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EMERGENCY MANAGEMENT ISSUES SPECIAL INTEREST GROUP
Emergency Management Issues Special Interest Group
Annual Meeting

Wind Regimes in Complex Terrain of the Great Valley of Eastern Tennessee

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Computational Sciences & Engineering
University of Tennessee, Department of Geography

Celebrating Silver
EMI SIG 25 years
Going for Gold
May 2–5, 2011 Charleston Marriott • Charleston, South Carolina

- ***Development of Wind Regime Analysis for Eastern Tennessee***
  - **Assess cluster analysis performance**
  - **Identification of statistically significant wind classes (not just ideal cases with respect to meteorology)**

- ***Determine Importance / Roles of Physical Wind Mechanisms with respect to Wind Class and Terrain Features***
  - **Forced Channeling**
  - **Vertically Coupled Flow**
  - **Pressure-Driven Channeling**
  - **Thermally-Driven Winds and Down Sloping**

- ***Development of Wind Flow Prediction Guidelines***
  - **Association with Mesoscale / Synoptic Weather**
  - **Association with Ambient Meteorological Variables**
  - **Major Wind Shifts**
  - **Wind Reversals**
  - **Wind Class Succession**

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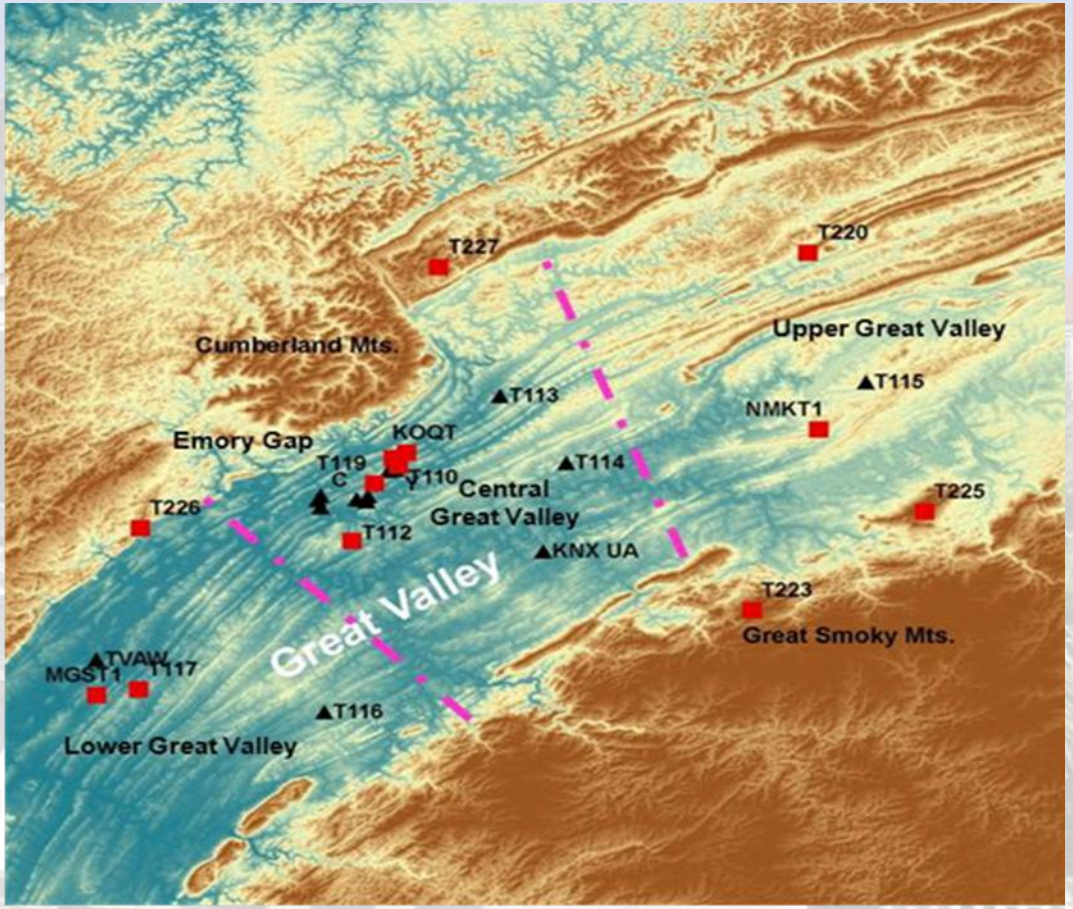
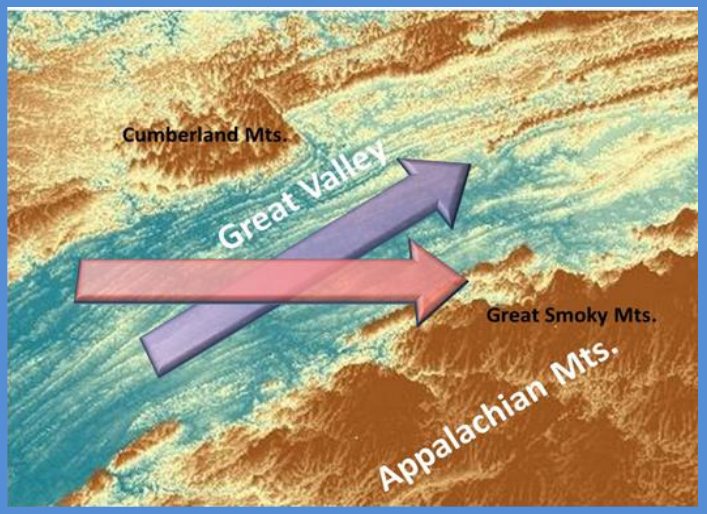
Study Area and Data



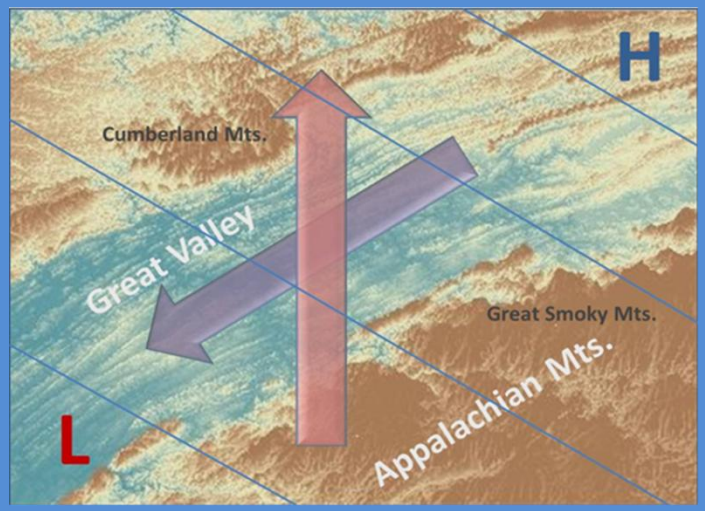
16-monthly, seasonally balanced data sets (11,712 hours)
Surface, multi-level, and upper air data

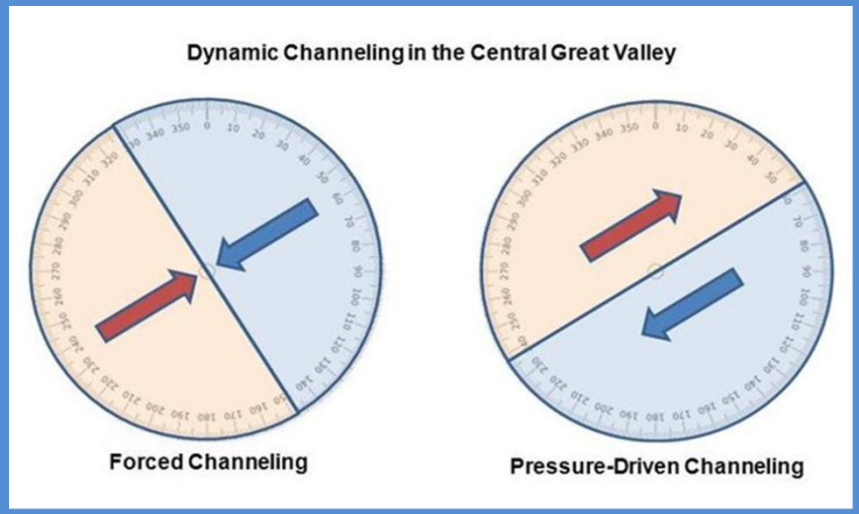
Complex Terrain Physical Wind Mechanisms

Forced Channeling



Pressure-Driven Channeling

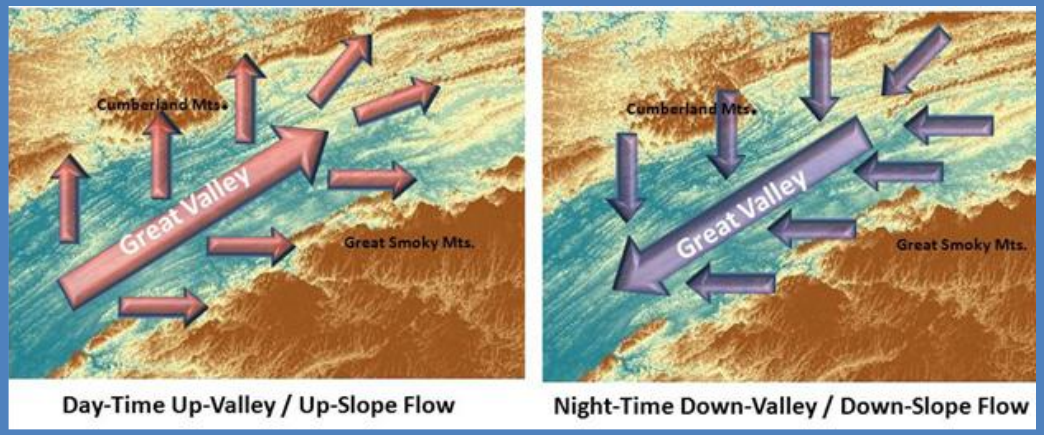




Complex Terrain Physical Wind Mechanisms

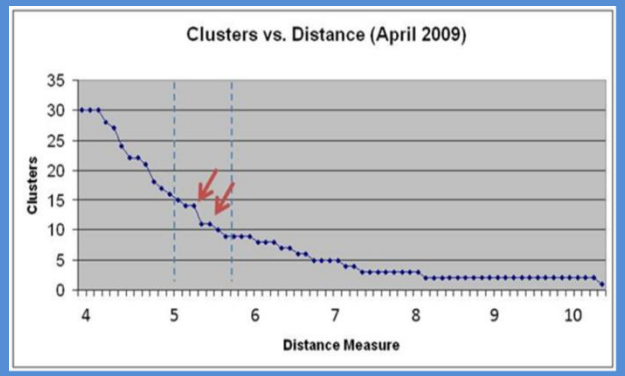
Vertically Coupled Flow

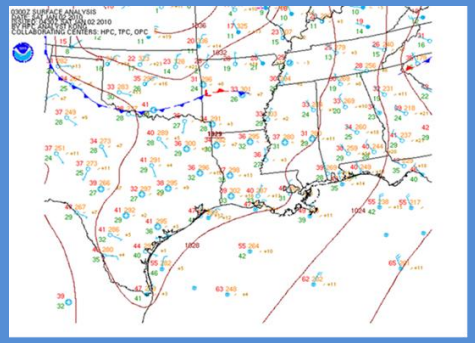
Thermally-Driven Winds

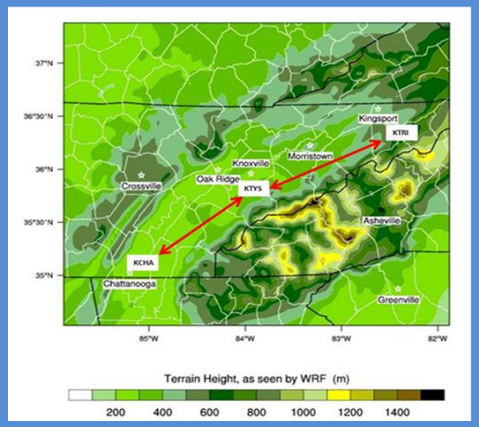


Methods

- *Quality Assurance and Double Data Normalization*
- *Two-Stage Cluster Analysis (Complete Linkage and K-Means)*
  - *Complete Linkage – Class Size and Centroid Selection*
  - *K-Means – Realignment and Final Cluster Selection (22% reclassified)*
- *Synoptic Weather Analysis (3600 surface maps) – (93% Cluster Agreement)*
- *Upper Air Data Analysis (hourly MAPS and Sodar data)*
- *Ambient Meteorological Variable Comparisons*
  - *Mixing Depth*
  - *Great Valley Atmospheric Stability*
  - *Surface Stability*
  - *Pressure Gradient Ratio*
  - *Synoptic Pressure Gradient (Direction and Magnitude)*
- *Wind Pattern Shifts and Succession*







Pre-Defined Synoptic Wind Class Characteristics

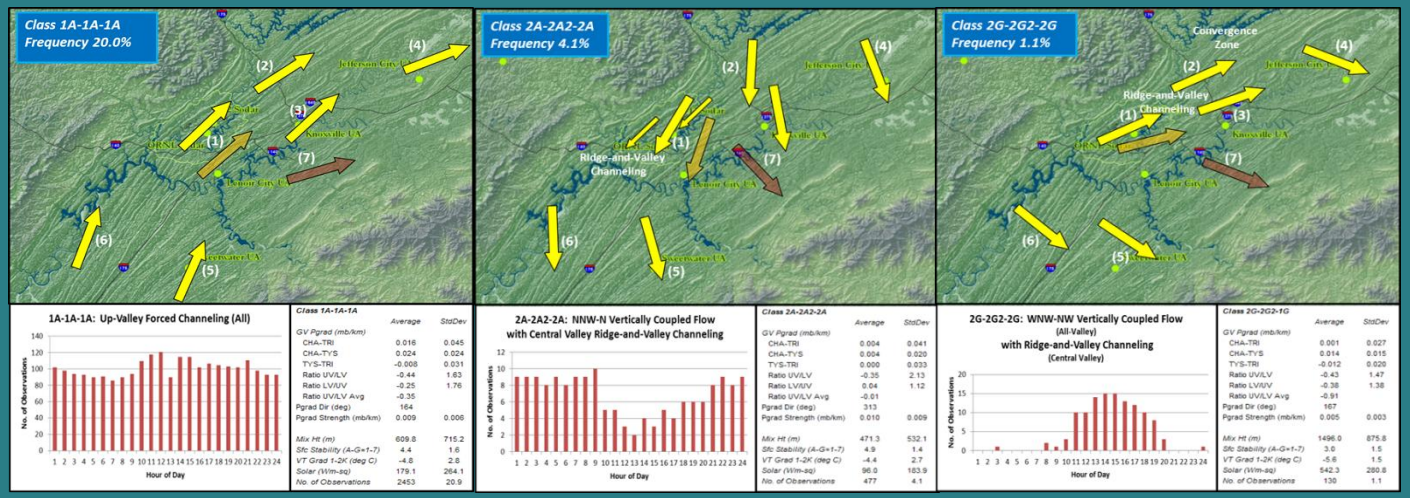
Wind Class	Valley Flow Direction	Synoptic Pres. Grad. Direction	Synoptic Pres. Grad. Strength mb/km	Synoptic Flow	Diurnal State
1A	WSW (Up)	E-WNW	All	ESE-WNW	All
1B	ENE (Down)	WNW-E	All	NW-E	All (Morning)
2A	NNW-N	WNW-NNW	Usually > 0.005	NW-N	All (Night)
2B	NNE-ENE (Down)	N-NE	Usually > 0.005	NNE-ENE	All (Evening)
2C	E-ESE	ENE-ESE	All	E-ESE	Day
2D	SE-SSE	ESE-SE	All	SE-SSE	All
2E	S-SSW	SSE-S	Usually > 0.005	S-SSW	All
2F	SW-WSW (Up)	SW-WSW	Usually > 0.005	WSW-W	All
2G	WNW-NW	W-WNW	Usually > 0.005	WNW-NW	All
3B	NE-ESE	ENE-SW	Usually > 0.005	NE-SE	All
4A	SW-WSW (Up)	All	<=0.006	S-SW (All)	Day
4B	ENE (Down)	All	<=0.006	All	Night
4C	SE-SSE	All	<=0.006	SE	Night
4D	SE-SSE	All	<=0.006	S-ESE	Day
5A	NW	SW-NW	<=0.006	W-NW	Day

Central Great Valley Wind Classifications

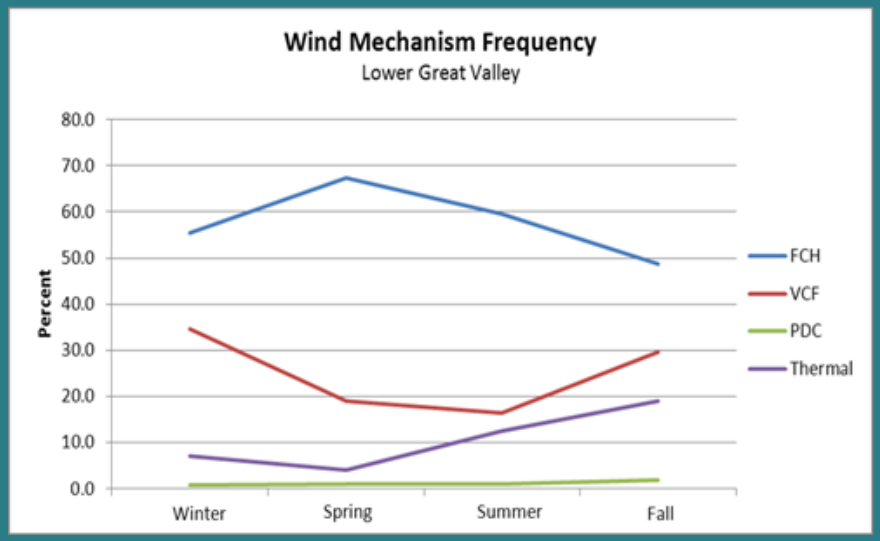
Type	*ID*	*Description*
Forced Channeling	1A	Up-Valley
	1AE	with Emory Gap Flow (WNW)
	1AL	with Local Ridge-and-Valley Flows
	1B	Down-Valley
Vertically Coupled Flow	2A	NNW-N
	2A2	with Down-Valley Ridge-and-Valley Flow
	2A3	with Down-Valley Narrow Ridge-and-Valley Flow
	2AE	with Emory Gap Flow (WNW)
	2A2L	with Down-Valley Ridge-and-Valley and Local
Flows		
	2B	NNE-NE
	2B2	with Down-Valley Ridge-and-Valley Flow
	2BE	with Emory Gap Flow (WNW)
	2C	E-ESE
	2D	SE-SSE
	2E	S-SW
	2F	WSW-W
	2G	WNW-NW
	2G1	with Partial Ridge-and-Valley Alignment
	2G2	with Full Ridge-and-Valley Alignment
	2G3	with Narrow Ridge-and-Valley Alignment

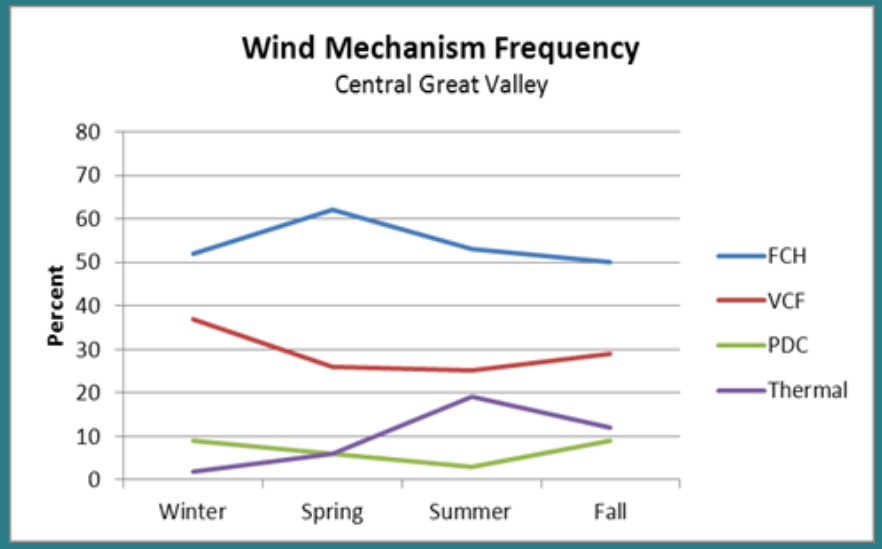
Central Great Valley Wind Classifications (continued)

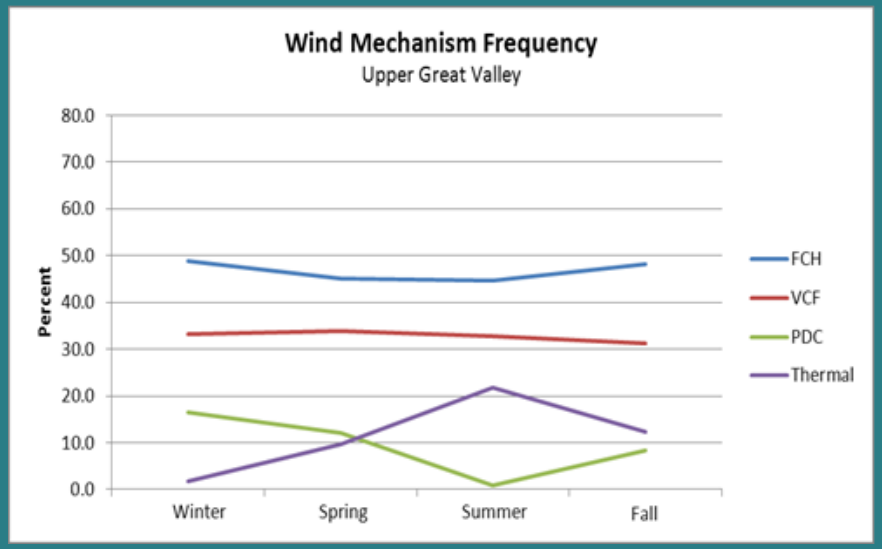
Type	ID	Description
Pressure-Driven Channeling	3A	Up-Valley (Secondary Mechanism Only)
	3B	Down-Valley
Thermally-Driven Flow	4A	Up-Valley Along-Valley Flow
	4B	Down-Valley Along-Valley Flow
	4C	Down-Slope Smoky Mountains Breeze (SE-SSE)
	4D	Up-Slope Cumberland Mountains Breeze (SE-SSE)
Down-Sloping	5A	From Cumberland Mountains and Plateau (W-NW)



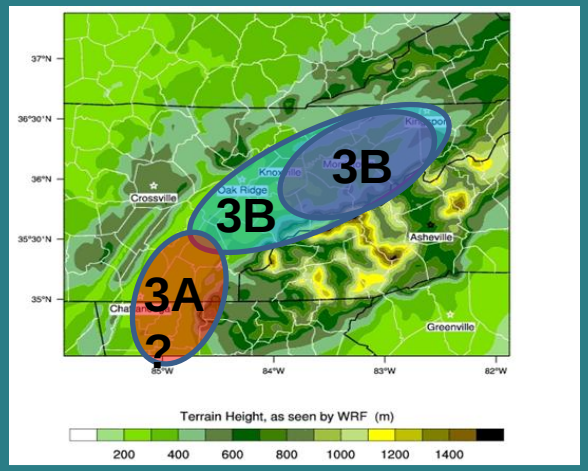
Dominant Physical Wind Mechanisms





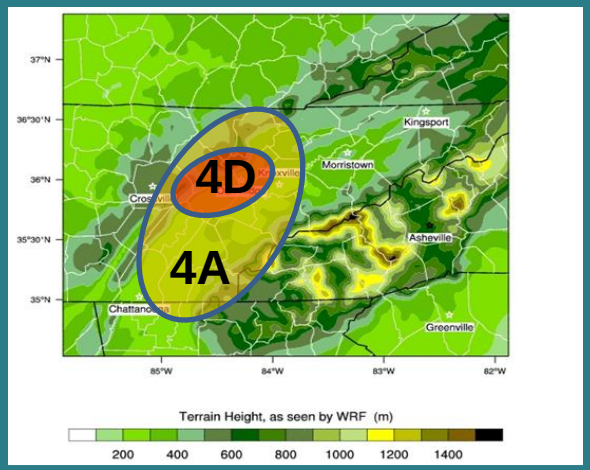


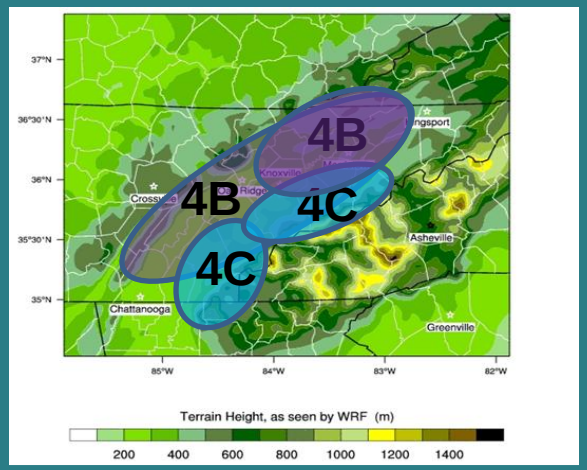
Pressure-Driven and Thermal Flow Preferences



Pressure-Driven

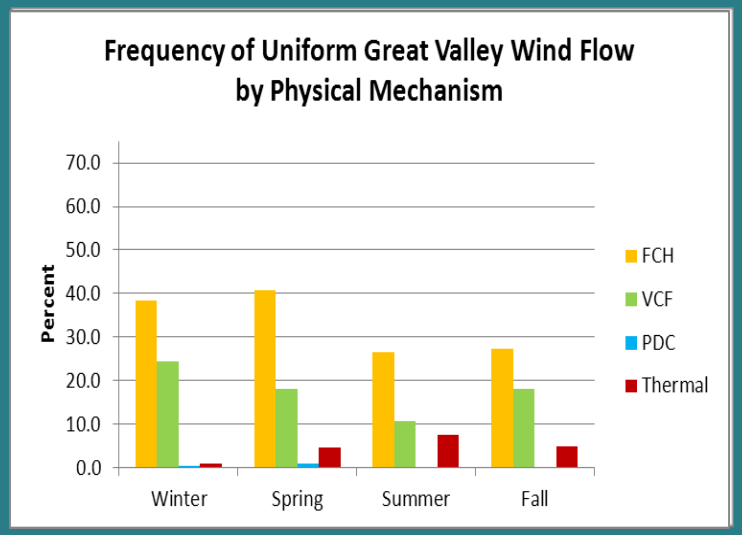
Thermal Day-Time

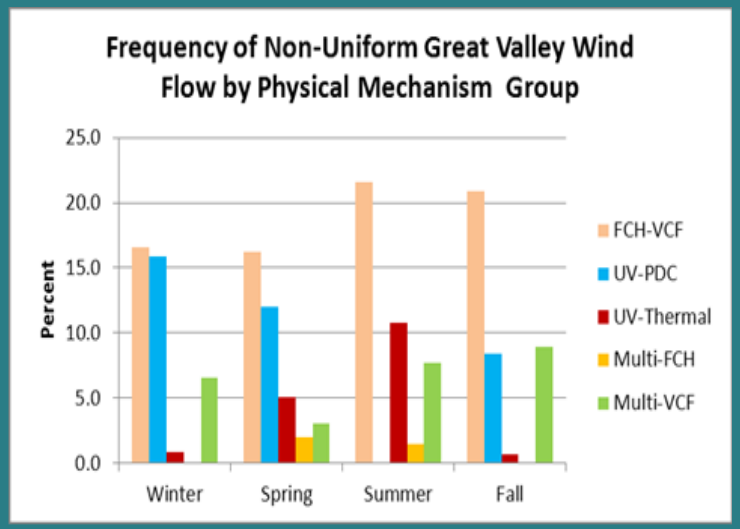


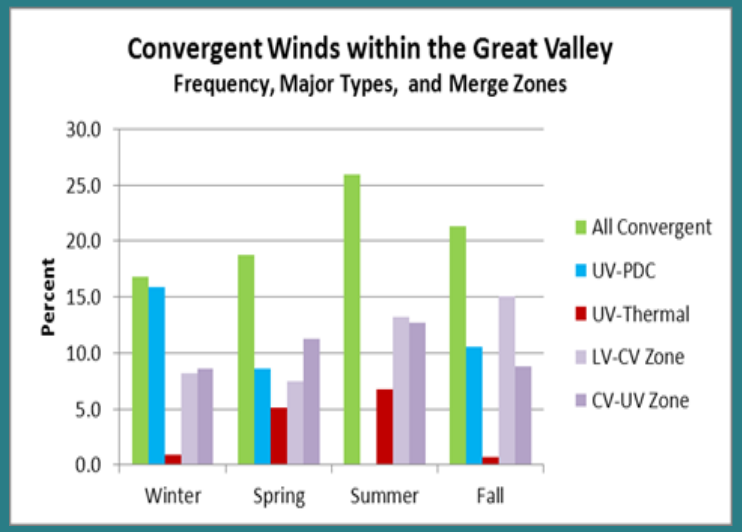


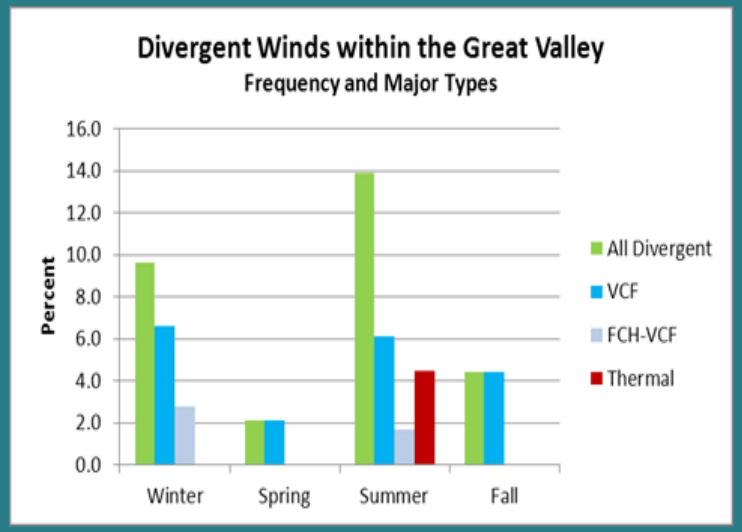
Thermal Night-Time

Great Valley At-Large Wind Class Behavior

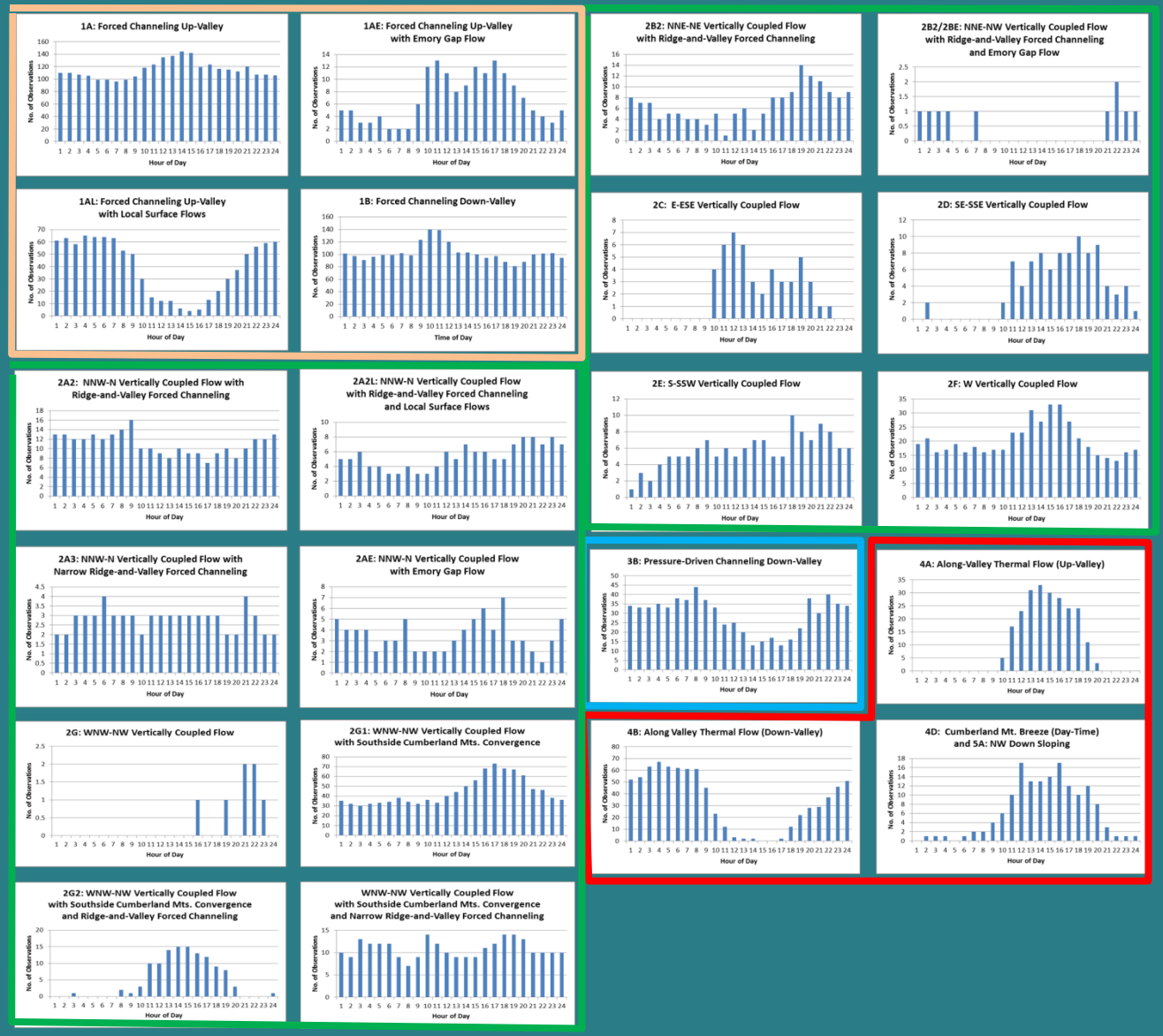






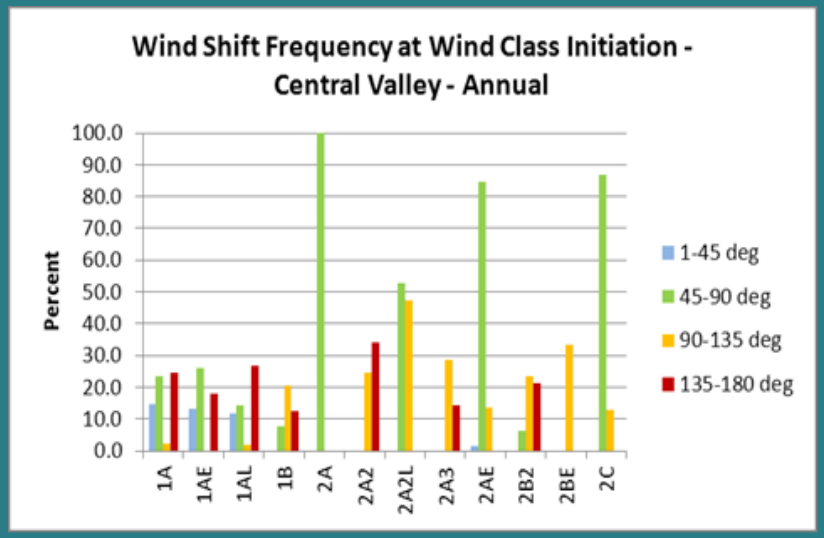


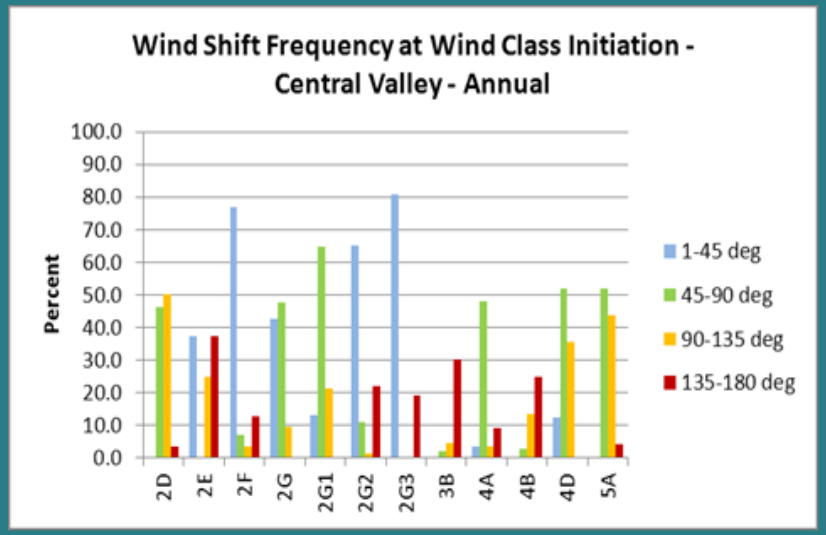
Diurnal Behavior of Wind Classes

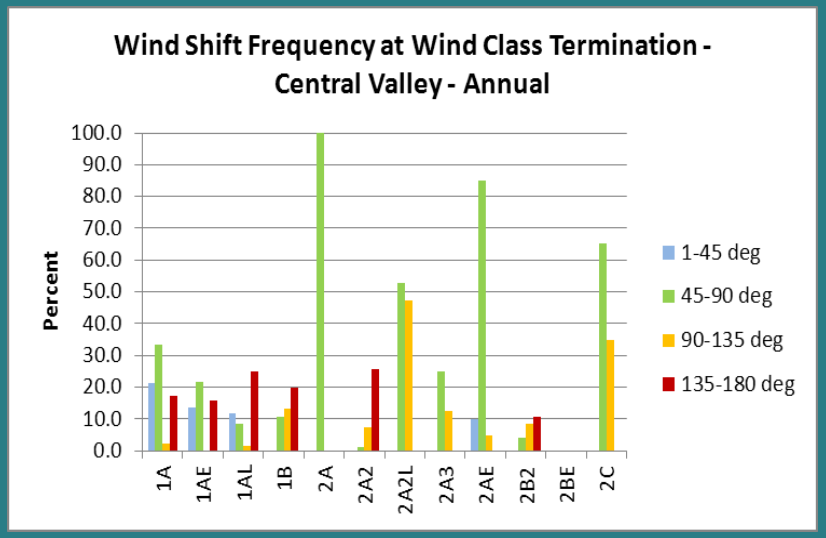


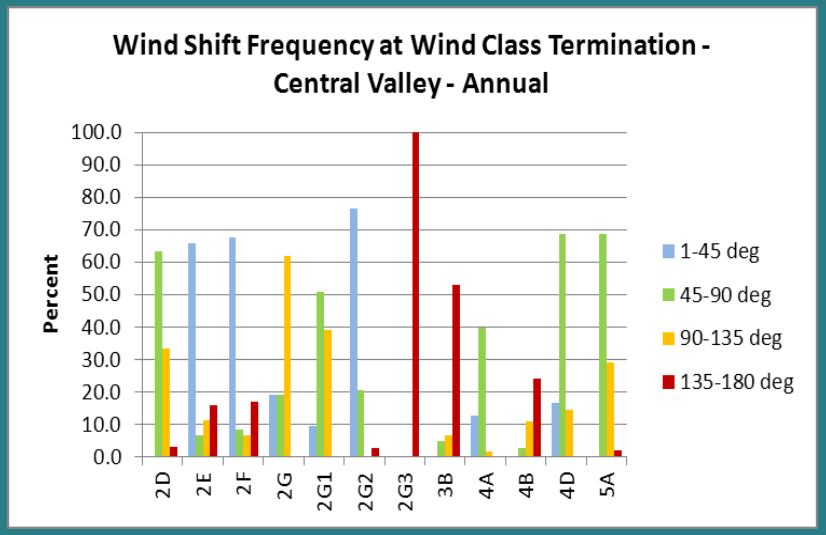
Wind Direction Shifts at Class Change

Central Valley

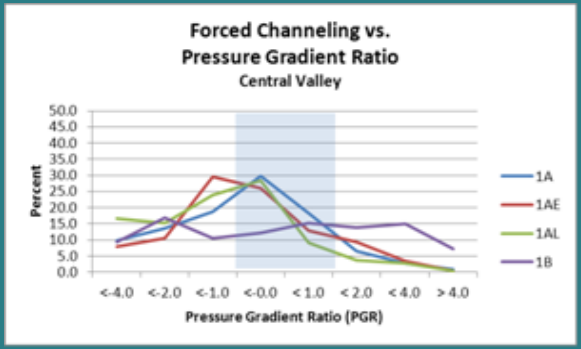


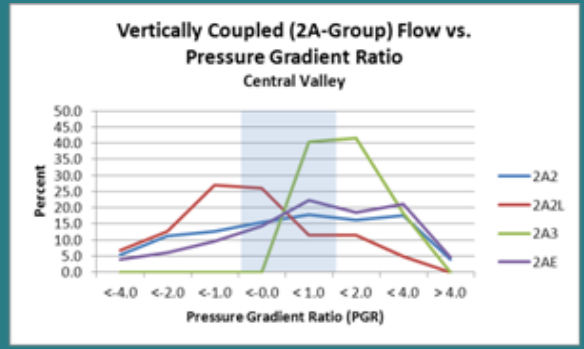


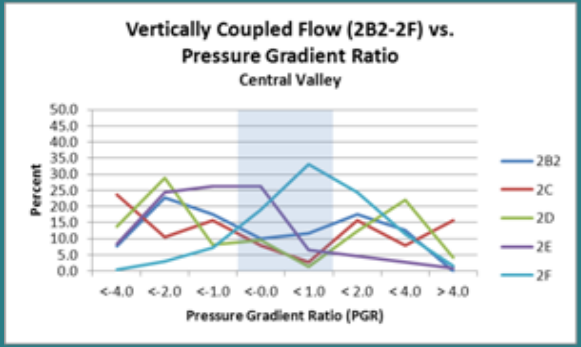


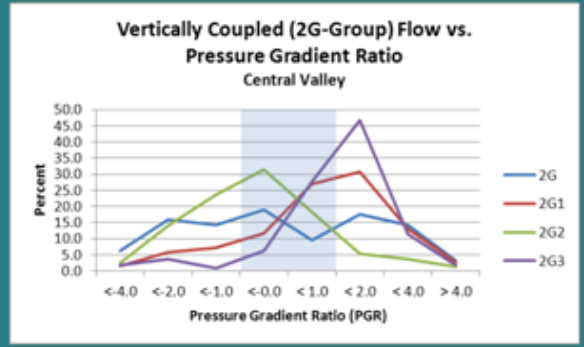


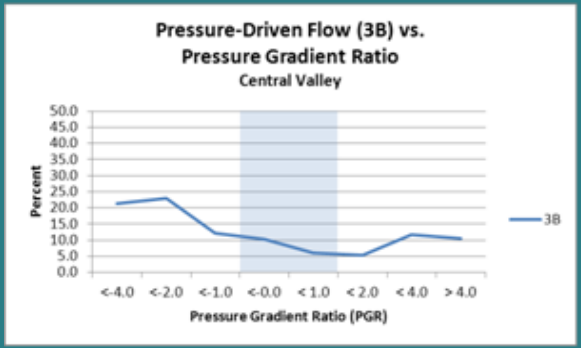
Physical Wind Mechanism vs. Pressure Gradient Ratio (Upper Valley / Lower Valley)

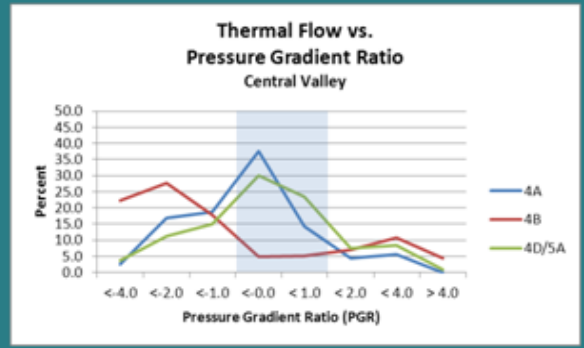












Meteorological Characteristics of Common Joined Wind Classes:
Pressure Gradient Ratio vs. Mixing Depth

PG Ratio	>8	4 to 8	2 to 4	1 to 2	0 to 1	-1 to 0	-2 to -1	-4 to -2	-8 to -4	< -8	
Mix Ht											Mix Ht
>1500						4D-4D-4A					>1500
1400						2G-2G2-2G					1400
1300											1300
1200											1200
1100							4A-4A-4A	1A-1AE-1A			1100
1000							2G-2G2-1A				1000
900									1A-1AE/1AL-1A		900
800				2G-2G1-2G							800
700				2G-2G3-2G			1A-2G2-1A				700
600				2G-2G1-1A		1A-1A-1A	1A-1A-2E				600
500	1B-1B-1B							1A-1B-1B		2B-2B2-2B	500
400	1B-1B-2B				2F-2F-1A	2A-2A2-2A					400
			1B-2A2-2G								
300			2A-2AE/2A2-2A			2A-2A2L-2A					300
						1A-1AL-4C		1A-4B-4B	4B/4C-4B-4B	4B-4B-4B	
						1AL-1AL-3B	1A-2E-3B	1A-1AL-4B	1AL-4B-4B	1A-3B-3B	
200	3B-3B-3B					1A-1AL-1A	1A-1AL-3B		3B-3B-2D	2D-3B-3B	200
100											100
PG Ratio	>8	4 to 8	2 to 4	1 to 2	0 to 1	-1 to 0	-2 to -1	-4 to -2	-8 to -4	< -8	

Also for:
Pressure Gradient Direction vs. Magnitude
Pressure Gradient Ratio vs. Synoptic Pressure Gradient Direction
Pressure Gradient Ratio vs. Synoptic Pressure Gradient Magnitude
Surface Stability vs. Great Valley Vertical Temperature Gradient (Stability)

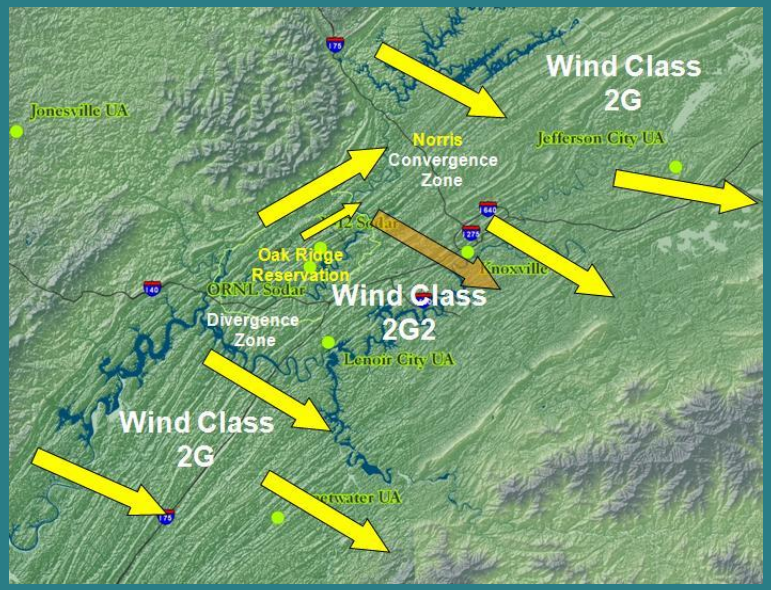
Ambient Meteorological Comparisons

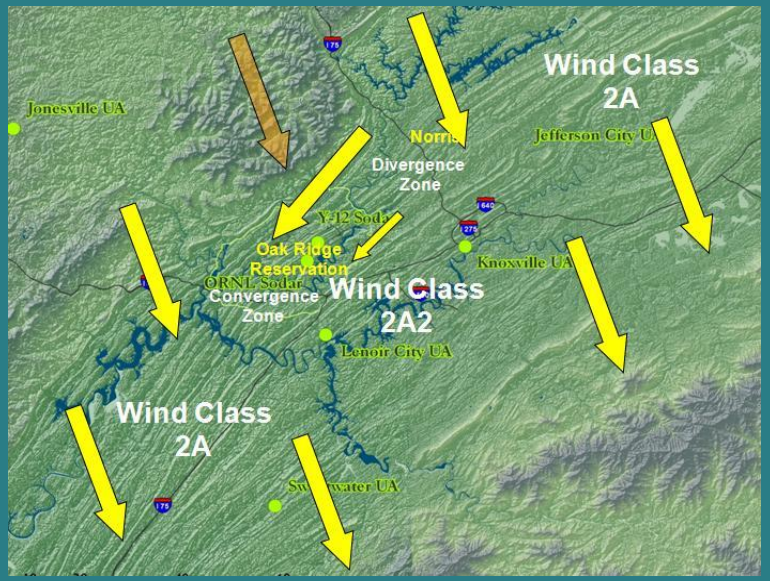
Wind Group*	Significant Secondary Mechanism	PGR	Pressure Gradient Dir. (deg.)	Pressure Gradient Mag. (mb/km)	Mixing Depth (m)	Surface Stability (A-G)	V. Temp. Grad. (° C)
FCH Up	50% PDC Up	–0.5	170°	0.005–0.009	215–615	D-F B (Day)	–4.5
FCH EGF	DS	–3.6	Variable	0.004–0.005	1050	A-D	–5.5
FCH Down	PDC Down THM Down	–4.5	2°	0.005–0.008	500	D-E B (Day)	–4.5
VCF 2A Group		+1.6	308°	0.010	385	D-E B (Day)	–3.0
VCF 2A2L	THM Down	–0.4	275°	0.006	315	E	–5.7
VCF 2F/2G Group		1.1	257°	0.008-0.016	475–900	D	–3.8
VCF 2G2	FCH Up	–1.0	175°	0.005	1050–1500	A-C	–6.0
PDC Down	FCH Down	–10.0	99°	0.006–0.012	243	E	–5.5
PDC Down All		+13.0	110°	0.008	235	E	–3.7
PDC Down UV		–1.5	131°	0.009–0.012	245	E-F	–4.0
THM Up	FCH Up	–1.0	150°	0.004	1100–1550	A-C	–5.5
THM Down			75°	0.003	255	E-F	–5.5
THM SMB UV	VCF Aloft	–1.0	160°	0.004	245	F	–5.2
THM SMB LV	VCF Aloft	–6.5	58°	0.004	245	F	–5.2
THM DS	DS	–0.1	170°	0.005	1525	A-C	–6.0
THM CMB	FCH Up	–0.1	170°	0.005	1525	A-C	–6.0

*FCH = Forced Channeling, VCF = Vertically Coupled Flow, PDC = Pressure-Driven Channeling, THM = Thermally-Driven Flow, UV = Upper Valley, LV = Lower Valley, Up = Up-Valley Flow, Down = Down-Valley Flow, EGF = Emory Gap Flow, DS = Down Sloping, All = Full-Valley Flow, SMB = Smoky Mountains Breeze, CMB = Cumberland Mountains Breeze

Effects of the Cumberland Mountains and Ridge-and-Valley Terrain

- **Slowing of synoptic winds (Cumberland Mountains)**
- **Channeling of flow (Ridge-and-Valley)**
- **Zones of local convergence and divergence (Cumberland Mountains)**
- **Minor shifts in synoptic wind aloft (< 30º) may result in flow reversal within the ridge-and-valley zones!**





Ridge-and-Valley Wind Speed Effects

Wind Class	Percent of Overall Wind Speed		
	Valley	Mid-Level	Ridge
	10 m	30 m	60–100 m
1A-1A-1A	122.6	122.8	122.9
1A-1AE-1A	112.7	110.4	97.9
1A-1AL-1A	40.4	49.7	81.6
1B-1B-1B	106.7	107.8	94.1
1B-1B-2B	105.5	107.8	105.0
2A-2A2-2A	94.2	88.2	92.1
2A-2A2L-2A	48.1	43.4	55.5
2B-2B2-2B	79.7	83.9	89.3
2F-2F-2F/1A	122.0	120.6	108.3
2G-2G1-2G	154.9	152.2	134.7
2G-2G2-2G	155.0	144.2	116.6
1A-1AL-3B	52.3	66.7	100.2
1A-3B-3B	54.2	55.4	67.5
2D-3B-3B	63.3	66.2	79.1
4A-4A-4A	127.2	110.8	85.1
4B-4B-4B	48.0	54.7	73.4
4B/4C-4B-4B	36.6	39.0	52.8

Wind Classification Summary

- 15 single wind classes in the Lower/Upper Valley
- 25 single wind classes and sub-groups in the Central Valley (due to more detailed analysis)
- 67 Great Valley At-Large wind classes (valley sections combined)
  1) 4 classes explained almost half of flow (46%)
  2) 12 classes explained two-thirds of flow (67%)
  3) 37 classes occurred with significance (92%)
  4) 67 classes occurred for 100%

- Winds between 350 to 700 m best characterized upper level flow

- 40% of joined wind classes flow along the Great Valley axis
- 10% of wind classes exhibited uniform off-axis flow
- 15-20% of patterns associated with converging patterns, 4% with divergent ones

- Most wind classes exhibited some diurnal tendencies due to mixing depth and surface stability effects.

Physical Wind Mechanism Characteristics

- **Forced Channeling most dominated winds (45-67%)**
  - **Weak-moderate synoptic pressure gradient magnitude (<0.010 mb/km)**
  - **Mixing depth (especially summer)**
  - **50% up-valley co-occurrence with pressure-driven flow**
  - **Up-valley flow significantly involved in wind reversals (>135)**

- **Vertically Coupled Flow, 2nd most dominant mechanism (22-38%)**
  - **Strong synoptic pressure gradient magnitude (winter)**
  - **Pressure gradient weaker for southerly VCF vs. northerly VCF**
  - **Mixing depth (especially summer)**
  - **90% locally channeled by ridge-and-valley terrain**
  - **2A/2F/2G-groups involved in major wind shifts (90-135)**

- **Pressure-Driven Channeling (0-17%)**
  - **Moderate strong pressure gradients (0.008-0.016 mb/km)**
  - **Several types favoring Central/Upper Great Valley)**
  - **Shallow mixing depths (200-250 m)**
  - **Unstable upper level atmosphere**
  - **Down-valley cases (3B) for east-southeast synoptic pressure gradient**
  - **Up-valley cases (3A) not observed as dominant wind mechanism**
  - **Significantly involved in wind reversals (>135)**

Physical Wind Mechanism Characteristics
(continued)

- **Thermally-Driven Winds, (2-20%)**
  - Favored Central/Upper Valley (especially upper)
  - Primarily occur during summer and fall
  - Existence of Cumberland Mountains and Smoky Mountains Breezes
  - Moderately involved in wind reversals (>135)

- **Down Sloping**
  - Observed in associated with some forced channeling (1AE) as Emory Gap Flow
  - Vertically coupled flow associations (2G, 2G1, 2G2) in two forms:
    a) strong day-time heating situations
    b) associated with post-frontal cold air advection

- **Prediction**
  - Knowledge of synoptic pattern allowed for 65-85% prediction of wind class (maximum winter/spring; minimum summer)
  - Knowledge of ambient meteorology described here allowed for wind pattern selection based on provided tables when synoptic situation was not sufficient
  - Wind class succession tables provided a probabilistic guide for such analyses

Summary of Topographic Effects on Wind Classes

- **Cumberland Mountains and Plateau**
  - (1) Down Sloping
  - (2) Day-Time Cumberland Mountains Breeze (Fall)

- **Great Smoky Mountains**
  - (1) Enhancement of Down-Valley Pressure-Driven Channeling
  - (2) Night-Time Smoky Mountains Breeze (Summer, Fall)
  - (3) Wind Deflection and Deceleration

- **Emory Gap Flow**
  - (1) Channeling of “Blocked” Flow (around Cumberland Mountains)
  - (2) Down Sloping

- **Ridge-and-Valley Terrain**
  - (1) Enhancement of Valley-wide and Local Drainage Winds
  - (2) Enhancement of Down-Valley Pressure-Driven Winds
  - (3) Channeling of Great Valley At-Large Vertically Coupled Flow
  - (4) Significant Increases of Wind Direction Reversals

Worst Case Meteorology By Wind Class

Wind Class	Frequency (%)	Air Quality Risk	Wind Class	Frequency (%)	Air Quality Risk
1A-1A-1A	20.9	Moderate	4A-4A-4A	2.0	Low
1B-1B-1B	12.6	Moderate	1A-1AE-1A	1.4	Low
1B-1B-2B	7.0	Moderate	2A-2A2-2A	1.4	Low
2G-2G1-2G	5.9	Low	2B-2B2-2B	1.4	Low
2F-2F-2F/1A	4.2	Low	1A-1A-2E	1.4	Low
1A-1AL-1A	2.8	High	1AL-1AL-3B	1.2	Moderate/High
2D-3B-3B	2.6	Moderate	2G-2G2-2G	1.1	Low
4B-4B-4B	2.6	High	2A-2A2L-2A	1.1	Moderate/Low
2G-2G3-2G	2.2	Low	1A-1AL-4B	1.0	High
1A-3B-3B	2.2	Moderate/High	2G-2G1-1A	1.0	Low
1A-1AL-3B	2.1	Moderate/High	1A-2G2-1A	1.0	Low
4B/4C-4B-4B	2.1	High			

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Future Projects

- ***Comparison of Wind Classes to Worst-Case Meteorology***
- ***Routine Analysis of Wind Fields for Wind Prediction (coding)***
- ***Characterization of Other Wind Environments***
- ***Weather Model Refinement***
- ***Environmental Characterization for Wind Power Generation***

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Further Information

- ***http://www.ornl.gov/~das/met/MT/KRB_ORNL.pdf***

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