution can contribute to the accuracy of the model's products. Most of the observed data concerning the ocean surface space-time variability is obtained remotely from instruments aboard satellites. Assimilated data includes sea surface height (SSH) and SST from the Advanced High Resolution Radiometer (AVHRR) (global and local coverage), Geostationary Operational Environmental Satellite (GOES), Meteosat Second Generation (MSG) satellite, Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) and ice concentration from DMSP. While these observations work well to define surface conditions, they are insufficient for specifying the subsurface variability. For this reason, vertical profiles from expendable bathy-thermographs (XBT), conductivity-temperature-depth (CTD) profilers, and profiling floats (e.g., Argo) provide another substantial source of data. By assimilating these different types of real-time observations, a more realistic ice/ocean forecast is produced.

Data assimilation is performed through NCODA (Cummings, 2005). Currently, NCODA implements a multivariate optimum interpolation (MVOI) scheme as the data assimilation system in GOFS V3.0 (1/12° global HYCOM/NCODA system) at NAVOCEANO. As testing of the ACNFS first began, updates to the ice concentration interpolation scheme were required for the system to run correctly in the Arctic domain. The NCODA interpolation scheme update from MVOI to 3DVAR was implemented during the ACNFS validation study. In this report, an evaluation of **ice fields only** using the 3DVAR is performed. An evaluation of ocean products using 3DVAR is to be completed next year as part of the GOFS V3.1 (/12° global HYCOM/NCODA/CICE

system) transition. During the ACNFS evaluation, NCODA generates the ocean and ice analyses. The ocean analysis variables include temperature, salinity, geopotential and the vector velocity components that are all analyzed simultaneously. NCODA can be run in stand-alone mode, but here it is cycled with HYCOM/CICE to provide corrections to the next model forecast in a sequential incremental update. Corrections to the ACNFS forecasts are based on all observations that have become available since the last analysis. All observations are quality controlled (QC) via NCODA-QC that is run operationally at NAVOCEANO. By combining these various observational data types via data assimilation and using the dynamical interpolation skill of the model, the 3D ocean environment is more accurately predicted. ACNFS has been assimilating real-time data (ocean and ssmi) since July 2007.

ACNFS is currently run using 320 processors on the Navy DSRC IBM Power 6 (Davinci) at NAVOCEANO. A typical one-day hindcast takes approximately 1.0 wall clock hour without data assimilation and approximately 1.25 wall clock hours with data assimilation. The ice (ocean) model uses a time step of 10 (4) minutes. Both CICE and HYCOM use lateral open boundary conditions. The boundaries are defined sufficiently far away from any sea ice covered regions to avoid possible contamination of any forecast fields. In HYCOM, the boundary conditions are nested inside GOFS V3.0 that uses a simple energy loan thermodynamic sea ice model in place of CICE. In the energy loan ice model sea ice grows or melts as a function of SST and heat fluxes.

The ocean model bathymetry is based on the NRL Digital Bathymetric DataBase 2 min (DBDB2) (see http://www7320.nrlssc.navy.mil/DBDB2_WWW/). DBDB2 is a

global database that is derived from a number of sources including the NAVOCEANO global dataset DBDBV (available online at http://gcmd.nasa.gov/records/GCMD_DBDBV.html), the Smith and Sandwell global dataset (Smith and Sandwell, 1997), the Data Assimilation and Model Evaluation Experiments (DAMEE) North Atlantic data (Haidvogel et al., 2000), the International Bathymetric Chart of the Arctic Ocean (IBCAO) data (Jakobsson et al., 2008), the Australian Bathymetric and Topographic data (available online at http://www.ga.gov.au/meta/ANZCW0703004403.html), and regional datasets from the Gulf of Mexico and Yellow Sea. Several of these datasets were hand-edited to more accurately define narrow passages and straits.

3 Validation of the 1/12° Arctic Cap Nowcast/Forecast System (ACNFS)

3.1 Assimilation Study

The effect of incorporating data assimilation in ACNFS is examined. ACNFS was first integrated without assimilation (i.e., without NCODA), using NOGAPS forcing over the period 01 June 2005 - 31 July 2008. Ice concentration fields for winter (15 March 2007) and summer (15 September 2007) time frames are shown in Figure 5. The black line in each plot is the independent ice edge location from the NIC. Since the ice edge data are not assimilated into the system it can be used as a validation metric. The ACNFS hindcast agrees fairly well with the observations despite the unusual extreme conditions during 2007 (warm atmosphere, thinner ice, atypical wind patterns, etc.) (Haas et al.,

2008). The largest discrepancy is seen during the summer months (Figure 5b), where ACNFS without assimilation overpredicts ice concentration northwest of the Bering Strait. However, for the purpose of daily real time ice edge forecasting, greater ice edge forecasting accuracy is desired.

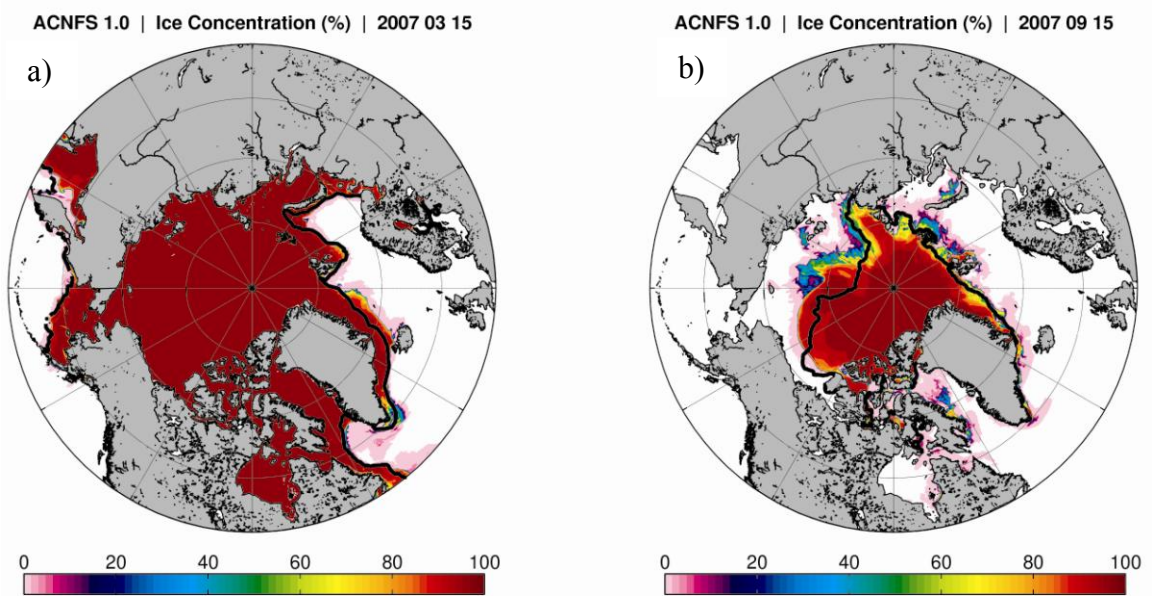

Figure 5. Ice Concentration (in percent) from ACNFS without data assimilation. Images represent two seasons a) winter (15 March 2007) and b) summer (15 September 2007). The black line is the independent ice edge from the NIC.

A second hindcast was performed using assimilation of all available oceanic data and SSM/I derived ice concentration fields via NCODA. Since GOFS V3.0 boundary conditions were available starting in July 2007, the second simulation was integrated using NOGAPS forcing over the period 01 July 2007 – 30 June 2009. The SSM/I concentration field is derived using the Navy's CAL-VAL algorithm (Hollinger, 1991). SSM/I has a resolution of 25 km. NCODA is initialized using the 24 hr ice concentration forecast from the prior day CICE output and then assimilates daily ice concentration data

from SSM/I. In PIPS 2.0, SSM/I ice concentration is directly inserted into the ice model along the marginal ice zone (MIZ), areas near the ice edge where ice concentration is less than 15%. In ACNFS, the ice concentration is directly inserted into the model over one timestep using a more advanced technique. Similar to PIPS 2.0, the ice analysis from NCODA is directly inserted along the MIZ. The NCODA ice analysis is then blended with the model's previous day forecast in areas with concentration up to 40%. NCODA ice analysis values above 40% are not used in the assimilation. The NCODA ocean analysis is incrementally inserted into HYCOM over a 6 hour period. This technique allows for more realistic ice and ocean conditions in the ACNFS system.

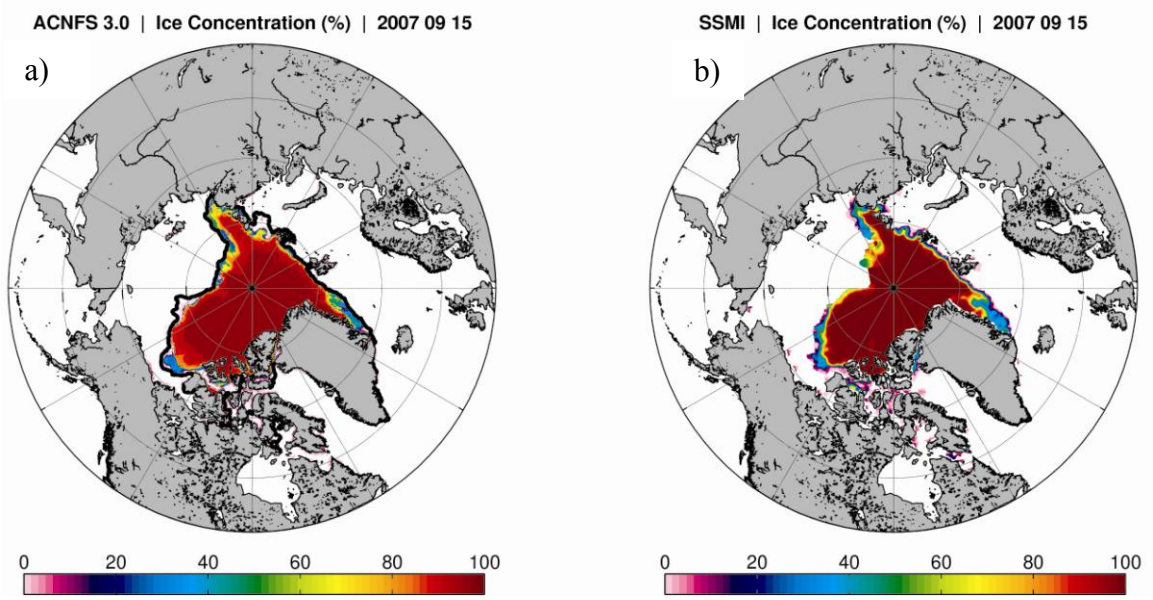

Figure 6. Ice Concentration (in percent) from a) ACNFS with data assimilation and b) SSM/I. Images valid for 15 September 2007. The black line is the independent ice edge from the NIC.

Figure 6a contains the resulting ice edge concentration from ACNFS with assimilation. Figure 6b is a plot of sea ice concentration obtained from SSM/I for the

same date. Comparison of summertime ice concentration from ACNFS without data assimilation (Figure 5b) with ACNFS and NCODA assimilation (Figure 6a) reveals that the assimilative hindcast compares much better qualitatively to the SSM/I for the same day, especially in the western Arctic. Quantitative comparisons are discussed in section 3.3. The ice edge location in the eastern Arctic region (Barents Sea and east of Greenland) has also improved dramatically in the assimilative case as opposed to the non-assimilative test. These results demonstrate that by assimilating real time observations, the system produces more realistic results when compared to independent observations. Previous sensitivity studies (Posey and Preller, 1997) have shown that daily initialization from SSM/I ice concentration can improve sea ice forecasts.

3.2 ACNFS vs. PIPS 2.0 Comparison

As ACNFS was integrated in time, a comparison of daily snapshots was made against the operational PIPS 2.0 system. From the beginning of the integration, the ice concentration and ice drift fields from ACNFS compare well qualitatively to the PIPS 2.0 products. ACNFS ice thickness fields from 29 December 2007 - 2009 (Figure 7, right panels) show a greater ice thickness (>3 m), especially along the Canadian Archipelago and the northern part of Greenland, as compared to the PIPS 2.0 fields (Figure 7, left panels). The larger ice thicknesses seen in ACNFS could be a result of the initial conditions. The ACNFS was initialized in July 2007 from the non-assimilative run, and is possible that this simulation did not have time to adjust to the anomalous conditions seen

during this decade. Also, the Arctic conditions were far from normal in 2007 with an extreme ice melt occurring during September.

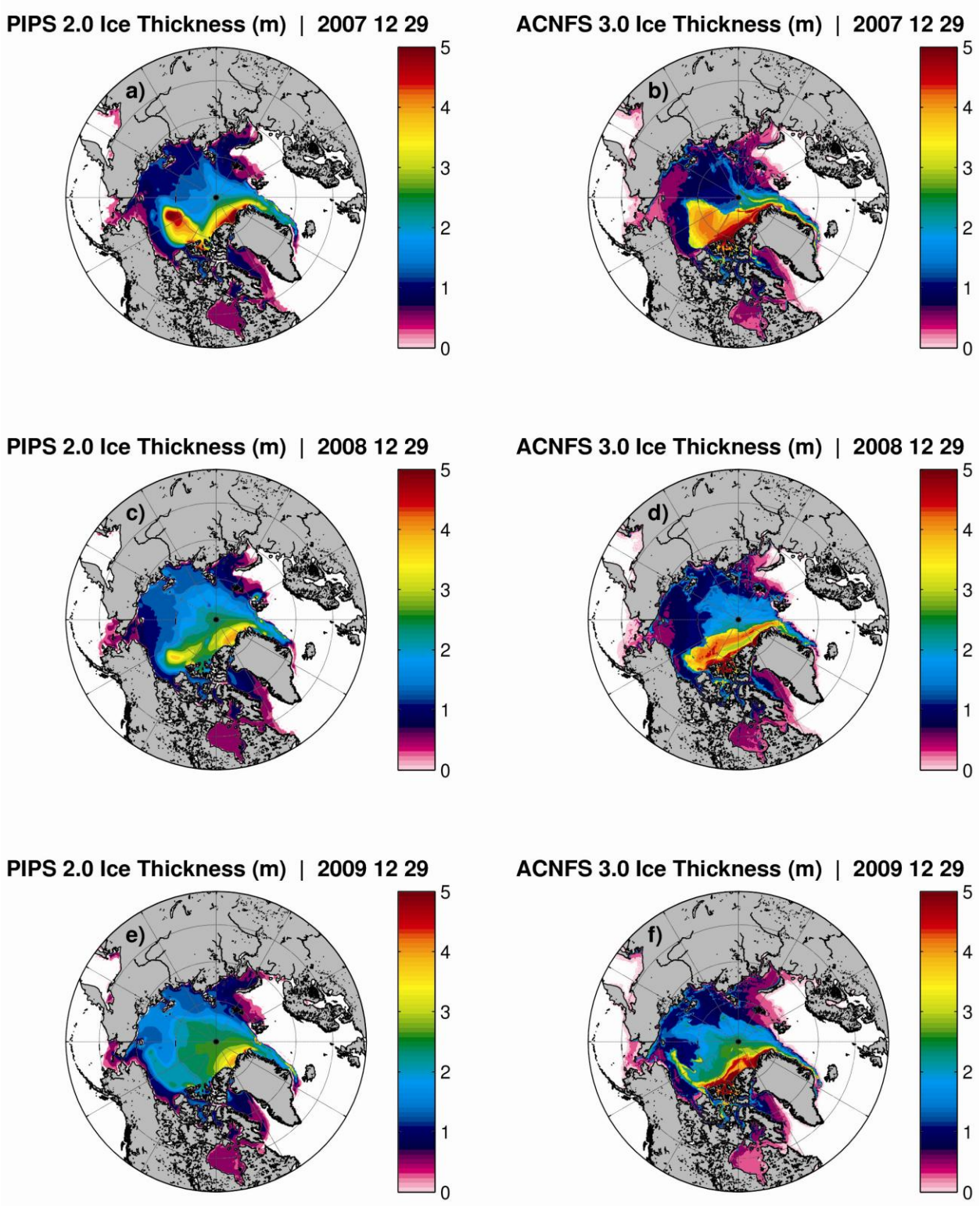

Figure 7. Ice thickness (m) snapshots from PIPS 2.0 (left) versus ACNFS (right). Top panel is from 2007, middle is 2008 and bottom panel is 2009 valid for 29 December.

3.3 Ice edge location

In order for the ACNFS to be declared operational, it must be shown that nowcasts and forecasts are an improvement over the currently operational PIPS 2.0 system. As part of this validation study, the daily mean distance between the independent, daily observed NIC ice edge and derived model ice edges from PIPS 2.0 and ACNFS are compared for July 2007 – June 2009 (Figure 8). Model ice edge locations are those grid points that exceed a certain threshold value for ice concentration and that also have a neighboring point that falls below that value. PIPS 2.0 is limited to a minimum threshold of 20% since open water in PIPS 2.0 is defined by concentrations of 15% or less. Because ACNFS defines ice concentration values less than 1%, its minimum threshold is not similarly limited to 20%. Daily means are calculated from the distances between each NIC observed point and the nearest model-derived ice edge location. Figure 8 shows the daily mean distances between NIC and model ice edge for PIPS 2.0 with a 20% ice concentration threshold and for ACNFS with 20% and 5% ice concentration thresholds.

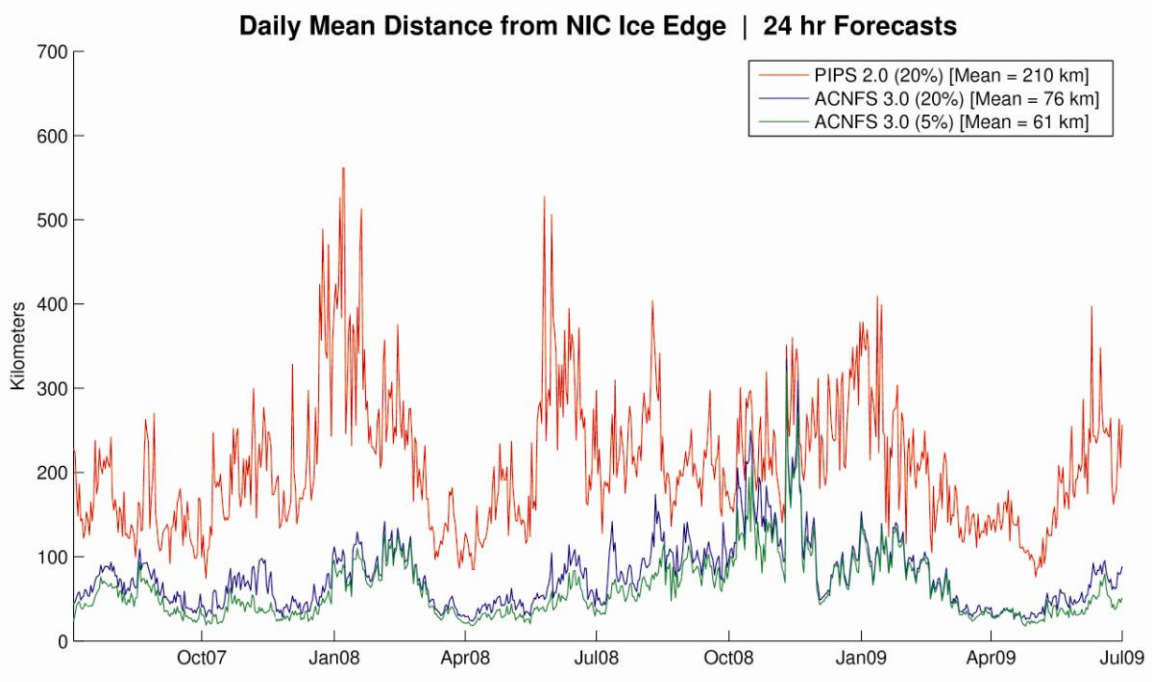

Figure 8. Daily mean distances (km) from the NIC observed ice edge locations to the ice edge locations using the 24 hr forecasts from ACNFS (20%-blue and 5%-green) and PIPS 2.0 (20%-red) for July 2007- June 2009.

During this time period, the mean distance between the 20% ACNFS ice edge and the NIC ice edge was 76 km, compared to 210 km for the 20% PIPS 2.0 ice edge. This represents a 134 km, or 63%, improvement by ACNFS over PIPS 2.0. Using 5% as the ice concentration cutoff in ACNFS, the mean distance decreased to 61 km, representing a 149 km, or 71% improvement over PIPS 2.0.

During the same period, the daily mean ice edge errors were calculated for the Western and Eastern Arctic (boxed regions in Figure 2) using 20% model ice edges. Time series plots of daily mean distance ice edge errors from each model are shown in Figure 9. The mean ice edge errors in the Eastern Arctic are 165 km for PIPS 2.0 and 55 km for ACNFS. For the Western Arctic, the mean ice edge errors are 226 km for PIPS

2.0 and 79 km for ACNFS. ACNFS shows a 67% improvement for the Eastern Arctic and a 65% improvement for the Western Arctic when compared to PIPS2.0.

For both panels in Figure 9, the larger PIPS 2.0 ice edge differences occur during the ice transition seasons (October-January and June-August) when the model is slow in either growing or melting the ice. A particularly large ice edge error in PIPS 2.0 (approximately 800 km) is shown in the Eastern Arctic in January 2008. Figure 10 shows the various ice edges in the Baltic Sea for 14 January 2008. The large ice edge error displayed in PIPS 2.0 is the result of the slow growth of ice (e.g., along the coasts of Sweden and Finland in the Gulf of Bothnia and the Gulf of Finland). The NIC and ACNFS locate ice in this area, whereas the closest PIPS 2.0 ice edge is along the Russian coast in the Barents Sea.

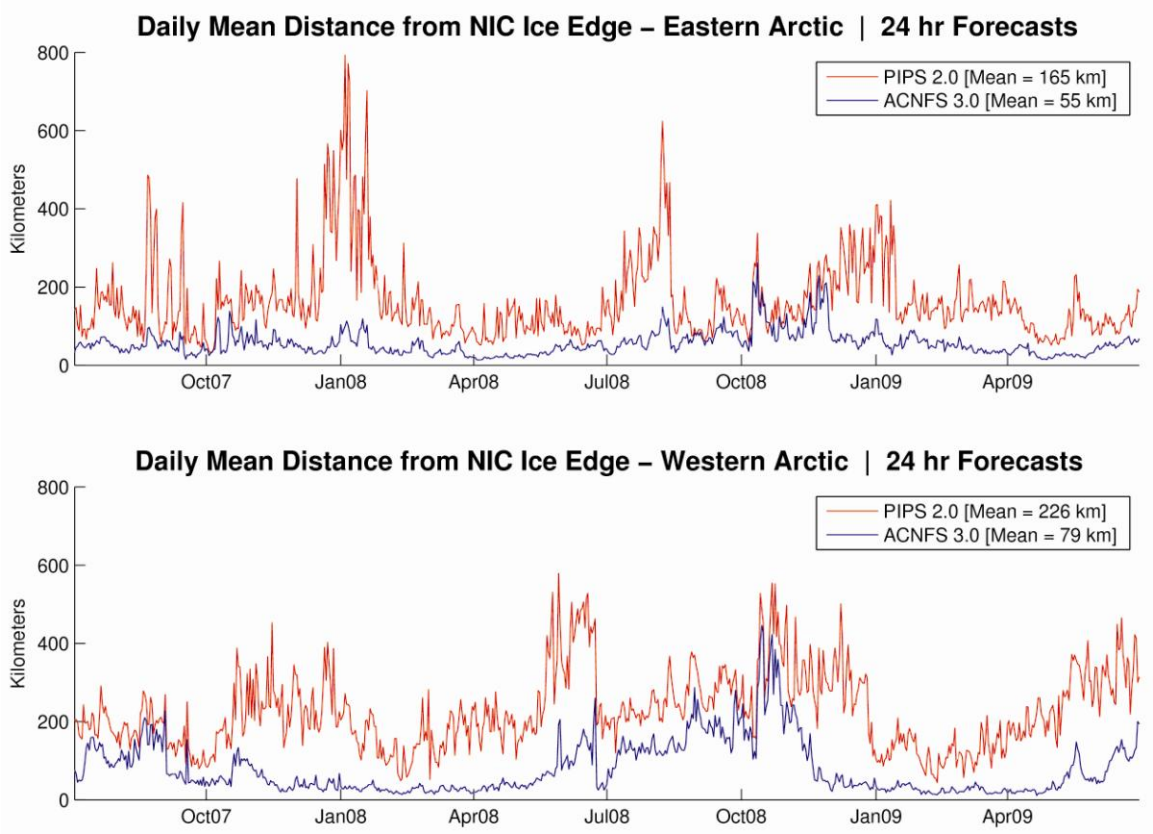

Figure 9. Regional daily mean distances (km) from the NIC observed ice edge locations to the ice edge location using the 24 hr forecasts from ACNFS (20%-blue) and PIPS 2.0 (20%-red) for the eastern Arctic (top) and the western Arctic (bottom) during July 2007 – June 2009.

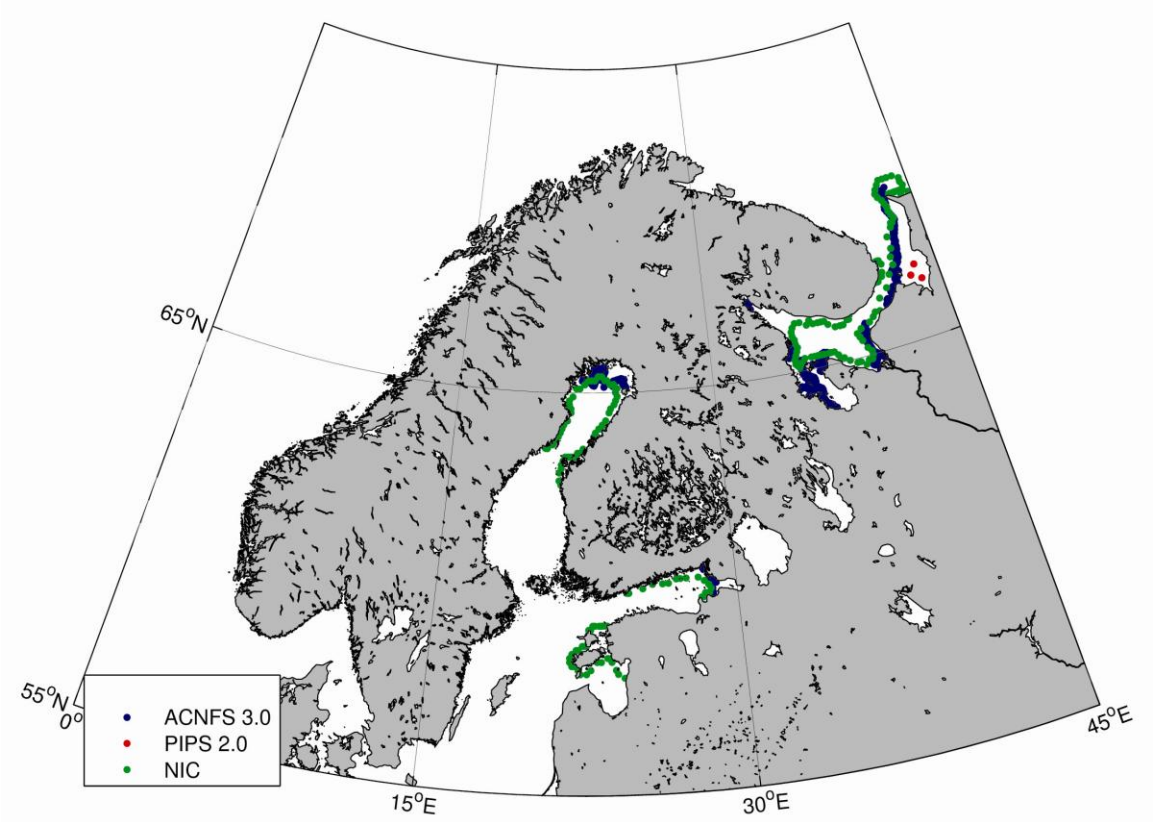

Figure 10. Ice edges in the Baltic Sea for 14 January 2008, illustrating the lack of ice in PIPS 2.0 (red) in the Gulf of Bothnia and the Gulf of Finland.

Seasonal regional mean ice edge errors between the NIC ice edge and the two systems are also calculated for winter (January-March [JFM]) and summer (July-September [JAS]) (Table 1). The last column is the percentage improvement in ACNFS, defined as (PIPS 2.0 – ACNFS)/PIPS 2.0 * 100. In each of the regions, the ACNFS shows an improvement over PIPS 2.0. The improvement is greater in the Eastern Arctic for JFM and greater in the Western Arctic for JFM. Overall, ACNFS shows a mean improvement of 64.8% over PIPS 2.0 in locating the ice edge. This improvement is likely due to the greater horizontal resolution in ACNFS than PIPS 2.0 (3.5 km vs. 27 km), the improved physics in the CICE model (as part of the ACNFS), the improved insertion

technique of NCODA over the simple ice edge insertion in PIPS 2.0 and the additional assimilation of ocean fields in ACNFS.

Table 1. Regional seasonal mean distances (km) between NIC ice edge and PIPS 2.0 and ACNFS ice edge locations.

Time Period	Region	PIPS 2.0	ACNFS	% Improvement
2007-JAS	Eastern Arctic	140	50	64.3%
	Western Arctic	175	105	40.0%
2008-JFM	Eastern Arctic	211	47	77.7%
	Western Arctic	154	27	82.5%
2008-JAS	Eastern Arctic	191	69	63.9%
	Western Arctic	256	151	41.0%
2009-JFM	Eastern Arctic	177	53	70.1%
	Western Arctic	121	26	78.5%

3.4 Ice thickness

3.4.1 Ice Mass Balance (IMB) Buoys

Over the years, observations such as ice thickness measurements have been difficult to record due to the extreme weather conditions in the Arctic. More recently, ice thickness observations are becoming more readily available to the research community. In this report, ice thicknesses obtained from numerous ice mass balance (IMB) buoys (Perovich et al., 2009) provided by the Cold Regions Research Engineering Laboratory (CRREL) are compared against simulated ice thicknesses. These buoys were deployed across the Arctic during 2006-2009 and drift times varied from 1 to 6 months. Figure 11 shows the tracks of the IMB buoys used in this report, color-coded to indicate which

model produced lower ice thickness errors. Information detailing the starting and ending dates and positions of the buoys is shown in Table 2.

Table 2. Ice Mass Balance Buoy starting/ending dates and positions used in validation.

Buoy Name	Starting Date	Ending Date	Starting Position	Ending Position
2006C	01 Jul 2007	05 Oct 2007	77.89N,140.40W	76.98N,142.56W
2006D	01 Jul 2007	02 Dec 2007	81.77N,142.67E	71.85N,15.84W
2006E	01 Jul 2007	11 Sep 2007	81.30N,136.93E	84.32N, 0.06E
2007B	01 Jul 2007	24 Aug 2007	73.23N,146.61W	77.37N,155.12W
2007C	01 Jul 2007	13 Dec 2007	88.23N,121.91E	71.46N, 3.12W
2007D	01 Jul 2007	23 Jul 2007	88.76N, 11.79W	86.19N, 6.89W
2007F	16 Aug 2007	23 Sept 2007	73.23N,149.69W	79.60N,148.53W
2007G	16 Sep 2007	01 Jan 2008	86.71N,134.10E	87.83N,63.79W
2007H	11 Sep 2007	05 Mar 2008	84.97N,132.26W	83.99N,109.63W
2008D	20 Apr 2008	01 Jun 2008	84.05N,123.54W	84.07N,120.66W
2009D	11 May 2009	31 May 2009	84.15N,36.63W	83.86N,30.63W

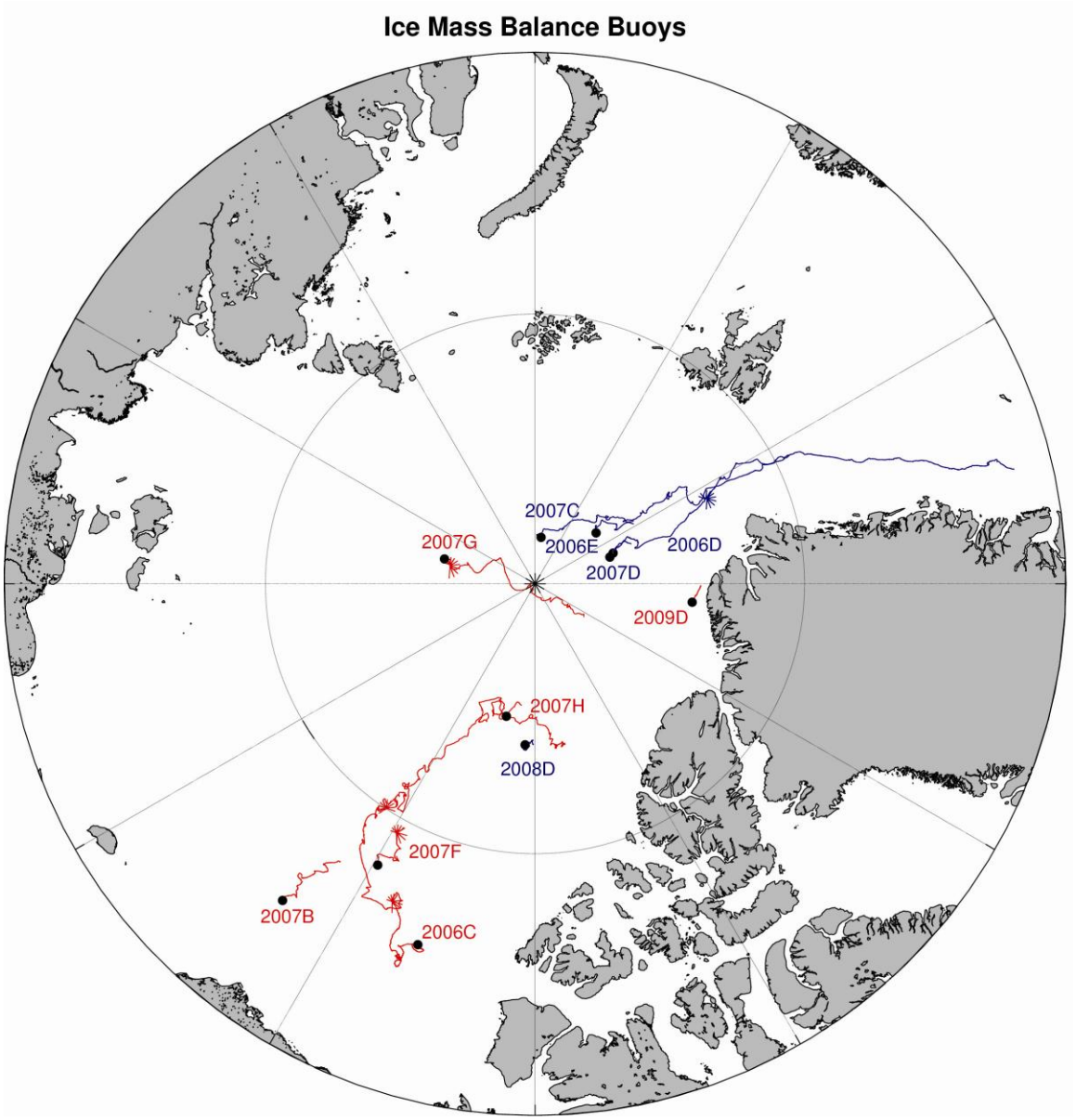

Figure 11. Drift paths of IMB from July 2007 – May 2009. A black circle indicates the starting position of each buoy. For the tracks in blue, the ACNFS produced lower ice thickness errors; for the tracks in red, the PIPS 2.0 produced lower ice thickness errors.

Daily mean ice thicknesses and positions are calculated from the IMB buoy data. Model thickness fields were interpolated via cubic splines to each daily mean IMB buoy position. Mean ice thickness errors are calculated from the differences between

interpolated model thicknesses and daily mean IMB thicknesses. Note that neither PIPS 2.0 nor ACNFS assimilate ice thickness data. Table 3 shows the mean ice thickness error for the PIPS 2.0 nowcasts (column 2) and the ACNFS nowcasts (column 3). Values in bold denote the system with the smaller difference. A negative difference means that the model under-estimated ice thickness, while a positive difference indicates an over estimate of ice thickness. Both systems produced similar results, with an overall mean ice thickness error of 1.02 m for PIPS 2.0 and 1.19 m for ACNFS.

Table 3. Mean ice thickness error (m) between the IMB buoys and the ice nowcast/forecasts systems. Bold numbers denote smaller error between PIPS 2.0 and ACNFS.

Buoy Name	PIPS 2.0	ACNFS
2006C	**2.02**	2.07
2006D	1.51	**1.50**
2006E	1.55	**1.26**
2007B	**1.07**	1.70
2007C	0.95	**0.92**
2007D	1.68	**1.40**
2007F	**0.63**	1.18
2007G	**0.53**	0.89
2007H	**-0.61**	0.97
2008D	-0.36	**0.11**
2009D	**-0.33**	1.12
Average	**1.02**	1.19

Figures 12 and 13 contain time series of observed IBM ice thicknesses (black) and interpolated PIPS 2.0 (red) and ACNFS (blue) thicknesses. The gaps in these plots indicate times when ice thickness observations were not available. PIPS 2.0 had a lower thickness bias in the Canadian Archipelago and the western Arctic (red tracks in Figure 11). The thicknesses associated with the six buoys in these regions (2006C, 2007B, 2007F, 2007G, 2007H and 2009D) are shown in Figure 12. Typically, the ACNFS has

lower ice thickness error in the central and eastern Arctic (blue tracks in Figure 11). The thicknesses for the five buoys in the eastern Arctic (2006D, 2006E, 2007C, 2007D and 2008D) are shown in Figure 13. Overall, both models followed the trends of the IMB buoys, but each model over predicted ice thickness by approximately 1 m. As discussed earlier, this over estimate of ice thickness in ACNFS, especially along the Canadian Archipelago, could possibly be a result of using the non-assimilative initialization fields during the excessive Arctic melt season of 2007.

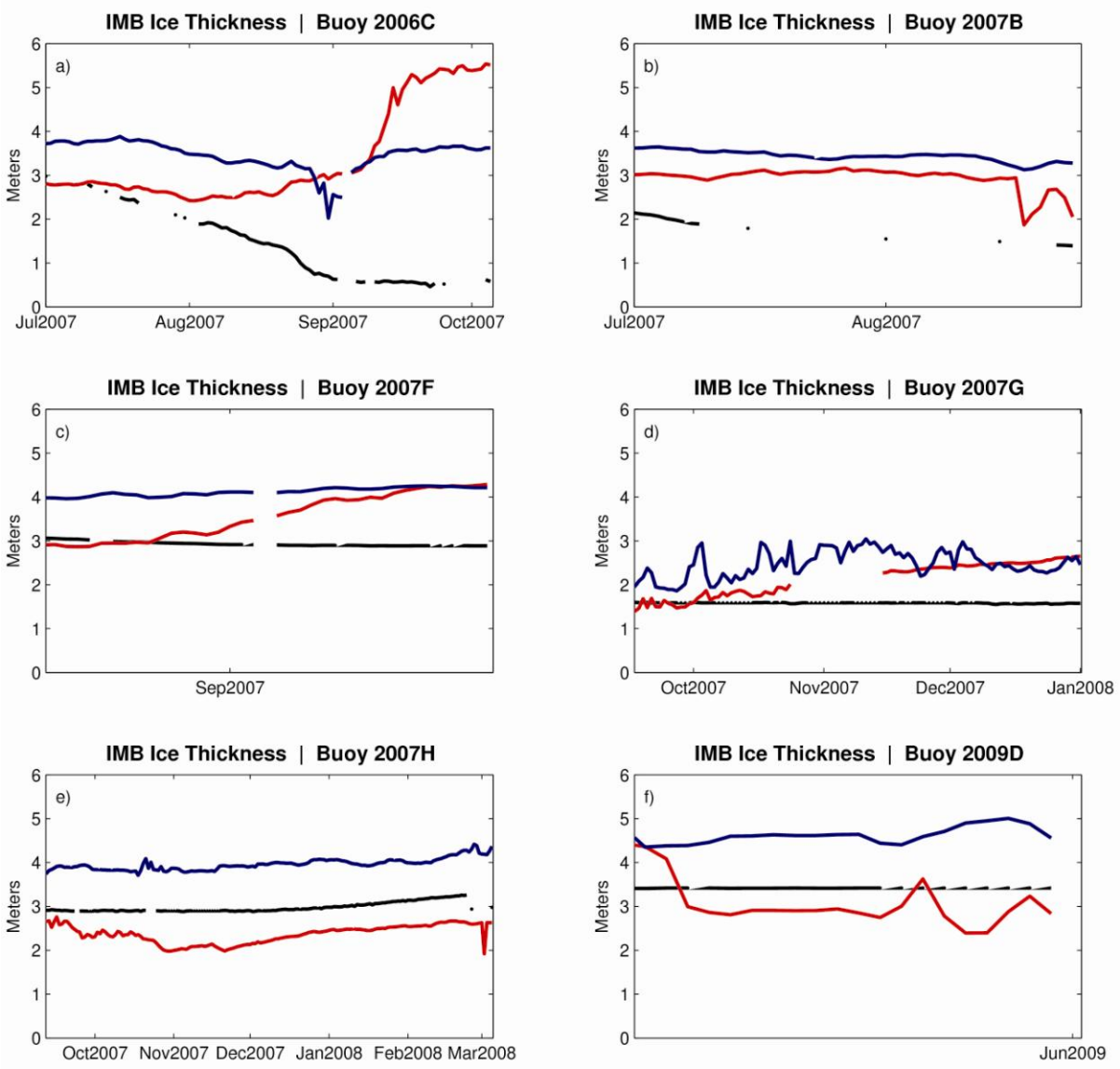

Figure 12. Ice thickness (m) for IMB buoys a) 2006C, b) 2007B, c) 2007F, d) 2007G, e) 2007H and f) 2009D observations (black) compared to interpolated PIPS 2.0 (red) and ACNFS (blue) thicknesses.

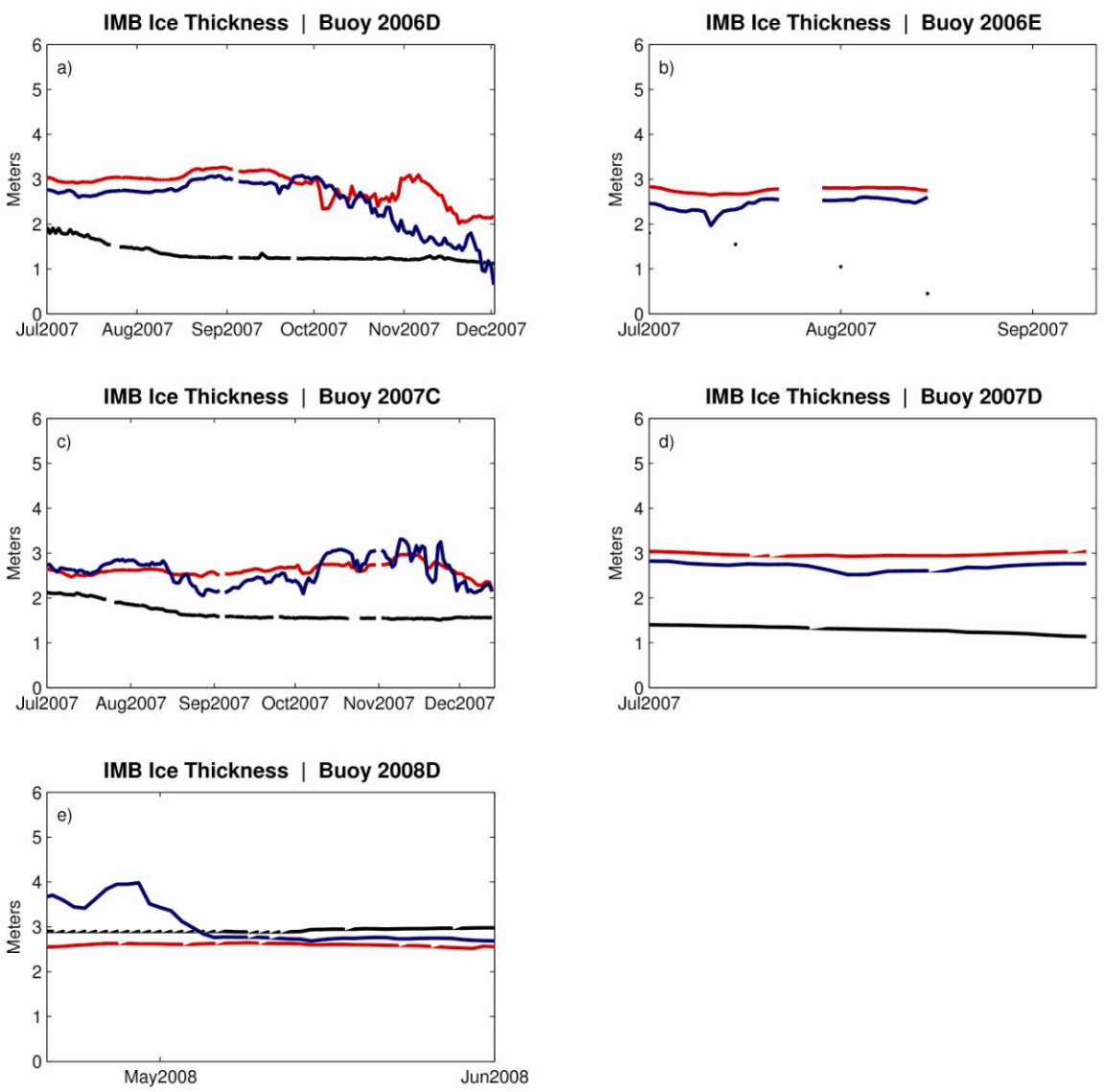

Figure 13. Ice thickness (m) for IMB buoys a) 2006D, b) 2006E, c) 2007C, d) 2007D and e) 2008D observations (black) compared to interpolated PIPS 2.0 (red) and ACNFS (blue) thicknesses.

3.4.2 Synoptic airborne thickness survey

Airborne electromagnetic (EM) ice thickness surveys were collected in April 2009 as part of the 2400 km long Pan-Arctic Measurements and Arctic Regional Climate Model Simulations (PAM-ARCMIP) project. EM sounding "allows for surveys of total (ice plus snow) sea-ice thickness utilizing the strong electrical conductivity contrast between ice and seawater" (Haas et al., 2010). The accuracy of EM measurements is ±0.1 m over level ice (Pfaffling et al., 2007; Haas et al., 2009). The ice thickness survey occurred over regions of the Arctic Ocean north of Svalbard, Greenland, Canada and Alaska that are predominantly covered by multiyear ice. The starting location of each survey is indicated by the flight number shown in Figure 14.

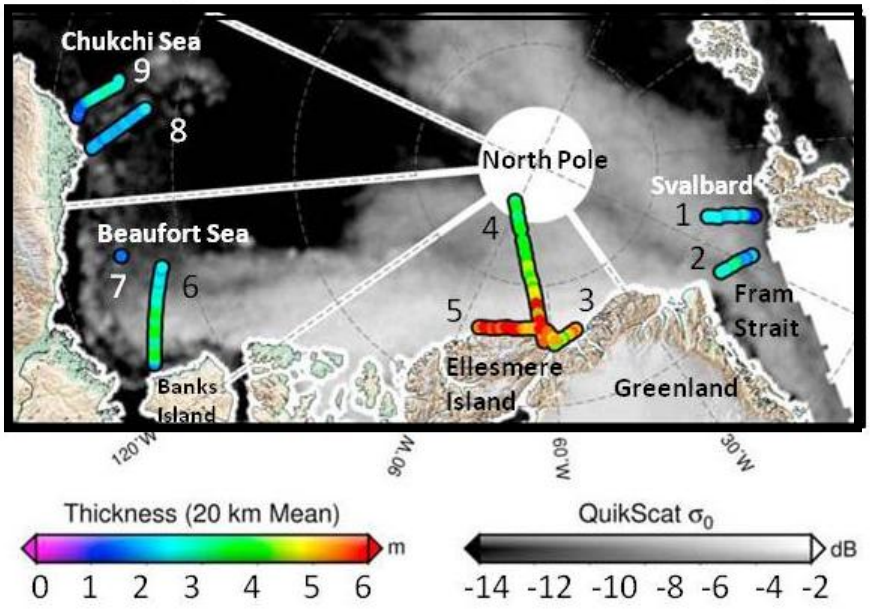

Figure 14. Map of the Arctic Ocean showing ice thickness surveys from April 2009. Colors indicate mean thickness of 20 km flight sections. Grey shades represent sea-ice HH-polarized radar backscatter obtained from the QuikScat satellite scatterometer. Flight numbers are indicated on map. [Adapted from Figure 1 of Haas et al. (2010)].

Data was acquired every 5 meters for each survey, a much higher spatial resolution than either model. To compare the survey data to model data, the observations were binned into 3 min intervals. The mean thickness and location of each segment is then recorded. The model ice thickness data, not including snow, is interpolated via cubic splines to each segment location for comparison. Plots of survey and model thickness for each flight are shown in Figure 15(a-c). Gaps shown in the PAM-ARCMIP data represents discontinuities in the recorded observations. The mean for each flight is shown in Table 4.

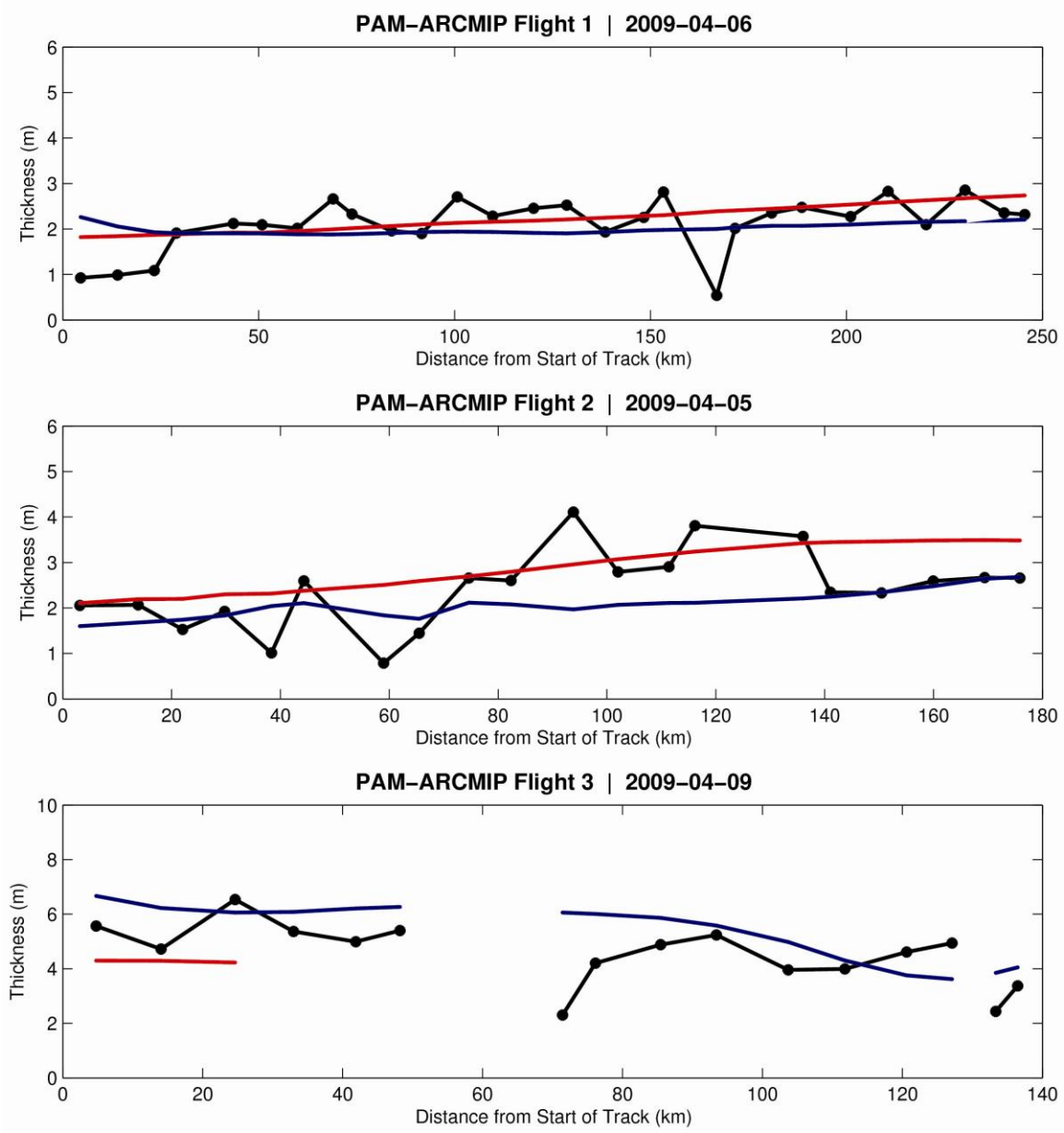

Figure 15a. Mean ice thickness (m) from PAM-ARCMIP (black), ACNFS (blue) and PIPS 2.0 (red) along survey flights 1-3.

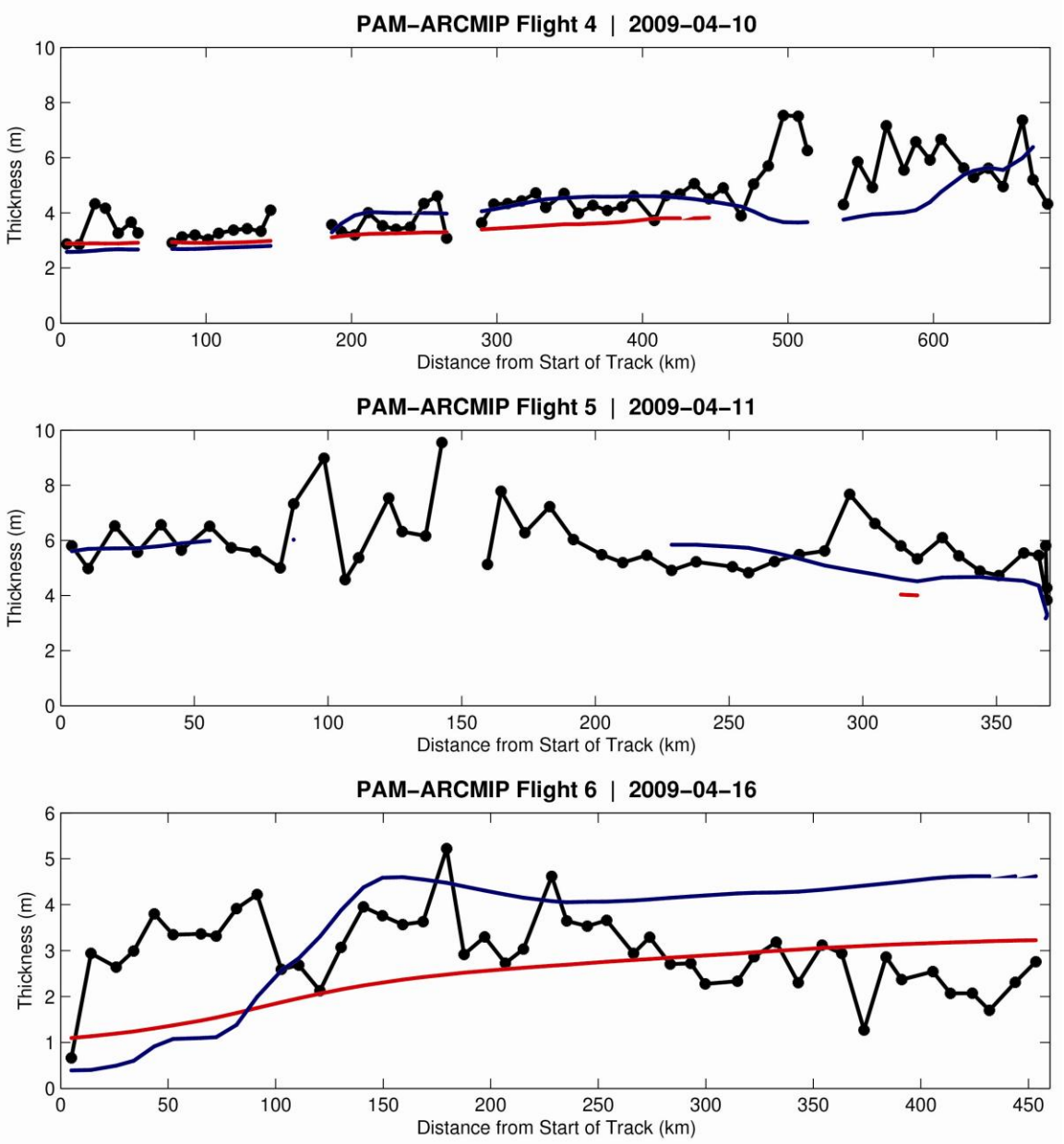

Figure 15b. Mean ice thickness (m) from PAM-ARCMIP (black), ACNFS (blue) and PIPS 2.0 (red) along survey flights 4-6.

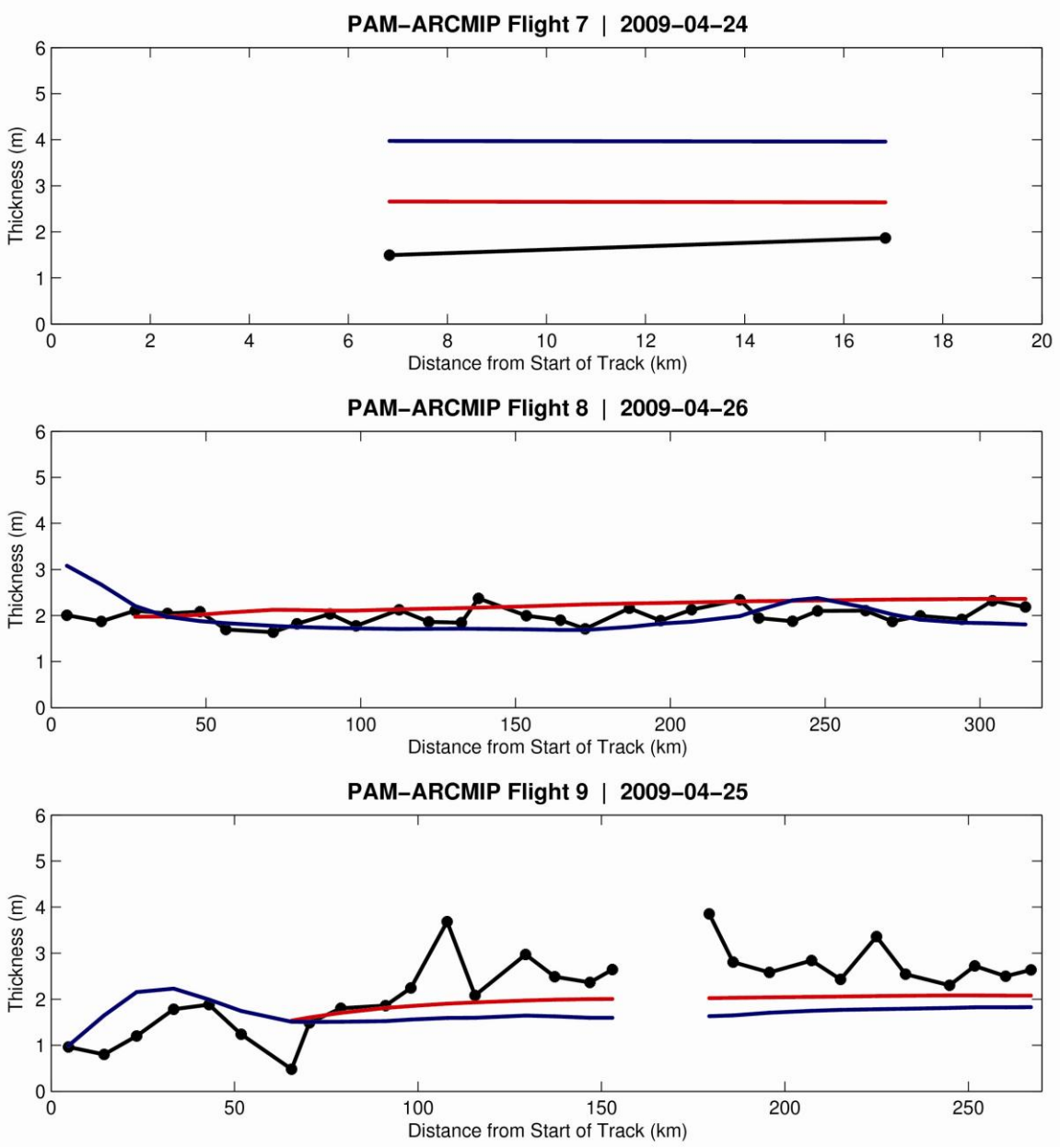

Figure 15c. Mean ice thickness (m) from PAM-ARCMIP (black), ACNFS (blue) and PIPS 2.0 (red) along survey flights 7-9.

Table 4. Mean ice thickness (m) from PAM-ARCMIP, PIPS 2.0 and ACNFS. Bold numbers denote the smaller error between PIPS 2.0 and ACNF. Notes: [1] Assuming a constant 20 cm snow depth for all flights. [2]Observational mean computed only at those locations where each system also outputs ice.

	Mean Thickness (m)			Mean difference (m)		Mean difference with snow (m)[1]	
	Obs[2] ACNFS/PIPS	ACNFS	PIPS	ACNFS - obs	PIPS -obs	ACNFS - obs	PIPS - obs
Flight 1	2.11/2.11	**2.01**	2.23	**-0.10**	0.12	**0.10**	0.32
Flight 2	2.42/2.43	**2.08**	2.87	**-0.34**	0.44	**-0.14**	0.64
Flight 3	4.53/4.53	5.35	**4.27**				
Flight 4	4.48/3.83	**3.94**	3.27	**-0.54**	-0.56	**-0.34**	-0.36
Flight 5	5.87/5.87	**5.06**	4.02				
Flight 6	2.97/2.98	3.52	**2.46**	0.55	**-0.52**	0.75	**-0.32**
Flight 7	1.68/1.68	3.97	**2.65**				
Flight 8	1.99/1.99	**1.95**	2.21	**-0.04**	0.22	**0.16**	0.42
Flight 9	2.23/2.23	1.69	**1.95**	-0.54	**-0.53**	-0.34	**-0.33**
Absolute value of average mean difference				**0.35**	0.40	**0.31**	0.40

The thickest ice, with means between 4.48 m and 5.87 m, is found along the coast of Ellesmere Island (flights 3, 4, 5). The thinnest ice occurs in the Beaufort and Chukchi Seas, with mean thicknesses between 1.69 m and 1.99 m (flights 7, 8). The length of each survey varies between 115 km (flight 3) and 569 km (flight 4), with the exception of flight 7 which covers a short distance of 22 km. Due to the short duration of flight 7, the data are not included in the mean in Table 4 (highlighted). Data from flights 3 and 5 (also highlighted in Table 4) are not included in the mean due to the influence of land

boundary on the interpolation scheme (noted by the scarce data in these flights shown in Figure 15).

The average mean difference shown in Table 4 indicates that ACNFS performs slightly better than PIPS 2.0 (0.35 vs. 0.40 m respectively). However, recall that for each model only ice thickness is analyzed, not ice + snow as in the survey data. The lack of snow in the model data explains the negative bias in each error term in Table 4. Adding a monthly climatological snow value of 0.20 m (for April in this region – see last columns in Table 4) to each negative bias, results in an average difference for ACNFS of 0.31 m and 0.40 m for PIPS 2.0. Thus, by including snow depth into the model ice thickness data, ACNFS continues to perform slightly better than PIPS 2.0. Future work concerning the addition a more realistic snow cover in the ice model is scheduled to begin in FY 12.

3.5 Ice draft

The Woods Hole Oceanographic Institution (WHOI) deployed four moored Upward Looking Sonar (ULS) moorings in the Beaufort Gyre region (Figure 16) from August 2007 – August 2008. These moorings are part of the Beaufort Gyre Freshwater Observing System - BGFOS (Proshutinsky, 2009) funded by the National Science Foundation. The ULS measures the distance from its moored location to the bottom of the ice. A pressure sensor provides the distance to the sea surface. The difference between the two distances is ice draft. According to Rothrock et al. (2003), approximately 89% of the ice thickness is underwater and seen as draft. Therefore, derived model ice draft fields are taken to be 89% of ice thickness output. Figure 17

shows the comparison between simulated ice draft at the nearest model grid points and the ULS observations.

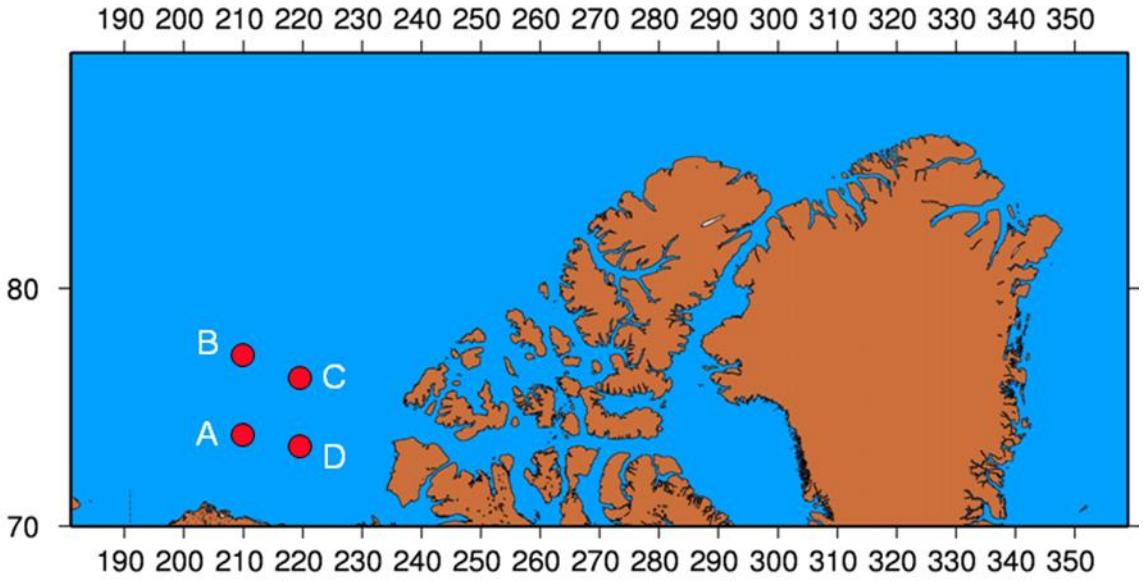

Figure 16. Locations of 4 ULS moorings deployed by WHOI in the Beaufort Gyre in August 2007.

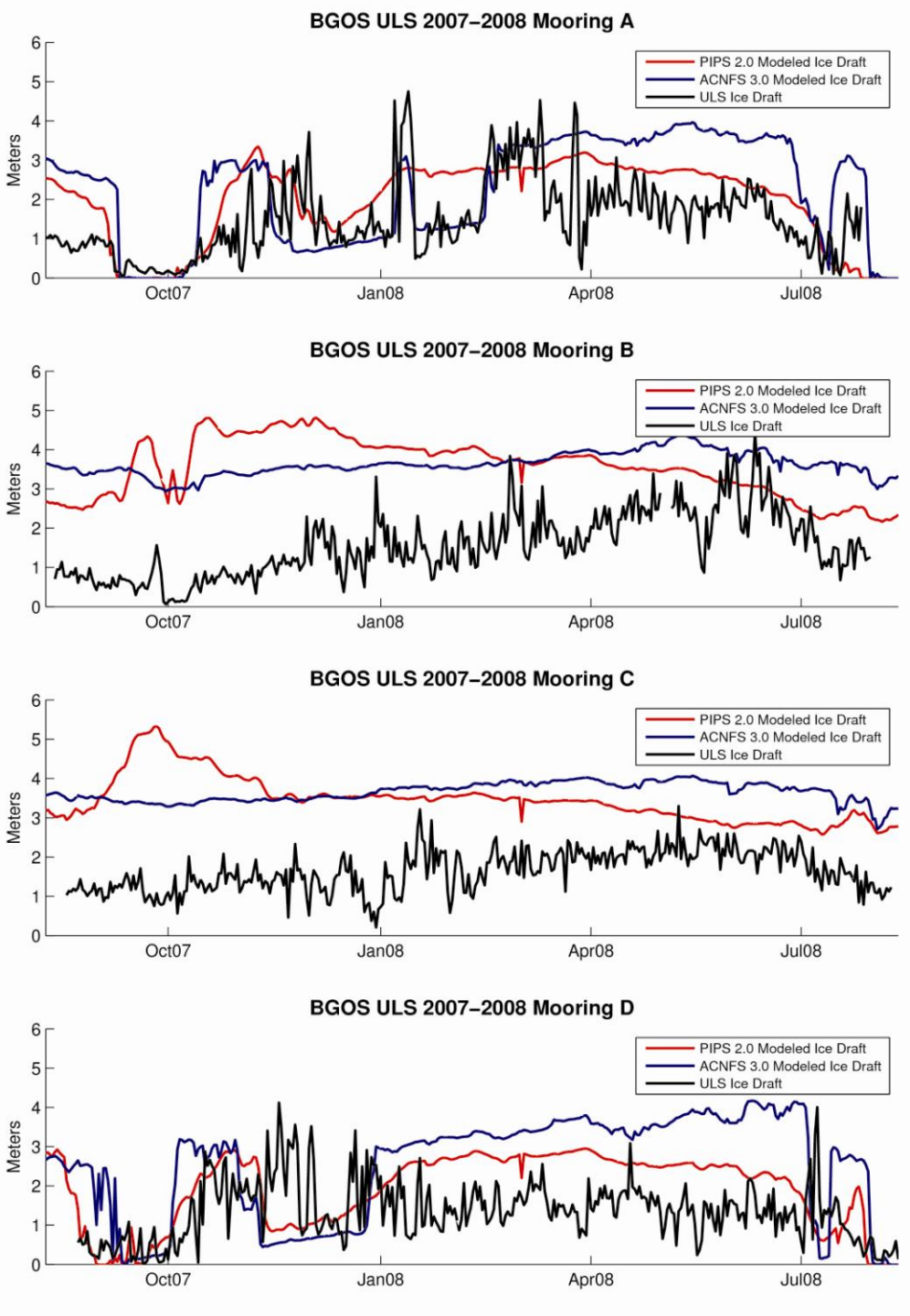

Figure 17. Observed ULS (black) and derived PIPS 2.0 (red) and ACNFS (blue) ice draft (m) for August 2007-August 2008.

Table 5 shows the mean ice draft of the four ULS moorings compared to PIPS 2.0 and ACNFS ice draft. Simulated ice drafts at moorings A and D (closer to land) are smaller than ice drafts at moorings B and C. The differences between model and observed ice drafts at moorings A and D vary from 0.5 and 1.2 m, while the differences at moorings B and C are approximately 2 m. Overall, the average PIPS 2.0 ice draft error (1.23 m) is slightly lower than the ACNFS error (1.51 m). ACNFS has a lower standard deviation (0.78 m) than PIPS 2.0 (0.80 m).

Table 5. Mean ice drafts (m) and standard deviation (m) from 4 ULS compared to PIPS 2.0 and ACNFS.

	Mooring A (08/09/07-07/27/08)	Mooring B (08/13/07-07/31/08)	Mooring C (08/18/07-08/09/08)	Mooring D (08/23/07-08/12/08)	Average	Mean Difference between model and moorings
Mean (m)						
ULS	1.49	1.54	1.64	1.35	1.51	
PIPS 2.0	2.04	3.59	3.47	1.86	2.74	1.23
ACNFS	2.31	3.64	3.65	2.49	3.02	1.51
StDev (m)						
ULS	0.96	0.83	0.53	0.77	0.77	
PIPS 2.0	0.97	0.71	0.58	0.94	0.80	
ACNFS	1.27	0.29	0.24	1.30	0.78	

3.6 Ice drift

During the validation study, ice drift from the two forecast systems is compared against Argos drifting buoys provided by Dr. Ignatius Rigor from the University of Washington's International Arctic Buoy Program (IABP). Figure 18 contains a plot of the starting location of 102 Argos drifting buoys during 2008. From daily latitude/longitude

pairs in the Argos observations, observed ice drift components are derived using the haversine formula to determine the x- and y-direction distances travelled each day. X- and y-component directions are determined by the sign of the differences in longitude and latitude, respectively. Results are then converted from km/day to m/s. Model ice velocity components were interpolated via cubic splines to observed positions.

For each day, the ice drift field is extracted from PIPS 2.0 and ACNFS and used to estimate the trajectory of each simulated drifter for 24 hrs, starting from the buoy's actual location. Latitude/longitude pairs at the end of a 24-hr period are obtained for each model via flat-Earth approximations. The separation distances between the models' locations after 24 hrs of drift and the next day's observation location are calculated using the haversine formula. A sample plot of the 24 hr separation error from each model and Argos buoy 3693 is shown in Figure 19, where ACNFS separation error of 6.6 km is slightly lower than the PIPS 2.0 error of 7.2 km. The trajectory for Argos buoy 3693 is shown in red on Figure 18.

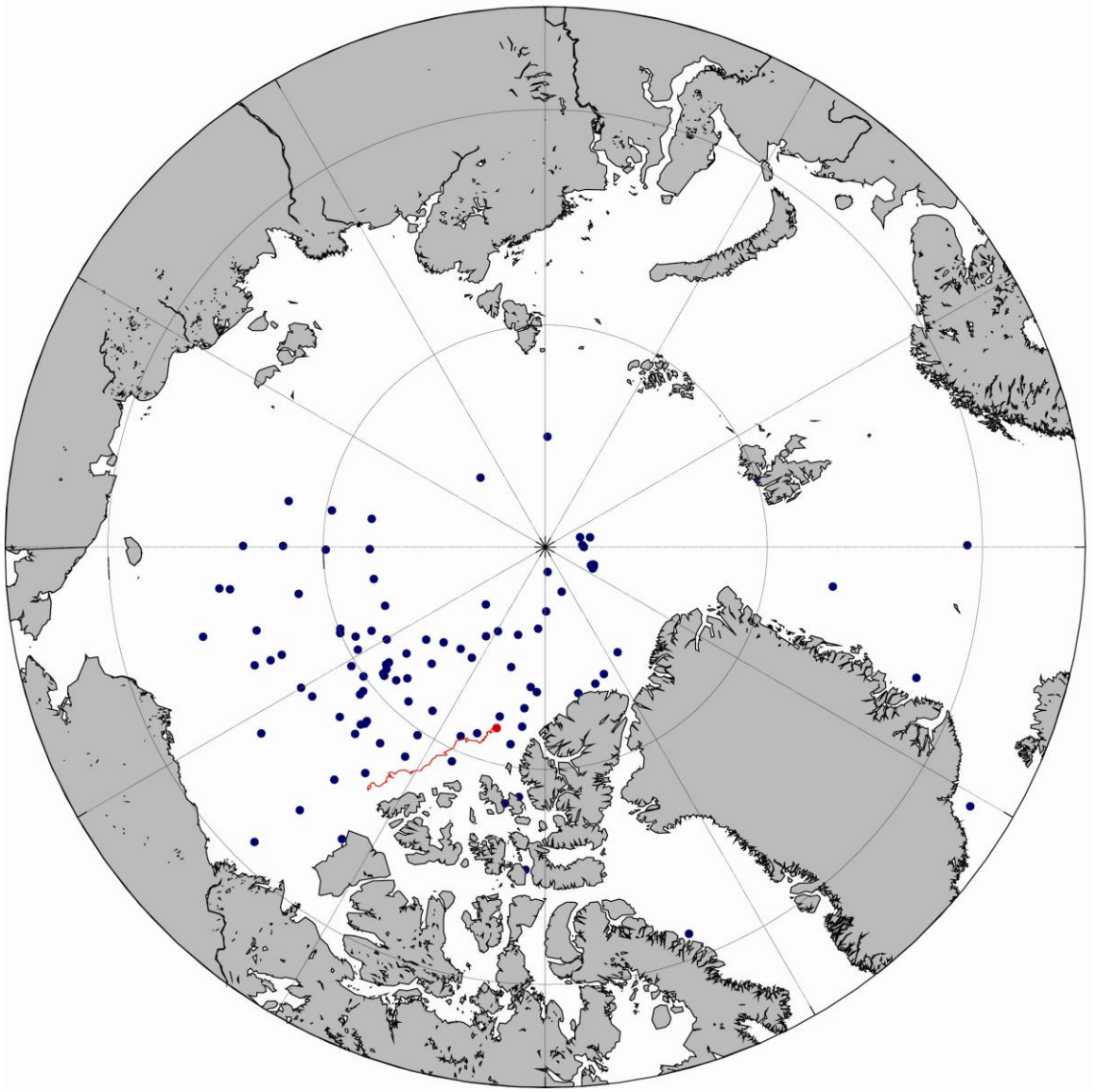

Figure 18. Starting locations of the 2008 Argos drifters. Red drift shows the trajectory for Argos drifter 3693 (comparison shown in Figure 17).

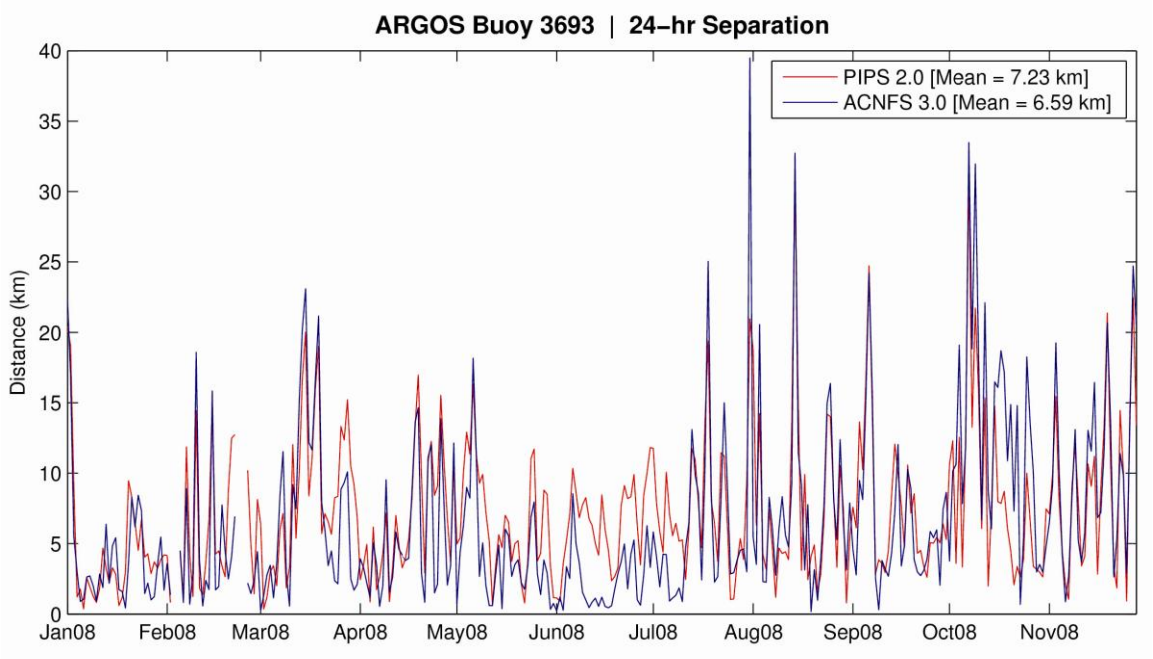

Figure 19. 24 hr prediction error between Argos buoy 3693 and the ACNFS (blue) and PIPS 2.0 (red) for January 2008 – December 2008.

Figure 20 shows the mean 24 hr separation error for each model plotted at the beginning location of each of the IABP buoys. Figure 21 illustrates the 24 hr separation error for the trajectory from each model. The lowest mean 24 hr separation errors (dark blue) are found in regions where the ice is thickest, particularly north of the Canadian Archipelago. In contrast, the largest 24 hr (yellows/reds) separation errors are in areas of thinner ice east of Greenland. This is expected, as thicker ice tends to drift slower than thinner ice. Slower ice drift results in less distance travelled, and thus less error. The mean separation error from both models compares very well against the Argos observations, but PIPS 2.0 has slightly better 24 hr forecast agreement than ACNFS (10 vs. 11 km) with only a 1 km error difference.

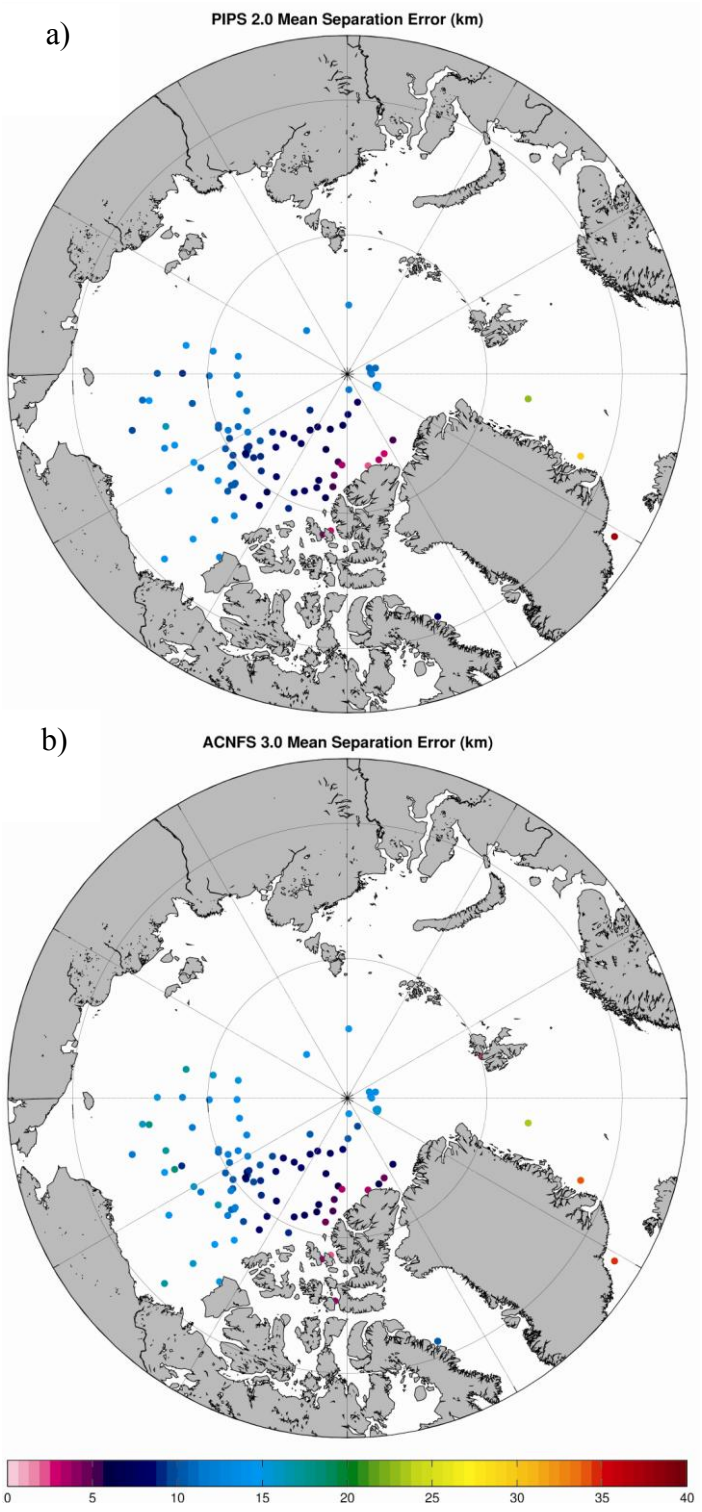

Figure 20. Mean 24 hr separation error (km) from a) PIPS 2.0 and b) ACNFS plotted at the start of each Argos buoy track.

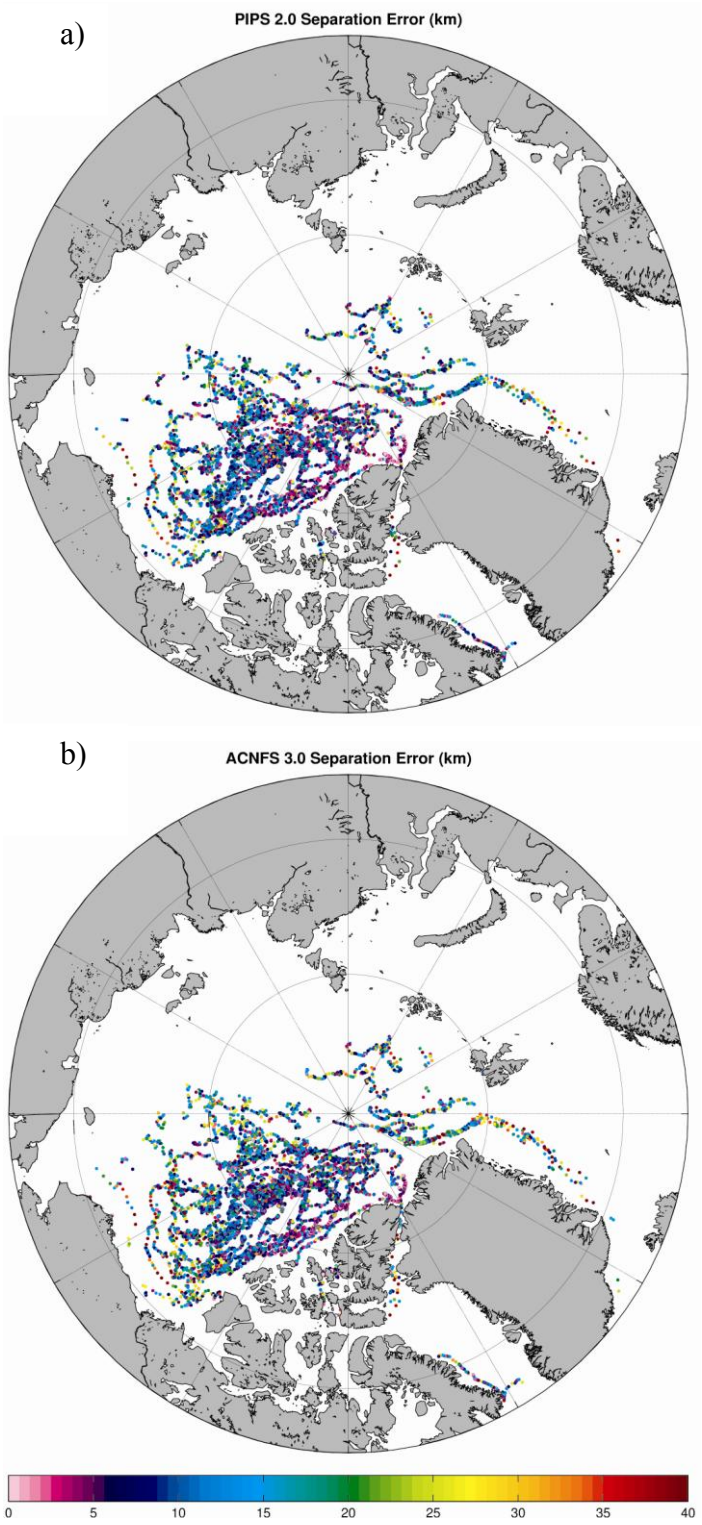

Figure 21. 24 hr separation error (km) from a) PIPS 2.0 and b) ACNFS for each Argos buoy position.

Argos buoy velocity components and magnitudes were compared to model ice drift values. The means are shown in Table 6. The mean velocities from both ACNFS and PIPS 2.0 compare well to the 2008 observations, with magnitude difference of less than 2 cm/sec. PIPS 2.0 performed slightly better in both the u component (-0.4 vs. 1.1 cm/sec) and the v component (-0.6 vs. 1.1 cm/sec). In general, PIPS 2.0 drifts were slower than observed drifts, while ACNFS drifts were faster than observations.

Table 6. Comparison of average magnitude, u- and v- component for models against Argos buoys observations (cm/sec).

	Mean value (cm/s)			Mean difference (cm/s)	
	Observation	PIPS 2.0	ACNFS	PIPS 2.0 - obs	ACNFS – obs
Mag	9.1	8.3	10.8	-0.8	1.7
u	5.4	5.0	6.5	-0.4	1.1
v	6.2	5.6	7.3	-0.6	1.1

Differences between the model ice drift and the derived Argos drifts are shown below. Figure 22 shows the mean ice drift (m/s) error from each model plotted at the beginning location of the Argos buoys. Figure 23 illustrates the trajectory ice drift error from each model. In each plot, ACNFS has slightly faster drift than the PIPS 2.0, and is in agreement with the results shown in Table 6. Overall, both models show good agreement with the Argos buoys during the 2008 time period.

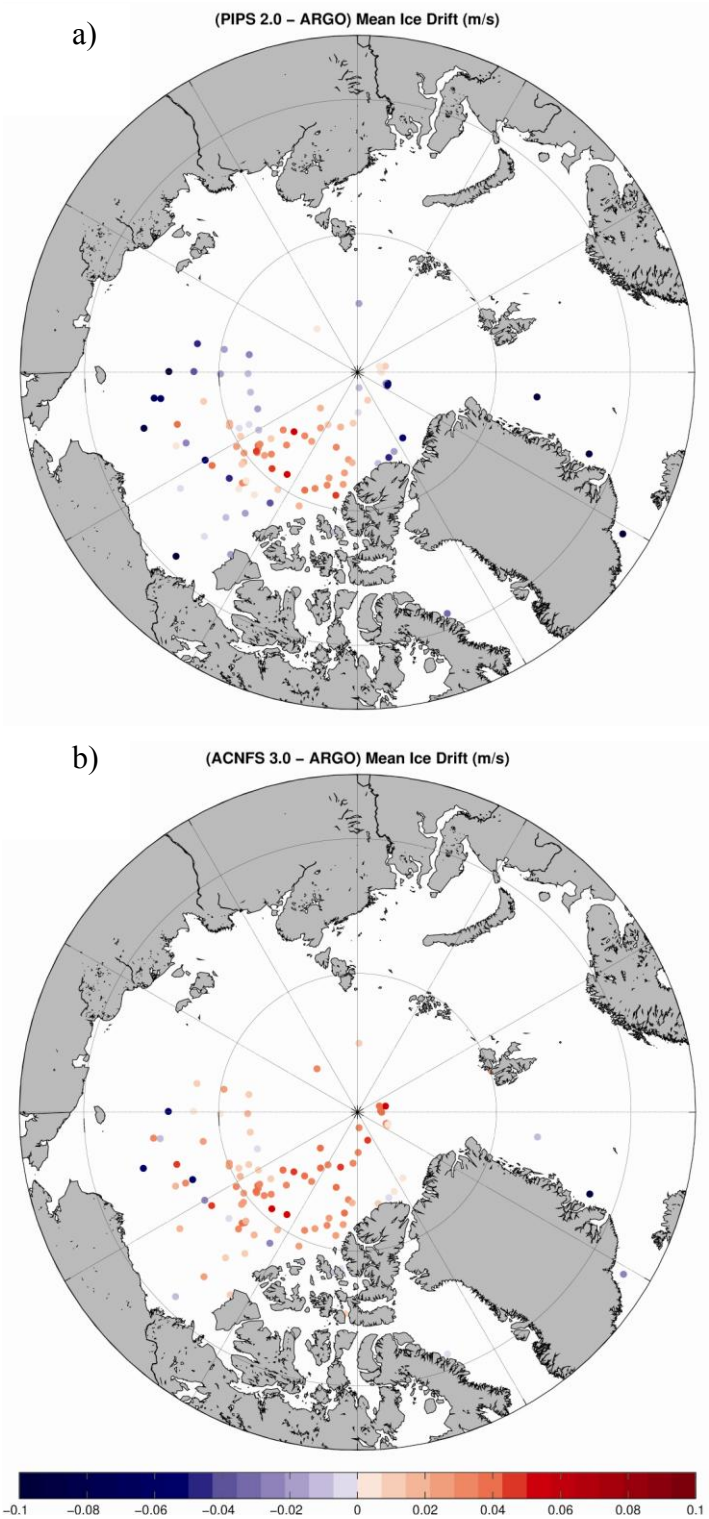

Figure 22. Mean ice drift error (m/s) from a) PIPS 2.0 and b) ACNFS plotted at the start of each Argos buoy track.

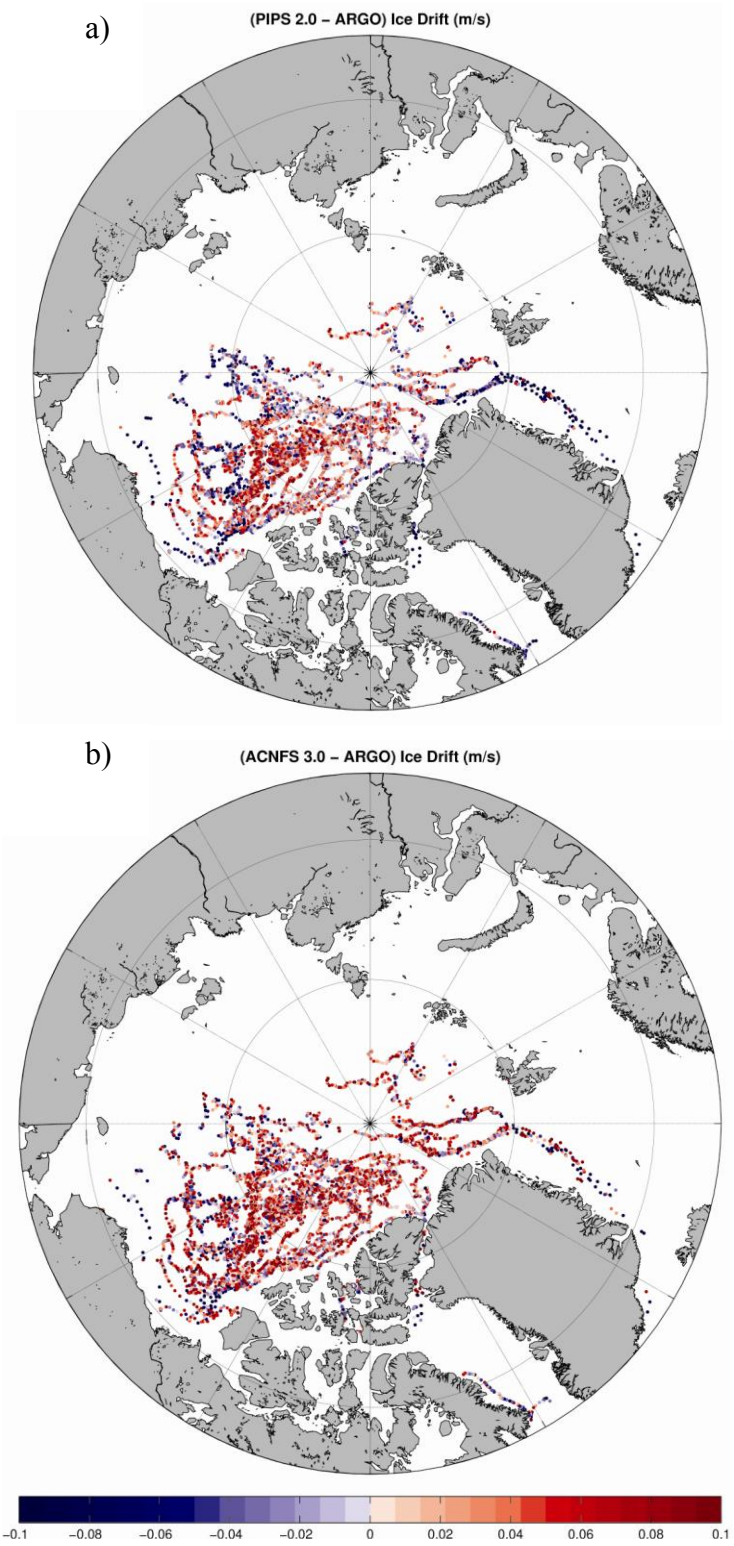

Figure 23. Ice drift error (m/s) from a) PIPS 2.0 and b) ACNFS for each Argos buoy position.

3.7 Ice leads

Ice leads are narrow cracks in the Arctic ice cover that form when ice floes diverge or shear as they move parallel to each other. An ice lead can vary from several meters to over a kilometer in width. During the evaluation period, areas of convergence/divergence in the central Arctic and north of Greenland during the summer melt period can be seen in ACNFS as "lines" of lower ice concentration. These features are not seen in PIPS 2.0 (Figure 24). Two likely reasons for the formation of these features in ACNFS are greater horizontal resolution in ACNFS and more complex thermodynamics and ice layers in ACNFS ice model (CICE). These lead-like features appear to be wind driven and occur usually during the transition period from May through September. These areas of ice convergence/divergence from ACNFS have not been currently validated but could be of possible interest to the Navy.

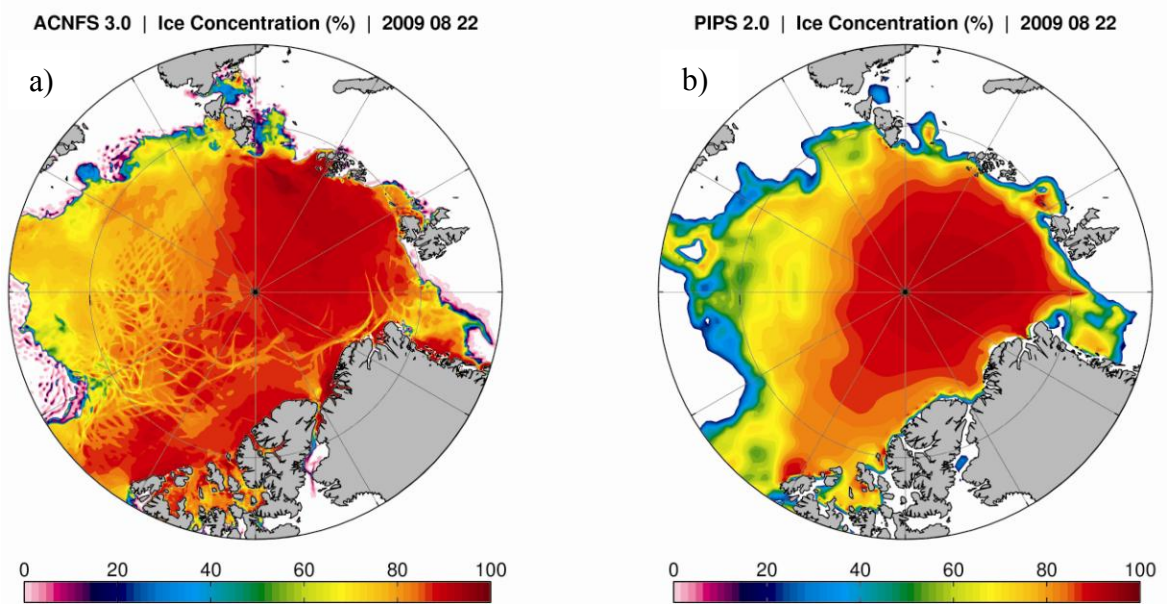

Figure 24. Ice concentration (%) from a) ACNFS and b) PIPS 2.0. Valid August 22, 2009. Areas of lower concentration can be seen just north of Greenland in ACNFS (a) but not in PIPS 2.0 (b).

4 Summary and Recommendation

ACNFS is a next generation system capable of nowcasting and forecasting the ice conditions in the Arctic region. ACNFS was developed using a state of the art sea ice model (CICE from Los Alamos National Laboratory) that is two-way coupled to the Navy's ocean model (HYCOM). The 3DVAR assimilation scheme is used in ACNFS via NCODA. ACNFS produces ice drift, ice thickness and ice concentration fields with a grid resolution of approximately 3.5 km near the North Pole. ACNFS uses 3-hourly forcing from NOGAPS and is scheduled to replace the existing nowcast/forecast system PIPS 2.0.

In this report, results of the validation testing of both ice prediction models are presented. In order for ACNFS to be declared operational, the forecasts must be as good

as or better than the current PIPS 2.0 operational model. During the time period of July 2007 through July 2009, observations used in the validation include: independent ice edge location from the NIC, ice thickness observations from CRREL ice mass balance buoys and an airborne thickness survey, ice draft from WHOI upward looking sonar buoys and daily ice drift data from the IABP. Daily and seasonal analyses of the ice edge location indicate that ACNFS has substantially lower ice edge error than PIPS 2.0 in both regional and Arctic wide validation areas. The daily mean distance error from the NIC ice edge location in the ACNFS in the full Arctic is 76 km, as opposed to the 210 km in PIPS 2.0. This represents a 64% improvement using ACNFS. When the ice edge location criterion in the ACNFS is reduced from 20% to 5%, the error decreased further to 61 km, or a 71% improvement. The ACNFS lower error trends continue in both the regional areas of the Eastern and Western Arctic (ACNFS distance errors of 55 and 79 km, respectively, while PIPS 2.0 errors are 165 and 226 km).

Due to the prior lack of observed ice thickness data, validations of modeled ice thickness products are seldom performed. Over the last several years, Arctic ice thickness observations have become more readily available from satellites and field experiments. During the validation period from July 2007 – June 2009, ice thickness observations from IMB and airborne thickness surveys are used to evaluate both PIPS 2.0 and ACNFS hindcasts of ice thickness. Both systems compare well against IMB ice growth trends (growing/melting), but each model over-predicts ice thickness by approximately one meter. In the comparison against airborne thickness survey data, ACNFS compared slightly better than PIPS 2.0 (0.31 m vs. 0.40 m). As thickness observations become

available over time, further sensitivity studies and possibly assimilation of thickness data, will be incorporated into ACNFS.

Modeled ice draft comparisons against the ULS mooring from WHOI during the validation period have similar trends as the ice thickness evaluation. Both models ice draft trends of growth/melt compare well to the observations, with each model over-predicting the amount of ice by approximately 1 meter. As more observations become available, further studies of ice draft will be used as a validation tool.

The IABP program archived 102 Argos drifting buoys during the ACNFS 2008 evaluation period. A comparison of 24 hr separation errors from both the ACNFS and PIPS 2.0 was performed. In both models, the 24 hr separation error from the observations during 2008 was very good, with values of 10 km for PIPS 2.0 and 11 km for ACNFS.

Overall, ACNFS is performing significantly better than PIPS 2.0 for the ice edge validation. ACNFS is performing similarly to PIPS 2.0 in both the ice thickness, ice drift and the ice draft comparisons. New products (i.e., snow thickness, albedo and convergence/divergence predictions) from ACNFS are also possible. With the increase in grid resolution, improvements in both the ice/ocean model physics and data assimilation scheme, ACNFS will help to understand the changing ice conditions in the Arctic and provide the Navy with more accurate ice forecasts. It is recommended that ACNFS be considered as a replacement for the PIPS 2.0 system.

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