3.5 EFFECTS OF NEAR-SURFACE ATMOSPHERIC STABILITY AND MOISTURE ON WILDFIRE BEHAVIOR AND CONSEQUENCES FOR HAINES INDEX

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1. INTRODUCTION

Since the 1950s, extensive research has been conducted to investigate the relationship between near–surface atmospheric conditions and large wildfire growth and occurrence. Observational studies have demonstrated that near–surface dryness (e.g., Fahnestock 1965) and atmospheric instability (e.g., Brotak and Reifsnyder 1977) are correlated with large wildfire growth and occurrence.

Based on the earlier work by Davis (1969) and Brotak (1976), Haines (1988) developed the Low Atmospheric Severity Index (LASI) which is calculated using low–level atmospheric stability and moisture based on two low atmospheric levels. The LASI is now known simply as the Haines Index, and is considered a valuable aid in predicting days with the potential for large and dangerous wildfire growth. The Haines Index is the sum of two terms: a stability term (A) indicating the near-surface atmospheric stability and a moisture term (B) indicating the near-surface atmospheric moisture conditions. The stability term (A) ranges from 1 to 3 according to the temperature difference between 95 and 85 kPa in low-elevation areas:

$$\begin{array}{rl} \text{If } T(p95) - T(p85) < 4^oC, & \text{then } A{=}1, \\ \text{if } 4^oC \leq T(p95) - T(p85) < 8^oC, & \text{then } A{=}2, \\ \text{if } T(p95) - T(p85) \geq 8^oC, & \text{then } A{=}3. \end{array} \quad (1)$$

The moisture term also ranges from 1 to 3 according to the difference between temperature and dew point at 85 kPa in low-elevation areas:

$$\begin{array}{rl} \text{If } T(p85) - T_d(p85) < 6^oC, & \text{then } B{=}1, \\ \text{if } 6^oC \leq T(p85) - T_d(p85) < 10^oC, & \text{then } B{=}2, \\ \text{and if } T(p85) - T_d(p85) \geq 10^oC, & \text{then } B{=}3. \end{array} \quad (2)$$

Thus the Haines Index ranges from 2 to 6. According to Haines, an Index of 6 indicates a high potential for large and dangerous wildfire growth, while the others indicate very low (2,3), low (4) and moderate (5) potential.

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Several studies have examined the effectiveness of the Haines Index as an indicator of the potential for high–risk wildfires. Some studies show that it is a useful indicator. Werth and Ochoa (1990) found a high correlation of Haines Index 5 and 6 days with large wildfire growth in Central Idaho. Saltenberger and Barker (1993) demonstrated that the Haines Index performed well during the Awbrey Hall fire in Central Oregon in 1990. However, other studies show that Haines Index breaks down in some situations. Werth and Werth (1998) studied Haines Index climatology for the western United States using the high elevation option of the Haines Index. They found that the Haines Index work well in some areas, but not in others. They also found that the effectiveness of the Haines Index over high elevation areas depends on the time of the day and that the Haines Index has a significant seasonal variation for some areas.

Since the Haines Index is routinely used operationally to evaluate the potential for severe fire behavior, either a better understanding of how and why Haines Index performs is necessary, or a better definition of the Haines Index is required.

Jenkins (2002) investigated, through four numerical simulations using Clark's coupled wildfire–atmosphere model (Clark 1996), the sensitivity of wildfires to low-level atmospheric stability and moisture. In the process, Jenkins also explored the correspondence between atmospheric stability and moisture, wildfire behavior, and the Haines Index. Jenkins (2002) found that high–risk wildfire development is sensitive to low–level atmosphere stability and moisture. In this pilot study, Jenkins (2002) suggested that there is a range of atmospheric stability and moisture conditions that is important to the development of severe or erratic wildfire behavior. This range is within the atmospheric stability and moisture conditions represented by a Haines Index for high potential for severe wildfire (Haines Index=6), which suggests that the Haines Index should be further divided or refined.

The purpose of this study is to extend the work by Jenkins (2002), and to investigate more thoroughly how low–level environmental stability and moisture within the Haines Index range (6) for high potential for severe wildfire influences fire behavior. A number of numerical experiments were designed and performed to examine the individual effect of near–surface humidity or stability on wildfire behavior. Because the vertical temperature structure of the low–level atmosphere is also important to wildfire behavior (e.g., Werth and Werth 1998, Potter 2000), numerical experiments concerning this aspect of the ambient environmental conditions were also designed and performed.

2. MODEL DESCRIPTION

In this study, the Clark atmospheric numerical model (Clark 1996) is coupled with the Canadian Forest Service Fire Behavior Prediction System or FBPS (Hirsch 1996). The Clark model is a three-dimensional cloud resolving non-hydrostatic numerical prediction model. It has a two-way interactive grid-nesting feature which enables it to capture both the fine-scale fire characteristics in the fire (inner) domain and large-scale environmental circulation features in the outer domain. The FBPS model is an operational model. It has very low computational requirements.

The coupling between the fire and atmospheric models is mainly through the sensible heat flux and latent heat flux that are supplied by the fire model to the atmospheric therodynamic equation. Canopy drag is neglected.

Detailed descriptions of the coupled wildfire-atmospheric numerical prediction model can be found in Clark (1996), FBPS (Hirsch 1996), and Jenkins (2002).

3. DESIGN OF EXPERIMENTS

Three sets of numerical experiments are completed to investigate the effects of variations of lower-level environmental stability, moisture and vertical temperature on wildfire behavior. Two domains were used in each simulation. An inner domain, 1.2 km $\times$ 1.2 km in size, was nested within an outer domain, 6.45 km $\times$ 6.45 km in size. The horizontal grid intervals were $\triangle x = \triangle y$ =25 m and the near-surface vertical grid spacing was $\triangle z$ =20 m in the inner domain, in the outer domain $\triangle x = \triangle y$ =75 m and $\triangle z$ =40 m. The horizontal fuel grid interval was 6.25 m, or 1/4 of horizontal grid intervals in the inner domain. The fuel conditions in each simulation are the same as described by Jenkins (2002). Fuel moisture was deliberately not allowed to respond to changes in surface relative humidity.

Each simulation lasted 90 minutes. A spot fire was set 30 minutes into each simulation. The 30 minute delay allowed the model boundary layer to develop its own circulation before introducing the surface fire and heat source. The initial size of the fire was approximately 27 m in radius. Model fire behavior is mainly represented by fire-related surface fields, ground fire intensity (GI), canopy fire intensity (CI), and fire spread rate (SR), sensible heat released by a ground fire (GS), latent heat released by the ground fire (GL), sensible heat released by a canopy fire (CS), and latent heat released by the canopy fire (CL).

For each experiment, the background temperature lapse rates and humidity conditions, represented by the A and B terms in the Haines Index respectively, were varied, and in each case $A + B$= 6. The Haines Index is used to gauge the fire behavior in moderate to low wind conditions. For each experiment, therefore, the background wind was uniform, from the west at 3 m/s, and constant with height. Surface pressure is 100 kPa for each simulation.

In the first set of experiments, four fires were simulated to examine the effects of different near-surface humidity conditions on wildfire behavior. The initial low-level stability condition was the same for each simulation, with a temperature drop of 8 K between the 95 and 85 kPa pressure levels. The temperature lapse rate was 8.68 K/km below 84 kPa pressure level, and slowly increasing above. Initial low-level moisture conditions were different for each simulation, with temperature-dewpoint differences of 10, 12, 15, and 23 K at the 85 kPa height level, representing the most humid, less humid, even less humid, and least humit cases.

In the second set of experiments, three fires were simulated to examine the effects of different near-surface atmospheric stability conditions on wildfire behavior. Initial low-level moisture conditions were the same for each simulation, with a temperature-dewpoint difference of 12 K at the 85 kPa pressure level. Initial low-level stability conditions were different for the three simulations, with temperature drops of approximately 8, 9 and 10 K between the 95 and 85 kPa pressure levels. The near-surface temperature lapse rates for the three simulations were 8.68K/km (stable atmosphere), 9.8K/km (neutral, adiabatic atmosphere), and 10.74K/km (unstable, superadiabatic atmosphere). In each case, the temperature lapse rate was constant below the 84 kPa pressure level, and slowly decreasing above.

In the third and final set of experiments, three fires were simulated to examine how variations in the near-surface vertical temperature profile impact wildfire behavior. Initial low-level stability conditions were the same for each simulation, with a temperature drop of 8 K between the 95 and 85 kPa pressure levels. Initial low-level moisture conditions were the same for each simulation, with a temperature-dewpoint difference of 12 K at the 85 kPa pressure level. In the other two

Table 1: Time means of max values of fire-related surface fields in moisture experiments

field name	$q10$ ($most$ $humid$)	$q12$ ($less$ $humid$)	$q15$ ($even$ $less$ $humid$)	$q23$ ($least$ $humid$)
GI	123	122	123	124
GS	1.97E07	1.95E07	1.97E07	1.98E07
GL	1.74E06	1.72E06	1.74E06	1.75E06
SR	0.160E-1	0.160E-1	0.160E-1	0.160E-1
CI	49.5	45.2	48.6	50.6
CS	8.2E06	7.19E06	7.9E06	8.4E06
CL	9.85E05	9.01E05	9.47E05	1.0E06

simulations, an isothermal inversion of 450.9 m and an isothermal frontal inversion of 1508 m were created below 95 kPa and from 84 to 66 kPa, respectively.

4. MODEL RESULTS

4.1. Results of Moisiture Experiments

The four fires simulated to examine the effects of different near-surface moisture conditions on wildfire behavior are q10, q12, q15 and q23, representing the most humid, less humid, even less humid, and least humit cases. Table 1 shows the time means of maximum values of the fire-related surface fields, GI, GS, GL, SR, CI, CS, and CL, in the fire domain. There are no or nearly no differences in the time means of fields GI, GS, GL, and SR. The time means of fields CI, CS and CL are different between the four simulations, and the maximum difference is 10% which occurred in CL. However, there is no steady trend upwards or downwards of those means with a decrease of moisture from q10 to q23. Time means of averaged values of the fire-related surface fields over the burning area are also examined for each simulation. No siginificant differences are found in these varables between the four simulations. Besides the time means of averaged and maximum values, the variation patterns of the fields are analyzed and shown that the variation patterns of both maximum value and averaged value in each field are similar between the four simulations.

Therefore, with the small model wildfire (27m in radius) and stable lapse rate (8.68K/km), moisture variation did not make significant difference to the behavior of the model wildfire. This will be discussed further in Section 5.

Table 2: Time means of averaged values of fire-related surface fields in stability experiments

field name	*t08 (stable)*	*t09 (neutral)*	*t10 (unstable)*
GI	29.4	29.5	30.8
GS	6.61E06	6.62E06	6.87E06
GL	5.85E05	5.86E05	6.08E05
SR	0.119E-02	0.12E-02	0.119E-02
CI	6.81	7.67	7.09
CS	1.51E06	1.66E06	1.55E06
CL	2.45E05	2.53E05	2.55E05

Table 3: Time means of max values of fire-related surface fields in stability experiments

field name	*t08 (stable)*	*t09 (neutral)*	*t10 (unstable)*
GI	122	122	143
GS	1.96E07	1.95E07	2.19E07
GL	1.73E06	1.73E06	1.94E05
SR	0.156E-01	0.157E-01	0.156E-01
CI	43	44.3	52.1
CS	6.83E06	7.22E06	8.08E06
CL	8.88E05	9.0E05	1.05E06

4.2. Results of Stability Experiments

The three fires simulated to examine the effects of different near-surface stability conditions on the wildfire behavior are t08, t09 and t10, representing the stable, neutral, and unstable stability cases. Tables 2 and 3 present the time means of averaged values and time means of maximum values of fire-related fields, GI, GS, GL, SR, CI, CS, and CL, over the burning area in the fire domain. Generally, there are differences between the three simulations. Differences between t09 and t08 are not large. However, the tables, especially Table 2, do show an overall increasing trend of time mean values from t08 (stable) to t09 (neutral). This overall increasing trend is even more obvious between t10 (unstable) and t08. This suggests that time means of fire-related fields increase due to decreasing in stability, and stability does affect the behavior of model wildfires significantly. Table 4 shows the Taylor statistics (Taylor 2001) of PK of the three stability simulations for the entire fire domain (Total RMS and Pattern RMS of t09 and t10 are all referred to t08. Pattern RMS

Table 4: Statistics of PK in fire domain in stability experiments

field name	*t08 (stable)*	*t09 (neutral)*	*t10 (unstable)*
Average	2.03E06	27.5E06	263.0E06
Total RMS	0.0	83.8	859.3
Pattern RMS	0.0	68.0	698.7
Standard deviation	1.0	68.5	699.1
Correlation	1.0	0.43	0.42

and Standard Deviation are normalized by t08). For an explanation of Taylor statistics see Jenkins (2002). As shown in Table 4, the differences in PK between t08, t09 and t10 are significant. Since PK is kinetic energy generated by a model wildfire, the differences in PK indicate that stability variations did have some impact on the kinetic energy generation and distribution in the fire domain, and the interaction between the fire and its ambient atmosphere is influenced by the environmental stability. Compared with the the differences in PK among the three stability simulations, the differences in PK among the four moisture simulations are very small (not shown). This suggests that moisture does not have appreciable impact on the kinetic energy distribution in the fire domain, and interaction between the fire and its ambient atmosphere.

4.3. Results of Verical Structure Experiments

Statistics (not shown) are calculated based on the results of the three vertical-structure experiments described in Section 3. No significant differences in fire-related variables are found among the three simulations. Further discussion of the effect of vertical structure on the model wildfire behavoir is given in Section 5.

5. ANALYSES AND DISCUSSION OF RESULTS

Buoyancy force is believed to be the most important force in fire convection, and the development of extreme fire behavior. The buoyancy force is responsible for the generation of strong, sometimes tornadic strength, updrafts, which in turn modify the ambient flow of the fire, and subsequently the fire spread rate and fire intensity. This is shown by a scale analysis of vertical momentum equation:

$$\frac{DW}{Dt} = \frac{1}{\bar{\rho}}\frac{\partial p'}{\partial z} + g\frac{\theta'}{\bar{\theta}} \qquad (3)$$

where p' is perturbation pressure relative to the average pressure at a certain height in the fire domain, $\bar{\rho}$ and $\bar{\theta}$ are the averaged density and potential temperature at the same height, θ' is the potential temperature difference between maximum potential temperature (in the fire column) and $\bar{\theta}$ (environment). In Equation 3, the term on the left is the vertical acceleration, the first term on the right is the nonhydrostatic pressure gradient force, the second on the right is the buoyancy force. In our simulations, the maximum value of p' usually occurs approximately at 300 m AGL, and the difference of p' between the surface and 300 m AGL is about 2 Pa. So $\frac{1}{\bar{\rho}}\frac{\partial p'}{\partial z} \sim \frac{2}{300}$. The typical value for θ' is about 2 K below 300 m AGL, with the maximum around 4 K. If we assume $\bar{\theta}$=300 K, then $g\frac{\theta'}{\bar{\theta}} \sim \frac{20}{300}$. Therefore, the contribution to the acceleration of vertical velocity from buoyancy term is an order of magnitude higher than that from the nonhydrostatic pressure gradient term in Equation 3, suggesting that the buoyancy force is the main force for the convection in our model fires.

In the moisture experiments, the model fires are small and the ambient atmosphere is stably stratified. The convection was not strong enough to produce cloud and precipitation. Therefore, the buoyancy force is

$$B = g(\frac{\theta'}{\bar{\theta}} + 0.61Q'_v) \qquad (4)$$

where Q'_v is the difference between the maximum and the averaged value of Q_v at the same height level as θ' and $\bar{\theta}$ in the fire domain. In the moisture experiments, the typical value of Q'_v is less than 1.0 g/kg, while the typical value of θ' is 3 K. For $\bar{\theta} = 300K$, $\frac{\theta'}{\bar{\theta}} = 0.01$ and $0.61Q'_v \sim 0.61 \times 10^{-3}$. Therefore, the moisture term contributes only about 5 percent of the buoyancy, indicating that the moisture effect can be neglected in the buoyancy force. Since the buoyancy force is the main driving force for fire convection, the above scale analysis suggests that low-level moisture variation in the atmosphere will not have significant effect on the model fire properties for the background stability and moisture conditions used in this study. This agrees with the results from the moisture experiments in the particular cases of a small fire, a stable atmosphere and in the Haines Index 6 range of lower-level stability and humidity conditions.

To investigate the effect of low-level atmospheric humidity on fire column development, the Potential Energy of Fire Column (PEFC), maximum vertical velocity, mass flux (M_u), and maximum height that vertical velocity is greater than 0.5 m/s ($MAXH_{W>0.5}$) are also examined for each simulation. PEFC and mass flux are calculated using the following formulas:

$$\text{PEFC} = \int_{z0}^{z1} g(\frac{\theta'}{\overline{\theta}} + 0.61Q'_v)dz \quad (5)$$

$$M_u = \frac{1}{A}\int\int_{plain} \rho W(+)dxdy \quad (6)$$

where A is the plane area of integration, $W(+)$ is positive vertical velocity, and ρ is the density at the same grid point as $W(+)$ over a certain height cross-section of the fire domain. The height of the cross-section is 515 m AGL. This height is close to but below the approximate maximum heights of the fire convections in our moisture experiments.

The time series plots of these variables for the moisture experiments are presented in Figures 1. The PEFC, maximum vertical velocity, mass flux (M_u), and $MAXH_{W>0.5}$ show very small differences between simulations. Although there are some differences in phase of variations, the magnitudes of the variations and the averaged values are about the same. It appears that low-level atmospheric moisture variation does not have significant effect on the fire convection in our experiments.

Stability is expected to have an influence on the fire, and the fire's behavior by affecting the buoyancy profile and therefore the convection. According to Classic Plume Theory (Emmanuel, 1994), environmental stability affects the vertical velocity profile, buoyancy profile, horizontal plume expansion, and the height of a convective plume. The convective column of a forest fire is like a plume to some degree. The fire's convection column is built by the strong buoyancy caused by the intense heat released by the burning fuel. If the wildfire convection column is much bigger in vertical than in horizontal extent, then a fire convection column can be considered a thermal plume in light environmental wind conditions. In our simulated wildfire cases, ambient winds were light at 3 m/s and stability is expected to play an important role in fire development. Again, the PEFC, maximum vertical velocity, mass flux (M_u) at 515 m AGL and $MAXH_{W>0.5}$ are examined for each simulation and compared to investigate the effect of stability on fire convection.

Time series of these variables for the stability experiments shown in the Figure 2. Time mean values are listed in Table 5. It is clear that the PEFC increases with decrease in stability. A comparison between Figure 1 for the moisture experiments and Figure 2 for the stability experiments shows that different environment stability can change the maximum vertical velocity, mass flux (M_u) at 515 m AGL and $MAXH_{W>0.5}$ among three simulations, especially in the beginning of the time series of mass flux (M_u) plot and the plot of $MAXH_{W>0.5}$.

Table 5: Convection related variables in stability experiments

field name	*t08* $(stable)$	*t09* $(neutral)$	*t10* $(unstable)$
PEFC (m^2s^{-2})	32.96	39.05	46.79
Max W (ms^{-1})	4.6	4.95	5.35
Mass flux $(kgm^{-2}s^{-1})$	104.6	113.2	219.7
max height (m)	653.7	698.5	796.0

Table 5 demonstrates a general increasing trend of the time-mean values of these variables with a decrease in stability, which means that the convection developed in the neutral and unstable environments is more intense than that developed in the stable environment.

The above analysis suggests that atmospheric stability does have an appreciable impact on the fire convection. More intense convection tends to develop in the neutral and unstable atmospheres than in a stable environment. We assume that the reason that stability does not show any large effect on fire behavior is that our model fires were small. If the model fires were big enough, then fire convection would be strong, and the differences in properties (height, strength of fire convection at high levels, etc) of convection between the three stability conditions would be significantly bigger. So would be the feedbacks, which would cause significantly different fire behavior.

To examine effects of inversion and frontal inversion on fire convection, time series of PEFC, maximum vertical velocity, mass flux (M_u) at 208 m AGL (in low-level inversion simulation, the height the convection is below 515 m AGL) and $MAXH_{W>0.5}$ are plotted and shown in the Figure 3. From this figure, it is obvious that an inversion retarded the convection development, and hence had a negative effect on the wildfire severity. A frontal inversion should have the same effect. However, the frontal inversion was located too high (about 1500 m AGL) above the main convection and hardly had any influence on the convection at all.

6. CONCLUSIONS

In this study, ten simulations were selected to investigate how low–level environmental stability, moisture, and vertical temperature structure within the Haines Index range (6) for high potential for severe wildfire affects fire behavior.

The results of the four moisture experiments suggest that the low-level moisture conditions in stable atmospheres used in this study did not have any direct or significant effect on the behavior of small model fires or fire convection. There are no or nearly no differences in the time means and patterns of the fire-related variables. This is consistent with a simple scale analysis of vertical momentum equation and the buoyancy equation. Using model data to determine the magnitudes of the buoyancy term and nonhydrostatic pressure gradient term in the vertical momentum Equation 3, and temperature term and moisture term in the buoyancy Equation 4, it was estimated that the buoyancy term dominates the nonhydrostatic term in the vertical momentum Equation 3 and the moisture term contributes less than 10% of the buoyancy force in the buoyancy equation (Equation 4). This order-of-magnitude estimate suggests that backgroung moisture in our simulations should not have a significant effect on the fire convection and fire behavior.

The three stability experiments and the three vertical structure experiments did demonstrate that stability and vertical structure influence fire convection. The results show that a stable atmosphere and an atmosphere with a low-level inversion (below 950 mb) retard the development of fire convection. More intense convection tends to develop in the neutral and unstable atmospheres than in a stable environment. However, the direct effect of stability on the fire behavior is not large or significant. The most likely reason is that our simulated fires were small. The frontal inversion should have a retarding effect on the fire convection development. But this retarding effect did not appear in our frontal inversion experiment. The frontal inversion was too high above the fire convection to have any impact on a small fire.

From above results, it can be summerized that, within the Haines Index range (6) for high risk wildfire, stability term is more important than the moisture term (given fuel moisture is not under consideration) for estimating potential for high–risk wild fires. A low-level inversion retards fire convection, and the Haines Index is not useful in this situation, while an upper–level inversion does not have an impact on small fire, and the Haines Index is still useful in this situation.

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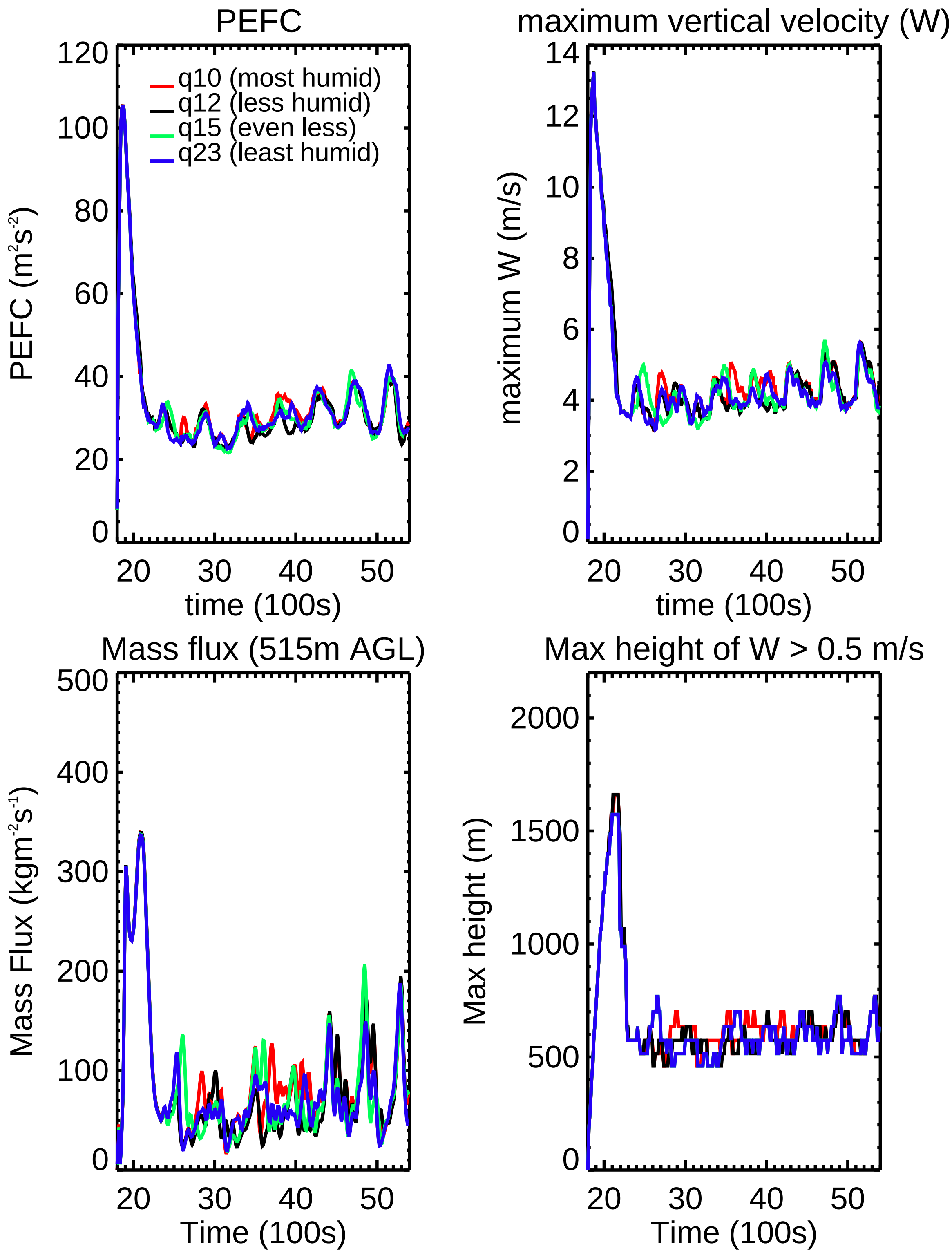

Figure 1: Time series of PEFC, maximum vertical velocity, mass flux, and MAXH > 0.5 m/s of four moisture experiments, q10, q12, q15 and q23

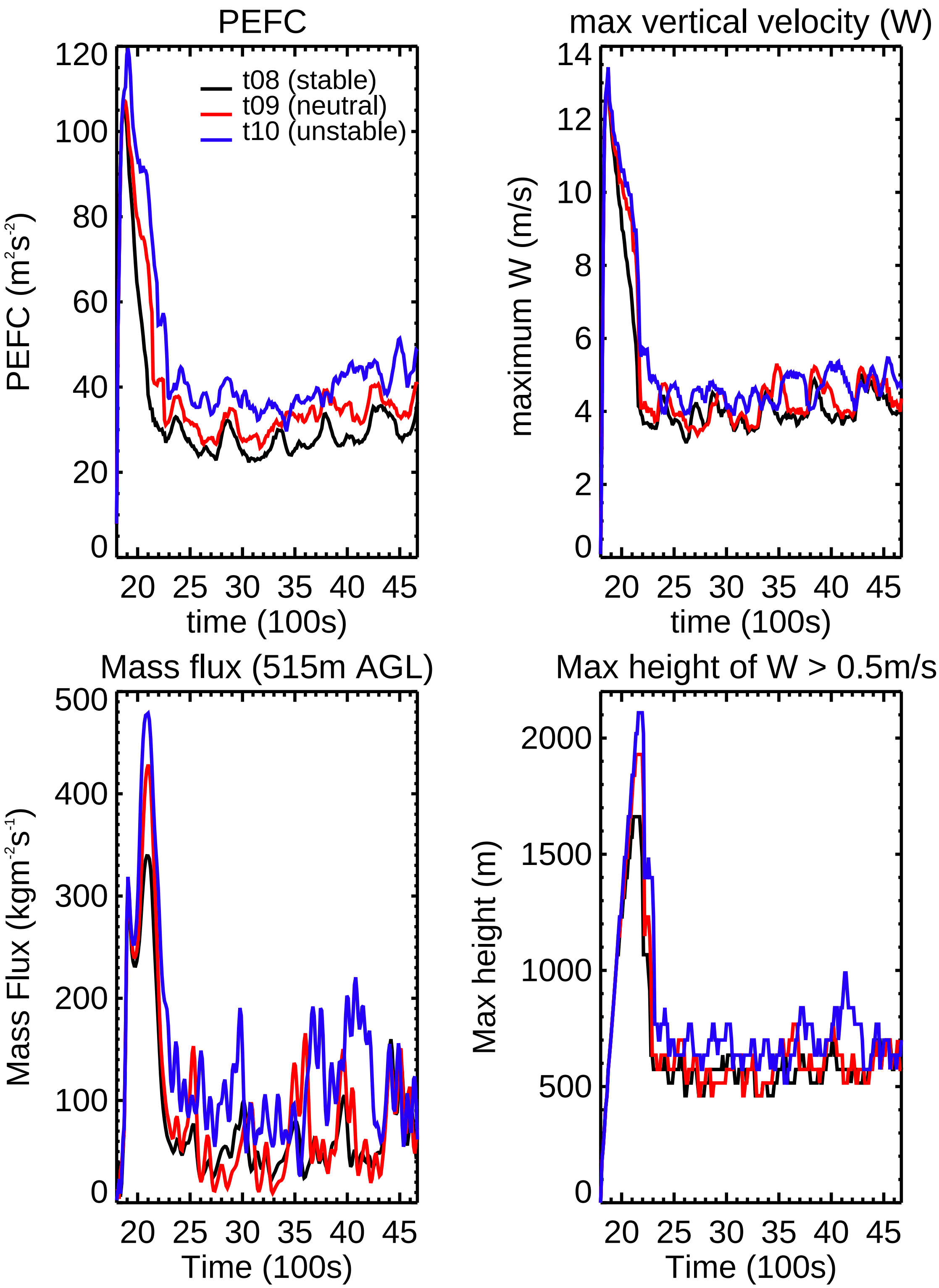

Figure 2: Time series of PEFC, maximum vertical velocity, mass flux, and MAXH $>$ 0.5 m/s of three stablility experiments, t08, t09 and t10

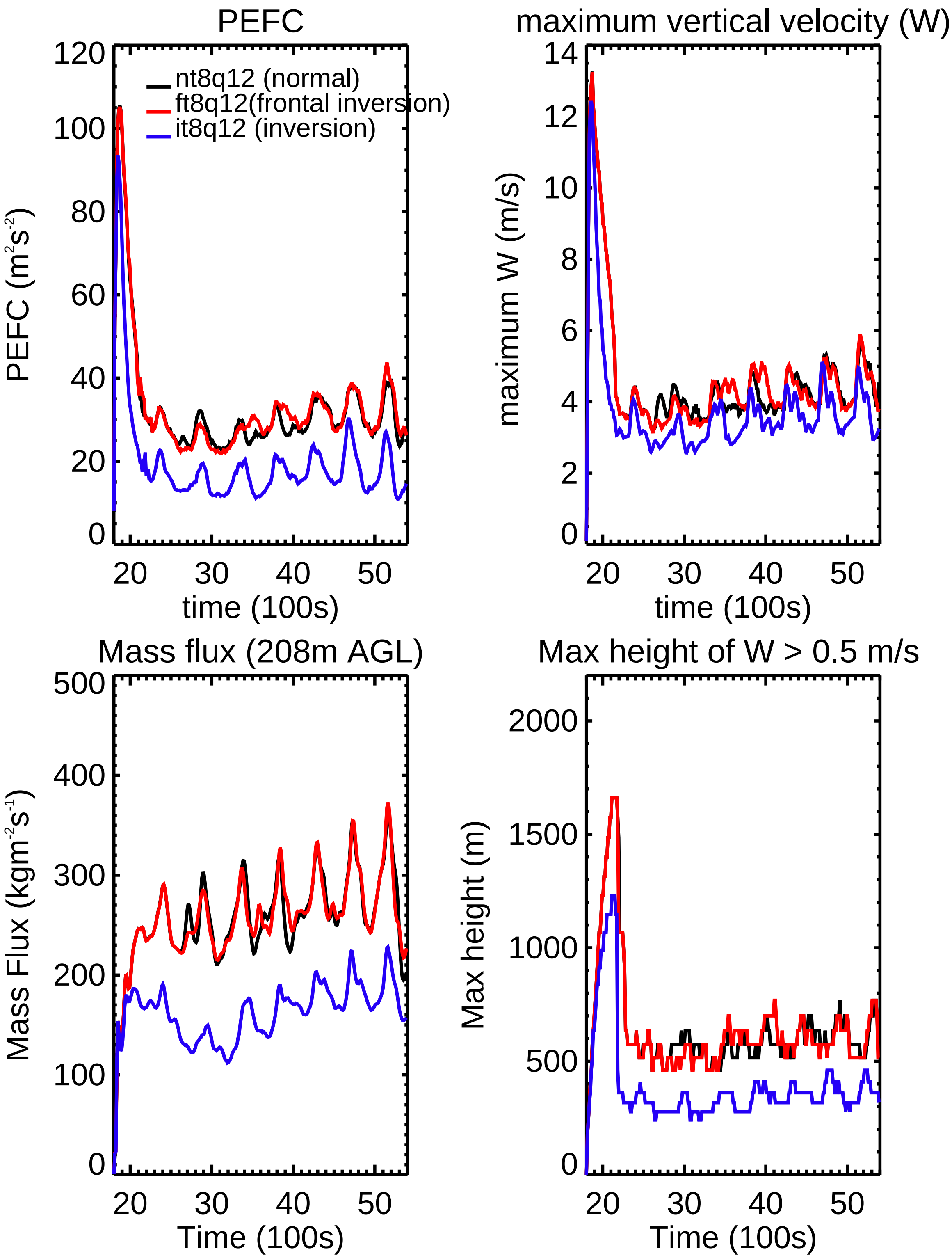

Figure 3: Time series of PEFC, maximum vertical velocity, mass flux, and MAXH > 0.5 m/s of three vertical structure experiments, nt08q12, it08q12 and ft08q12