INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **26**: 1727–1736 (2006)

(www.interscience.wiley.com) DOI: 10.1002/joc.1337

SHORT COMMUNICATION

SYNOPTIC SEA-LEVEL PRESSURE PATTERNS GENERATED BY A GENERAL CIRCULATION MODEL: COMPARISON WITH TYPES DERIVED FROM NCEP/NCAR RE-ANALYSIS AND IMPLICATIONS FOR DOWNSCALING

I. G. MCKENDRY[a,*] K. STAHL[a] and R. D. MOORE[a,b]
[a] *Geography Department, The University of British Columbia, 1984 West Mall, Vancouver, BC Canada V6T 1Z2, Canada*
[b] *Department of Forest Resources Management, The University of British Columbia, 2424 Main Mall, Vancouver, BC Canada V6T 1Z4, Canada*

Received 25 November 2005
Revised 2 March 2006
Accepted 4 March 2006

ABSTRACT

A principal component analysis (PCA)-based synoptic typing scheme is used to assess the ability of the Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled Global Climate Model (CGCM2) to reproduce daily mean-sea-level (MSL) synoptic patterns and their frequencies for the Pacific Northwest region of North America. Model output for the ‘control’ period 1961–1989 is compared against the climatology based on National Center for Environmental Prediction (NCEP) re-analysis data. Although CGCM2 is able to reproduce the full range and seasonality of 13 synoptic types it significantly under-represents three cold types and over-represents (by about 50%) three warm/wet winter types. This effect is most pronounced in winter months. Differences in frequencies between the CGCM2 runs (1961–1989 climatology and 1990–2100 IPCC SRES ‘A2’ greenhouse gases (GHG) and aerosol forcing scenario) are smaller than the differences between NCEP and CGCM2 synoptic type frequencies for the 1961–1989 control. Unresolved orographic influences and atmosphere-ocean coupling are cited as possible explanations for model deficiencies. Results suggest that application of CGCM2 output in downscaling studies examining regional impacts should take account of these potential biases. The approach adopted provides a methodology for not only assessing progress in emerging generations of more sophisticated higher resolution General Circulation Models (GCMs) (e.g. CGCM4 is under development), but also choosing the most appropriate model for regional downscaling studies. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: general circulation model; synoptic climatology; downscaling; Pacific Northwest; NCEP

1. INTRODUCTION

Coupled Atmosphere-Ocean General Circulation Models (GCMs) represent the standard tool for generating projections of climatic changes associated with anthropogenic Greenhouse gases (GHG). However, due to the coarse resolution of such models (300–500 km), three major categories of ‘downscaling’ or ‘regionalization’ techniques have been developed to provide the fine scale variability in climate variables that is required for climate impact assessments at the regional scale: (1) high resolution and variable resolution Atmosphere General Circulation Model (AGCM) experiments; (2) nested limited area or regional climate models (RCM); and (3) empirical/statistical and statistical/dynamical methods, which include weather generators, transfer

---

[*] Correspondence to: I. G. McKendry, Geography Department, The University of British Columbia, 1984 West Mall, Vancouver, BC Canada V6T 1Z2, Canada; e-mail: ian@geog.ubc.ca

functions (e.g. regression models) and weather typing schemes based on synoptic climatology concepts. IPCC (2001) provides a thorough review and critique of these methods. The first approach is in its infancy and, despite encouraging results, has not yet demonstrated improvements over other approaches. Although RCMs are widely used and show significant improvements, they are still limited by the quality of the GCM driving fields (i.e. boundary conditions). The ability of empirical/statistical and statistical/dynamical methods to establish the linkage between synoptic and regional scales directly relies on the ability of GCMs to replicate both the full range (after variance inflation) and frequency of variables, flow indices, and synoptic patterns.

For both RCM-based and statistical approaches, the ability of GCMs to accurately represent the day-to-day climatic state at the synoptic scale (the scale at which individual cyclones and anticyclones are adequately resolved) is clearly critical to the success of downscaling (IPCC, 2001). For RCMs it is these synoptic patterns that provide the boundary conditions for the higher resolution simulations, whereas for statistical methods, the ability of GCMs to replicate both the full range and the frequency of synoptic patterns is critical to establishing the linkage between synoptic and regional scales. Given the increasing use of GCM output to assess regional, weather-based impacts of global climate change using downscaling methods (e.g. Diaz-Nieto and Wilby, 2005; Whitfield *et al.*, 2003), there is a clear need for tests of the accuracy of GCM-simulated synoptic-scale circulation.

Few studies appear to have examined the ability of GCMs to reproduce synoptic-scale circulation patterns. McKendry *et al.* (1995) compared frequencies of synoptic mean-sea-level (MSL) and 500 hPa types (based on the Kirchhofer typing scheme) for the Canadian Climate Centre GCM 'control' run to those based on National Center for Environmental Prediction (NCEP) re-analysis fields. Although the model could reproduce the entire range of synoptic types, statistically significant differences in the frequencies of the three most frequent mean-sea-level pressure (MSLP) synoptic types were evident in all seasons. This inability to accurately replicate the synoptic climatology in the control run represents a significant challenge to the downscaling of regional, weather-based impacts from enhanced GHG simulations. Lapp *et al.* (2002) used the first generation Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled Global Climate Model (CGCM)1 to link seven North America wide 500 hPa synoptic patterns to precipitation patterns in western North America using a statistical downscaling approach. Although CGCM1 was deemed to satisfactorily represent the frequencies of synoptic patterns in the control run, differences in the frequencies of the small number of 500 hPa types were evident. Unfortunately, Lapp *et al.* (2002) did not examine the ability of the model to represent the lower tropospheric patterns at a regional scale. Schoof and Pryor (2006) examined the synoptic-scale veracity of CCCma CGCM2 in the USA midwest with respect to 500 hPa types. In contrast to Lapp *et al.* (2002), they found significant differences between the GCM and NCEP/NCAR re-analysis derived map-pattern frequencies over a 'control' period. These differences were greater than either (1) recent historical changes in map-pattern frequencies or (2) changes in the map-pattern frequencies as derived from the twenty-first century GCM simulations. Consequently, they concluded that model uncertainty precludes reliable projection of synoptic type frequencies into the future.

In our previous studies we have observed that upper level patterns are less variable than surface patterns, and that particular upper level patterns may be associated with a wide range of surface synoptic types (McKendry *et al.*, 1995). Given that, for practical purposes near surface fields with their embedded synoptic systems provide a first-order control on spatial and temporal variations in precipitation, winds and temperature, we have chosen in this short communication to focus on the examination of model veracity with respect to MSL fields. We believe that this represents a rigorous test having downscaling implications, although acknowledging that many downscaling studies adopt a more sophisticated approach incorporating multiple levels.

The goal of this study is to compare the surface synoptic patterns and their frequencies as generated by the CGCM2 to those derived from NCEP re-analysis data fields. This represents an extension of a previous study, which described in detail the surface climate associated with these 'synoptic types' (Stahl *et al.*, 2006). Like McKendry *et al.* (1995), we focus on the rigorous test represented by the Pacific Northwest region of North America, a mid-latitude baroclinic zone that incorporates both continental and oceanic effects and is strongly influenced by the orographic effects associated with the Western Cordillera. This study builds on McKendry *et al.* (1995) the improvements in GCMs over the last decade, which include higher resolution, better parameterizations and atmosphere-ocean coupling of models, and the introduction of ensemble methods.

We also apply a more sophisticated, eigenvector-based synoptic typing scheme, which avoids some of the problems inherent in the Kirchhofer typing scheme that was used in the earlier study (Blair, 1998).

2. METHODS

The general approach was to classify daily MSLP grids from CGCM2 and to compare both the mean surface pressure patterns for each type and the type frequencies to those generated through analysis of daily average MSLP data from the NCEP/NCAR re-analysis-I project (Kalnay *et al.*, 1996). The data were obtained from the NOAA-CIRES Climate Diagnostics Center (CDC), Boulder, Colorado, USA, from their website at http://www.cdc.noaa.gov/. The domain of the 2.5-degree resolution 20 × 10 grid covers the North Pacific and British Columbia (BC) between 157.5 °W and 110.0 °W and 40 °N and 60 °N. Stahl *et al.* (2006) described in detail the classification technique and the resulting types' related surface climatology for BC, and only a brief description is provided below.

Daily grids of MSLP from 1948 to 2003 were subjected to a commonly used pattern recognition scheme using principal component analysis (PCA) followed by an unsupervised *k*-means cluster analysis on the derived variables (scores on the retained components) using *Synoptic Typer 2.2*, an application developed by the Australian Bureau of Meteorology (Dahni and Ebert, 1998; Dahni, 2004). The grids were not standardized and not de-seasonalized because one purpose of the study, among others, was to examine the seasonal changes as well as recent trends and shifts of circulation patterns. The PCA was performed on the correlation matrix and no rotation was applied. The first six principal components, which explained 91% of the variability, were retained and the 13-cluster solution was chosen semi-objectively based on a local optimum of group homogeneity and the representation of the major synoptic circulation situations in the region.

Daily-modelled fields were based on averages of two instantaneous values at 00 and 12Z from the second generation CCCma CGCM2. Flato and Boer (2001) described CGCM2 and compared its response to increasing GHG forcing, relative to that of CGCM1. Further details and data can be found online (http://www.cccma.bc.ec.gc.ca/eng_index.shtml), on the website from which the data were downloaded. Improvements in CGCM2 include a change in the ocean mixing parameterization from a horizontal/vertical diffusion scheme to an isopycnal/eddy stirring parameterization and improved sea-ice dynamics. Although third-generation model runs (CGCM3) are now available online, we have chosen to use CGCM2 output due to its specific provision for downscaling and climate impact studies in Canada (e.g. through the Canadian Climate Impacts Scenarios Project, http://www.cics.uvic.ca/scenarios/), and to have a basis for comparison with other downscaling studies (i.e. Schoof and Pryor, 2006).

The available daily CGCM2 output cover the control run period from 1961 to 1989 and the scenario period from 1990 to 2100. The control run data are based on an ensemble of three 201-year simulations using the IPCC 'IS92a' forcing scenario in which the change in GHG forcing corresponds to that observed from 1900 to 1990 and increases by 1% per year thereafter until year 2100. The direct effect of sulphate aerosols (A) is also included. All three ensemble runs are performed with the same GHG and aerosol forcing but are started from perturbed initial conditions. The intent of the ensemble is to reduce the inherent variability in the model simulations. Differences between the individual integrations are entirely due to natural variability and not due to the differences in the model or forcing. The future scenario used herein corresponds to the first member of an ensemble of three 111-year simulations using the provisional IPCC SRES 'A2' GHG and aerosol forcing scenario. This simulation begins at year 1990 with initial conditions from the corresponding member of the GHG + A runs.

Before applying the typing scheme to the model output, the CGCM2 data were interpolated with an inverse distance weighting method from *ca.* 3.75° CGCM2 grid onto the 2.5° NCEP grid. Original and interpolated grids were compared visually to ensure that the interpolation did not cause undesired effects or shifts. Synoptic type frequencies based on NCEP data were originally derived for the period 1948–2003 for the longest possible comparison with observed surface climate data (Stahl *et al.*, 2006). MSLP grids from the GCM model output were classified using the principal components and cluster centroids from this original typing. Six variables (component scores) for a given daily MSLP grid were first derived by the matrix product with the principal

DOI: 10.1002/joc

components, then the multidimensional Euclidean distance from each cluster centroid was calculated and the grid (day) was assigned to the 'closest' cluster.

With a synoptic type assigned to each day of the original NCEP re-analysis-I period and each day of the CGCM2 control run and scenario period, we compared the average MSLP grids (composites) and the frequencies of each type:

(1) between the NCEP and the CGCM2 data for the control run period (1961–1989), and
(2) between the control run period 1961–1989 and the scenario period 1990–2100.

Differences in the MSLP patterns were evaluated visually and individual grid cell differences were assessed by a t-test (significance level = 0.05). To assess changes in the frequencies of the synoptic types, χ^2 tests were applied (significance level = 0.01).

3. RESULTS

MSLP map composites for the control run period (1961–1989) and the scenario period (1990–2100) along with their spatial differences (shaded by their significance) are presented in Figure 1. The composites for the CGCM2 output are all visually similar to those based on the NCEP grids. However, the MSLP patterns of several types based on CGCM2 output have less ridging over the Coast Mountains over BC (e.g. types 5, 8, and 11). The composites for type 3 based on GCM output show low-pressure having a more zonal orientation and extending inland across the Coast Mountains. Similarly the GCM-based composites for type 6 indicate weaker pressure gradients across the Coast Mountains and more zonally oriented isobars. The different panels all show differences of varying degrees between fields for each type. Of note is the extent to which large and significant differences are evident across the northern BC, a region of significant orography, and where high-pressure is particularly underestimated by CGCM2 in types 1, 3, 9, 10, 11, and 13.

Relative frequencies (all months) are presented in Figure 2 for each data set. Frequencies of synoptic types are virtually identical for the 1948–2003 and 1961–1989 NCEP data sets, indicating that the 1961–1989 period is a robust representation of the climatology. However, although CGCM2 adequately represents the frequencies of some types for the 1961–1989 period (types 1, 4, 5, 7, 8, 10, and 11), it significantly under-represents types 2, 3, and 6 and over-represents the frequencies of types 9, 12, and 13 (by approximately 50%). In a χ^2 test of significance, comparing the individual type frequencies (all year) for the NCEP and CGCM2 'control' runs (1961–1989) differences are shown to be significant ($p \leq 0.01$) for types 2, 3, 5, 6, 9, 12, and 13. It is interesting to note that the differences in frequencies between the two CGCM2 runs (1961–1989 and 1990–2100) are smaller than the differences between NCEP and CGCM2 synoptic type frequencies for the 1961–1989 control. Furthermore, the breakdown of the CGCM2-A2 scenario into four sub-periods reveals changes in some weather type frequencies as the scenario progresses. For example, types 1, 3, 6, 7, 8, 10, and 11 show little variation in type frequency throughout the scenario (i.e. at the end of the scenario the frequencies are similar to the early decades of the scenario). However, frequencies of types 4 and 5 decrease as the scenario progresses, whereas frequencies of types 12 and 13 increase significantly towards 2077–2100.

Seasonal variations in synoptic frequencies are presented in Figure 3. The CGCM2 appears to perform best during summer (JJA) months when the circulation over the region is less vigorous and a subset of types predominates. In winter (DJF), when the synoptic circulation is more vigorous and variable, the agreement between the NCEP climatology and CGCM2 is poor. The CGCM2 model over-predicts the frequencies of warm, wet types (9, 12, and 13) and under-predicts the frequencies of cooler types (2, 3, and 6). Types 2, 3, and 6 are characterized by below average temperatures during winter (Stahl *et al.*, 2006). Type 6 represents the well-known 'winter arctic outflow' type in which strongly negative temperature anomalies occur as cold air flows coastward from the interior of the continent through valleys in response to the strong pressure gradient developed perpendicular to the coastline. Types 9, 12, and 13, on the other hand are all characterized by southwesterly flow and are associated with positive temperature anomalies across the province of BC and, in the case of types 9 and 13, positive precipitation anomalies as well (Stahl *et al.*, 2006). Agreement in the spring and fall appears transitional between these summer and winter extremes.

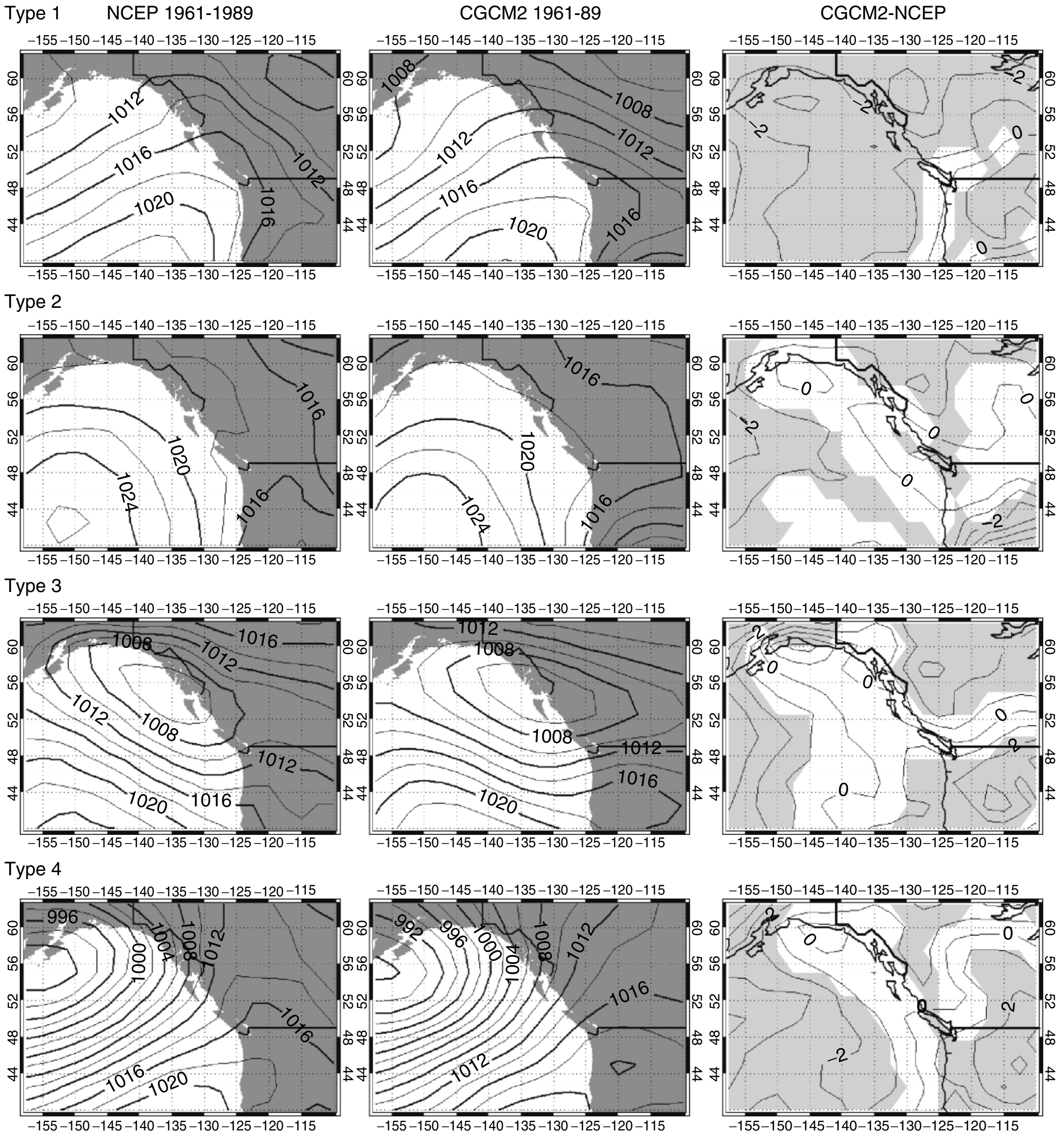

Figure 1. Comparison of synoptic type composites (average MSLP for all days of the type) based on NCEP fields (1961–1989), CGCM2 control run (1961–1989), and the difference between the two. Grid cells with significant differences are shaded in grey ($a = 0.05$, t-test for difference in mean)

4. DISCUSSION

The CGCM2 model appears to be able to reproduce the full range of surface synoptic types and their main characteristics but not the frequencies of types in the 'control' run. This finding is consistent with those of McKendry *et al*. (1995) for CGCM1 and Schoof and Pryor (2006) for 500 hPa patterns produced by CGCM2. The main differences between the patterns based on GCM output and those from NCEP fields are likely due

DOI: 10.1002/joc

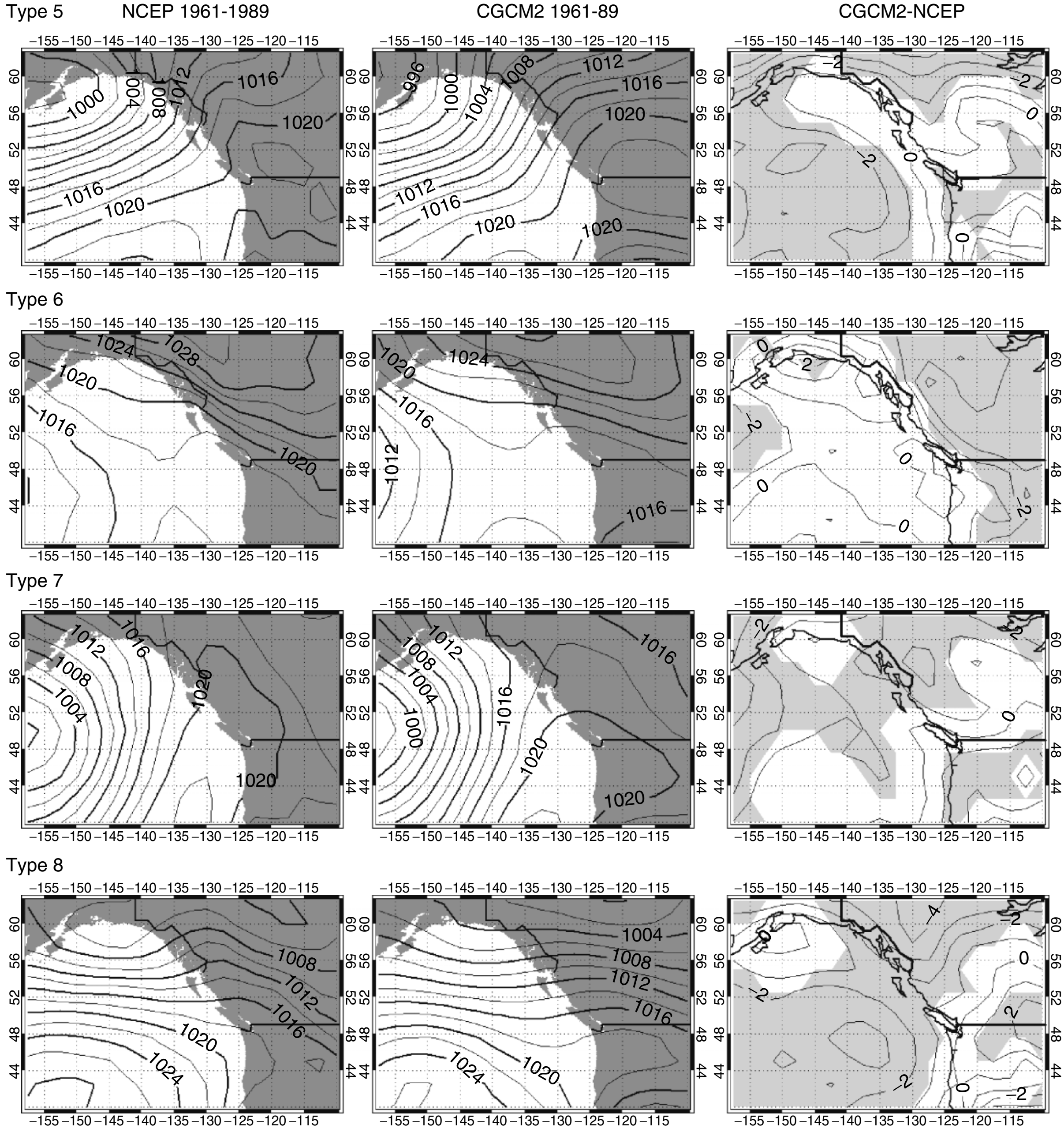

Figure 1. (*Continued*)

to the coarse resolution and incomplete representation of the effects of the mountain ranges, especially for types 3 and 6. An interesting issue is why CGCM2 under-represents cold types and over-represents warm types. We propose two possibilities. First, frequencies produced in CGCM2 1961–1989 are similar to those described in Stahl *et al.* (2006) for the case of positive Pacific Decadal Oscillation (PDO) and El Niño teleconnections. During such winters there is a significant tendency for higher frequencies of warm and wet types and lower frequencies of colder types (notably types 3 and 6) over western North America. Although perhaps coincidental, the source of the bias evident in the 1961–1989 ‘control’ may therefore be related to

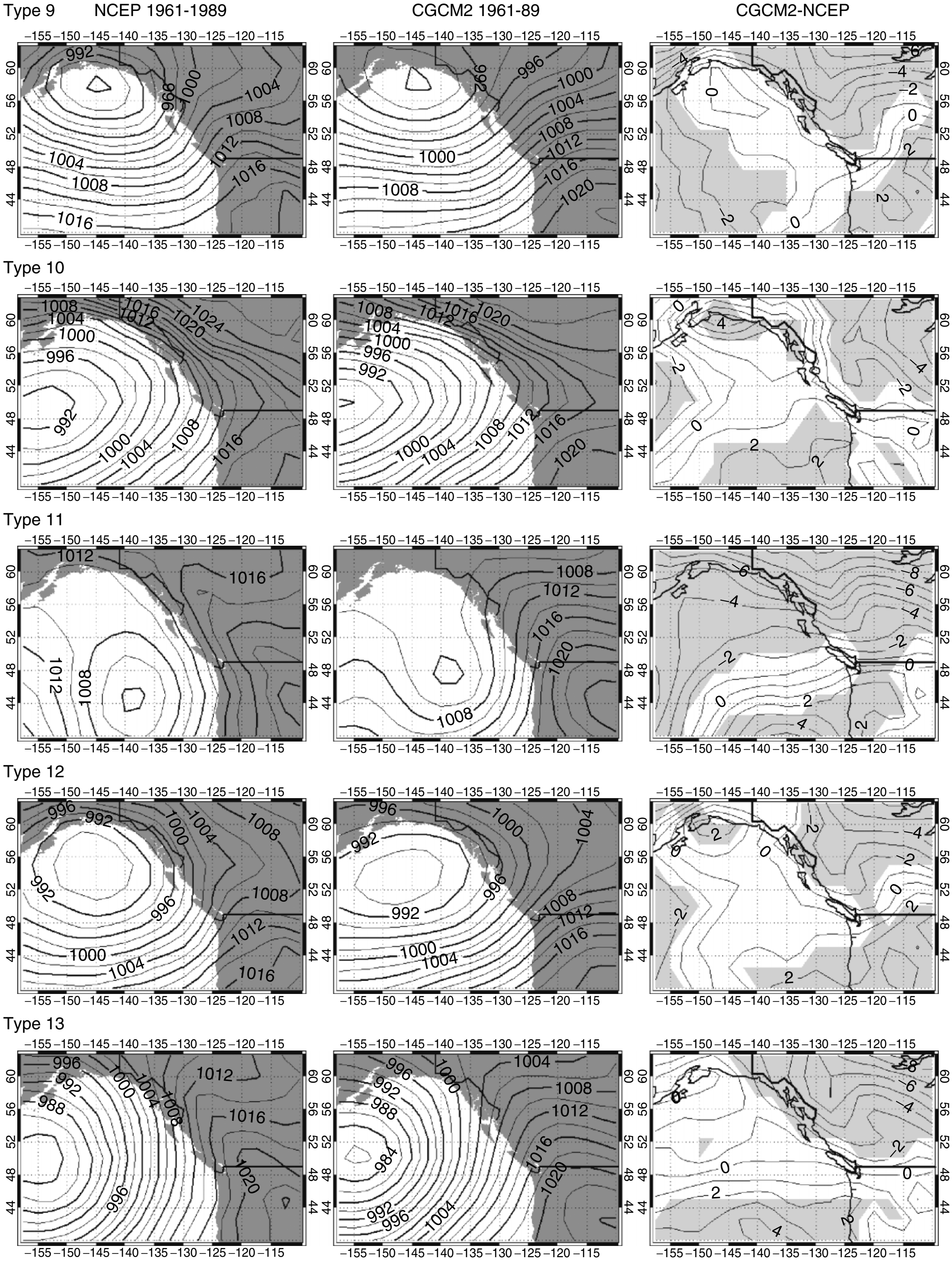

Figure 1. (*Continued*)

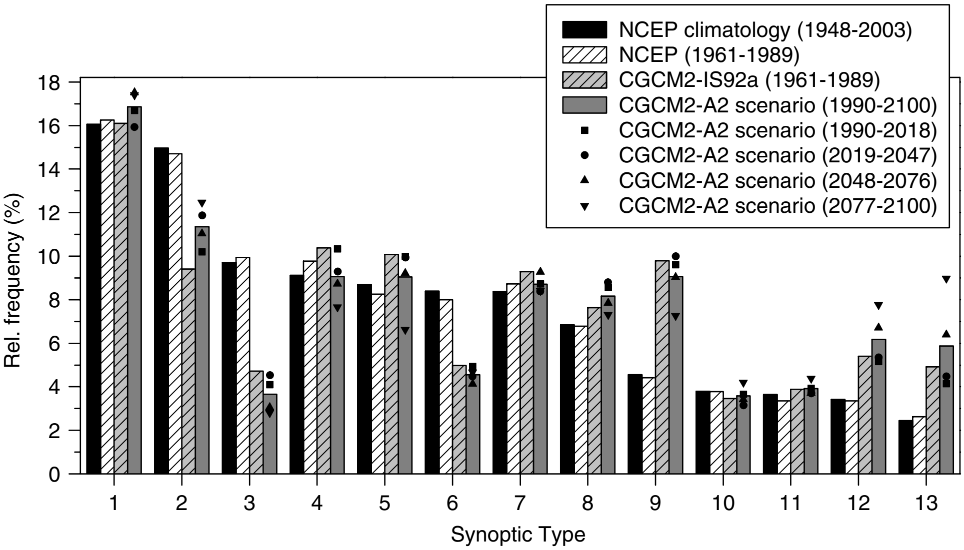

Figure 2. Frequencies of circulation types for the different data sets and periods

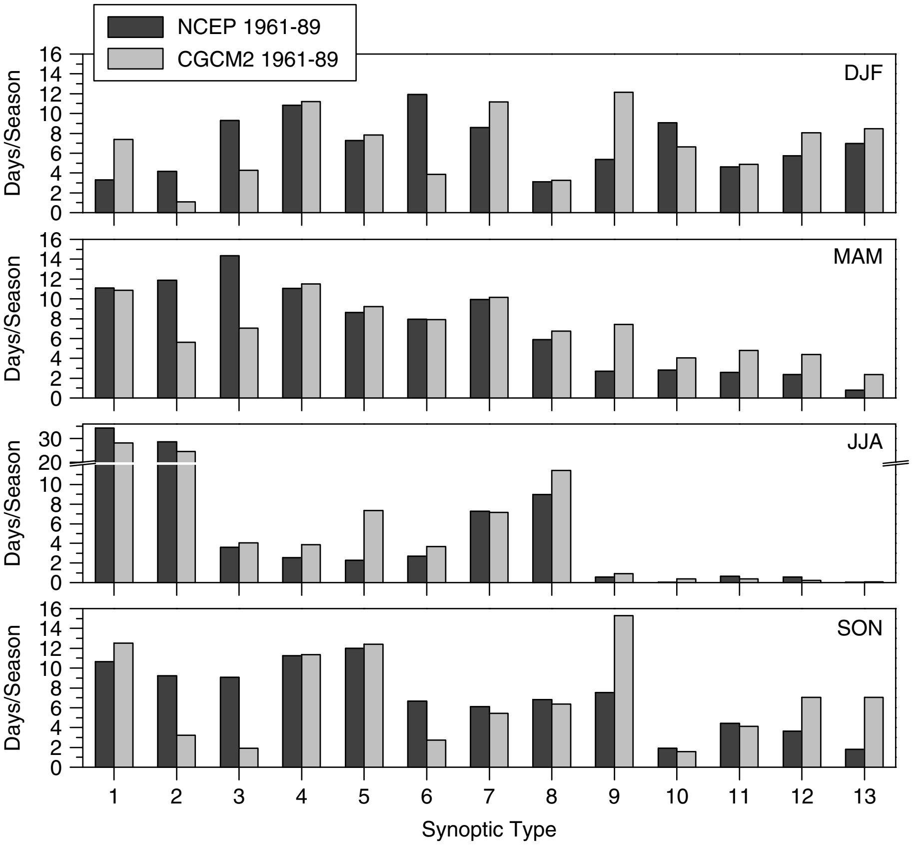

Figure 3. Seasonal frequencies of circulation types for the control period 1961–1989

DOI: 10.1002/joc

atmosphere-ocean coupling and a tendency for CGCM2 to not adequately capture the amplitude and frequency of ENSO/PDO variability. Second, the inability of the GCM to adequately reflect the orographic influence of the western Cordillera could influence type frequencies. Given the importance of orographic effects associated with type 6 (cold arctic air dammed to the east by the Rocky Mountains and then cold air spillage westward through narrow valleys coastward) it is not surprising that CGCM2, due to inability to resolve such effects, identifies fewer occurrences of this type.

This bias in synoptic type frequencies is troubling in view of the application of such models to assessing the ecological and socio-economic impacts of global warming scenarios. The results of Stahl *et al*. (2006) suggest that the biases in synoptic type frequencies could have significant ramifications in downscaling studies used to generate regional precipitation and temperature scenarios. For example, British Columbia is currently experiencing a persistent and widespread outbreak of mountain pine beetle, a forest pest that is partly controlled by winter cold mortality associated with occurrences of type 6. The inability of GCMs to represent the frequency of this type limits their applicability to making inferences about future climatic suitability for mountain pine beetle populations.

5. CONCLUSIONS

The second generation CGCM2 was able to represent the full range of synoptic types evident in the 1961–1989 NCEP climatology. However, visual examination revealed bias in the composites based on GCM output, including weaker ridging over the Coast Mountains and a more zonal orientation of isobars. Furthermore, the model did not accurately represent the frequencies for all types, especially in the winter months (when most precipitation is delivered to the region). In particular, the model under-predicted colder types and over-predicted the occurrence of warm/wet types. The synoptic biases evident in CGCM2 are consistent with a model biased towards conditions associated with positive PDO or El Niño conditions, but could also reflect a lack of resolution that prevents the model from resolving regionally significant orographic effects. The approach adopted herein provides a methodology for not only assessing progress in emerging generations of more sophisticated higher resolution GCMs (e.g. CGCM4 is under development), but also choosing the most appropriate model for regional downscaling studies.

ACKNOWLEDGEMENTS

Financial support from the Government of Canada's Climate Change Impacts and Adaptations Research Program via Grant A676 is gratefully acknowledged, as are funds from Natural Sciences and Engineering Research Council Discovery Grants to RDM and IGM. R. Dahni, Australian Meteorological Bureau, provided invaluable assistance with the application of Synoptic Typer. Valuable comments were provided by Greg Flato, Alex Cannon, Phil Austin, and two anonymous reviewers.

REFERENCES

Blair D. 1998. The Kirchhofer technique of synoptic typing revisited. *International Journal of Climatology* **18**: 1625–1635.

Dahni RR. 2004. *Synoptic Typer Reference Manual Version 2.2*. Commonwealth Bureau of Meteorology: Melbourne, Australia, February 2004.

Dahni RR, Ebert EE. 1998. Automated objective synoptic typing to characterize errors in NWP model QPFs, J31–J34. In *12th Conference on Numerical Weather Prediction*, Phoenix, AZ, 11–16/1/98.

Diaz-Nieto J, Wilby RL. 2005. A comparison of statistical downscaling and climate change factor methods: impacts on low flows in the river Thames, United Kingdom. *Climatic Change* **69**: 245–268.

Flato GM, Boer GJ. 2001. Warming asymmetry in climate change simulations. *Geophysical Research Letters* **28**: 195–198.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds). Cambridge University Press: Cambridge, New York, 881.

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* **77**: 437–471.

Lapp S, Byrne J, Kienzle S, Townshend I. 2002. Linking global circulation model synoptics and precipitation for western North America. *International Journal of Climatology* **22**: 1807–1817.

McKendry IG, Steyn DG, McBean G. 1995. Validation of synoptic circulation patterns simulated by the Canadian climate centre general circulation model for western North America. *Atmosphere-Ocean* **33**: 809–825.

Schoof JT, Pryor SC. 2006. An evaluation of two GCMs: simulation of North American teleconnection indices and synoptic phenomena. *International Journal of Climatology* **26**(2): 267–282.

Stahl K, Moore RD, McKendry IG. 2006. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter surface climate in British Columbia, Canada in press. *International Journal of Climatology* DOI: 10.1002/joc.1286 **26**: 541–560.

Whitfield PH, Wang JY, Cannon AJ. 2003. Modelling future streamflow extremes–floods and low flows in Georgia Basin, British Columbia. *Canadian Water Resources Journal* **28**: 633–656.