8.1 NUMERICAL FORECASTS OF FREEZING RAIN: PHYSICAL PROCESSES AND MODEL BIASES

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1. INTRODUCTION

In many winter weather situations, small changes in the vertical temperature profile can affect precipitation type, the amount of freezing or frozen precipitation observed at the surface, and other sensible weather conditions. Forecasters must therefore consider all physical processes that may impact the thermal profile. Although the latent heat associated with melting and freezing precipitation is small relative to that due to evaporation and condensation of an equal mass of water substance, it is often concentrated within shallow atmospheric layers, and can therefore produce locally significant alterations to the temperature profile (Kain et al. 2000). During sustained moderate or heavy precipitation when horizontal temperature advection is weak, melting snow can lead to the development of a near-freezing isothermal layer (e.g., Stewart 1985). Although it has received less attention, latent heat release accompanying the freezing of liquid precipitation during sleet and freezing rain can significantly impact the temperature profile in an analogous fashion.

Temperature changes brought about via freezing and melting of precipitation are difficult to forecast because (i) many NWP models are not configured to adequately account for these processes, and (ii) model biases in these situations are linked to quantitative precipitation forecasts (QPF). The challenge to operational forecasters is amplified by the fact that during wintry precipitation, there is a heightened demand for information regarding how much precipitation will fall. This exposes a known NWP weakness: QPF.

Here, we provide a case-study example from 12 February 2001 to examine temperature biases arising from the manner in which the Eta model represents phase changes of precipitation reaching the surface. The objectives of this paper are to (i) alert operational forecasters to potential model biases resulting from the misrepresentation of freezing rain, and (ii) review physical processes that may be important during wintry precipitation.

2. REVIEW OF PHYSICAL PROCESSES

In the situation depicted in Fig. 1a, freezing rain is observed at the surface, resulting in the release of latent heat there, warming both the ground and lower atmosphere. Owing to the fact that freezing rain typically occurs in the presence of stable atmospheric conditions characterized by shallow sub-freezing layers, the warming effects of the latent heat are often confined to these shallow layers, and can quickly warm the layer to 0°C with subsequent precipitation running off. Thus, in the absence of a near-surface cooling mechanism, freezing rain is a self-limiting process; the heat released by freezing can eradicate the sub-freezing layer (Stewart 1985) as depicted in Fig. 1b. Other processes, including upward heat flux from the ground, warm-air advection, downward infrared radiation from a warm cloud base, and sensible heat transport by falling rain can also act to limit the severity of freezing rain events.

When prolonged freezing rain does occur, it is usually accompanied by one or more of the following: (i) the presence of extremely cold and/or dry air (and/or soil) at the onset of precipitation, (ii) lower-tropospheric cold- and/or dry-air advection, (iii) adiabatic cooling with upslope flow, or (iv) light freezing precipitation. In some circumstances, warm-cloud processes can produce light freezing rain or freezing drizzle in a completely sub-freezing environment (e.g., Huffman and Norman 1988).

As surface process representation in operational NWP models has increased in sophistication, some models now include quasi-independent land-surface models (LSMs) to handle communication between the surface and atmosphere. The Eta LSM (Chen et al. 1997) determines a surface energy balance that incorporates incoming solar and terrestrial radiation, reflected radiation, turbulent fluxes of latent and sensible heat, heat fluxes into or out of the ground, fluxes related to snow melt and freezing rain, and precipitation-surface fluxes in the presence of a snowpack. Based on the surface energy balance, a “skin temperature” is computed by the LSM. It is through the skin temperature that surface processes are communicated to the overlying atmosphere, via turbulent fluxes of heat, moisture, and momentum, outgoing longwave radiation, and albedo effects in the case of snow.

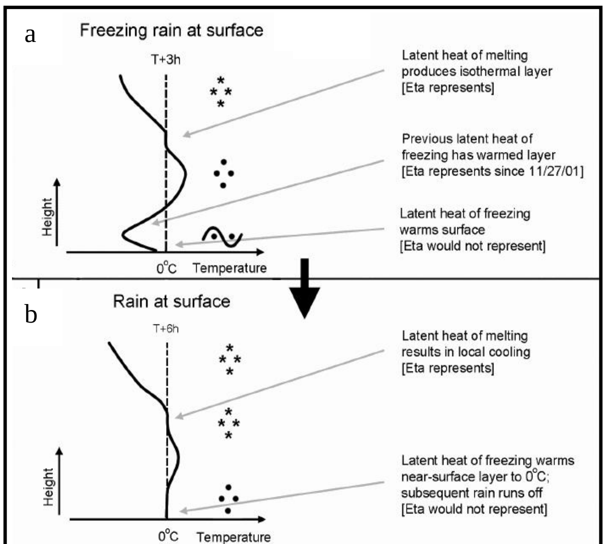

Figure 1. Sequence of idealized vertical temperature profiles accompanying a transition from freezing rain to rain, with account of latent heat absorption (release) via melting (freezing).

Given that precipitation is falling in the model, the Eta LSM determines precipitation type by examining the air temperature at the lowest model level. If the lowest air temperature is above freezing, rain is assumed; if the lowest air temperature is below freezing, snow is assumed. Most freezing rain events are accompanied by sub-freezing near-surface air temperatures; therefore the LSM generally does not represent freezing rain correctly (snow is assumed).

In the case depicted in Fig. 1a, the LSM would erroneously determine that snow was falling, owing to the fact the lower-tropospheric air temperature is below freezing. *The resulting neglect of latent heat release would contribute to a near-surface cold bias during freezing rain.* The consequences of LSM misrepresentation of freezing rain are not limited to the thermodynamic impact of latent heat release. For example, if the LSM assumes that snow has accumulated at the surface, the communication of soil heat fluxes to the atmosphere, and surface radiative properties (e.g., the local albedo) may be affected.

3. CASE STUDY: 12 FEBRUARY 2001

A classical Appalachian cold-air damming pattern had become established by 12 UTC 12 February, with a narrow ridge of high pressure extending from Virginia into northern Georgia (Fig. 2a). At this time, precipitation was overspreading cold air near the surface, while temperatures had fallen only slightly below freezing. Analyzed 2-m temperatures for 00 UTC 13 February indicated that a small area in north-central North Carolina and central Virginia remained below freezing (Fig. 2b). Although central North Carolina received between 6 and 12 mm (0.25 and 0.5 in) of liquid precipitation equivalent, only trace amounts of frozen precipitation were reported.

Figure 3 presents the 36-h Eta model 2-m temperature and precipitation forecasts corresponding to Fig. 2b. The 36-hour forecast maintained a band of sub-freezing air across the central Carolinas, with precipitation totals in excess of 25.4 mm (1 in) over central North Carolina and upstate South Carolina (Fig. 3). Comparison of Fig. 2b with Fig. 3 reveals a 3°C cold bias over north-central North Carolina. The bias was most pronounced in the 30-h forecast, approaching 5°C at that time (not shown).

The combination of heavy precipitation, warm air aloft, and near-surface sub-freezing temperatures in the Eta model forecast supported predictions of a major icing event. Indeed, forecasters issued winter storm warnings, and in fact freezing rain was observed, although amounts did not approach warning criteria (1/4").

Given that the lowest model air temperature was below freezing across the central Carolinas, the

Eta LSM would have erroneously determined that any model precipitation reaching the surface would be in the form of snow. Therefore, the Eta model was able to maintain a sub-freezing layer near the surface in spite of heavy precipitation in part because it did not account for the release of latent heat accompanying freezing rain. Secondly, the LSM configuration would be consistent with a significant amount of snow accumulating at the surface. This could contribute to a cold bias in several ways, including alteration of surface radiative properties, melting effects, and perhaps more importantly, by insulating the lower atmosphere from an upward heat flux from the ground.

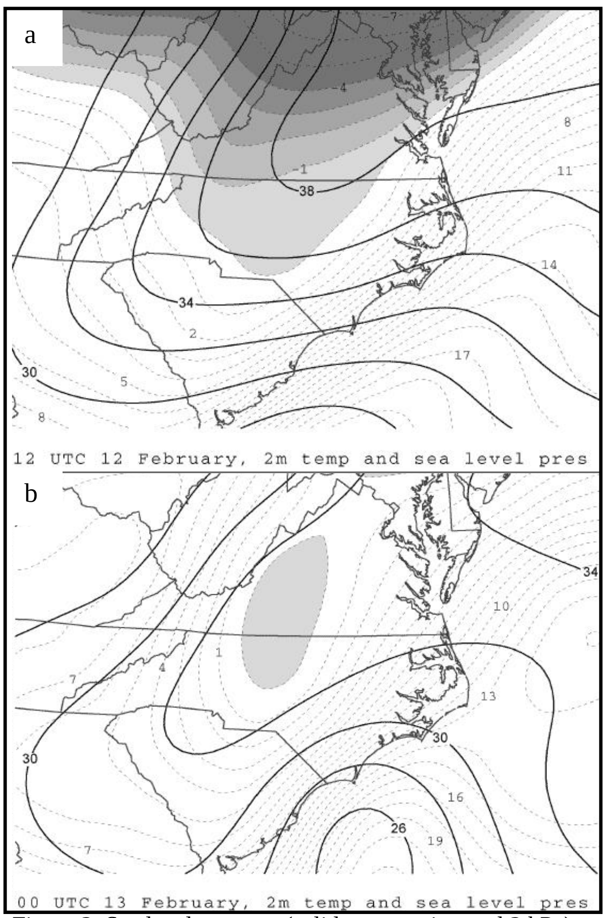

Figure 2. Sea level pressure (solid, contour interval 2 hPa) and 2-m temperature (dashed and shaded, contour interval 1°C). Shaded regions correspond to temperatures below 0°C. (a) Eta analysis valid 12 UTC 12 February 2001; (b) Eta analysis valid 00 UTC 13 February.

If the Eta LSM had correctly identified falling precipitation as freezing rain across the central Carolinas in this event, would the resulting latent heat release have been sufficient to warm the sub-freezing layer in the model to the freezing point? To address this question, we applied a "correction" to the model forecast temperature profile using the following form of the first law of thermodynamics:

$$\Delta T \cong \frac{F_A\, L_f\, \rho_\ell\, R_m}{M\left(C_p + L_v \dfrac{\partial q_s}{\partial T}\right)} \qquad (1)$$

In (1), M is the mass of air (per unit area) over which the latent heat release is distributed, ΔT is the temperature change due to latent heat release, L_f is the latent heat of fusion at 0°C, ρ_ℓ is the density of liquid water, and R_m is the depth of liquid-equivalent precipitation in meters. The factor F_A accounts for the partition of heat between soil and air.

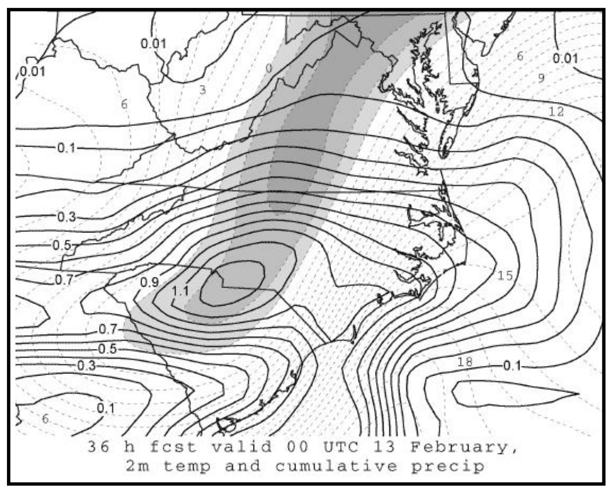

Figure 3. Eta forecast sequence of 2-m temperature (contour interval 1°C, dashed lines, shaded below 0°C) and cumulative precipitation (solid, values in hundredths of inches, interval 0.01, 0.05; and every 0.1 inch thereafter) for 00 UTC 13 February.

Based on the temperature of the uppermost soil layer, we estimate that only the top few centimeters of soil were below freezing in this case. A quantitative estimate of F_A can be obtained by determining the proportional heating if sufficient heat were released to warm the entire sub-freezing mass of soil and air to the freezing mark. Based on this analysis, it appears that on the order of 10% of the heat would be expended on the soil.

Figure 4 displays the modified 36-h 2-m temperature forecast corresponding to that shown in Fig. 3. The 0°C isotherm had retreated to the Virginia-North Carolina border. The latent heat released by the freezing of model-predicted precipitation was sufficient to warm the lowest 100 hPa of the model atmosphere to 0°C across upstate South Carolina and central North Carolina, even without accounting for the development of spurious snow cover in the model forecast cycle.

4. CONCLUSIONS

During freezing rain, Eta model forecasts rely upon the LSM. The current version of the Eta LSM determines precipitation type by examining the air temperature in the lowest model level. This assumption generally fails in the event of freezing rain because it is generally accompanied by sub-freezing near-surface air temperatures. The result is a lower-tropospheric cold bias.

On 12 February 2001, a cold bias approaching 3°C was observed in Eta-model 2-m temperature forecasts. Analysis confirms that the heat released by freezing was capable of explaining a large portion of the bias. The lack of observed freezing rain was likely due to a combination of factors, including an upward heat flux from the ground. The Eta LSM assumptions are consistent with the spurious generation of snow cover in the model, which likely exacerbated the cold bias by artificially insulating the lower atmosphere from a strong upward heat flux from the soil. This case highlights the impact of soil temperature on potential ice accumulation.

The following is a summary of our analysis:

- Freezing rain is a self-limiting process owing to the warming associated with the latent heat released by freezing raindrops. This warming process is not correctly represented in most current configurations of operational models.
- Be wary of model forecasts that indicate sub-freezing surface temperatures in association with heavy freezing precipitation, especially if there are no obvious surface cooling mechanisms.
- Processes such as thermal advection, adiabatic cooling, cooling due to evaporation or sublimation, soil heat fluxes, and radiation must be accurately assessed in order to ascertain the relative importance of freezing or melting.

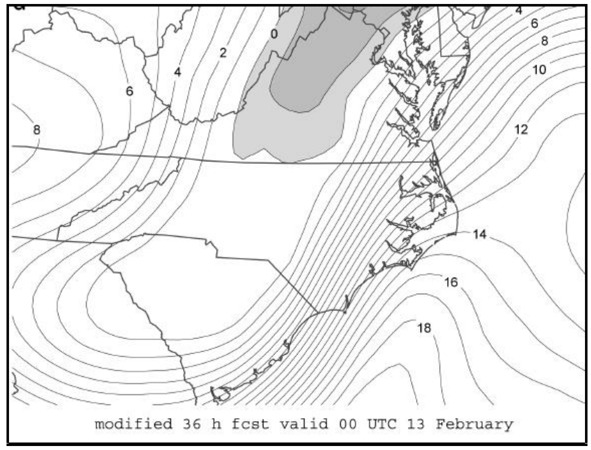

Figure 4. Modified Eta 2-m temperature forecast with a correction for latent heat released by freezing rain from (1) for 36-h forecast valid 00 UTC 13 February.

It is likely that the Eta-model biases documented here will be corrected. Operational forecasters are urged to remain aware of model updates. For information regarding model changes, see http://www.emc.ncep.noaa.gov/mmb/research/eta.log.html; for information regarding upcoming changes, see http://www.nco.ncep.noaa.gov/pmb/.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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