Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)
Fondation canadienne pour les sciences du climat et de l'atmosphère (FCSCA)

Final Progress Report

Project Title: Soil moisture analysis and seasonal forecast of drought

DRI Investigator: Charles Lin

1.0 Project Work

1.1 **Provide a summary description of a) the objectives of the study, b) the scientific findings and c) the project work undertaken.**

a. The objectives of the study

For our DRI contributions, we build upon our experience over the past 15 years on the coupling of atmospheric and land surface hydrological models for flood and drought simulation. Within Theme 3 of DRI, we focus on assessing and reducing uncertainties in the prediction of drought and its structure. This is done through using a macro-scale land surface hydrology model to reconstruct sixty year (1950-2009) daily soil moisture over the Canadian Prairies (Wen et al., 2010) and the fifty-nine year (1951-2009) drought history of China (Wu et al., 2010), and through the development and application of a real time drought monitoring and forecasting system over the prairies (Wen et al., 2010) and China (Wu et al., 2010). The issue of uncertainties in the prediction of droughts is addressed through the use of ensemble forecasts of numerical models and the use of gauge precipitation to complement the model precipitation for driving the hydrological model in real time drought forecast.

b. The scientific findings

A real time drought monitoring and forecasting system has been developed, tested and implemented over the Canadian Prairies (1,964,000 km^2) and China (9,600,000 km^2). In the prairies, the system uses the VIC (Variable Infiltration Capacity) model to simulate daily soil moisture values starting from 1 January, 1950, and continually running through present into the future with a forecast lead time up to 35 days. VIC is driven by daily maximum and minimum air temperature and precipitation from 1,167 meteorological stations for reconstructing and monitoring runs up to the present, and by the operational Canadian GEM (Global Environmental Multiscale) model forecast (0 to 6 days), the operational 40-number super ensemble forecast of Canadian Meteorological Center (CMC; 7 to 15 days), and the operational CMC ensemble seasonal forecast (16 to 35 days) for the forecasting runs. A novel feature of the methodology is the use of both gauge and model data to drive VIC for real time drought forecasting. The methodology was developed, tested and implemented successfully in our one-way coupled hydro-meteorological modeling system for real time flood forecast over the Huaihe River Basin (270,000 km^2) of China (Lin et al., 2010).

VIC simulated soil moisture values are used to calculate the Soil Moisture Anomaly Percentage Index (SMAPI) as an indicator for measuring the severity of agricultural and hydrological droughts. SMAPI values can be classified into nine categories that are similar to that of Palmer Drought Severity Index (PDSI; Palmer, 1965). In contrast to many other real time hydrological modeling, our VIC drought reconstructing, monitoring and forecasting system emphasizes on the idea of maintaining consistency between the real time and long term soil moisture simulations/conditions.

The prairie SMAPI is qualitatively compared with three independent drought datasets, which are the North American Drought Monitor (NADM), the Palmer Drought Index (PDI) of Agriculture and Agri-Food Canada, and the PDSI of Environment Canada. The result shows that the SMAPI compares favorably with these datasets and is useful to quantifying the most documented prairie drought events of the past 60 years. Our VIC prairie soil moisture simulation is updated daily, and the SMAPI results with different temporal scales of daily, monthly, seasonal and annual are publicly accessible online (http://www.meteo.mcgill.ca/~leiwen/vic/prairies/).

c. The project work undertaken

Predicting precipitation is the most important and difficult component in any drought monitoring and forecasting system. It represents the major prediction challenge because of the wide range of space and time scales of precipitation phenomena and the diversity of processes that give rise to occurrence. This is especially true for seasonal precipitation forecasting using numerical models. We have being working closely with Dr. Hai Lin of Environment Canada on the improvement of our prairie drought forecasts, who has developed a new 35-day forecast product in which certain biases are corrected. It should be soon ready for use in our real time drought monitoring and forecasting system.

Another prediction issue is related to the role of different data sets used in forcing seasonal forecast models. This is linked to the soil moisture initialization project that we have been collaborating with Dr. Aaron Berg. Berg demonstrated that soil moisture initialization has a statistically significant impact on monthly air temperature prediction.

1.3 **Describe the tangible results or the measurable outputs generated by the project and how these results have been taken up by user groups for policy development or operational improvements.**

a. Tangible results on real time drought forecasts

Tangible results of our real time drought monitoring and forecasting system can be first demonstrated through an examination of the recent severe drought case of 2009 in western Canada. Since the late summer of 2008, new large scale droughts had been developing in southern Saskatchewan and the Peace River region of northern Alberta, which were documented in the August 2008 NADM report. The two drought regions can be clearly indentified in the SMAPI distribution of the August-2008 average in the top 1 m as shown in the panel (*d*) of Figure 1 for drought monitoring purpose. Meanwhile, using the combined meteorological forcing of real time gauge precipitation and temperatures, the operational Canadian GEM model forecast, and the operational CMC 40-member super ensemble forecast as meteorological inputs, the drought evolution was predicted 15 days in advance as shown in panels (*a, b, c*) of Figure 1. To evaluate the skill of our drought prediction, the VIC forecast SMAPI distributions are qualitatively

compared with the NADM monitored drought conditions for the last day of June, July and August 2009, which are shown in Figure 2. The forecast lead time was also 15 days. The comparison shows that the VIC SMAPI prediction is able to capture well the large scale drought development. VIC could also provide a detailed spatial distribution of drought with fine features, as it is applied over the prairie domain consisting of 4393 grid points with a resolution of 0.25º × 0.25º.

Our real time drought monitoring and forecasting system also performs well in China. For example, the evolution of the 2009-2010 severe drought in Southwest China was successfully monitored and forecasted. We show in Figure 3 the VIC forecast SMAPI distributions verifying on April 4, 2010 with different lead times. China Meteorological Administration (CMA) produces a comprehensive Index (CI) for drought monitoring over China in real time. This daily CI product is publicly accessible online (http://cmdp.ncc.cma.gov.cn/influ/dust.php). Our daily SMAPI forecast can thus be compared to CI continuously. Figure 3 clearly illustrates that the drought condition on April 4 was well predicted by our drought forecasting system even with a 35-d lead time. The quality of our daily drought forecast was gradually improved towards April 4 the verifying date. This result also shows the effectiveness of VIC calibration over China.

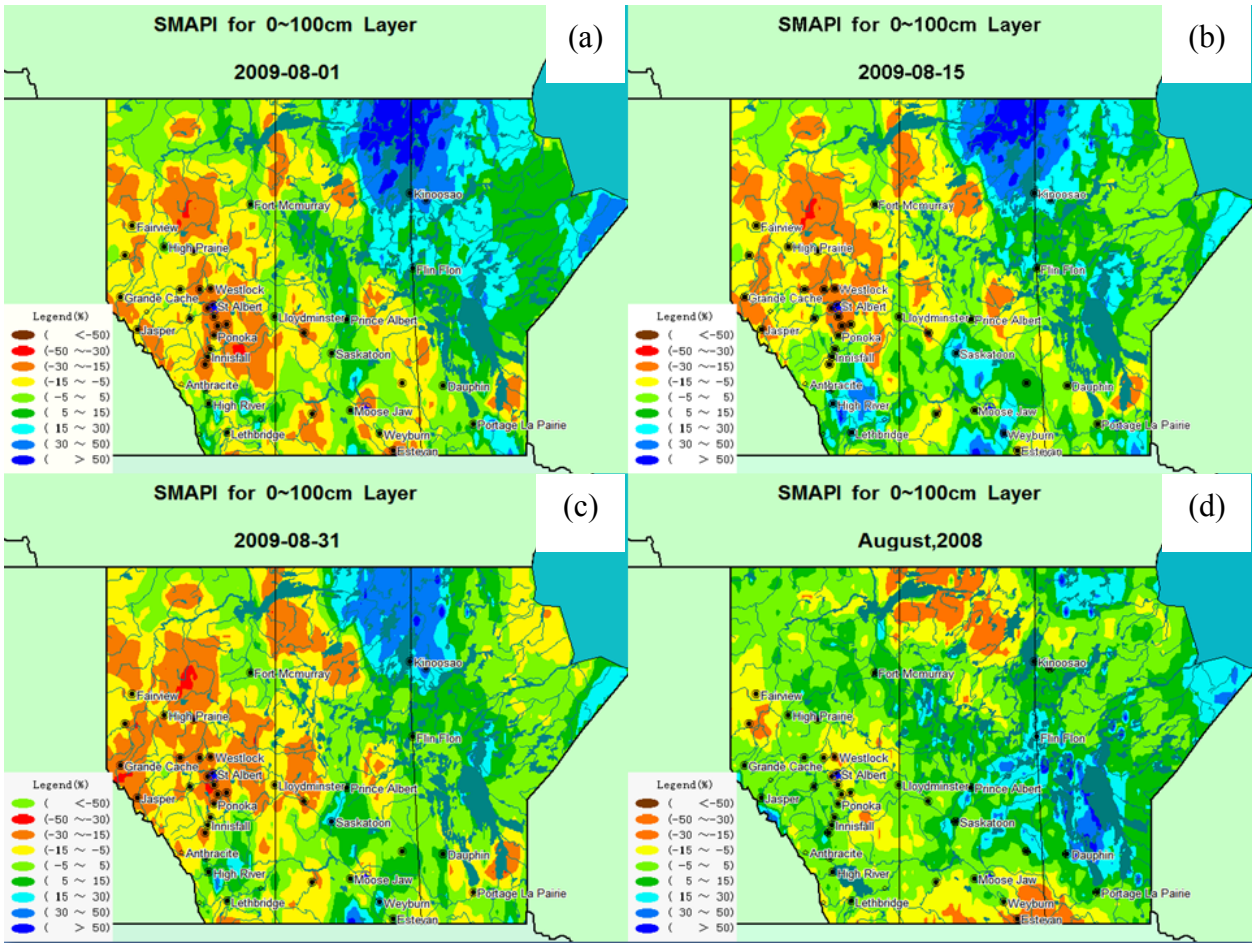

Figure 1. The VIC based SMAPI (Soil Moisture Anomaly Percentage Index) distributions of the top 1-m soil layer for August 1, 15, and 31, 2008, together with the August-2008 SMAPI average.

VIC Predicted Drought Conditions

NADM Monitored Drought Conditions

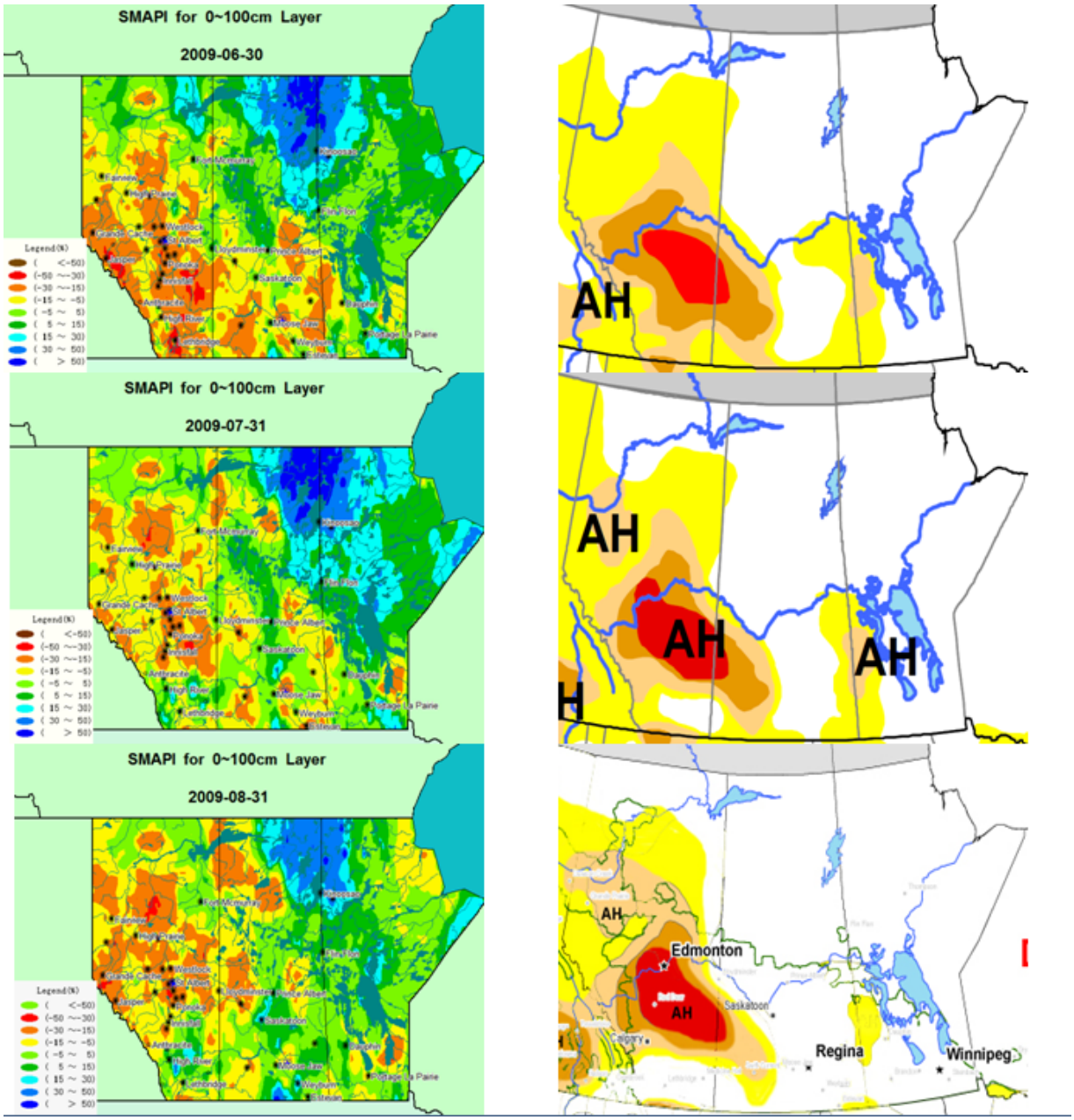

Figure 2. VIC predicted drought conditions (left column) for the last day of June, July and August 2009, compared with the North American Drought Monitor monitored drought conditions (right column).

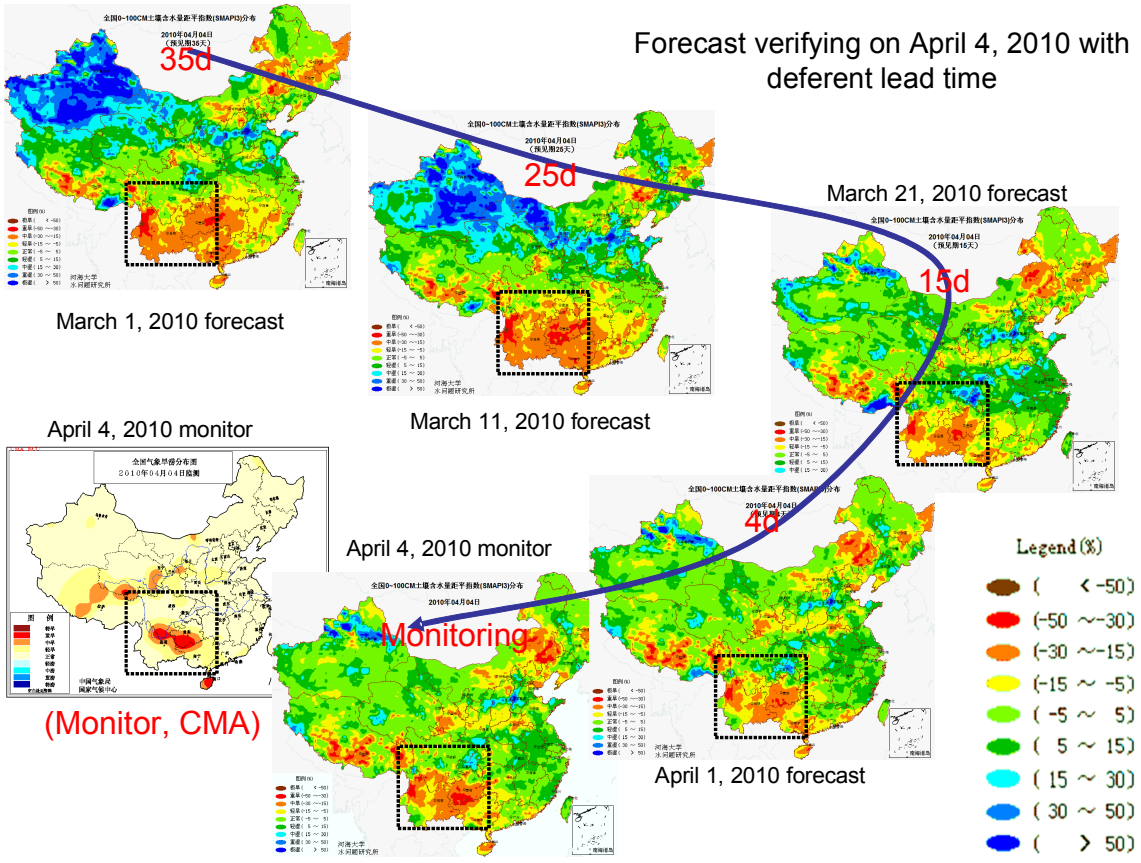

Figure 3. Forecasted SMAPI (0-100cm) maps for Apr. 4, 2010 with lead time of 4d, 15d, 25d and 35d, compared to the SMAPI map from the real time drought monitoring, as well as the CI map of CMA. The dashed boxes highlight the Southwest China.

b. Potential values to drought operation

Our real time prairie drought monitoring and forecast product is regularly consulted by Agriculture and Agri-Food Canada for their preparation of the North American Drought Monitor. Dr. Lei Wen was invited to present the SMAPI and its applications at the North American Drought Monitor Canadian Workshop held in Edmonton, AB on December 7-8, 2010.

Our real time China drought monitoring and forecast product is also considered by the Office of State Flood Control and Drought Relief Headquarters of China. For example, our daily drought forecast for the 2009-2010 severe drought in Southwest China provided authorities with valuable information in their practices of the drought management during the event.

1.6 **Describe the participation of government (federal, provincial or local), university, industry or foreign researchers in the project.**

Several Environment Canada staffs have provided us with the data needed to drive VIC: Drs. Hai Lin and Peter Houtekamer, Juan Sebastien Fontecila and Yufei Zhu. We have established a good working relationship with Trevor Hadwen's group in Agriculture and Agri-Food Canada on the NADM. We continued our established linkages with Eric Wood (Princeton University) and Dennis Lettenmaier (University of Washigton) on using

VIC over Canada, as these two groups use the North America Land Data Assimilation System real-time meteorological forcing and the VIC model for drought monitoring and hydrological forecasting in near real-time in the continental United States.

Dr. Zhiyong Wu of Hohai University in China has participated in the application of the real time flood and drought monitoring and forecasting system over China since 2005.

2.0 Impact

2.1 Describe in broad terms how your work has contributed to the overall objectives of DRI and to our scientific understanding of drought.

The objective of DRI is "to better understand the physical characteristics of and processes influencing Canadian Prairie droughts, and to contribute to their better prediction, through a focus on the recent severe drought of 1999 - 2004/05." Our contribution is mainly in reconstructing and forecasting Prairie daily soil moisture using the coupled hydro-meteorological approach.

The rationale for focusing on soil moisture analysis and forecast in our DRI study is because soil moisture is a key parameter for the understanding of climatology and water cycle in a region, which includes droughts. Soil moisture is of direct interest to agricultural operations and is linked to the atmosphere through precipitation and evapotranspiration. Having accurate soil moisture information is thus essential and important to assessing and predicting agricultural drought that is one of the focusing issues in Theme 3 of DRI.

It is difficult to obtain soil moisture measurements from field surveys on large scales. There is no consistent soil moisture monitoring networks that can provide long datasets of soil moisture conditions in Canada. The development of macroscale land surface hydrological models offers the potential to reconstruct and continually update spatial and temporal distribution of soil moistures over a large area. The VIC model is such a land surface macroscale hydrology model, and is our hydrological modeling tool used for DRI.

2.2 Describe the significance / impact of the results in terms of some or all of the following areas:

Our study is the first attempt in Canada to systematically reconstruct 60-year daily historical soil moisture conditions and to deterministically forecast droughts with a lead time up to 35 days for the entire Prairie Provinces using a marcoscale hydrology model. This is built upon our 15-year experience on the coupling of atmospheric and land surface hydrological models for flood and drought simulation in both Canada and China. Our collaborations with scientists and professors from Chinese Ministry of Water Resources and Hohai University have been strengthened in the past 5 years, which resulted in jointed journal publications and conference presentations, as well as mutual scientific visits.

Our VIC prairie soil moisture simulation is updated daily and our SMAPI results are publicly accessible online, which has already attracted visitors from cross-disciplinary sectors in both Canada and China.

4.0 Reverse Impact Statement

4.1 Provide a reverse impact statement, describing what would have happened in terms of the project, the resulting science and the impacts on users/stakeholders, if the work had not been funded by CFCAS.

As mentioned earlier, our study is the first attempt in Canada to systematically reconstruct and deterministically forecast drought in real time for the entire Prairie Provinces, which covers the area of 1,964,000 km^2. Our methodology can be potentially used in operational management of droughts over large areas. This achievement could not be obtained without the support of CFCAS.

5.0 Follow-on Science

5.1. Based on the findings of your research identify any outstanding scientific questions that need to be addressed in future drought studies.

Trends of drought in the Canadian Prairies should be the priority in future drought studies. This is especially relevant to the issue of changing climate.

The daily runoff depths at each of the 4,393 modeling points from VIC on the Prairies are potentially useful for Prairie water resources studies. Hydrographs simulated at different cross-sections on the Prairie river system could be used for flood forecasting.

6.0 Dissemination

6.1 Provide information on the dissemination of the research results (publications, including journal names and whether refereed), conference contributions, seminars, workshops or videos, websites or other methods of transferring the results.

Refereed journal publications

Lei Wen, Charles A. Lin, Zhiyong Wu, Guihua Lu, John Pomeroy, Yufei Zhu: Reconstructing sixty year (1950-2009) daily soil moisture over the Canadian Prairies using the Variable Infiltration Capacity model; 2010, Canadian Water Resources Journal, *in press.*

Zhiyong Wu, Guihua Lu, Lei Wen, Charles A. Lin: Reconstructing and analyzing China's fifty-nine year (1951-2009) drought history using hydrological model simulation; 2010, Science in China Series E: Technological Sciences, *under revision.*

Charles A. Lin, Lei Wenb, Guihua Lu, Zhiyong Wu, Jianyun Zhang, Yang Yang, Yufei Zhu and Linying Tong: Real-time forecast of the 2005 and 2007 summer severe floods in the Huaihe River Basin of China; 2010, J. Hydrology, 381, 33-41, DOI 10.1016/j.jhydrol.2009.11.017.

Referred conference proceedings

Lei Wen, Charles A. Lin, Zhiyong Wu, Guihua Lu, John Pomeroy, Yufei Zhu: Analysis of Real-Time Prairie Drought Monitoring and Forecasting System; 2010, CMOS-CGU 2010.

Zhiyong Wu, Guihua Lu, Lei Wen, Charles A. Lin: A real-time drought monitoring and forecasting system in China; 2010, 5th International Symposium on Integrated Water Resources Management and 3rd International Symposium on Methodology in Hydrology, Nanjing, China; IAHS Publ., *in press*.

6.2 Describe data management/sharing activities including organization of the metadata. Also, are the data being archived, and how will they be made available to other researchers?

As mentioned earlier, some of the model and reanalysis data are already available through the Data Access Integration portal. The 60-year (1950-2009) daily soil moisture over the Prairies from VIC is also available through the DRI web site.

7.0 Training

7.1 Quantify student and PDF involvement (indicate the level of each: undergraduate, masters, doctorate or PDF). If possible and within the Federal Privacy Act rules governing the collection of personal information, provide a general indication of their subsequent employment (i.e., university, industry, government, other, etc.), and indicate whether the employment was foreign or domestic.

Research associate Dr. Lei Wen participated in all aspects of the project. Rabah Aider was a M.Sc. student under the joint supervision of J. Derome and C. Lin and participated in the seasonal forecast work.