D. Durnford[#] *, M. Carrera[#], F. Dupont[#], D. Deacu[#], É. Gaborit[#], C. Garnaud[#], V. Fortin[#], S. Bélair[#], F. Lespinas[#], B. Bilodeau[#], D. Khedhaouiria[#], N. Gauthier[#], G. Roy[#], P. Matte[#], V. Vionnet[#], B. Badawy[#], X. Liu[#], B. Bekcic[#], Y. L. Shin[#], O. Champoux[#], M. Abahamowicz[#], S. Keita[#], L. Morales-Marin[#], J. Morin[#], Y. Hata[#], Y. Martinez[#]

[#] Environment and Climate Change Canada, Dorval, Quebec, Canada

1. INTRODUCTION

Environment and Climate Change Canada's (ECCC) Canadian Meteorological Centre (CMC) maintains two operational numerical hydrological prediction systems. The Water Cycle Prediction System (WCPS; Fig. 1) is implemented on the Great Lakes St. Lawrence River basin. WCPS represents the full water cycle as water moves from the atmosphere to the surface, through the river network into the Great Lakes and back to the atmosphere. The system includes atmospheric, ocean-lake, marine ice and river routing models. Analyses and 3.5-day forecasts are generated twice a day. WCPS has been running in Operations since June 2016. In 2019, WCPS was promoted to full operational status with 24/7 support. WCPS is a collaboration between the ocean and hydrology groups in Research and Development at CMC.

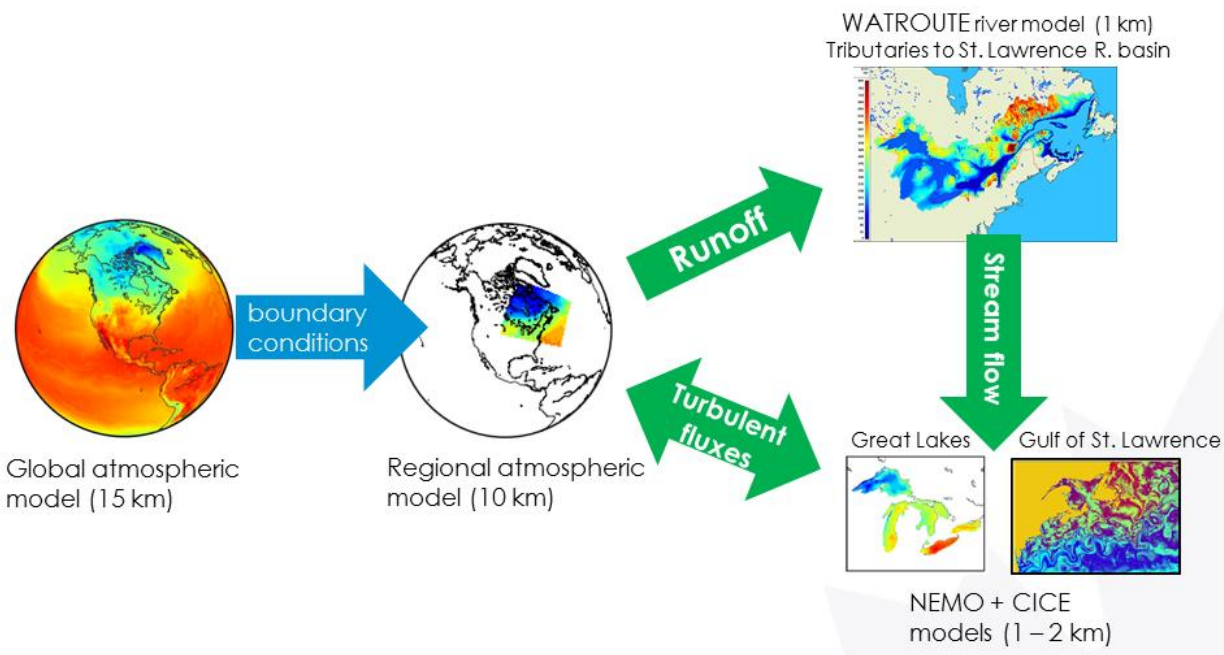

Fig. 1. The configuration of WCPS that is proposed for Innovation Cycle 3 including the information that is transferred between the system components. The core components of WCPS are the regional atmospheric model (GEM-LAM) which utilises the land surface scheme ISBA, the ocean-lake model (NEMO) which is coupled with the marine ice model CICE, and the river routing model WATROUTE.

In contrast to WCPS, the National Surface and River Prediction System (NSRPS; Fig. 2), also known as the GEM-Hydro forecasting system, was delivered to Operations in Summer 2019. This system aims to provide the best possible representation of the current and future states of the land surface and of the movement of water over and through the soil column and through the lake and river network without any feedback to an atmospheric model. This system includes components for precipitation, the surface, and rivers both small and large. NSRPS covers Canada at a 2.5-km resolution for the surface components. The river routing component covers six major Canadian watersheds, representing some 50% of Canada's land mass or approximately five million km^2, at a 1-km resolution. Analyses and 6-day forecasts are produced twice a day. NSRPS has experimental status. This system is a collaboration between the surface and hydrology groups in Research and Development at CMC.

* *Corresponding author address*: Dorothy Durnford, Environment and Climate Change Canada, 2121 TransCanada Highway, Dorval, QC, H9P 1J3, Canada; e-mail: Dorothy.Durnford@canada.ca.

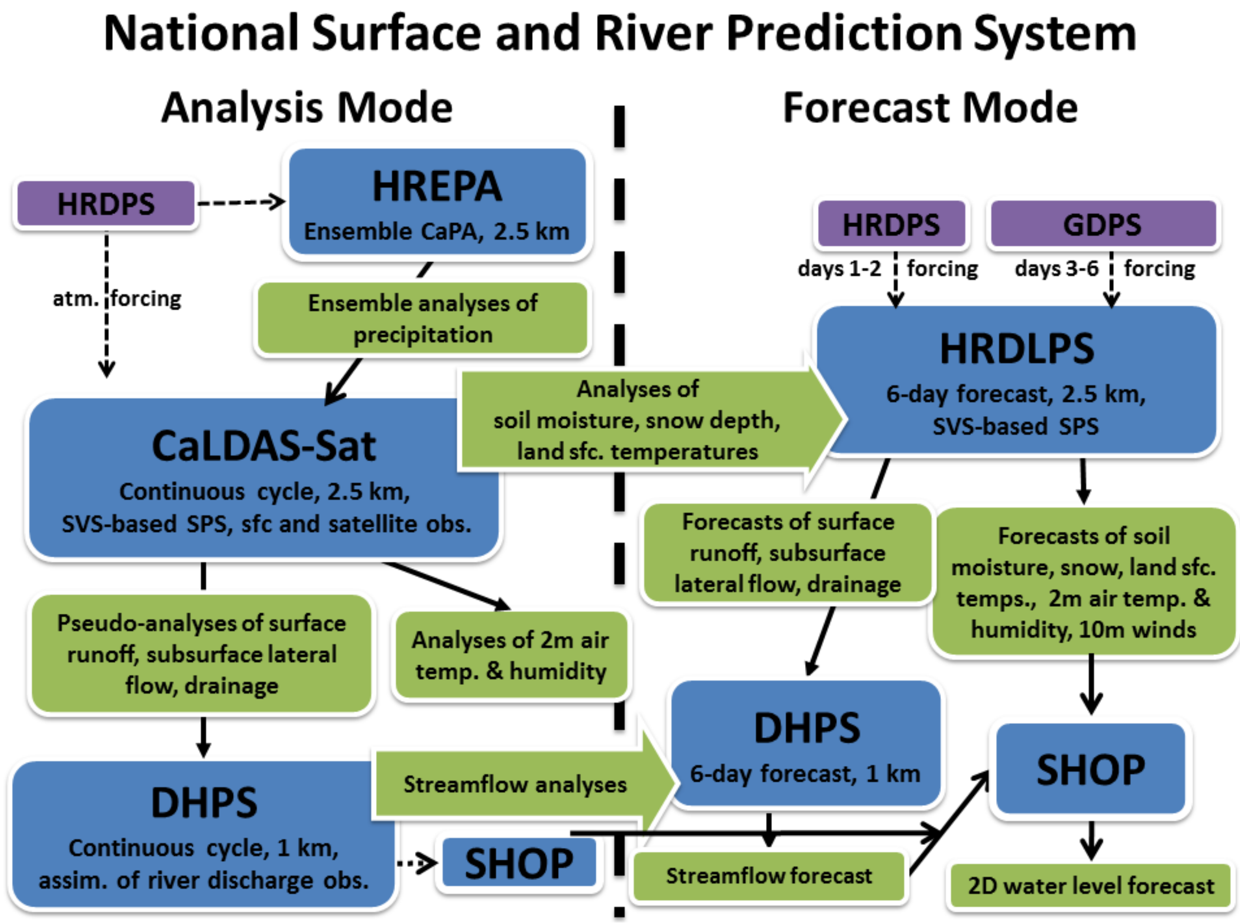

Fig. 2. The configuration of NSRPS that is proposed for IC-3 and the information that is transferred between the system components. These components include an ensemble of precipitation analyses (HREPA), land surface analysis (CaLDAS) and prediction (HRDLPS) systems, the 1-D river routing system (DHPS) and the 2-D hydrodynamic system (SHOP) for wider rivers and shallow lakes.

All analysis and prediction models at Environment and Climate Change Canada's Canadian Meteorological Centre are being upgraded simultaneously in the context of Innovation Cycle 3 (IC-3). In the current presentation, we describe the innovations proposed for IC-3 for the individual component systems of WCPS. We are also introducing NSRPS and presenting the proposed innovations for its components. In early 2021, we will test the impact of updates to upstream components of these systems on the systems' downstream components. Additionally, we will evaluate the impact on WCPS and NSRPS of the updated atmospheric models that provide their piloting fields. The descriptions that we provide here of the proposed innovations will be brief since the updates will be described in greater detail elsewhere for individual components.

2. WATER CYCLE PREDICTION SYSTEM (WCPS)

WCPS contains three component systems: a 3D regional atmospheric model (GEM-LAM) that is utilising the 2D surface model Interaction Sol-Biosphere-Atmosphere (ISBA; Bélair et al. 2003a, 2003b), a 3D ocean-lake model (NEMO; Madec et al. 1998, 2008) coupled with a 2D marine ice model (CICE; Hunke and Lipscomb 2010), and a 1D river routing model (WATROUTE; Kouwen 2010). GEM-LAM is an implementation of the atmospheric Global Environmental Multiscale model (GEM; Côté et al. 1998a, 1998b). GEM-LAM and NEMO-CICE exchange information concerning the transfer of momentum, heat and moisture every seven minutes. GEM-LAM provides hourly estimates of surface runoff to WATROUTE. WATROUTE, in turn, provides hourly estimates of terrestrial runoff entering the bodies of water on which NEMO-CICE is implemented. Thus, the complete water cycle is represented. The original version of WCPS, delivered in 2016, was described in detail in Durnford et al. (2018). In 2019, GEM-LAM was upgraded from GEM v4.6 to v4.8. We describe below the innovations proposed for each component of WCPS in the context of the ongoing IC-3.

2.1 Regional Atmospheric Model (GEM-LAM)

For IC-3, GEM-LAM is being upgraded from GEM v4.8 to v5.1. For GEM v5, the developers focused on the physics of the model and, more particularly, on all aspects of the water cycle. An evaluation of the precipitation produced by the updated version of GEM-LAM shows a decrease in the overestimation of precipitation in the Great Lakes region at all lead times for accumulations of at least 2 mm (Fig. 3). However, an evaluation by accumulation amount in the same region indicates that the model has become too dry for accumulations of at least 5 mm (Fig. 4). The skill in location is unchanged or slightly improved (not shown). Similar skill in predicting precipitation is found in the Gulf of St. Lawrence region.

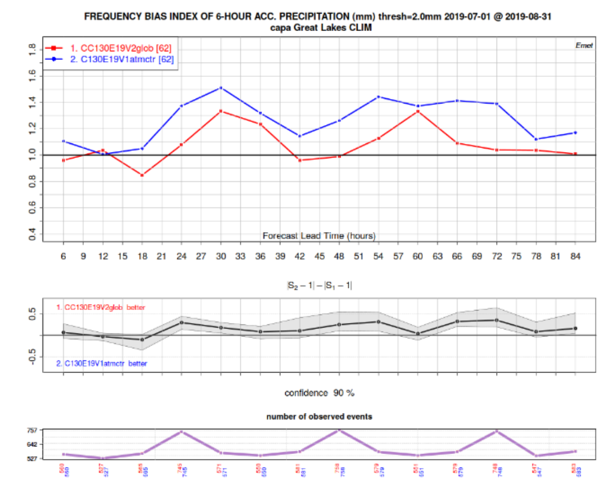

Fig. 3. Shown, as a function of lead time over the 3.5-day forecast, is the Frequency Bias Index in the Great Lakes region for 6-hour accumulations greater than 2 mm. The blue line represents the score for the operational version of the model. The red line represents the version proposed for IC-3.

2.2 Ocean-Lake and Marine Ice Models (NEMO-CICE)

For IC-3, the horizontal resolution of NEMO on the Great Lakes has been increased from 2 km to 1 km. Also, a version of the high resolution implementation of NEMO on the East coast (Coastal Ice Ocean Prediction System East (CIOPS-E; 1-2 km) has been added to WCPS. This addition of CIOPS-E replaces the current implementation on the Gulf of St. Lawrence that has a 5-km horizontal resolution. The new higher resolution grids for both the Great Lakes and Gulf are better able to resolve the coastline and also the fine scale structures of the state of the water.

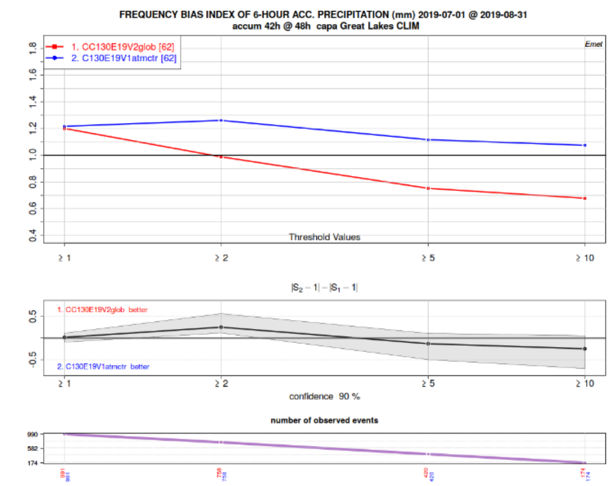

Fig. 4. The Frequency Bias Index in the Great Lakes region for 6-hour accumulations over the length of the 3.5-day forecast as a function of precipitation accumulation. The blue line represents the score for the operational version of the model. The red line represents the version proposed for IC-3.

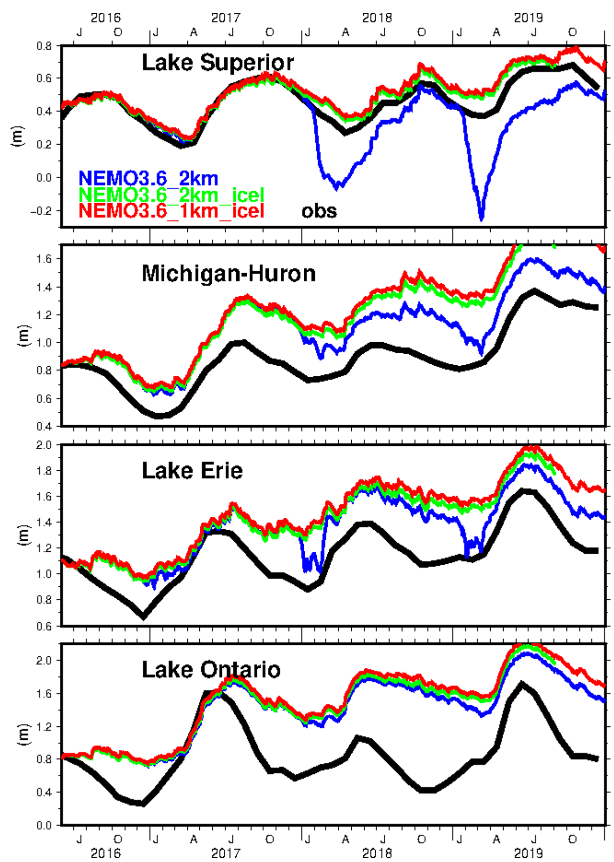

Fig. 5. Water level on the Great Lakes simulated by NEMO. The issue related to ice loading that is present in the operational version (similar to blue line) has been corrected in the proposed version (red).

Also for IC-3, the version of NEMO in both the Great Lakes and Gulf of St. Lawrence regions has been upgraded from v3.1 to v3.6. Additionally, an issue with the water level of the Great Lakes due to the representation of the ice load that is present in the operational version has been corrected (Fig. 5). Note that the drift seen in the lake levels of Fig. 5 is likely caused by inaccuracies in the overall water budget. However, any bias is removed during the issuance of alerts.

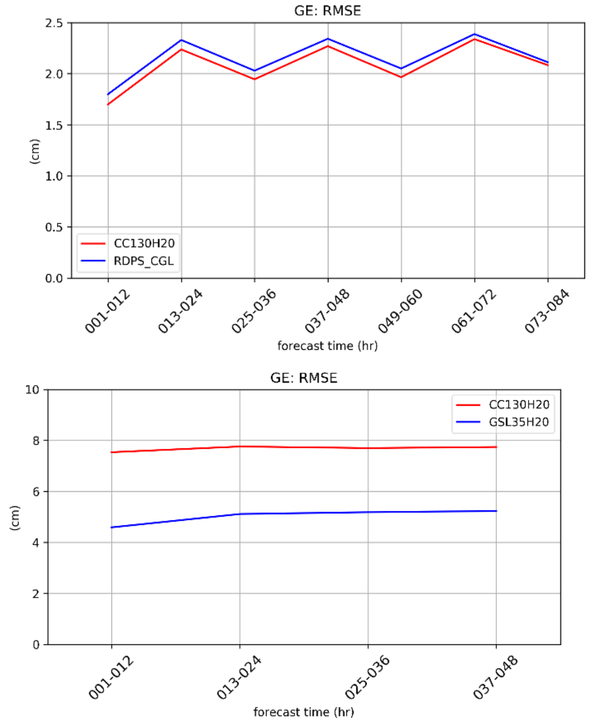

Fig. 6. RMSE of the ice thickness (m) as a function of forecast lead time averaged over 1 January – 29 February 2020 for the Great Lakes (top) and the Gulf of St. Lawrence (bottom). The reference is provided by RADARSAT data. The operational version is represented by the blue line and the proposed version by the red line.

For IC-3, the Regional Ice Prediction System (Lemieux et al. 2016) will provide the initial conditions of marine ice for the GEM-LAM-NEMO-CICE coupled forecasts. Currently, satellite-derived estimates are inserted directly into the simulated ice cover. The direct insertion method will be retained only for the continuous pseudo-analysis cycle that provides the coupled forecast's initial conditions for the state of the water.

The prediction of marine ice has improved in the IC-3 version in the Great Lakes (Fig. 6) and Gulf of St. Lawrence (Fig. 7) regions except for the predicted ice thickness in the Gulf region. However, according to the subjective evaluation of people on site, it is likely that the observations along the western coastline of the Gulf are missing the regions of thick ice.

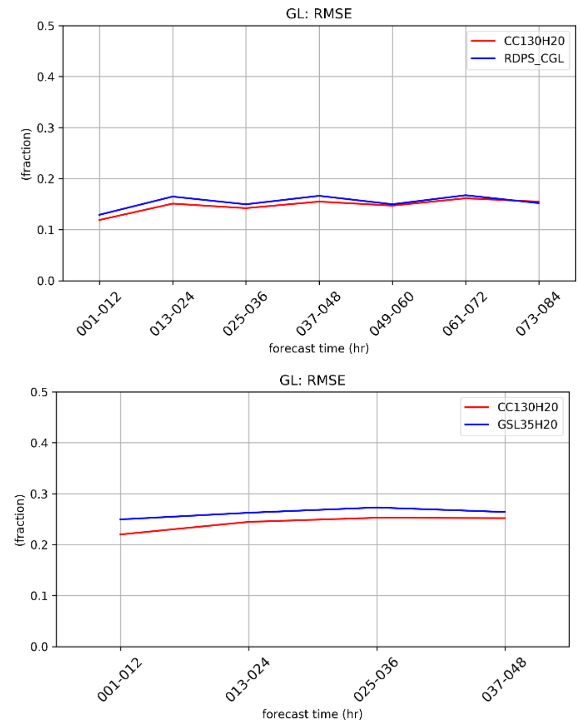

Fig. 7. RMSE of the concentration of ice (fraction) as a function of forecast lead time averaged over 1 January – 29 February 2020 for the Great Lakes (top) and the Gulf of St. Lawrence (bottom). The reference is provided by RADARSAT data. The operational version is represented by the blue line and the proposed version by the red line.

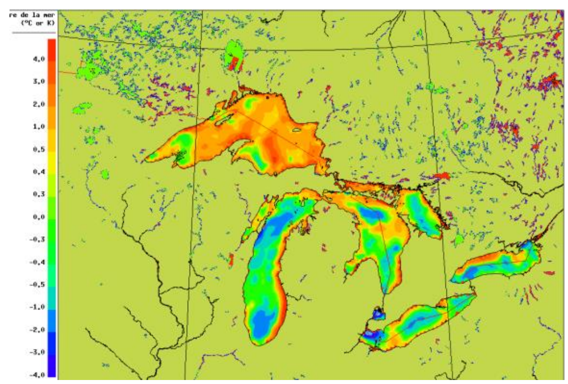

Fig. 8. The difference (degrees; proposed – operational) in surface water temperature on a random date between the operational and proposed versions of NEMO for the Great Lakes.

We find that the representation of surface water temperature can change noticeably in the proposed version compared to the operational version. The temperatures on the random date chosen were cooler in the southern Great Lakes with the proposed version and warmer in the northern regions (Fig. 8). The greatest difference is the warming, by up to 4 degrees, in Lake Superior.

A final change for IC-3 is that NEMO-CICE on the Great Lakes and in the Gulf of St. Lawrence will now interact with a single GEM-LAM. Until now, the Great Lakes and Gulf domains interacted with different versions of GEM-LAM. Thus, for IC-3, the Gulf and Great Lakes systems are being combined and simplified.

2.3 River Routing Model (WATROUTE)

The river routing component of WCPS (WCPS-WH) is being upgraded to DHPS v3.1. This represents numerous innovations for WCPS-WH. Firstly, we are updating the numerical scheme. This scheme removes instabilities that had been detected in the flow in NSRPS/DHPS. The same scheme became operational in NSRPS/DHPS in September 2019.

Another new feature for WCPS-WH with IC-3 is the implementation of the propagation upstream during data assimilation of information derived from observations of river discharge. This update eliminates error during the 12-h data assimilation cycle on rivers having an observation (Fig 9). This feature became operational in NSRPS/DHPS in July 2020.

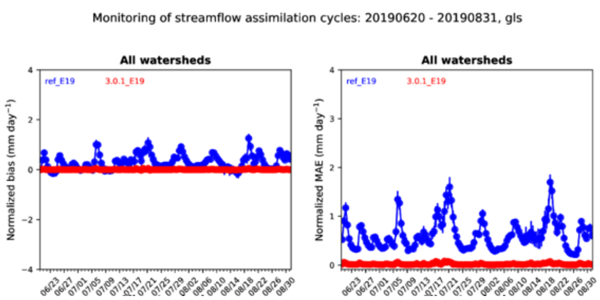

Fig. 9. The bias (left) and mean absolute error (right) of river discharge from individual 12-hour segments of the data assimilation cycle of WATROUTE for summer 2020. Scores are calculated at individual observation stations and normalised by the station's drainage area. The mean normalised score is shown in red for the proposed version and in blue for the operational version.

Innovations for IC-3 for WCPS-WH that were finalized only recently include an update to the data assimilation system whereby the observation-derived information that is propagated upstream during data assimilation now also corrects the water level of natural lakes; the lake with its corrected water level will continue to release water for several days at a rate that is comparable to that derived from observations downstream (Fig. 10). The example shown is for the Churchill River basin of NSRPS/DHPS over Fall 2019; it was in this basin that the correction of water levels of natural lakes had the greatest impact.

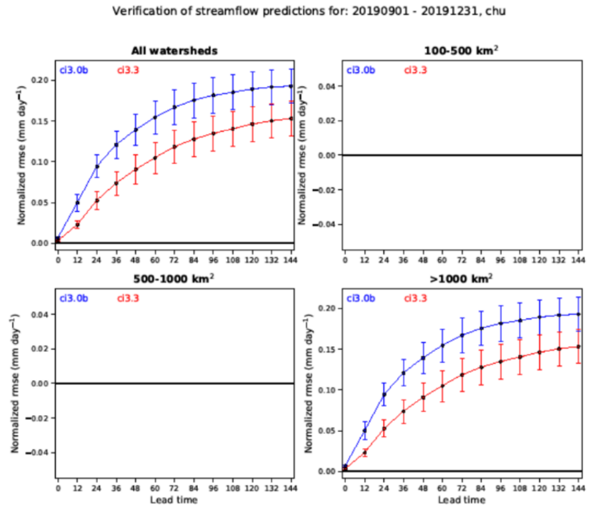

Fig. 10. RMSE of river discharge normalized by each station's drainage area for all (upper left) and large (lower right) watersheds of the Churchill domain. The blue line is the operational version of DHPS while the red line has added the correction of the water level of natural lakes during data assimilation.

Additionally, WCPS-WH gains the implementation of a modified version of the DZTR model for regulated reservoirs (Fig. 11; Poster 582 of Gaborit et al.) described in Yassin et al. (2019). In the Great Lakes St. Lawrence River and Gulf of St. Lawrence domains this amounts to 21 and 4 reservoirs, respectively. The regulation of some 15 reservoirs in the Ottawa River valley alone is now represented explicitly. We find that the use of the DZTR model improves the simulated river discharge downstream of regulated reservoirs during certain periods; the timing of the period varies by reservoir.

A final important update for WCPS-WH is the assimilation of observations of river discharge from USGS and the Centre d'Expertise Hydrique du Québec of the Ministère de l'Environnement et de la Lutte contre les changements climatiques. Currently, WCPS-WH assimilates observations of river discharge from ECCC alone.

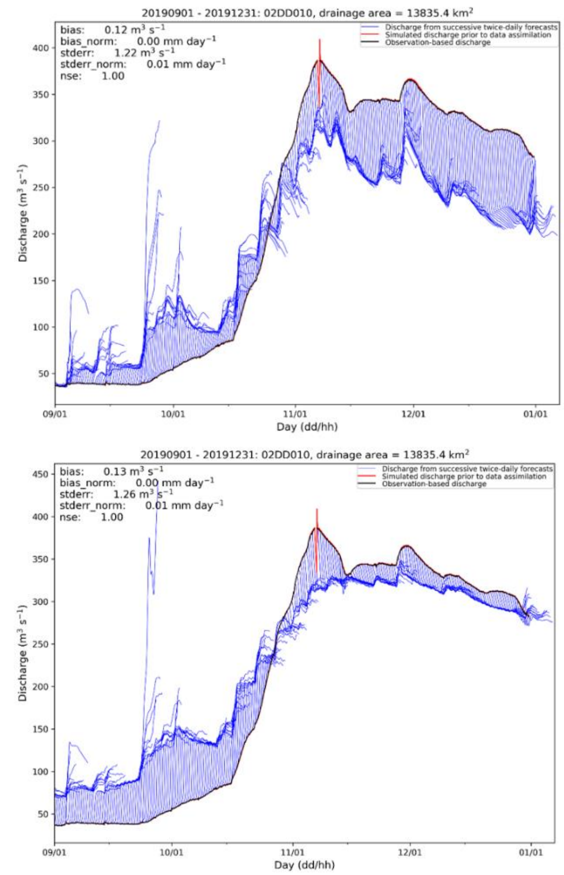

Fig. 11. River discharge downstream of Lake Nipissing as simulated for Fall of 2019 by the operational version of WCPS-WH (top) and by the DZTR model (bottom). Observations are in black, the analysis in red and the successive twice-daily 6-day forecasts in blue.

And, finally, there are two updates for IC-3 that apply only to WCPS-WH and not to NSRPS/DHPS. Firstly, as mentioned above, piloting fields for WCPS-WH are taken from GEM-LAM. This version of GEM-LAM utilises the ISBA land surface scheme. Unfortunately, estimates of drainage, or the water that exits the base of the soil column, from ISBA are unreliable. Consequently, WCPS-WH uses climatological estimates of drainage. For IC-3, the climatology will be updated. The new version is based on September 2002 through August 2017 of an offline run at a 10-km resolution of the Surface Prediction System (SPS; Bernier et al. 2011) that uses CMC's new land surface scheme Soil Vegetation Snow (SVS; Alavi et al. 2016, Husain et al. 2016). This run was piloted by CMC's new regional reanalysis of the surface and precipitation (see Gasset et al. 2020 for a description of a preliminary version of the reanalysis).

The second update that applies only to WCPS-WH is that we are adding the Gulf of St. Lawrence domain. However, the terrestrial runoff provided by the new Gulf domain will not be ingested by NEMO-CICE until Innovation Cycle 4. The Gulf domain, which consists of all the land that drains into the Gulf, has been part of NSRPS/DHPS since July 2020.

In conclusion, for IC-3, WCPS-WH is being updated to the latest version of the river routing model. Thus, following the implementation in Operations of the proposed innovations, WCPS-WH will be very similar to NSRPS/DHPS. A comparison of the two river routing components is provided in Sect. 3.4.

3. NATIONAL SURFACE AND RIVER PREDICTION SYSTEM (NSRPS)

NSRPS contains five component systems (Fig. 2). These are the High Resolution Ensemble Precipitation Analysis (HREPA; Khedhaouiria et al. 2020), the version of the 2D Canadian Land Data Assimilation System that assimilates satellite data (CaLDAS; Carrera et al. 2015), the 2D High Resolution Deterministic Land Prediction System (HRDLPS; Deacu and Bélair 2019), the 1D Deterministic Hydrologic Prediction System to route flows through the river network (DHPS) and the 2D Simulation Hydrodynamique OPérationnelle (SHOP; Morin et al. 2006, Matte et al. 2017a, 2017b) to represent currents and water levels in wide rivers and shallow lakes. At the surface, CaLDAS and HRDLPS both run the Surface Prediction System (SPS; Bernier et al. 2011) and utilise the Soil, Vegetation and Snow (SVS; Alavi et al. 2016, Husain et al. 2016) land surface scheme.

Since NSRPS is an offline system for the surface, it requires piloting models to inform it of changing atmospheric conditions near the surface. HREPA ingests hours 0-6 of the precipitation forecasts from the High Resolution Prediction System (HRDPS). CaLDAS uses the first six hours of the forecast by HRDPS. For HRDLPS, the initial conditions are provided by CaLDAS. Days 1-2 of its forecast are piloted by HRDPS and Days 3-6 are piloted by the Global Deterministic Prediction System (GDPS). For DHPS, the data assimilation cycle is piloted by CaLDAS while the forecasts are piloted by HRDLPS. SHOP's piloting models will be discussed in Sect. 3.5. Together, the components of NSRPS form a seamless, physically-consistent prediction system. Products taken from any component of NSRPS can be used in conjunction with products from other components.

HREPA and CaLDAS are ensemble systems. They each have 24 members plus a control member. From its 24 members, CaLDAS generates a deterministic analysis. HRDLPS, DHPS and SHOP are deterministic systems; they each provide a single estimate of the future state.

HRDLPS takes its initial conditions from CaLDAS. Currently, all snow variables are taken from the control member. This member has not seen assimilation of data other than ground-based precipitation observations. Soil moisture is taken from the control member if a grid cell contains snow in either the control member or the analysis. If no snow is present in a given grid cell in either the control member or the analysis, soil moisture for the top four layers is taken from the analysis and for the bottom three layers from the control member. The temperature of the soil and of the vegetation, as well as the water that is intercepted by vegetation, are taken from the analysis. The use of initializing fields from a combination of the analysis and the control member of CaLDAS was motivated by issues detected in the representation of the snowpack in CaLDAS (see below).

DHPS takes its piloting fields of surface runoff, subsurface lateral flow and drainage from CaLDAS for its data assimilation cycle and from HRDLPS for its forecast. No analyses are available from CalDAS for any of these three piloting fields given the absence of direct observations for CaLDAS to assimilate. Thus, to pilot its data assimilation cycle during the warm season, DHPS uses the estimate of all three piloting fields from the ensemble member of CaLDAS having the surface runoff that is closest to the median of the estimates of surface runoff from the 24 members of CaLDAS. Using all three piloting fields from the same member provides an internally consistent estimate of the water that is available to enter rivers. However, a different member may be selected to provide the piloting fields at different grid points. This is reasonable as CaLDAS is a column model with no interaction between neighbouring grid points. During the cool season, DHPS currently takes the piloting fields for its data assimilation cycle from the control member of CaLDAS. The seasonal change in source of piloting fields for the data assimilation cycle of DHPS was motivated by issues detected with the representation of the snowpack in CaLDAS (see below).

The initial delivery of NSRPS was in Summer 2019. HREPA, CaLDAS and HRDLPS were implemented over Canada at a 2.5-km resolution. DHPS was implemented at a 1-km resolution on the Great Lakes St. Lawrence River and the Nelson River basins.

In Fall 2019, the numerical scheme for DHPS was updated to eliminate instabilities detected in the simulated flows. Additionally, CaLDAS replaced GOES-15 by GOES-16 as a source of skin temperature retrievals since the former satellite was being retired. Both updates were considered urgent.

In Spring 2020, the coupling between system components was weakened to the configuration described above as the river routing component had detected issues in the estimates of the snowpack by the ensemble members of CaLDAS. Two issues were detected. Firstly, since the onset of snowmelt is late in SVS, during periods where snow was melting in the real world, the assimilation of observations of snowpack depth continuously removed snow from the model. Secondly, the simulated density of the snowpack is not always reliable. Thus, if the snow water equivalent (SWE) is reasonable, the assimilation of observations of snowpack depth reduces the SWE too much when the density is underestimated and increases the SWE too much when the density is overestimated. Since the changes to SWE during data assimilation are not accompanied by changes in water content elsewhere in the model, water is not conserved. This leads to a degradation of streamflow simulations. Given this issue, HRDLPS and DHPS are currently, as described above, piloted during the cool season by a combination of the control member and the ensemble members of CaLDAS; the control member's snowpack contained a greater, more realistic amount of snow. In the warm season, piloting fields are sourced purely from the ensemble members of CaLDAS, which benefit from the assimilation of satellite-derived surface temperature and soil moisture data.

As an additional feature of the Spring 2020 update, the Churchill River basin was added to DHPS. In July 2020, new domains for the Mackenzie and Yukon River basins and the Gulf of St. Lawrence were added. This last domain is all the land that drains into the Gulf. At the same time, an update to the data assimilation system of DHPS was delivered. In the updated system, information derived from observations is propagated upstream (Sect 2.3). This greatly reduces errors in river discharge in the analyses on rivers having an observation. It also reduces errors in the forecast river flows for several days.

NSRPS has been running in Operations now for one and a half years. Work to upgrade the system is continuous. We describe below the innovations proposed for the individual components of NSRPS in the context of IC-3.

3.1 High Resolution Ensemble Precipitation Analysis (HREPA)

HREPA provides an ensemble of analyses of 6-hour accumulations of precipitation. The ensemble includes 24 members, which are produced by perturbing stochastically the unperturbed control member. The control member resembles the High Resolution Deterministic Precipitation Analysis. In this analysis, short-term forecasts of precipitation are taken from CMC's High Resolution Deterministic Prediction System (HRDPS). The forecasts are then modified by the assimilation of observations from ground-based networks and from radars.

For innovations for HREPA in the context of IC-3, we are adding 5 new S-band radars in Canada and three networks of precipitation gauges in Manitoba and Ontario. We are withdrawing a network of precipitation gauges in Ontario as a result of errors in the processing of the observations. Once the treatment of the raw data has been corrected, this network will be added back in. To correct the extent of precipitation estimated by radar, data from GOES-16 and -17 are being added. This replaces data from the retired GOES-15. Additionally, the masks of eight radars have been updated to limit terrain-related errors introduced by the radars. However, a ninth radar (Dryden, Ontario) has been withdrawn following the detection of issues with the precipitation analysis in the vicinity of the radar.

3.2 Canadian Land Data Assimilation System (CaLDAS)

CaLDAS generates analyses of the state of the surface and the soil column. The analyses and other estimates from CaLDAS provide the initial conditions for forecasts by HRDLPS. Additionally, estimates from CaLDAS of surface runoff, subsurface lateral flow and drainage that are constrained by the numerous observations that are assimilated by CaLDAS (but not by observations of those three variables themselves since none is available) pilot the data assimilation cycle of DHPS.

In the context of IC-3, several innovations are being proposed for CaLDAS. They can be grouped into three subsets: those related to the configuration of the Surface Prediction System (SPS) and the land surface scheme Surface Vegetation Snow (SVS), those related to the representation of the snowpack, and the remaining assortment of updates. The different sets of updates have been prepared by different teams.

The innovations related to SPS and SVS are being proposed for both CaLDAS and HRDLPS. For these systems, a revised set of geophysical fields for orography and slope from USGS, Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010; Danielson and Gesch 2011), will be used. The resolution of this data set is approximately 225 m. Also. the version of SPS will shift from v5.9 to v6.1. Furthermore, the Obukhov length will now be limited in stable conditions over all surface types. Over the land surface (or soil), the length used will vary seasonally to reduce the warm bias in summer that is caused by too much vertical mixing. Finally, the thermal coefficient, aerodynamic roughness length and emissivity of the urban surface have been modified to be more realistic. The main effect of the latter changes is a drastic reduction of the nocturnal cold bias in the summer in the grid cells with dominant urban land cover.

For the snowpack, the assimilation of observations of snowpack depth are being withdrawn since their assimilation degrades the analysed snow water equivalent. In non-mountainous areas, we are adding the assimilation of data from the National Ice Center's Interactive Multisensor Snow and Ice Mapping System (IMS; 1-km resolution; U.S. National Ice Center 2008). These daily satellite-derived estimates correct the extent of the snowpack in CaLDAS. The assimilation of IMS data will be limited by elevation difference. Finally, given that the non-physical perturbation of the precipitation analysis during the production of the ensemble of precipitation analyses does not consider orography, snow depth estimates are debiased in mountainous areas. See Camille Garnaud's presentation for further information on these snowpack-related updates.

Further updates for CalDAS in the context of IC-3 are related to satellite data. The assimilation of brightness temperatures from the Soil Moisture Active Passive (SMAP; Entekhabi et al. 2010) mission are being added; currently only data from the Soil Moisture and Ocean Salinity (SMOS; Kerr et al. 2012) satellite are assimilated. This will increase the spatial and temporal coverage in CaLDAS of passive L-band brightness temperatures. It will also provide some redundancy. Thus, should either SMOS or SMAP data be unavailable, data from the alternate satellite is still expected to be available for assimilation. This improves the robustness of the system. Similarly, GOES-17 data are being added as a source of skin temperature retrievals.

Finally, we propose for IC-3 to implement a tighter configuration for the coupling of the components of NSRPS. For CaLDAS, this means that the ensemble of precipitation analyses that it ingests will be provided by HREPA instead of being generated within CaLDAS. With this update, CaLDAS will benefit immediately from the assimilation of precipitation observations from additional ground-based networks and also from radars. In future, CaLDAS will also benefit from updates to HREPA, such as the assimilation of data from new ground-based observations and radars, and from satellites.

3.3 High Resolution Deterministic Land Prediction System (HRDLPS)

HRDLPS is a downscaling system. As mentioned at the top of Sec. 3, while Days 1-2 of its prediction are piloted by HRDPS, Days 3-6 are piloted by GDPS. HRDPS and HRDLPS both use a 2.5-km horizontal resolution. However, the resolution of GDPS is currently at 15 km. HRDLPS takes the forecasts from GDPS of the state of the near-surface atmosphere, applies a downscaling accounting for elevation difference between the 15-km and the 2.5-km grids, and provides a fine-scale forecast of the near-surface atmosphere, the land surface, and the soil column. The scores of Days 3-6 of its forecasts for the near-surface atmosphere are superior to those of GDPS.

Additionally, HRDLPS constitutes a test bed for new configurations of SPS and SVS. Computationally, it is less expensive to perform experiments with the 2D HRDLPS rather than a fully 3D atmospheric prediction system. Thus, updates are tested and introduced in HRDLPS and then introduced into CaLDAS. They can also then be tested in the atmospheric prediction systems.

For innovations for HRDLPS in the context of IC-3, the updates proposed for SPS and SVS are described in Sect. 3.2 for CaLDAS. Additionally, the coupling between HRDLPS and CaLDAS is expected to be updated to the proposed tighter configuration. In this configuration, HRDLPS will take its initializing fields solely from the ensemble members of CaLDAS; the control member will no longer be used as a source of piloting fields in the cool season. The benefit of the proposed tighter configuration for the coupling is that all initializing fields will have been constrained by observations and will be internally consistent.

3.4 Deterministic Hydrologic Prediction System (DHPS)

DHPS is the 1D river routing component of NSRPS. It takes estimates from CaLDAS and HRDLPS of water that's available to enter the rivers and routes it through the river network at a horizontal resolution of 1 km. Currently, it represents rivers in six watersheds: Great Lakes St. Lawrence River, the Nelson, Churchill, Mackenzie and Yukon river basins, and the terrain draining into the Gulf of St. Lawrence. These six watersheds together cover approximately 50% of Canada's land mass or about 5 million km^2.

For IC-3, NSRPS/DHPS will be updated to DHPS v3.1. The innovations associated with DHPS v3.1 are described in detail in association with WCPS-WH (see Sect. 2.3). For DHPS, this upgrade consists of the correction of lake levels of naturals lakes during data assimilation, the implementation of the DZTR model for regulated reservoirs, and the assimilation of observations from Alberta Environment and Parks, the Centre d'Expertise Hydrique du Québec of the Ministère de l'Environnement et de la Lutte contre les changements climatiques, and from USGS. For DHPS, there are, as per WCPS-WH, 21 and 4 regulated reservoirs in the Great Lakes St. Lawrence River and Gulf of St. Lawrence domains, respectively. Additionally, in NSRPS/DHPS there are 11 regulated reservoirs in the Nelson River domain and 1 in the Mackenzie River domain.

A final update for DHPS with IC-3 is that, as per HRDLPS, the coupling between CaLDAS and DHPS is expected to be updated. With the proposed tighter configuration, no piloting fields for either HRDLPS or DHPS will be taken from the control member of CaLDAS (see Sect. 3.3). The benefits expected for HRDLPS also apply to DHPS.

Since both WCPS-WH and NSRPS/DHPS will be running DHPS v3.1, the two river routing models will be identical. The primary difference between the two river routing systems will be the source of the piloting fields. For WCPS-WH, piloting fields of surface runoff are taken from GEM-LAM with its 10-km resolution and its use of the ISBA land surface scheme. ISBA's version of surface runoff incorporates subsurface lateral flow. Also, as mentioned in Sect. 2.3, WCPS-WH uses climatological estimates of drainage as a result of the unreliable estimates of drainage that are produced by ISBA. In contrast, NSRPS/DHPS uses estimates of surface runoff, subsurface lateral flow and drainage that are all provided individually in near real-time at a 2.5-km resolution by the land surface scheme SVS in NSRPS's CaLDAS and HRDLPS.

The piloting fields of WCPS-WH and NSRPS/DHPS also differ because, while GEM-LAM mimics RDPS, NSRPS is piloted by HRDPS for the analysis of CaLDAS and Days 1-2 of the prediction by HRDLPS. Days 3-6 of the HRDLPS' prediction are piloted by the Global Deterministic Prediction System (GDPS; see start of Sect. 3). This is relevant as the generation of precipitation is different in RDPS, HRDPS and GDPS. Additionally, the forecasts from HRDPS are then randomly perturbed by the version of CaLDAS that is coupled with HRDPS. Subsequently, precipitation observations are assimilated by NSRPS/CaLDAS. For IC-3, it will be NSRPS/HREPA that will assimilate these observations. Similarly, the ensemble of snowpack analyses ingested by CaLDAS differs from the snowpack analysis of RDPS as a result of snowpack-related processes in CaLDAS (Sect. 3.2). Given the differences in precipitation forecasts and snowpack analyses, the water entering the river networks, or the piloting fields for the river routing component, will also most certainly differ in WCPS and NSRPS regardless of the land surface scheme used.

There are two further less important differences between WCPS-WH and NSRPS/DHPS. Firstly, the river routing forecasts of the former system are launched at 06 and 18 UTC while they are launched by the latter system at 00 and 12 UTC. Thus, the two river prediction systems are ingesting somewhat different observations of riverine discharge. Secondly, WCPS provides forecasts of 3.5 days while NSRPS predicts the next 6 days.

3.5 Simulation Hydrodynamique OPérationnelle (SHOP)

SHOP, a 2D (depth-averaged) hydrodynamic modelling system, is being added to NSRPS with IC-3. This system provides water levels and currents on wide rivers and shallow lakes. It is currently implemented on the St. Lawrence River. With its unstructured mesh, it is capable of representing intricate coastlines and zones with multiple channels. It can also represent the lateral spreading of water according to the water level and the topography. The average horizontal resolution is lower than 200 m.

As a first step to becoming a component of NSRPS, SHOP will source tributary flows from NSPRS/DHPS instead of from WCPS-WH. As part of the switch to using tributary flows from DHPS, the debiasing system within SHOP will be partially removed. The quality of SHOP's analyses and forecasts will be maintained by the addition, for CI-3, of the assimilation by DHPS of observations from the Province of Quebec; the usage of these observations has transferred from one component of NSRPS to another. Further experiments planned for SHOP for 2021 will examine the impact of removing SHOP's debiasing system entirely.

SHOP is also starting to source information from CaLDAS. For CI-3, SHOP will take the 1.5-m temperature in the middle of lac St. Pierre from NSRPS/CaLDAS instead of from the regional precipitation analysis. The temperature at the point of interest is used to determine the extent of the marine ice cover. For Fall, it is planned 2021 that SHOP will source its piloting winds from NSRPS's CaLDAS and HRDLPS. Interestingly, the change in source of tributary flows and temperature for IC-3 have little impact on the performance of SHOP.

The innovation associated with IC-3 that has the greatest impact on the performance of SHOP is the replacement of the source of boundary conditions at the tidal end of the domain. The required information is currently taken from Fisheries and Oceans Canada's 1D model, Service de Prévision et d'Interpolation des Niveaux d'Eau (SPINE). This is being replaced by new harmonic boundary conditions. This update yields a significant improvement of water level forecasts up to 200 km from the tidal boundary.

3.6. Future Additional Ensemble Components for NSRPS

The IC-3 version of NSRPS contains two ensemble systems (HREPA, CaLDAS) and three deterministic systems (HRDLPS, DHPS, SHOP). In early 2021, we will add an ensemble version of the land surface forecasting component HRDLPS (HRELPS) and of the 1D river routing component DHPS (EHPS). Both HRELPS and EHPS will have 21 members. Both systems will launch one forecast per day with a lead-time of 16 days. On Thursdays, the forecast will extend to 32 days. These systems will use the deterministic initial conditions and the model configuration of HRDLPS and DHPS; only their piloting fields will distinguish the members. HRELPS will be piloted by the Regional Ensemble Prediction System for Days 1-3 and by the Global Ensemble Prediction System for Days 4-16. EHPS will be piloted by HRELPS.

5. CONCLUSION

We have described CMC'S two complex coupled systems that include hydrological components. The two systems have different purposes. WCPS represents the full water cycle and provides river flows and information about the state of large bodies of water. It is currently implemented on the St. Lawrence River basin including the Great Lakes. For IC-3, it will be extended to include the Gulf of St. Lawrence. Given its operational status, the innovations of IC-3 will become operational in Fall 2021.

NSRPS aims to provide the best possible representation of the current and future states of the land surface, the moisture content of the soil column, and river flows. Most components of NSRPS are implemented over Canada; river flows are currently available for some 50% of Canada. Given its experimental status, the innovations proposed for NSRPS in the context of IC-3 will become operational in Spring 2021.

Both WCPS and NSRPS provide information that is of interest to a variety of clients. But these systems are also of interest in that they are able to inform us of weaknesses in the representation of processes; weaknesses in upstream components are evident in the performance of downstream components. For instance, the river routing component of NSRPS identified a problem with a lack of snowmelt during the Spring freshet. The root cause of this symptom was determined to be the analysis of the snowpack. Following extensive investigations, several modifications for the generation of the analysis are being proposed for IC-3 to correct the issues (Sect. 3.2). Similarly, for WCPS, the river routing component determined that the atmospheric component was overestimating precipitation in the Great Lakes region. The corrections found for these issues propagate back up the chain into the atmospheric prediction systems. Thus, as well as providing useful information, WCPS and NSRPS constitute useful teaching tools.

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