Has the Conversion of Natural Wetlands to Agricultural Land Increased the Incidence and Severity of Damaging Freezes in South Florida?

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ABSTRACT

On several occasions, winter freezes have wrought severe destruction on Florida agriculture. A series of devastating freezes around the turn of the twentieth century, and again during the 1980s, were related to anomalies in the large-scale flow of the ocean–atmosphere system. During the twentieth century, substantial areas of wetlands in south Florida were drained and converted to agricultural land for winter fresh vegetable and sugarcane production. During this time, much of the citrus industry also was relocated to those areas to escape the risk of freeze farther to the north. The purpose of this paper is to present a modeling study designed to investigate whether the conversion of the wetlands to agriculture itself could have resulted in or exacerbated the severity of recent freezes in those agricultural areas of south Florida.

For three recent freeze events, a pair of simulations was undertaken with the Regional Atmospheric Modeling System. One member of each pair employed land surface properties that represent pre-1900s (near natural) land cover, whereas the other member of each pair employed data that represent near-current land-use patterns as derived from analysis of Landsat data valid for 1992/93. These two different land cover datasets capture well the conversion of wetlands to agriculture in south Florida during the twentieth century. Use of current land surface properties resulted in colder simulated minimum temperatures and temperatures that remained below freezing for a longer period at locations of key agricultural production centers in south Florida that were once natural wetlands. Examination of time series of the surface energy budget from one of the cases reveals that when natural land cover is used, a persistent moisture flux from the underlying wetlands during the nighttime hours served to prevent the development of below-freezing temperatures at those same locations. When the model results were subjected to an important sensitivity factor, the depth of standing water in the wetlands, the outcome remained consistent. These results provide another example of the potential for humans to perturb the climate system in ways that can have severe socioeconomic consequences by altering the land surface alone.

1. Introduction

Agriculture has always been the mainstay of Florida's economy. In particular, Florida-based production of citrus, winter fresh vegetables, and sugarcane make up a large share of the U.S. market for these products. During 2002, Florida ranked first in the nation for cash receipts of citrus crops, and either first or second for several fresh fruit and vegetable crops, including tomatoes, strawberries, snap beans, squash, sweet corn, bell peppers, watermelons, radishes, and avocados (FDACS 2002). By some estimates, more than half of the fresh vegetables consumed by Americans during the core winter months are harvested in south Florida (Hansen et al. 1999).

Moderate freezes, which can destroy tender vegetable crops and may damage or kill foliage and blossoms on citrus trees, occur with some regularity in northern and central areas of the Florida peninsula, but they are not typically so severe as to kill or result in permanent wood damage to citrus trees (Weischet and Caviedes 1987). Nevertheless, historic winter freezes occasionally have wrought severe destruction on northern and central Florida agriculture. Catastrophic losses have continued to impact Florida agriculture in recent years, despite improvements in frost and freeze protection technologies and continued southward migration of production to less freeze-prone regions. Attaway (1997) documents the citrus-killing freezes that have resulted in successive migrations of the citrus industry southward over the past

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150 yr, culminating in what he refers to as ''The Catastrophic Period from 1981–1989.'' Around the turn of the twentieth century, a series of citrus-tree-killing freezes prompted a dramatic southward shift in production from northern to central areas of the state. Prior to that time, orange groves were planted as far north as Jacksonville and Tallahassee. Historically, northern and central areas of the peninsula have been preferred over less freeze-prone areas farther south for agricultural development because the well-drained, sandy soils of the more northern portions of the state provide a less disease-prone environment than the wetlands and saturated organic soils of south Florida.

After the southward shift in citrus cultivation to central Florida during the early twentieth century, production flourished. However, during the 1980s, a series of devastating freezes affected the groves of the central peninsula. Following these events, evidence suggests that perceptions changed permanently amongst Florida's citrus community regarding the risk of freeze in central areas of the state. Many producers elected to relocate to the less freeze-prone wetlands regions of south Florida, resulting in another dramatic shift southward in citrus production on the peninsula (Whittaker 1985; Miller 1991). Prior to and during this time, wetlands in south Florida were being drained and converted to agricultural land, particularly for winter vegetable and sugarcane production. In many cases, citrus producers relocated to areas in and near converted wetlands. Figure 1 illustrates the number of citrus trees by county as well as the key areas of vegetable production in Florida during 2000.

The anomalous cold waves around the turn of the twentieth century and during the 1980s that resulted in killing freezes and the southward migration of Florida's agricultural production centers may have been linked to mechanisms associated with large-scale circulation anomalies in the ocean–atmosphere system (Haddock 1981, 1984; Mogil et al. 1984). Previous investigators have noted the relationship of Florida freeze events to the Pacific–North American pattern (PNA; Horel and Wallace 1981) and the phases of the El Niño–Southern Oscillation (ENSO; Ropelewski and Halpert 1986) and the North Atlantic Oscillation (NAO; Rogers 1984). These studies show that freezes are more likely in south Florida when the PNA (NAO) is in a positive (negative) phase. The combination of these phases is often associated with intrusions of Arctic high pressure at the surface and accompanying troughs in the mid- and upper-level synoptic patterns (e.g., 500-hPa geopotential height) over the southeastern United States. In their review article relating all three phenomena to the occurrence of agriculturally important freezes in central and south Florida, Downton and Miller (1993) concluded that the phases of the PNA and NAO are highly relevant, whereas the phase of ENSO exhibits little correlation with freeze frequency and severity. A recent analysis by the Florida Climate Center indicates that killing freezes are more likely during winters in which the phase of ENSO is neutral (see online at http://www.coaps.fsu.edu/~grant/flclimate/spotlight).

These studies address the role of large-scale atmospheric processes in the occurrence of killing freezes and the subsequent southward migration of Florida's citrus and vegetable industries. However, an interesting and largely unexamined question involves whether *it is also possible that the conversion of natural wetlands to accommodate the expanding agricultural production in south Florida could itself have an impact on the incidence or severity of freeze events in those areas.*

Other studies have shown that the dramatic landscape transformation that occurred on the peninsula during the twentieth century, including those areas of wetlands that have been converted to agricultural land, may have had an impact on the weather of south Florida by altering the spatial distribution of surface sensible heat flux, physical evaporation, and transpiration. For example, Pielke et al. (1999) and Marshall et al. (2004) suggest that the draining of the Kissimmee floodplain during the twentieth century may have resulted in a weakening of the sea-breeze circulations, which in turn resulted in a spatial redistribution of warm-season convective rainfall patterns. Their modeling results also agree with observational evidence that suggests an overall decrease in regional summer rainfall and an increase in daytime maximum temperature. To date, however, relatively few studies have addressed any possible impacts of the landscape change on the cool-season weather of the peninsula. The purpose of this paper is to present the results of a modeling study that was designed to investigate whether anthropogenic landscape change in south Florida, and in particular the conversion of natural wetlands to agricultural land, could have an impact on the frequency and/or severity of damaging freeze events in that region.

2. Background and methods

a. Background on examined freeze events

Three recent freeze events that resulted in damage to south Florida agriculture were analyzed for the study presented in this paper. These freezes occurred on 26 December 1983, 25 December 1989, and 19 January 1997. The meteorological conditions associated with these events are typical of those that lead to agriculturally damaging freezes in south Florida. Figures 2, 3, and 4 illustrate the sea level pressure (SLP) and 850-hPa temperature patterns for the 1983, 1989, and 1997 events, respectively. In all three cases, significant surface high pressure, of Arctic origin, had migrated southward and eastward over the continental United States during the previous few days. On the morning that freezes occurred in south Florida (defined here as that portion of the peninsula south of Lake Okeechobee), temperatures at 850 hPa had fallen to near or below 5°C, and the SLP gradient had become weak. These synoptic con-

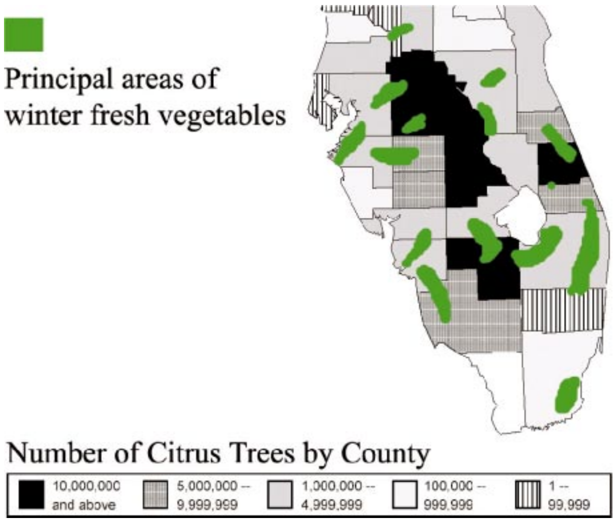

FIG. 1. The number of citrus trees by county, and key areas of winter vegetable cultivation during 2000 [figure adapted from FDACS (2002)].

ditions combined to produce clear skies and calm winds. With a very dry air mass in place, the loss of infrared radiation from the land surface during the nighttime hours was optimized. The strong loss of infrared radiation allowed for the development of a steep, surface-based thermal inversion over south Florida, with a shallow layer of below-freezing temperatures near ground level. Figures 5–7 illustrate the observed minimum temperatures for available stations from the National Weather Service Cooperative Observer Network.

These types of freeze events are referred to by the Florida meteorological and agricultural communities as ''radiation freezes,'' in contrast to ''advective freezes,'' which are associated with the intrusion of a large-scale Arctic air mass and widespread freezing temperatures over a deep vertical layer of the lower troposphere (Rogers and Rohli 1991). The latter type of event is relatively rare as far south as the agricultural areas of south Florida. When freezing conditions do occur in those areas, they are usually of the ''radiation'' variety, and minimum temperatures rarely fall much below the freezing mark for any significant duration of time (Waylen 1988; Waylen and LeBoutillier 1989). Often, advective freezes occur over more northern areas of the peninsula on nights preceding a radiation freeze over the agricultural areas of south Florida. In many cases, these advective freezes occur on the first or second night following the passage of the cold front associated with the leading edge of the associated Arctic air mass, when the gradient of SLP is still significant enough to sustain appreciable low-level winds throughout the night. Radiation freeze conditions then sometimes occur over areas farther south on subsequent nights, when the axis of the high pressure is near and the SLP gradient decreases. This study is focused on radiation freeze events that occurred over the agricultural areas of south Florida.

During the 1983 and 1989 events, advective freezes did occur to the north of the agricultural areas of south Florida on the preceding night. However, during the 1997 event, widespread advective freeze conditions did not occur over northern and central Florida on the night before. As a result, the development of freeze conditions over south Florida on the morning of 19 January was not well forecast by the local agricultural and meteorological communities. The poor forecast resulted in a lack of steps to implement freeze and frost protection

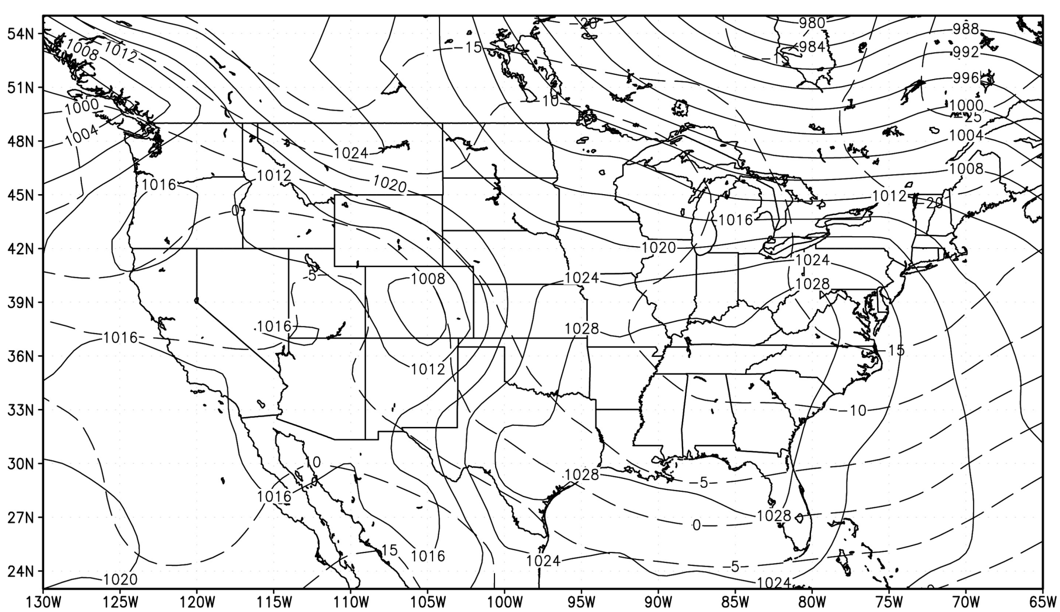

FIG. 2. Sea level pressure (hPa; solid contours) and 850-hPa temperature (°C; dashed contours) analyses over the conterminous United States valid 1200 UTC 26 Dec 1983. Data supplied by NCEP–NCAR reanalysis.

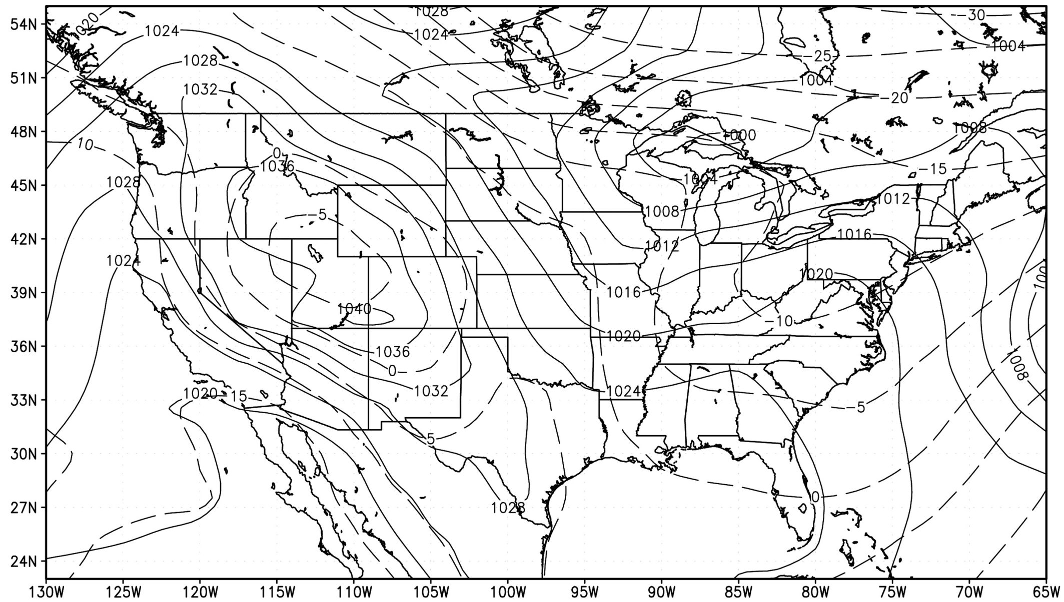

FIG. 3. Same as in Fig. 2, except for 1200 UTC 25 Dec 1989.

measures, and thus the socioeconomic costs of the event were quite severe. Losses in the fresh vegetable and sugarcane sectors alone, with the near total loss of crops in the area of cultivation centered immediately south of Lake Okeechobee, were near 300 million U.S. dollars (ERS USDA 1997). In addition, nearly 100 000 migrant farm workers became displaced or unemployed (UCD 1997).

Because events similar to the cases presented here are driven by radiative cooling of the surface under atmospheric conditions that are otherwise only marginally supportive of below-freezing temperatures near ground level, the nighttime minimum temperature at any particular location can be quite sensitive to local properties of the land surface that modulate the exchange of energy with the overlying atmosphere. These properties include small tropographic variations, the amount and type of vegetation, and soil water content. In the case of south Florida, these properties are strongly linked to the spatial distribution of wetlands. These events impacted areas of south Florida where these properties had been changed markedly during the twentieth century by the

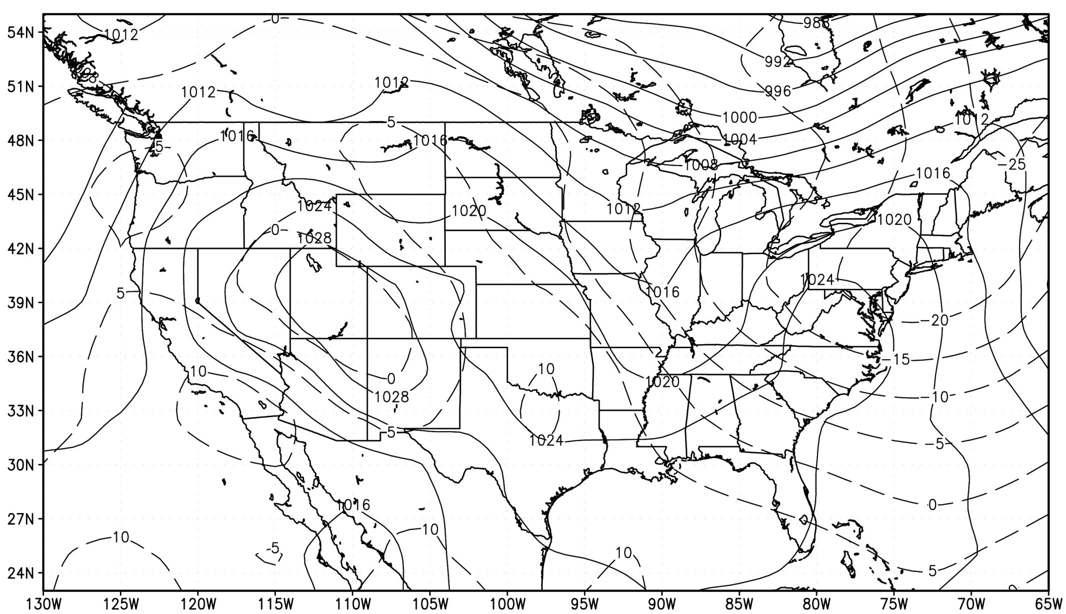

FIG. 4. Same as in Fig. 2, except for 1200 UTC 19 Jan 1997.

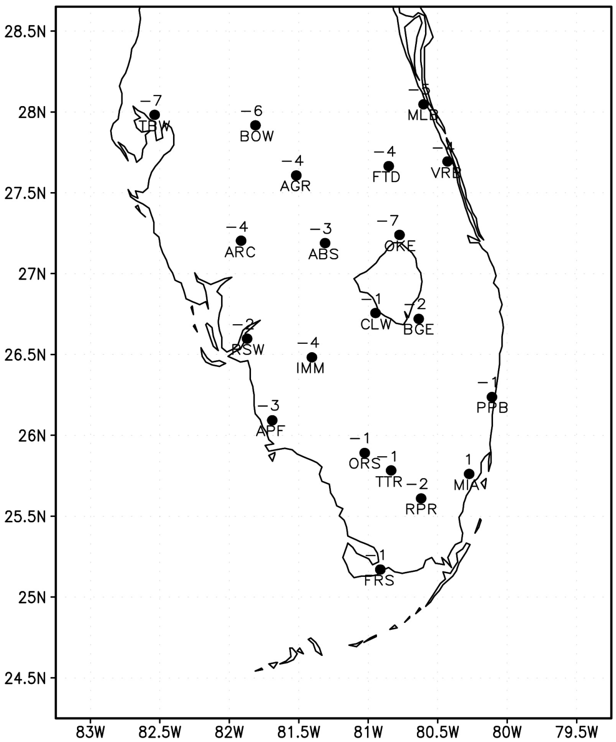

FIG. 5. Observed minimum temperatures (rounded to the nearest whole °C) on the morning of 26 Dec 1983 from the National Weather Service Cooperative Observer Network.

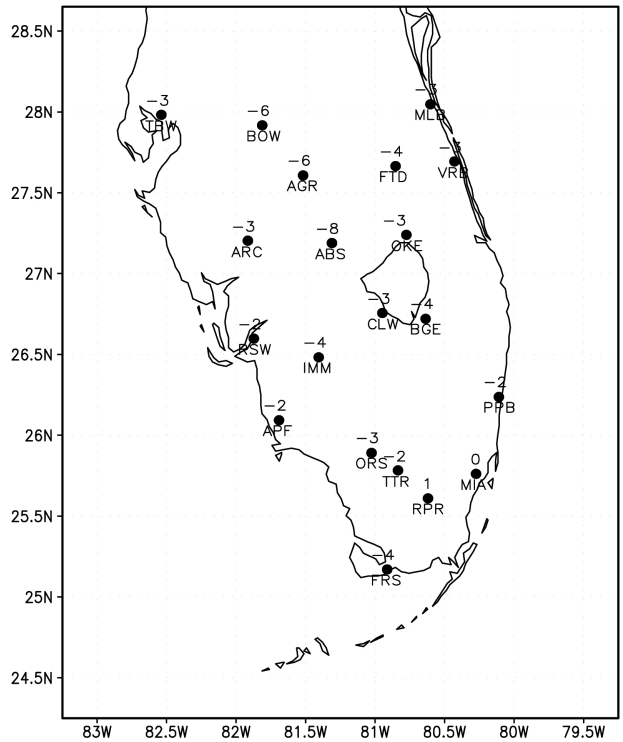

FIG. 6. Same as in Fig. 5, except for 25 Dec 1989.

conversion of wetlands to agricultural production. Therefore, these cases provide an opportunity to address the question of whether there is any possible feedback between the occurrence of recent agriculturally damaging freeze events in south Florida and the conversion of the natural landscape to agriculture itself.

b. Experimental design and model configuration

To address the question of whether anthropogenic landscape change could have impacted the extent and severity of freezing conditions in south Florida during these events, experiments were conducted by undertaking numerical simulations with the Regional Atmospheric Modeling System (RAMS; Pielke et al. 1992). RAMS, a comprehensive meteorological modeling system, includes a sophisticated land surface parameterization, known as the Land Ecosystem–Atmosphere Feedback-2 scheme (LEAF-2; Walko et al. 2000). For each freeze event, a pair of numerical model simulations was undertaken. Within a given pair, the model configuration was identical, except one member employed land surface properties specified to represent pre-1900s (near natural) cover, whereas the other was conducted with properties specified to represent 1993 (near current) land-use patterns. The twentieth century anthropogenic alteration of the spatial distribution of vegetation types and other land surface features, including wetlands, is

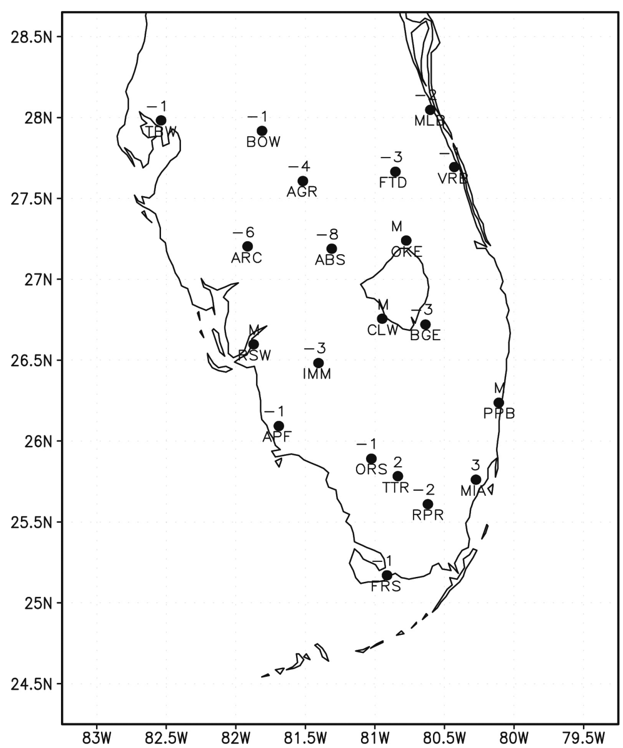

FIG. 7. Same as in Fig. 5, except for 19 Jan 1997.

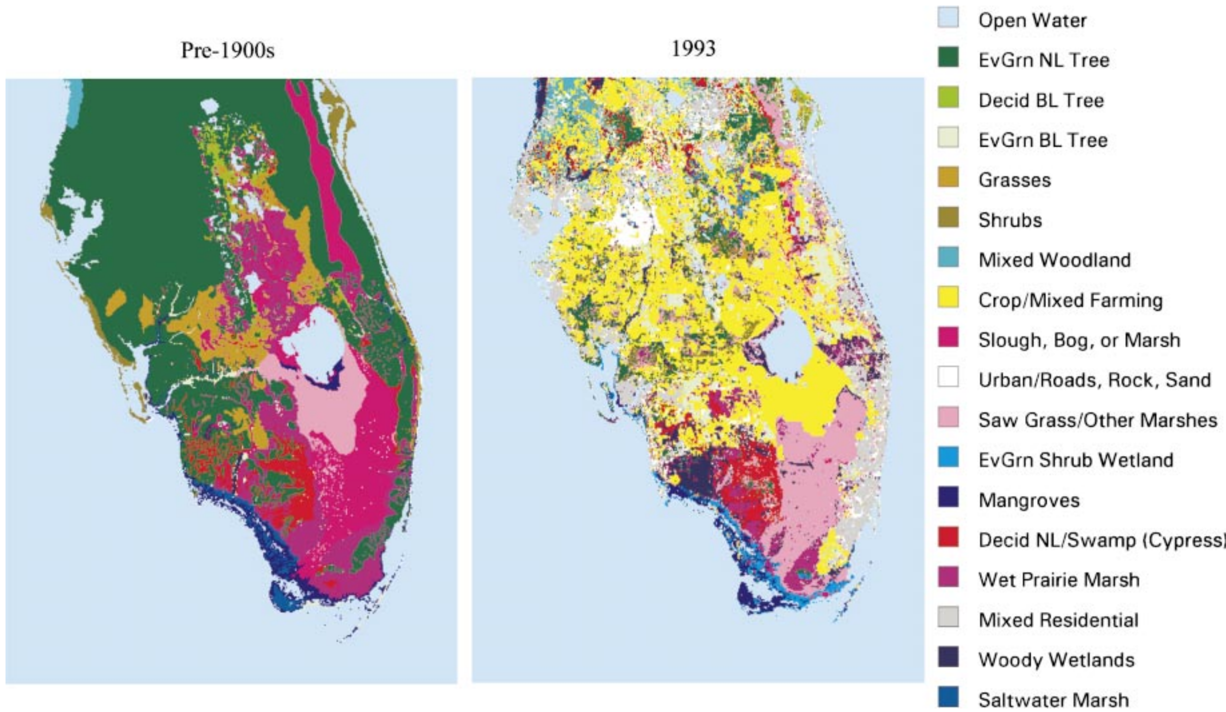

FIG. 8. Predominant land cover classes for (left) the pre-1900s (natural) land cover scenario and (right) the 1993 (near current) land cover scenario.

well captured in these two different datasets (Fig. 8). Thus, comparison of the results of the two different simulations of a given event that utilize these two different land cover scenarios can be used to address the question of whether the conversion of wetlands to agricultural production in south Florida could have an impact on a damaging freeze event under otherwise identical meteorological circumstances. Unfortunately, it is not possible to provide long-term trends of observed minimum temperatures at the locations in question in this study for corroboration of the model ''before and after'' results. This limitation arises because the areas in question, where wetlands have been converted to agriculture, were largely devoid of meteorological observing platforms *before* they were converted to agriculture.

The datasets used to provide these two land cover databases for the RAMS model were originally constructed by the U.S. Geological Survey by combining information from a variety of data sources (Marshall et al. 2004). The pre-1900s land cover scenario was based on maps of natural vegetation, which were adapted according to historical records and U.S. Geological Survey paleovegetation studies of pollen from sedimentary core samples extracted within the Everglades. The current land-use datasets were based on data from Landsat Thematic Mapper scenes taken during the 1992–93 time frame. Use of these two datasets required that the number of existing LEAF-2 classes (and related biophysical parameters) be expanded to include sloughs, sawgrass marshes, wet prairies, saltwater marshes, mangroves, and various mixed woody wetland complexes. With the addition of the classes shown in Fig. 8 to those already existing in LEAF-2, 40 categories were available for use in the simulations presented in this paper.

An important feature of these datasets is the representation of wetlands. For all classes that were identified as a swamp or marsh type, the model surface was inundated with 10 cm of standing water, provided the location was determined to be saturated in accordance with a specified, class-dependent hydroperiod. The hydroperiod is defined as that time of year during which the surface is inundated with standing water. For all wetlands classes, these hydroperiods were determined following Kushlan (1990). It will be shown in later sections that the presence of standing water at wetlands locations had important consequences on the simulation of the freeze events. Given the level of detail provided by these datasets, the experimental design should accurately reflect the contrasting distribution of land cover properties in south Florida between the natural and near-current model scenarios.

RAMS Version 4.3 was employed for all of the numerical simulations presented in this study. Meteorological initial and lateral boundary conditions were provided the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) global reanalysis dataset (Kalnay et al. 1996). All simulations were conducted on a nested grid configuration (Fig. 9), with an outer grid of 42 $\times$ 48 points at 40-km

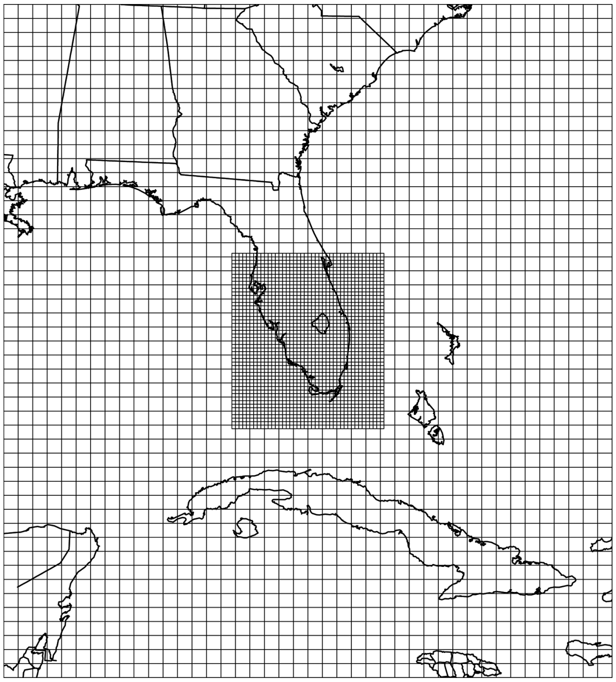

FIG. 9. Grid configuration for the RAMS domain used in this study.

spacing covering the Atlantic and Gulf Coast states and adjacent coastal waters. An inner grid consisting of 42 $\times$ 50 points at 10-km spacing was nested over central and south Florida. Both grids extended over 30 vertical levels, with the lowest level at near 20 m above ground level. The vertical grid spacing was geometrically increased with height, to a maximum of 1 km at the top of the model domain (near 15 km). A 1-min time step was employed on the outer grid, with a 30-s time step on the nested grid. Each simulation was integrated over a 48-h period, ending at 1200 UTC (0800 LST) on the morning of the freeze event. Unresolved, precipitating convection was represented with the Kain–Fritsch (1993) cumulus parameterization scheme. The vertical fluxes of short- and longwave radiation were parameterized following Chen and Cotton (1983). Prognostic turbulent kinetic energy was used to represent subgrid-scale turbulent fluxes following Mellor and Yamada (1974), with the Louis (1979) representation of the surface exchange coefficients.

The subgrid ''tile approach'' (Walko et al. 2000) was used to allot each RAMS model grid cell four separate land cover classes. These four classes were chosen by their frequency of occurrence within a RAMS grid cell, as determined from aggregation of the original pre-1900s and 1993 datasets described above. These classes were used as part of LEAF-2 to determine the surface energy budget. LEAF-2 includes prognostic equations for soil temperature and moisture. The soil model consisted of 11 vertical layers spanning a depth of 2 m. The initial soil temperature was determined by a slight offset to the air temperature at the first model level above ground. At locations of standing water, the initial temperature of that water was set equal to the air temperature and was allowed to evolve in accordance with the modeled surface energy budget. Soil moisture was initialized from the dataset provided by the University of Washington Variable Infiltration Capacity (VIC) model archive [see Maurer et al. (2002) for a description of both the VIC model and the production of this archive dataset]. In order to initialize volumetric water content, the prognostic variable for soil water in LEAF-2, VIC soil moisture data were normalized to the soil hydraulic properties from the 3-km database provided by the Food and Agriculture Organization of the United Nations (FAO 1997). For those locations of wetlands where the surface was inundated with standing water, the underlying soil moisture was set to the saturation value of volumetric water content, at all vertical levels. Sea surface temperature was specified using the one-degree, monthly climatological dataset available from NCEP (Reynolds and Smith 1994).

In the next section, results from each of the pairs of simulations are presented. For all three cases, the simulated minimum temperatures and the time spent below freezing during the event are compared using the simulation that employed natural land cover and the simulation that employed near-current land-use patterns. Because of the surprise nature and the severity of the 1997 events, this case has been chosen for further examination. In particular, detailed examination of the surface energy budget is presented.

3. Results

a. Analysis of minimum temperatures

The model-simulated minimum temperature at 2 m above ground level for the three events is shown in Figs. 10–12, for both land cover scenarios. The bottom panel of the figures shows the difference in the minimum temperature between these scenarios (current scenario minus natural scenario). The results from the simulations with near-current land cover (middle panels of the figures) are reasonably consistent with the observational data shown in Figs. 5–7 in that the model reproduced the observed freeze, and the spatial pattern of the model minimum temperatures is also consistent with the observations. Of course, there is not exact agreement between all gridpoint values and the corresponding observed data. Such disagreement could be due to any number of factors, including the representativeness of the point-specific observations with respect to the corresponding model grid cell, which represents and area of 10 km $\times$ 10 km.

Comparison of Figs. 10–12 with Fig. 8 reveals a strong spatial correlation between those areas that were converted from wetlands to agriculture during the twentieth century, and those areas that experienced colder

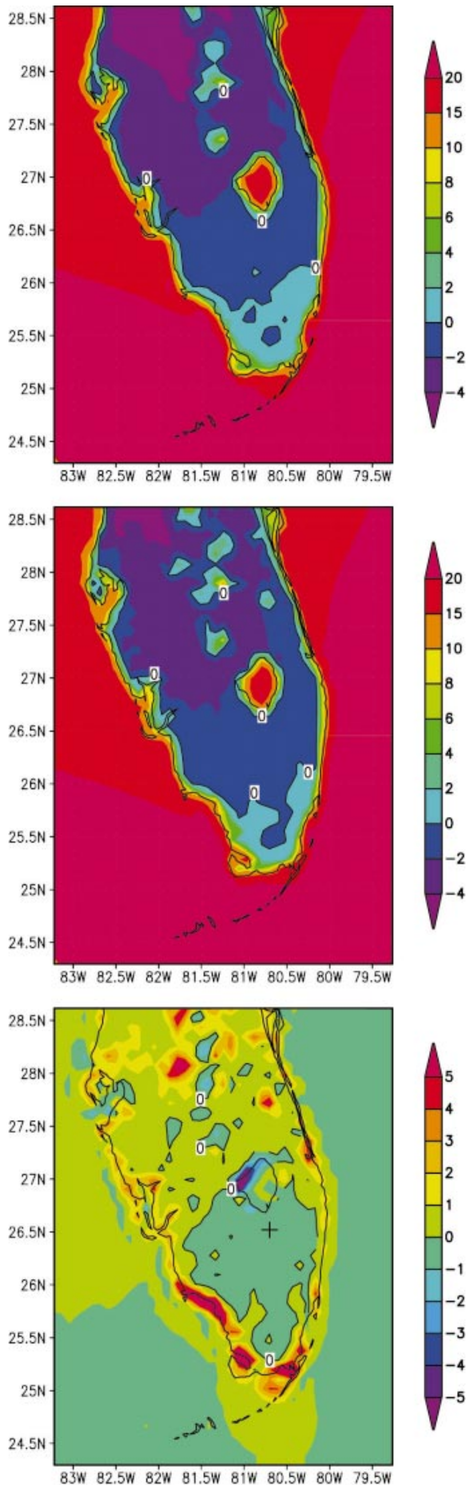

FIG. 10. Minimum temperature (°C) at 2 m above ground level simulated by RAMS for 26 Dec 1983 with (top) the natural land cover, (middle) the near-current land use, (bottom) the difference between the two (difference defined as the near-current minus natural scenario).

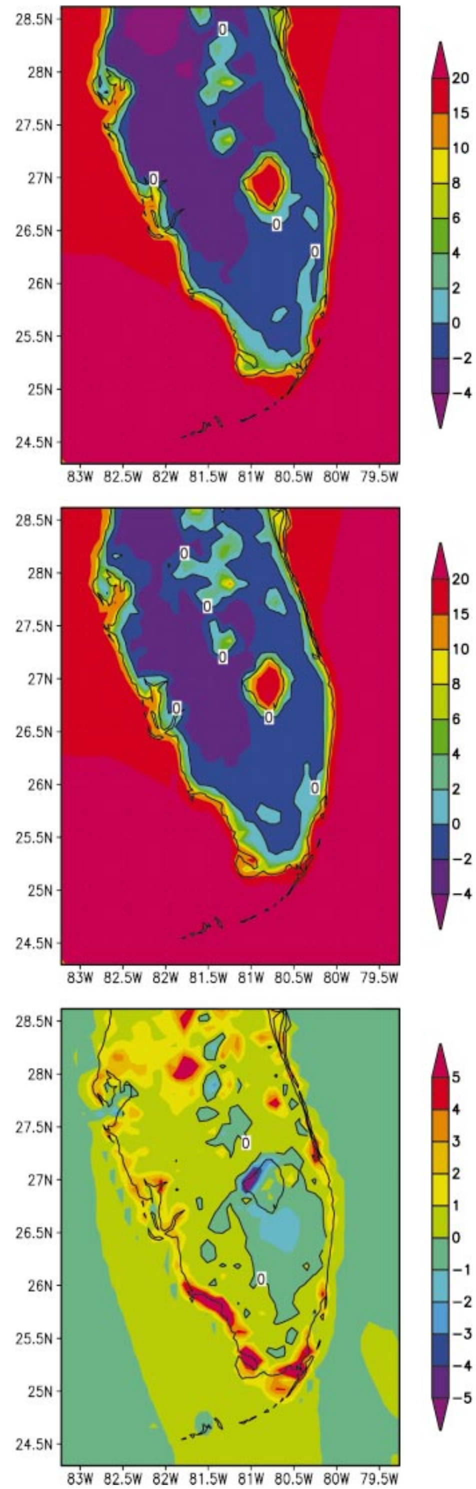

FIG. 11. Same as in Fig. 10, except for 25 Dec 1989.

minimum temperatures in the current land-use model scenario. These areas are located principally to the south and west of Lake Okeechobee and along the formerly inundated floodplain of the Kissimmee River valley (the

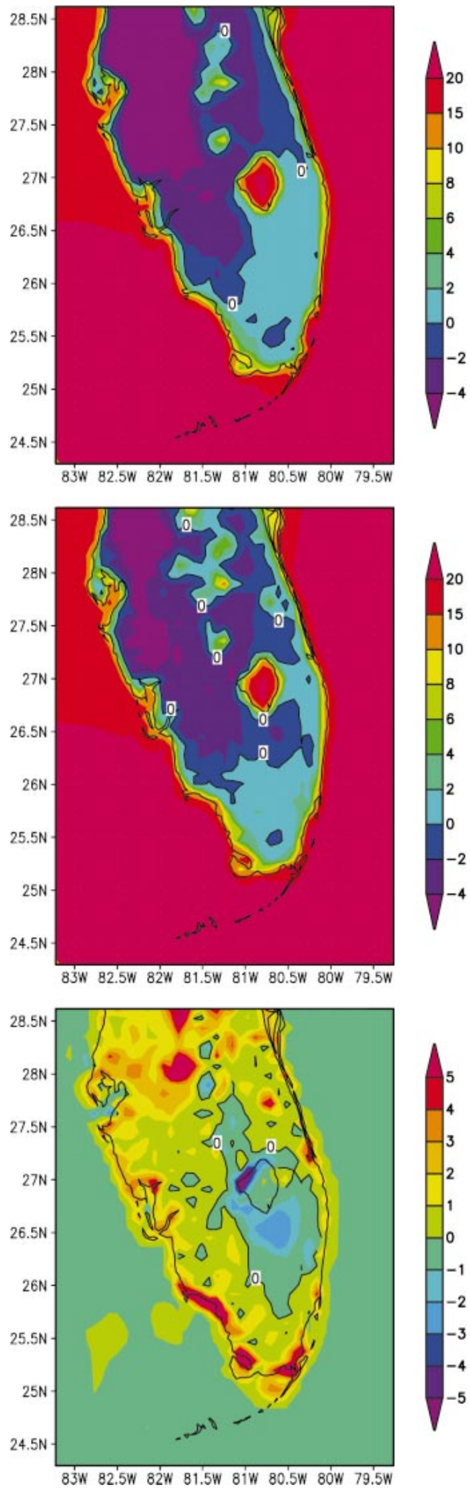

FIG. 12. Same as in Fig. 10, except for 19 Jan 1997.

Kissimmee valley is located within the northwest–southeast-oriented axis of wetlands over the interior peninsula as shown on the left panel of Fig. 8). With the use of near-current land surface classes, minimum temperatures in those areas were colder by more than 2°C at key locations of dense winter vegetables and sugarcane cultivation. While this may not seem like a large difference, it is worth noting that it constitutes the difference between a devastating agricultural freeze and light freeze conditions. In some cases where agriculture has replaced natural wetlands (e.g., just south of Lake Okeechobee in Fig. 12), minimum temperatures remained above freezing altogether when the land cover was specified as natural wetlands.

It is also noted that over other areas of the peninsula, particularly east-central and west-central coastal areas flanking the Kissimmee valley, use of the current land use actually results in slightly *warmer* minimum temperatures. Over interior portions of these areas, natural pine forests were replaced by crops during the twentieth century. Because the pine canopy transpires less than crops, the availability of more low-level moisture may have resulted in slightly warmer minimum temperatures in those areas. As will be discussed in the next section, evaporation from the underlying surface was a key factor in determining the differences in minimum temperatures between land cover scenarios. At some locations in the interior, the replacement of natural land cover resulted in significantly warmer temperatures. Many of these locations are associated with urbanization and the development of other infrastructure that are not isolated. For example, a large area of natural pine forest to the east of Tampa Bay is now an open-pit phosphate mine surrounded by urbanization. Spots in this area of the domain exhibited significant warming in the near-current scenario.

Over immediate coastal locations of west-central and east-central Florida, localized spots in the model domain were significantly warmer with use of the current land cover data. This difference is partly an artifact of changes in the coastlines and the representation of these changes in the two land cover datasets. These changes are due to both natural forces acting on the coastlines (e.g., hurricanes) and anthropogenic factors, including the removal of saltwater marshes. Thus, some areas of open ocean in the current land-use scenario were classified as wetlands (e.g., mangroves and saltwater marsh) in the natural cover database. This disparity in the classification means that at those grid points, the temperature of the underlying water was significantly warmer in the current model scenario, thereby resulting in significantly warmer minimum temperatures. Because the focus of this paper concerns those areas of dense cultivation in the interior peninsula that were once natural wetlands, where most of the agricultural damage associated with these events occurred, these issues are not of significant concern for this analysis.

Depending upon the particular crop, and the stage of growth and development, the amount of time spent below a critical temperature threshold can be just as important as the magnitude of the minimum temperature itself in determining the amount of damage realized by exposure to subfreezing temperatures. This is because the plants, buds, fruits, and vegetables themselves have finite thermal inertias. Some amount of time is required for heat loss and freeze damage to occur. For example, mature, full-size oranges can escape damage even when temperatures fall to $-4°C$ for 1 h (Wolford 1955). These factors warrant a consideration of the impact of the specification of land cover on both the occurrence of freezing temperatures and the duration of time spent below 0°C in the model simulations of these events. In all three cases, the most densely cultivated areas south and southwest of Lake Okeechobee and other key agricultural areas in the Kissimmee River valley that were colder with the use of current land surface properties also experienced subfreezing conditions for a longer period of time (Figs. 13–15).

The combination of difference in time and difference in minimum temperature, however, varied among the simulations. For example, in the 1983 case, the area south of Lake Okeechobee was not significantly colder with current land use. However, the duration of time below 0°C was more than 5 h longer with the use of current land cover. In the 1997 case, areas south of Lake Okeechobee remained above freezing throughout the duration of the night when they were classified as wetlands in the natural land cover scenario. However, those same areas were subjected to subfreezing temperatures for more than 5 h when classified as agricultural land in the current land-use scenario. Because of its severe socioeconomic impact, and because of the readily apparent disparity between the land cover scenarios, the physical mechanisms behind the differences seen in the simulations of the 1997 event have been examined in further detail. Attention is now turned toward investigating the impact of the land cover change on the evolution of the modeled surface energy budget.

b. Analysis of the surface energy budget

As stated above, the impact of land surface properties on the evolution of an event such as the south Florida freezes presented in this paper results from the strong modulation by the land surface of the exchange of energy with the overlying atmosphere. Many of the areas that experienced colder temperatures for a longer duration with current land use in the simulations of these events were natural wetlands before conversion to agricultural land in the twentieth century. In the model configuration, areas that were specified as wetlands were specified to have saturated soil with standing water. The presence of saturated soils and standing water on the land surface should be expected to have a substantial impact on the exchange of energy with the overlying atmosphere. That exchange must obey the surface energy balance relationship:

$$\mathrm{Rn} = H + \mathrm{LE} + G, \tag{1}$$

where the net radiation received at the surface (Rn) is partitioned among the surface sensible heat flux (H), the surface latent heat flux (LE), and the ground heat flux (G).

Model time series from the simulations of the 1997 freeze event for the four quantities in Eq. (1) are shown

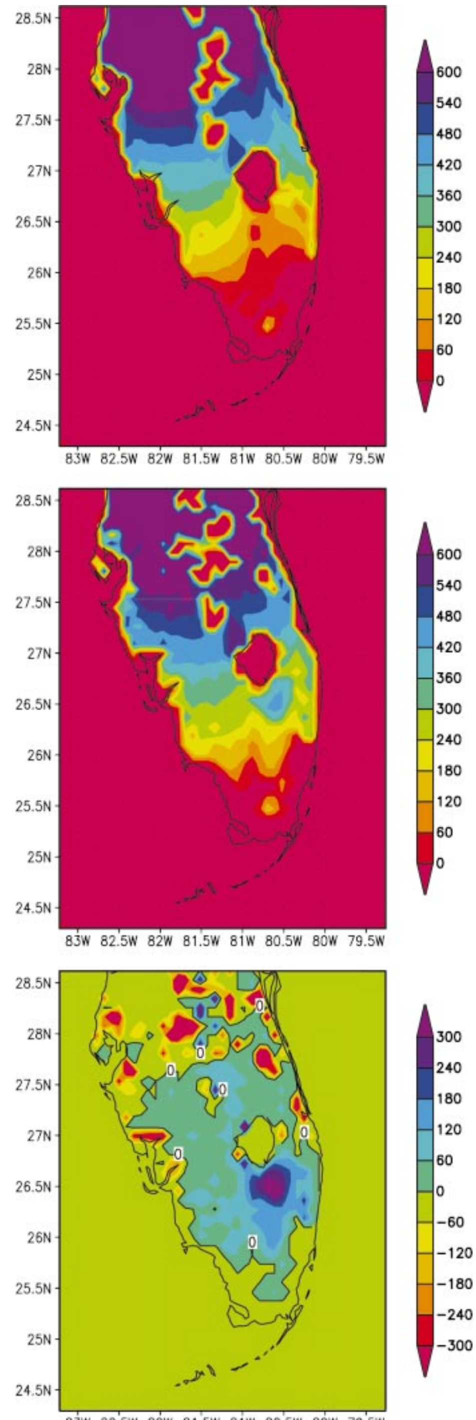

FIG. 13. Time spent below 0°C (min) in the RAMS simulations on the morning of 26 Dec 1983. Panel convention same as in Fig. 10.

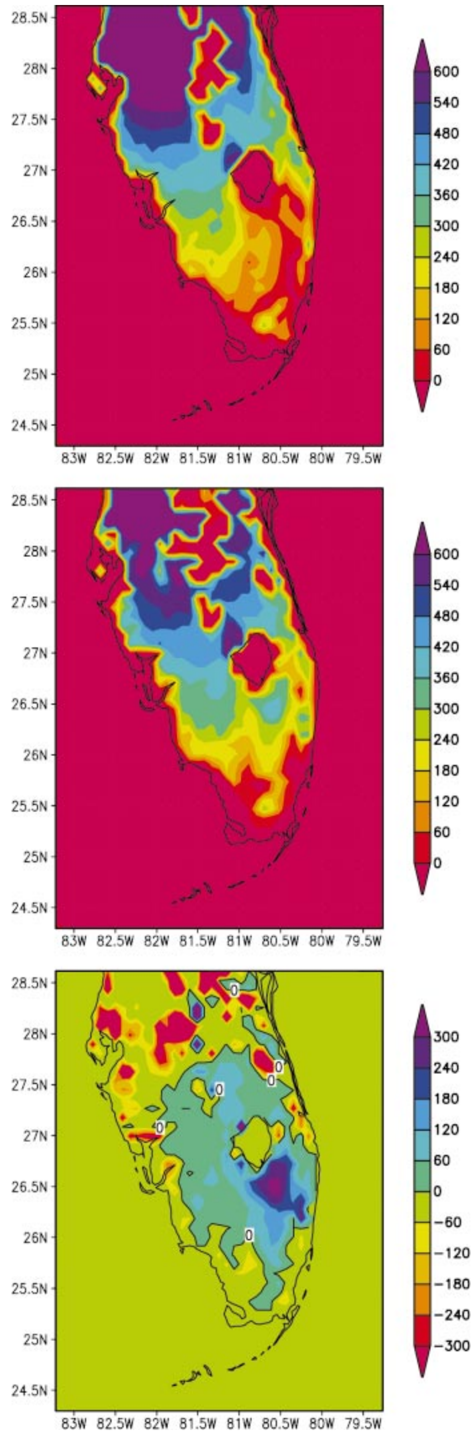

FIG. 14. Same as in Fig. 13, except for 25 Dec 1989.

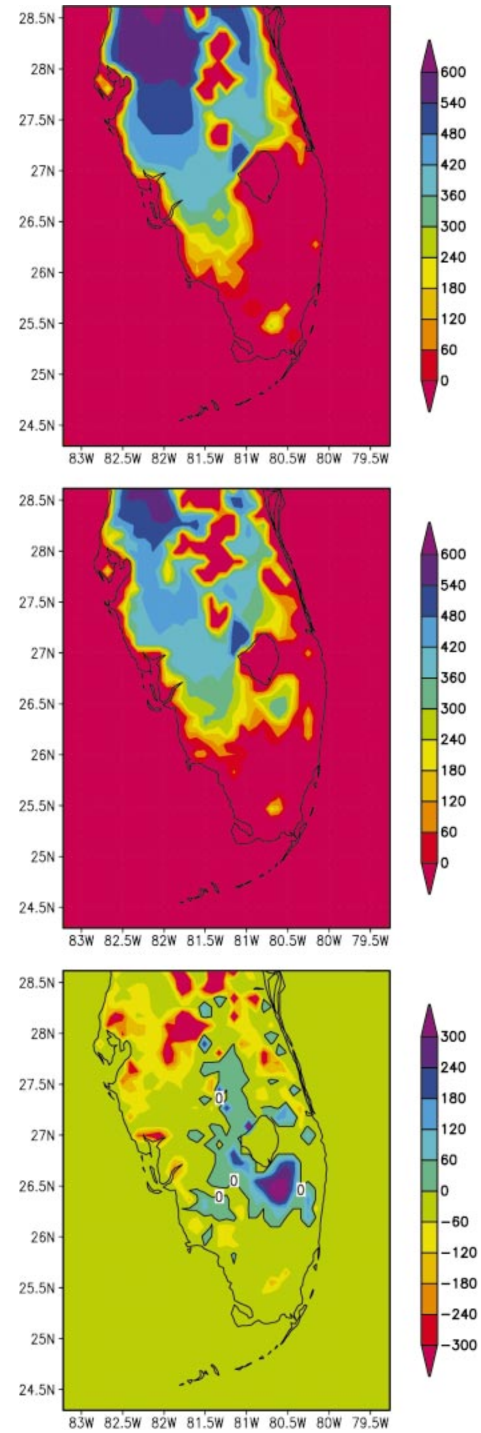

FIG. 15. Same as in Fig. 13, except for 19 Jan 1997.

in Fig. 16, for a grid point located just south of Lake Okeechobee. Before the construction of the Hoover Dike in 1930, which dammed overland flow southward out of Lake Okeechobee and into the Everglades, this was an area of inundated sawgrass and freshwater marsh. Today, it is one of the most densely cultivated locations of winter vegetable and sugarcane production in south Florida. At this location, the model sensible heat flux for the natural cover scenario is much less during the daytime hours than for the current land cover scenario. The model latent heat flux for the natural land cover scenario is much greater than for the current sce-

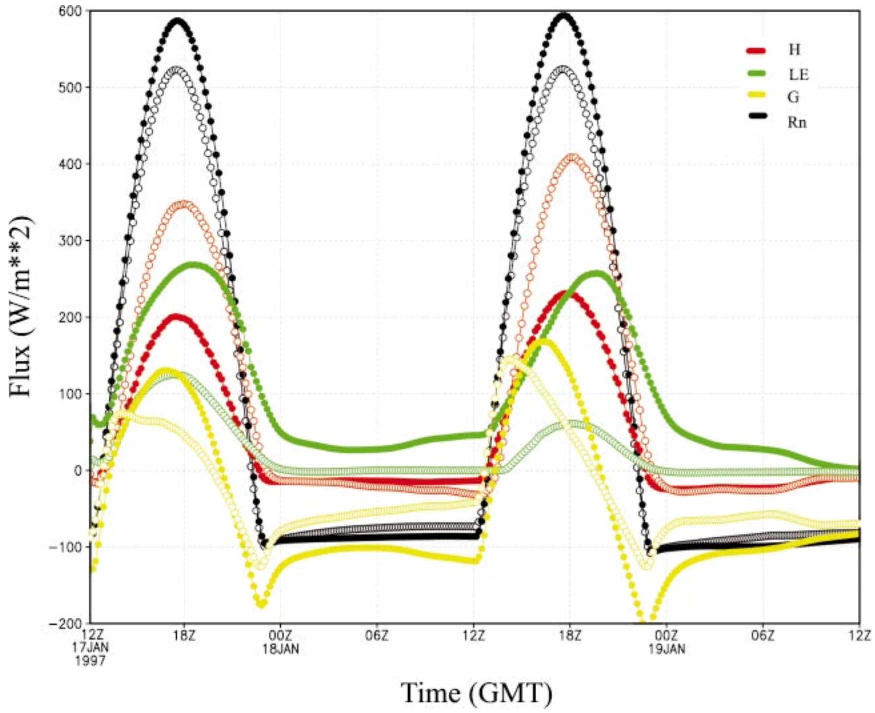

FIG. 16. Time series of the four components of the surface energy budget (W m^{-2}; see color code provided in legend) for both RAMS simulations of the 19 Jan 1997 event, at a model grid point centered just south of Lake Okeechobee (location indicated by the ''+'' on the bottom panel of Fig. 10). Filled (open) circles indicate data for the natural (near current) land cover scenario.

nario. These differences are a direct consequence of the presence of saturated soils and standing water at this location in the natural cover scenario. In the natural cover scenario, more of the available net radiation is expended by the evaporation of water. Because more of the available net radiation is expended as latent heat flux, the sensible heat flux is lower than for the current scenario.

During the nighttime hours, the sensible heat flux is similar between land cover scenarios and is negative, indicating the loss of heat from the lower atmosphere to the land surface as the land surface itself cools via radiative loss, as indicated by the negative net radiation. When the current land cover is used, the nighttime latent heat flux drops to near zero. However, a small but persistent latent heat flux continues during the nighttime hours in the natural cover case because the presence of standing water permits water vapor loss via physical evaporation, even at night when available net radiation is negative and plant transpiration ceases. The water vapor content of the overlying atmosphere exerts a partial control over the surface latent heat flux. Thus, the unusual dryness of the air mass during this particular event may have contributed to the persistence of physical evaporation from wetlands at night.

In the absence of other mechanisms, more evaporation from the surface throughout the simulation should result in greater water vapor content of the air near ground level. The time series of 2-m water vapor mixing ratio (Fig. 17a) at the same location as for the data shown in Fig. 16 indicates that, for both land cover scenarios, the mixing ratio generally decreased throughout the simulation, as the dry air mass associated with the passage of a cold front nearly 2 days prior to the event was being advected into the south Florida region. However, the near-surface air mass at this location, while quite dry in both scenarios, remained persistently moister in the natural land cover scenario because of the greater water vapor flux from the underlying wetlands. By the morning of 19 January, the mixing ratio for the natural land cover case was nearly 1 g kg^{-1} greater than for the current land-use case. This increased water vapor content overhead results in less rapid cooling as longwave radiation is lost to space. Indeed, the time series of 2-m temperature (Fig. 17b) indicates that during the early morning hours of 19 January, the rate of cooling at this grid point was less for the natural cover scenario, and the resulting minimum was more than 2°C warmer than for the current land cover scenario.

The entire time series demonstrates greater amplitude in the diurnal cycle of 2-m temperature with the current land cover scenario. This signature is physically consistent with what should be expected when saturated

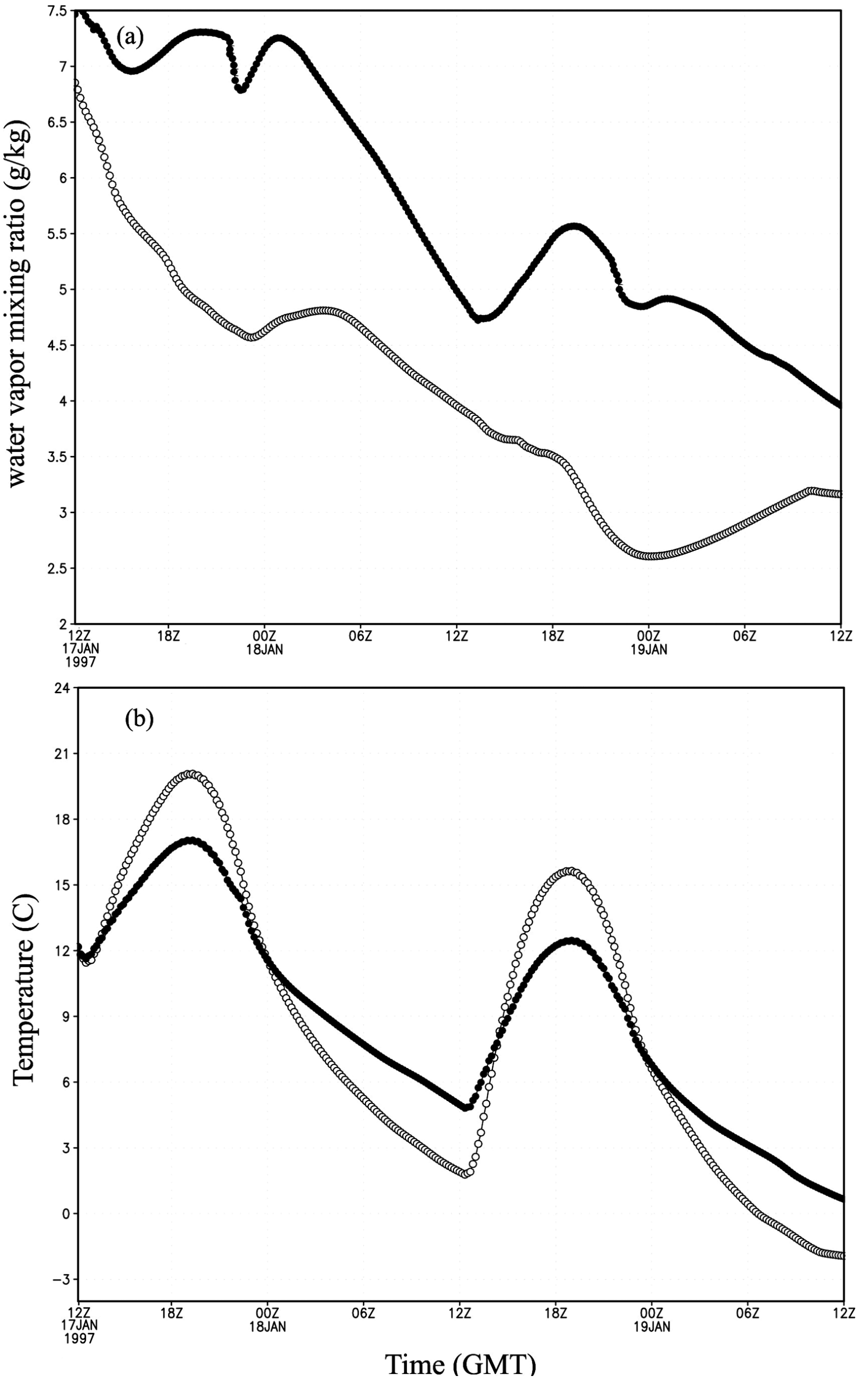

FIG. 17. Time series of the (a) water vapor mixing ratio (g kg^{-1}) and (b) temperature (°C) at 2 m above ground level for the same grid point as for the data shown in Fig. 16. Filled (open) circles indicate data for natural (near current) land cover scenario.

soils with standing water are replaced with drier land. In this particular case, natural wetlands were replaced with agricultural fields, and the effect on the model surface energy budget was sufficient to result in the development of a damaging freeze, which, according to the model results, would not have otherwise occurred at this location.

c. Sensitivity to water depth

As mentioned above, locations of wetlands vegetation classes were inundated with 10 cm of standing water if those locations were within the specified annual hydroperiod. According to Kushlan (1990), most of the wetland areas just south of Lake Okeechobee and in the

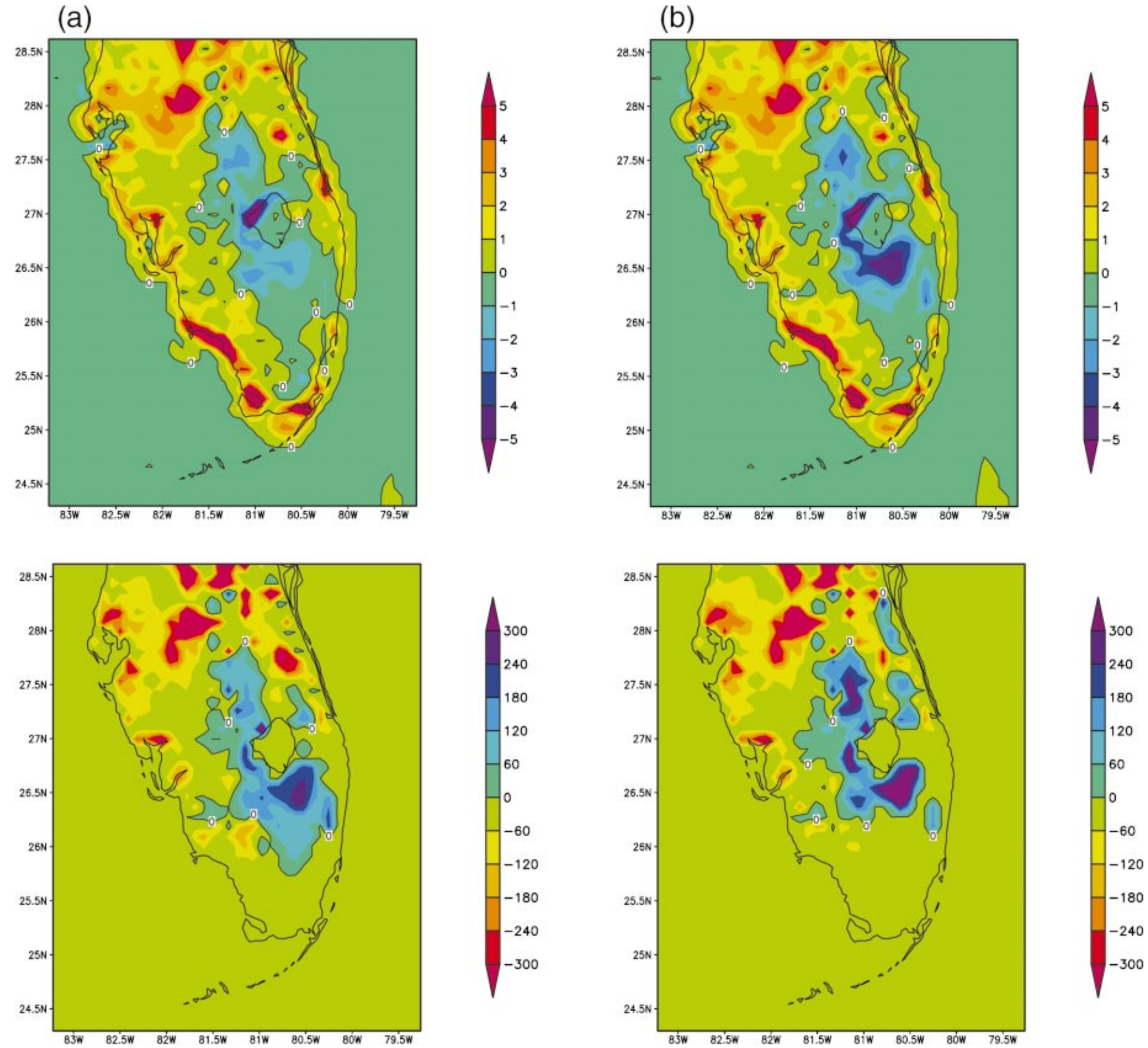

FIG. 18. Difference (near-current minus natural land cover scenarios) in (top) the simulated minimum temperatures (°C) and (bottom) the amount of time spent below freezing (min) when the depth of water at wetlands locations was specified to be (a) 5 and (b) 20 cm.

Kissimmee valley would be inundated through January. Here, 10 cm was chosen to represent an effective depth for the model grid spacing (10 km) used in the simulations. However, it is recognized there is considerable subgrid-scale variability in the actual water depth. The model-specified depth of the water can have a substantial impact on the effective heat capacity of the land surface, and thus the evolution of the simulated surface fluxes and the minimum temperatures. To address this issue, sensitivity tests were performed. Specifically, the simulations of the 19 January 1997 event were repeated, except with half (5 cm) the default depth and then again with double (20 cm) the default depth. Figure 18 provides results of these simulations. The top panels of this figure correspond to the bottom panel of Fig. 12, illustrating the difference (current minus natural land cover scenario) in the simulated minimum temperatures. The bottom panels correspond to the bottom panel of Fig. 15, illustrating the difference in the amount of time spent below freezing between land cover scenarios. Figure 18a illustrates that when the depth is halved, the difference in the simulated minimum temperature and amount of time spent below freezing is consistent with the results from the simulations that use the default depth. Comparison with the bottom panels of Figs. 12 and 15 shows that with the shallower specified depth, the differences between land cover scenarios are less in magnitude. However, at the key locations of winter vegetable and sugarcane cultivation, the minimum temperatures are still colder and below freezing for a longer period than if natural wetlands were specified for those locations. These results are not surprising, because as the depth of the standing water decreases, its impact on modulating the surface fluxes and thus the evolution of the near-surface temperature decreases for the reasons discussed above. Conversely, when the depth was doubled (Fig. 18b) the effect was magnified relative to the default case, meaning that with even deeper water at the locations in question, the minimum temperatures remained even warmer and were below freezing for even less time when wetlands were specified instead of agriculture. The key point of this sensitivity analysis is that over a reasonable range of specified depths, the presence of standing water in the natural land cover scenario serves to limit the severity of the simulated freeze or even prevent its occurrence.

4. Concluding remarks

In this study, RAMS was used to examine the impact of land cover change on the evolution of three recent agriculturally damaging freeze events that occurred in south Florida. In all three cases, modeled minimum temperatures were generally colder and temperatures were below freezing for longer period at locations that had been converted from natural wetlands to agricultural production. Further examination of the 19 January 1997 event reveals that when natural wetlands are present at these locations, evaporation from the surface was maintained during the nighttime hours. In that case, this water vapor flux was sufficient to moisten the surface layer enough to prevent the development of subfreezing temperatures near ground level at key agricultural locations south of Lake Okeechobee. In the other two cases presented, and at other locations in the model domain, freezing temperatures occurred despite the specification of land cover class. However, even in those cases and at those locations, minimum temperatures generally were colder and below 0°C for a longer period when natural wetlands were replaced with agricultural land. A sensitivity analysis revealed that these results remained consistent despite the depth specified for standing water in the wetlands. Therefore, the results suggest that the conversion of wetlands alone may have been a sufficient mechanism to exacerbate the damage inflicted upon agricultural production in south Florida during these recent freeze events.

During the twentieth century, a series of devastating freeze events in northern and central Florida precipitated sharp southward migrations in the key production centers of the state's agricultural industries. These migrations, along with increases in areas of winter vegetable and sugarcane production, have resulted in increased conversion of wetlands to cropland in south Florida. The results presented in this paper suggest the ironic possibility that, *in the attempt to avoid devastating freezes by relocating agricultural production centers to the wetlands of south Florida, the required land cover conversion could itself result in an increase in the frequency and severity of freezes in that region.* This feedback of the land use on the frequency, duration, and intensity of freezes is yet another example of the nonlinear coupling of the land surface and the atmosphere within the climate system (Kabat et al. 2004). Furthermore, these results demonstrate the potential to perturb the climate system in a manner that can have severe socioeconomic consequences by anthropogenic alteration of land surface properties alone.

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