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THE DEVELOPMENT OF A DYNAMICALLY-BASED FIRE WEATHER FORECAST INDEX

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1. INTRODUCTION

If improvements are to be made to fire weather forecasts it will likely require the development of both improved numerical models as well as predictive indices, which more accurately represent key processes that organize a favorable environment for fire spread. It is widely understood that key ingredients for erratic fire spread weather conditions are very low relative humidity, warm air and gusty winds that reach the surface. In order to achieve these surface conditions, one would anticipate that a unique sequence of synoptic weather conditions would likely be required that could evolve over a certain period of time. The arrival of key ingredients could be fast and fleeting. If a predictive index could be developed, which indicated that favorable fire weather conditions were being established in advance due to the unique upstream atmospheric dynamical processes, such an index might serve as a reliable advanced warning signal for the rapid and fine scale evolution of high fire weather potential assuming that the numerical model employed to simulate these conditions accurately replicated nature. This paper describes an attempt to develop such an index based on the horizontal and vertical mass/momentum adjustment processes crucial to transporting dry, high momentum and high potential temperature air to the surface. This new index, i.e., the NCSU3 index, is based on these dynamical principles in contradistinction to other widely-used indices, such as the Haines index, e.g., Haines (1988), which relies solely on static stability considerations, i.e., the temperature and dew point distribution in the vertical over differing atmospheric layers.

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2. SYNOPTIC/DYNAMIC FOUNDATION OF THE NCSU3 INDEX

The index we have developed is designed to maximize when and where an observed series of synoptic and mesoscale processes occur that is hypothesized to precede the development of ideal fire weather. The assumption being that deep atmospheric adjustment processes must phase to produce very short period and optimal fire weather conditions over isolated regions. Knowing these conditions will produce the most reliable index for predicting isolated regions where highly conducive fire spread weather is most likely to occur. There are three key synoptic elements/circulations whose dynamical interaction leads to conditions that are represented in the index. These three elements are: 1) a synoptic scale balanced and thermally indirect ageostrophic jet streak circulation downstream from an amplifying ridge of high pressure in which the right exit region velocity convergence produces deep upper-level sinking motions, 2) a subsynoptic scale unbalanced circulation in the midtroposphere ahead of a transient elevated mixed layer and 3) a well-mixed convective planetary boundary layer (PBL). The latter of the 3 being ubiquitous while the phasing of all 3 being relatively rare and hence, isolated in the atmosphere. Figs. 1-3 depict schematics describing these key components. When all 3 components phase, three elements come together in downstream locations, i.e., the horizontal convergence, vertical convergence and planetary boundary layer turbulent mixing of potentially warm, dry air. These processes ultimately couple warm dry air from the upper troposphere to the convective planetary boundary layer creating favorable fire spread weather conditions.

Fig. 1 depicts the first 3 stages of the paradigm in which a massive ridge develops upstream from the fire location. Air parcels, at the apex of the ridge, are accelerated by the pressure gradient force to the left of the stream and develop inertia. These air parcels ultimately turn downstream from the ridge to the right of the stream as they decelerate and descend in the jet exit region. The descending air is the result of velocity convergence aloft in the right exit region accompanying the transverse, and to some extent streamwise, ageostrophic thermally indirect circulation. Stages 4 - 7 are depicted schematically in Figs. 2-3. Here the descending air parcels in the right exit region of the upper tropospheric jet encounter a second baroclinic zone in the mid-lower troposphere resulting from the downstream transport of an elevated mixed layer. The exit region of the upper-level jet becomes superimposed on a second shallower baroclinic zone. Air parcels in the exit region encounter the thickness increase accompanying this second elevated mixed layer/baroclinic zone and begin to turn to the left of the stream as they are accelerated by the mid-level leftward-directed pressure gradient force, which is increasing ahead of this warm pool. This leftward-directed acceleration represents an unbalanced adjustment for the typically decelerating flow in the right exit region and forces air parcels to increase their velocity and confluent flow structure as they enter the downstream trough. The confluent mid-level flow phases with the upper-level descending flow just upstream or above the surface cold front in the trough. If these two circulations, one aloft and one at mid-levels, both of which are thermally indirect, phase with a region of surface sensible heating and a deepening convective PBL, the three processes all act to transport air parcels surfacewards thus maximizing the surface potential temperature and winds while minimizing the surface moisture producing a favorable environment for fire weather *near a dry surface cold front*.

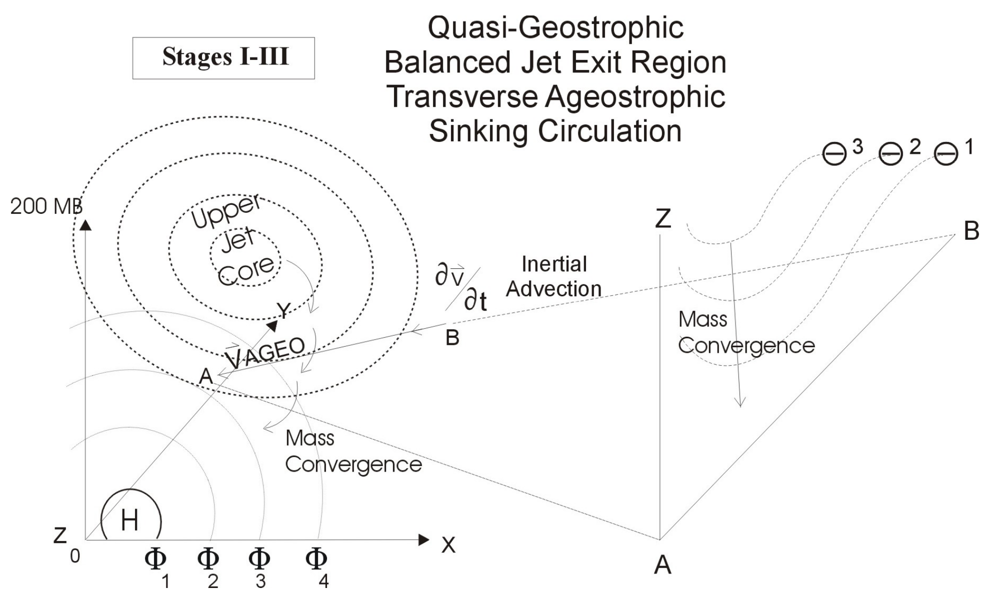

Fig. 1. Stages I-III of the fire weather paradigm.

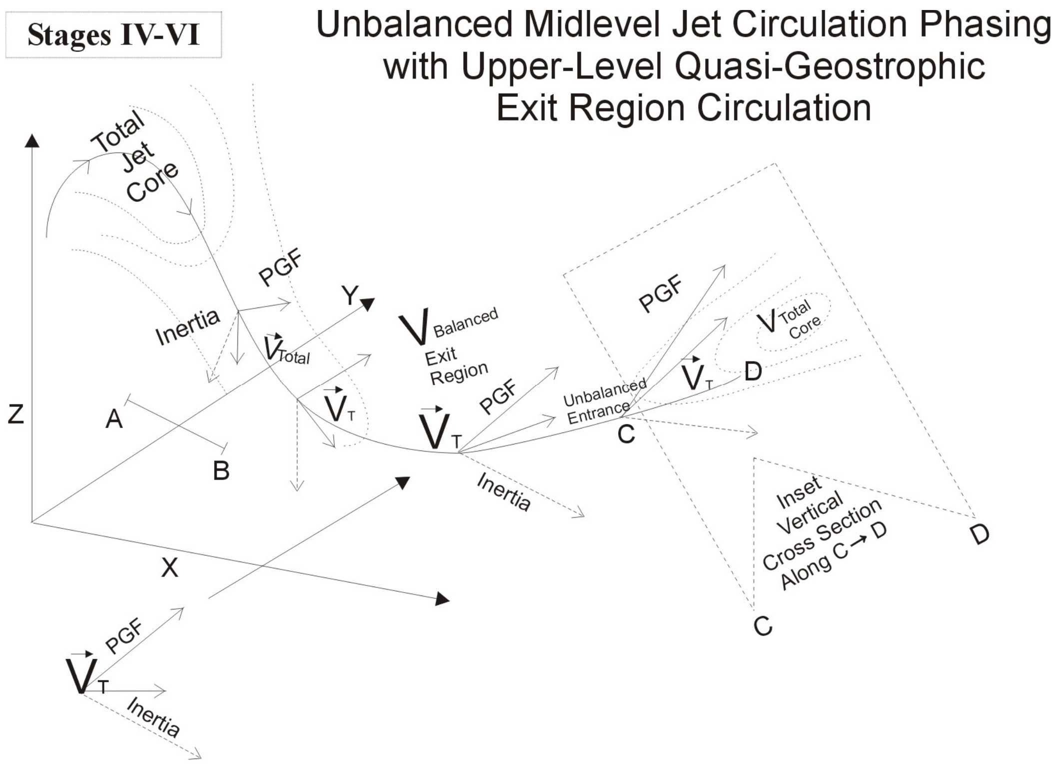

Fig. 2. Stages IV-VI of the fire weather paradigm.

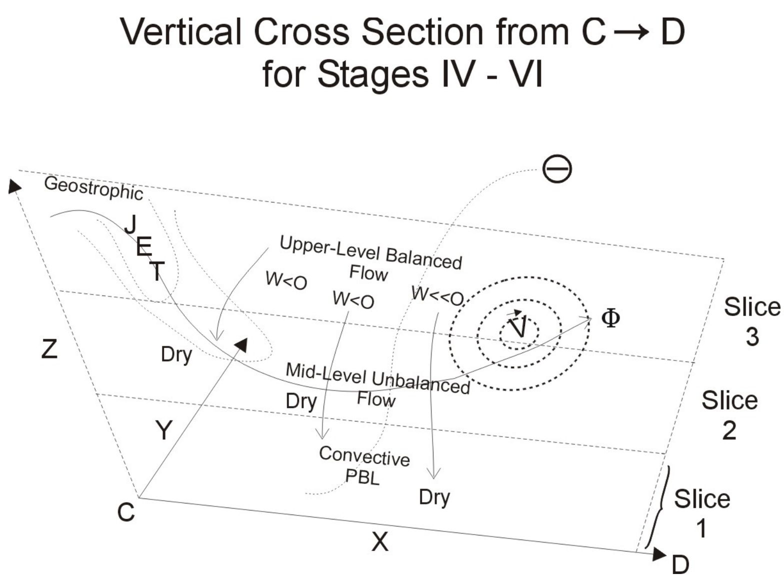

Fig. 3. Vertical cross section for C-D in Fig. 2.

- NCSU3 INDEX

- HORIZONTAL AND VERTICAL DRY AIR CONVERGENCE INDEX

$$NCSU3 = \underbrace{\int_0^{H_T} -\nabla \cdot \left(\frac{\rho}{RH}\vec{V}\right) dh}_{\text{NCSU2}} - \frac{H_{PBL}}{Ri} * \frac{\partial}{\partial z}\left(\frac{\rho}{RH} w\right)$$

where H_T is the height of tropopause;
H_{PBL} is the boundary layer height;
Term 1 is the integrated inverse moisture flux divergence;
Term 2 is the vertical inverse moisture flux divergence.

Fig. 4. NCSU3 index formulation.

We have developed an index that represents the dynamics embodied in these aforementioned 3 processes, i.e., the NCSU3 index. The first term, i.e., formerly the NCSU2 index represents the integrated horizontal velocity convergence as well as the integrated horizontal convergence of dry air on the anticyclonic side of a deep jet streak. The second term accounts for the mid-level sinking in the unbalanced thermally indirect circulation ahead of an elevated mixed layer. As sinking motions increase vertically and dry air descends the second term becomes large thus representing the vertical convergence of dry air. In essence determining where the second or mid-level thermally indirect circulation is best developed. Term 2 maximizes when the convective planetary boundary layer deepens and thus the height of the PBL is substantial and the Richardson (RI) number very small in proximity to the vertical convergence of dry air. Therefore turbulent mixing increases the exchange between the descending air parcels and the growing convective PBL.

The NCSU3 index needs to be compared to the Haines index (Haines 1988) in Fig. 5.

The differences between the two indices being that the LASI tends to be large wherever dry less stable air exists above the mixed layer and NCSU3 tends to be large where the convective boundary layer develops *in proximity to the 3-dimensional convergence of warm dry air.*

3. A CASE STUDY EXAMPLE

We will briefly now describe an example of the application of the index. This case study represents a highly isolated, intense and short lived fire that developed in Double Trouble State Park along the central New Jersey coast on the afternoon of 2 June 2002. The total extent of the fire was focused on a small portion of the state park for only a couple of hours. Surface observations at Philadelphia, PA (KPHL), Trenton, NJ (KTTN) and Atlantic City, NJ (KACY) (Figs. 6-8) all indicate a midmorning to early afternoon period of very strong surface heating and air mass drying before the fire, which occurred just after 1700 UTC.

The extraordinary surface drying at KACY, KTTN and KPHL occurs in association with a surface cold front just downstream from the exit region of an anticyclonically curved jet streak. GPS integrated precipitable water at Sandy Hook, NJ in Fig. 9 shows a very dramatic column drying at nearly the same time as the warming and drying at the surface stations.

Haines index (Low Atmosphere Severity Index, LASI): Dry, unstable air increase the probability for large, erratic wild land fires

$$LASI = a\,(T_{p1} - T_{p2}) + b\,(T_p - T_{dp})$$

(stability) (dryness)

T is the temperature at two pressure levels (p1, p2); T_p and T_{dp} are the temperature and dew point temperature at one of the levels.

Fig. 5. Haines index formulation.

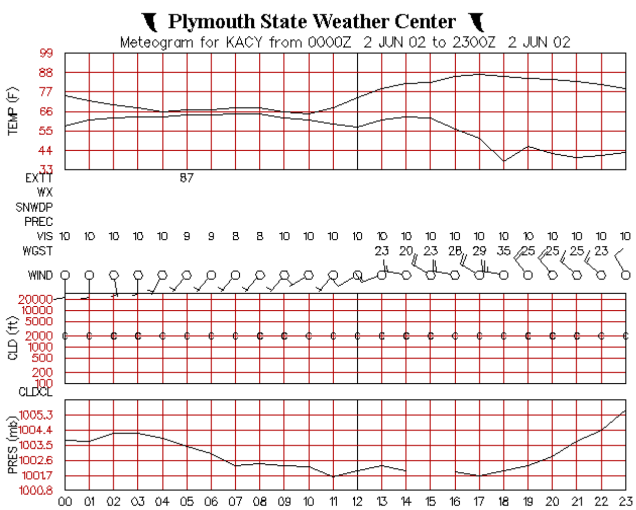

Fig. 6. Meteogram for KACY valid from 0000 Z – 2300 Z 2 June 2002.

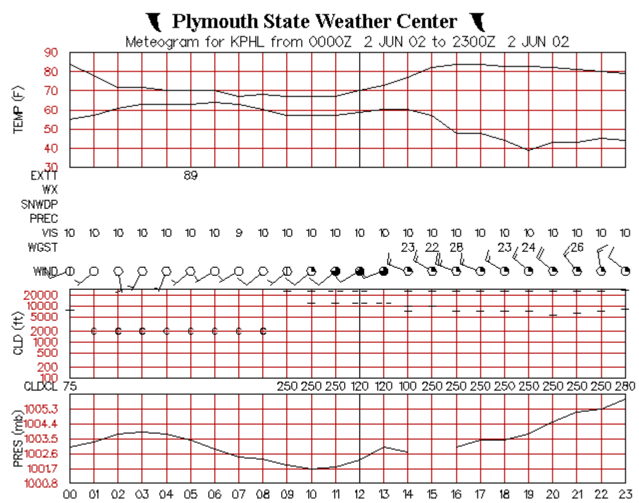

Fig. 8. Meteogram for KPHL valid from 0000 Z – 2300 Z 2 June 2002.

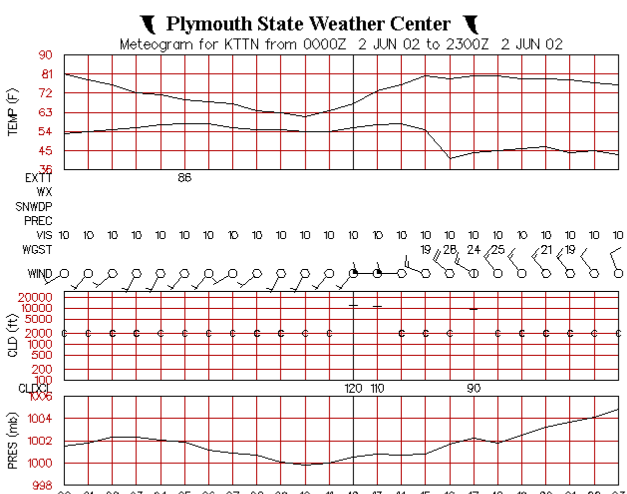

Fig. 7. Meteogram for KTTN valid from 0000 Z – 2300 Z 2 June 2002.

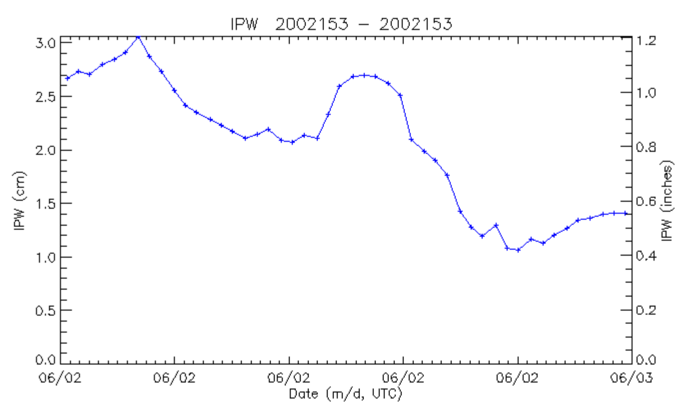

Fig. 9. GPS integrated precipitable water (in) at Sandy Hook, NJ, valid from 0000 Z 2 – 0000 Z 3 June 2002.

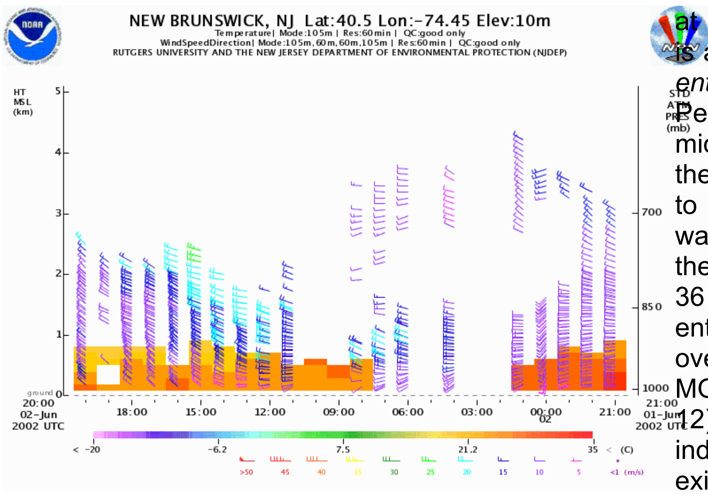

Fig. 10. New Brunswick, NJ, wind profiler obs (m/s) and RASS obs (C) valid from 2100 Z 1 – 2100 Z 2 June 2002.

Sandy Hook is located just up the New Jersey coastline from Double Trouble (note red star for location of Double Trouble in Fig. 11). Additionally, at a nearby wind profiler site in New Brunswick, NJ in Fig. 10, mid-level winds indicate the passage of a westerly wind maximum at ~750 hPa nearly coincident with the surface warming and drying associated with the west-northwesterly wind shift at the three surface stations. These features are consistent with the concepts in the fire weather paradigm described above, i.e., 1) deep upper tropospheric subsidence under the right exit region of a jet streak drying out the column, 2) mid-level sinking behind a second lower-level and accelerating jet streak entrance region further transporting dry air surfacewards and 3) the development of a convective boundary layer, which should maximize the values of the NCSU3 index near the fire location depicted in Fig. 11. The mixing of warm dry and high west-northwesterly momentum air towards the surface is consistent with the surface, GPS and wind profiler data. All of these features comprise the environment surrounding dry cold front formation and southeastward motion towards Double Trouble.

These assertions are further supported by 8 km simulated fields in Figs. 13-15. 300 hPa winds and heights indicate that at 1500 UTC, eastern Pennsylvania and New Jersey are located under the right exit region of a jet streak downstream from a massive ridge and approaching an upper-level trough. Rightward-directed ageostrophic flow is directed towards eastern Pennsylvania and northern New Jersey at 1500 UTC. Directly under the right exit region is a second jet streak at ~850 – 750 hPa whose *entrance* region is crossing eastern Pennsylvania under the right exit region of the mid-level jet. This entrance region lies parallel to the leading edge of a mid-level warm pool just to the southwest (not shown). This elevated warm pool has been transported eastward from the western High Plains over the preceding 24-36 hour period. Aligned with the mid-level entrance region is the stretched out haze plume over Pennsylvania and New Jersey depicted in MODIS satellite imagery at 1600 UTC (note Fig. 12). These simulated and observed features indicate a juxtapositioning of the upper jet's right exit region, mid-level jet's right entrance region and surface warming and drying close to 1500 UTC or just ahead of the approaching cold front and very dry warm surface air surge. The haze plume reflects the curvature and stretching associated with the mid-level jet's entrance region when compared to Figs. 14-15 and Fig. 12. The implications are that a group of circulations is establishing a favorable environment for fire weather over central New Jersey. The challenge is how to synthesize all of these diverse processes into a predictive index.

Figs. 16-18 depict the simulated NCSU3 and low-level Haines indices, respectively, for this case study valid at 1900 UTC 2 June, i.e., 1500 LDT. This time period was selected because the surface heating had increased the depth of the simulated PBL allowing vertical coupling between the PBL and the deeper upper-level circulations during the warmest period of the day. Also, it was selected because it was during the Double Trouble fire period. In Figs. 16-18, the Haines index is derived from a 2 km horizontal resolution simulation and the NCSU3 index is derived from both a 2 km and 500 m simulation. The numerical model employed for the fields depicted in Figs. 13-18 is the Nonhydrostatic Mesoscale Atmospheric Simulation System (NHMASS) (Kaplan et al. 2005a,b). The 2 km and 500 m simulations were nested from a 32 km coarse mesh and 8 km nested-grid simulation. The model employs a turbulence kinetic energy PBL and very detailed vertical resolution within the PBL. The coarse mesh simulation was initialized at 0000 UTC 2 June 2002 from NCEP Reanalysis Datasets.

Double Trouble Fire

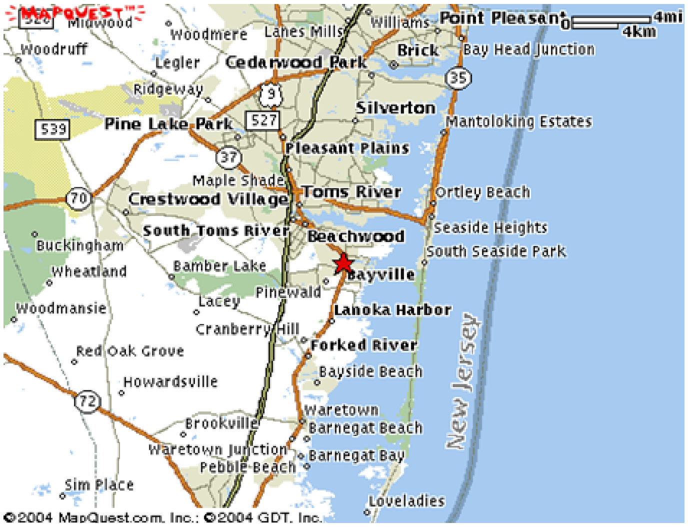

Fig. 11. Location of Double-Trouble State Park, NJ.

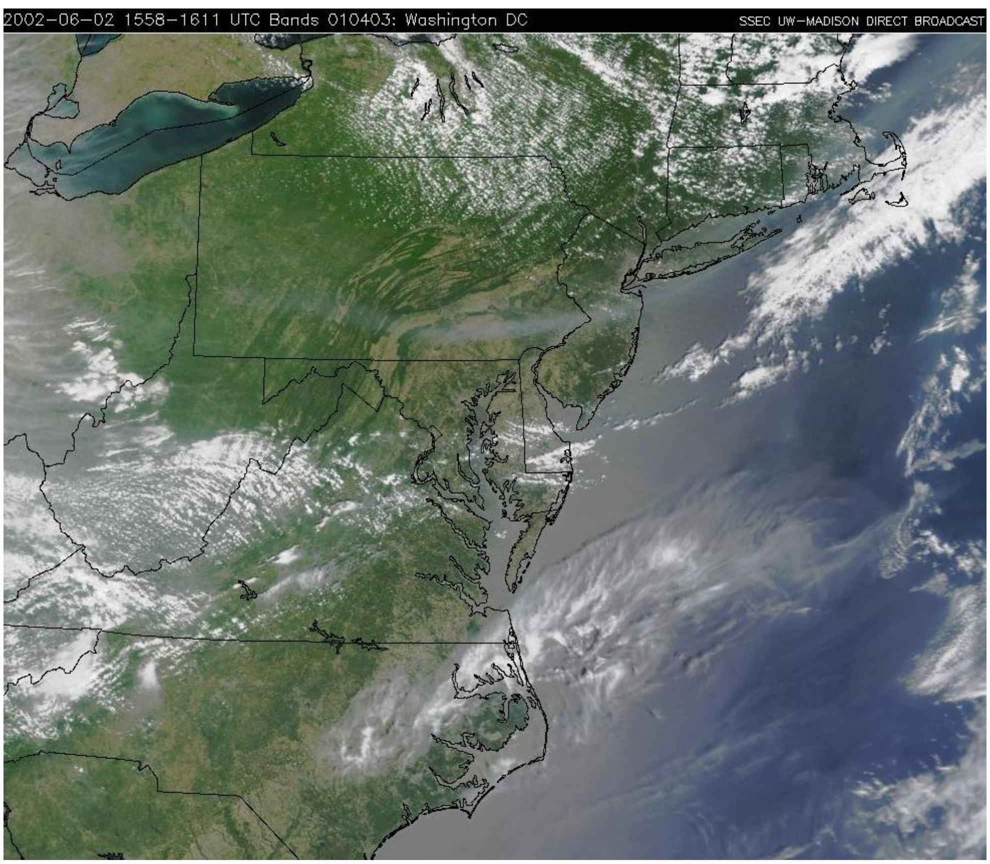

Fig. 12. MODIS satellite imagery valid at ~ 1600 Z 2 June 2002.

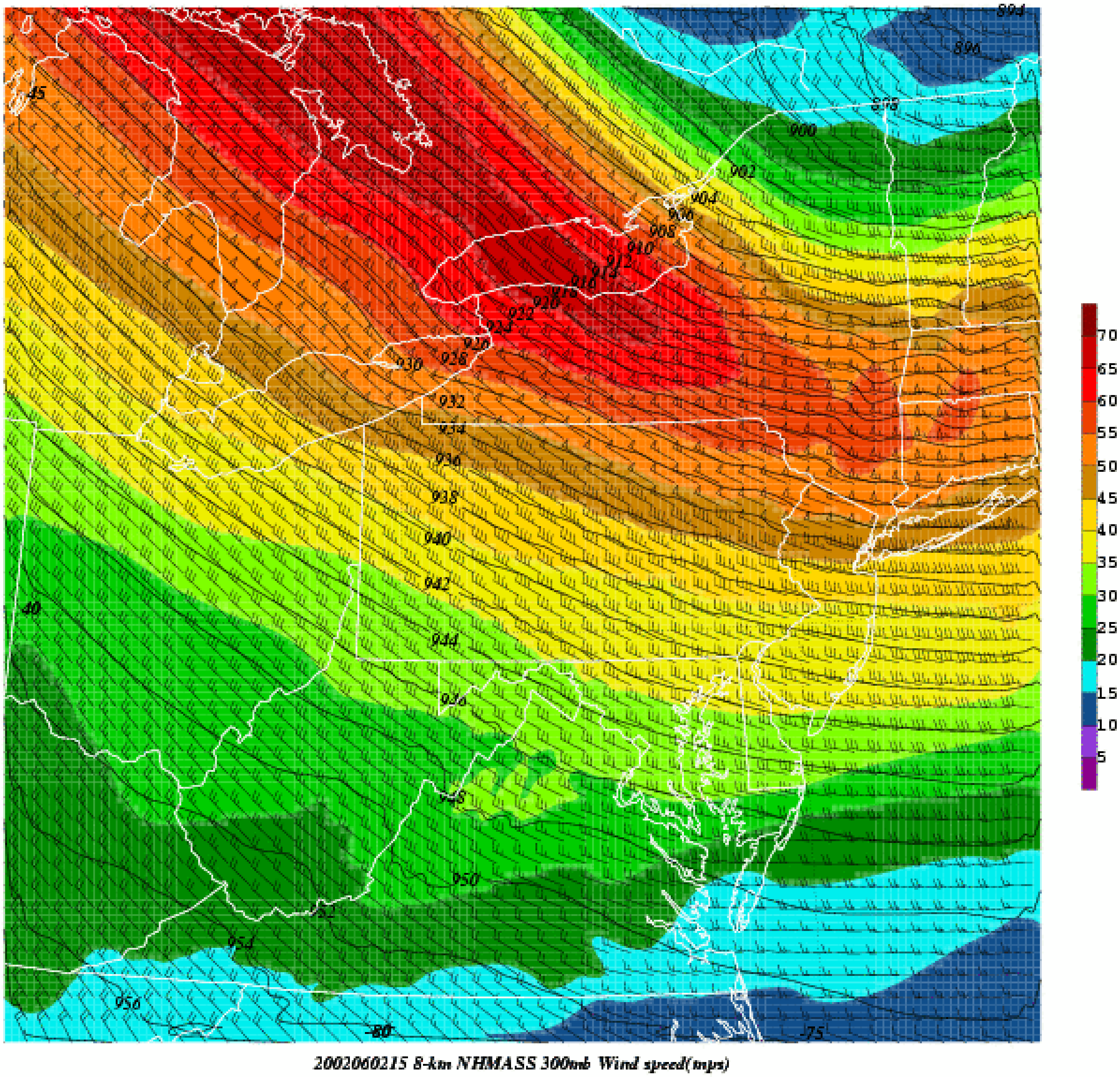

Fig. 13. NHMASS 8 km simulated 300 hPa heights (m) and winds (m/s) valid at 1500 Z 2 June 2002.

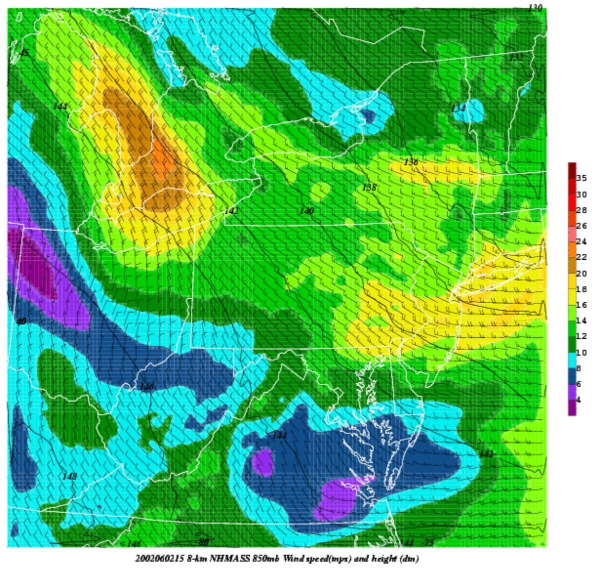

Fig. 14. NHMASS 8 km simulated 850 hPa heights (m) and winds (m/s) valid at 1500 Z 2 June 2002.

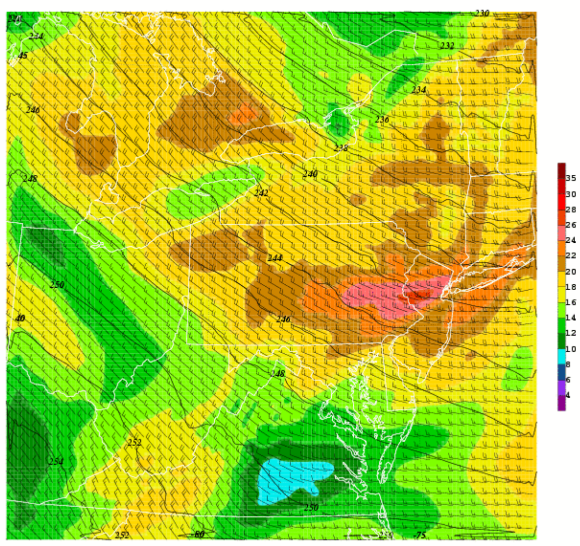

Fig. 15. NHMASS 8 km simulated 750 hPa heights (m) and winds (m/s) valid at 1500 Z 2 June 2002.

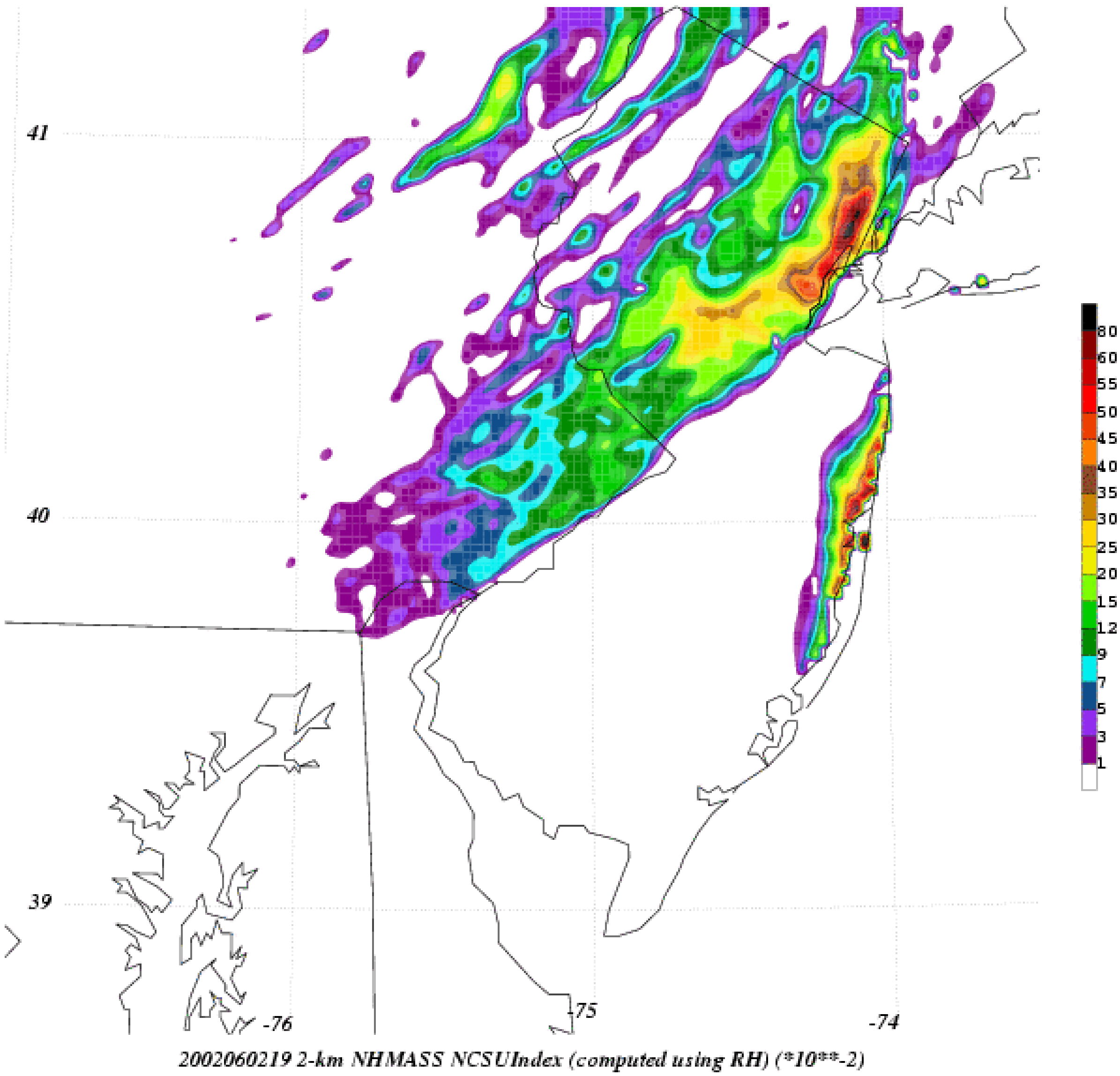

Fig. 16. NHMASS 2 km simulated NCSU3 index units valid at 1900 Z 2 June 2002.

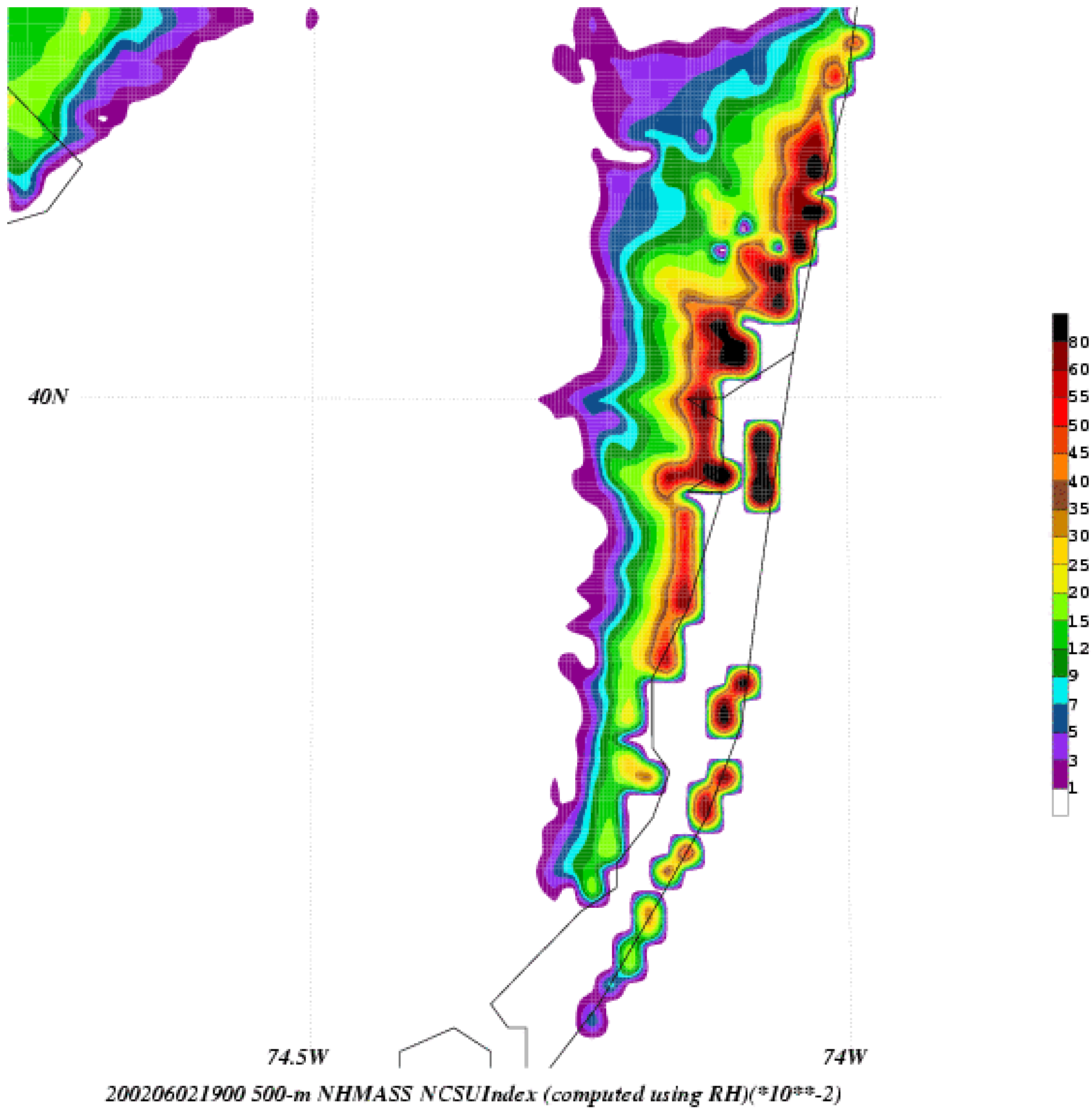

Fig. 17. NHMASS 500 m simulated NCSU3 index units valid at 1900 Z 2 June 2002.

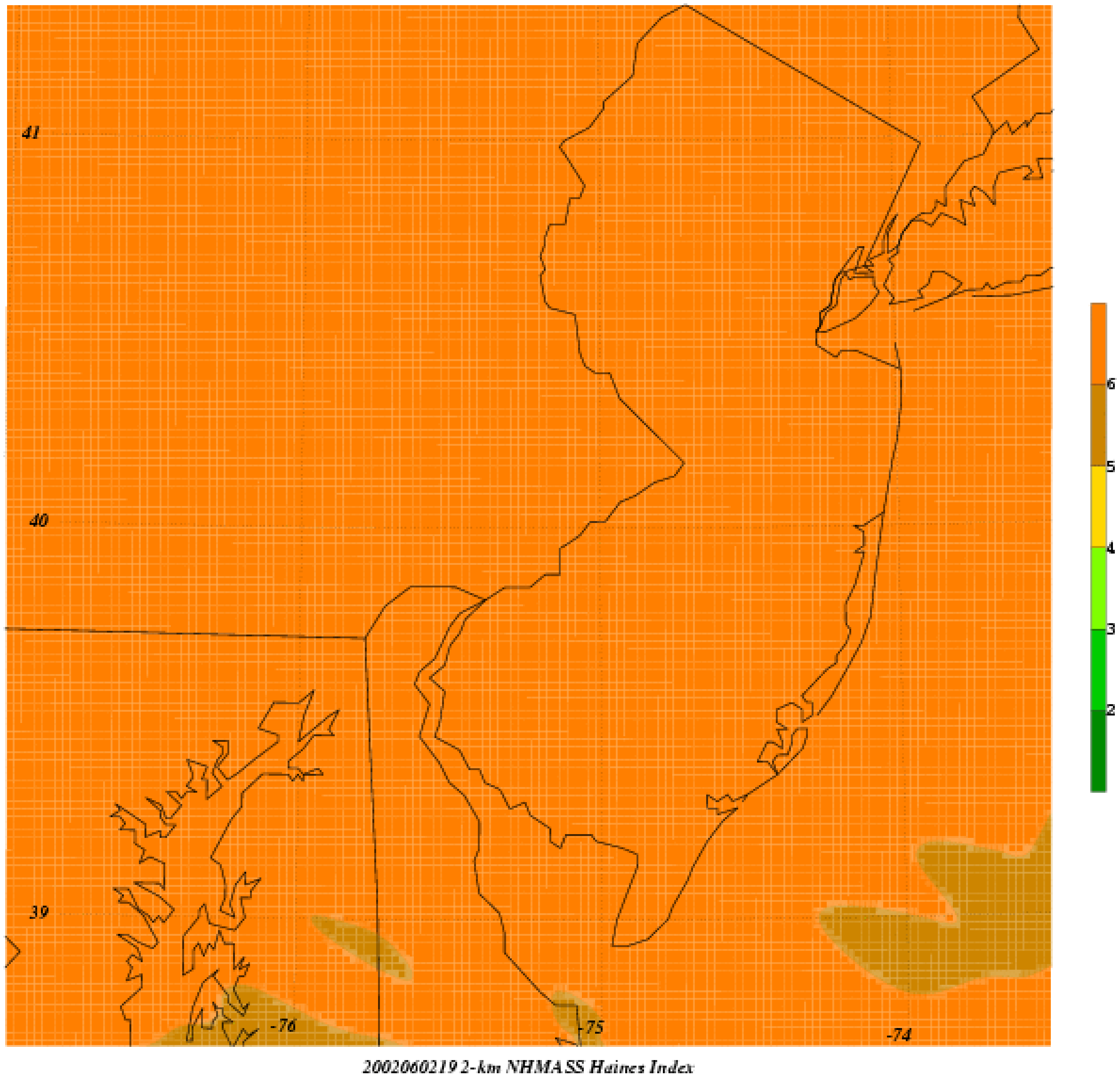

Fig. 18. NHMASS 2 km simulated Haines index units valid at 1900 Z 2 June 2002.

The difference between the simulated index fields is rather striking. Because a large region is covered by a deep well-mixed PBL with dry and less stable air above it in the 2 km simulation, virtually the entire grid registers the highest category of fire weather potential based on the Haines index calculation (Potter 2001). The 2 km and 500 m simulated NCSU3 index fields show a focus of relatively high values situated over a narrow stretch of the central New Jersey coastline virtually centered on Double Trouble. This secondary maximum relative to one to the west-northwest over the Delaware River Valley indicates how narrow and focused the regions of the vertical phasing among various circulations are that make this index large in magnitude. It is this ability of the NCSU3 to discriminate among local regions with a wide diversity of values that should render it potentially useful for fire weather forecasting.

4. Summary and Conclusions

A new index for application to fire weather forecasting has been developed and is being tested by North Carolina State University and the Desert Research Institute. It is based on the concept that unique vertical circulations phase with the convective boundary layer to generate very dry cold fronts. Air near these surface dry fronts is warm, dry and windy thus conducive for fire spread conditions. The three-dimensional convergence of dry air primarily controls the development of maxima of this index as opposed to *exclusively* deep convective boundary layer development into a dry unstable layer. While convective boundary layer formation is an important component of the NCSU3 index it is not exclusively driving the index. The downward transport of dry air by two jet circulations, which phase vertically and their coupling to the convective boundary layer maximizes this index locally. Simulated values of the index during an isolated fire case study indicate that it focuses maxima at the meso-β scale region where the fire occurs with better spatial and temporal accuracy than does the low-level Haines index, which spreads the maxima over a very large region relative to the NCSU3 index.

5. References

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6. Acknowledgements

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