Meteorological Data Collection, X/Q and D/Q, Critical Receptors

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Presented at the 23rd Annual RETS-REMP Workshop Training Session
Westminster, CO / 24 Jun 2013

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Regulatory Basis and Guidance

- <u>Guidance for Meteorological Data Collection</u>
  - Safety Guide 23, issued in 1972
  - Various drafts of Regulatory Guide 1.23 released in 1970s-80s; never formally issued
  - Regulatory Guide 1.23, Revision 1 officially issued in 2007, primarily to support new construction
  - ANSI/ANS 2. 5, issued 1984
  - ANSI/ANS 3.11, issued 2000, 2005, ongoing

Regulatory Basis and Guidance

- <u>Guidance for Atmospheric Dispersion Calculations</u>
  - Regulatory Guide 1.111, issued in 1977
  - “Meteorology and Atomic Energy – 1968”, D.H. Slade editor... the “bible” for dispersion calculations and equations
  - NRC XOQDOQ software application, developed in 1982, updated to modern PC platforms; NUREG/CR-2919 user manual

Basic Meteorological Data

- Wind direction – affects which sector and receptor is affected
  - Ensure sensors are aligned to true north, not magnetic north or plant north
- Wind speed – affects plume travel time and dilution; also affects dispersion/mixing
- Atmospheric stability – affects dispersion and mixing of pollutant in atmosphere... dilution
- Accuracy requirements for these elements are specified in Regulatory Guide 1.23

Joint Frequency Data

- 3 meteorological elements must be present simultaneously
  - Wind speed
  - Wind direction
  - Indicator of atmospheric dispersion; most commonly vertical temperature difference (Delta-T), but can be wind direction variability (Sigma-Theta)
- Often assessed at multiple heights; ground level (usually 10-meters) and elevation(s) of interest

Joint Frequency Data (continued)

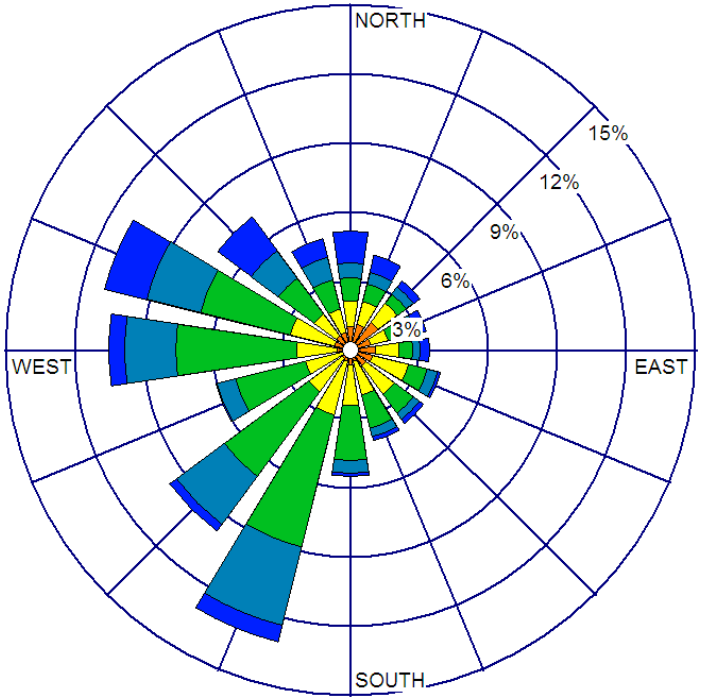
- Usually based on 1-hour averaged data, but some plants use 15-minute averages
- Data are binned by wind direction (compass sectors = 16), wind speed category (7 to 11), and atmospheric stability class (7 classes)... 784 to 1232 discrete bins
- NRC specifies a target annual JFD recovery goal of >90% in Regulatory Guide 1.23

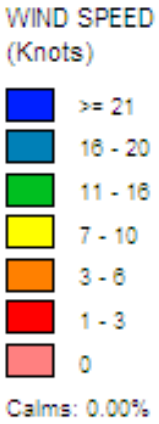
Points Regarding Averaging

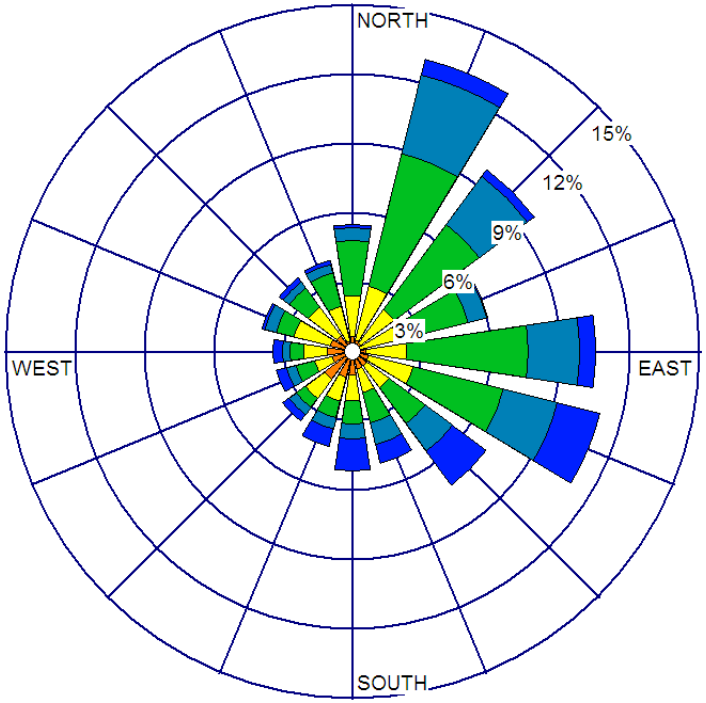
- Hourly and 15-minute averages are typically calculated from all “instantaneous” records collected over period of interest; if once/second, hourly average would represent 3600 data points
- Conventional arithmetic averaging can be used for wind speed and temperature readings, *BUT NOT* wind direction
- Wind direction averaging must be performed using a scalar average or vector average. Consider two wind direction records of 358° and 4°:
  - Arithmetic average = (358 + 4) ÷ 2 = 181°, the wrong answer
  - Scalar Average = 361° or 1°, the correct answer

Wind Rose

- Wind rose can be used as a useful tool to visualize predominant wind speed and direction patterns
- “Wind From” versus “Wind Toward” rose







Pasquill Stability Class Table

from Regulatory Guide 1.23, Rev.1

- Provides an indication of how unstable the atmosphere is, which affects how rapidly a parcel of air is mixed and dispersed... degree of spatial dilution

Table 1. Classification of Atmospheric Stability

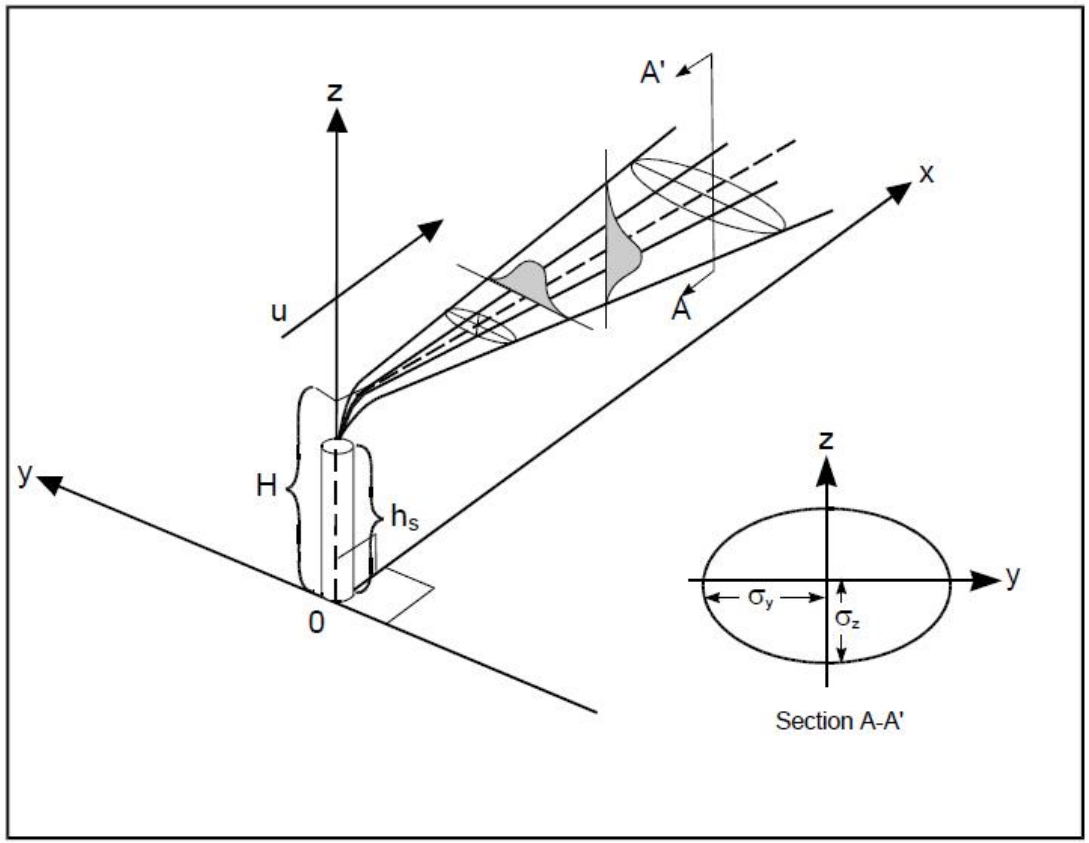
Stability Classification	Pasquill Stability Category	Ambient Temperature Change With Height (°C/100m)
Extremely unstable	A	$\Delta T \leq -1.9$
Moderately unstable	B	$-1.9 < \Delta T \leq -1.7$
Slightly unstable	C	$-1.7 < \Delta T \leq -1.5$
Neutral	D	$-1.5 < \Delta T \leq -0.5$
Slightly stable	E	$-0.5 < \Delta T \leq 1.5$
Moderately stable	F	$1.5 < \Delta T \leq 4.0$
Extremely stable	G	$\Delta T > 4.0$

General Approach

- Apply mathematical equations to predict how meteorological conditions will disperse airborne radioactivity once it is released from site; most models assume a Gaussian dispersion pattern
- Resulting airborne concentrations (uCi/cc, pCi/m^3) can be calculated at various receptor locations based on “typical” meteorological conditions
- NRC advises use of “...long-term, annual average meteorology...” for calculation of dose impact from routine releases; NRC encourages use of 3 to 5 years of meteorological data

Gaussian Plume Dispersion

- Plume spreads in vertical and horizontal directions following a Gaussian distribution



Dispersion X/Q Equation

$$\frac{X}{Q} = \underbrace{\frac{1}{2\pi\sigma_y\sigma_z\bar{u}}}_{\text{Plume Centerline Concentration at Distance x}} \bullet \underbrace{\exp\left(-\frac{y^2}{2\sigma_y^2}\right)}_{\text{Horizontal Dispersion Component}} \bullet \underbrace{\left(\exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right]\right)}_{\text{Vertical Dispersion Component, Including Reflection}}$$

σ_y = horizontal dispersion coefficient at distance x, meters

σ_z = vertical dispersion coefficient at distance x, meters

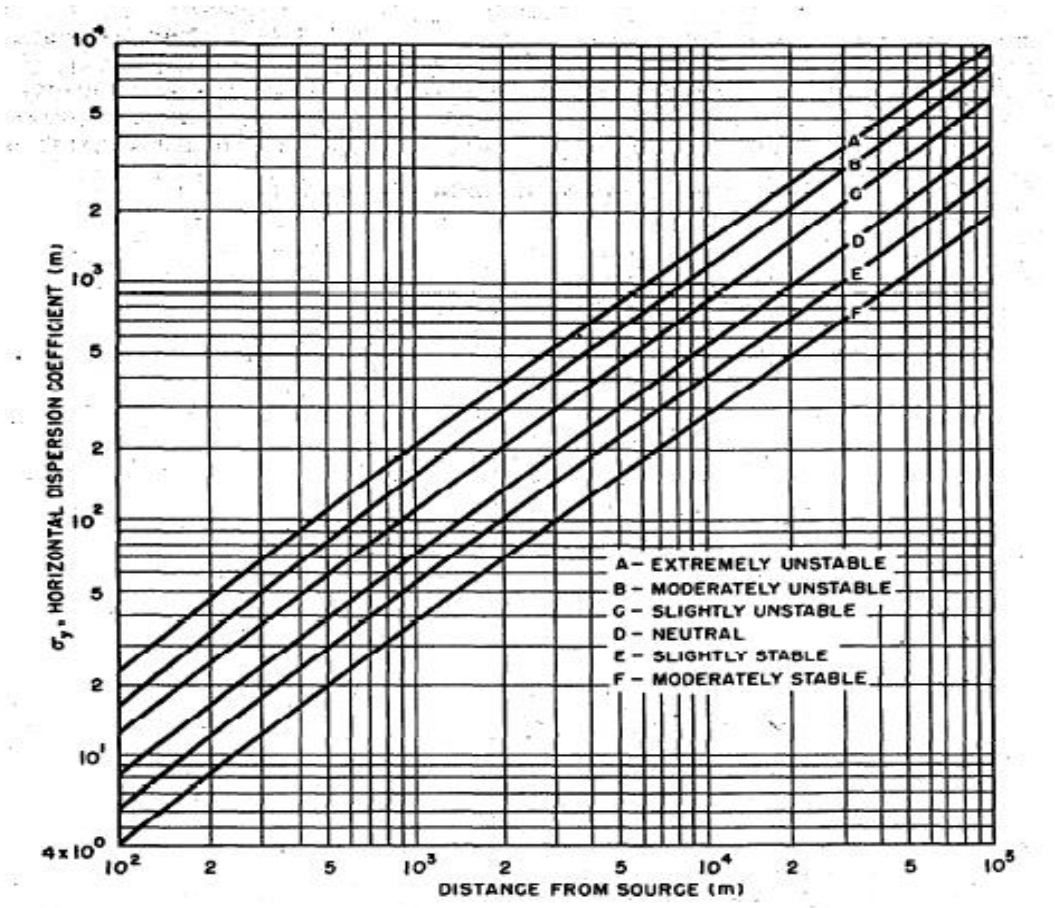
$\bar{u}$ = mean wind velocity at height of release, meters/sec

y = horizontal distance from plume centerline at distance x, meters

z = terrain height above ground at distance x, meters

h = elevation of release point above ground, meters

Horizontal Dispersion – σ_y

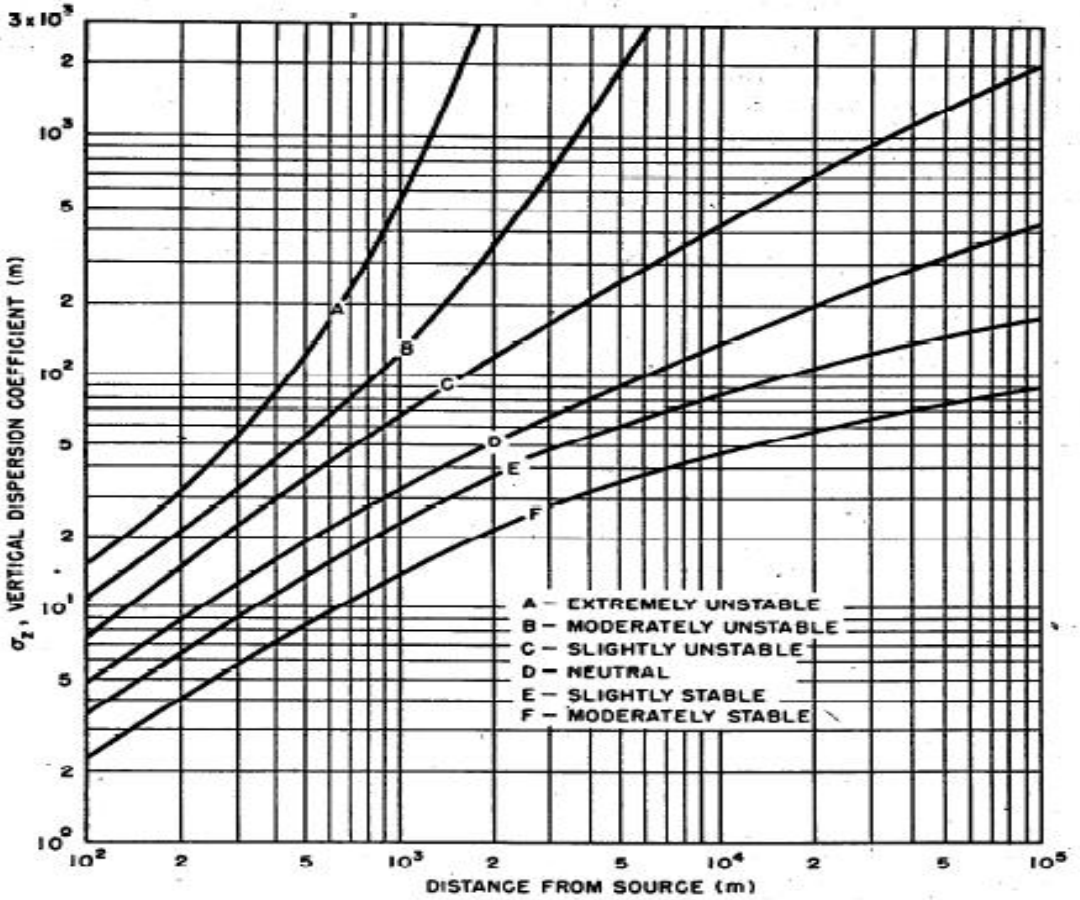


Horizontal Dispersion Coefficient - σ_y

- Horizontal dispersion coefficient – meters

Category	Distance - km				
	0.1	0.3	1	3	10
A	26.9	71.8	208.7	546.4	1541.3
B	19.3	52.2	154.1	409.2	1174.0
C	12.5	34.3	103.1	279.0	820.1
D	8.2	22.6	68.1	184.6	543.6
E	6.1	16.9	50.9	138.1	406.9
F	4.1	11.2	33.9	91.9	270.9

Vertical Dispersion – σ_z



Vertical Dispersion Coefficient - σ_z

- Vertical dispersion coefficient – meters

Category	Distance - km				
	0.1	0.3	1	3	10
A	14.0	47.4	453.9	4642.9	5000.0
B	10.6	30.1	109.3	364.8	1366.8
C	7.4	20.3	61.1	167.0	502.3
D	4.7	12.1	32.1	65.1	134.9
E	3.5	8.7	21.6	42.2	79.1
F	2.3	5.6	14.0	27.0	46.4

Effect of Release Height

- Height of release above the ground – “removes” release away from the ground, allows for more dilution
- Stack height must exceed twice the height of adjacent structures to be considered elevated
- Several factors can influence effective release height
  - Physical height of stack
  - Exit velocity – “pushes” release higher up into atmosphere
  - Wind velocity – causes release to “bend” horizontally
  - Gas Temperature – adds convective buoyancy to effluent

Dispersion X/Q Equation

$$\frac{X}{Q} = \underbrace{\frac{1}{2\pi\sigma_y\sigma_z\bar{u}}}_{\text{Plume Centerline Concentration at Distance x}} \bullet \underbrace{\exp\left(-\frac{y^2}{2\sigma_y^2}\right)}_{\text{Horizontal Dispersion Component}} \bullet \underbrace{\left(\exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right]\right)}_{\text{Vertical Dispersion Component, Including Reflection}}$$

σ_y = horizontal dispersion coefficient at distance x, meters

σ_z = vertical dispersion coefficient at distance x, meters

$\bar{u}$ = mean wind velocity at height of release, meters/sec

y = horizontal distance from plume centerline at distance x, meters

z = terrain height above ground at distance x, meters

h = elevation of release point above ground, meters

Ground-level Release

- Release occurs at or near ground-level
- Mixes immediately in surface air
- Ground-level concentrations are highest at point of emission, and decrease with increasing distance from point of emission
- Air follows ground surface contour – terrain has no effect on concentrations from ground-level release
- Calculated based on lower-level meteorological data

Ground-level Release X/Q

- Ground level release, wind speed 2 m/sec or about 4.5 mph
- Plume centerline X/Q value - sec/m3

Category	Distance - km				
	0.1	0.3	1	3	10
A	2.1E-04	2.3E-05	8.4E-07	3.1E-08	1.0E-08
B	3.9E-04	5.1E-05	4.7E-06	5.3E-07	5.0E-08
C	8.6E-04	1.1E-04	1.3E-05	1.7E-06	1.9E-07
D	2.1E-03	2.9E-04	3.6E-05	6.6E-06	1.1E-06
E	3.7E-03	5.4E-04	7.2E-05	1.4E-05	2.5E-06
F	8.4E-03	1.3E-03	1.7E-04	3.2E-05	6.3E-06

Elevated Release

- Stack height must exceed twice the height of adjacent structures to be considered elevated
- Height of release above the ground – elevates release away from the ground, allows for more dilution
- Release plume can travel some distance before mixing down to ground level; plume can “skip over” receptors close to release point
  - Although nuclides may not occur in air at ground level, external radiation “shine” can result in direct radiation exposure on ground
- Plume touchdown occurs closer with unstable classes (A, B) and more distant with stable classes (E,F,G)
- Calculated based on elevated-level meteorological data

Elevated Release, Ground-level Receptor Vertical dispersion component

- 60 meter stack height, wind speed 2 m/sec or about 4.5 mph
- Vertical dispersion component at ground level – dimensionless
- Multiply by plume centerline concentration

Category	Distance - km				
	0.1	0.3	1	3	10
A	1.9E-04	9.0E-01	2.0E+00	2.0E+00	2.0E+00
B	2.2E-07	2.8E-01	1.7E+00	2.0E+00	2.0E+00
C	1.5E-14	2.6E-02	1.2E+00	1.9E+00	2.0E+00
D	1.5E-36	9.0E-06	3.5E-01	1.3E+00	1.8E+00
E	5.5E-63	9.3E-11	4.3E-02	7.3E-01	1.5E+00
F	5.6E-145	3.9E-25	1.9E-04	1.7E-01	8.7E-01

Elevated Release, Ground-level Receptor X/Q Value

- 60 meter stack height, wind speed 2 m/sec or about 4.5 mph
- Plume centerline X/Q value at ground level - sec/m3

Category	Distance - km				
	0.1	0.3	1	3	10
A	4.1E-08	2.1E-05	1.7E-06	6.3E-08	2.1E-08
B	8.7E-11	1.4E-05	8.1E-06	1.1E-06	9.9E-08
C	1.3E-17	2.9E-06	1.6E-05	3.2E-06	3.8E-07
D	3.1E-39	2.6E-09	1.3E-05	8.7E-06	2.0E-06
E	2.0E-65	5.0E-14	3.1E-06	9.9E-06	3.7E-06
F	4.7E-147	4.9E-28	3.2E-08	5.4E-06	5.5E-06

Elevated Release, Elevated Receptor Vertical dispersion component

- 60 meter stack height, wind speed 2 m/sec or about 4.5 mph
- Vertical dispersion component at 30 m height – dimensionless
- Multiply by plume centerline concentration

Category	Distance - km				
	0.1	0.3	1	3	10
A	9.9E-02	9.8E-01	2.0E+00	2.0E+00	2.0E+00
B	1.8E-02	6.2E-01	1.7E+00	2.0E+00	2.0E+00
C	3.0E-04	3.4E-01	1.2E+00	1.8E+00	2.0E+00
D	9.3E-10	4.6E-02	6.7E-01	1.3E+00	1.8E+00
E	2.3E-16	2.6E-03	3.8E-01	8.8E-01	1.5E+00
F	7.3E-37	6.7E-07	9.9E-02	5.4E-01	9.6E-01

Elevated Release, Elevated Receptor X/Q Value

- 60 meter stack height, wind speed 2 m/sec or about 4.5 mph
- Plume centerline X/Q value at 30 m height - sec/m3

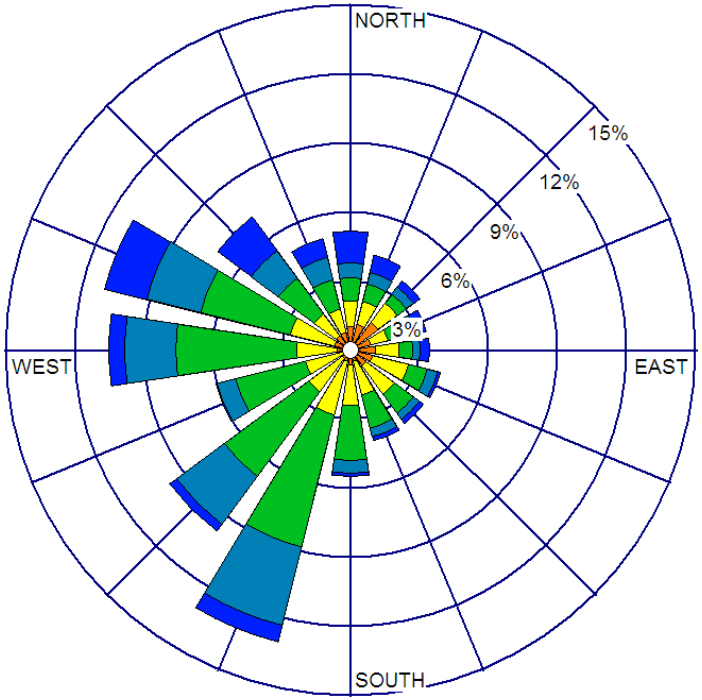
Category	Distance - km				
	0.1	0.3	1	3	10
A	2.1E-05	2.3E-05	1.7E-06	6.3E-08	2.1E-08
B	7.1E-06	3.1E-05	7.9E-06	1.0E-06	9.9E-08
C	2.5E-07	3.8E-05	1.5E-05	3.2E-06	3.8E-07
D	1.9E-12	1.3E-05	2.4E-05	8.5E-06	1.9E-06
E	8.4E-19	1.4E-06	2.8E-05	1.2E-05	3.6E-06
F	6.1E-39	8.4E-10	1.7E-05	1.7E-05	6.1E-06

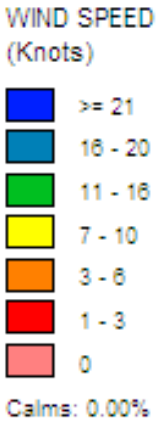
Effect of Terrain

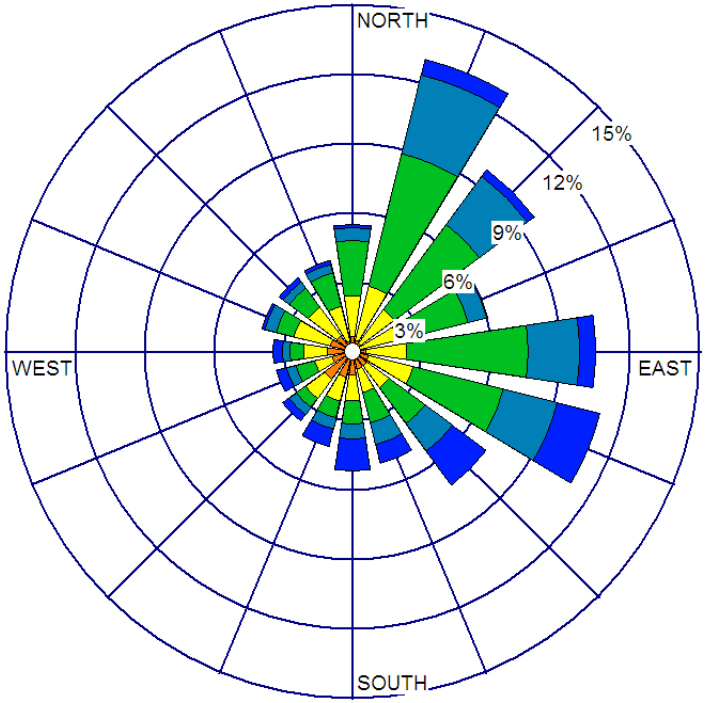
- Important only for elevated releases
- Terrain “pushes” the ground up toward or into the plume
- Shortens distance needed for plume touchdown
- Can result in upwind or cross-wind sectors yielding relatively high X/Q values

Wind Rose

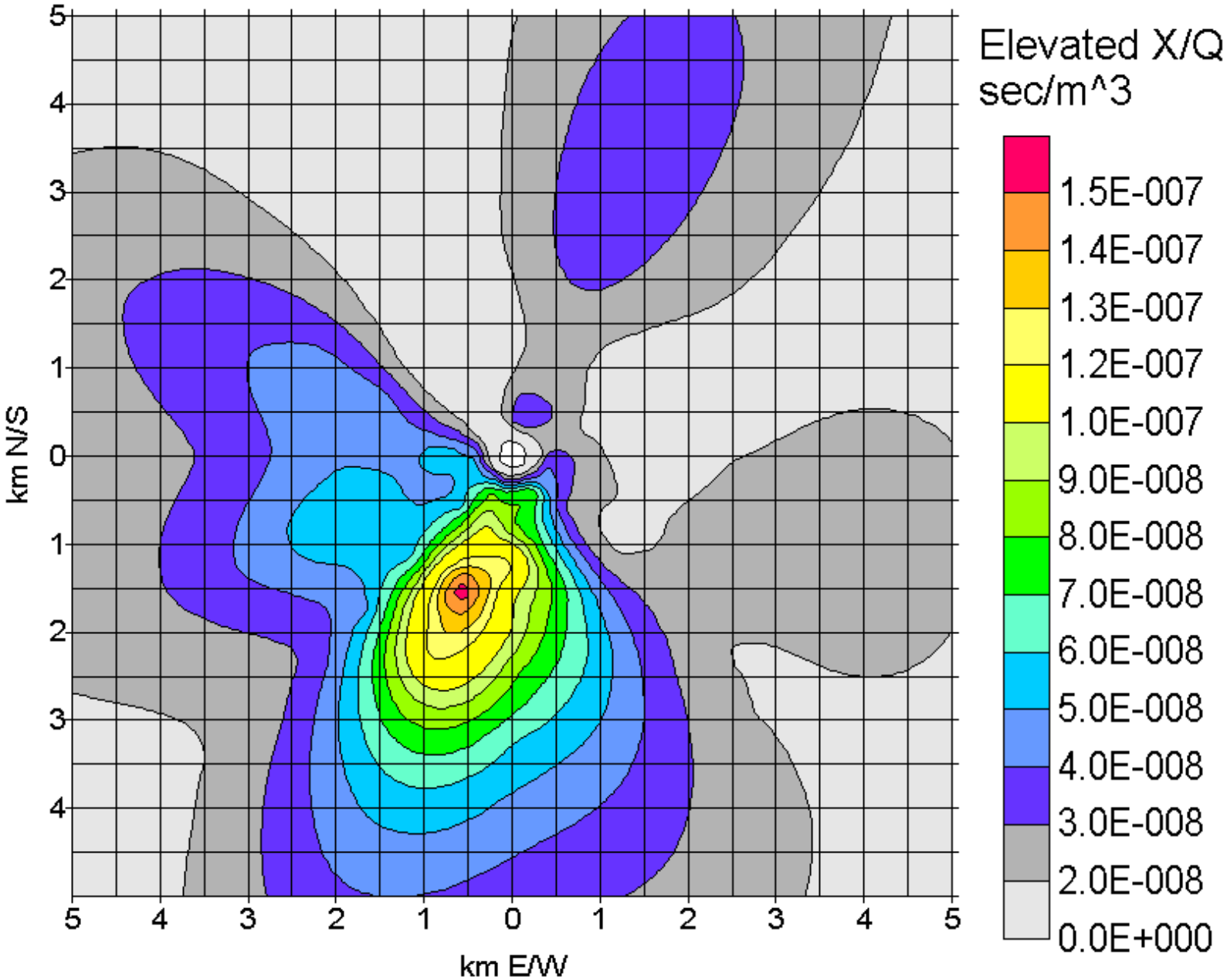
- Wind rose can be used as a useful tool to visualize predominant wind speed and direction patterns
- “Wind From” versus “Wind Toward” rose

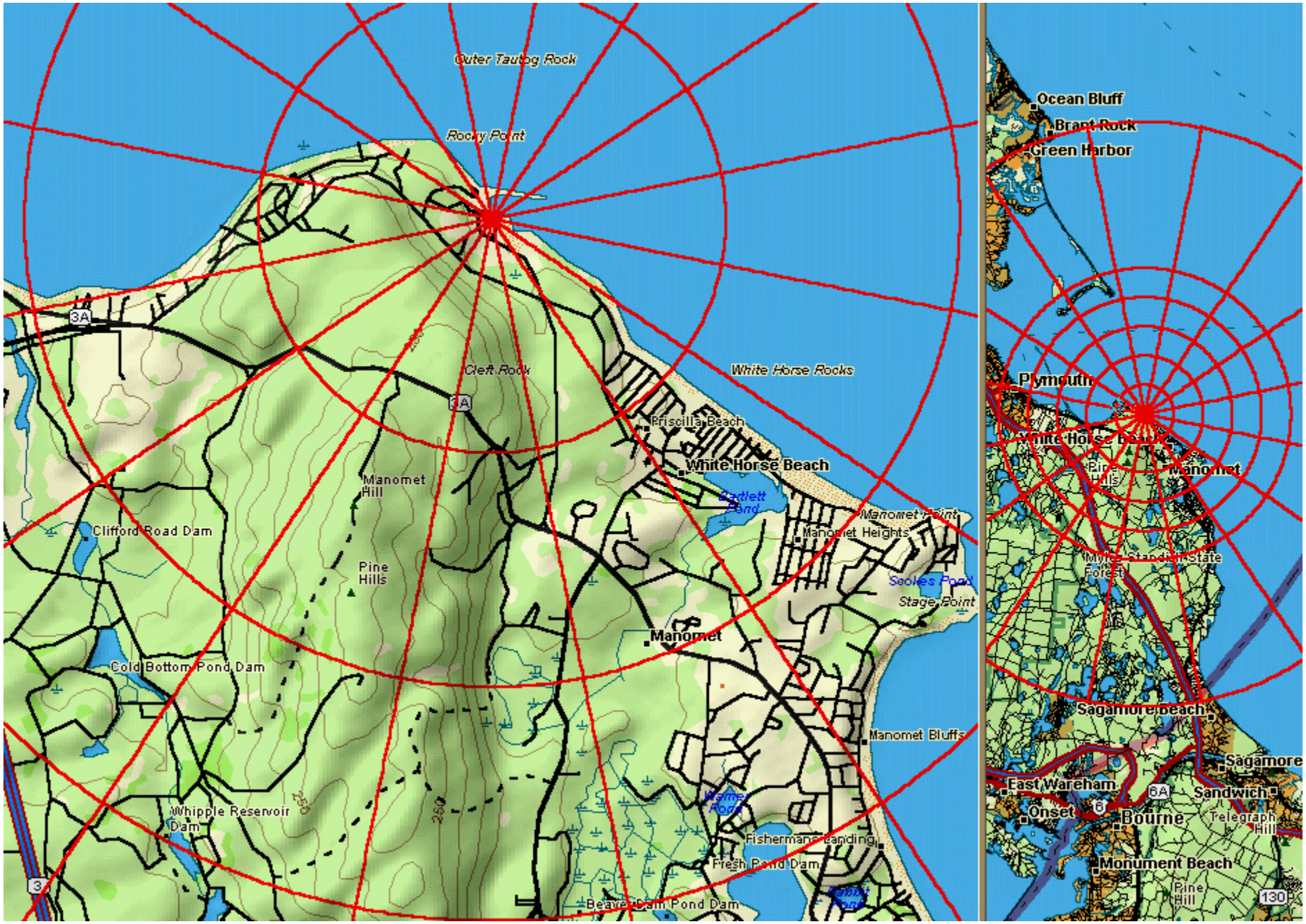






Pilgrim Station Elevated X/Q




Outer Tautog Rock
Rocky Point
Cleft Rock
White Horse Rocks
Priscilla Beach
White Horse Beach
Bartlett Pond
Manomet Point
Manomet Heights
Sookes Pond
Stage Point
Manomet
Manomet Hill
Pine Hills
Clifford Road Dam
Cold Bottom Pond Dam
Whipple Reservoir Dam
Manomet Bluffs
Warner Pond
Fishermans Landing
Fresh Pond Dam
Beaver Dam Pond Dam
Rabbit Pond
3A
3
250
Ocean Bluff
Brant Rock
Green Harbor
Plymouth
Manomet
Myles Standish State Forest
Sagamore Beach
Sagamore
East Wareham
Onset
Bourne
Sandwich
Telegraph Hill
Monument Beach
Pine Hill
6A
6
130

Ocean Bluff
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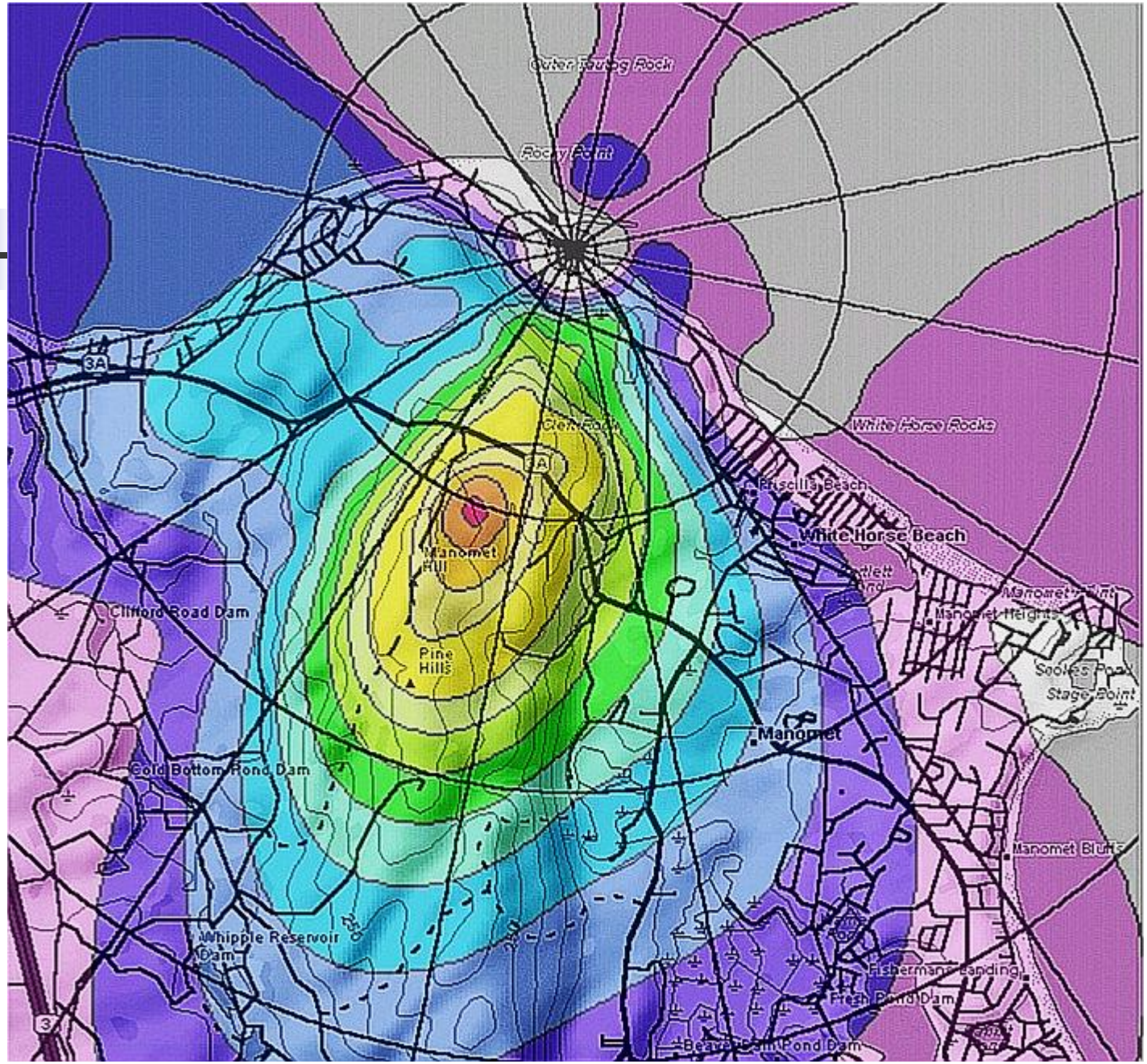
Bourne
Telegraph Hill
Monument Beach
Pine Hill
6A
6
130

PNPS Release Characteristic

- Stack Height: 335 feet
- Stack Base: 66 feet MSL
- Effective Release Height: 401 feet MSL
- Maximum terrain height near plant:
  - Manomet Hill
  - 395 feet MSL
  - 1.35 miles SSW
- “Ground-level” relative to stack exit


Rocky Point
White Horse Rocks
Priscilla Beach
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Manomet Hill
Pine Hills
Clifford Road Dam
Manomet Heights
Stage Point
Manomet
Cold Bottom Pond Dam
Manomet Bluffs
Whipple Reservoir Dam
Fisherman's Landing
Fresh Pond Dam
Beaver Dam Pond Dam
3A
3

Removal Mechanisms

- Depletes airborne concentration in plume; latter two can deposit radioactivity on soil and plants
- Radioactive Decay – function of wind speed and downwind distance; only important for nuclides with half-lives of seconds or minutes, may affect some noble gases, not important for particulates with half-life>8 days
- Dry Deposition – function of particle settling velocity, results in deposition of activity on soil & plants, affects D/Q
- Wet Deposition – function of precipitation

X/Q Modifications - 1

- Removal mechanisms result in different types of X/Q value
  - Concentration X/Q - undepleted, undecayed; usually used for gaseous nuclide calculations
  - Decayed X/Q - corrected for radioactive decay, thus is nuclide dependent
  - Depleted X/Q - corrected for deposition/removal of particles out of plume; usually used for particulate nuclide calculations
  - Depleted-decayed X/Q - corrected for both radioactive decay and deposition
- "Gamma" X/Q – adjusted for direct gamma radiation shine from radioactive material contained in plume by applying the "I Function"
  - Guidance provided in Regulatory Guide 1.109, Appendix F
  - Since it is dependent on gamma intensity (energy+yield), the correction is nuclide-dependent
  - Not addressed in NRC's XOQDOQ software

X/Q Modifications -2

- <u>Time of year adjustments</u>
  - Potential consideration for calculation of concentrations for crop production with defined growing season
  - Calculate X/Q based on long-term dataset for growing season (Apr-Oct), which may have different wind speed, wind direction, and stability class frequencies than long-term annual average dataset

X/Q Modifications -3

- Time of day adjustments
  - Special consideration for calculation of concentrations of Carbon-14 in vegetation, in which C-14 is absorbed from the air mosly during daylight hours via photosynthesis
  - Calculate X/Q based on long-term dataset for daytime hours, which will likely have higher wind speeds and higher frequency of Class A, B, C stability classes than long-term annual average dataset, due to solar heating

D/Q – Deposition Coefficient

- Calculated in similar manner to X/Q, but incorporates particle settling or dry deposition of material from the plume
- Calculated from X/Q multiplied by particle settling velocity:
  $sec/m^3 * m/sec = 1/m^2$
- Used to determine the deposition of radioactivity per unit area of ground or on vegetation
- General pattern of D/Q follows that of X/Q; subject to same behavior for ground-level and elevated releases... general reduction with increasing distance, “skip over” phenomenon for elevated releases

Receptor Considerations

- "Critical Receptor" is usually the location of receptor receiving highest calculated dose
- Highest calculated dose usually corresponds with highest X/Q and D/Q, but also affected by which exposure pathways occur at receptor location
  - For ground-level releases, highest dose receptors will always be closest to plant; doses will decrease with increasing distance
  - For elevated releases, highest dose may occur at locations well beyond the nearest resident
  - Receptor locations that involve ingestion pathways, even though at a lower X/Q location can yield higher doses than a higher X/Q location where only inhalation pathway occurs

Receptor Considerations
(continued)

- Special consideration must be given to sites with multiple release points
  - The highest dose receptor for each individual release point may not be the highest dose receptor when both release points are combined
  - Changes in mix of radionuclides released can result in critical receptor location changing from year to year; e.g., I-131 may result in one receptor with a milk pathway being the highest one year, but in years with low I-131 releases a different receptor location with a garden may yield the highest dose ;issue becomes even more complicated with multiple release points

REMP Sampling Considerations

- Many of the aspects for selecting critical receptor location also apply to REMP sampling locations
- Original placement of REMP air samplers likely took into account meteorological conditions; some licensees have questioned need to relocate historical air samplers due to changes in meteorolgical patterns
- Selection of new garden and milk animal sampling locations is based on a comparison of D/Q values

Updating X/Q and D/Q

- The NRC recommends evaluating meteorology and X/Q, D/Q every 5 to 10 years to look for changes in patterns that can affect critical receptor
- The NRC provides a criterion for adding a new garden or milk animal if it yields a dose 20% higher than an existing location in the REMP sampling program
  - Technically, is a 20% increase justifiable given the HUGE uncertainties in X/Q and D/Q calculations?
  - Wind speeds and directions are binned into discrete terminators, but likely represent a continuum; neighboring houses can have X/Q values an order of magnitude apart, just because they are in different compass sectors
  - Delta-T values are treated as discrete terminators for atmospheric stability class, while stability/mixing is more likely a continuum
  - The Pasquill sigma-y and sigma-z curves are only approximations on a log-log graph; how precise are these values?

Summary

- Meteorological data collection and dispersion calculations are not for the faint-of-heart, but don't be intimidated
- Examine equations in RG-1.111 and other documents to gain understanding of how each meteorological parameter affects dispersion values; the internet has much informative information
- Pay attention to the characteristics of your gaseous release points. Are they properly classified? Does your stack meet the criteria for an elevated release point?

Summary (continued)

- Evaluate your critical receptors, giving consideration to all release points, applicable exposure pathways, and interdependencies on radionuclides released

Questions?