Reply

STEVEN BUSINGER

Department of Marine, Earth and Atmospheric Sciences, North Carolina State University, Raleigh, North Carolina

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The profusion of disturbances that have been observed to form in cold air masses has resulted in an extensive and at times confusing nomenclature (e.g., Businger and Reed 1989). Complicating this issue is the fact that several physical mechanisms have been advanced as likely energy sources in the cyclogenesis, including baroclinic instability, CISK, and air–sea interaction instability. Observational evidence and numerical simulations have shown that these mechanisms can act in concert to intensify a disturbance, with the importance of a particular source of energy depending significantly on environmental and topographical factors and the evolutionary stage of the disturbance.

In the case of the Bering Sea storm (Businger and Baik 1991), initial development occurred when a pronounced potential-vorticity anomaly aloft passed over an area of enhanced low-level baroclinicity in the western Bering Sea; the source of the low-level baroclinicity being differential surface heat fluxes. As the storm matured, a symmetric pattern of convection surrounding a clear eye emerged, and was maintained as the storm tracked eastward across the Bering Sea, with dissipation occurring rapidly upon landfall. It is argued in Businger and Baik that the incipient stage of this storm was dominated by asymmetric baroclinic processes, followed by an air–sea interaction and/or CISK mechanism maintaining the latter mature stage. This complex evolution is analogous to the development documented by Bosart and Bartlo (1991), in which a baroclinic midlatitude cyclone underwent a transformation into a tropical hurricane.

In applying the term "arctic hurricane" to the Bering Sea storm, the authors are referring specifically to its mature stage, drawing attention to the disequilibrium between the atmosphere and the underlying ocean surface as a source of energy for maintaining the storm circulation, much as it is in tropical cyclones (Emanuel 1986). It is not our intention to imply that arctic hurricanes are identical in structure and energy source to tropical hurricanes. Observational and theoretical studies show that in cold air masses the sensible heat flux is of comparable magnitude to the latent heat flux, unlike tropical hurricanes where the sensible heat flux is limited by the small air–sea surface temperature difference. This enhanced sensible heat flux in cold-air cyclones produces large amounts of buoyant air and convective instability by warming the surface air. Therefore, arguments about a lack of buoyancy to drive the CISK process in the tropical atmosphere may not apply to the cold-air systems. Despite these observations, the potential for a storm system to intensify over northern waters due to the nonlinear effect of sea surface heat fluxes is not as great as it is in the tropics, where significantly greater latent heat is available; hence, a lower threshold wind speed is applied. The point of the threshold is to differentiate potentially hazardous storms from weak low-level circulations that have symmetric cloud signatures, as, for example, are sometimes seen in stratus clouds in the wake of islands.

It is important to emphasize that it is not our intention that the terms "arctic hurricane" and "wind threshold" be applied to all cases of cold-air cyclogenesis. For example, the environmental conditions and early cyclogenesis associated with the case described in Shapiro et al. (1987) and the case of ERICA IOP 8 (Businger et al. 1991) are comparable to those observed in our case. In both of these cases early cyclogenesis was associated with the presence of a pronounced potential vorticity anomaly aloft and enhanced low-level baroclinicity. Additionally, there is no question that sea surface fluxes played an important role in the development of these systems. However, the presence of a stronger and deeper tropospheric baroclinicity, and greater thermal wind shear, prevented these storms from achieving the symmetric steady-state conditions that characterized the final mature phase of the Bering Sea storm.

Reed has pointed out that storms similar to the Bering Sea case have been observed over the Mediterranean Sea in conjunction with large, cold polar vortices aloft. Climatology suggests, however, that the high latitudes in winter are the favored habitat of these relatively rare developments. Both midlatitude and tropical

Corresponding author address: Dr. Steven Businger, Dept. of Marine, Earth and Atmospheric Sciences, North Carolina State University, Box 8208, Raleigh, NC 27695-8208.

cyclones are observed outside the bounds their appellation would dictate.

One may argue that the application of the term "arctic hurricane" may be premature based on the evidence available at this time with regard to the primary energy source responsible for the maintenance of the mature stage of such storms. Our ability to examine the contribution of physical mechanisms during the evolution of an arctic hurricane is limited both by the absence of detailed observations and the very fine grid resolution required to adequately simulate these small-scale storms. Much of what is known about tropical hurricanes has come from vital information gathered by instrumented aircraft that deliberately fly through them. There are no plans to establish a similar research program for arctic storms. Clearly, there is a need for additional in situ observations during various stages of a polar low's life cycle to fully resolve the issues raised in Reed's comment and this response. We hope that this discourse will help foster continued curiosity in an interesting problem.

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