Atmosphere-Ocean

Publication details, including instructions for authors and subscription information:
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Hai Lin & Zhiwei Wu

Meteorological Research Division, Environment Canada, Dorval, Québec, Canada


To cite this article: Hai Lin & Zhiwei Wu (2012): Contribution of Tibetan Plateau Snow Cover to the Extreme Winter Conditions of 2009/10, Atmosphere-Ocean, 50:1, 86-94

To link to this article: http://dx.doi.org/10.1080/07055900.2011.649036

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Contribution of Tibetan Plateau Snow Cover to the Extreme Winter Conditions of 2009/10

Hai Lin* and Zhiwei Wu

Meteorological Research Division, Environment Canada, Dorval, Québec, Canada

[Original manuscript received 4 August 2011; accepted 16 November 2011]

ABSTRACT Most of the northern hemisphere experienced extreme climate conditions during winter 2009/10. This winter in Canada was characterized by the warmest and driest conditions in the past 60 years. Across much of the United States, Europe and northern Asia, persistent below-normal temperatures caused a significant adverse economic and societal impact. Dynamical seasonal forecasting systems failed to predict this winter’s extreme conditions. Here we show that the snow-cover anomaly over the Tibetan Plateau and adjacent areas is significantly correlated with the atmospheric circulation pattern that contributes to these anomalous winter conditions. A statistical model using this snow-cover information and the El Niño signal in autumn 2009 was able to predict the general distribution of the anomalous conditions for this winter. This implies that an improved understanding of the Tibetan Plateau snow-cover effect and its representation in general circulation models are important for seasonal predictions, particularly of high-impact climate events.

RÉSUMÉ Pendant l’hiver 2009/10, les conditions climatiques ont été extrêmes dans la majeure partie de l’hémisphère Nord. Cette année-là, les mois d’hiver au Canada ont été les plus chauds et les plus secs jamais enregistrés au cours des 60 dernières années. Un peu partout aux États-Unis, en Europe et dans le nord de l’Asie, les températures inférieures à la normale persistantes ont eu des conséquences catastrophiques sur le plan socio-économique. Or les systèmes dynamiques de prévisions saisonnières ne sont pas parvenus à prévoir les conditions extrêmes de cet hiver. Dans la présente étude, nous démontrons la corrélation étroite entre l’épaisseur anormalement faible de la couverture de neige sur le plateau Tibétain et dans les régions limitrophes, d’une part, et la configuration de la circulation atmosphérique, responsable de ces conditions hivernales anormales. Grâce au traitement des données sur la couverture de neige et du signal El Niño au moyen d’un modèle statistique, nous avons réussi à prédire la répartition générale des conditions anormales pour l’hiver. Nous en déduisons qu’il est important de mieux comprendre les effets de la couverture de neige du plateau Tibétain et sa représentation dans les modèles de circulation générale pour les prévisions saisonnières, notamment les phénomènes météorologiques lourds de conséquences.

KEYWORDS snow cover; extreme climate; Tibetan Plateau; NAO; ENSO; teleconnection

1 Introduction

The winter of 2009/10 (December–February) was extremely unusual over the global northern hemisphere. In Canada, the national average temperature for this winter was 4.0°C above normal, making it the warmest winter on record since nationwide records began in 1948 (Fig. 5d illustrates the surface air temperature anomaly distribution for this winter). Canada also experienced its driest winter in the 63-year record with precipitation 22.0% below normal (Environment Canada, 2010). In the United States, below-normal temperatures and above-normal precipitation were recorded. A large region of cold temperatures was observed with below-normal temperatures of 3.0°C–7.0°C. The mid-Atlantic region of the United States experienced an all-time record high seasonal snowfall. In Europe, record low temperatures and heavy snowfall were experienced in many places, causing significant economic damage and human death. For example, this winter was the coldest in 40 years in the United Kingdom (Dugan et al., 2010).

Because of the enormous economic and societal impact of such extreme weather conditions, an understanding of the causes and a useful seasonal prediction would be of great importance. It is known that the El Niño Southern Oscillation (ENSO) is a primary predictor on a seasonal time scale (e.g., Shukla et al., 2000; Derome et al., 2001). By autumn 2009 a moderate El Niño had developed in the tropical Pacific. Another striking feature in the atmospheric circulation during the winter of 2009/10 was the extremely negative North Atlantic Oscillation (NAO). The NAO is one of the most important modes of variability in the northern hemisphere’s extratropical atmosphere and is characterized by a

*Corresponding author’s email: hai.lin@ec.gc.ca

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dipole spatial structure of sea level pressure over the North Atlantic (e.g., Hurrell, 1995, 1996). A study by the NOAA Attribution Team (2010) suggests that the principal factor responsible for the record snowfall along the metropolitan corridor of the mid-Atlantic and the extreme climate was the com-mingled impact of the NAO and El Niño. However, the NAO represents natural climate variability which is unlikely to be predictable beyond about two weeks. This may, at least in part, explain why most dynamical seasonal predictions for the extreme winter of 2009/10 were unsuccessful.

The effect of Eurasian snow cover on global climate has long been noticed (Barnett et al., 1988). The winter NAO was reported to be modulated by the variability of Eurasian snow cover through tropospheric-stratospheric interactions (e.g., Cohen and Saito, 2003; Gong et al., 2007). In comparison with the snow cover over other areas, in particular Siberia, the snow cover over the Tibetan Plateau (TP) is of special importance, because it represents an elevated cooling source in the middle troposphere. The snow-cover anomalies over the TP were found to have a close connection with the Asian climate, especially the East Asian summer climate (e.g., Wu and Kirtman, 2007). In a recent study, Seager et al. (2010) analyzed the impact of ENSO and the NAO on the northern hemisphere snow-cover anomaly for the winter of 2009/10. The contribution of the TP snow-cover anomaly to the extreme winter conditions of 2009/10 is unclear.

Our recent study (Lin and Wu, 2011; hereafter LW11) found that the variability in snow cover over the TP and adjacent areas in the previous autumn (September–November (SON)) is significantly correlated with global circulation and the dominant mode of North American winter surface air temperature (SAT). An empirical model was constructed to predict the leading SAT mode using a combination of autumn TP snow-cover anomalies and sea surface temperature (SST) anomalies. Hindcasts and real forecasts were performed for the 1972–2003 and 2004–09 periods, respectively. Both show a statistically significant prediction skill. For the North American dominant temperature pattern, the empirical model hindcast performs better than the ensemble mean of four dynamical models from the Canadian Meteorological Centre (CMC). Here, the association of the TP snow-cover anomaly in autumn with the northern hemisphere winter circulation is compared with the contribution of El Niño. The combined contribution of the TP snow cover and ENSO is used to explain and predict the extreme winter conditions of 2009/10.

In Section 2 the data used in this study are introduced. Section 3 describes the statistical association between Tibetan snow cover in autumn and the atmospheric circulation anomaly in the following winter. In Section 4, the combined contributions of TP snow cover and El Niño to the 2009/10 winter conditions is discussed. In Section 5, a one-month lead seasonal forecast is made using a two-parameter statistical model for the 2009/10 winter, and a comparison is conducted with an operational dynamical model. Section 6 provides a summary and discussion.

2 Data
We make use of the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) global reanalysis (Kalnay et al., 1996). Variables used here include monthly mean geopotential height at 500 hPa (Z500) and SAT.

Monthly northern hemisphere snow-cover area extent data (in percent) gridded at 2.0° × 2.0° resolution are also used; these were calculated using weekly snow cover data from the National Oceanic and Atmospheric Administration (NOAA, 2011a). The data period covers 1972 to 2010. As in LW11, a TP snow-cover index (TPSCI) is defined as the snow-cover anomalies averaged over the TP and adjacent areas (25°–50°N, 90°–105°E) in autumn. The anomalies are relative to the 39-year climatology for autumn. To represent the ENSO signal, the Niño3.4 index is obtained from NOAA (2011b), which is defined as SST anomalies averaged over the region 5°N–5°S, 170°–120°W and calculated using the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST1) dataset (Rayner et al., 2003).

3 Association of DJF atmospheric circulation with SON TPSCI
Figure 1 depicts time series of TPSCI and the Niño3.4 index for SON and shows the interannual variability of these two indices. It can be seen that the 2009 autumn TP snow-cover anomaly reaches its highest value since 1972. At the same time the value of the Niño3.4 index indicates a moderate ENSO event. The TPSCI has only a weak correlation with the Niño3.4 SST, with a correlation coefficient of 0.22 during the 38 SONs from 1972 to 2009, indicating that these two indices are not likely to be related. We first look at correlations between SON TPSCI and December, January and February (DJF) atmospheric circulation during the 38 winters from 1972/73 to 2009/10, and then compare them with the correlations between the SON Niño3.4 index and the same DJF circulation. This lagged association represents a delayed atmospheric response to a persistent thermal forcing. For example, Mo et al. (1998) found that the

Fig. 1 Time series of SON TPSCI normalized by its standard deviation in black and SON Niño3.4 index in red.
maximum correlation of DJF Z500 with ENSO SST occurs in the preceding October. In LW11, it was found that the SON Tibetan snow-cover anomaly can persist into the following winter through atmosphere-snow feedbacks. On the other hand, the lagged association provides a predictive value for the atmospheric conditions. As seen in Fig. 2b, TPSCI in autumn is significantly correlated with above-normal Z500 over the polar region, with large values over Greenland and northern Canada in the following winter. Negative correlations are found over the North Pacific and over the southeast United States. The distribution looks similar to the correlation map for the SON Niño3.4 index (Fig. 2a). For the TPSCI correlation, the values at high latitudes are larger than the Niño3.4 correlation. North of 30°N, the percentage of the area that has a statistically significant correlation (0.05 level according to a Student’s t-test) are 40% and 22% for TPSCI and the
Niño3.4 index, respectively. The pattern resembles a positive phase of the Pacific-North American (PNA) pattern (Wallace and Gutzler, 1981). Over the North Atlantic, the TPSCI correlation is similar to the negative phase of the NAO.

The DJF SAT over the northern hemisphere is well correlated with the SON TPSCI in many areas (Fig. 2d). Over most of northern Europe and northern Asia, negative temperature anomalies are associated with a positive TPSCI. Significant warm temperatures are found along the west coast of North America, northern Canada and at high latitudes in the North Atlantic. In comparison, the temperature anomaly associated with the SON Niño3.4 index is confined mainly to the North Pacific and the west coast of North America (Fig. 2c). North of 30°N, the percentage of the area having a statistically significant correlation with the TPSCI and Niño3.4 index are 28% and 13%, respectively. The distribution of the temperature anomaly associated with the TPSCI is very similar to that observed during the 2009/10 winter (Fig. 5d).

4 The combined contribution of TP snow cover and El Niño to 2009/10 winter conditions

As shown in Fig. 1, a moderate El Niño developed in autumn 2009, with an Niño3.4 index of 1.78 in SON. At the same time, the TPSCI reached its highest value for the last 38 autumn seasons. To assess the relative role of the TP snow cover and El Niño during the 2009/10 winter, we analyze how each factor, and their linear combinations, affected the DJF Z500 and SAT. A linear regression model is constructed with the SON TPSCI and Niño3.4 index as predictors and DJF Z500 or SAT as the predictand, which can be expressed as

\[ Z_f = \alpha_1 \text{TPSCI} + \alpha_2 \text{N34} + \varepsilon, \]  

where \( Z_f \) is the forecast DJF Z500 or SAT anomaly at a grid point, TPSCI and N34 are the TPSCI and Niño3.4 indices during SON, respectively. \( \alpha_1 \) and \( \alpha_2 \) are the regression coefficients and \( \varepsilon \) the residual. The two regression coefficients are calculated using the observed historical DJF Z500 or SAT anomaly and SON TPSCI and Niño3.4 index and the least squares method in a cross-validation framework (i.e., when computing the regression coefficients for a given forecast year, that year is excluded). Therefore, the statistical model is trained with data that are independent of the prediction data. \( \varepsilon \) is considered to be noise and is omitted from the calculations (training and forecast).

Shown in Fig. 3 is the forecast skill of the statistical model calculated as the temporal correlation between the observation and forecast over the 38 winters. As can be seen, a large portion of the northern hemisphere extratropics is covered by statistically significant forecast skill. Skill in forecasting Z500 appears over the polar region including Greenland and northern Canada, the North Pacific, the southeastern United States, western Europe and North Africa. For SAT, skill can be found along the west coast of North America, northern Canada and southeastern Europe.

The contributions of TP snow cover and ENSO are also evaluated separately using a single variable regression model. For the winter of 2009/10, the regression coefficients in Eq. (1) are
and the single variable regression models are calculated based on the 1972–2008 data. Then we use the TPSCI and Niño3.4 values for SON 2009 to predict the DJF Z500 and SAT.

Shown in Fig. 4 are the contributions of SON TP snow cover and El Niño to the DJF Z500 anomaly of 2009/10. Although the impact of ENSO (Fig. 4b) has a somewhat similar distribution to the observations (Fig. 4d), much of the spatial pattern and amplitude is quite different. In contrast, the TP snow-cover anomaly leads to a Z500 field that matches the observations quite well (Fig. 4a). The observed negative NAO in winter 2009/10 is, to a large extent, related to the TP snow-cover anomaly. Figure 4c represents the combined contribution of TP snow cover and El Niño, calculated from Eq. (1). The similarity between Fig. 4c and the observations (Fig. 4d) is apparent. To quantify the performance of the linear regression model in predicting the winter anomaly of 2009/10, pattern correlation (PCOR) and root mean square error (RMSE) are calculated for Figs 4a to 4c with respect to the observations.
TABLE 1. Pattern correlation (PCOR) and root mean square error (RMSE) for the northern hemisphere extratropics north of 20°N.

<table>
<thead>
<tr>
<th>Predictors</th>
<th>SON TPSCI</th>
<th>SON ENSO</th>
<th>SON TPSCI + ENSO</th>
<th>SO TPSCI + ENSO</th>
<th>CMC Forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z500 PCOR</td>
<td>0.74</td>
<td>0.52</td>
<td>0.75</td>
<td>0.77</td>
<td>0.24</td>
</tr>
<tr>
<td>SAT PCOR</td>
<td>0.67</td>
<td>0.03</td>
<td>0.64</td>
<td>0.54</td>
<td>0.50</td>
</tr>
<tr>
<td>Z500 RMSE</td>
<td>34.38</td>
<td>43.97</td>
<td>33.04</td>
<td>38.88</td>
<td>47.76</td>
</tr>
<tr>
<td>SAT RMSE</td>
<td>1.41</td>
<td>1.88</td>
<td>1.44</td>
<td>1.67</td>
<td>2.03</td>
</tr>
</tbody>
</table>

Fig. 5 As in Fig. 4, but for SAT. The contour interval is 1°C.
to the observed anomaly of Fig. 4d over the northern hemisphere extratropics north of 20°N. The results are listed in Table 1. As can be seen, the forecast using TPSCI alone gives a pattern correlation of 0.74, compared with 0.52 when using ENSO alone. The combination of TPSCI and ENSO slightly improves the forecast using TPSCI alone, with is evident from both PCOR and RMSE scores.

For SAT (Fig. 5), the SON TP snow-cover anomaly plays a dominant role in determining the conditions during the 2009/10 DJF. The reconstruction of SAT based on the contribution of TP snow cover (Fig. 5a) matches the observations very well with all the anomaly centres represented, although the intensity is underestimated. From Table 1, the forecast using TPSCI alone gives a pattern correlation of 0.67, whereas the
forecast using ENSO is not correlated with the observed SAT anomaly (0.03). The combination of TPSCI and ENSO has slightly less skill than using TPSCI alone. This is also true for RMSE.

5 One-month lead seasonal forecast

The above analysis can be regarded as a 0-month lead forecast for Z500 and SAT for DJF 2009/10, because November information is used. Here we look at the 1-month lead forecast using information up to the end of October. A comparison is made with the operational seasonal prediction of CMC issued 1 November 2009. The CMC seasonal forecasting system (Lin et al., 2008) is a two-tier system of four global atmospheric models: GCM2 and GCM3 from the Canadian Centre for Climate Modelling and Analysis (CCCma) (Boer et al., 1984; McFarlane et al., 1992), a reduced-resolution version of the global spectral model (SEF) from Recherche en prévision numérique (RPN) (Ritchie, 1991), and the Global Environmental Multiscale (GEM) model also from RPN (Côté et al., 1998). Each model produces 10 members of ensemble integrations initialized 12 hours apart before 1 November 2009, using persistence of the October 2009 SST anomaly to predict global SST.

In this case, a linear regression model is constructed with two-month averaged September + October (SO) TPSCI and Niño3.4 index as predictors, and DJF Z500 or SAT as the predictand. The two-month average TPSCI and the Niño3.4 index are able to represent a more stable signal than monthly data. Including August would introduce summer information. As shown in LW11, the TPSCI signal is more persistent in autumn, that is why SO is used instead of August, September and October (ASO). The regression coefficients are calculated based on 1972–2008 data. The TPSCI and Niño3.4 values of SO 2009 are used to predict the 2009/10 DJF Z500 and SAT.

Both the Z500 and SAT predictions from the linear regression model (Figs 6a and 6c) match the observed anomalies (Figs 4d and 5d), albeit with weaker amplitudes. As is seen in Table 1, the pattern correlations with the observed DJF anomaly are 0.77 and 0.54 for Z500 and SAT, respectively. The dynamical model predictions (Figs 6b and 6d), however, missed the Z500 negative NAO feature completely, the warm SAT anomaly in Canada and the cold anomaly over northern Eurasia. The pattern correlation with the observed DJF anomaly is negative for both Z500 and SAT. The RMSE for Z500 and SAT is larger than that of the statistical model.

6 Summary and conclusions

In this study, the association of the TP snow-cover anomaly in autumn with the northern hemisphere winter circulation is analyzed. The relative impact of the snow-cover anomaly and that of El Niño are compared. Their contributions to the extreme winter conditions of 2009/10 are assessed. A linear regression model with the TP snow cover and ENSO signal as predictors is used to predict winter Z500 and SAT. One-month lead predictions are compared with the operational seasonal forecast of CMC issued on 1 November 2009.

Results indicate that the autumn TPSCI is significantly correlated with the global Z500 and SAT in the following winter. In the extratropical northern hemisphere, the area with a statistically significant correlation is almost double the area correlated with Niño3.4.

Compared with the El Niño signal, the TP snow cover is the dominant contributor to the extreme winter conditions of 2009/10. The statistical model using snow-cover information and the El Niño signal in autumn 2009 was able to predict the general distribution of the anomalous winter conditions.

Like other dynamical models, the CMC operational seasonal forecasting system failed to predict the extreme winter conditions of 2009/10. It is possible that the contribution of the TP snow-cover anomaly was not properly represented in the dynamical models. This calls for improvement in our understanding of land processes related to snow cover and its representation in numerical models.

The TP represents the highest elevated land on earth. Snow-cover anomalies in this area lead to changes in atmospheric diabatic heating in the middle troposphere that forces atmospheric circulation anomalies. In a separate study, which will be reported elsewhere, using a simple general circulation model with anomalous cooling in the middle troposphere over the TP region, we were able to reproduce the general features of the circulation anomaly of Fig. 2b. Rossby wave generation and propagation in a zonally non-uniform basic flow are found to be responsible for such an atmospheric response to TP snow-cover anomalies.

Acknowledgements

We thank Dr. Bertrand Denis for helpful comments on an early version of this manuscript. Zhiwei Wu is supported by the Sustainable Agriculture Environment Systems (SAGES) research initiative of Agriculture and Agri-Food Canada through the Natural Sciences and Engineering Research Council of Canada (NSERC) Fellowship Program.

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