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Influence of Arctic Wetlands on Arctic Atmospheric Circulation

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ABSTRACT

The Arctic's land surface has large areas of wetlands that exchange moisture, energy, and momentum with the atmosphere. The authors use a mesoscale, pan-Arctic model simulating the summer of 1986 to examine links between the wetlands and arctic atmospheric dynamics and water cycling. Simulations with and without wetlands are compared to simulations using perturbed initial and lateral boundary conditions to delineate when and where the wetlands influence rises above nonlinear internal variability. The perturbation runs expose the temporal variability of the circulation's sensitivity to changes in lower boundary conditions. For the wetlands cases examined here, the period of the most significant influence is approximately two weeks, and the wetlands do not introduce new circulation changes but rather appear to reinforce and modify existing circulation responses to perturbations. The largest circulation sensitivity, and thus the largest wetlands influence, occurs in central Siberia. The circulation changes induced by adding the wetlands appear as a propagating, equivalent barotropic wave. The wetlands anomaly circulation spreads alterations of surface fluxes to other locations, which undermines the potential for the wetlands to present a distinctive, spatially fixed forcing to atmospheric circulation. Using the climatology of arctic synoptic-storm occurrence to indicate when the arctic circulation is most sensitive to altered forcing, the results suggest that the circulation is susceptible to the direct influence of wetlands for a limited time period extending from spring thaw of wetlands until synoptic-storm occurrence diminishes in midsummer. Sensitivities in arctic circulation uncovered through this work occur during a period of substantial transition from a fundamentally frozen to thawed state, a period of major concern for impacts of greenhouse warming on pan-Arctic climate. Changing arctic climate could alter the behavior revealed here.

1. Introduction

The Arctic's land surface has large areas of relatively flat terrain where surface water flow is poorly organized (Vörösmarty et al. 2001; Smith et al. 2005), yielding wetlands characterized by saturated soil and pools

of surface water. Arctic wetlands have long been recognized for their importance in the global carbon cycle (e.g., Gorham 1991) and continue to receive substantial attention because of their potentially changing role as carbon sinks or sources (e.g., Oechel et al. 2000; Smith et al. 2000, 2004; Harding et al. 2001; Lafleur et al. 2001; Harazono et al. 2003; Strom et al. 2003; Aurela et al. 2004). Wetlands also exchange moisture, energy, and momentum with the atmosphere, which may allow them to influence atmospheric circulation and associated transports. In this paper, we examine the capacity of arctic wetlands to influence atmospheric dynamics and thus arctic water cycling.

Despite desertlike (low precipitation) conditions in

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many areas of the far north, arctic wetlands present a perpetually wet surface to the atmosphere between late spring and early autumn, when the ground is thawed. Long arctic summer days imply that these regions will have substantial solar radiation impinging the top of the atmosphere (e.g., Wallace and Hobbs 1977) that can promote evapotranspiration if it reaches the surface. These regions potentially can supply substantial water to the atmosphere while presenting a surface cooled by evapotranspiration.

Arctic wetlands are seldom recognized in surface vegetation datasets used by numerical models. For example, the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) has standard 1° and 30-min combined terrain–land-use data (Guo and Chen 1994) that depict vegetated surfaces in the Siberian Arctic as tundra, deciduous forest, and coniferous forest. However, the U.S. Geological Survey (USGS) Global Land Cover Characteristics database (Loveland et al. 2000; USGS 2005) shows wetlands covering roughly 3% of the land surface poleward of 50°N . The wetlands may be missed in datasets specifying land surface properties because they are spatially dispersed and may cover only a small portion of a numerical model's grid box. Wetlands may also be changing significantly from permafrost degradation in poorly organized, lake-dominated lowland drainage systems, with gains followed by losses of water (Smith et al. 2005). As a result, their role in the arctic climate system has been incompletely studied. To examine the potential influence of arctic wetlands on the region's circulation, we conduct a sensitivity study using a version of MM5 developed to study feedbacks among land, ocean, and atmosphere in the region's hydrologic cycle (Wei et al. 2002). In the present study, we incorporate wetlands over broad areas indicated by the USGS Global Land Cover Characteristics database to explore how their presence affects surface fluxes and atmospheric circulation.

Adding wetlands or changing their characteristics, such as the area they cover, constitute changes in lower boundary conditions for atmospheric simulation. Any manifestation of this change in circulation must be measured against the constant fluctuations the circulation will experience by virtue of its own internal, nonlinear dynamics. The change must emerge as larger than these fluctuations, otherwise it is insignificant relative to the "noise" of the internal variability. One way to estimate the magnitude of the noise, which we use here, is to perform ensemble runs that are identical except for perturbations added to initial or lateral boundary conditions (Giorgi and Bi 2000). The perturbations grow with time, producing eventual differences among the

runs that fluctuate in time but with quasi-steady amplitudes. The magnitude of these differences provides a scale against which one can measure the influence of imposed lower boundary changes.

The perturbation runs also serve another purpose. Atmospheric circulation sensitivity to disturbances varies with time (e.g., Buizza and Palmer 1995). This behavior has spawned considerable effort to understand atmospheric responses to imposed disturbances (e.g., Farrell 1990; Palmer et al. 1994; Farrell and Ioannou 1996; Vukicevic and Raeder 1995; Palmer et al. 1998, among many others), most especially because the behavior affects forecast predictability. An important outcome from this effort is that a simulation's departures from the real world or another simulation most likely grow over short periods (a few days) as nonmodal differences (e.g., Farrell 1989; Morgan and Chen 2002), as opposed to unstable, exponentially growing normal modes. If a model's adjoint is available, singular vectors can identify the time and space varying sensitivity to small disturbances (e.g., Buizza and Palmer 1995). The adjoint of our modified version of MM5 is not available. However, perturbation runs help to identify the episodes during which the circulation is sensitive to disturbances, thus indicating when including wetlands has the greatest potential to influence atmospheric circulation. We shall see that the wetlands influence studied here appears to be governed strongly by variable atmospheric sensitivity to imposed changes.

Section 2 describes the model and simulations we performed. Section 3 gives analysis of the output in terms of circulation changes induced by the wetlands, and section 4 gives our conclusions and some speculations on long-term, climatological behavior that might be inferred from the results.

2. Model and simulations

a. Arctic MM5

Wei et al. (2002) describe our adaptation and validation of MM5 for arctic simulation; we repeat pertinent details here. MM5 computes resolved atmospheric circulation using an Arakawa C grid with split-explicit time stepping. Additional, parameterized atmospheric processes include radiative transfer (Briegleb 1992), cumulus convection (Grell et al. 1991; Grell 1993), cloud microphysics (Dudhia 1989), and boundary layer dynamics (Zhang and Anthes 1982). Atmospheric initial and lateral boundary conditions are prescribed from the U.S. National Centers for Environmental Prediction (NCEP)–NCAR reanalysis (Kalnay et al. 1996), as are also sea surface temperatures and ocean ice cover. By specifying the state of the ocean surface, we are thus

FIG. 1. Model domain and location of wetlands (dotted regions) for (left) the WET:BIG case and (right) the WET:SMALL case. The interior frame on each panel marks the inner boundary of the model's buffer zone for ingesting lateral boundary conditions.

not looking at a complete feedback cycle with oceans included but rather links between surface wetlands and behavior of land and atmosphere processes.

To simulate the arctic land surface, we coupled to MM5 the land surface model (LSM) version 1.0 of Bonan (1996). LSM includes detailed treatment of water, energy, momentum, and carbon exchanges between the atmosphere and vegetated surfaces, using 28 vegetated-surface types. We use the standard MM5 surface-conditions dataset (Guo and Chen 1994) to specify a vegetation category that is translated into one of Bonan's (1996) vegetation surfaces for each model grid box. This dataset depicts the arctic watershed (excluding Greenland) as 31% tundra, 29% deciduous forest, 28% coniferous forest, 11% grassland, and 1% permanent ice. Some vegetation properties, such as the leaf area index, are specified to vary with the calendar. Soil moisture can freeze and thaw, altering soil thermal conduc-

tivity. Active plants can transpire, producing a moisture flux into the atmosphere. Plants also contribute to surface roughness, thereby influencing directly sensible heat and momentum exchanges between the surface and the atmosphere. As is typical for current simulation models, soil textures are mineral and thus the model does not include organic soils. However, a precise definition of soil textures in the wetland areas may not matter much here because for specified wetlands we fix soil moisture at saturation.

b. Simulation domain

The model domain is a polar stereographic projection of a 51×91 array of grid points with 120-km grid spacing, centered over the Arctic Ocean and oriented to cover the North American and Eurasian arctic watersheds (Fig. 1). For this domain, the model's lateral buffer zone that introduces large-scale forcing into the

TABLE 1. Sensitivity simulations.

Model run	Alteration from reference run
WET:BIG	Wetlands designated for all grid boxes with >10% wetlands in USGS data
WET:SMALL	Wetlands designated for all grid boxes with >30% wetlands in USGS data
LBCL	Large random additions to lateral boundary conditions Ranges: $\pm 1 \text{ m s}^{-1}$ (wind), $\pm 1 \text{ K}$ (temperature), $\pm 5\%$ (relative humidity)
LBCL	Small random additions to lateral boundary conditions Ranges: $\pm 0.5 \text{ m s}^{-1}$ (wind), $\pm 0.5 \text{ K}$ (temperature), $\pm 2.5\%$ (relative humidity)
ICL	Large random additions to initial conditions Ranges: $\pm 1 \text{ m s}^{-1}$ (wind), $\pm 1 \text{ K}$ (temperature), $\pm 5\%$ (relative humidity)
ICS	Small random additions to initial conditions Ranges: $\pm 0.5 \text{ m s}^{-1}$ (wind), $\pm 0.5 \text{ K}$ (temperature), $\pm 2.5\%$ (relative humidity)

interior is located within areas where relatively high-quality observational data are ingested into the reanalysis. We avoid placing a boundary, for example, across the Arctic Ocean, where there are fewer high-quality observations of the three-dimensional state of the atmosphere. Much of the arctic circumpolar vortex is thus contained within the model domain and is simulated internally, allowing the model to develop a response to changes in the lower boundary conditions that is not strongly limited by the imposed lateral boundary conditions.

For this domain, the model performs well, reproducing general features of the pan-Arctic's geopotential height, temperature, moisture, and surface radiation fields during a 1-yr simulation (after model spinup) from October 1985 to September 1986 (Wei et al. 2002). Some evidence was found, through comparison with rawinsonde winds, that the model gives a more accurate rendition of arctic circulation than the NCEP–NCAR reanalysis that provides its lateral boundary conditions. This result gave a posteriori support to the decision to avoid focusing on one continent and placing a lateral boundary across the observation-poor Arctic Ocean.

c. Simulations

We use the 1-yr simulation analyzed in Wei et al. (2002) as a reference case for two types of sensitivity runs. Table 1 summarizes characteristics of the sensitivity runs. In the first type, we include wetland areas as defined below; in the other type, we perturb the reference case to help delineate internal variability in the model. The reference case ran from 1 October 1985 to

30 September 1986. All additional simulations presented here start from the reference run's state at 0000 UTC 1 April 1986. Because the wetlands are frozen in winter and also likely covered with snow, the wetlands interaction with the atmosphere during winter should be little different from that in the standard run for these regions. Simulations last until the end of September 1986.

In the wetlands simulations, we specify wetland regions in the Arctic guided by the USGS (2005) database. Our intent is not to reproduce the precise distribution of wetlands, but rather to consider distributions spanning a range that includes the primary wetland regions in the USGS database in order to assess the sensitivity of the model to the amount of wetlands area. We have defined two wetlands cases:

- 1) WET:SMALL—all MM5 grid boxes with >30% wetlands in the USGS database are specified wetlands.
- 2) WET:BIG—a more liberal case in which all MM5 grid boxes with >10% wetlands in the USGS database are specified wetlands.

The resulting areas in the Arctic that become wetlands appear in Fig. 1 for both the WET:SMALL and WET:BIG cases. For WET:SMALL, the wetlands area is 1 060 000 km² (2.5% of land area north of 50°N) and for WET:BIG, the specified wetlands area is 2 730 000 km² (6% of land area north of 50°N). There are three primary wetland regions: one in central Siberia between the Ob (approximately 65°E) and Yenesei (approximately 85°E) Rivers, one in eastern Siberia, and the third in the Canadian Arctic. All are in regions of relatively flat topography.

In a model grid box specified as “wetlands,” we assume that the region is vegetated with saturated soil. Specified vegetation distributions remain the same as in the standard form of the model (as used in Wei et al. 2002), so we assume that the wetlands are not broad, open stretches of water but rather marshy regions with perpetually saturated but vegetated soil. Properties, such as surface roughness, are thus those of the vegetation.

In the second type of simulation, we perturb initial or lateral boundary conditions to estimate internal variability of the circulation that arises from the atmosphere's nonlinear dynamics. The model's nonlinear dynamics can generate substantial internal variability, which is potentially as large as any produced by the wetlands. To distinguish differences due to the presence of the wetlands from internal variability in the model, we have followed Giorgi and Bi (2000) and run an ensemble of four simulations, adding perturbations

to initial or lateral boundary conditions. For all four cases, we generate initial and lateral boundary conditions with the same set used in the wetlands simulations. Two members of the ensemble have random perturbations in horizontal wind, temperature, and relative humidity added everywhere to the initial, three-dimensional state of the atmosphere. Perturbations at each model level for each grid point are a random number in $[-1, +1]$ multiplied by an amplitude factor. Following Giorgi and Bi (2000), one simulation uses a “large” set of amplitudes (ICL) and the other a “small” set of amplitudes (ICS). The large amplitudes are 1 m s^{-1} for winds, 1°C for temperature, and 5% for relative humidity, and the small amplitudes are 0.5 m s^{-1} for winds, 0.5°C for temperature, and 2.5% for relative humidity. These amplitudes are comparable to estimates of observational error for these fields (e.g., Pratt 1985; Nuss and Brown 1987). For the final two members, lateral boundary conditions receive large (LBCL) or small (LBCS) perturbations instead of the initial conditions. The perturbations are updated at the same frequency as the lateral boundary conditions, every 6 h. Like the lateral boundary conditions, they are interpolated linearly in time between each update, so that they are applied continuously throughout the simulations.

While this specification of perturbed runs is not exhaustive, we shall see that after a few days, the departure of the perturbed run from the reference case is not proportional to perturbation size. As observed by Giorgi and Bi (2000), this set of perturbed runs appears to be sufficient for revealing the magnitude of internal atmospheric variability generated by the model. We report when the wetlands influence exceeds this variability, which we view as noise.

3. Analysis

a. Circulation anomalies

We measure circulation differences between simulations by computing the root-mean-square difference (RMSD) from the reference case of 500-hPa geopotential heights. Figure 2 shows time series for RMSD computed at 0000 and 1200 UTC each day for the model domain inside the zone where lateral boundary conditions are ingested. The perturbed simulations diverge immediately from the reference case after initialization on 1 April, with simulations using perturbed initial conditions having the largest RMSD over the first two weeks. The large and small perturbation cases yield almost the same RMSD for both the lateral and initial conditions cases. Consistent with Giorgi and Bi (2000), RMSD is not proportional to the magnitude of the perturbation. For example, for this set of simulations,

FIG. 2. Time series of 500-hPa geopotential height RMSD for the six disturbance simulations (vs reference run).

the small initial-conditions perturbation yields larger RMSD than the large initial-conditions perturbation from mid-April to mid-May. Overall, RMSDs among the simulations are comparable to the 500-hPa height differences in the domain interior between the reference simulation and the NCEP–NCAR reanalysis. Note that although the NCEP–NCAR reanalysis provides lateral boundary conditions, the circumpolar vortex is only weakly controlled by them (e.g., Fig. 2), so that daily differences between model and observations will tend toward the climatological amplitude of 500-hPa fluctuations, much like error growth in numerical weather prediction (Wei et al. 2002). Thus, differences between a perturbed simulation and the reference run become comparable to the amplitude of climatological 500-hPa fluctuations (cf. Peixoto and Oort 1992).

The lateral boundary conditions perturbations give more slowly growing RMSD, and over the first month and a half of simulation, RMSD for each of these two runs is usually as small or smaller than the RMSD for all other cases. This is in contrast with Giorgi and Bi (2000) for which all perturbations produced initial growth in RMSD that was about the same for each perturbation. The Giorgi and Bi (2000) simulations were for a midlatitude zone (eastern Asia) for which lateral boundary conditions on upstream sides were swept into the interior throughout the run by monsoonal and upper-level westerly flow. In the present simulations, the 500-hPa flow tends to be a roughly circular vortex centered on the North Pole, which restricts the penetration of lateral boundary perturbations into the interior. However, consistent with Giorgi and Bi (2000), initial-conditions perturbations create RMSD that persists throughout the simulation period, and the lateral boundary perturbations eventually pro-

duce RMSD with approximately the same magnitude as the initial conditions perturbations. Most important, despite their different perturbation structures, the perturbation simulations all point to the same period, 20–30 days into the simulation period, when the evolution of the model atmosphere becomes especially sensitive to disturbances.

The two wetland cases show approximately the same evolution over their first 60 days (Fig. 2), so their influence is not proportional to wetlands area (Fig. 1), at least for the period examined. Thereafter, RMSD for each case meanders in the range 20–60 m, with the WET:BIG case having larger values slightly more than half the time. The wetlands RMSD emerges only after about three weeks into the simulation, when RMSD for both cases grows rapidly to larger values than given by any of the perturbation runs. Largest differences from the perturbation runs occur during a two-week period, 20 April–3 May, when RMSD in each wetlands run exceeds the largest perturbation-run RMSD by 20%–50%, averaging 34% more than the ICS RMSD, which is the third largest overall during this period. After having the largest values for about two weeks, the wetlands RMSDs decline to values similar to the perturbation runs. Thereafter, the wetlands influence as measured by 500-hPa RMSD does not rise above the internal variability for any substantial period of time.

We have assessed the statistical significance of the separation of the wetlands RMSD from the perturbation RMSD using a standard procedure (Snedecor and Cochran 1989) for testing the equality of two distributions that focuses on their variances. Because mean deviations are relatively small compared to RMSD during each run, the $(\text{RMSD})^2$ and variance are essentially the same. We assume that the simulations with random perturbations collectively represent samples of the “noise” due to internal variability in the model. Thus, at each 12-h time point, we compute net “noise” variance $(\sigma_N)^2$ using all grid points that are interior to the buffer zone in all four perturbation runs. Similarly, we obtain a wetlands variance $(\sigma_W)^2$ using all interior grid points from the WET cases. Under the assumption that the input samples are approximately normally distributed, the relevant test statistic is $F = (\sigma_W)^2/(\sigma_N)^2$, which has an F distribution with (n_W, n_N) degrees of freedom corresponding to the wetlands and noise samples, respectively. The null hypothesis is that the two variances are the same. We seek significant occurrences of $(\sigma_W)^2 > (\sigma_N)^2$, for which a one-sided F test is appropriate to determine if we should reject the null hypothesis in favor of this alternative. In essence, we are testing to see if the wetlands simulations have significantly greater differences from the baseline simulation com-

FIG. 3. The F statistic vs time. Horizontal lines mark the 95% (solid) and 99% (dashed) levels of significantly greater variance in the wetland runs vs the perturbation runs.

pared to the perturbations runs, especially at large deviation (the tails of the deviation distributions).

To estimate the degrees of freedom, at each time for each run, we sample $41 \times 81 = 3321$ grid points. However, the deviations from the reference run have spatial correlation, so we use a conservative estimate of $n_W = n_N = 30$ degrees of freedom for each set. Figure 3 shows F versus time, along with the 95% and 99% significance levels. For the period of greatest interest, 20 April–3 May (days 20–33), the wetlands variance is significantly greater than the perturbations’ variance at the 99% level. The result is relatively insensitive to the estimated degrees of freedom: the period 20 April–3 May has greater than 99% significance for $n_W = n_N = 25$ or greater. After this time, F declines, and there is no further episode of significantly larger variance in the wetlands simulations. Introduction of the wetlands thus shows a significant but ephemeral influence on the circulation.

Analysis of the spatial distribution of 500-hPa differences between the ICL and reference simulations is instructive for understanding the evolution of the WET:BIG and WET:SMALL differences from the reference case. (Qualitatively similar behavior occurs for the ICS – reference differences.) The largest ICL differences during 19 April–2 May emerge in western Asia between 60° and 100°E and spread through the region occupied by the model’s central Siberian wetlands. The difference pattern (Fig. 4) has a quadrupole-like appearance whose vertical structure is roughly equivalent barotropic. The difference field also has nonzero am-

FIG. 4. The (ICL – reference) height differences for (a) 500 and (b) 850 hPa at 0000 UTC 28 Apr 1986 (start of day 28 of the ICL run). [Contour interval (CI): 20 m. 0 contour suppressed.]

plitude over northern Canada, but the differences emerge later and are not as large.

For all runs, the difference field has relatively small amplitude in the vicinity of the model's wetlands in far eastern Siberia, though this may be due to that region's close proximity to the buffer zone (Fig. 1), where the model ingests lateral boundary conditions, which will tend to suppress any differences between runs except for the small perturbations added to the LBC cases.

The perturbation runs show that the arctic circulation during the simulation period is sensitive to small changes in its environment in late April but not before. They also show that the central Siberian and Canadian wetlands are both located where the largest differences occur in 500-hPa heights, and hence 500-hPa circulation, though the Siberian wetlands between the Ob (approximately 65°E) and Yenesei (approximately 85°E) Rivers are more centrally embedded in regions of large 500-hPa height differences than their Canadian counterparts.

The reference simulation's circulation thus becomes sensitive to perturbations in western and central Asia during late April. The largest (WET:BIG – reference) height differences (Fig. 5) occur at this time in central Siberia, with later, though weaker, development over northern Canada (Fig. 6). Over the far eastern Siberia

wetlands, relatively little difference occurs. Overall, the wetlands act like a perturbation source, producing differences from the control run at about the same time (Fig. 2) and location (Fig. 5) as the other perturbations. The wetlands thus appear to reinforce and modify the sensitivity of the circulation to perturbations, rather than create it.

Like the perturbation runs, the vertical structure of the (WET:BIG – reference) differences is roughly equivalent barotropic. However, in contrast to the ICL differences, these differences have a wave train appearance in a low-high-low sequence. The pattern appears to rotate in response to the zonal winds in which it is embedded, though it moves at a slower speed. For example, at 55°N, the pattern shifts eastward at a speed of about $6.6^\circ \text{ day}^{-1}$ in longitude, or 4.9 m s^{-1} , whereas the zonal wind at 500 hPa in the vicinity of the pattern averages over 20 m s^{-1} . In addition, the high in the wave train propagates through the pattern envelope in a roughly southward direction at a rate of about 3.7 m s^{-1} . As the difference pattern evolves, the low center at 55°N over Russia on 28 April weakens, while a new high emerges over the Arctic Ocean by 2 May. Adding the wetlands thus appears to induce in the circulation a wave group with southward phase propagation. The appearance of a wave group in the difference field is a

FIG. 5. The (WET:BIG – reference) height differences at (a) 500 and (b) 850 hPa at 0000 UTC 28 Apr 1986 (start of day 28 of the WET:BIG run). (CI: 40 m. 0 contour suppressed.)

plausible outcome if the presence of the wetlands yields reference and WET:BIG 500-hPa fields containing waves with slightly different wavelengths and frequencies (e.g., Holton 2004). As we shall see, the propagation of the difference pattern plays an important role in enhancing and then diminishing the wetlands response to the anomalous circulation.

More specifically, assume that the reference (r) and wetlands (w) simulations both have waves described by the linearized barotropic vorticity equation on a β plane:

$$\frac{\partial}{\partial t} \zeta'_r = -U_r \frac{\partial}{\partial x} \zeta'_r - v'_r \beta \quad (1)$$

and

$$\frac{\partial}{\partial t} \zeta'_w = -U_w \frac{\partial}{\partial x} \zeta'_w - v'_w \beta, \quad (2)$$

where ζ' is the vorticity of the wave flow, U is the basic-state zonal flow, v' is the meridional wind of the wave flow, and β is the latitudinal gradient of the Coriolis parameter.

Then the difference field's behavior is

$$\frac{\partial}{\partial t} (\zeta'_w - \zeta'_r) = - \left(U_w \frac{\partial}{\partial x} \zeta'_w - U_r \frac{\partial}{\partial x} \zeta'_r \right) - (v'_w - v'_r) \beta \quad (3)$$

or

$$\frac{\partial}{\partial t} (\delta \zeta') = -U_w \frac{\partial}{\partial x} (\delta \zeta') - (\delta v') \beta - \left(\delta U \frac{\partial}{\partial x} \zeta'_r \right), \quad (4)$$

where $\delta X = X_w - X_r$.

If we assume the localized difference field has negligible influence on the basic-state (background) zonal flow, then $\delta U \approx 0$, and (4) yields a Rossby wave solution for the wave in the difference field. The separation of low and high centers gives an approximate wavelength range of 3200–4200 km. Assuming equal zonal and meridional wavelengths within the wave group, the Doppler-shifted meridional phase speed at 60°N is then 1.5–2.6 m s^{−1}. The speed is of comparable magnitude to the actual pattern movement, though slower. The result suggests that Rossby wave dynamics play a role in governing the phase propagation of the difference field.

b. Surface evolution near wetlands

The anomaly circulation induced by the wetlands-based perturbation advects air into the region of the central Siberian wetlands that alters surface processes and their coupling with the atmosphere compared to the reference simulation. During the period of largest WET:BIG RMSD in late April, the anomaly flow at 850 hPa (Fig. 5b) has a southerly component at ap-

FIG. 6. Same as in Fig. 5 but for 0000 UTC 2 May 1986 (start of day 32 of the WET:BIG run). (CI: 40 m. 0 contour suppressed.)

proximately (65°N , 75°E), giving warm air advection. The anomaly advection occurs during a period of substantial snowmelt and runoff generation in the model, as well as in the real world (cf. Fig. 11 of Wei et al. 2002). Thus, an immediate effect of the anomaly advection is increased snowmelt and surface runoff (Fig. 7) in the region. The runoff is further enhanced in the WET:BIG simulation by the specified saturated soil of the wetlands, though the enhanced runoff occurs over a somewhat wider area than just the wetlands. Associated with enhanced snowmelt is a negative surface sensible heat flux anomaly (not shown) that occurs as a consequence of the advected warm air's contribution to snowmelt.

Eventually, all the snow melts, allowing surface temperature to climb above freezing, and the wetlands water contributes to enhanced latent heat flux (Fig. 8). The largest evapotranspiration differences for the wetlands region occur at the time of largest RMSD in the WET:BIG 500-hPa field. However, the wind field of the height anomaly changes direction during this period and anomaly warm-air advection switches to cold-air advection, so much so that even though the 850-hPa wind in the vicinity of 65°N , 75°E has episodes of warm-air advection during the week 29 April–5 May (e.g., Fig. 6b), the average anomaly 850-hPa wind during this week has a northerly component, most likely producing

cold advection. Enhanced evapotranspiration in the vicinity of the wetlands thus starts diminishing, lessening the coupling of the wetlands to the atmosphere, and eventually positive anomalous evapotranspiration occurs elsewhere (e.g., Fig. 9) in response to evolving

FIG. 7. The (WET:BIG – reference) change in runoff for the Eurasian half of the model domain, averaged over week 4 of the perturbation simulation (21–28 Apr). (CI: 10 mm day⁻¹. 0 contour suppressed; negative contours dotted. Areas with change magnitude exceeding 20 mm day⁻¹ are shaded.)

FIG. 8. The (WET:BIG – reference) change in ET (contours) for the Eurasian half of the model domain, averaged over week 5 of the perturbation simulation (29 Apr–5 May). Also shown are (WET:BIG – reference) differences in 850-hPa horizontal wind (vectors), averaged over week 5. (CI: 2 mm day^{-1} . 0 contour suppressed; negative contours dotted. Areas with change magnitude exceeding 4 mm day^{-1} are shaded. Vector scale appears in lower right corner. Tightly clustered vectors near pole suppressed.)

circulation anomalies. As a consequence, the wetlands-induced circulation anomaly (relative to the no wetlands reference case) undermines the wetlands influence by its propagation. Ultimately, much of the altered evapotranspiration occurs away from the wetlands, as in Fig. 9. Bonan (1995) studied climatological effects of adding inland water surfaces to a global climate model. Examination of the evapotranspiration changes in his study (his Fig. 6) also shows the largest Siberian changes displaced relative to the central Siberian water surfaces in his model, in his case toward the southwest. Thus, the wetlands do not present a fixed forcing of the atmospheric circulation.

4. Conclusions and discussion

Adding arctic wetlands to a pan-Arctic climate model changes the large-scale circulation, but the change rises above internal variability for only about two weeks in the case examined here. Thereafter, the changes are no larger than those produced by perturbing initial or lateral boundary conditions. The circulation changes induced by adding the wetlands appear as a propagating equivalent barotropic wave. The wave train in the (WET:BIG – reference) 500-hPa height anomaly propagates to the edge of the model domain, suggesting a possible teleconnection pattern of the wetlands influence into southern Siberia and beyond. This influence

FIG. 9. Same as in Fig. 8 but averaged over week 8 of the perturbation simulation (20–26 May).

would only occur during the period of significant circulation change related to the status of the wetlands. The magnitude of the circulation response is not proportional to the area covered by the wetlands. As with the initial conditions and lateral boundary conditions perturbations, the wetlands perturbations to the circulation catalyze dynamical processes that allow the disturbances to grow, rather than supply energy for thermally governed circulations.

Ultimately, the wave's propagation produces the demise of the wetlands influence, for the anomaly circulation reinforces and then impedes surface–atmosphere interaction by sensible and latent heat fluxes. The anomaly circulation also spreads alterations of surface energy fluxes to other locations, further eroding the potential for the wetlands to present a distinctive, spatially fixed forcing to atmospheric circulation.

The wetlands influence in these simulations appears when the large-scale circulation is sensitive to external perturbations, suggesting that the timing of their influence is strongly dependent on the seasonal evolution of arctic circulation. Suppose the passage of storm systems renders the atmosphere in a region sensitive to external perturbations. The 30-yr monthly climatology of cyclone and anticyclone counts produced by Serreze et al. (1997) shows that central Siberia has relatively large cyclone counts in April through June, with numbers diminishing in July and August. Concurrently, anticyclones, which can block the passage of synoptic storms, tend to increase in frequency in the region between April and September, though not always uniformly with time. The climatology of Arctic synoptic-storm occurrence thus suggests that there is a limited time period when the circulation is sensitive to disturbances,

such as altered boundary conditions, and thus susceptible to changing the central Siberia wetlands. The period extends from the initial thaw of the wetlands until the frequency of synoptic storms diminishes in midsummer.

Further examination of the Serreze et al. (1997) climatology also shows that the regions of the Canadian and far east Siberian wetlands tend to have fewer cyclones than central Siberia in late spring, indicating that including wetlands in these regions is less likely to induce circulation changes. The climatological cyclone frequency thus suggests that the prominence of the central Siberian wetlands in the results presented here is consistent with circulation dynamics based on long-term climatology. (The reader is reminded, however, that the model has the far east Siberian wetlands in its lateral forcing region and so may not allow significant differences between simulations in any case.) Cyclone counts are larger in the vicinity of the Canadian wetlands in June, indicating potential for the state of wetlands to influence atmospheric circulation at a later period than the central Siberian wetlands.

This study focuses on the evolution of the influence of arctic wetlands on atmospheric circulation for just one warm season. Although the wetlands of greatest influence are consistent with climatology, interannual variability of arctic circulation may well alter the specific details of wetlands versus no wetlands differences from one year to the next. Also, although the wetlands influence on circulation in any year appears to be ephemeral, multiyear simulation might reveal more subtle effects that appear only after long-term averaging allows them to emerge above the “noise” of synoptic variability. For example, wetlands may play a significant role in determining climatological boreal summer temperatures and humidity (Krinner 2003). Redistribution of wetlands in response to climate change, permafrost degradation, and altered patterns of net convergence could also have important but currently unquantified ramifications.

The sensitivities in arctic circulation uncovered through this work occur during a period of substantial transition from a fundamentally frozen to thawed state. Changes in the timing and intensity of this transition are one of the major concerns for impacts of greenhouse warming on pan-Arctic climate (Overpeck et al. 2005). Changing arctic climate could alter influences of wetlands on this transition period. Recent decades have seen increases in moisture advection in the Arctic (Serreze et al. 1997) and increases in arctic river discharge from Eurasia (Peterson et al. 2002), behaviors that might alter the distribution, extent, and atmospheric coupling of the wetlands. Also, disturbance of land

cover, such as through fire, could yield substantial soil drying or waterlogging (Yoshikawa et al. 2003). Understanding the hydrologic influence of land disturbances is thus important for projecting how wetlands in the Arctic might alter circulation in the future.

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