

# BASIC METEOROLOGY AND ATMOSPHERIC TRANSPORT MODELING

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## Purpose



Present an overview of atmospheric dispersion principles and applications appropriate for environmental radiological risk assessment activities

#### **Outline of Presentation**



- Fundamentals of meteorology
- Introduction to atmospheric modeling
- Gaussian plume model
- ► Alternative dispersion models
- Model validation studies

#### **Basic Questions**

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**Magnitude of an Airborne Exposure** 

- ► WHERE is the release going?
  - -- Wind direction
- ►WHEN will the release arrive at a location?
  - -- Wind speed
- ► WHAT is the release concentration?
  - -- Atmospheric diffusion

## Physical Concepts Atmospheric Motion

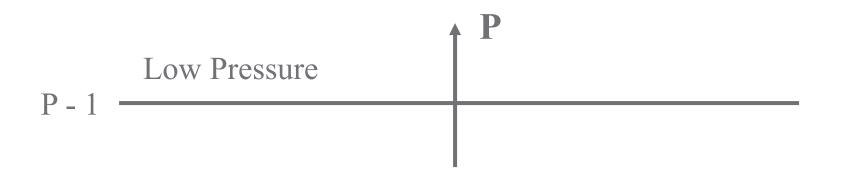
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- **►**Mass
- **Energy**
- **►**Heat
- **►**Momentum

#### **Pressure Gradient Force**



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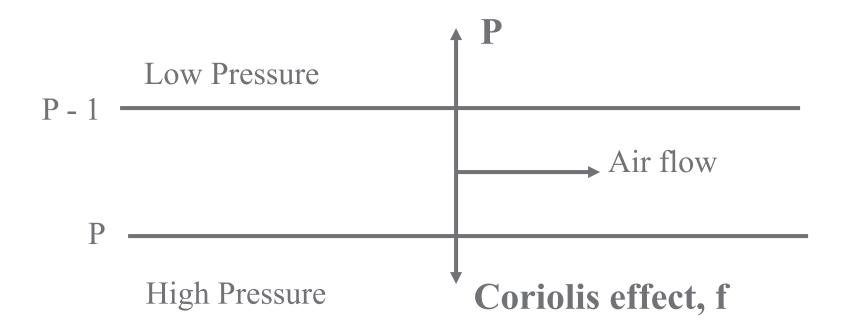


P

High Pressure

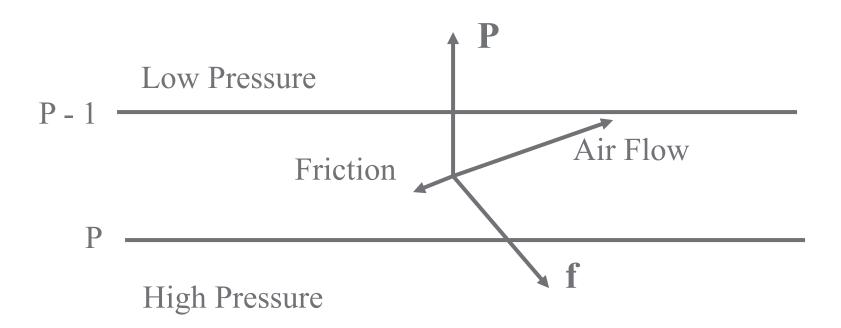
## **Geostrophic Wind**





### **Frictional Effects**





## Representative Surface Roughness Lengths

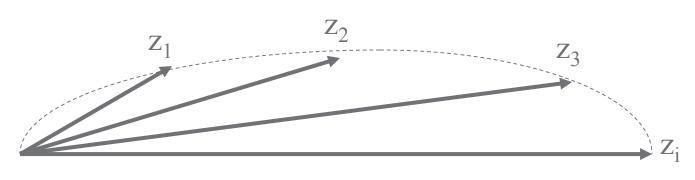


Type of surface	Surface Roughness (m)
Very smooth (ice, mud flats)	0.00001
Grass lawn	0.001 - 0.01
Thin grass up to 50 cm high	0.05
Thick grass up to 50 cm high	0.1
Woodland forest	0.2
Urban areas	1 - 3





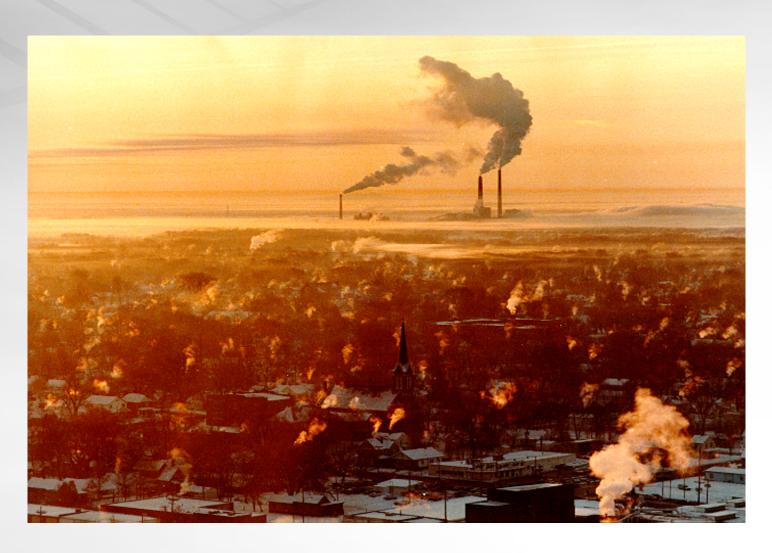
#### The Ekman Spiral



Geostrophic Wind Speed

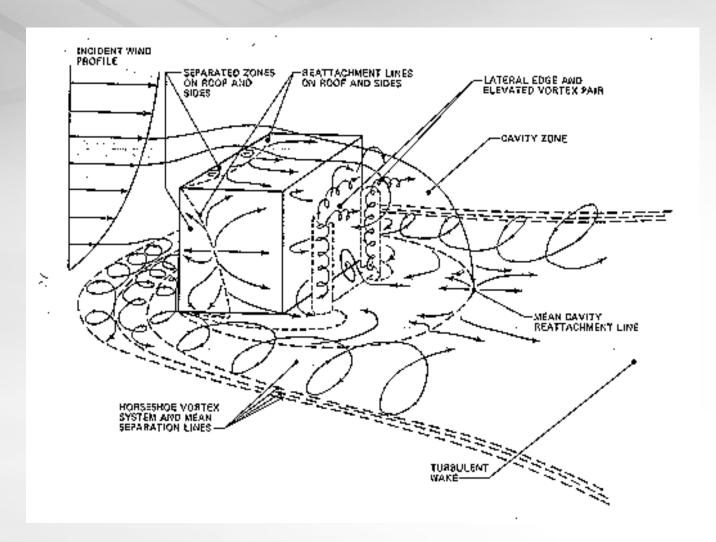
## Early Morning Winter Plumes Springfield, Illinois January 31, 1990





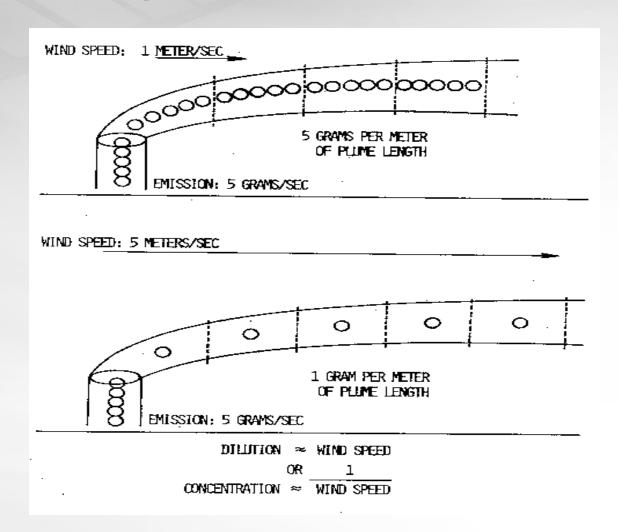
## Flow Around a Large Structure





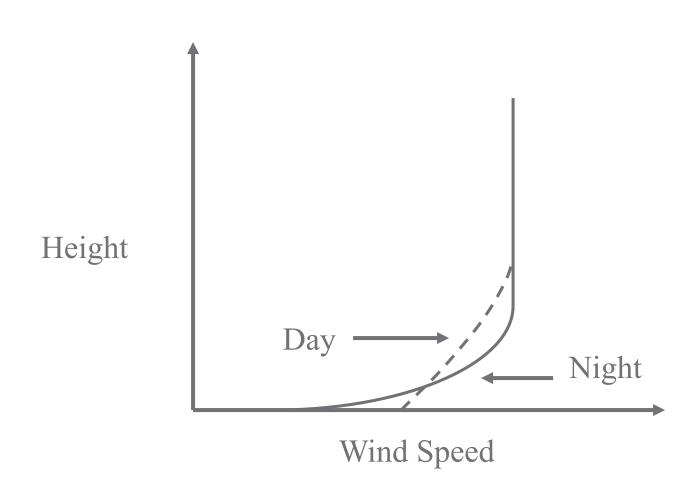


#### **Effect of Wind Speed on Air Concentration**



## Wind Speed vs. Height Diurnal Variations





#### **Turbulence**



- ► A very disorganized motion of the air
- Studied as a statistical random process
- ► Fluctuations of the wind velocity about its mean value

### **Types of Turbulence**



- Mechanical
  - Result of frictional drag of earth's surface
  - Proportional to the wind speed and the roughness of the underlying surface
- Thermal
  - Result of heating of earth's surface by sun
  - Creates rising thermals
  - Depends on strength of incoming insolation and nature of underlying surface

#### The Lower Atmosphere



Temperature

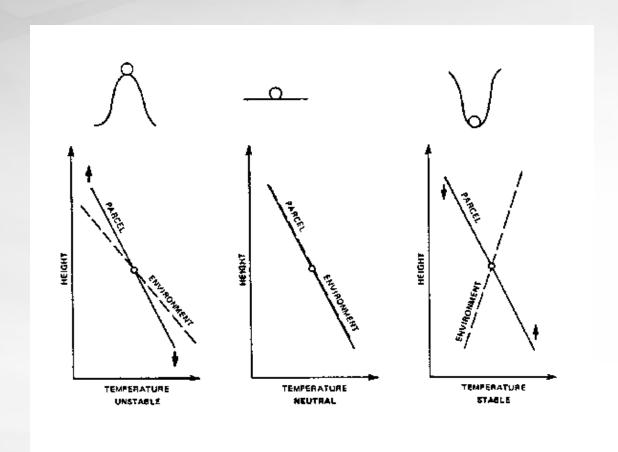
STRATOSPHERE

Tropopause
10 km
TROPOSPHERE

Atmospheric Boundary Layer
0 km
The Earth's Surface

### **Atmospheric Stability**









- Should be continuously measurable
- ►Often divided into finite classes, A -G
- ►Often inferred, e.g. from solar insulation
- Methods of determination do not always agree

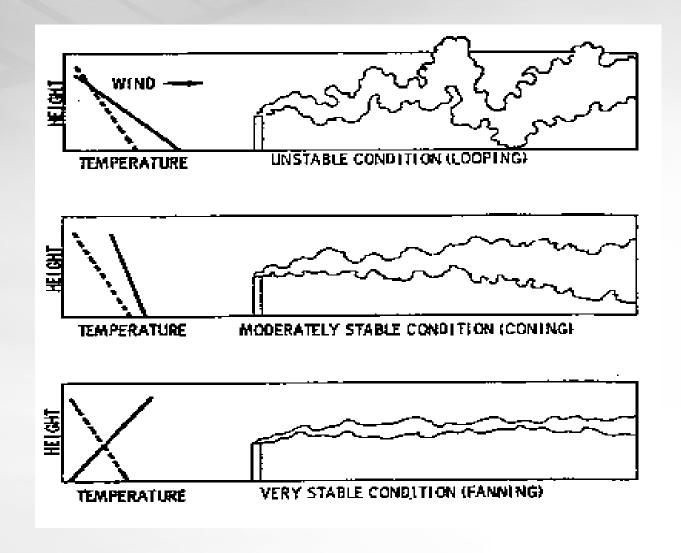
### **Pasquill Stability Categories**



Wind speed	Daytime Insolation			Nighttime Conditions	
at 10 m (m s <sup>-1</sup> )	Strong	Moderate	Slight	>3/8 clouds	<3/8 clouds
<2	А	A – B	В		
2 – 3	A – B	В	С	Е	F
3 - 5	В	B – C	С	D	Е
5 – 6	С	C – D	D	D	D
>6	С	D	D	D	D

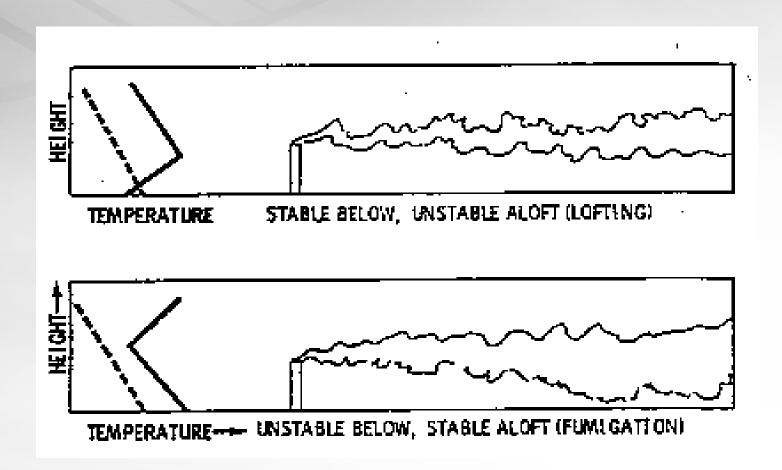


#### Plumes vs. Stability Class



## Plumes vs. Stability Class Continued





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#### **Monin-Obukhov Length**

- A measure of atmospheric stability
- Absolute value is depth of mechanically mixed layer near the surface
- ► Continuous rather than discreet
- Can be related to the Pasquill stability classes

#### **Advection - Diffusion Equation**

$$\frac{\partial C}{\partial t} = K_x \frac{\partial^2 C}{\partial x^2} + K_y \frac{\partial^2 C}{\partial y^2} + K_z \frac{\partial^2 C}{\partial z^2} - u \frac{\partial C}{\partial x} \pm S$$

C = air concentration (activity m<sup>-3</sup>)

t = time(s)

 $K_x$ ,  $K_y$ ,  $K_z$  = diffusion coefficients in the x, y, and z directions, respectively

S = sources and sinks

 $u = \text{average wind speed (m s}^{-1})$ 

### **Solution Approaches**

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- Analytical (Closed Solutions)
  - Exact solution
  - Easy to program, fast to run
  - Limited to simple cases
- Numerical
  - More general & flexible
  - Complex geometries
  - Temporal variations
  - Treat more processes explicitly
  - Often need extensive data and resources

## Important Source Term Characteristics



- Height of release above ground
- ►Time and duration of release
- Geographical location of release
- ► Structures near release
- Buoyancy of release

### **Source Term Characteristics**



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(Continued)

- Point, line, or area source
- ► Gaseous or particulate
- Chemically reactive in atmosphere
- ▶ Radioactive

#### **Theories of Diffusion**



- Statistical theory
- ► Gradient transport, or K-theory
- ► Similarity theory
- ► Higher-order closure theory

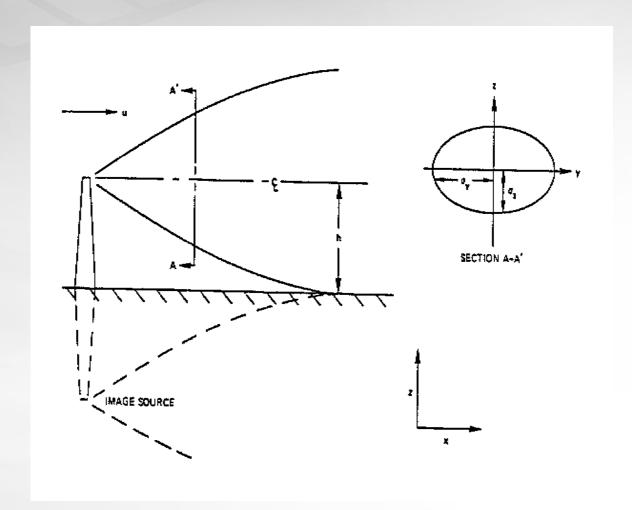
#### **Gaussian Plume Model**



- Most commonly used atmospheric dispersion model
- ▶ It is consistent with the random nature of turbulence
- ▶ It is a solution to the Fickian (K-theory) diffusion equation for constants K and u

#### **Gaussian Plume Model**





## Gaussian Plume Model Ground-level, Centerline



$$\frac{\chi(x)u}{Q} = \frac{1}{\pi\sigma_y(x)\sigma_z(x)} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z(x)}\right)^2\right]$$

 $\chi(x) = \text{Air concentration (activity m}^{-3})$ 

u = Wind speed (m s<sup>-1</sup>)

Q = Total release of radionuclide (activity) or release per unit time (activity s<sup>-1</sup>)

$$\frac{\chi(x)u}{Q}$$
 = The Gaussian diffusion factor

 $\sigma_y(x)$ ,  $\sigma_z(x)$  = The Gaussian plume diffusion factors in the crosswind (y) and vertical (z) directions, respectively, as a function of the downwind distance (x) (m) H = height of the release (m)

## Gaussian Plume Model Ground-level, Sector-averaged



$$\frac{\chi(x)u}{Q} = \frac{2.032}{\pi x \sigma_z(x)} \exp\left[-\frac{1}{2} \left(\frac{H}{\sigma_z(x)}\right)^2\right]$$

 $\chi(x) = \text{Air concentration (activity m}^{-3})$ 

 $u = Wind speed (m s^{-1})$ 

Q = Total release of radionuclide (activity) or release per unit time (activity s<sup>-1</sup>)

$$\frac{\chi(x)u}{Q} = \text{The Gaussian diffusion factor}$$

 $\sigma_z(x)$  = The Gaussian plume diffusion factors in the vertical (z) direction as a function of the downwind distance (x) (m) H = Height of the release (m)

## Limitations of the Gaussian Plume Model



- Low wind speeds
- Complex terrain
- Spatial and temporal changes in wind velocity
- Deposition and transformation within the plume during travel

## Why is the Gaussian Plume Model Used Today?

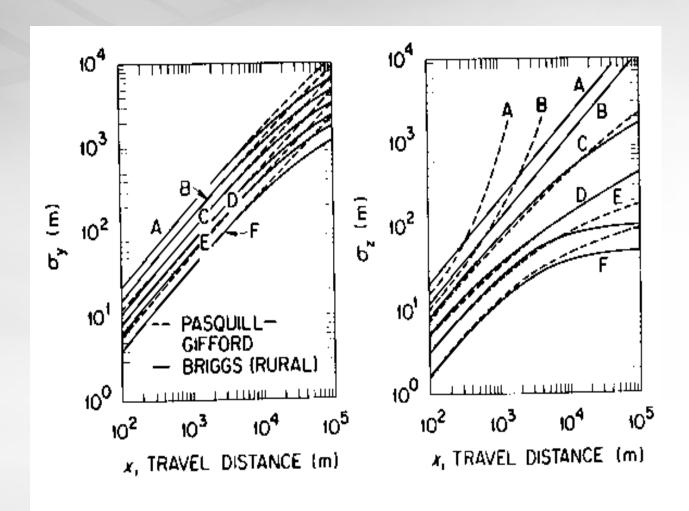


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### It works!!

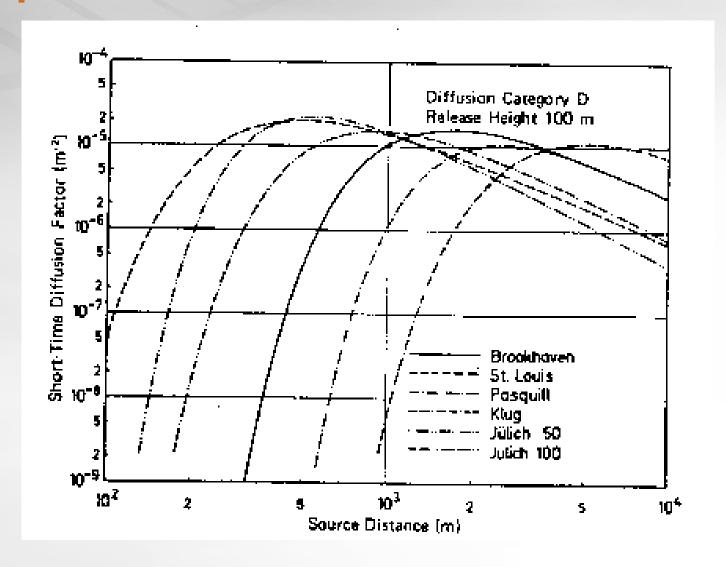
#### **Diffusion Parameters**







#### **Comparison of Diffusion Factors**

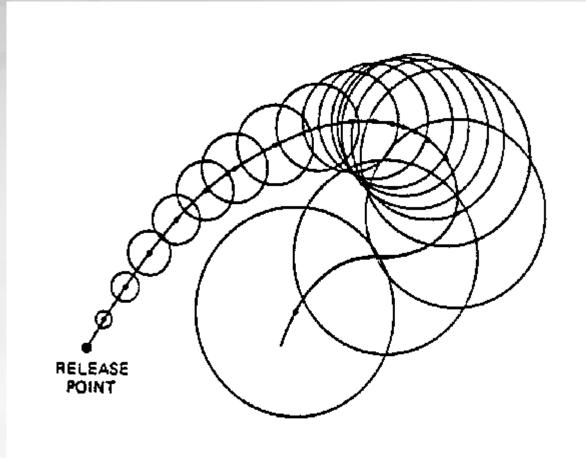


## Pacific Northwest NATIONAL LABORATORY Uncertainty in Gaussian Plume Mode Proudly Operated by Battelle Since 1965

Conditions	Range, Predicted over Observed air concentration (P/O)
Highly instrumented site; ground-level, centerline; within 10 km of a continuous point source	0.65 to 1.35
Specific time and location, flat terrain, steady meteorology, within 10 km of release point	0.1 to 10
Annual average, specific location, flat terrain, within 10 km of release point	0.5 to 2
Annual average, specific location, flat terrain, 10 m to 150 km downwind	0.25 top 4
Complex terrain or meteorology, episodic releases	0.01 to 100
Episodic, surface-level releases, wind speeds less than 2 m s <sup>-1</sup>	1 to 100

### **Puff Trajectory Model**





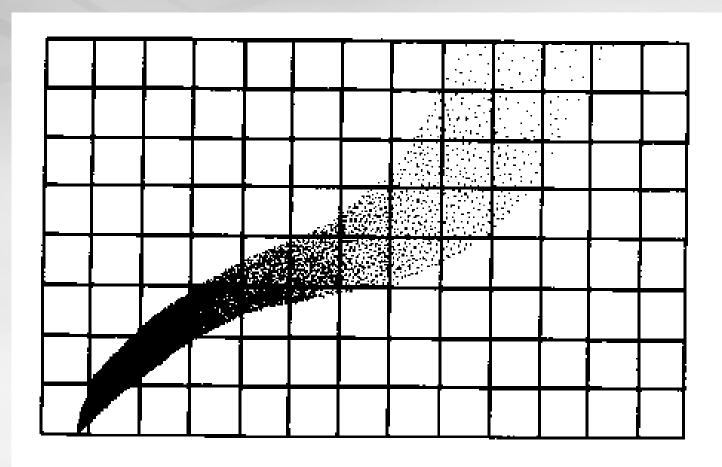
#### **Puff Trajectory Model**



- Series of discrete puffs used to approximate a continuous plume
- Wind direction, wind speed, mixing depth, and stability updated regularly
- Allows temporal variations in source characteristics
- Allows spatial and temporal variations in meteorological conditions
- Diffusion within each circular puff generally assumed to be Gaussian in nature

#### Particle-in-Cell Model





#### Particle-in-Cell Model



- Source emissions approximated by a large number of particles
- Each particle is followed over a fixed coordinate system
- Concentration in each grid square is found by adding the contribution from each particle
- Requires specification of a wind field
- Specified wind velocity is three-dimensional, and may vary from cell to cell
- Terrain effects may be incorporated

## More Complex Models Require More Pacific NATION Resources



- Data input requirements are larger and more complex
- Larger computer capacity required
- Generally longer computer running times
- ► Model predictions more difficult to verify





- ► The atmosphere is complicated
- Wind direction is a key variable in atmospheric dispersion modeling
- ► Turbulence theory is being incorporated into assessment models
- ► Empirically-based Gaussian plume models are still widely used







Object General Information			
Object General Information			
Easting coordinate 0 km	Class Fate & Transport	▼	
Northing coordinate 0 km	Group Air	▼	
Elevation 0 km	Object Id air3		
User Label Air	Previous Model GENII V.2 Air Mod	ule - Chronic Plume	
Select from Applicable Models	Model Description		
GENII V.2 Air Module - Acute 95th Percentile GENII V.2 Air Module - Acute Plume	MODULE VERSION 2.10.1 Compiled September 2012		
GENII V.2 Air Module - Acute Puff GENII V.2 Air Module - Chronic Plume	MODULE DESCRIPTION GENII Chronic Plume Air Module		572
GENII V.2 Air Module - Chronic Puff		GENII Chronic Plume Model - air3	XX
GENII V.2 Air XQ Acute Module GENII V.2 Air XQ Chronic Module	The GENII air module, Chronic Plume, of potential ambient air concentration deposition rates, and cloud shine do and surface depositions are computed Gaussian dispersion models. The moduland area sources along with multiple	File Reference	
GENII V.2 NESHAPS Air Module - Chronic Plume MEPAS 5.0 Air Module		Model Information   Source Information	
1	need to be located at the center of can use either hourly meteorological stability measurments summarized in distribution.	Radial Grid Definition   Model Parameters   Default Parameters   Meteorlogical Files	- 1
	Limitations: Only designed for radionuclides _ does not do chemicals.		
Non-applicable Models	Release rates are assumed to be cons Calculates Annual (or longer) impact	■ 16 Sectors in radial grid  Unit  m  Ref: 0	
	MODULE REFERENCES GENII Manual Section 5	○ 36 Sectors in radial grid	
	VALID CONNECTIONS Valid Input Reads 1 to 5 aff Air required as input 1 to 1 con required as input		
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