

# Atlas of high altitude wind power

Cristina L. Archer  
Ken Caldeira

Department of Global Ecology  
Carnegie Institute for Science  
260 Panama Street  
Stanford, CA 94305

16 June 2008

# Contents

<b>1</b>	<b>Wind power density distributions by level</b>	<b>3</b>
1.1	Annual percentiles . . . . .	3
1.2	DJF percentiles . . . . .	20
1.3	MAM percentiles . . . . .	37
1.4	JJA percentiles . . . . .	54
1.5	SON percentiles . . . . .	71
<b>2</b>	<b>Optimal wind power density and optimal height distributions</b>	<b>88</b>
<b>3</b>	<b>Dealing with intermittency</b>	<b>94</b>

# Chapter 1

## Wind power density distributions by level

### 1.1 Annual percentiles

This section contains selected percentiles of wind power density at all levels between 80 and 12,000 m above ground level calculated for the years 1979-2006 from the 6-hourly NCEP/DOE reanalyses. The seasonal percentiles are available in the next sections.

## Level = 80 m - Annual

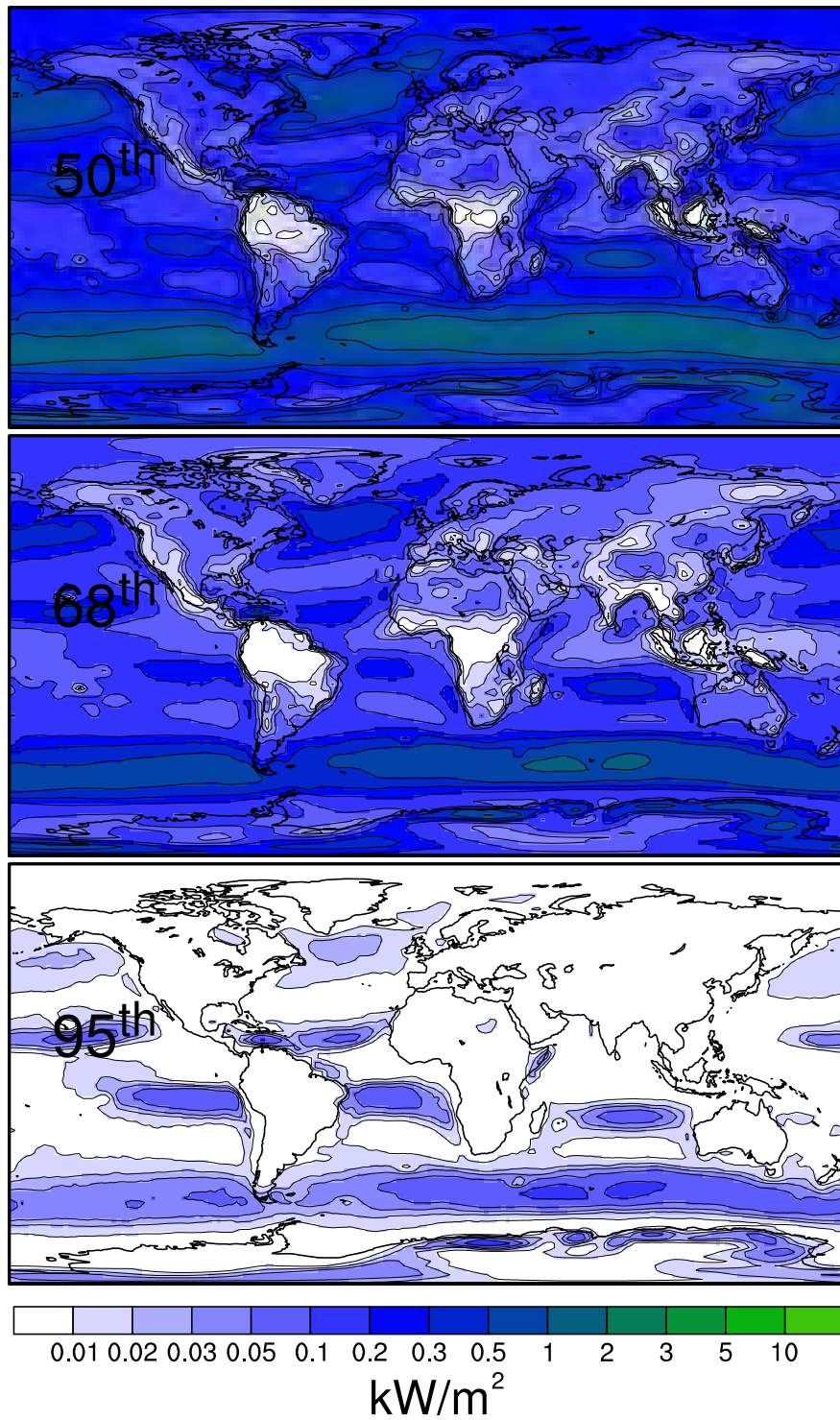


Figure 1.1: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 80 m during years in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 500 m - Annual

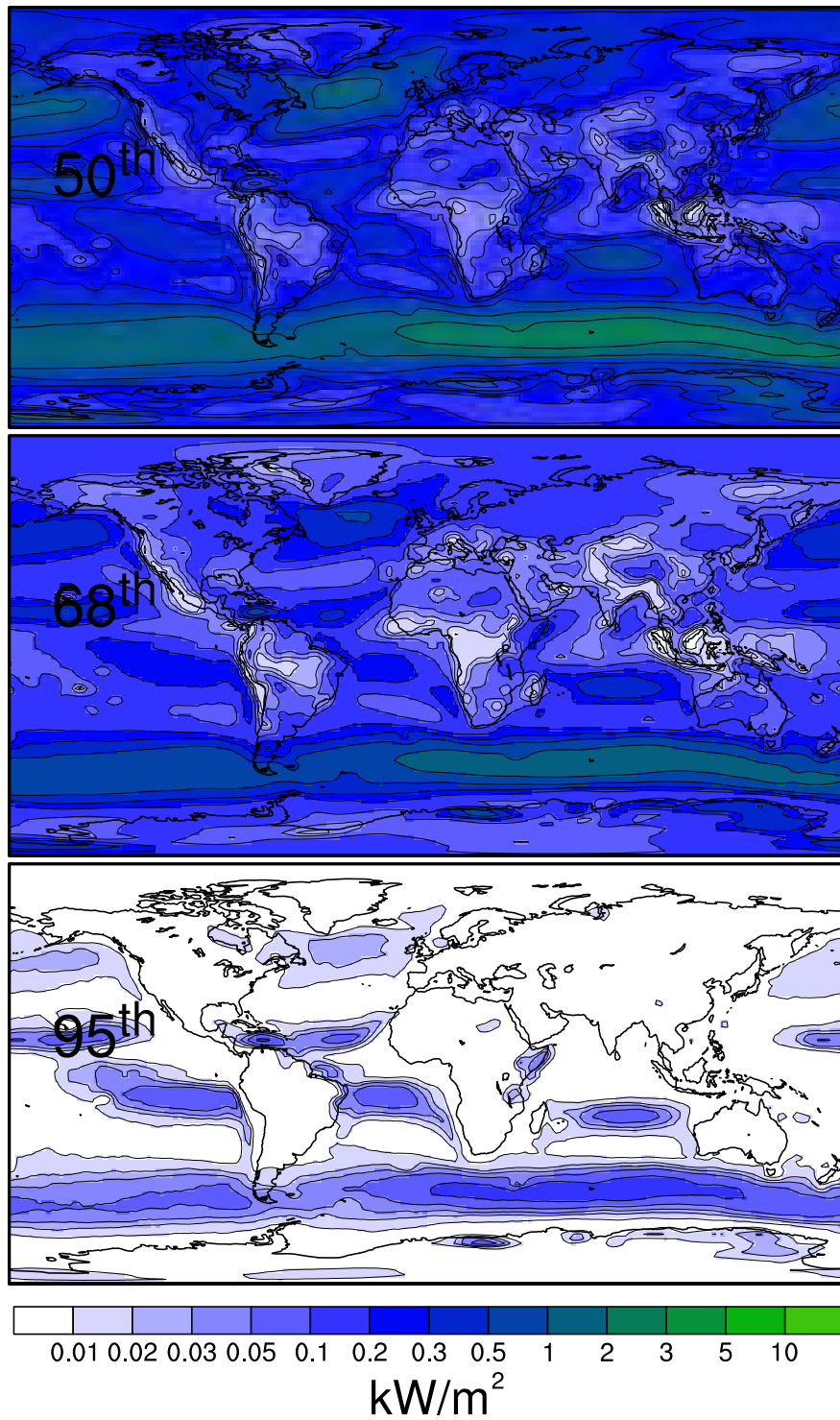


Figure 1.2: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 500 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 750 m - Annual

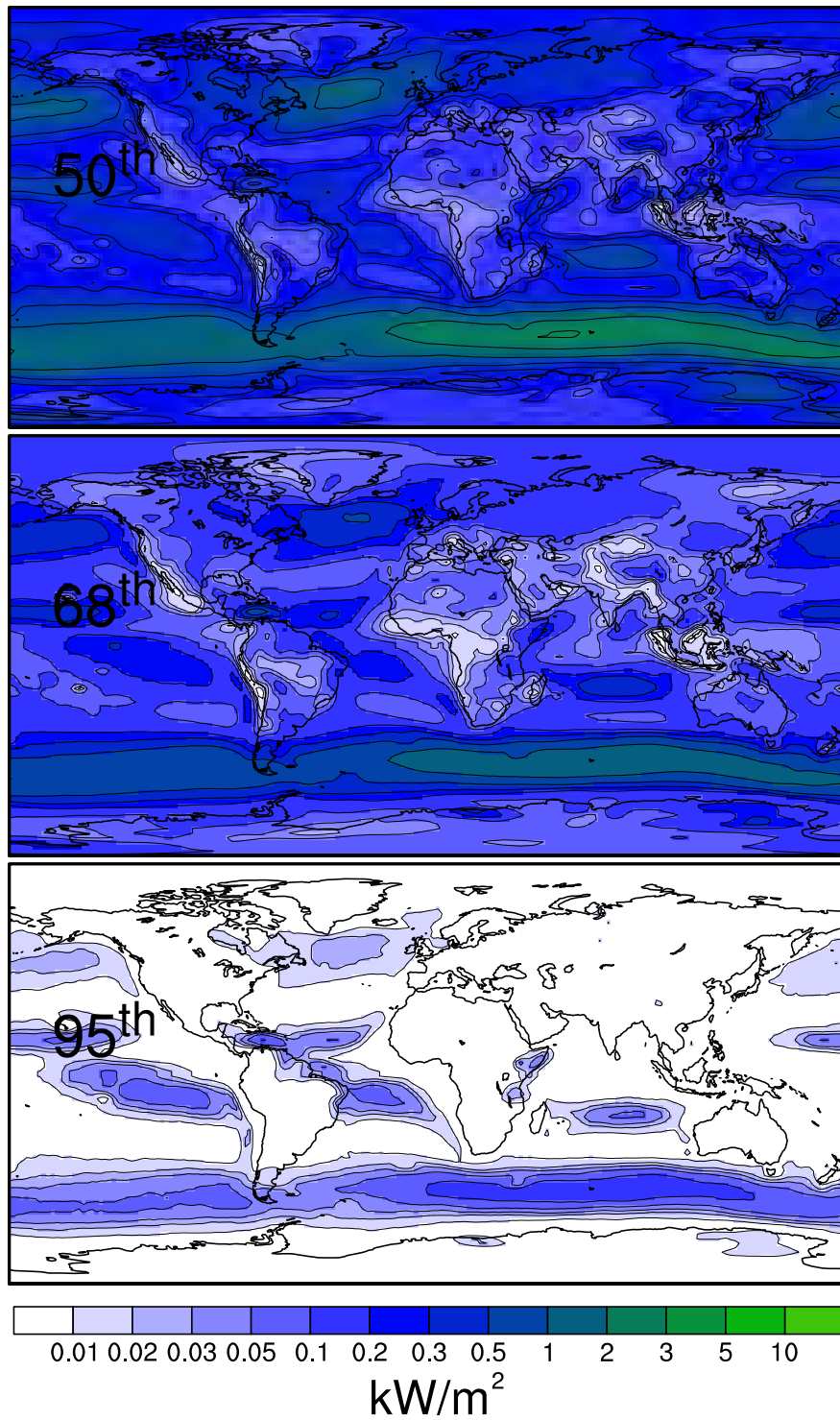


Figure 1.3: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 750 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 1000 m - Annual

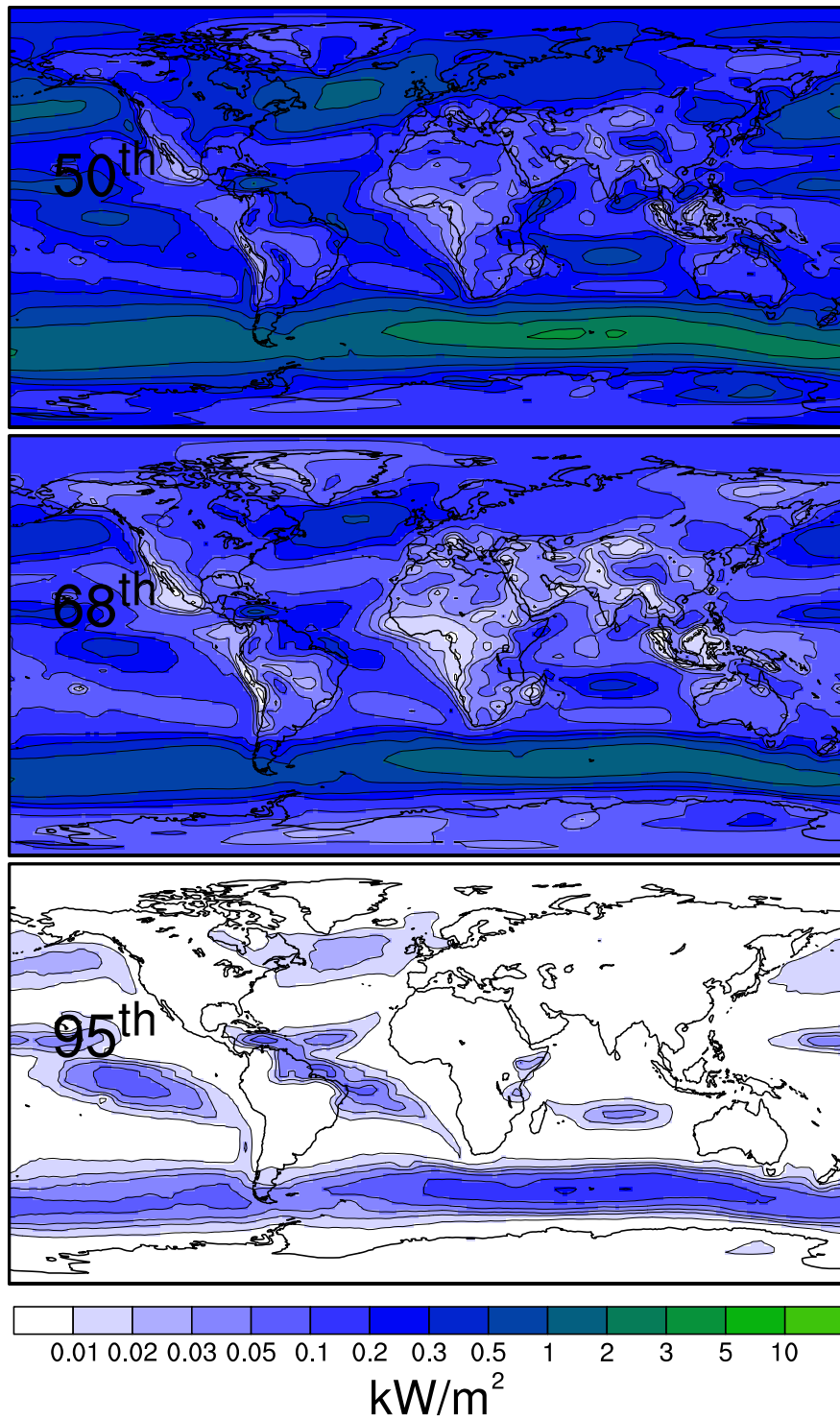


Figure 1.4: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 1000 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 1500 m - Annual

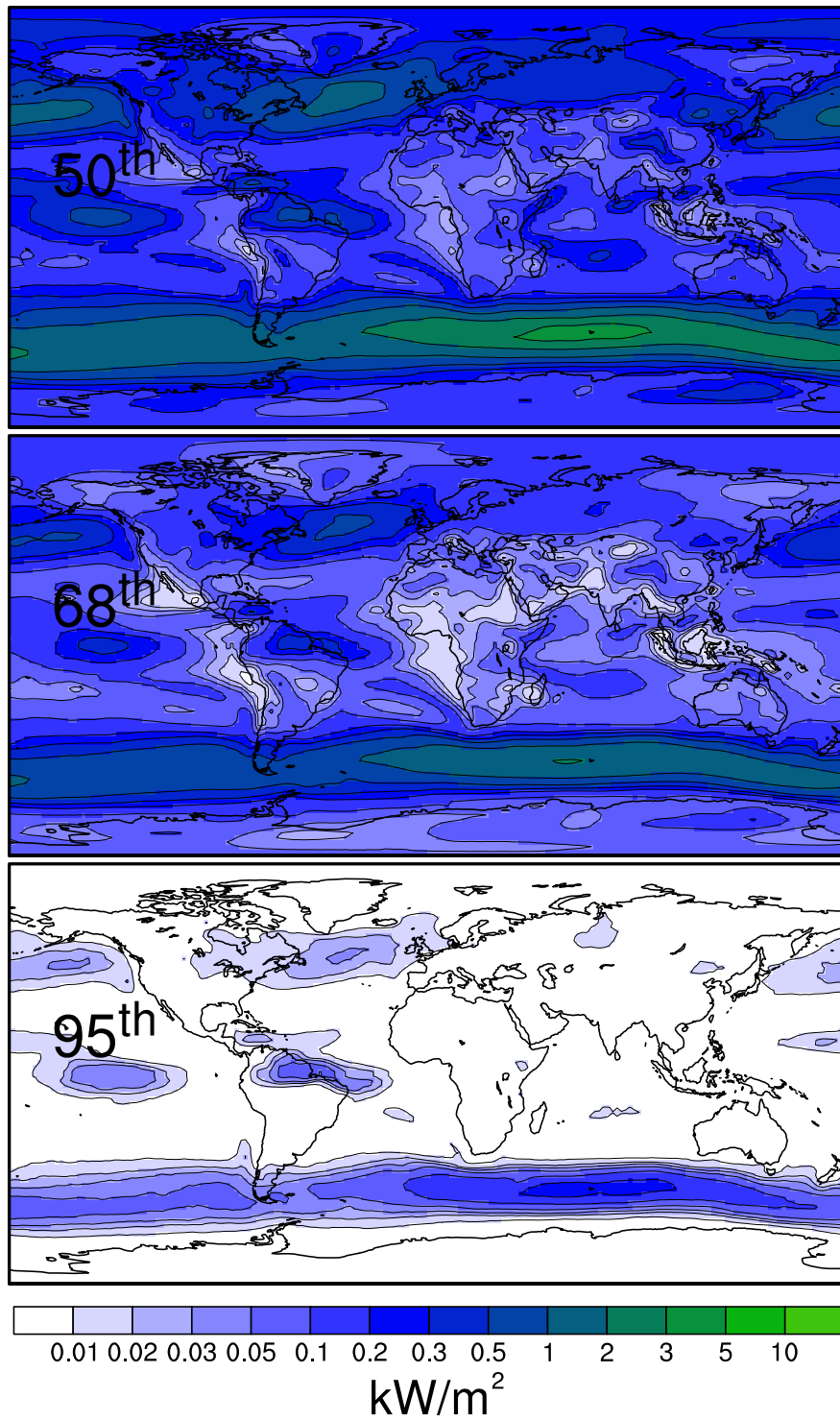


Figure 1.5: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 1500 m during years in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 2000 m - Annual

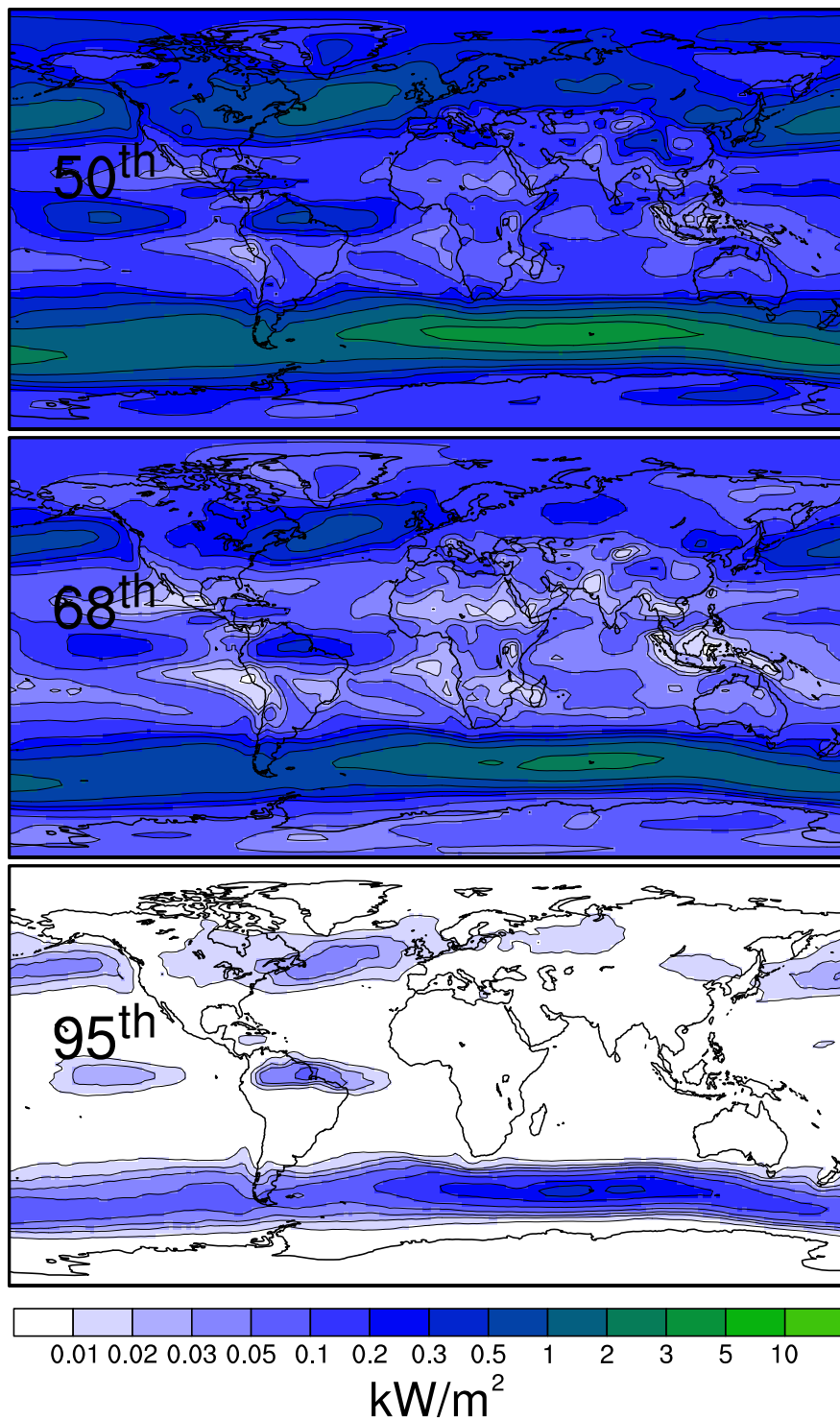


Figure 1.6: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 2000 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 3000 m - Annual

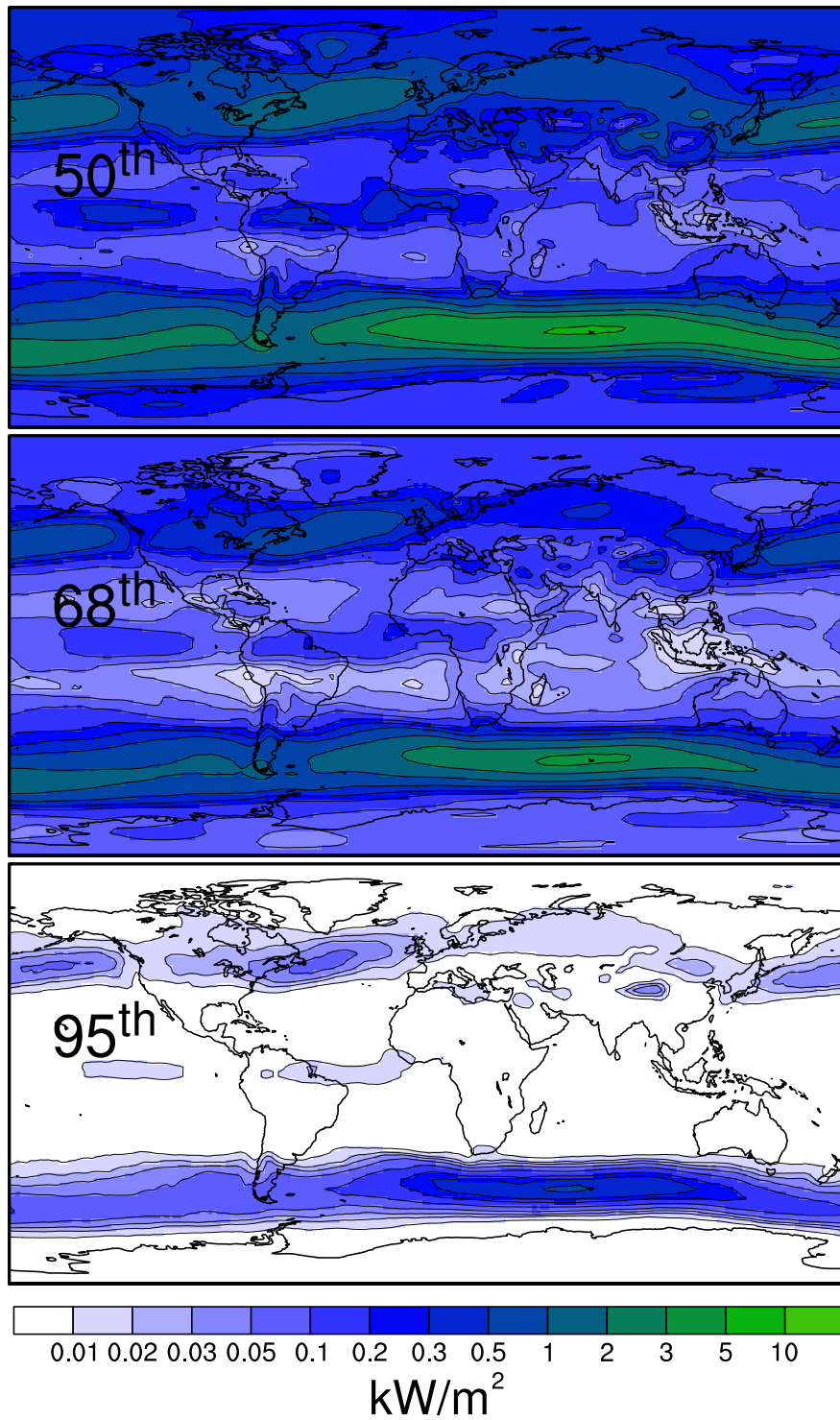


Figure 1.7: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 3000 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 4000 m - Annual

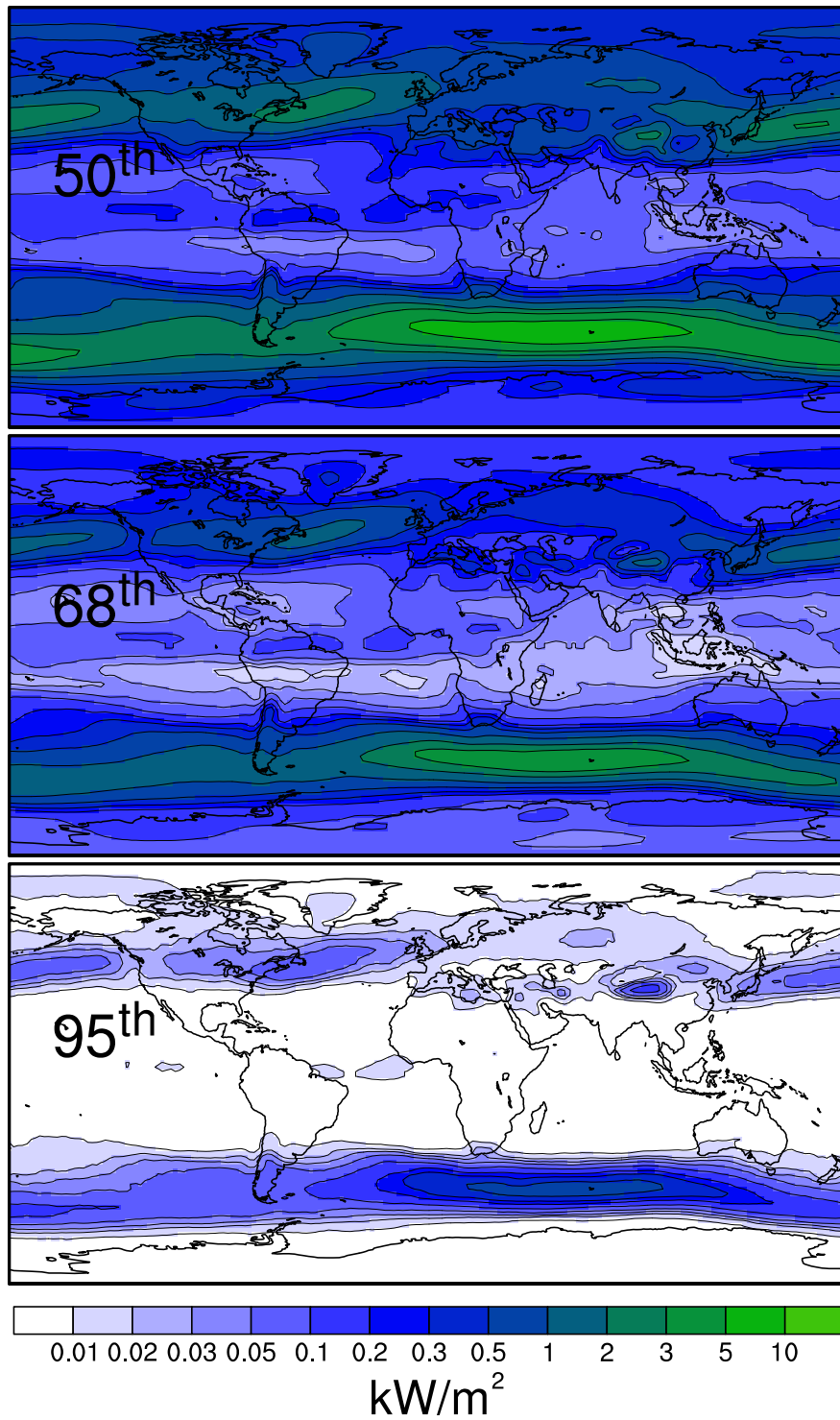


Figure 1.8: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 4000 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 5000 m - Annual

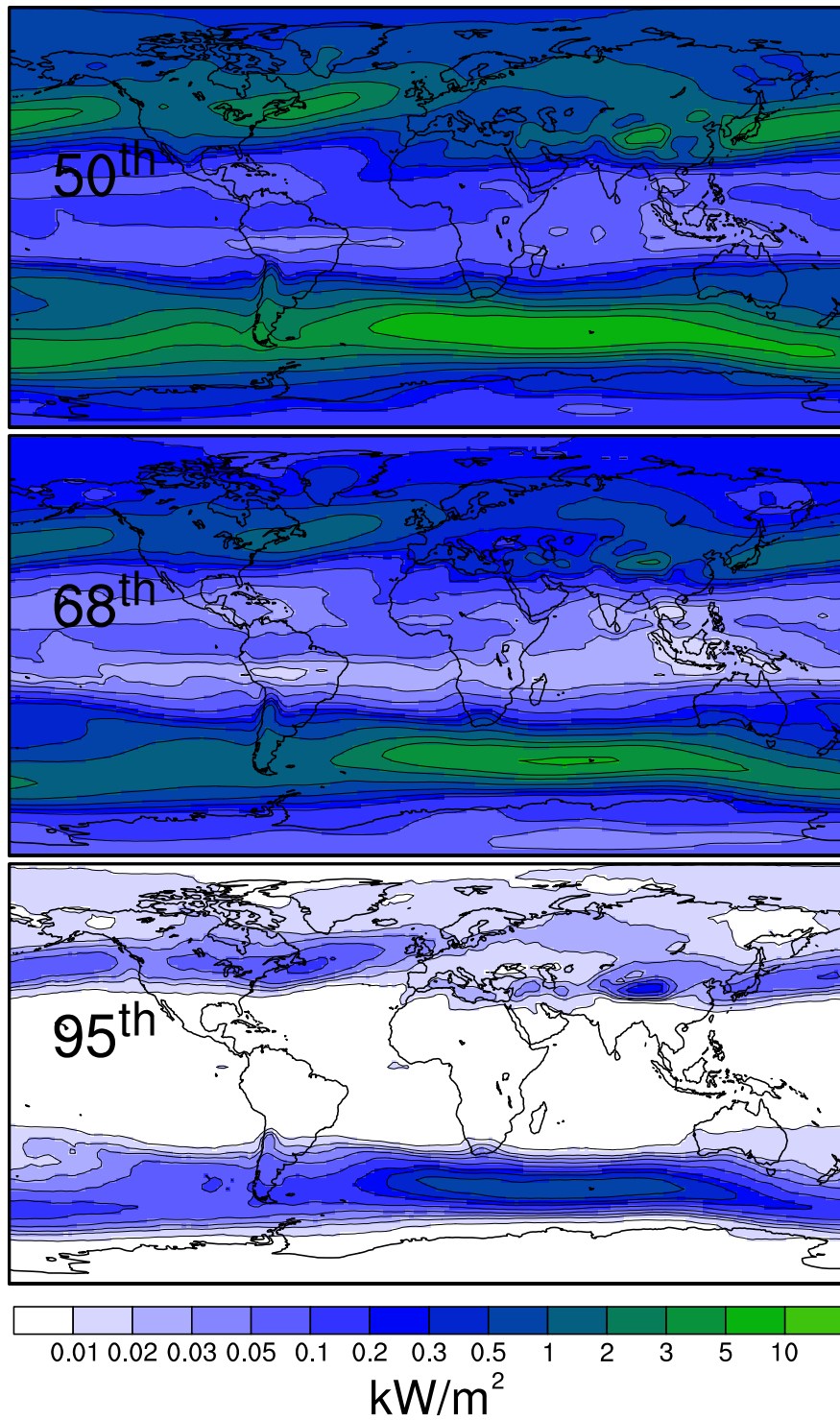


Figure 1.9: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 5000 m during years in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 6000 m - Annual

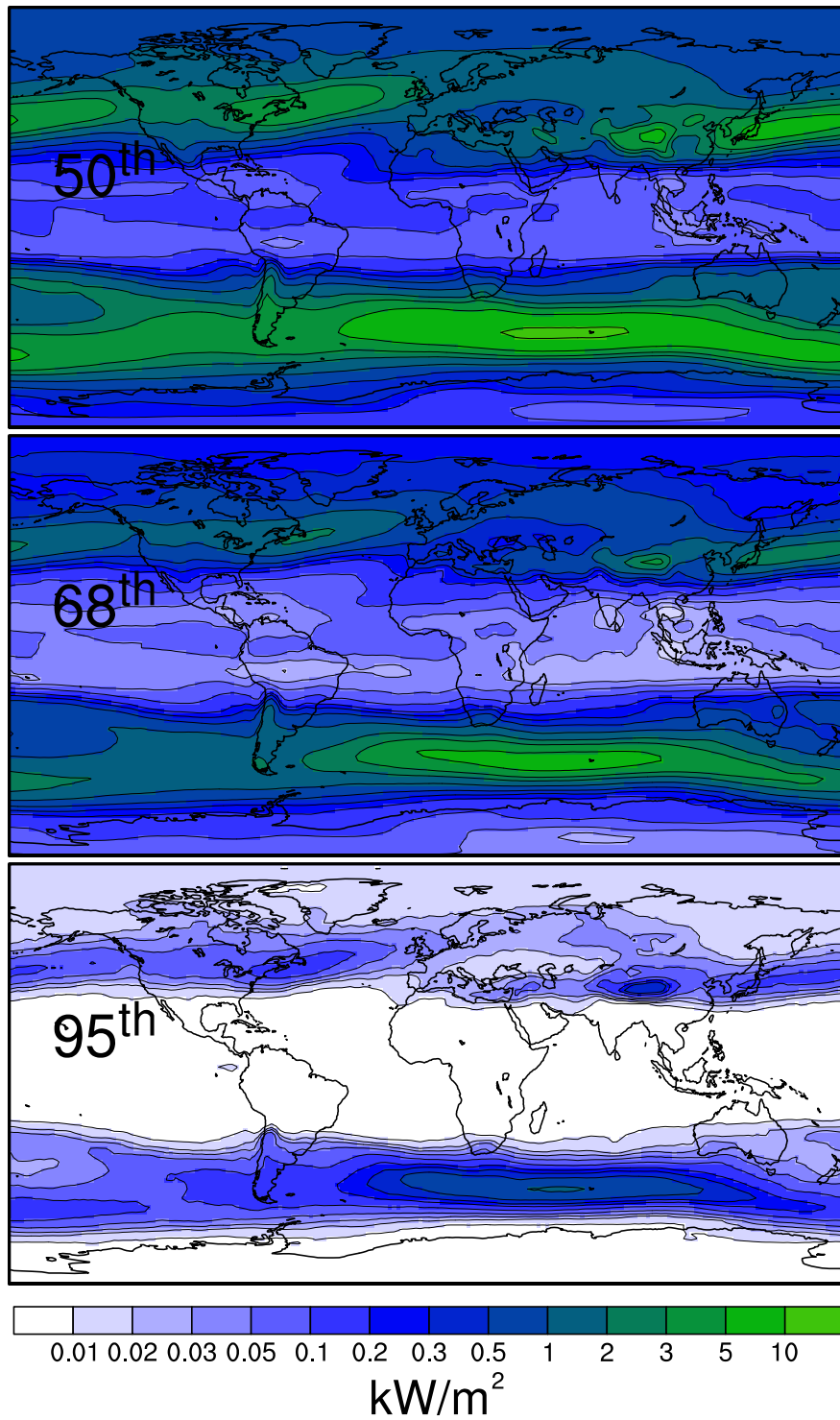


Figure 1.10: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 6000 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 7000 m - Annual

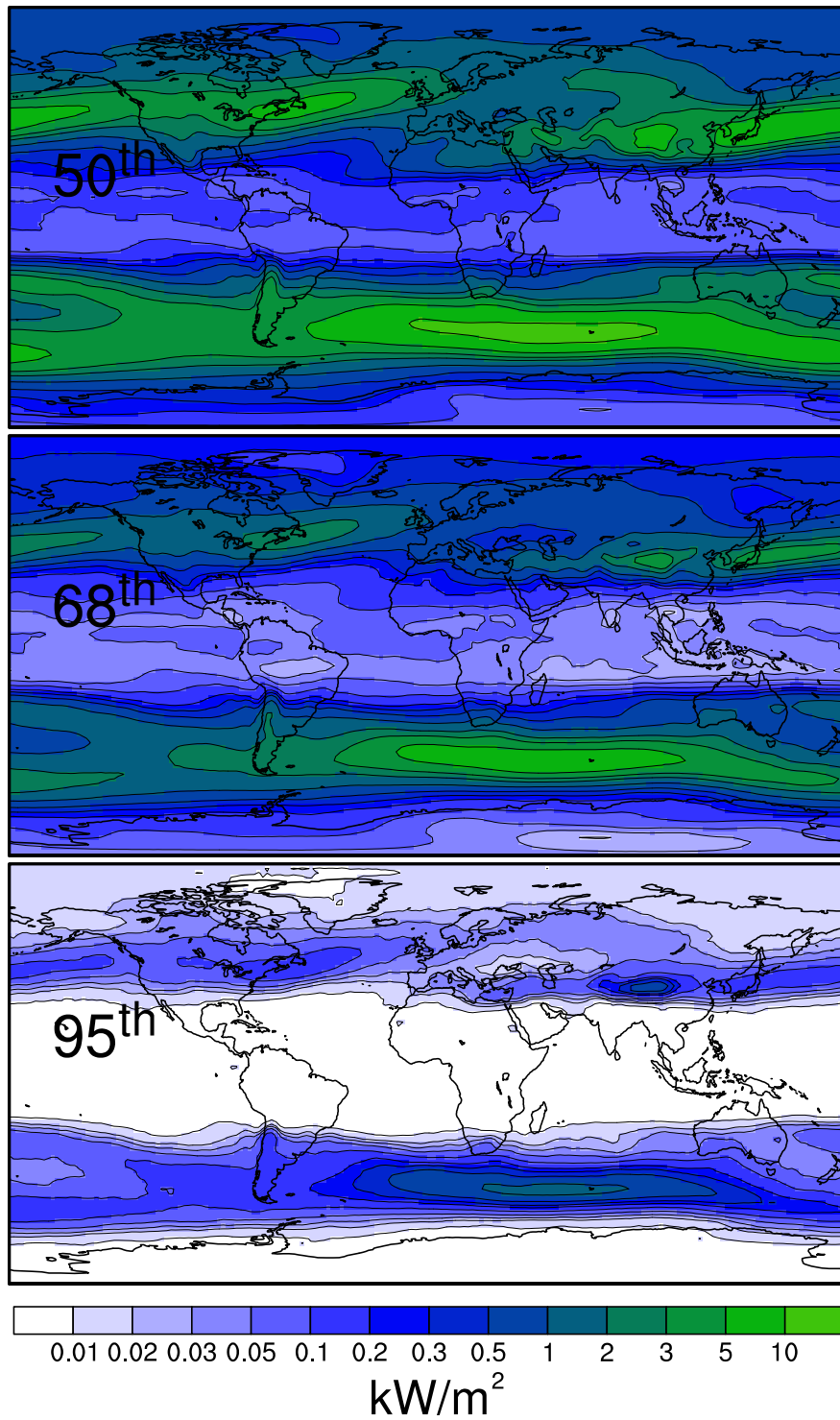


Figure 1.11: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 7000 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 8000 m - Annual

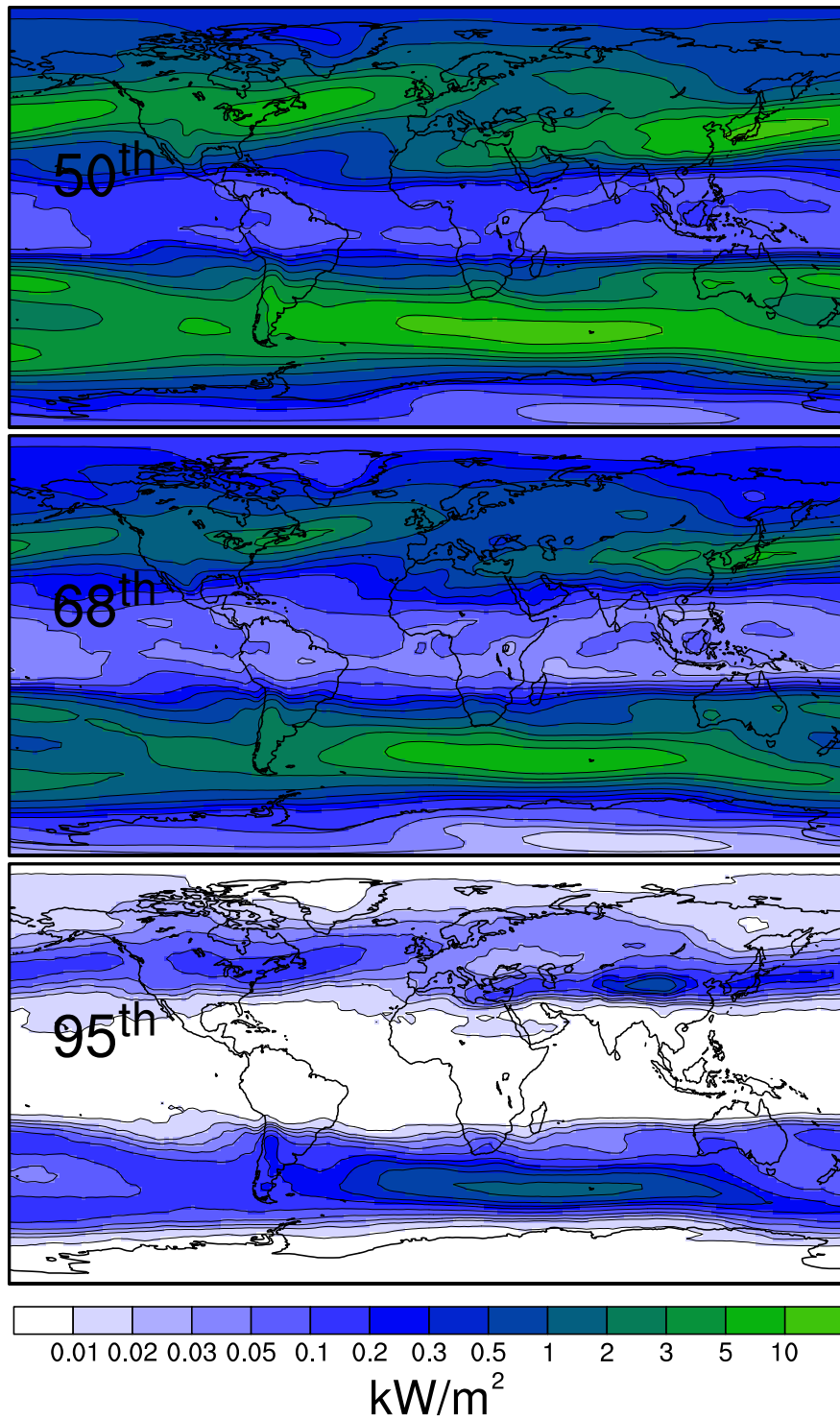


Figure 1.12: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 8000 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 9000 m - Annual

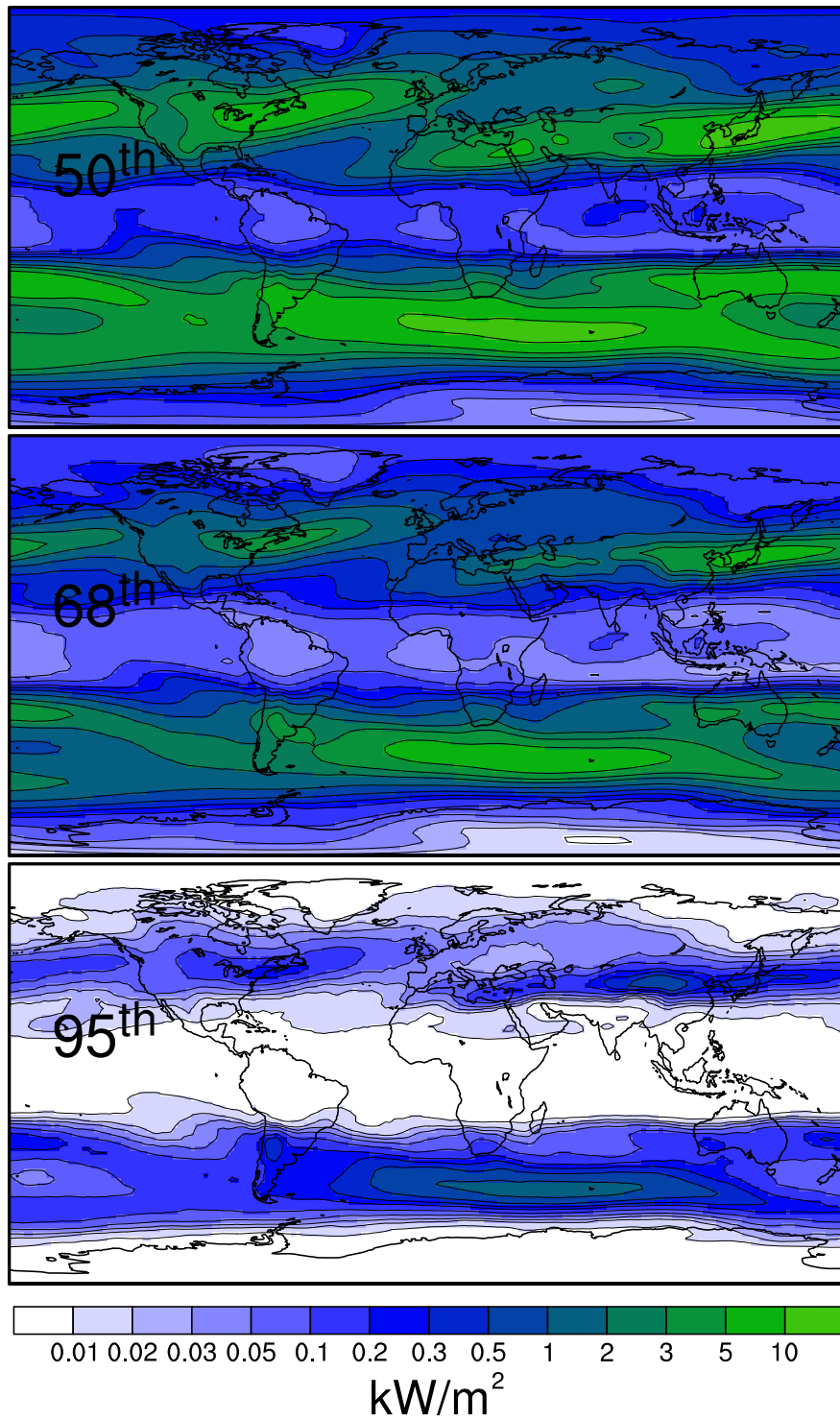


Figure 1.13: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 9000 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 10000 m - Annual

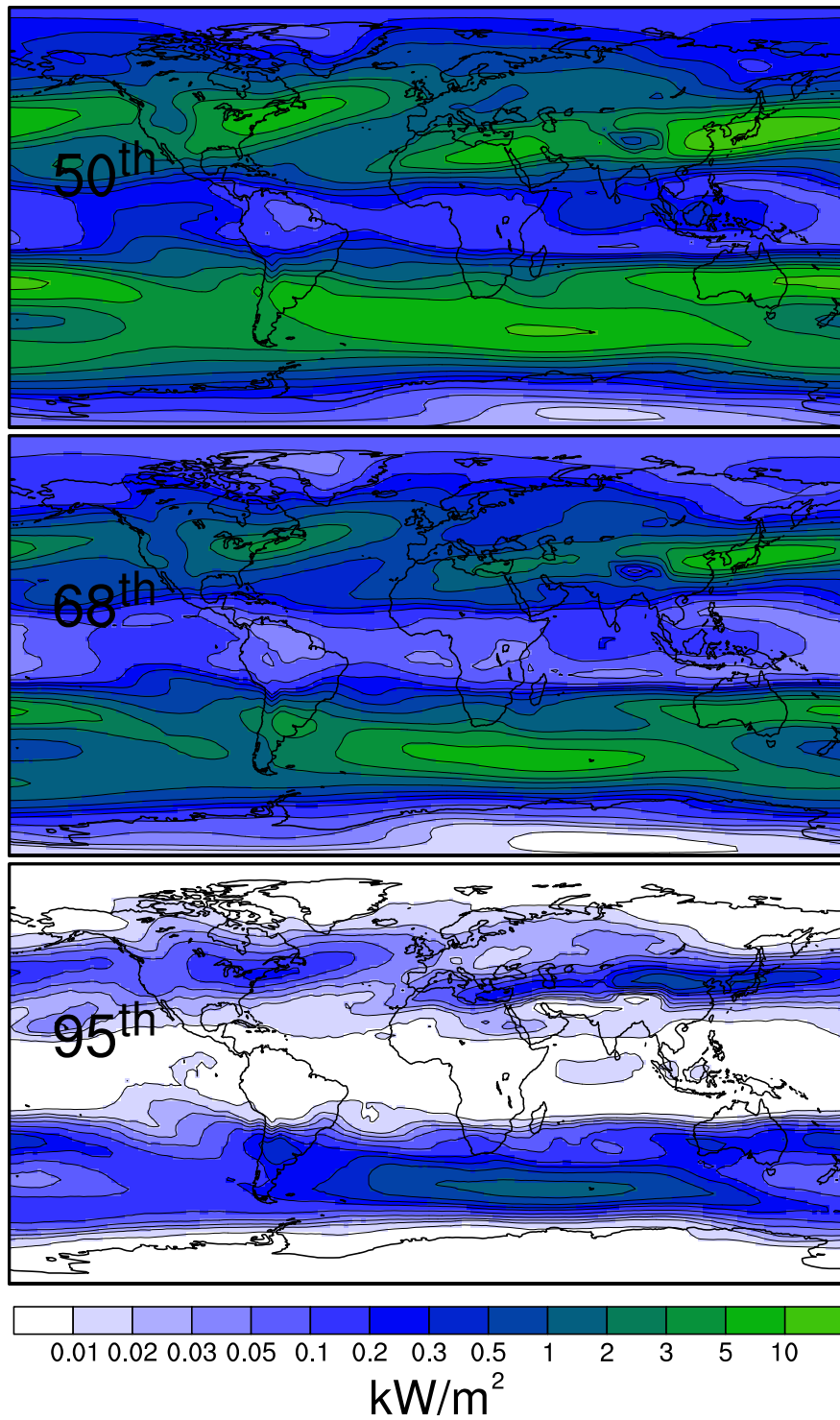


Figure 1.14: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 10,000 m during years in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 11000 m - Annual

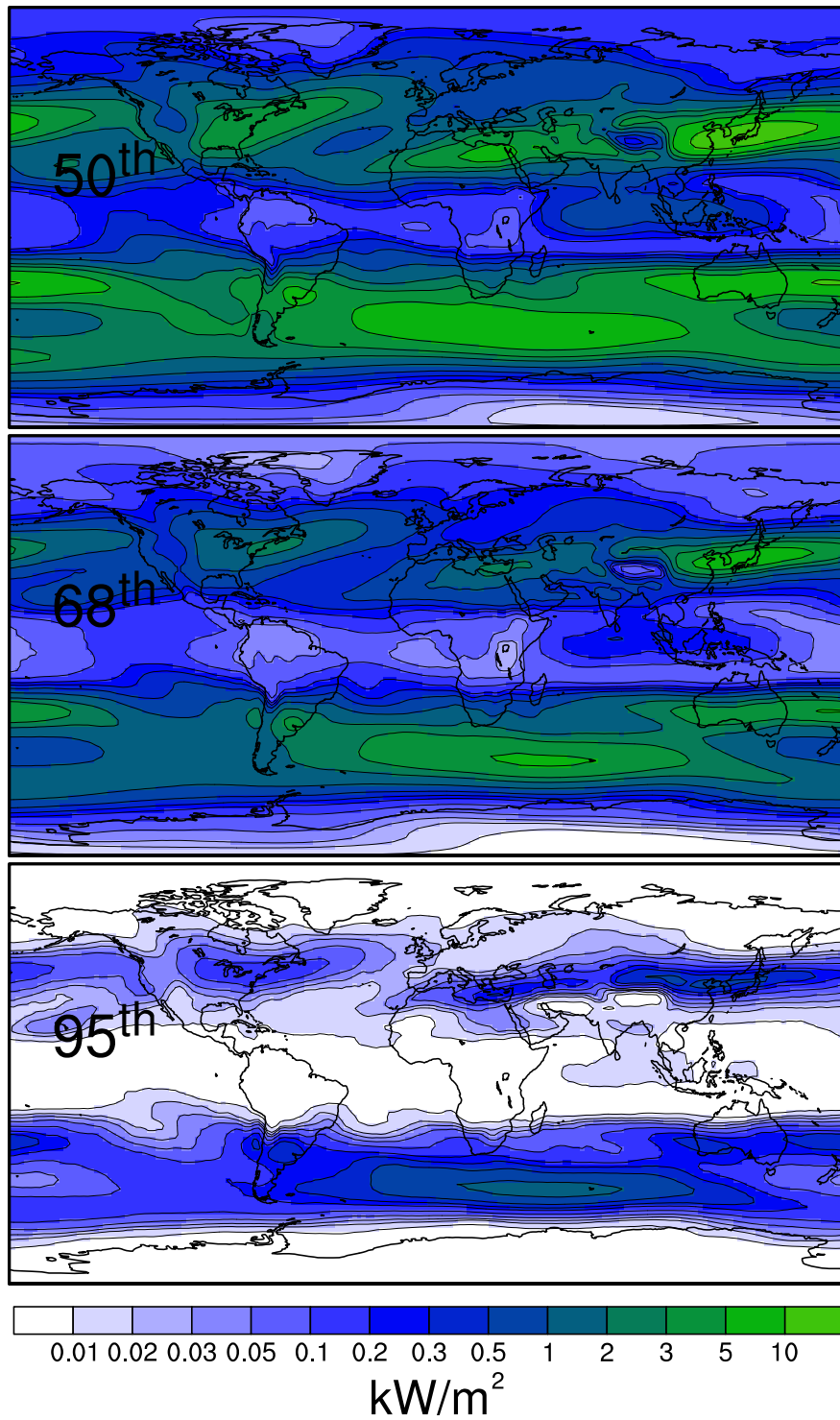


Figure 1.15: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 11,000 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 12000 m - Annual

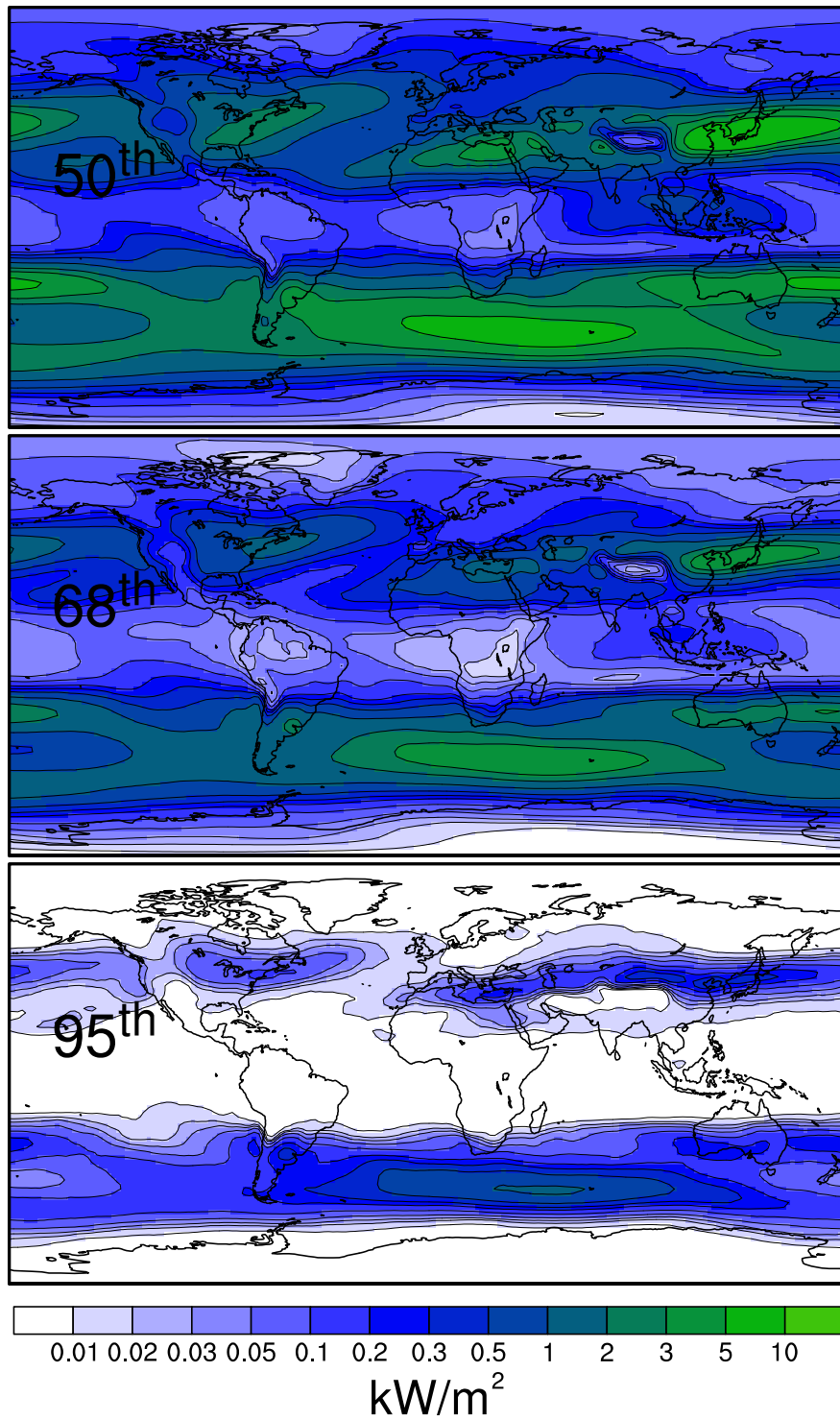


Figure 1.16: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 12,000 m during years in 1979-2006 from the NCEP/DOE reanalyses.

## 1.2 DJF percentiles

This section contains selected percentiles of wind power density at all levels between 80 and 12,000 m above ground level, calculated for December-january-February (DJF) in 1979-2006 from the 6-hourly NCEP/DOE reanalyses.



## Level = 80 m - DJF

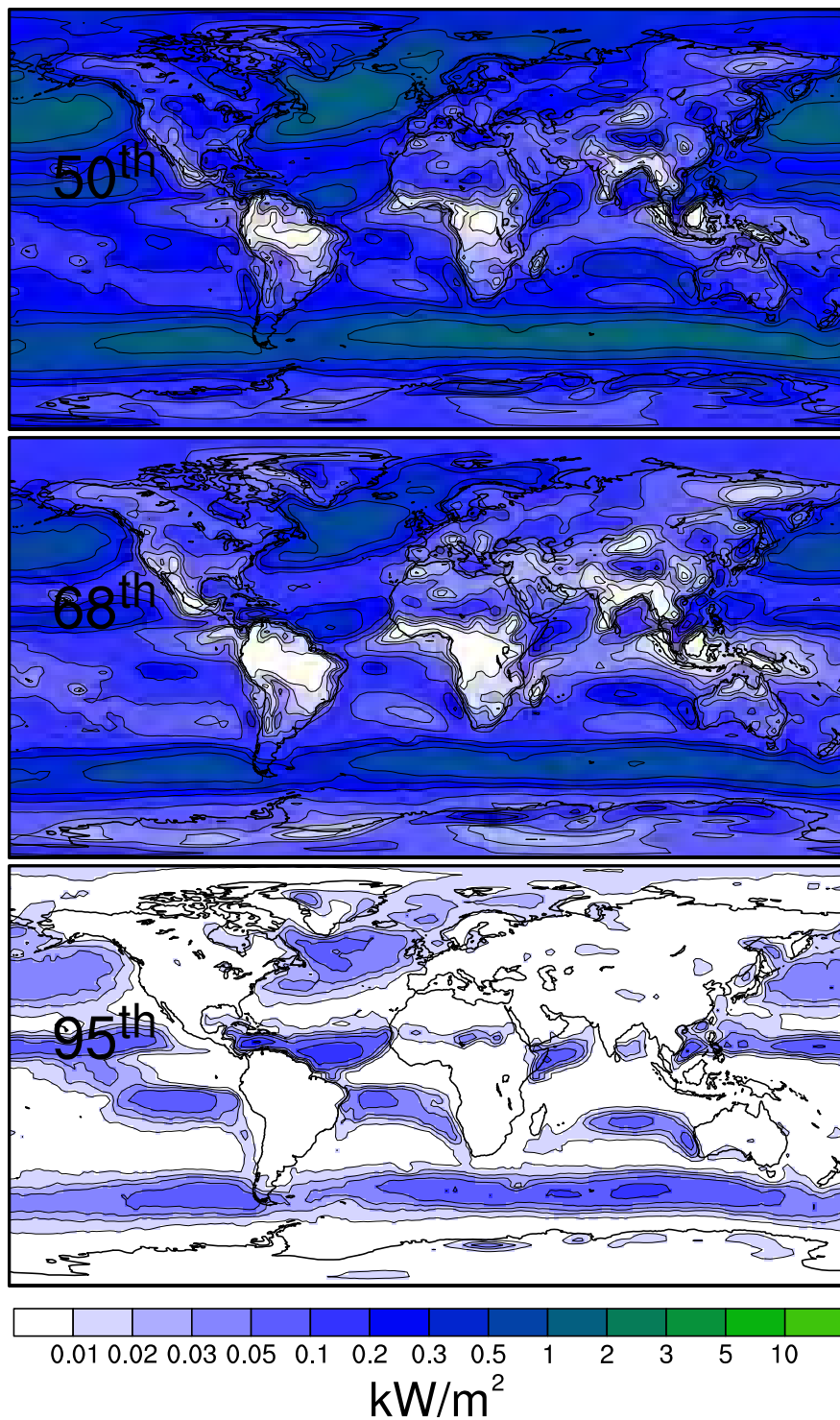


Figure 1.17: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 80 m during December-January-February in 1979-2006 from the NCEP/DOE re-analyses.

## Level = 500 m - DJF

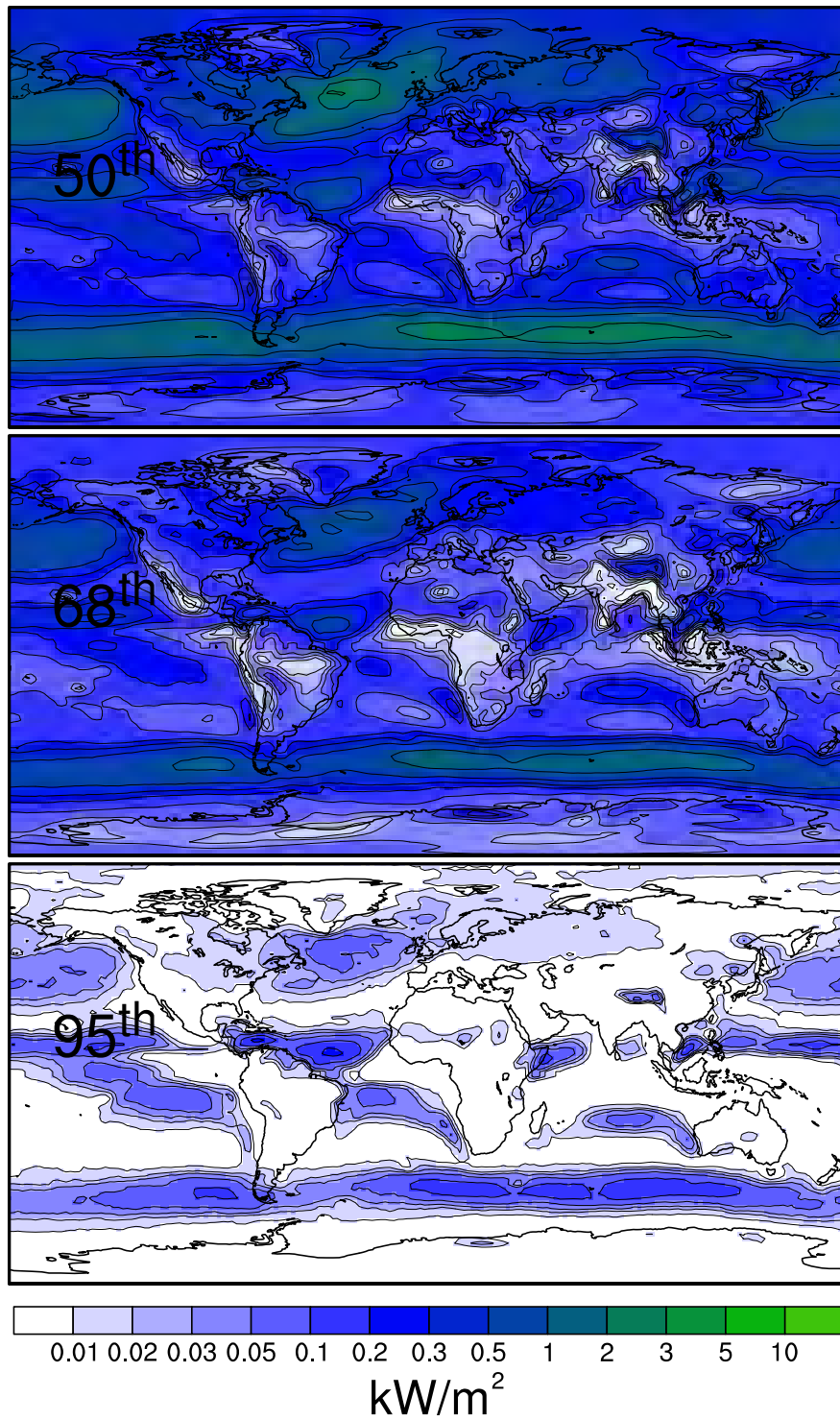


Figure 1.18: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 500 m during December-January-February in 1979-2006 from the NCEP/DOE re-analyses.

## Level = 750 m - DJF

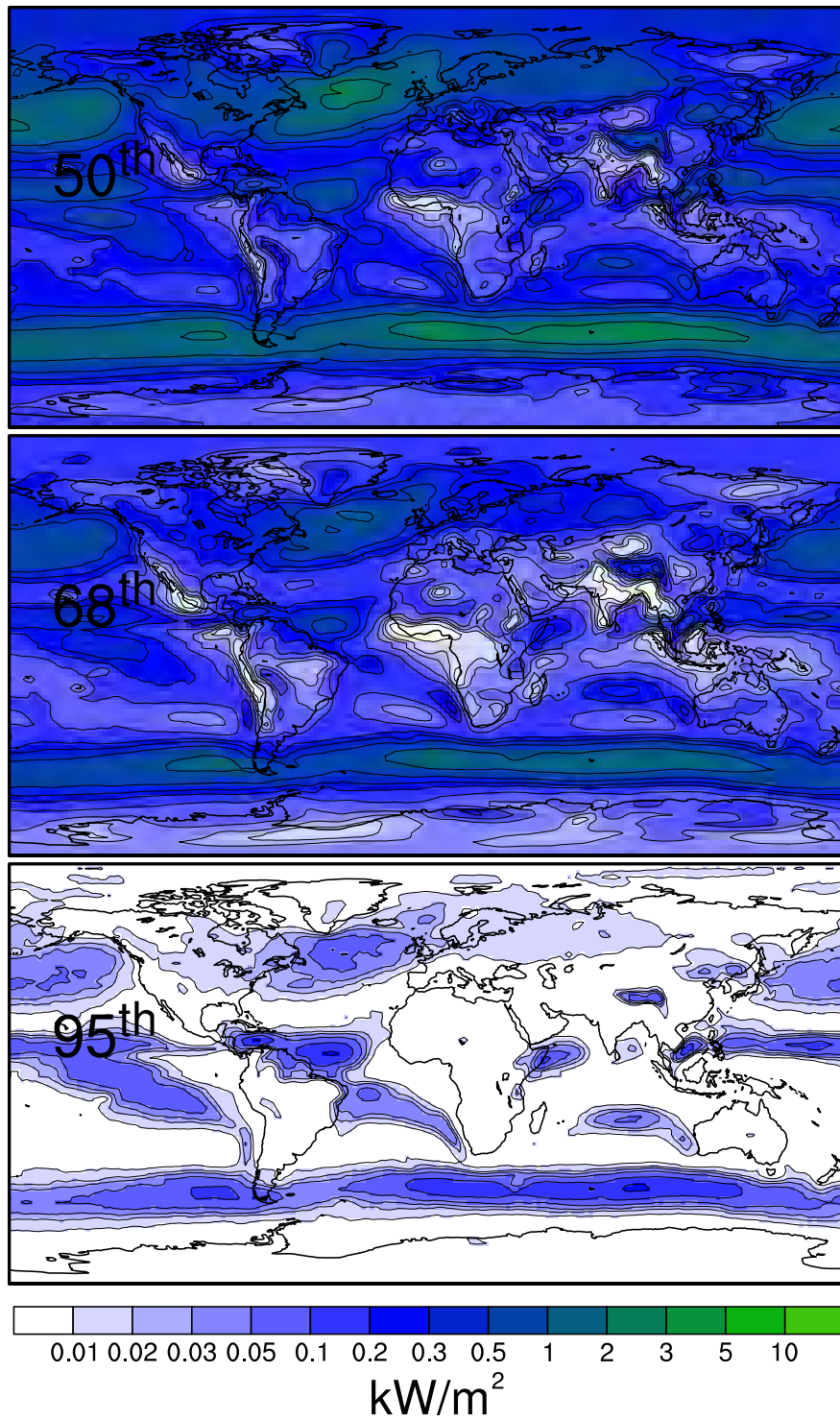


Figure 1.19: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 750 m during December-January-February in 1979-2006 from the NCEP/DOE re-analyses.



## Level = 1000 m - DJF

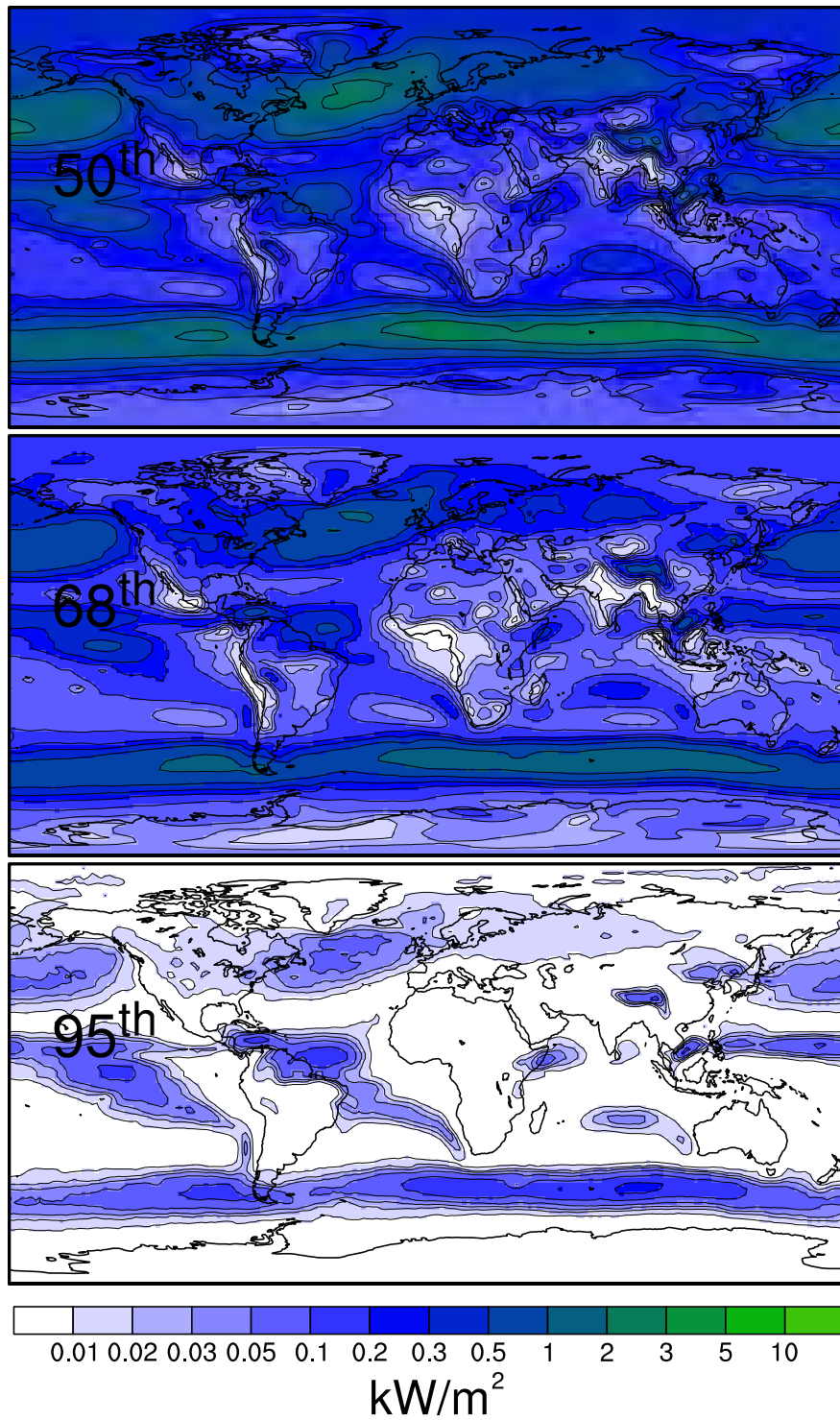


Figure 1.20: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 1000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 1500 m - DJF

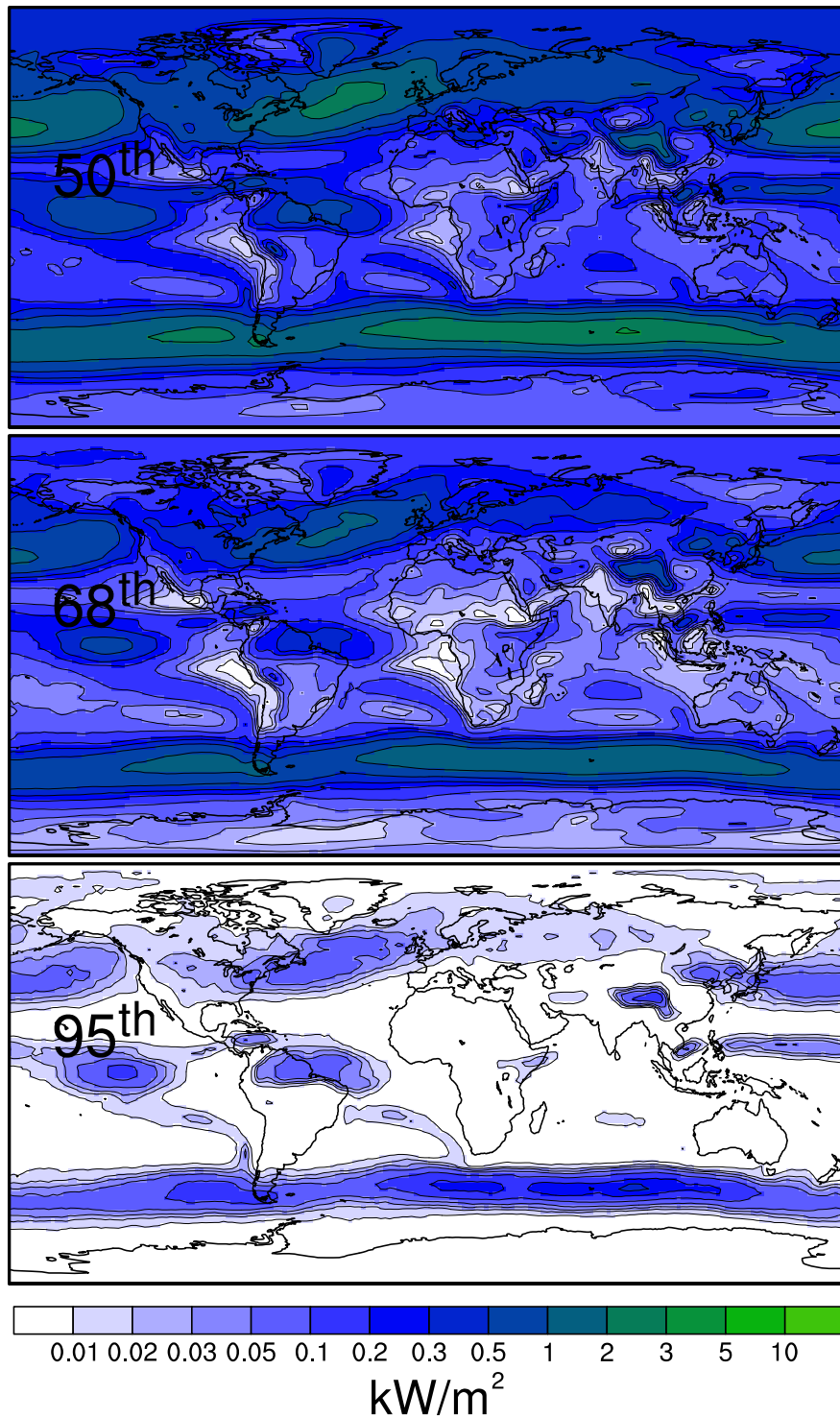


Figure 1.21: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 1500 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 2000 m - DJF

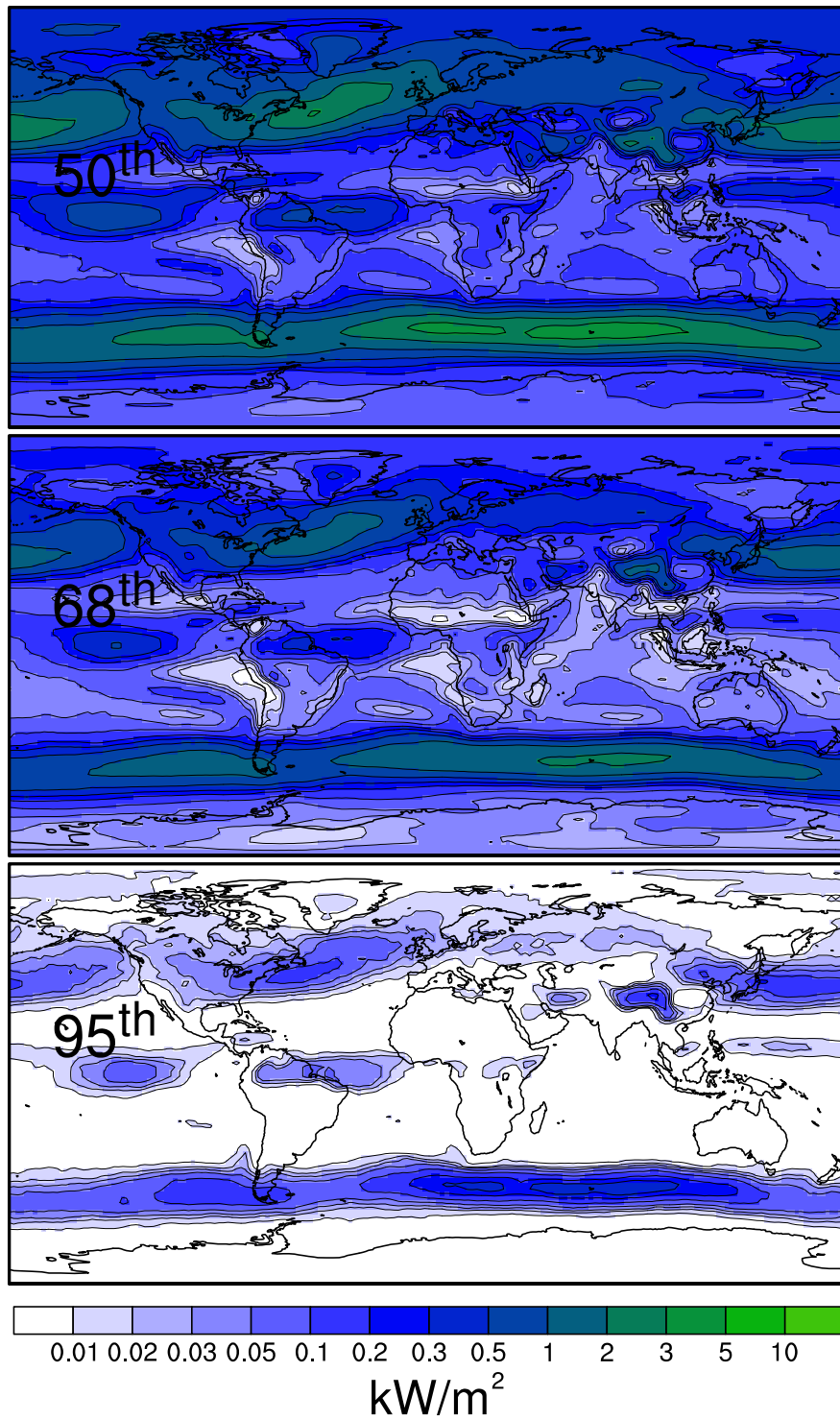


Figure 1.22: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 2000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 3000 m - DJF

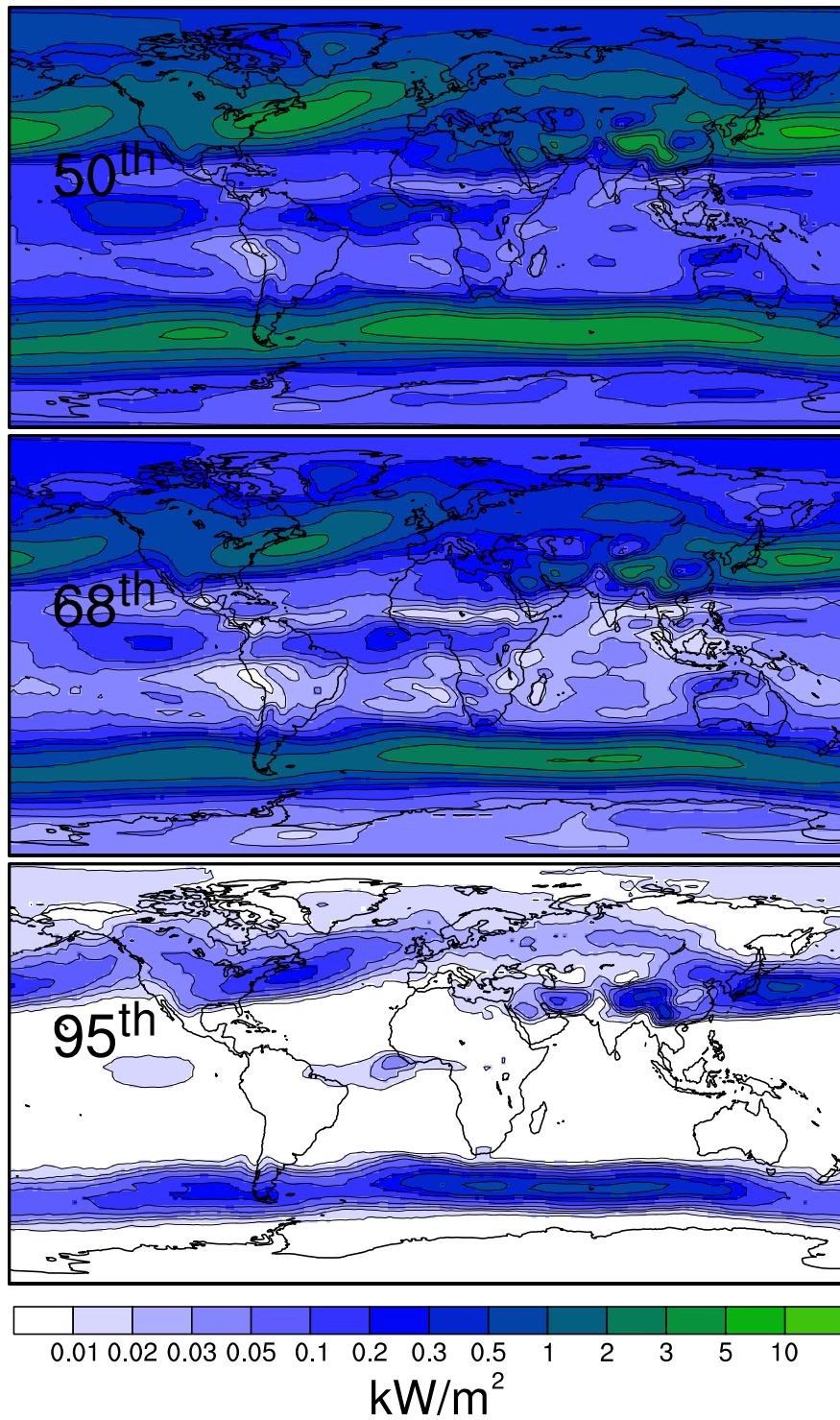


Figure 1.23: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 3000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 4000 m - DJF

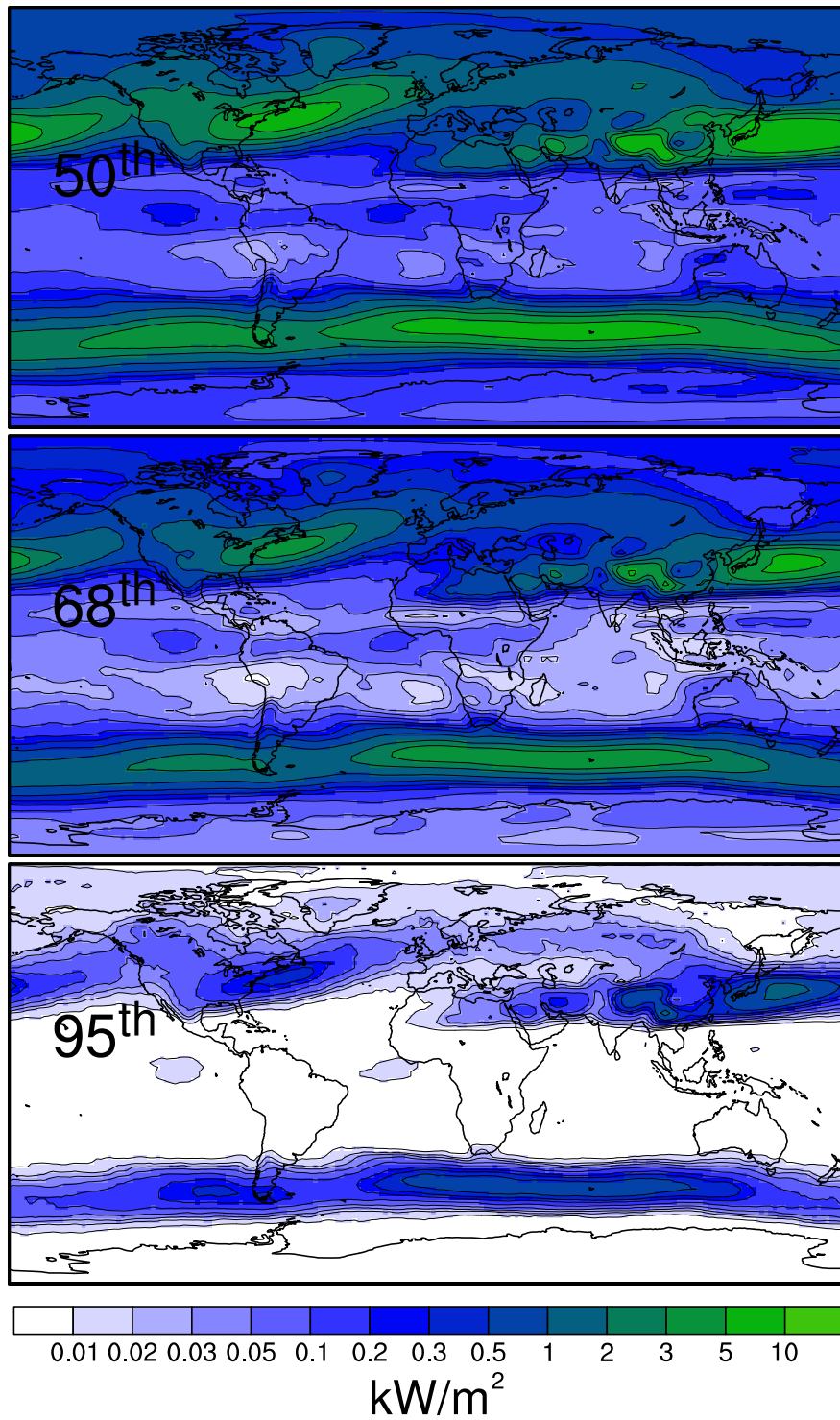


Figure 1.24: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 4000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 5000 m - DJF

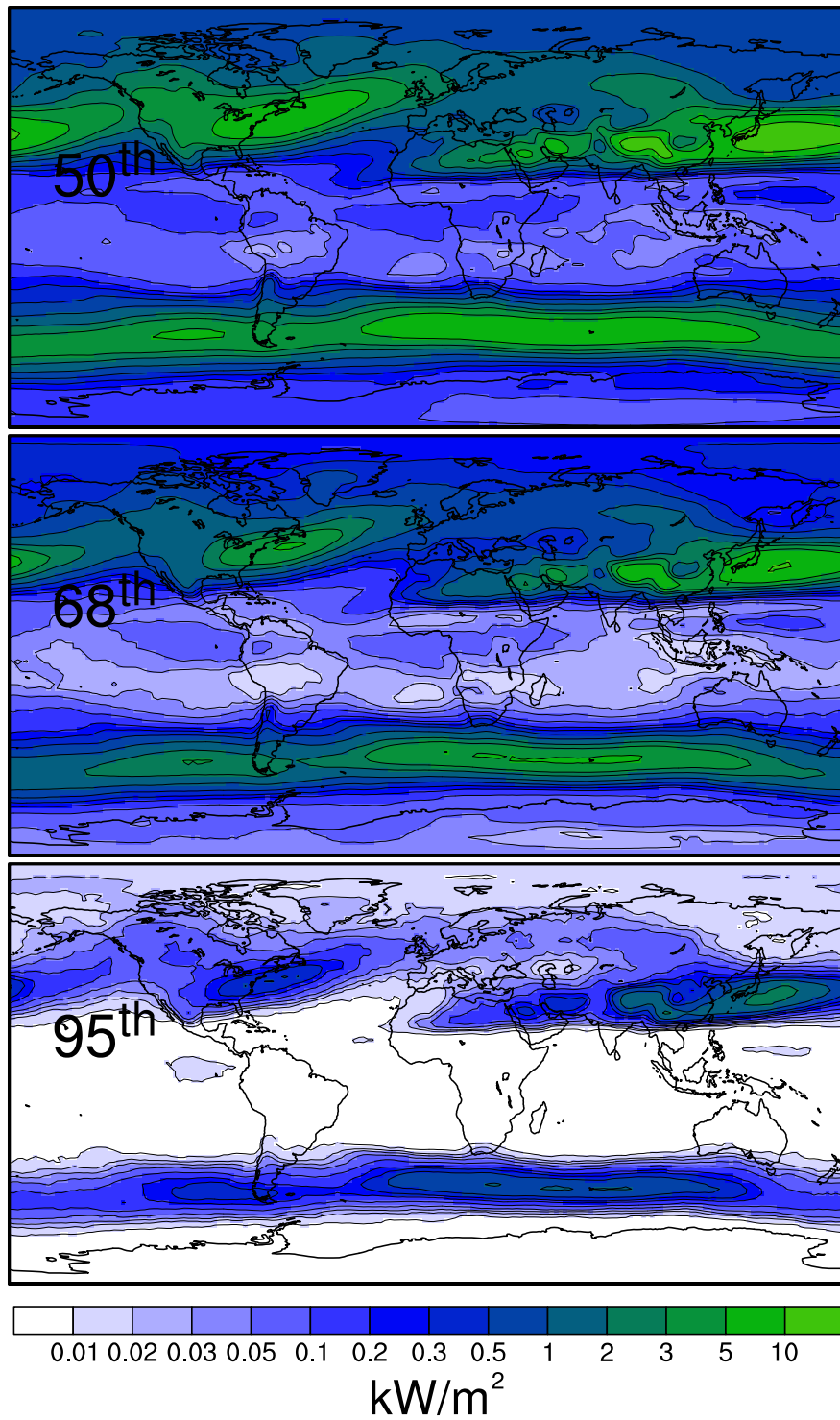


Figure 1.25: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 5000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 6000 m - DJF

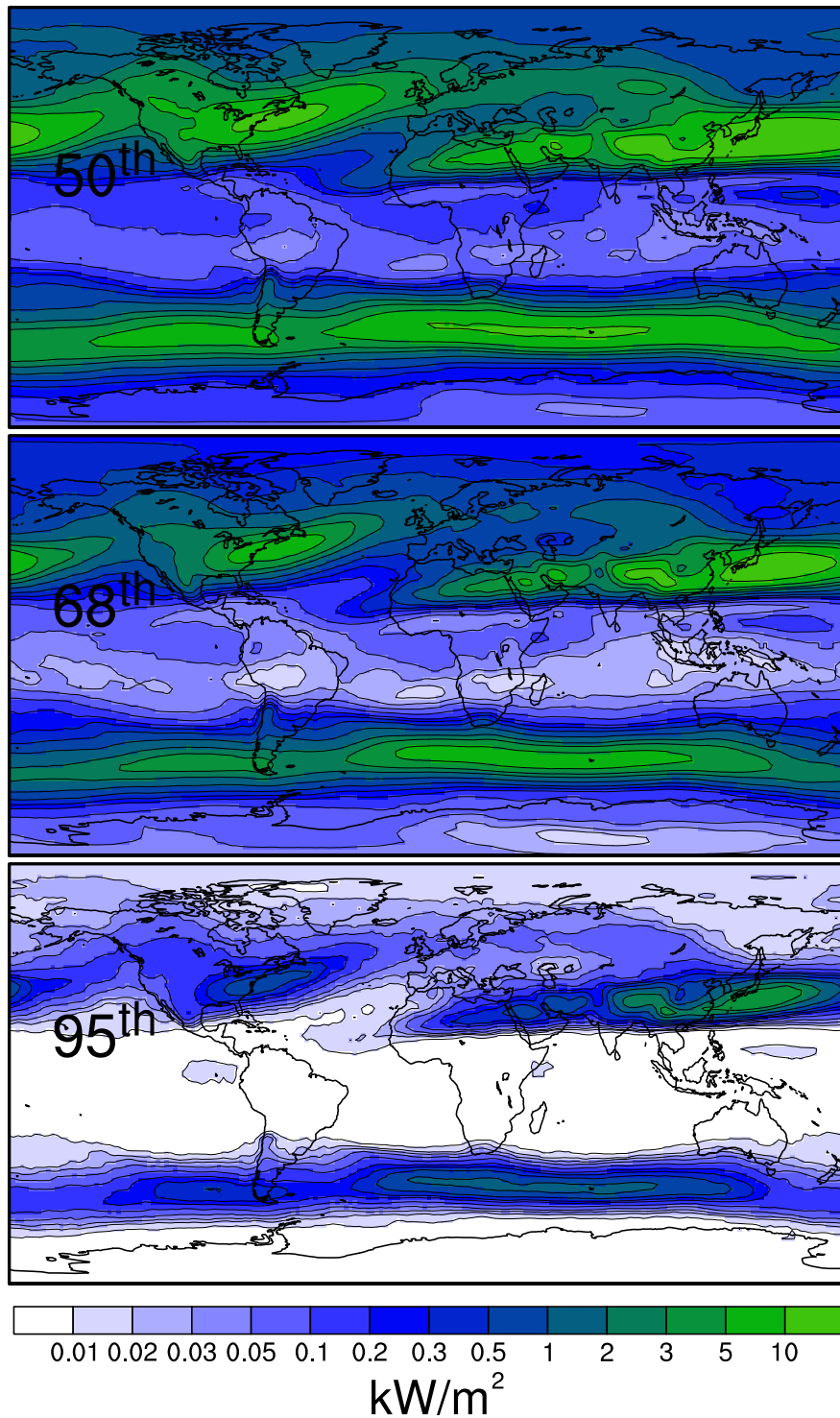


Figure 1.26: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 6000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 7000 m - DJF

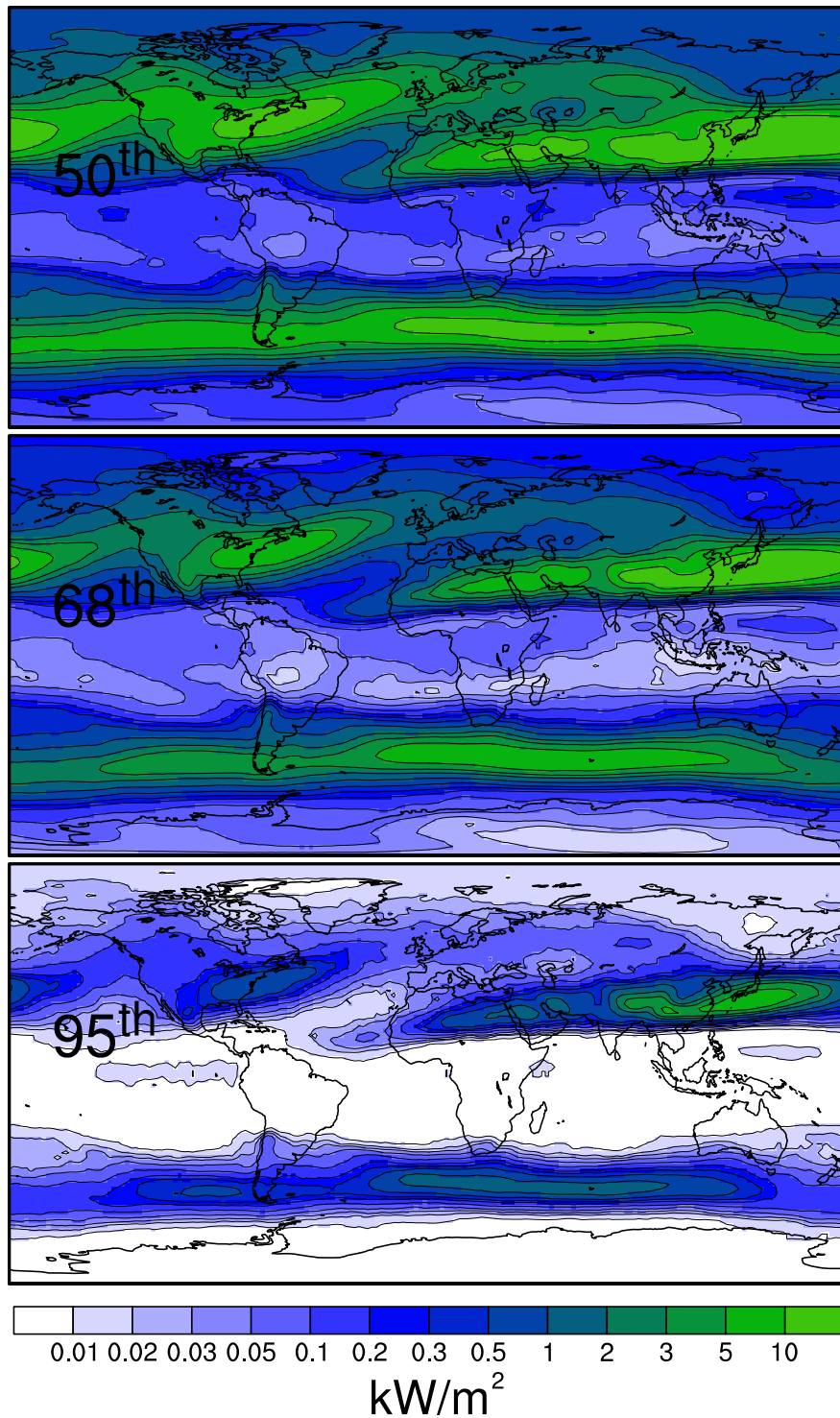


Figure 1.27: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 7000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 8000 m - DJF

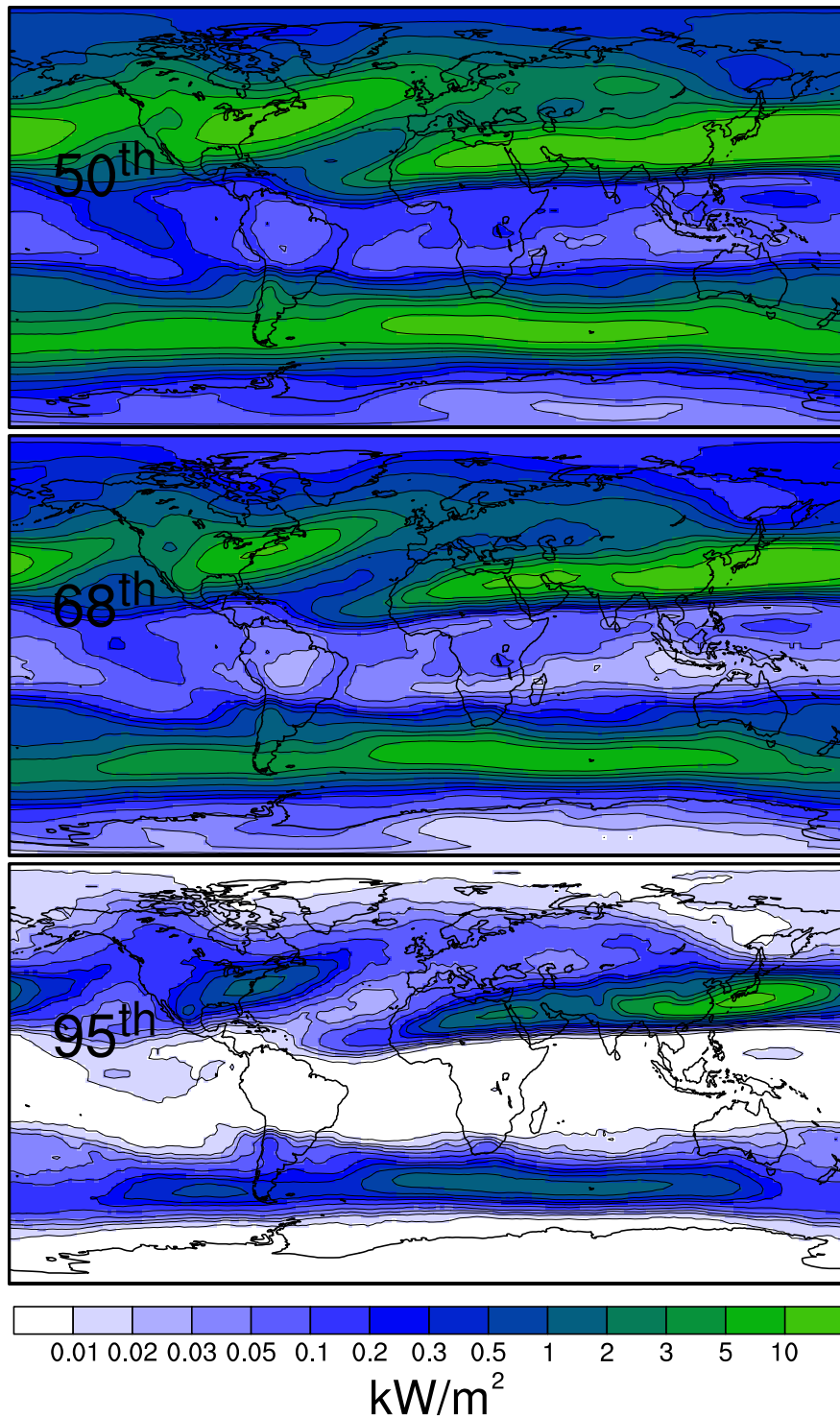


Figure 1.28: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 8000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 9000 m - DJF

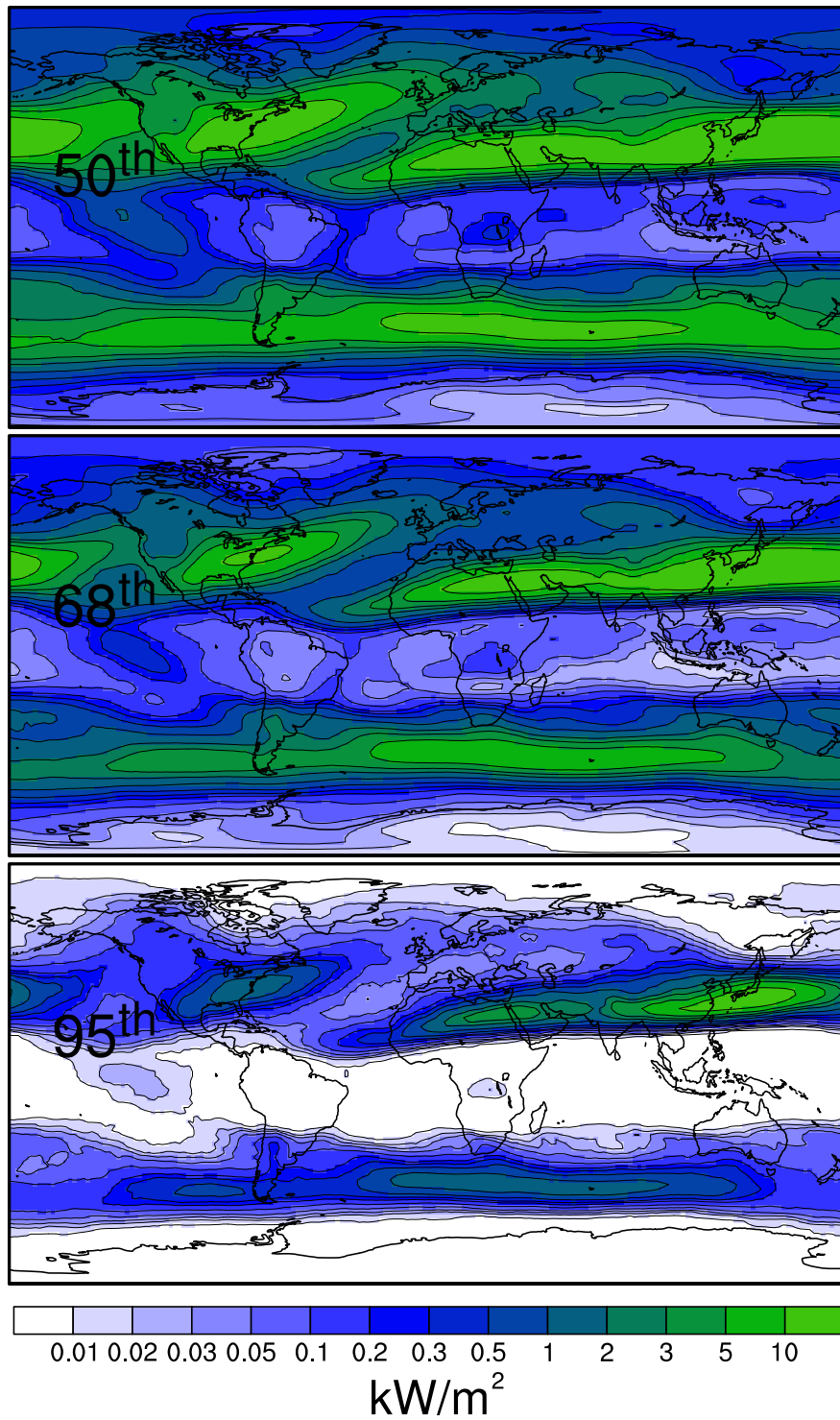


Figure 1.29: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 9000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 10000 m - DJF

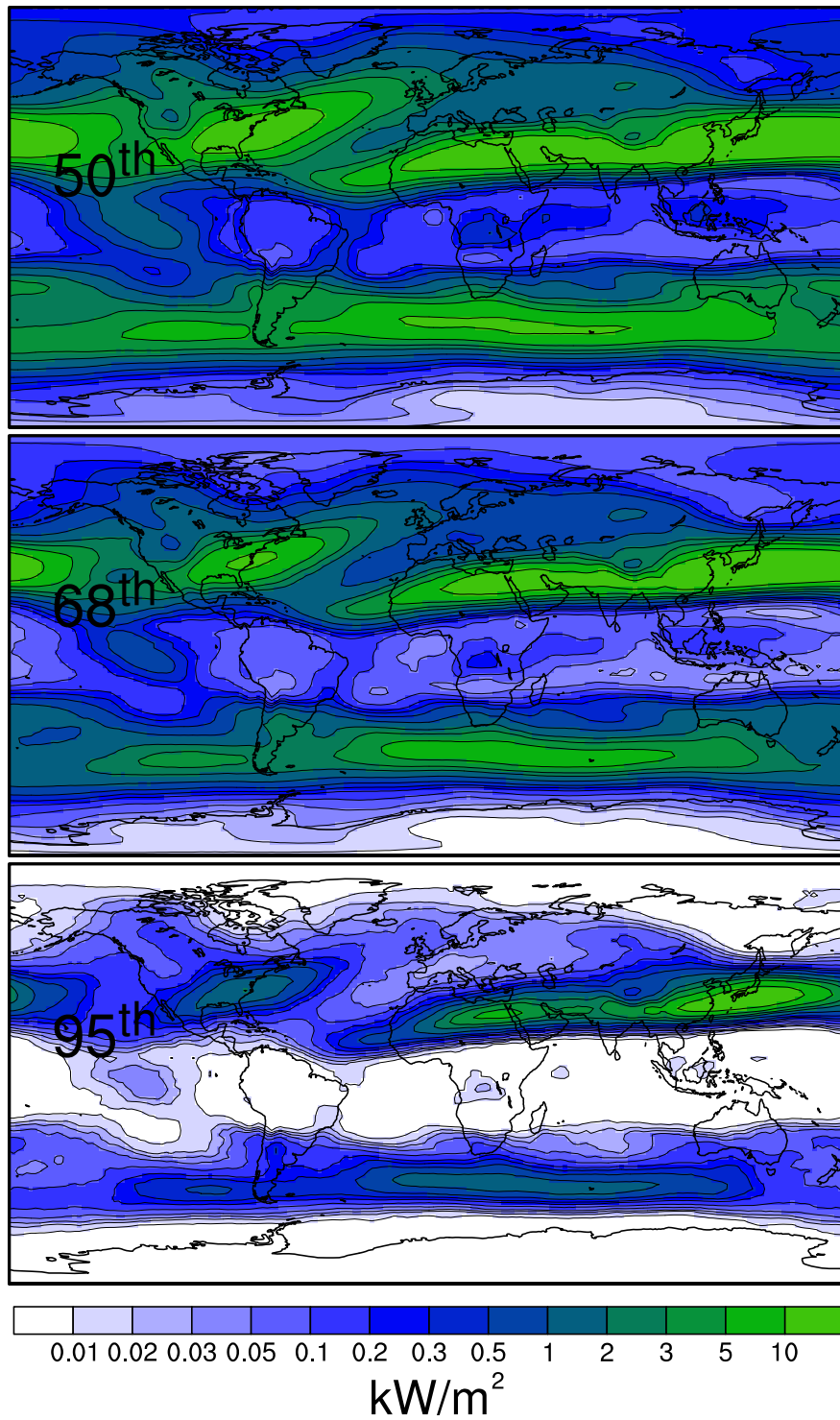


Figure 1.30: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 10,000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 11000 m - DJF

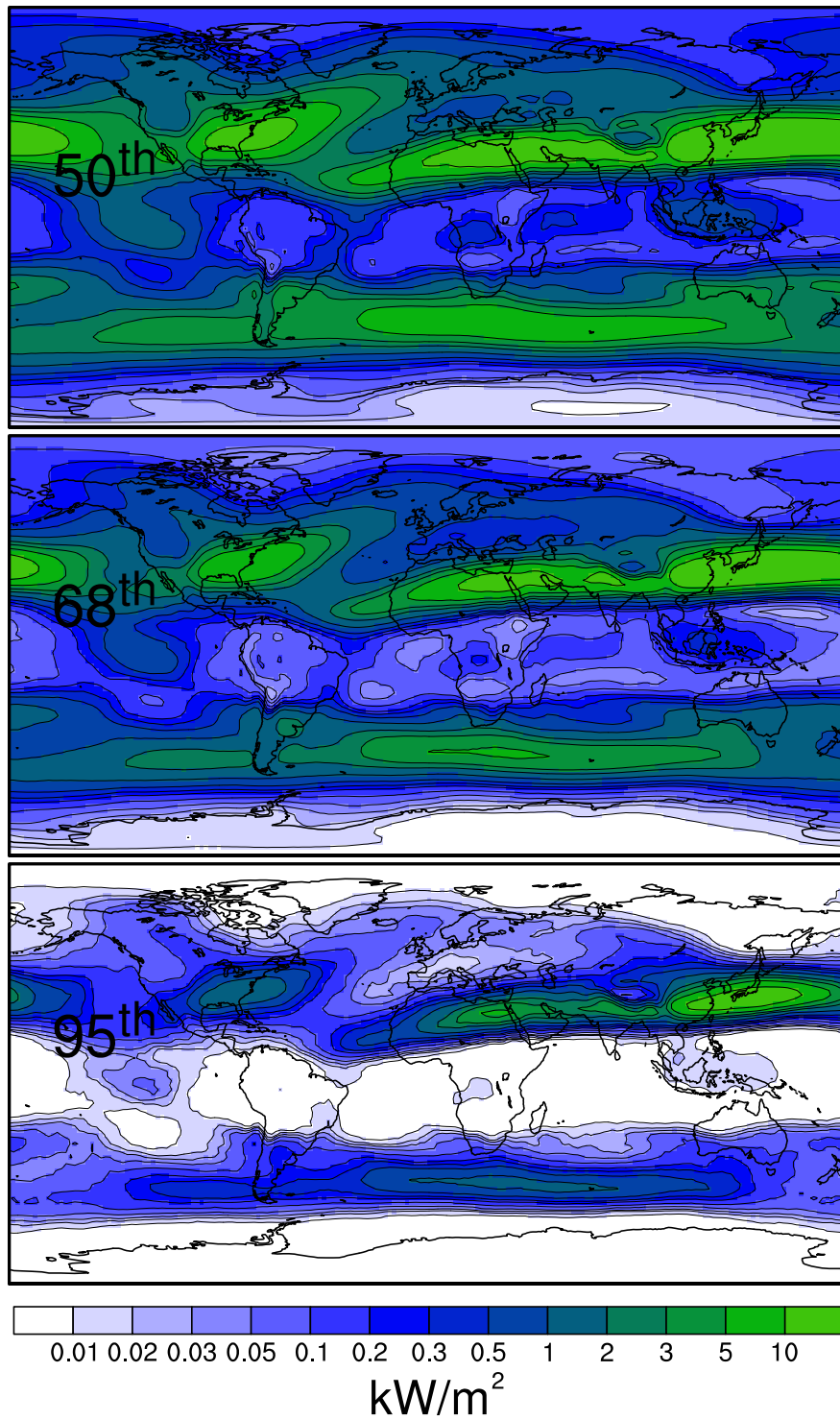


Figure 1.31: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 11,000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 12000 m - DJF

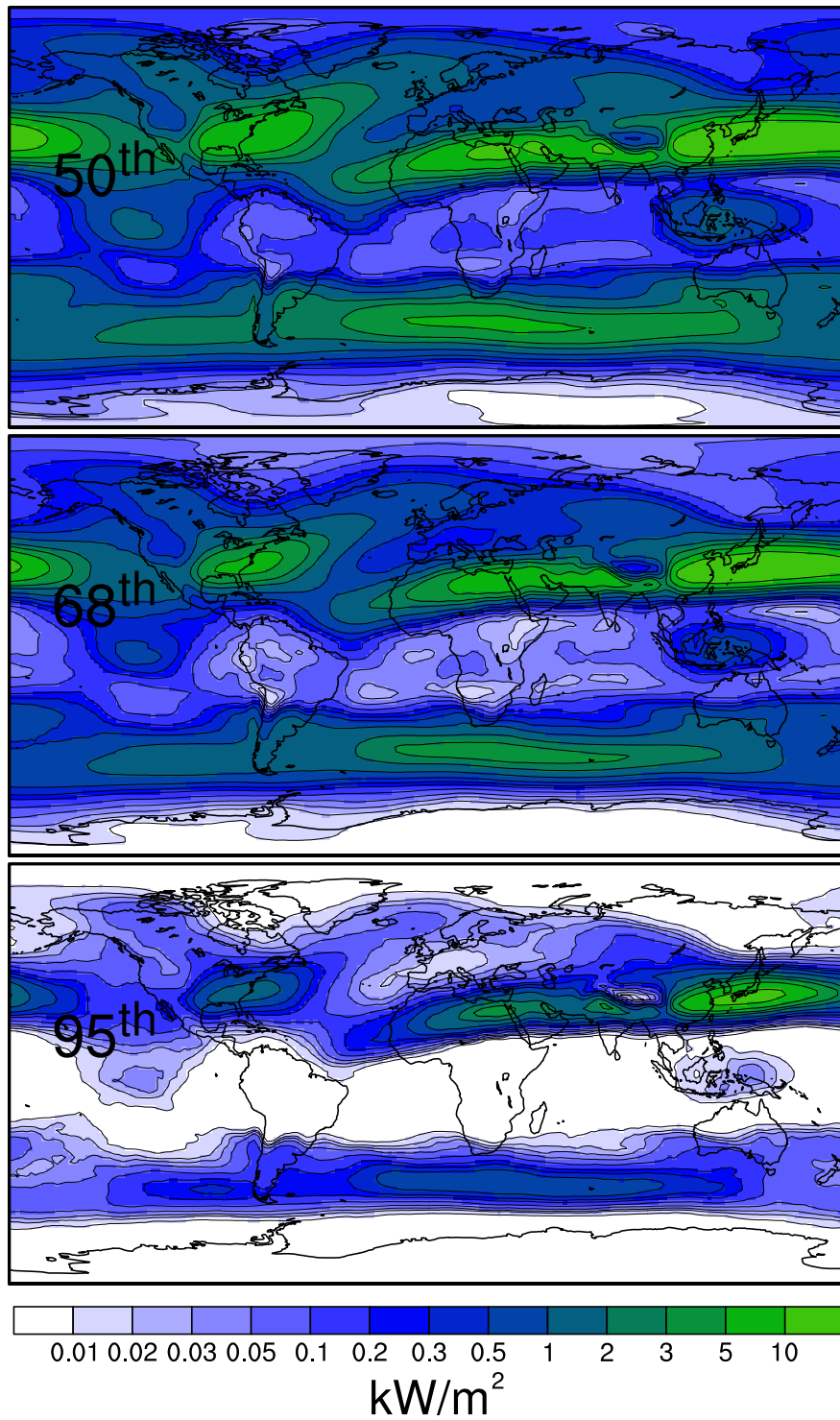


Figure 1.32: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 12,000 m during December-January-February in 1979-2006 from the NCEP/DOE reanalyses.



## 1.3 MAM percentiles

This section contains selected percentiles of wind power density at all levels between 80 and 12,000 m above ground level, calculated for March-April-May (MAM) in 1979-2006 from the 6-hourly NCEP/DOE reanalyses.

## Level = 80 m - MAM

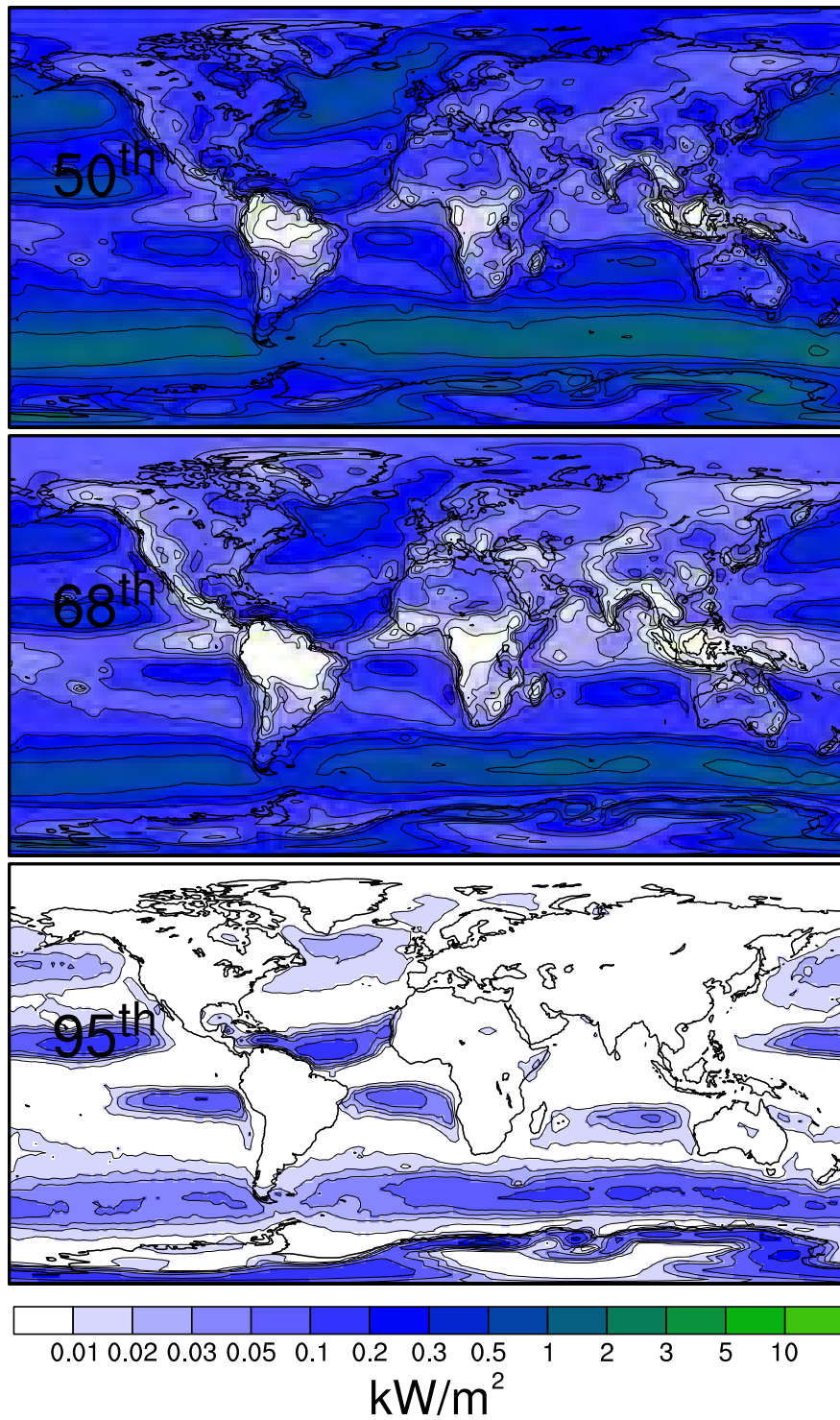


Figure 1.33: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 80 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 500 m - MAM

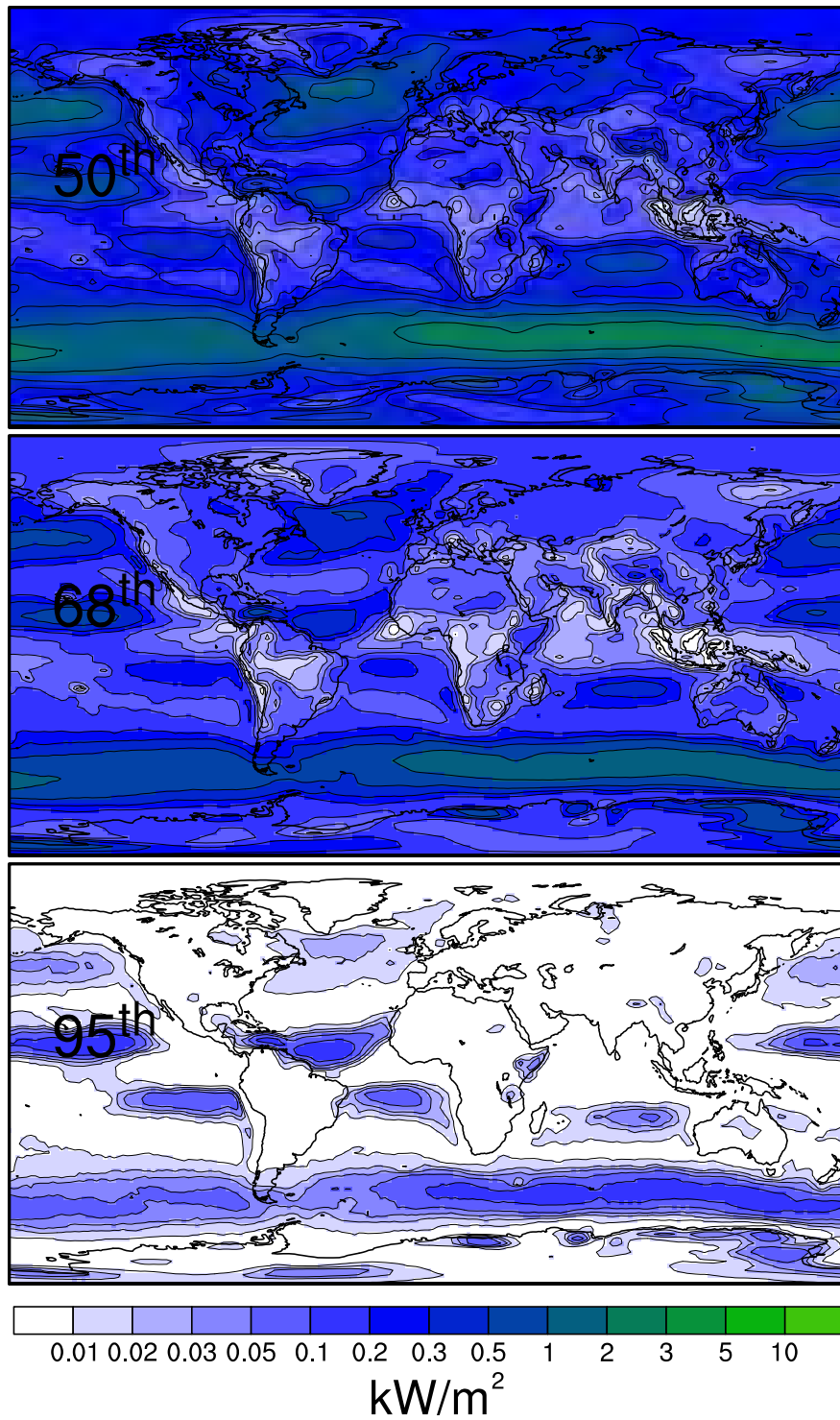


Figure 1.34: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 500 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 750 m - MAM

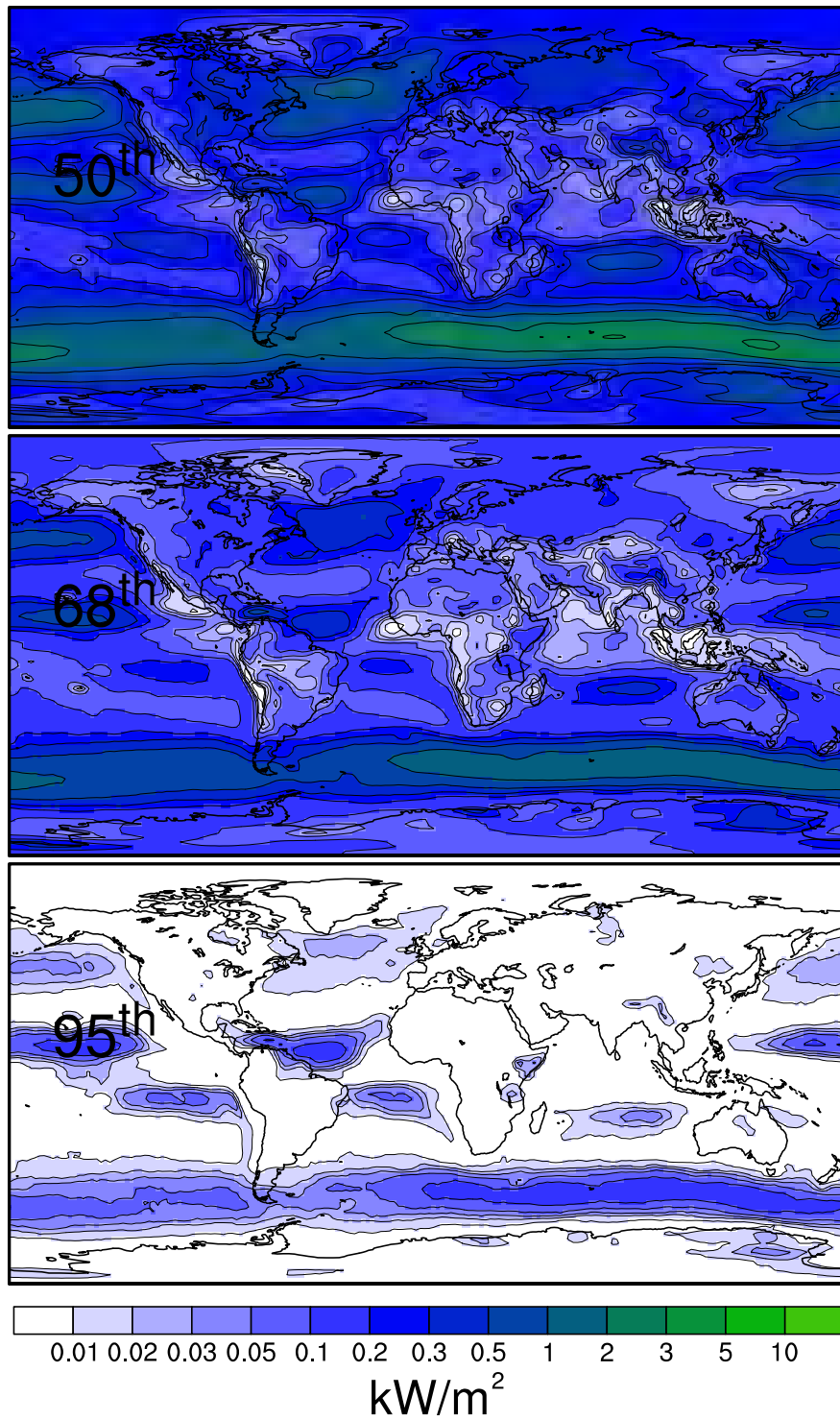


Figure 1.35: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 750 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 1000 m - MAM

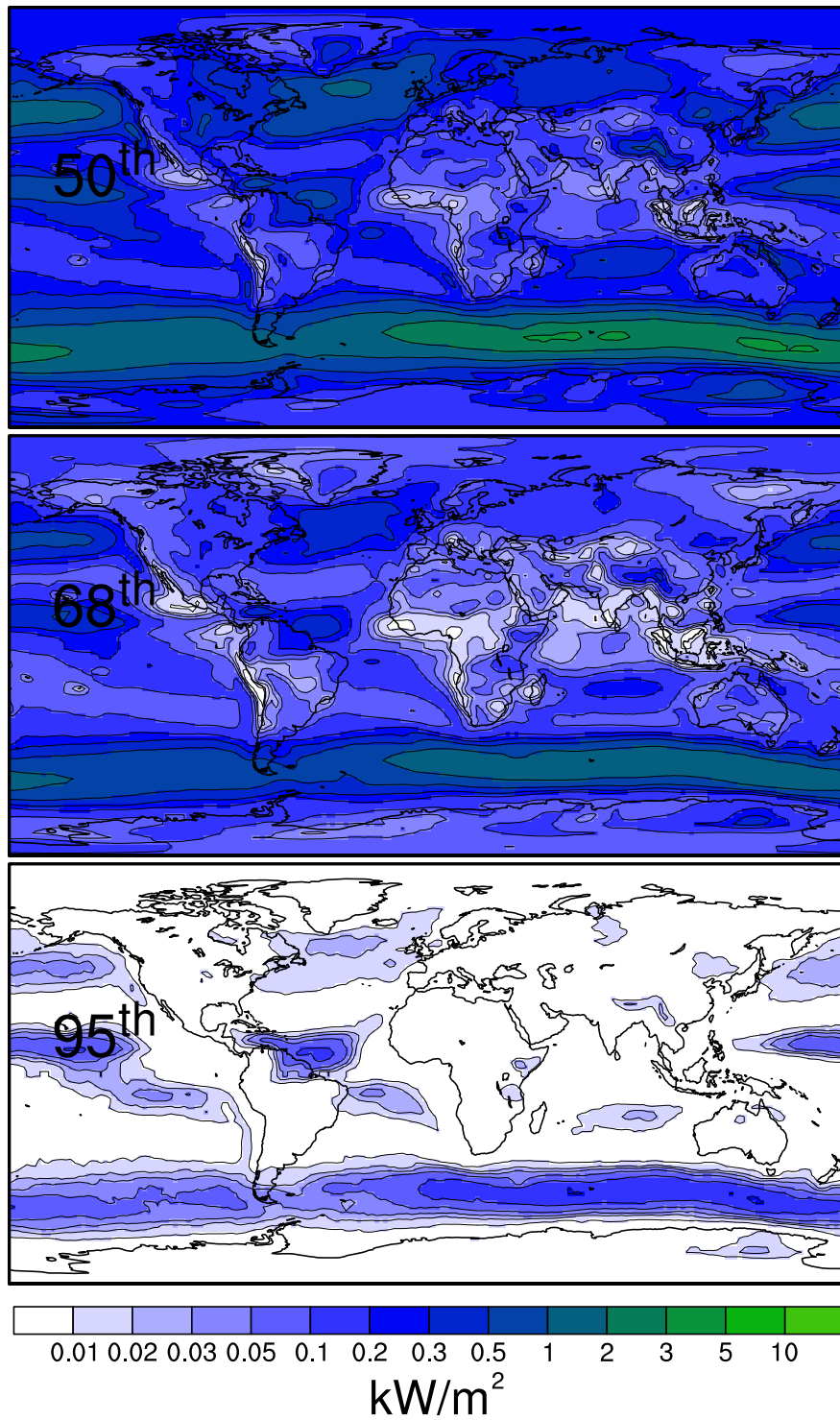


Figure 1.36: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 1000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 1500 m - MAM

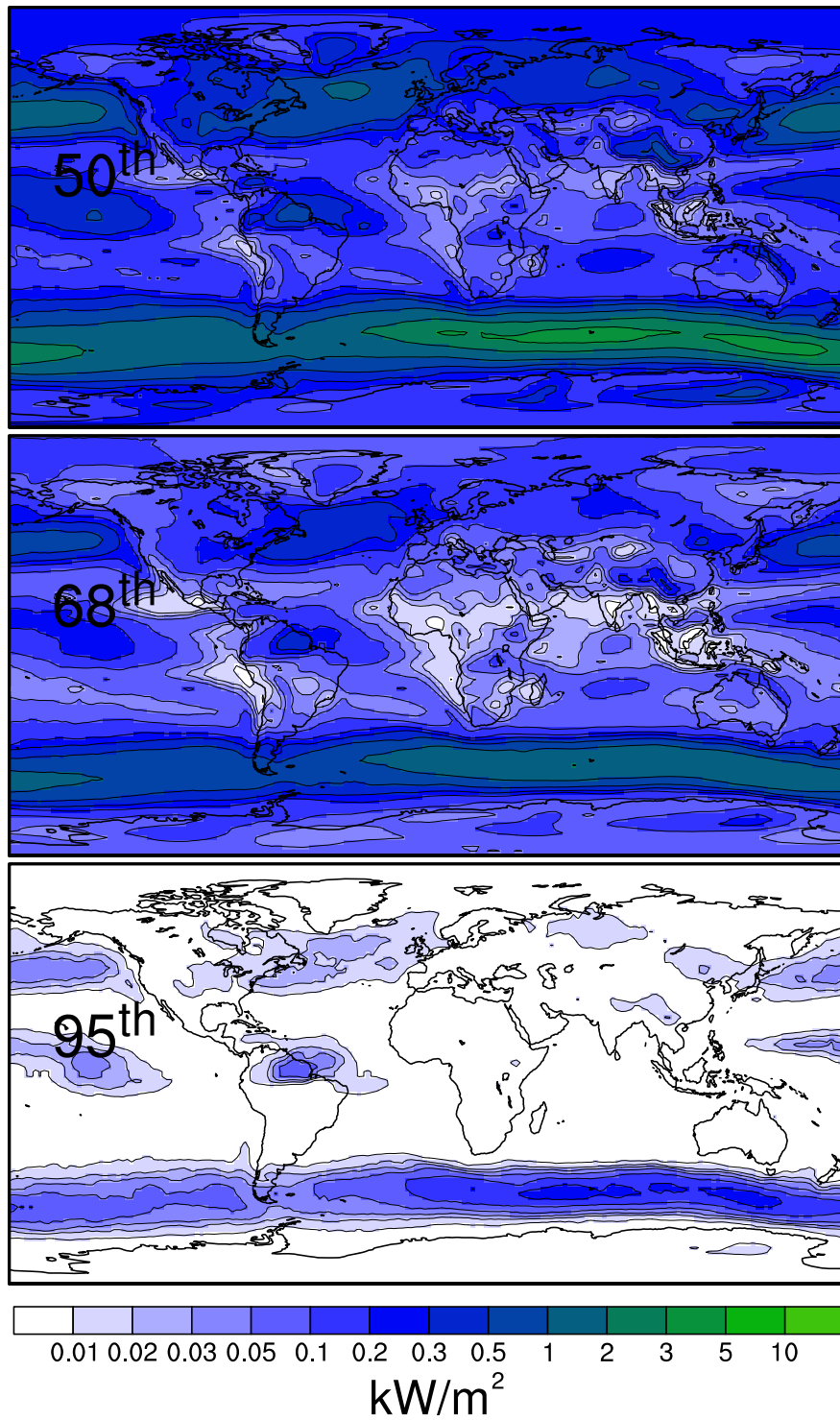


Figure 1.37: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 1500 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.

Level = 2000 m - MAM

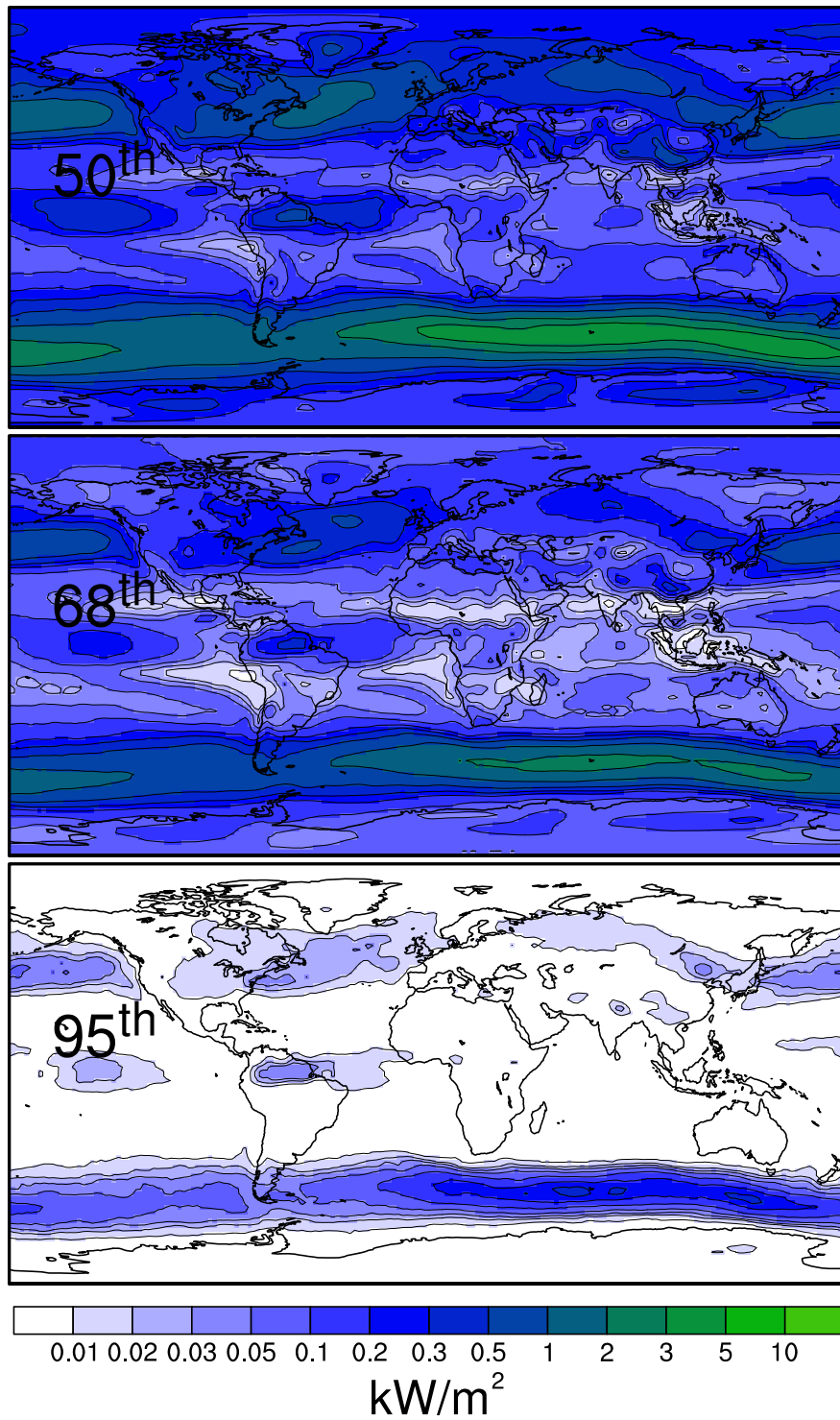


Figure 1.38: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 2000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.



Level = 3000 m - MAM

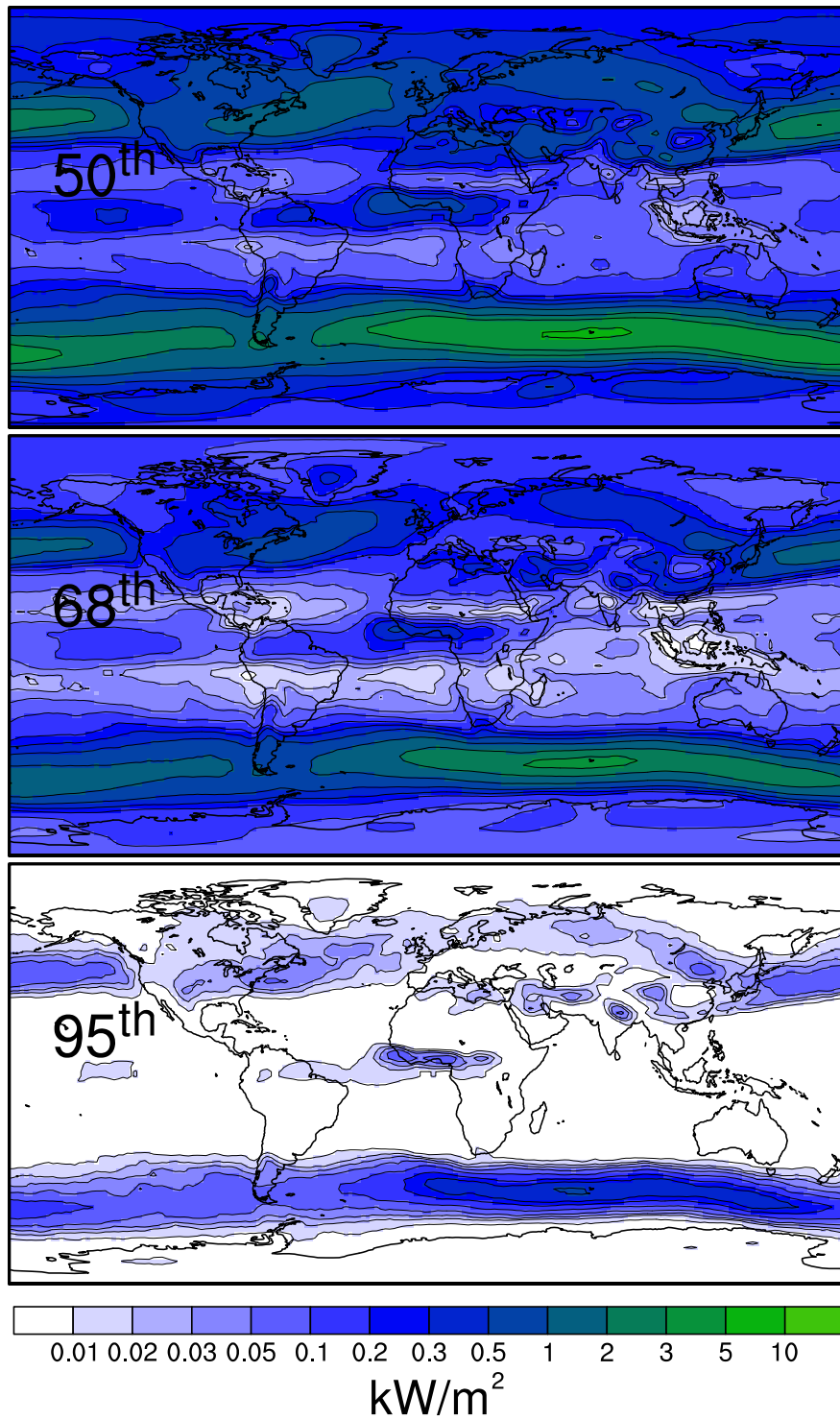


Figure 1.39: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 3000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.

Level = 4000 m - MAM

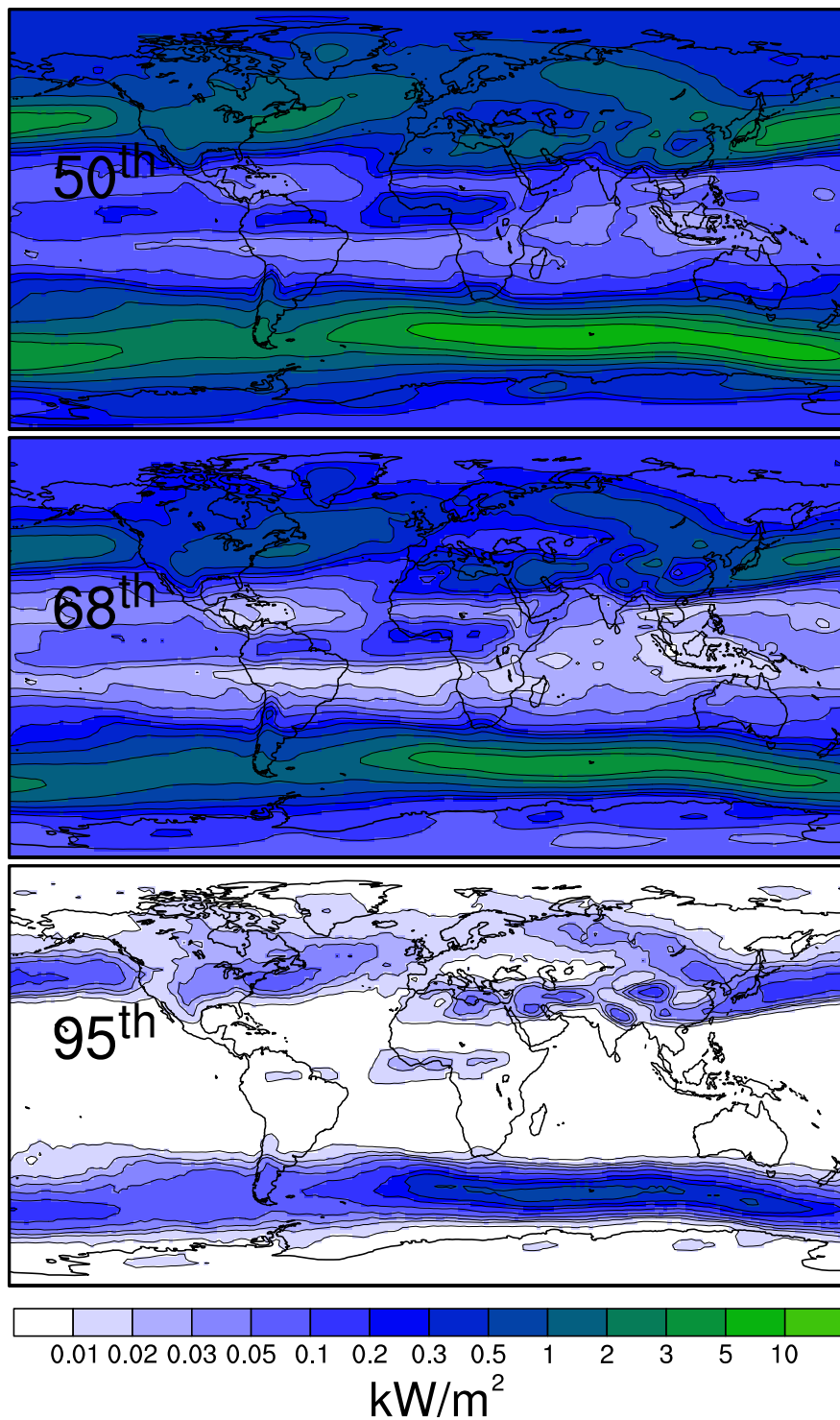


Figure 1.40: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 4000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 5000 m - MAM

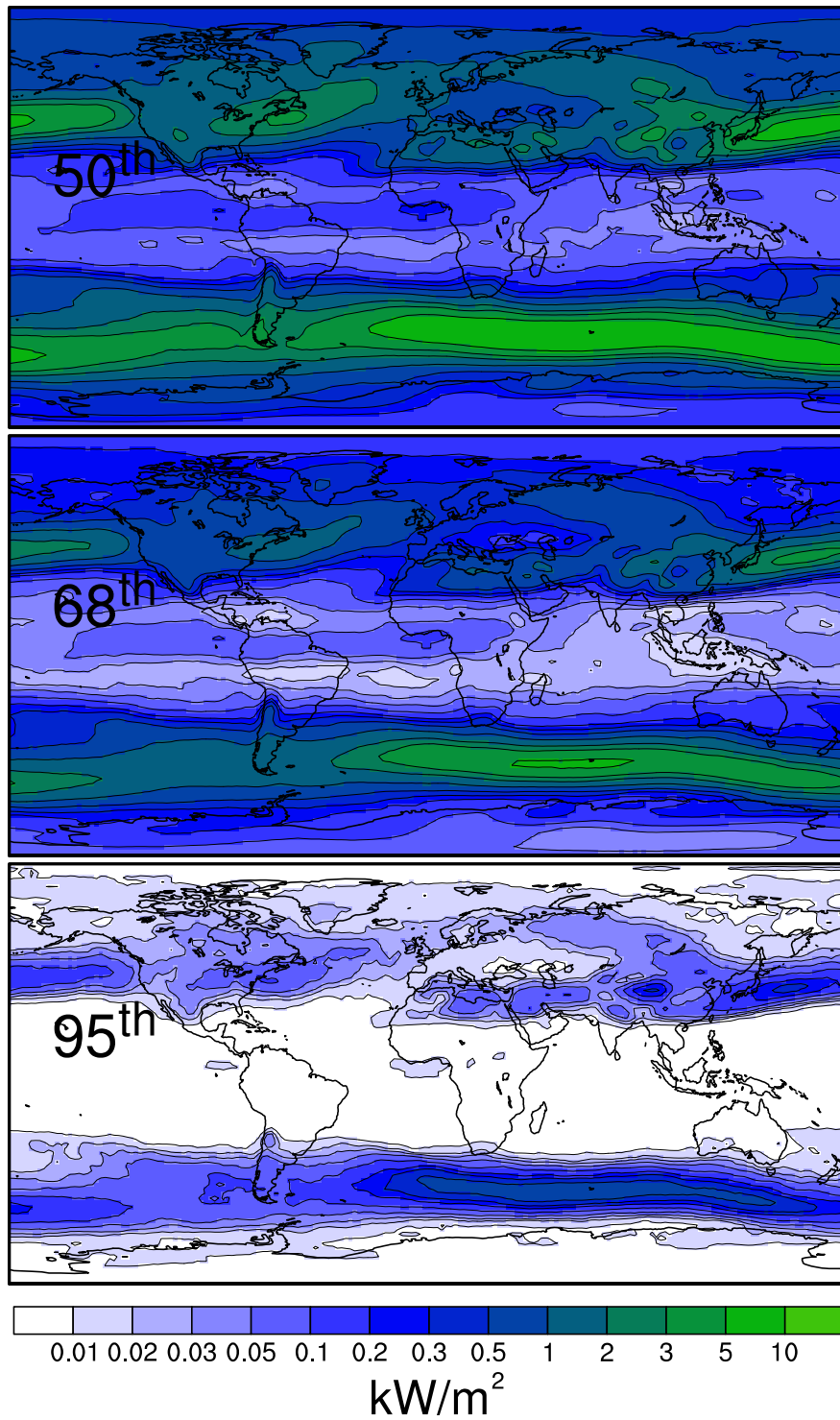


Figure 1.41: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 5000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.

Level = 6000 m - MAM

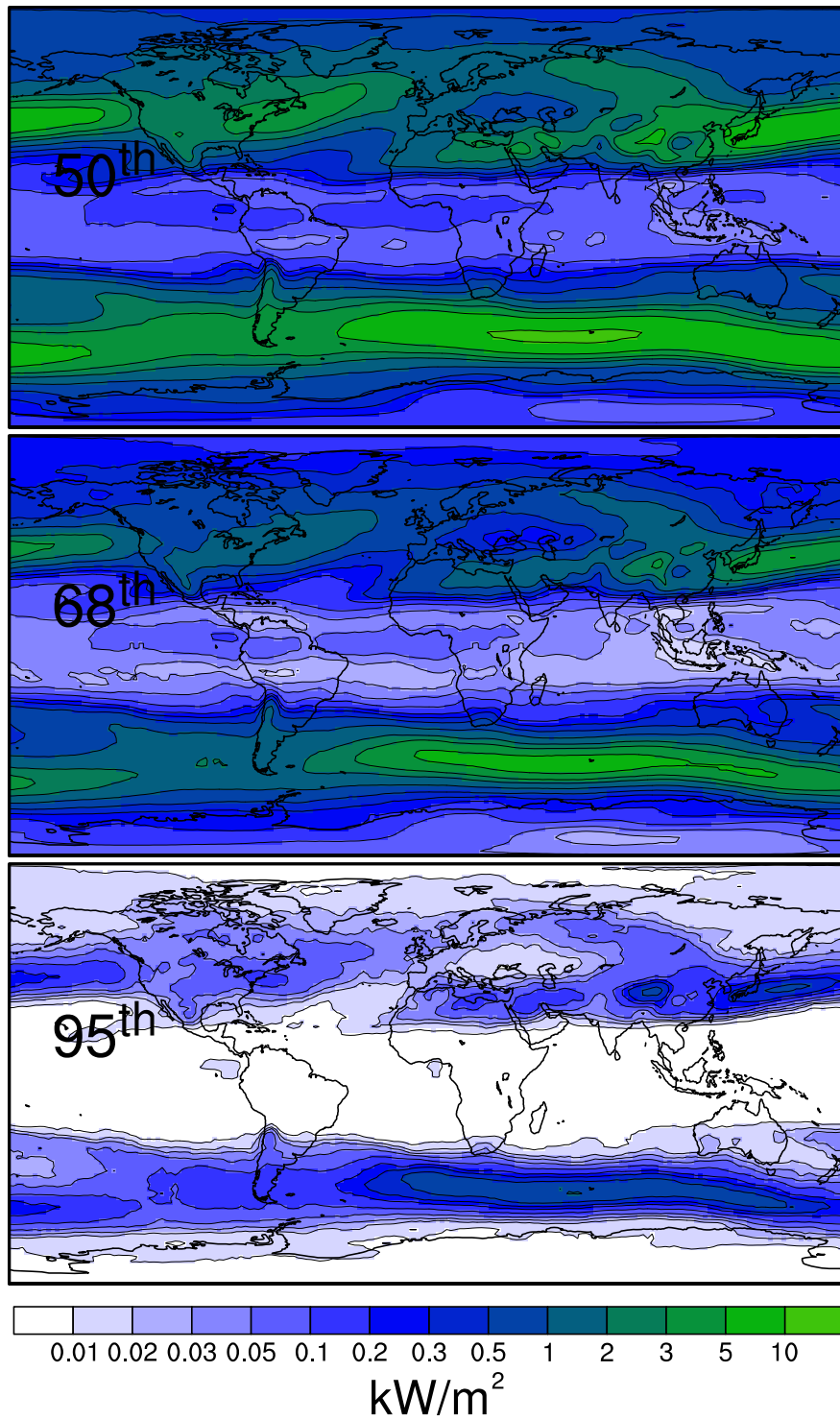


Figure 1.42: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 6000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 7000 m - MAM

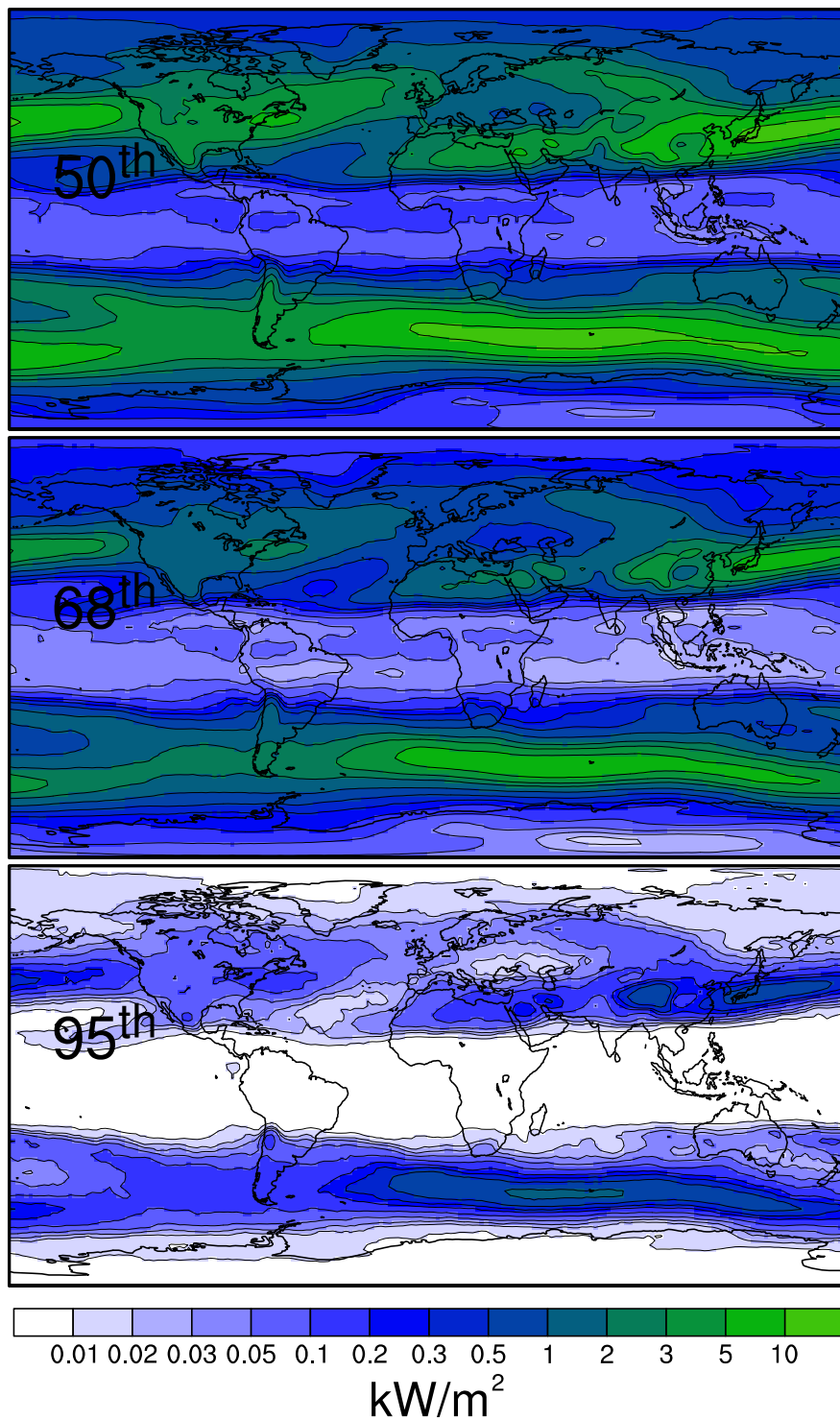


Figure 1.43: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 7000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 8000 m - MAM

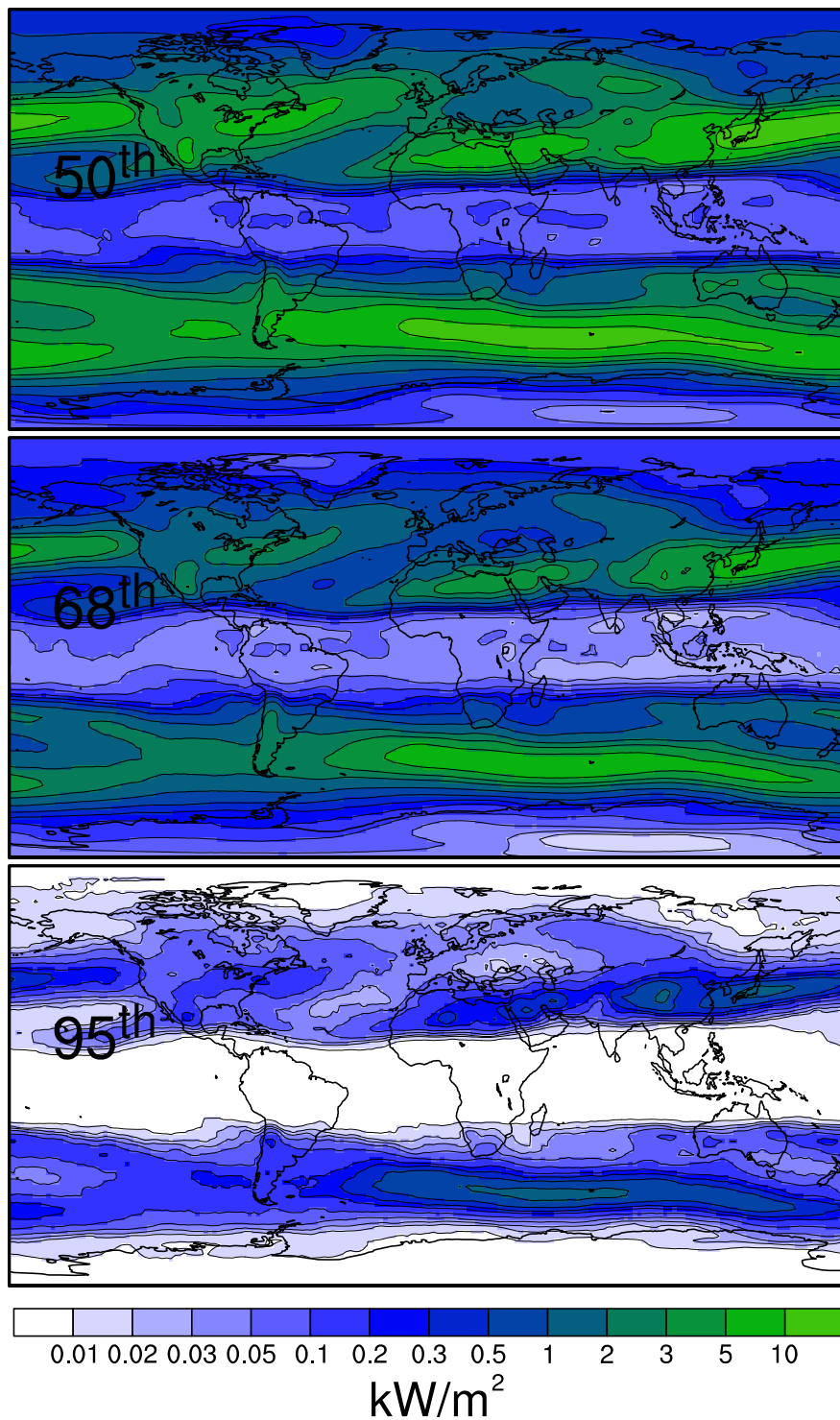


Figure 1.44: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 8000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 9000 m - MAM

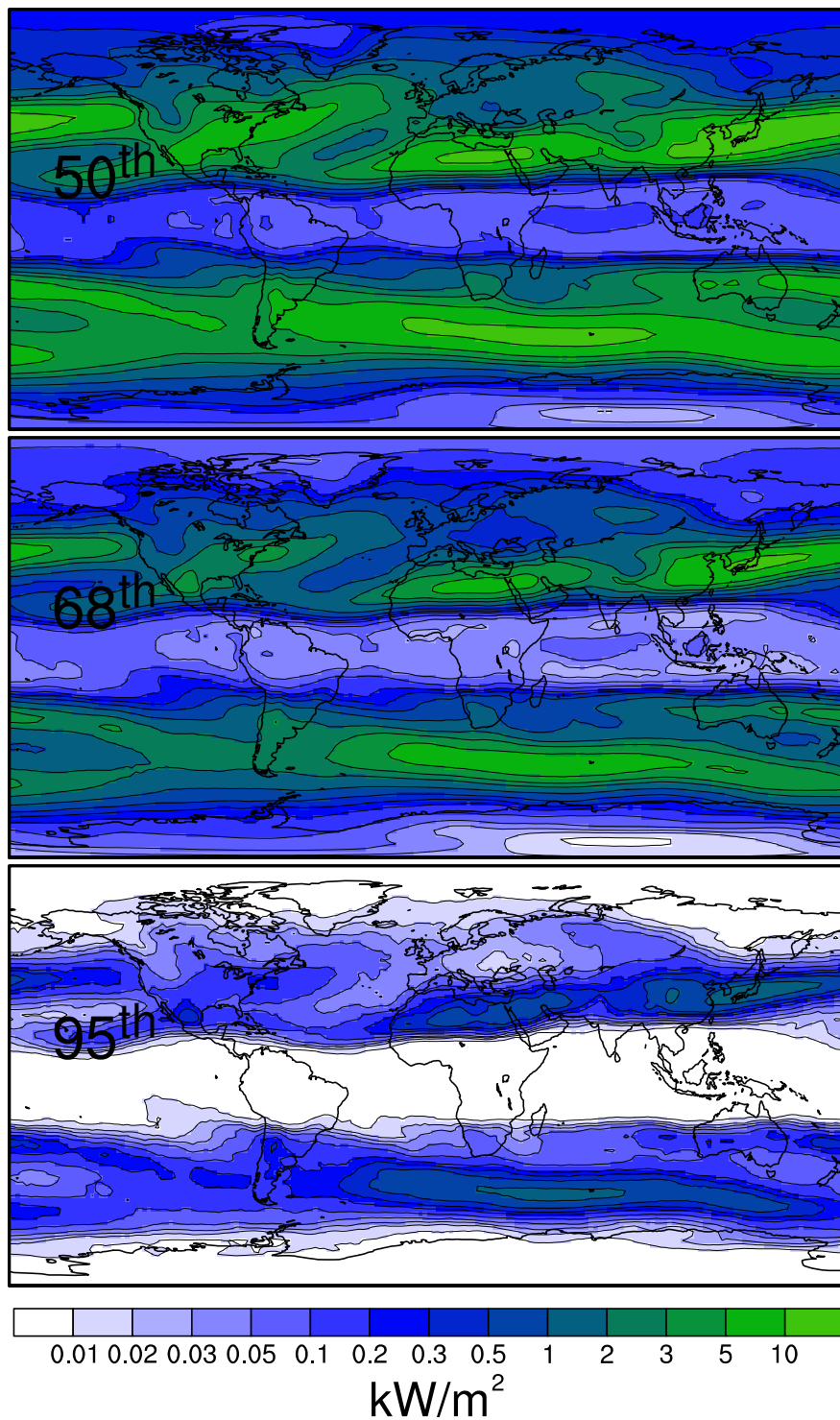


Figure 1.45: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 9000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.

Level = 10000 m - MAM

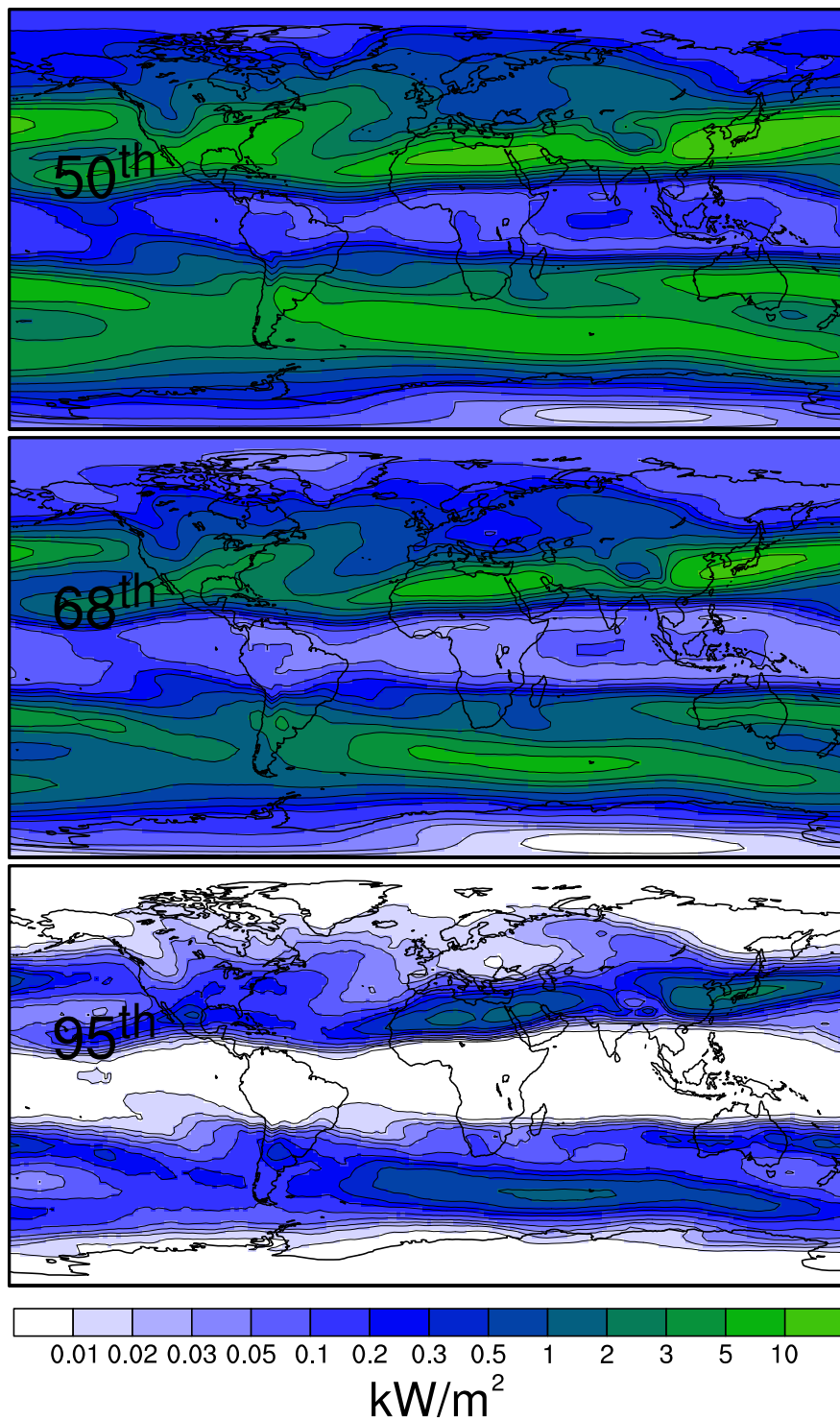


Figure 1.46: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 10,000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 11000 m - MAM

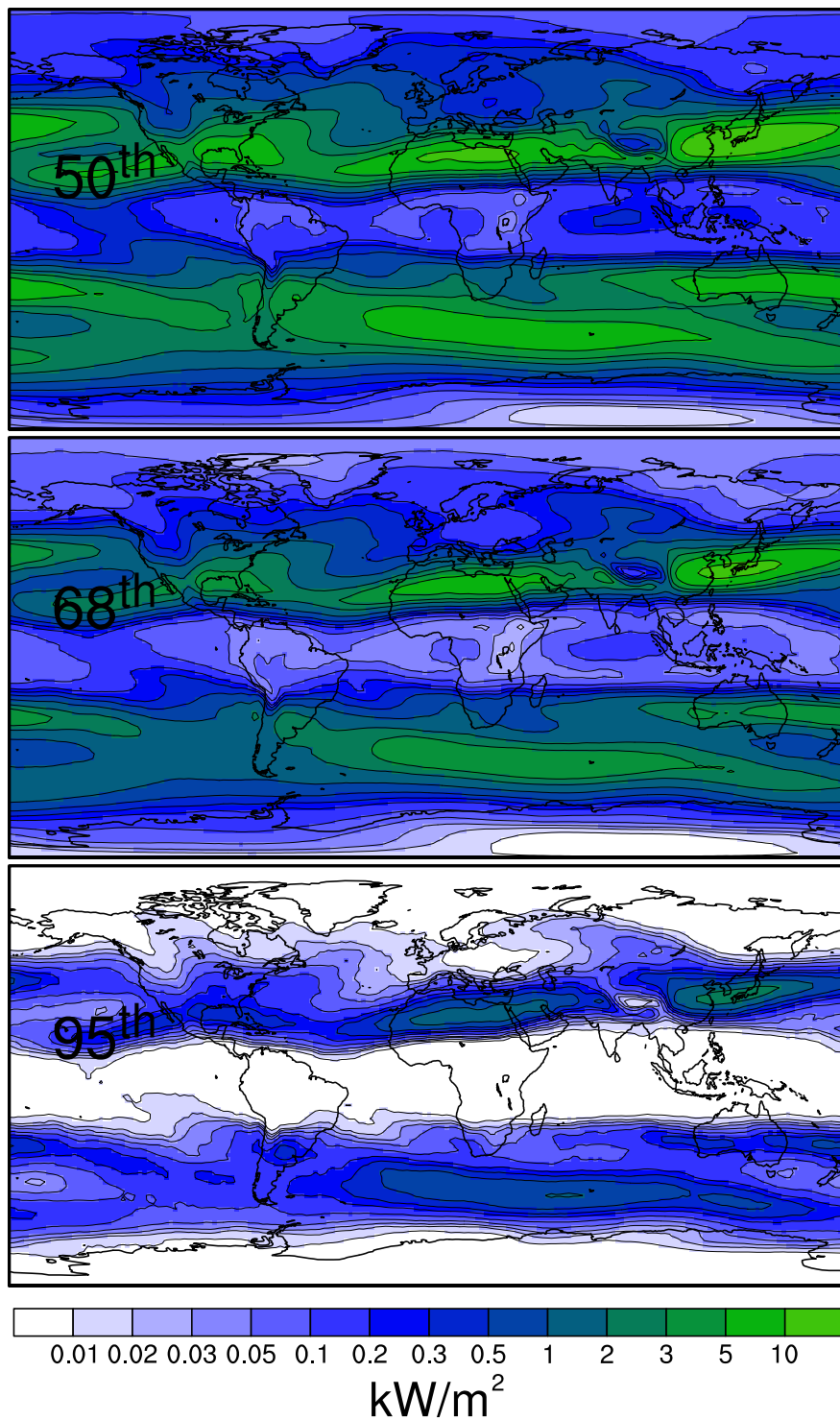


Figure 1.47: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 11,000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 12000 m - MAM

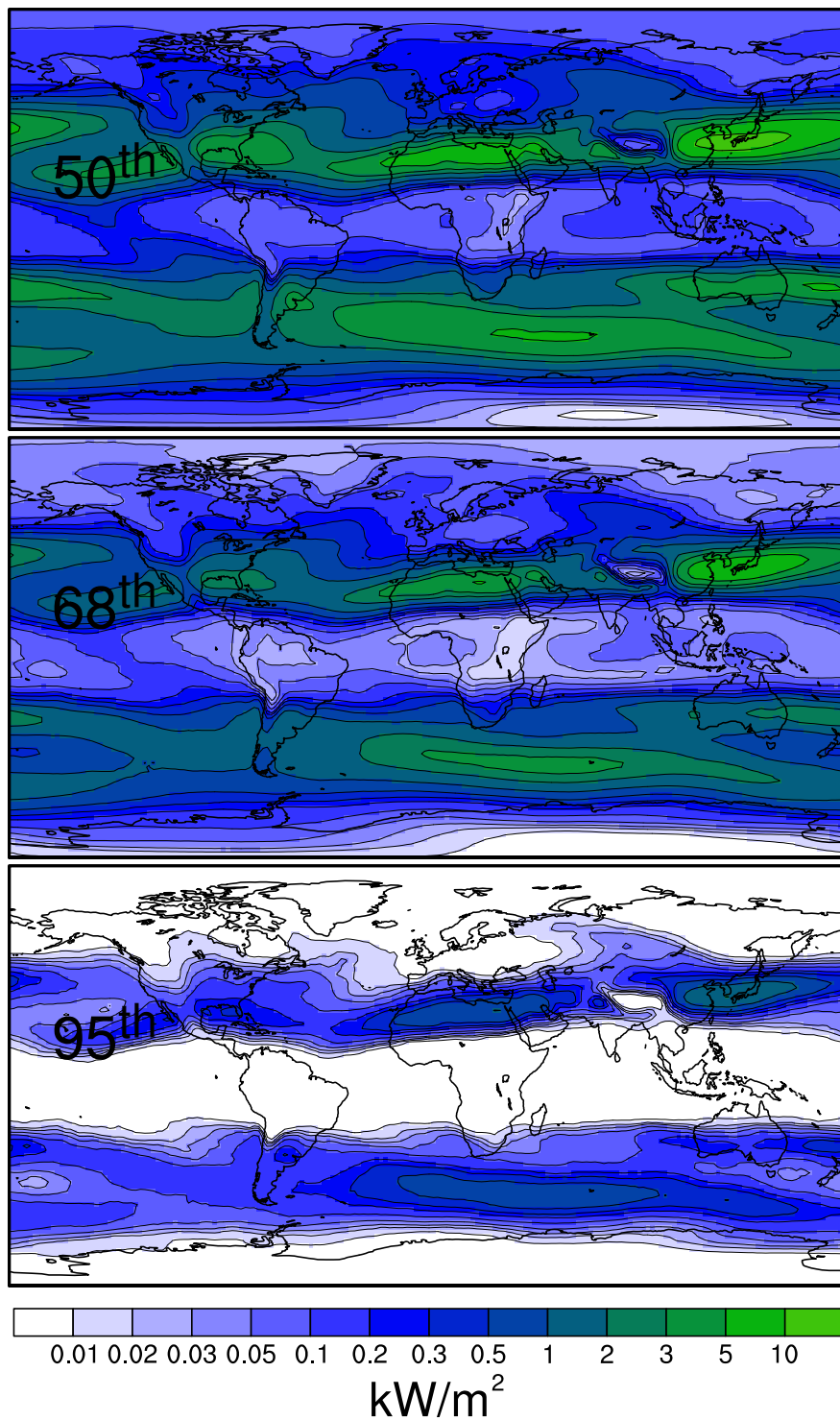


Figure 1.48: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 12,000 m during March-April-May in 1979-2006 from the NCEP/DOE reanalyses.



## 1.4 JJA percentiles

This section contains selected percentiles of wind power density at all levels between 80 and 12,000 m above ground level, calculated for June-July-August (JJA) in 1979-2006 from the 6-hourly NCEP/DOE reanalyses.

## Level = 80 m - JJA

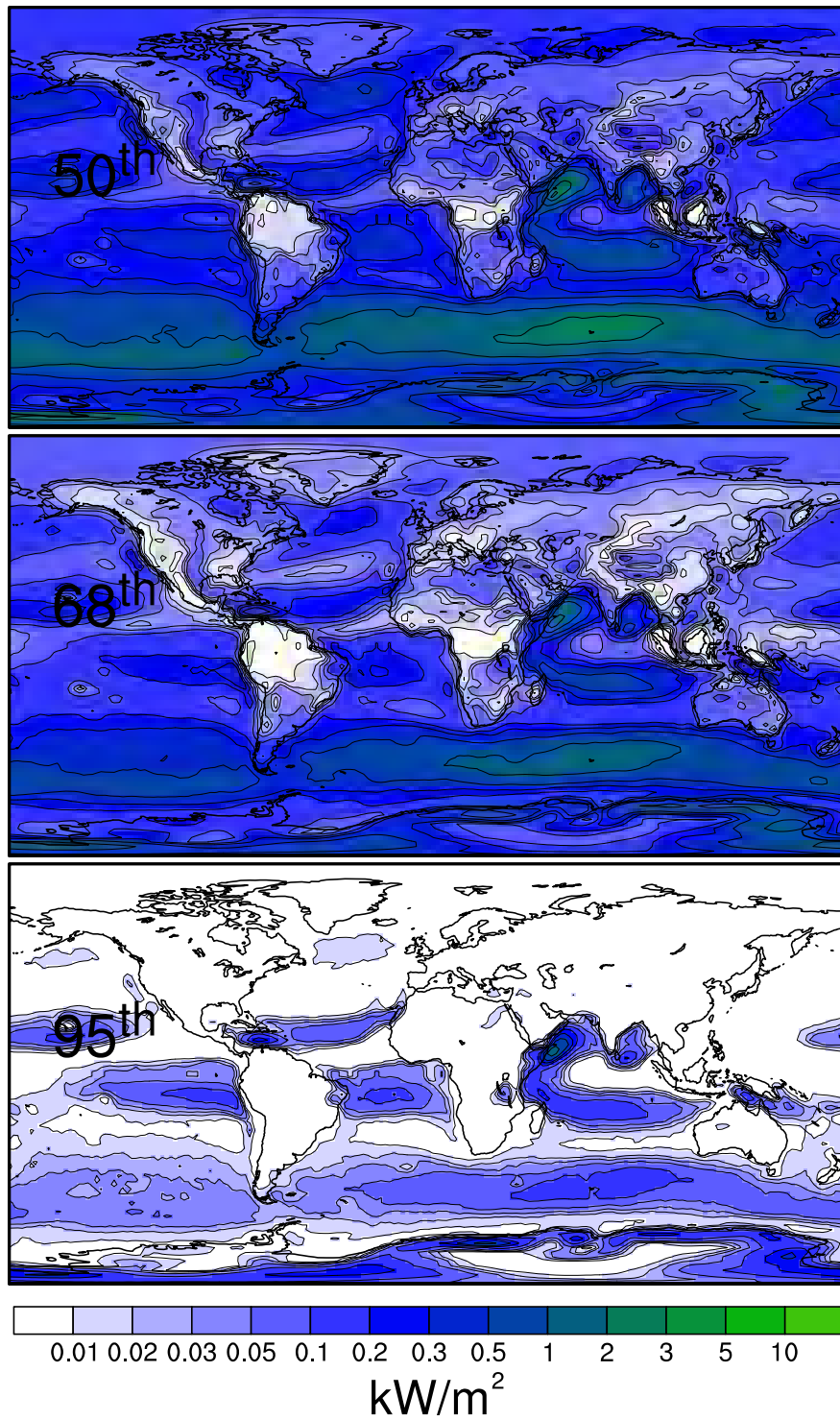


Figure 1.49: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 80 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 500 m - JJA

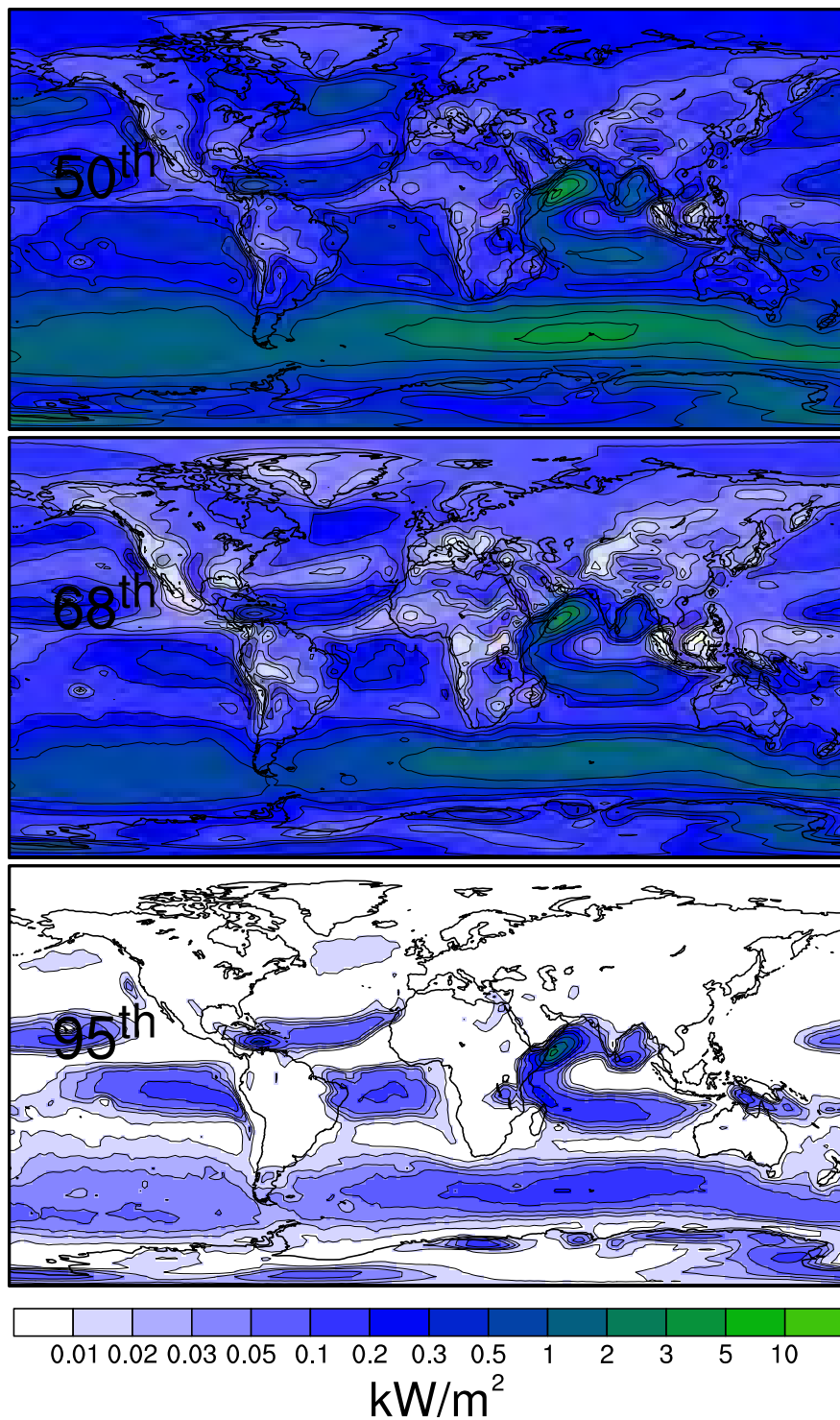


Figure 1.50: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 500 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 750 m - JJA

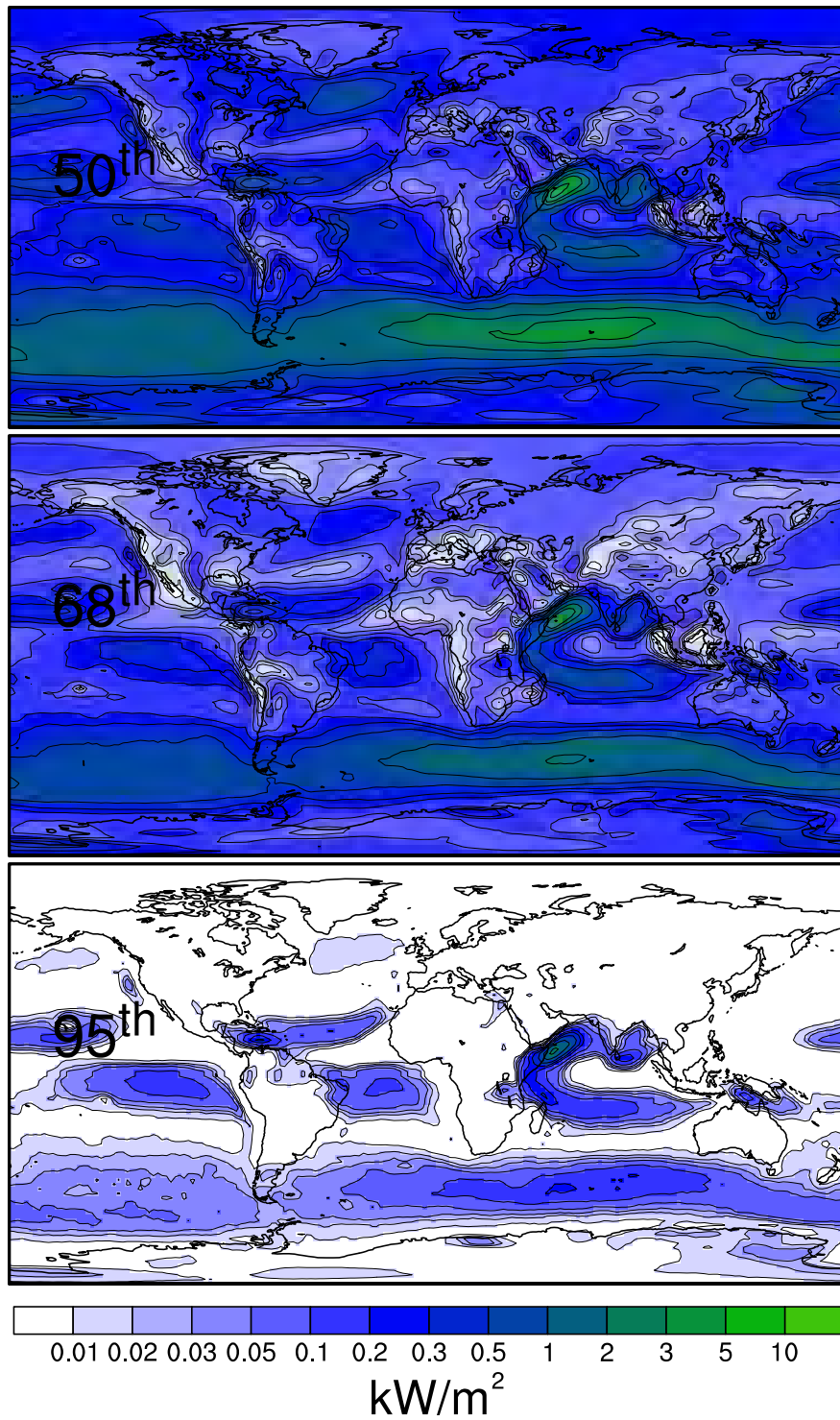


Figure 1.51: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 750 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 1000 m - JJA

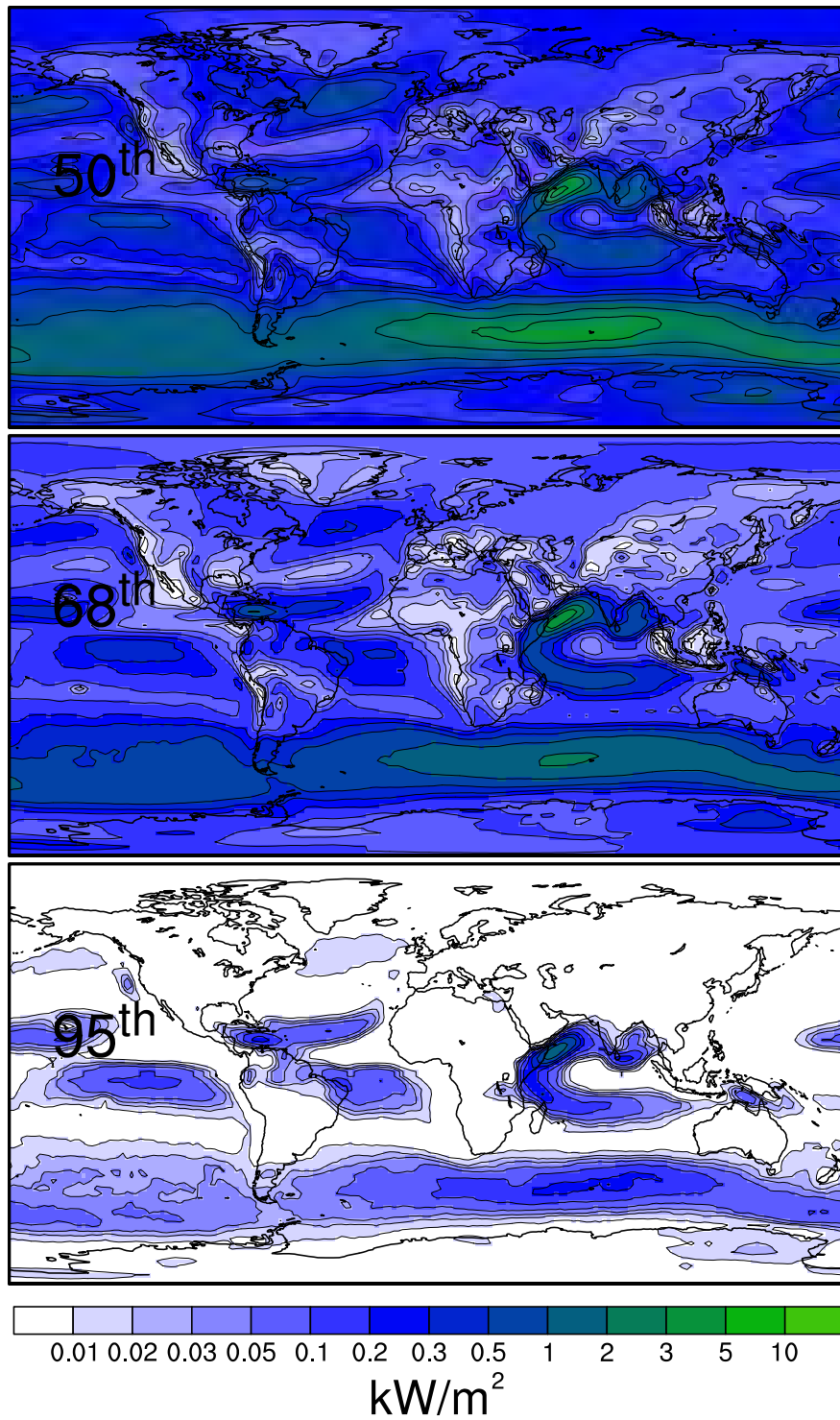


Figure 1.52: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 1000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 1500 m - JJA

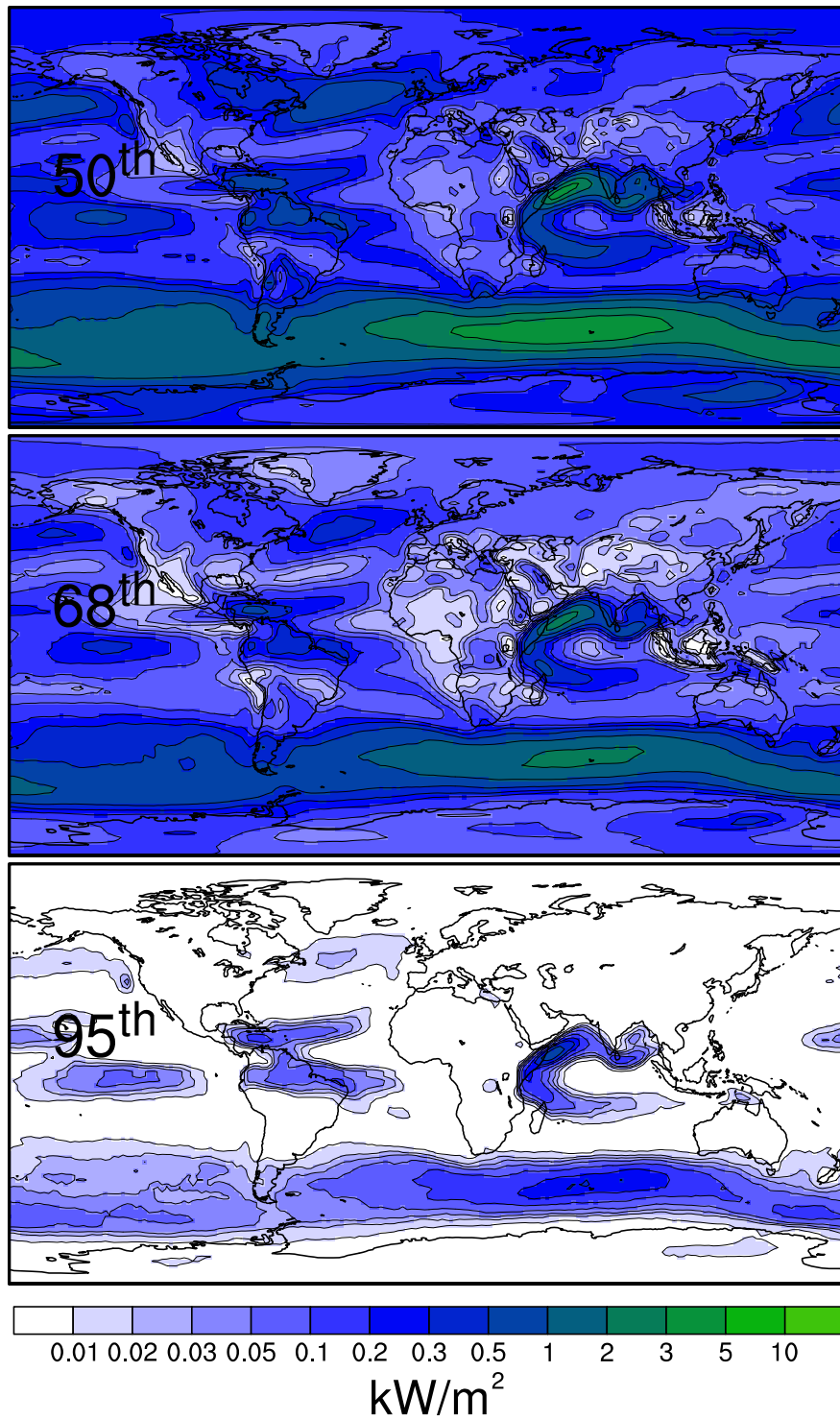


Figure 1.53: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 1500 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 2000 m - JJA

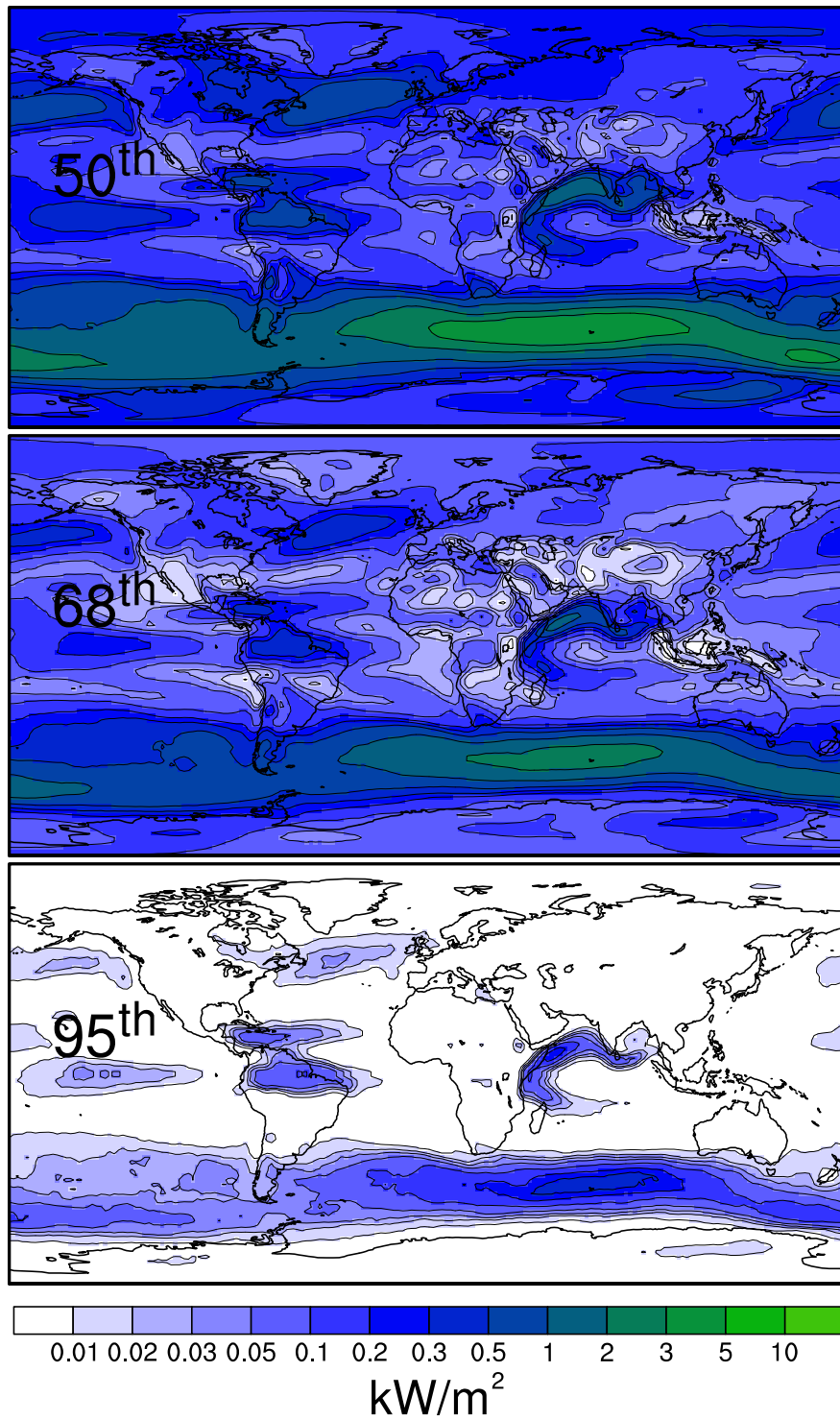


Figure 1.54: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 2000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 3000 m - JJA

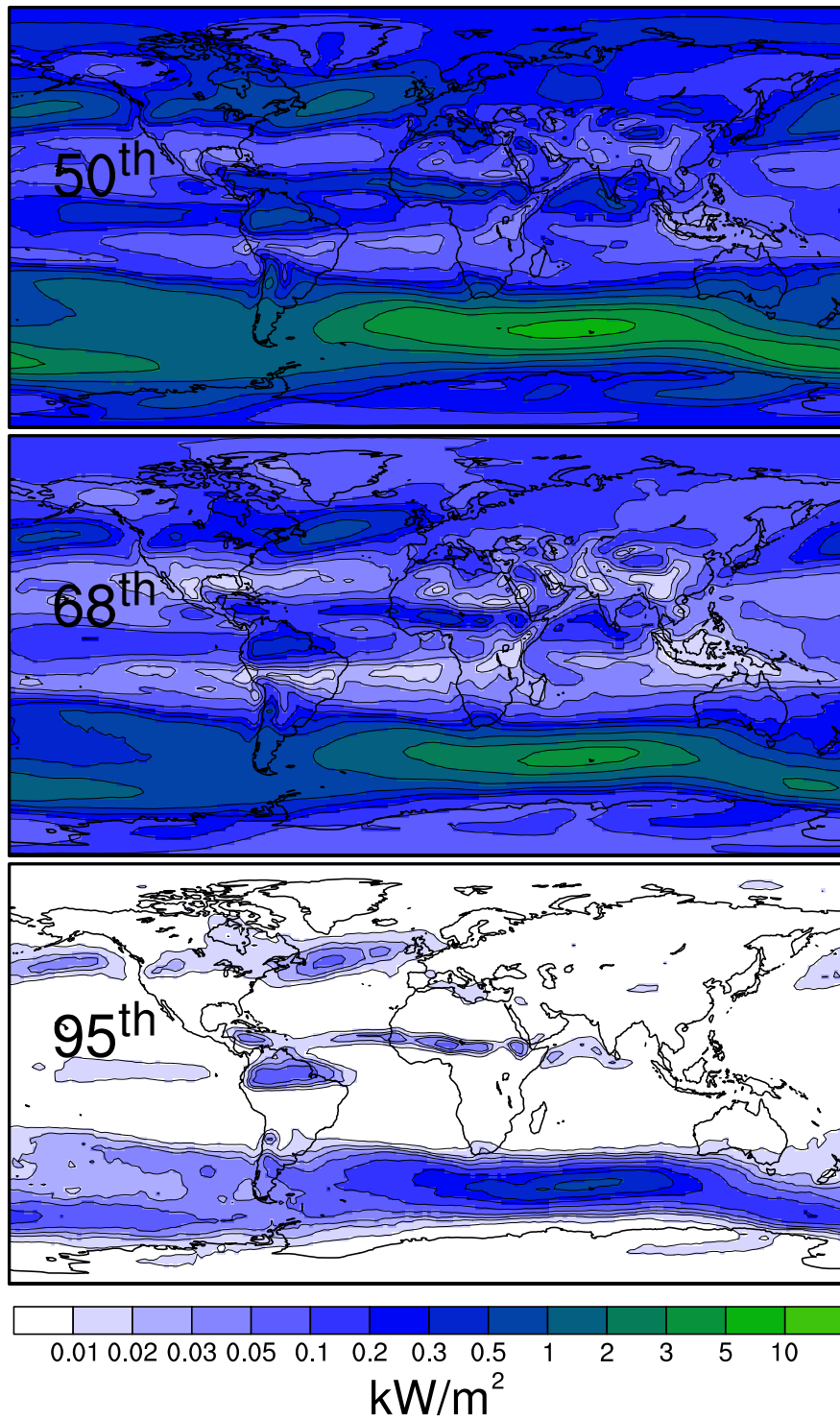


Figure 1.55: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 3000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 4000 m - JJA

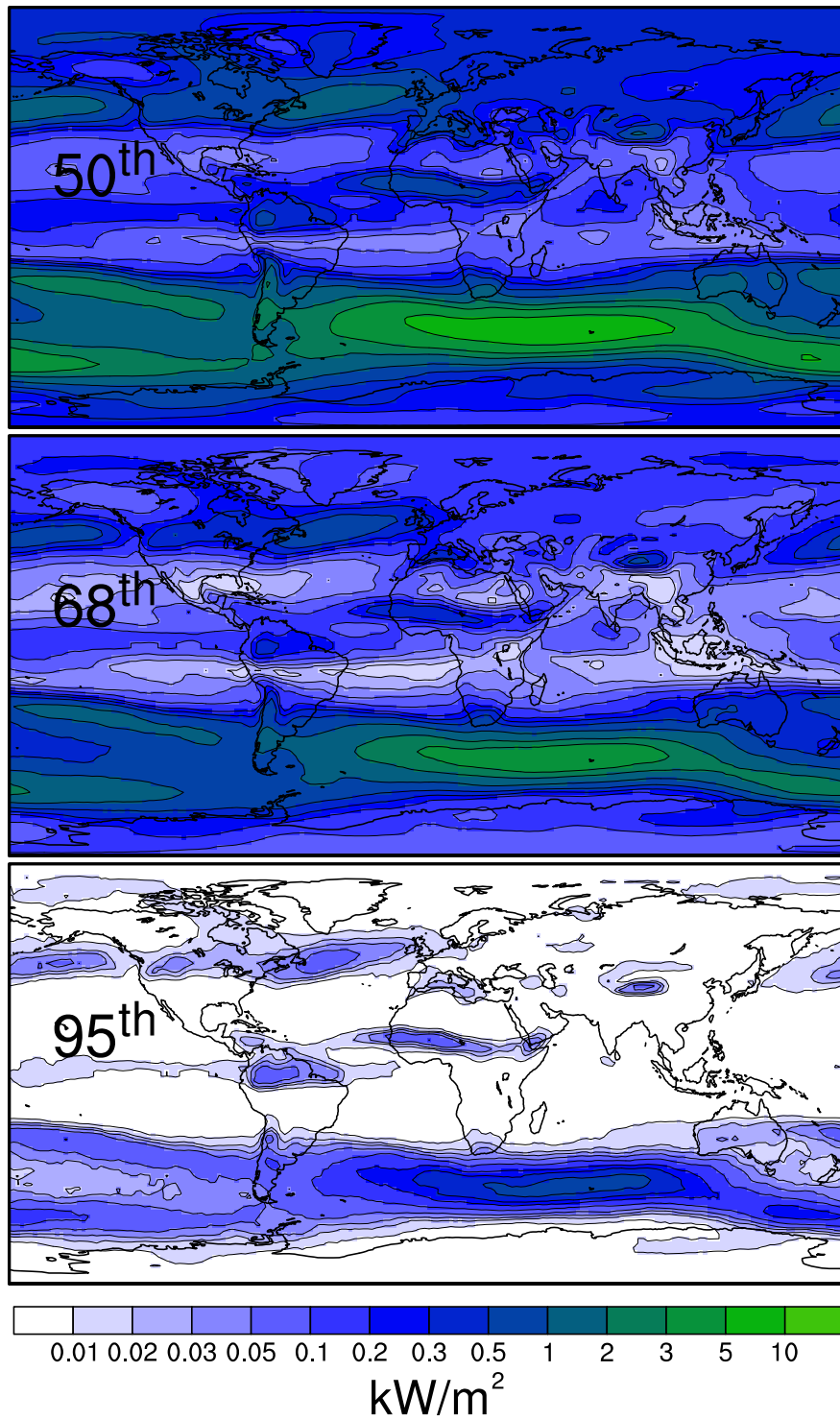


Figure 1.56: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 4000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 5000 m - JJA

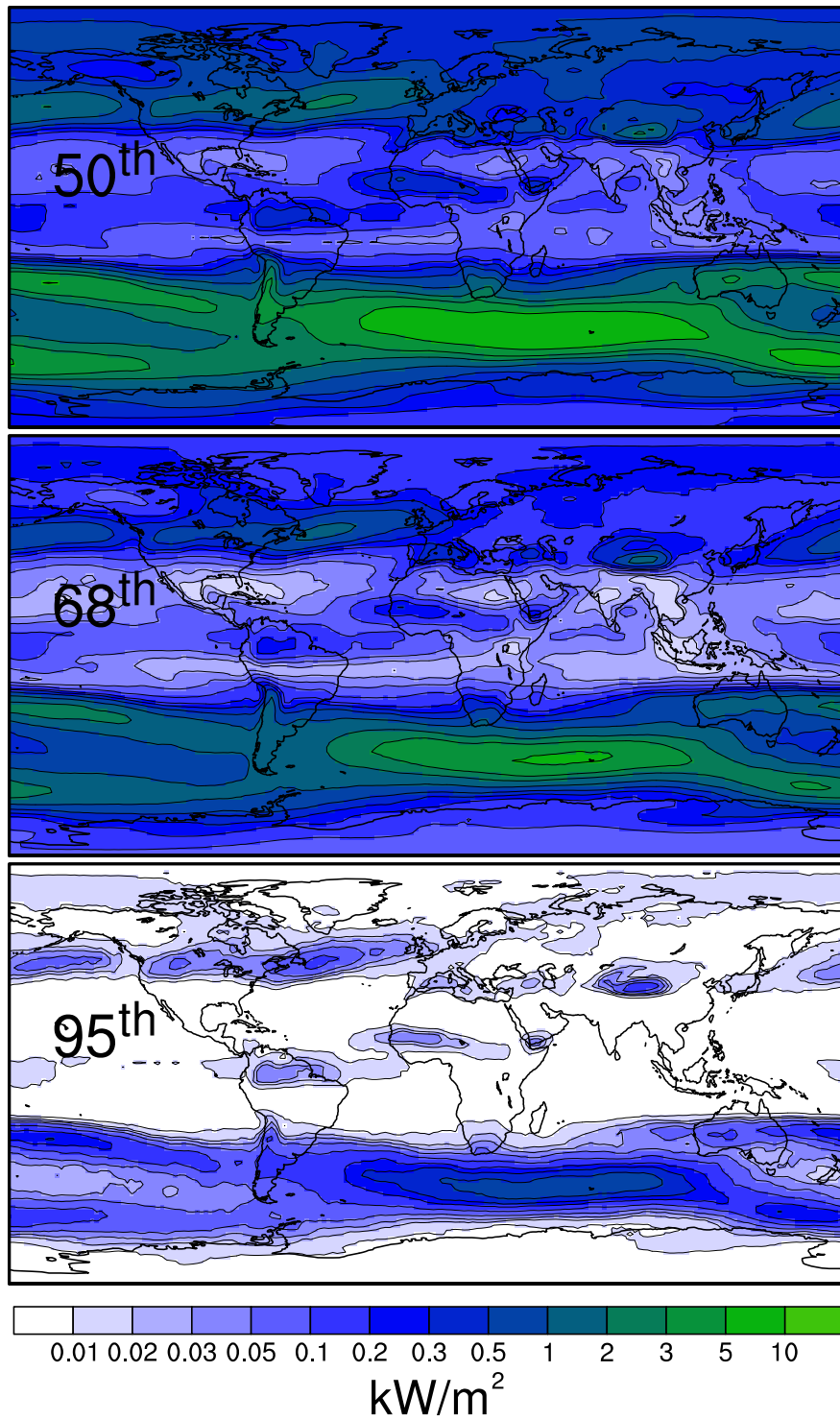


Figure 1.57: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 5000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 6000 m - JJA

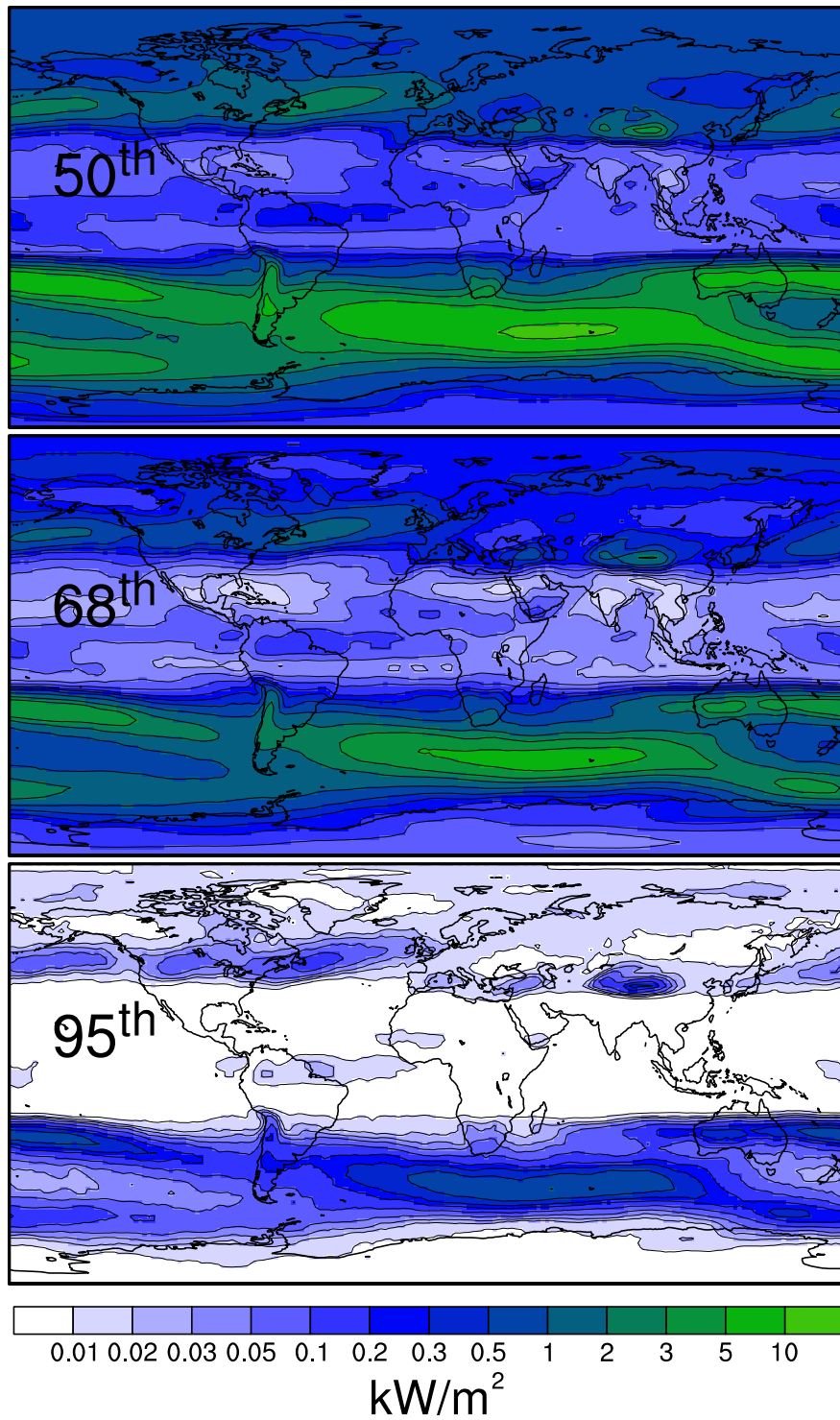


Figure 1.58: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 6000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 7000 m - JJA

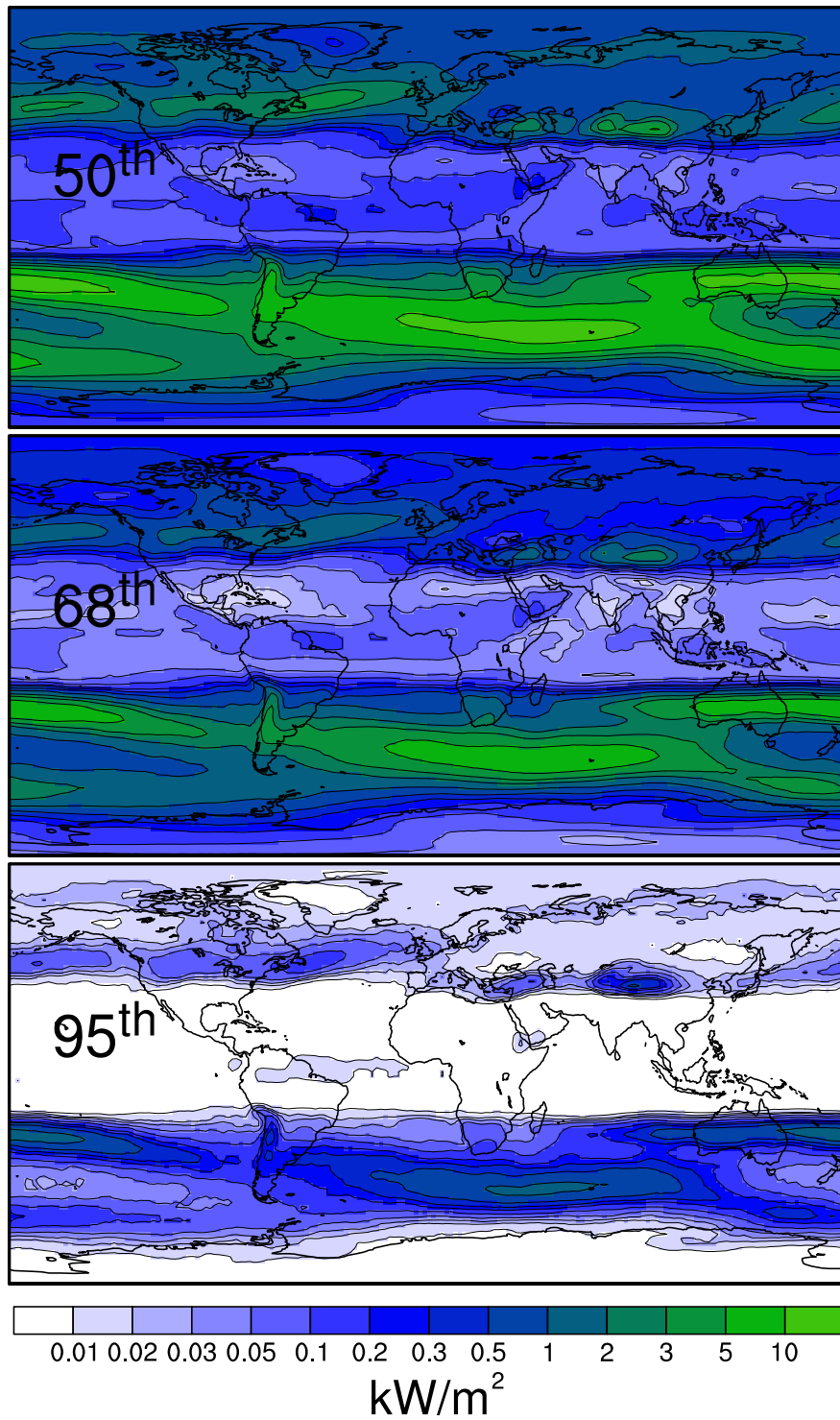


Figure 1.59: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 7000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 8000 m - JJA

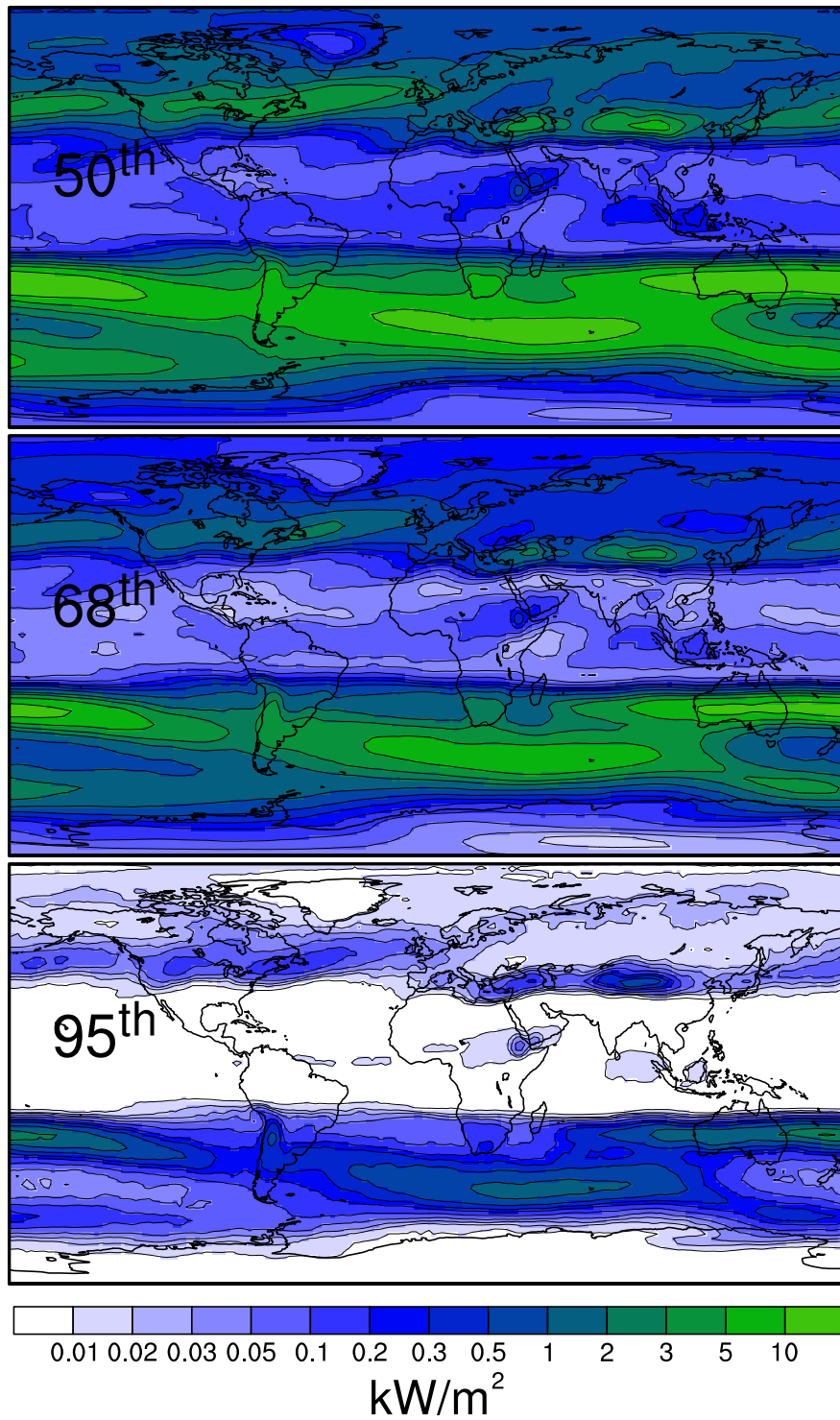


Figure 1.60: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 8000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 9000 m - JJA

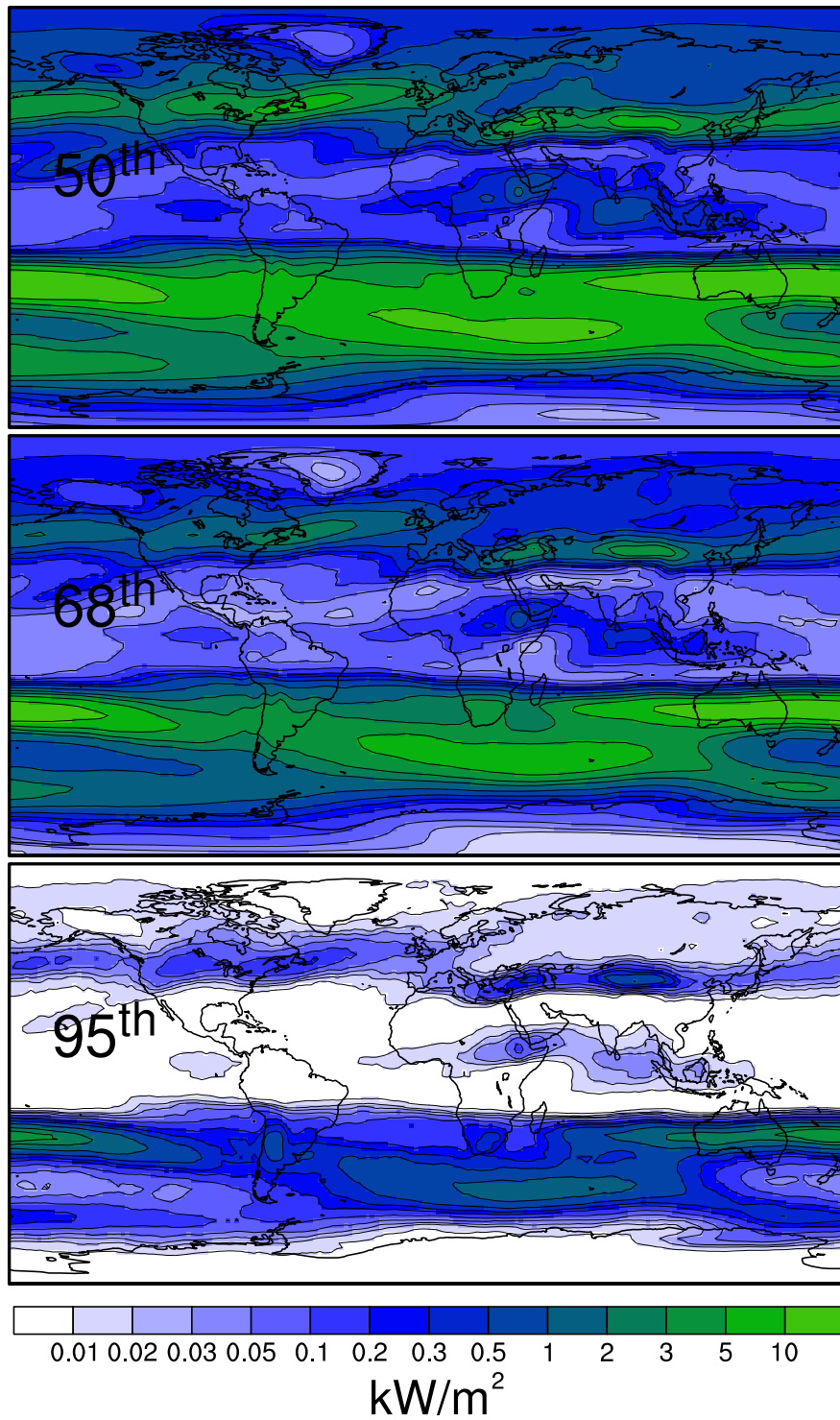


Figure 1.61: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 9000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 10000 m - JJA

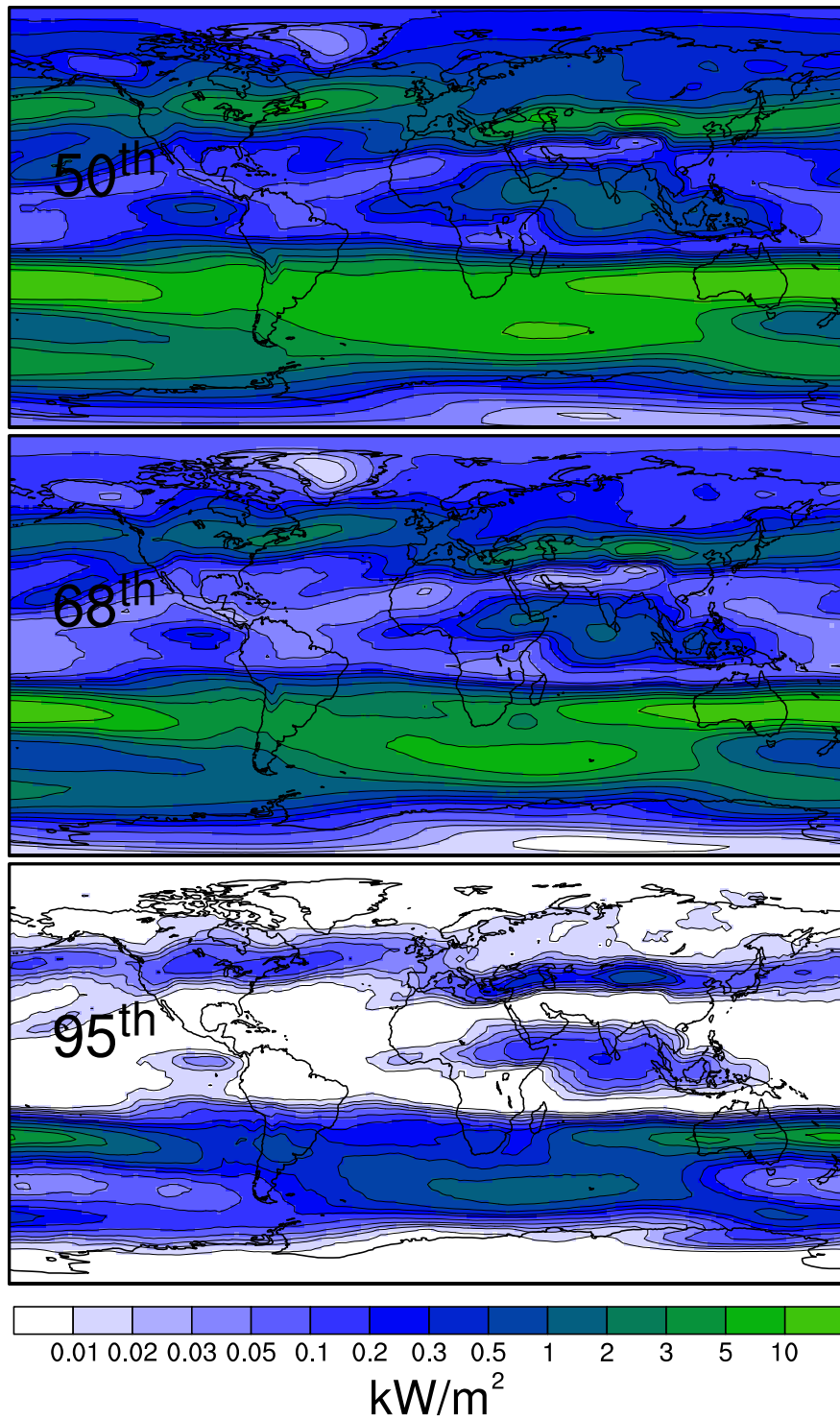


Figure 1.62: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 10,000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 11000 m - JJA

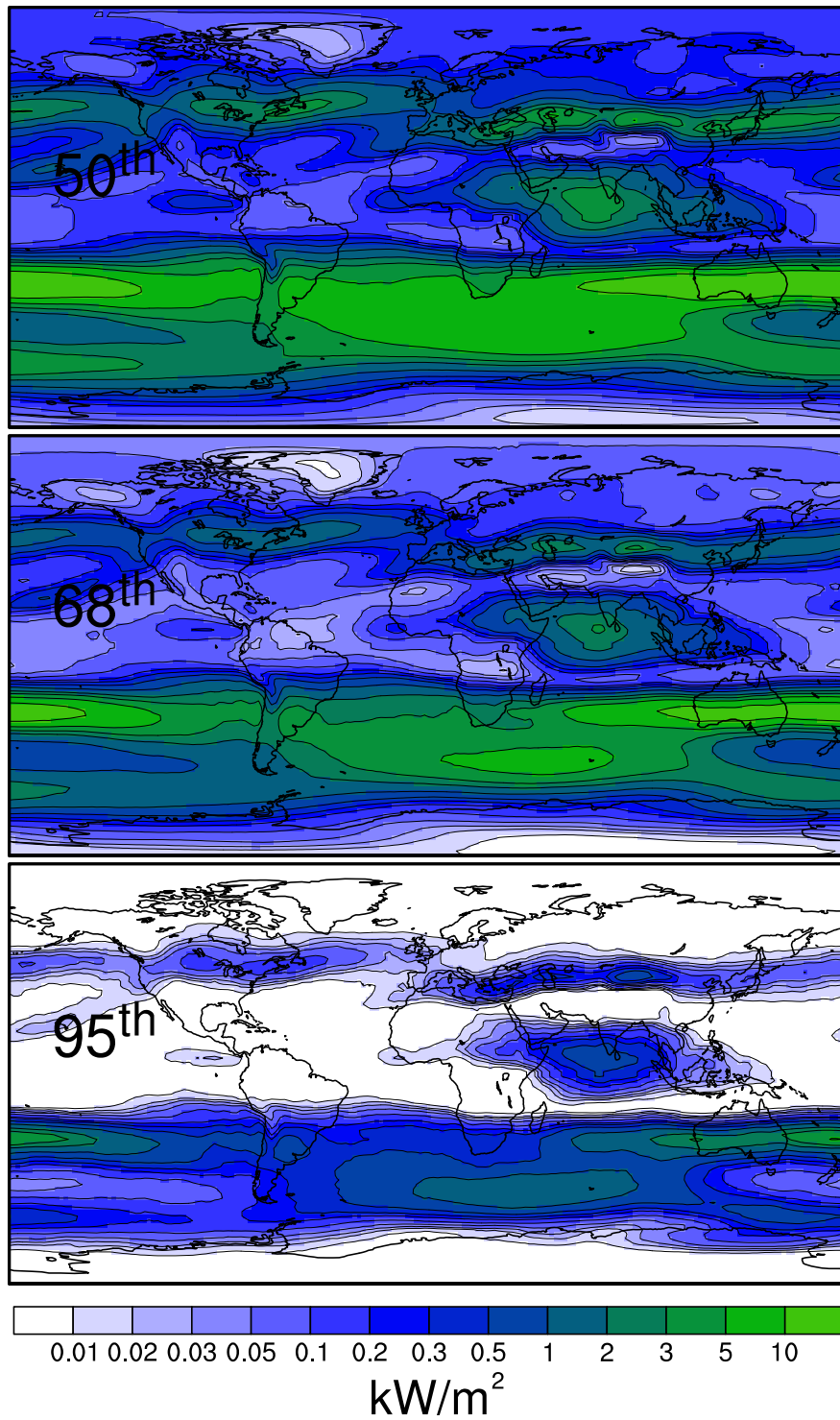


Figure 1.63: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 11,000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 12000 m - JJA

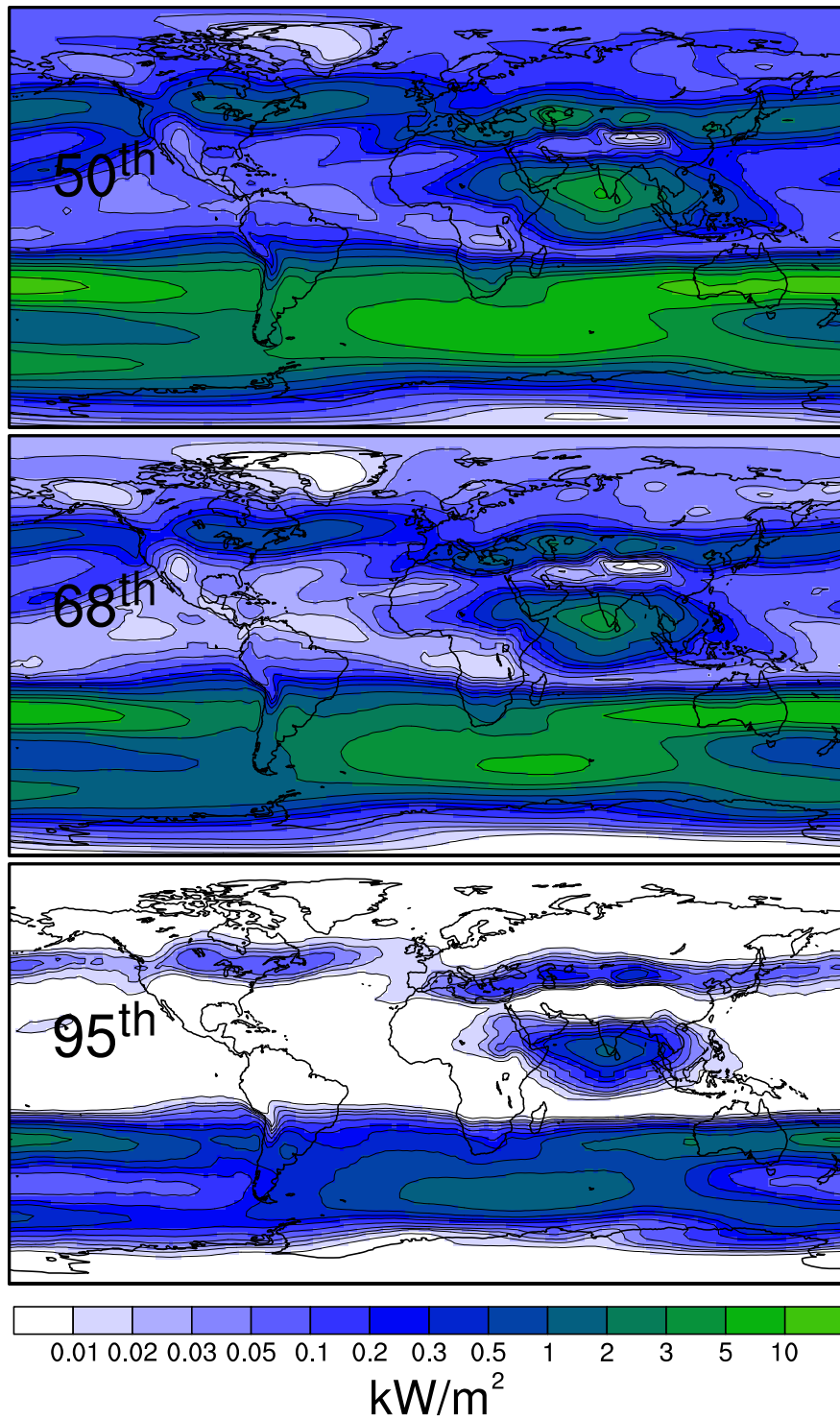


Figure 1.64: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 12,000 m during June-July-August in 1979-2006 from the NCEP/DOE reanalyses.

## 1.5 SON percentiles

This section contains selected percentiles of wind power density at all levels between 80 and 12,000 m above ground level, calculated for September-October-November (SON) in 1979-2006 from the 6-hourly NCEP/DOE reanalyses.

## Level = 80 m - SON

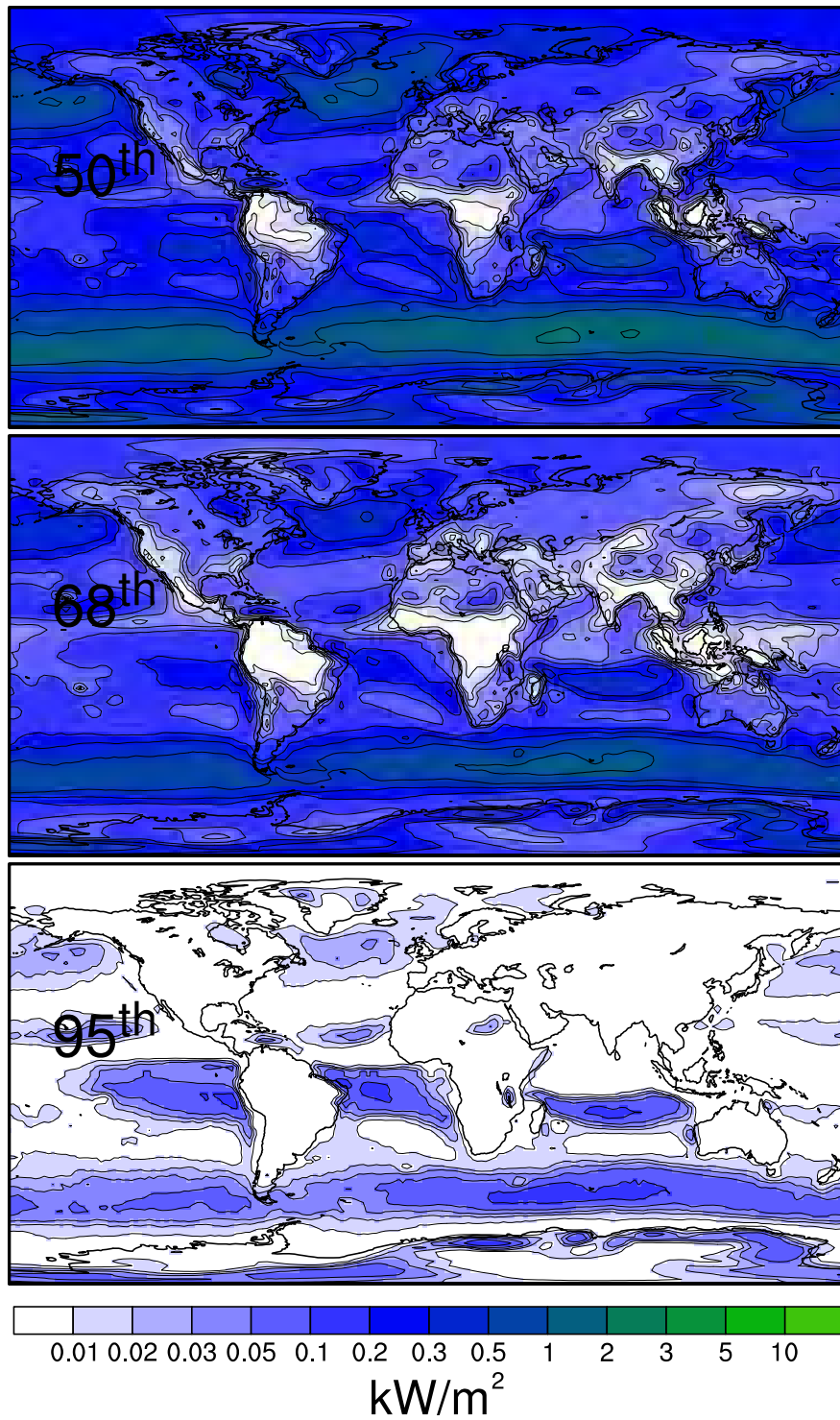


Figure 1.65: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 80 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 500 m - SON

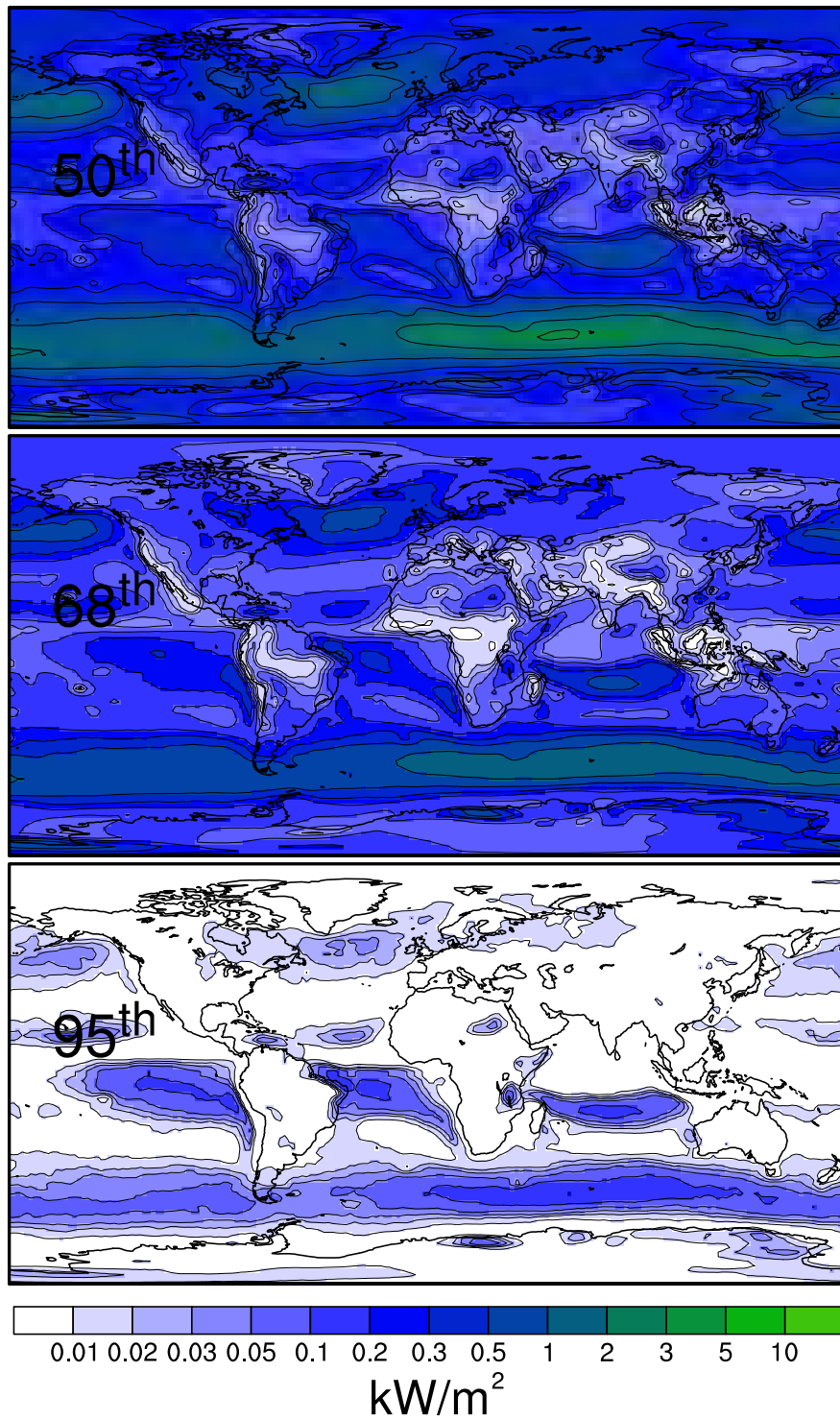


Figure 1.66: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 500 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 750 m - SON

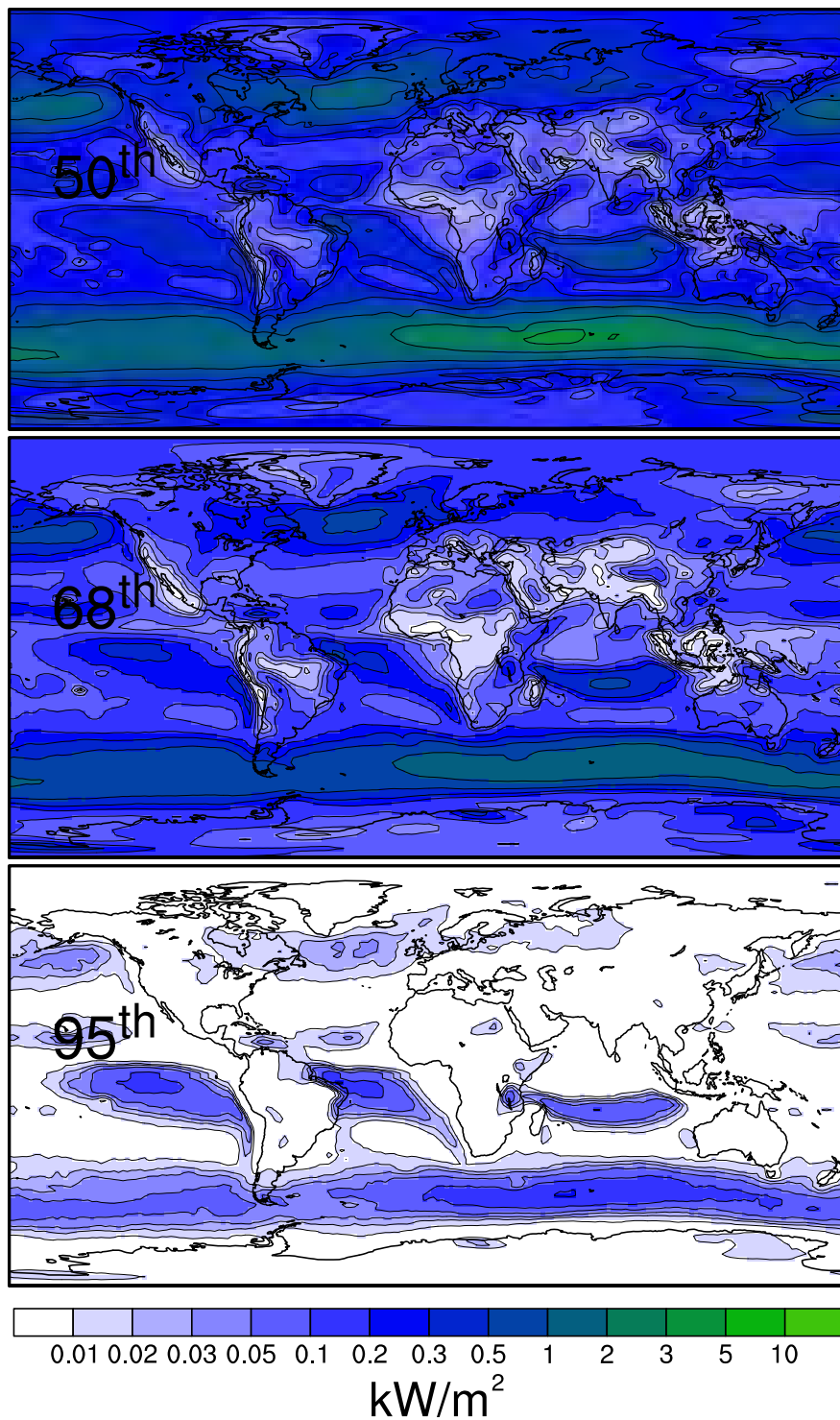


Figure 1.67: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 750 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 1000 m - SON

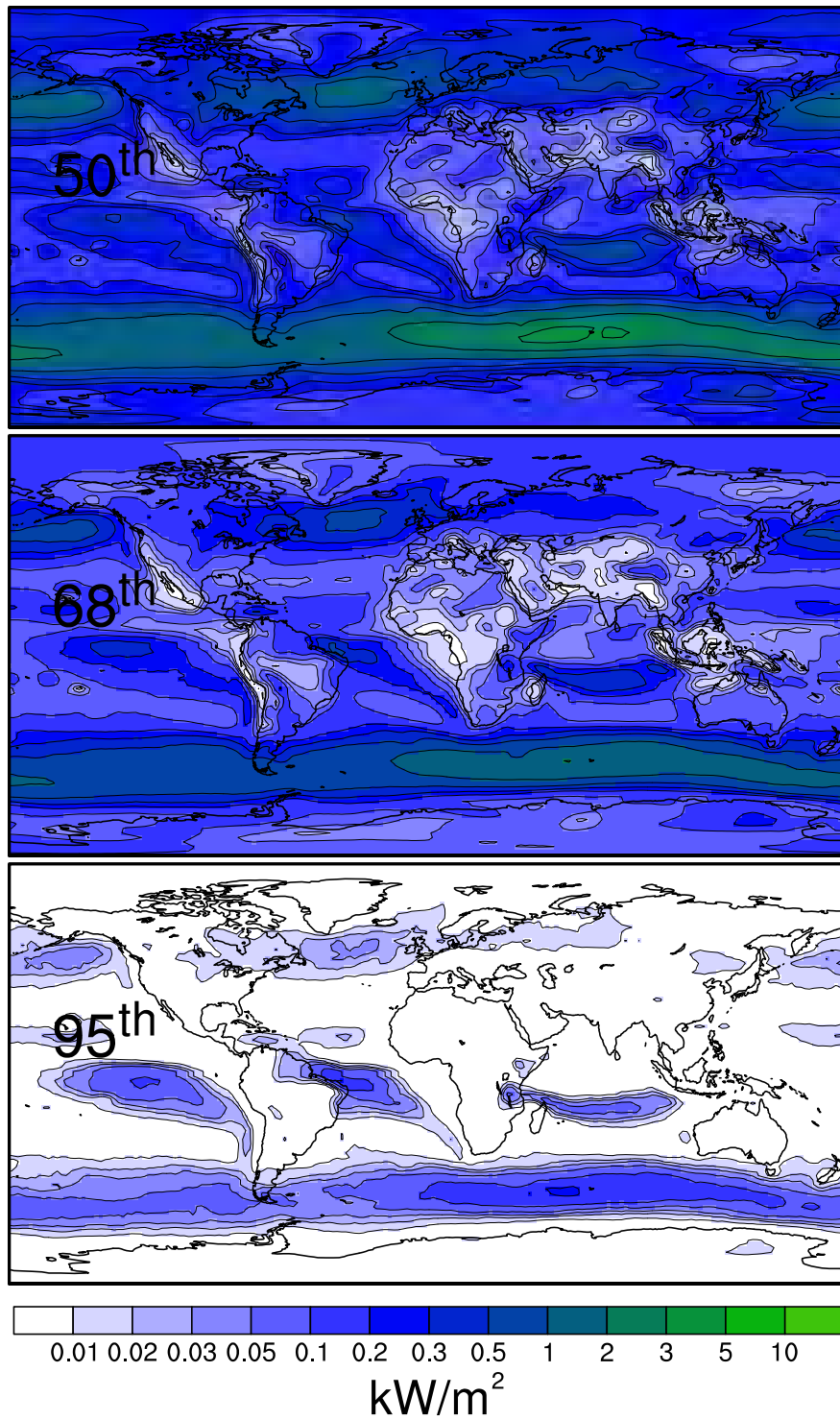


Figure 1.68: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 1000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 1500 m - SON

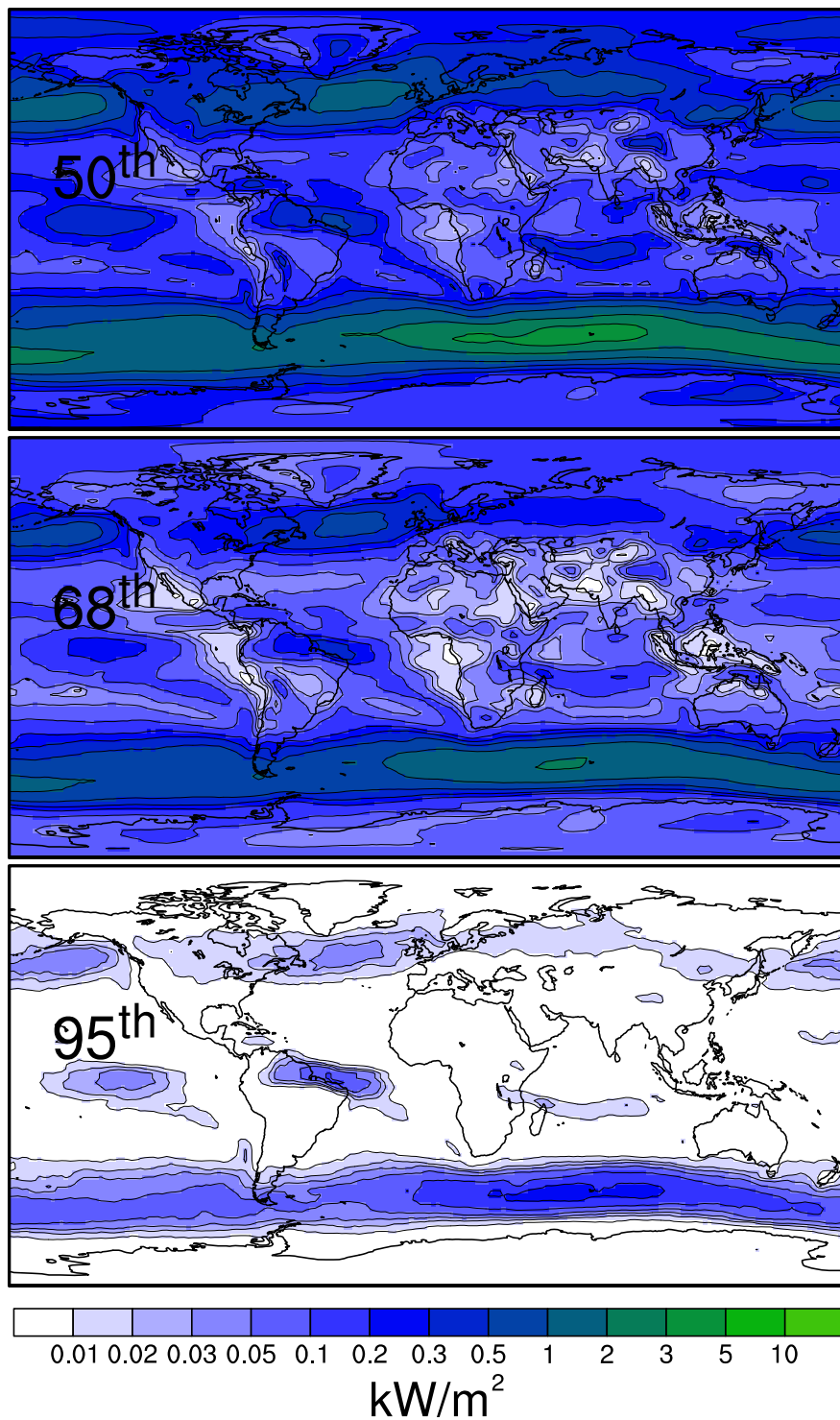


Figure 1.69: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 1500 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 2000 m - SON

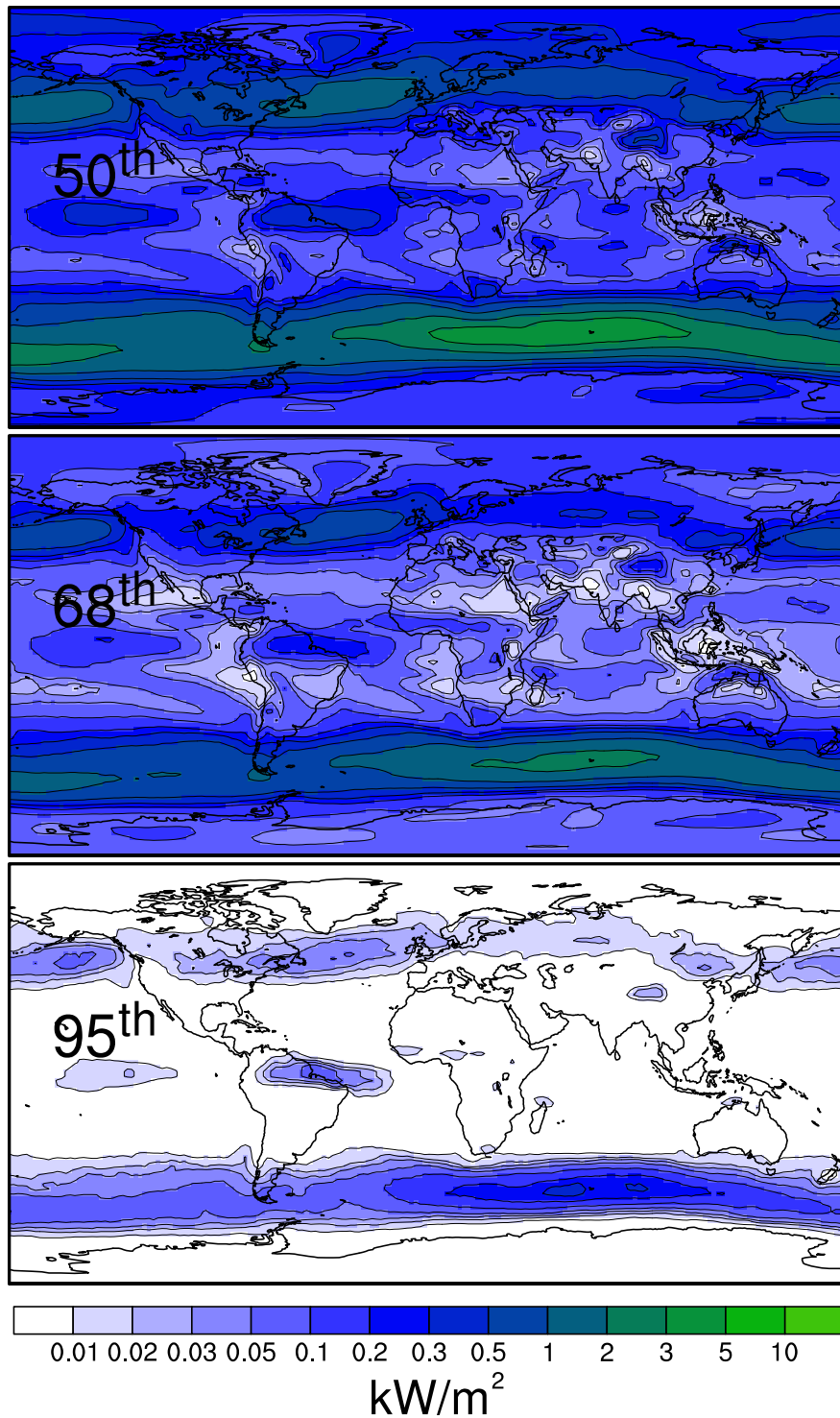


Figure 1.70: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 2000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 3000 m - SON

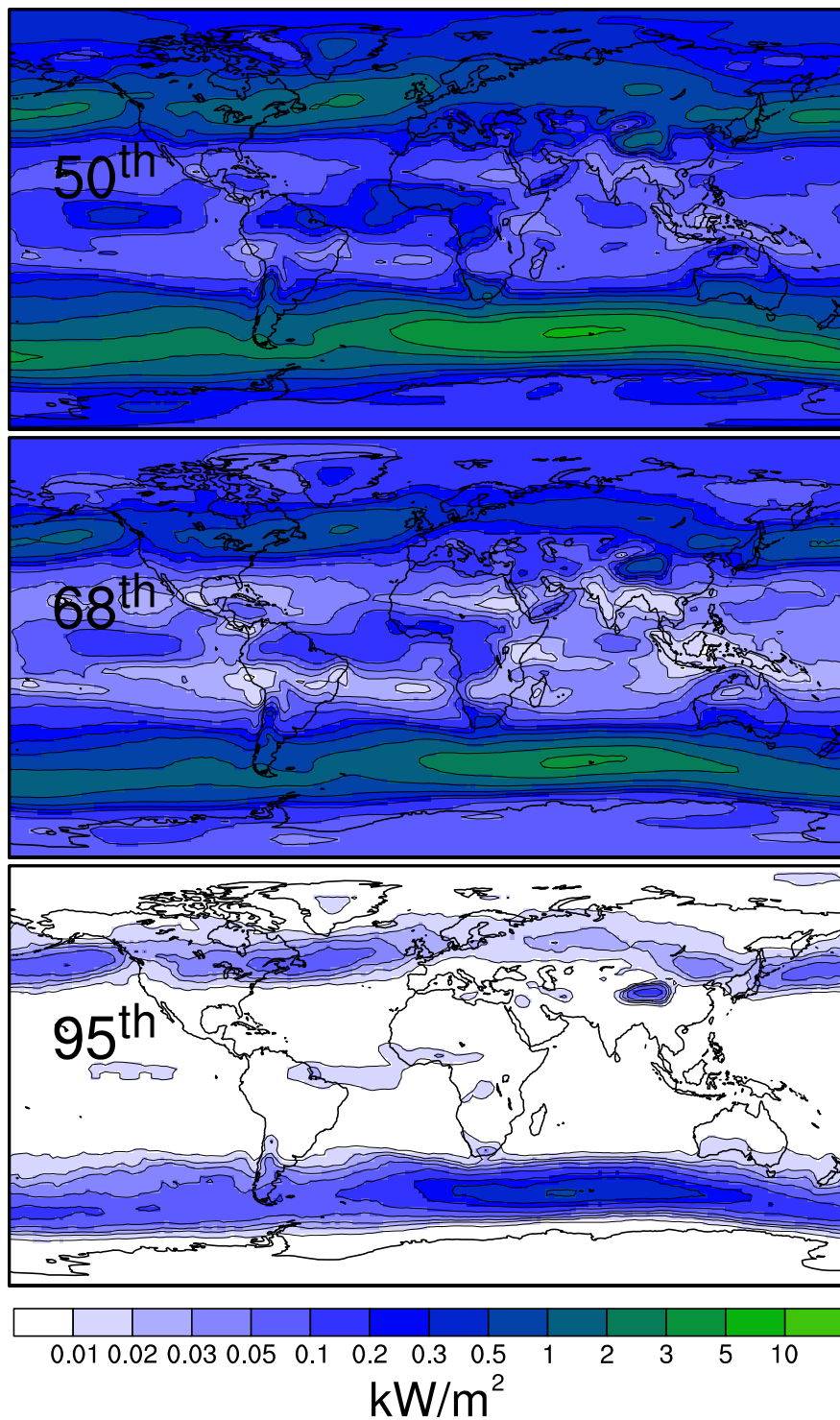


Figure 1.71: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 3000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 4000 m - SON

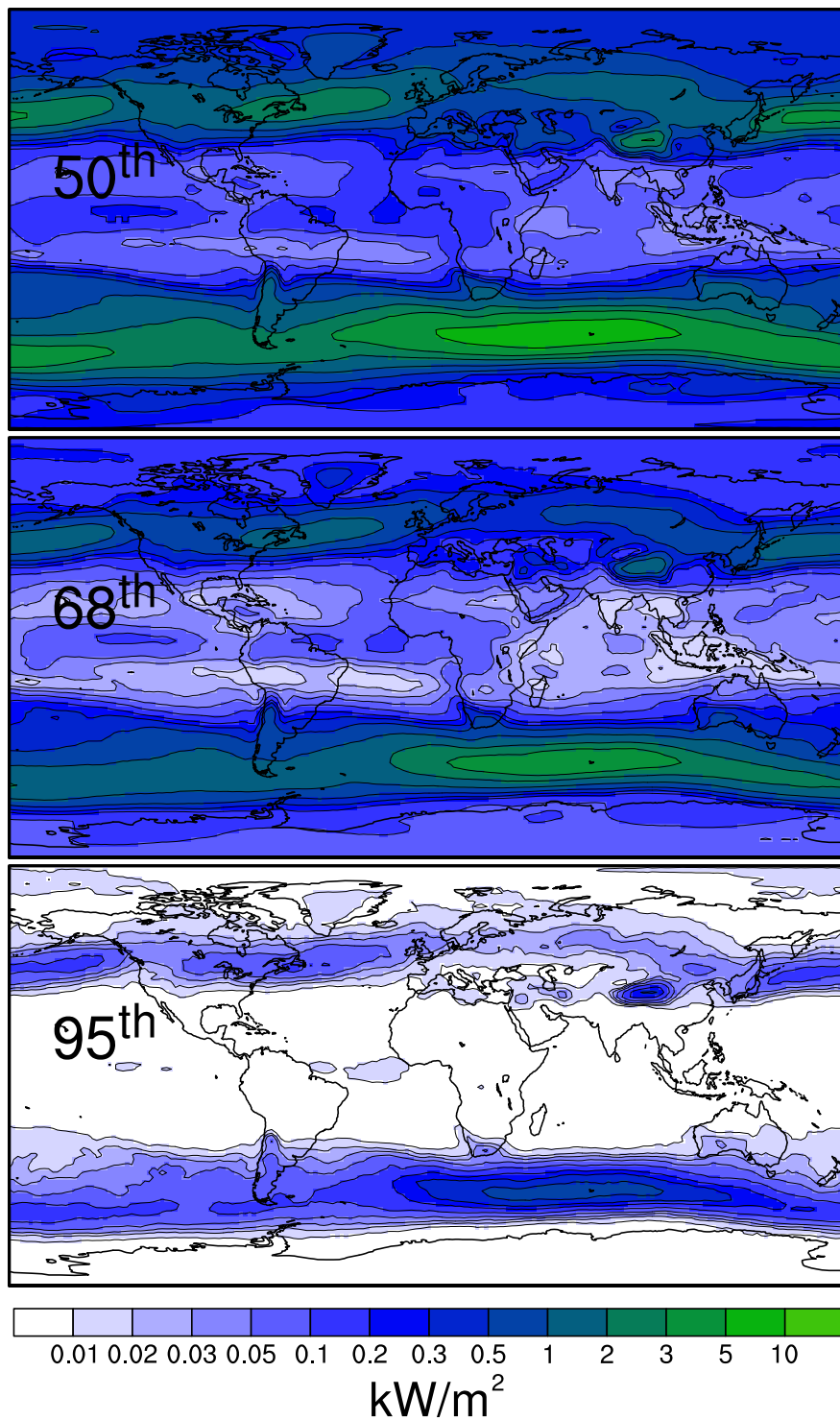


Figure 1.72: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 4000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 5000 m - SON

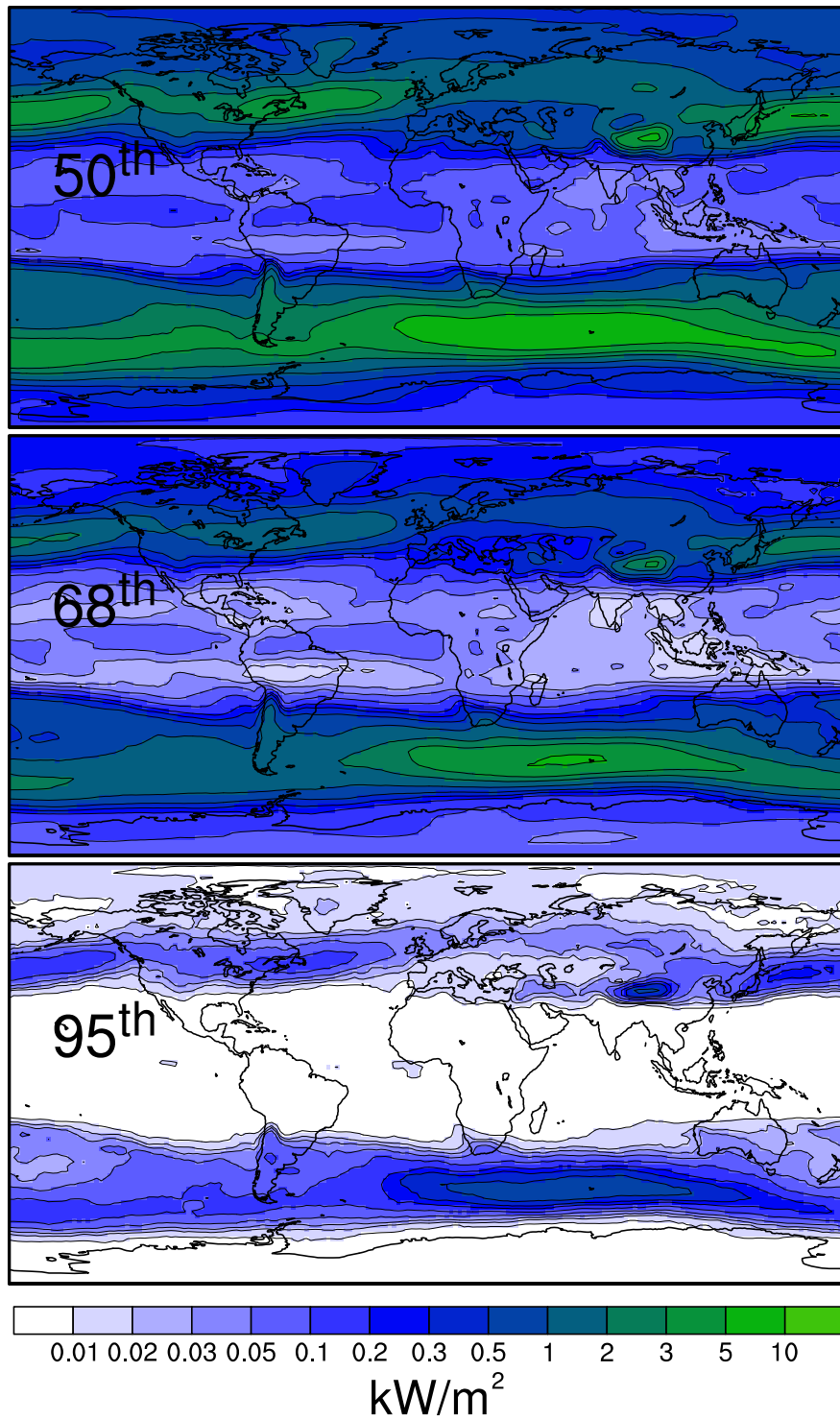


Figure 1.73: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 5000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 6000 m - SON

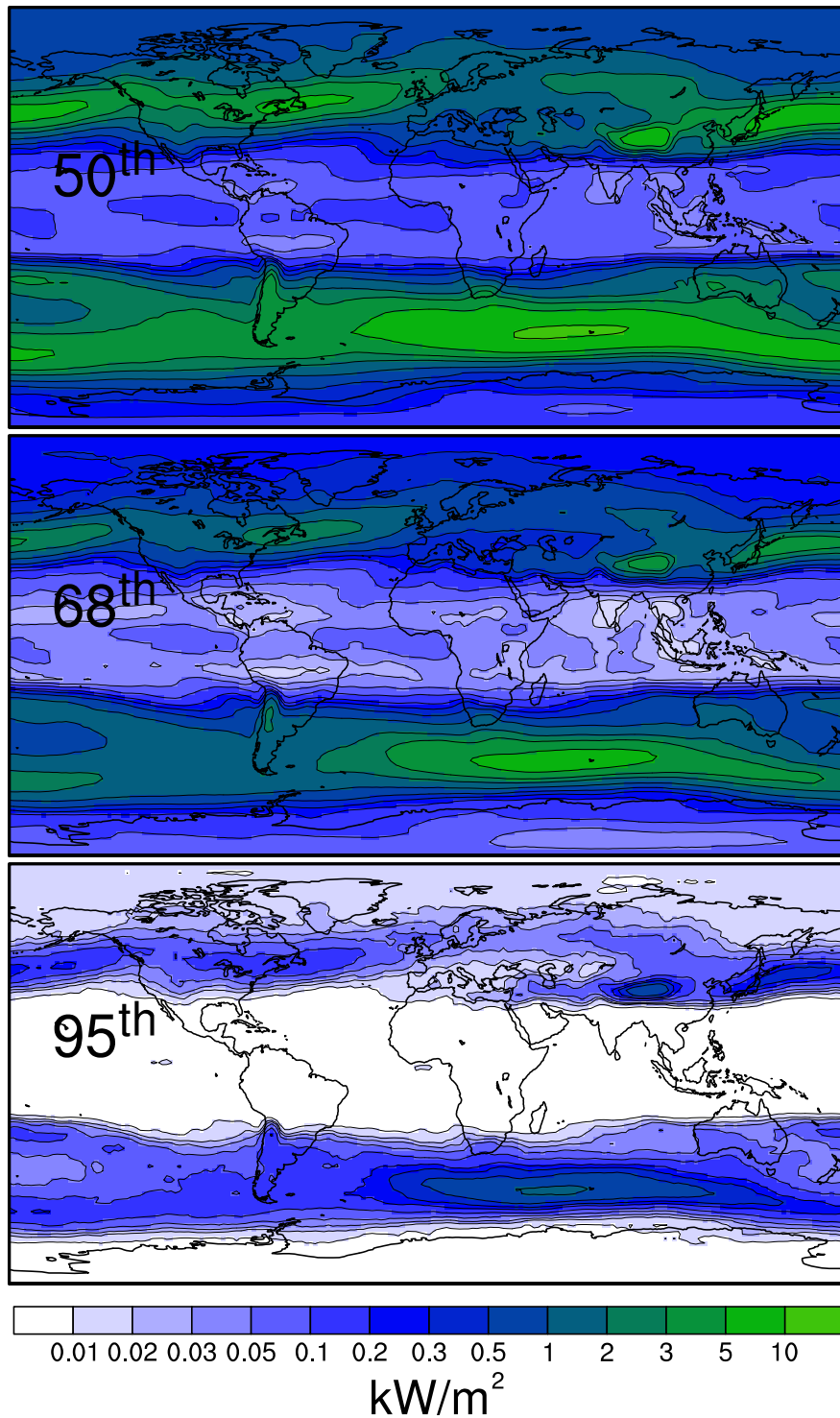


Figure 1.74: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 6000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 7000 m - SON

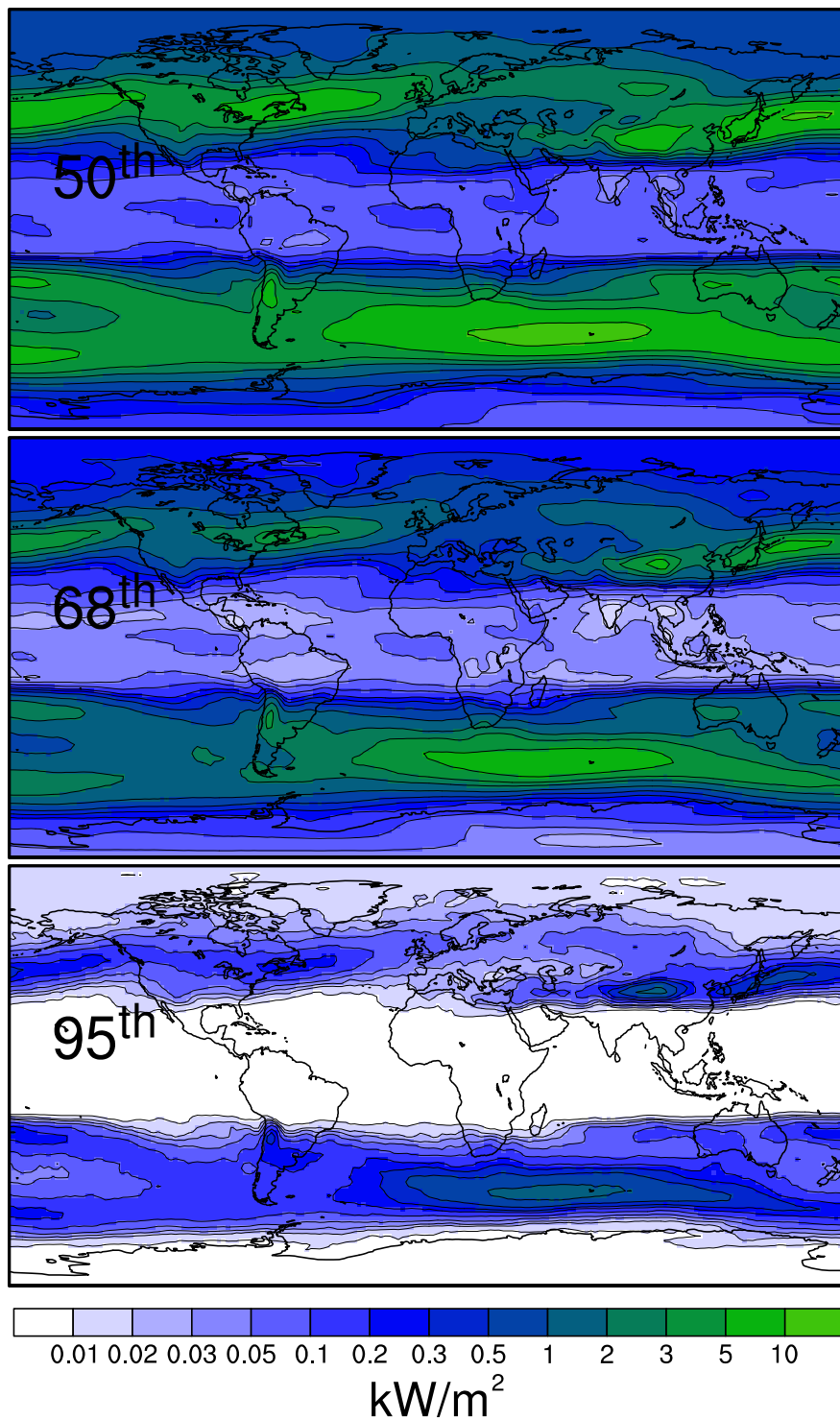


Figure 1.75: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 7000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 8000 m - SON

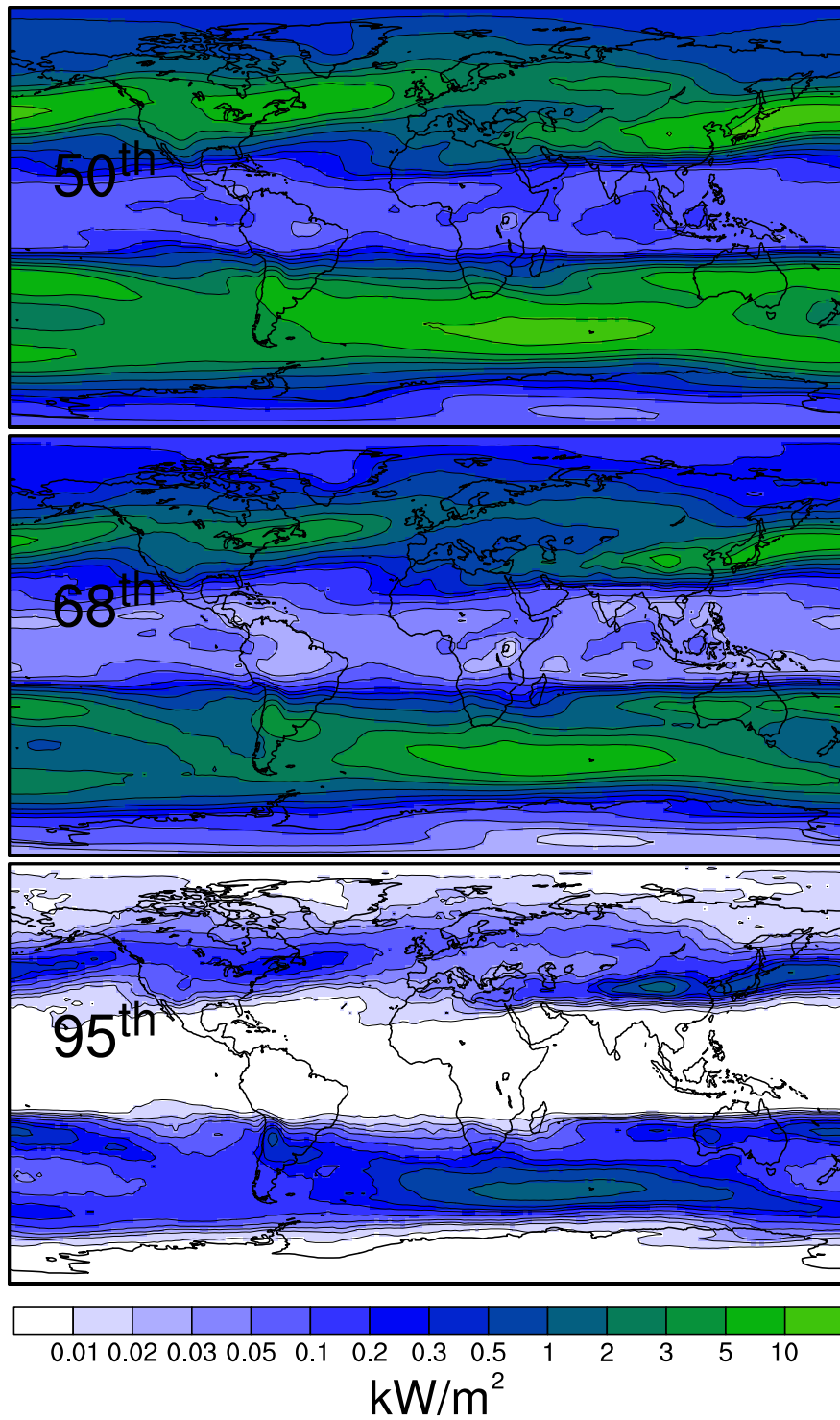


Figure 1.76: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 8000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.



## Level = 9000 m - SON

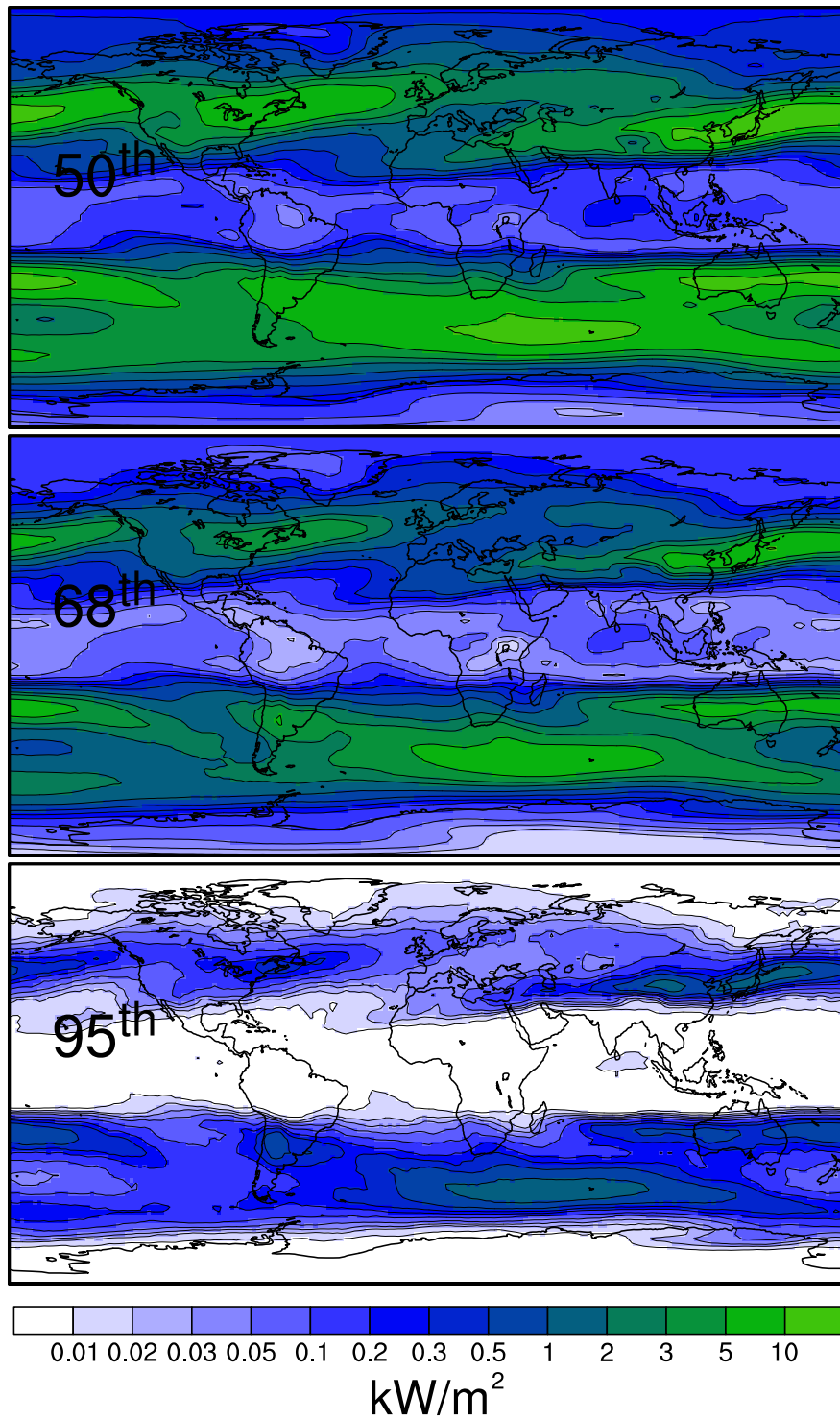


Figure 1.77: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 9000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 10000 m - SON

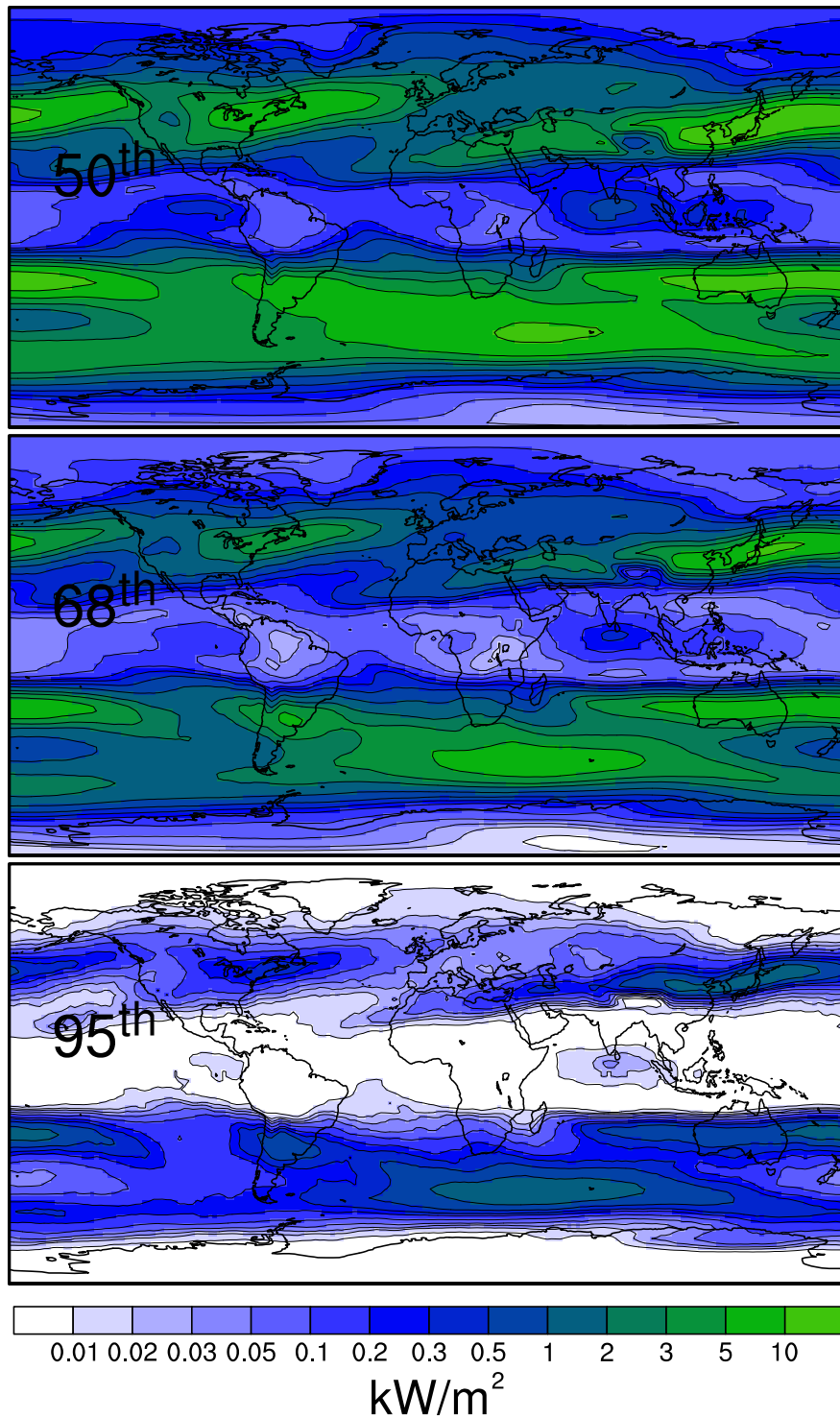


Figure 1.78: Wind power density ( $\text{kW/m}^2$ ) that was exceeded 50%, 68%, and 95% of the times at 10,000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 11000 m - SON

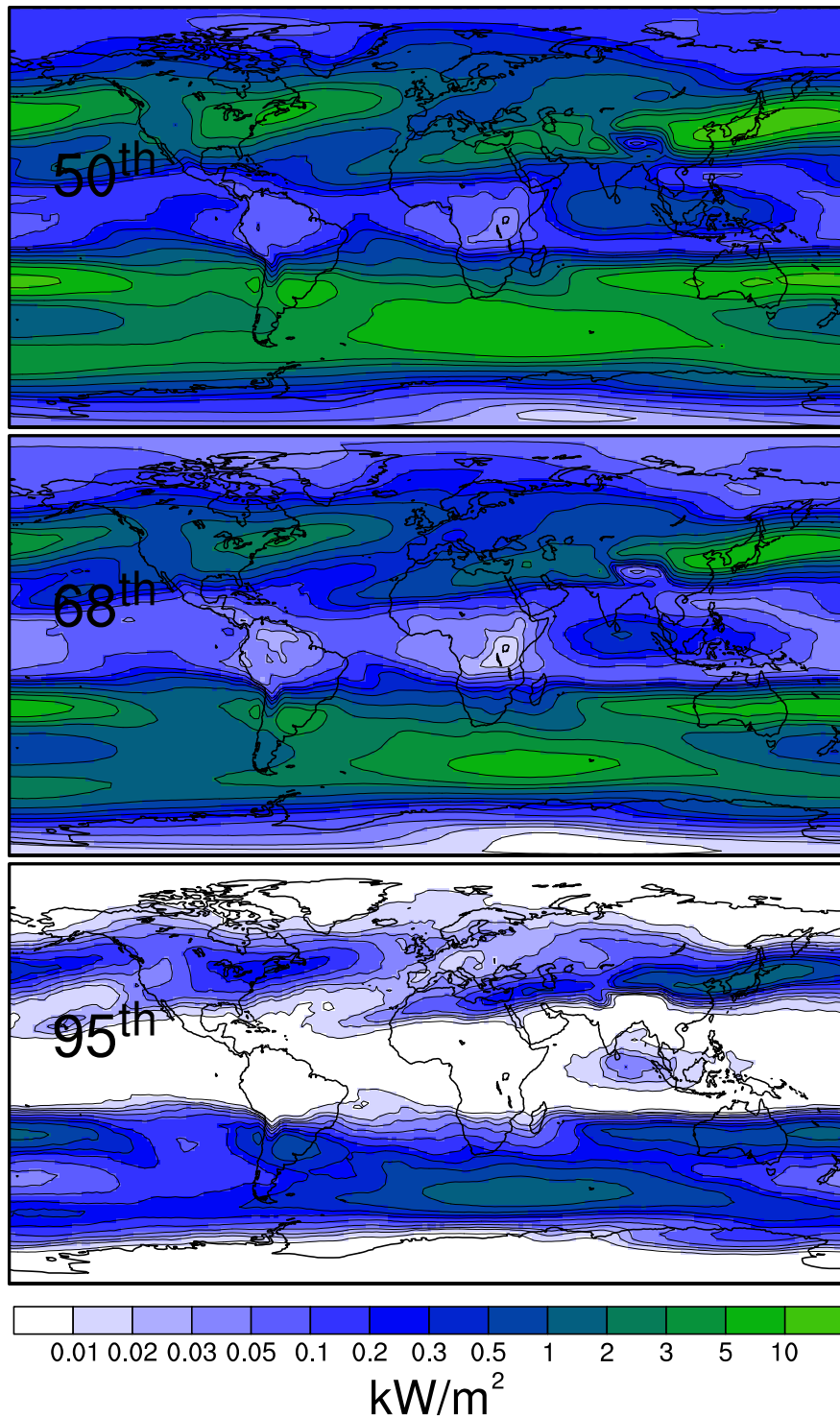


Figure 1.79: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 11,000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Level = 12000 m - SON

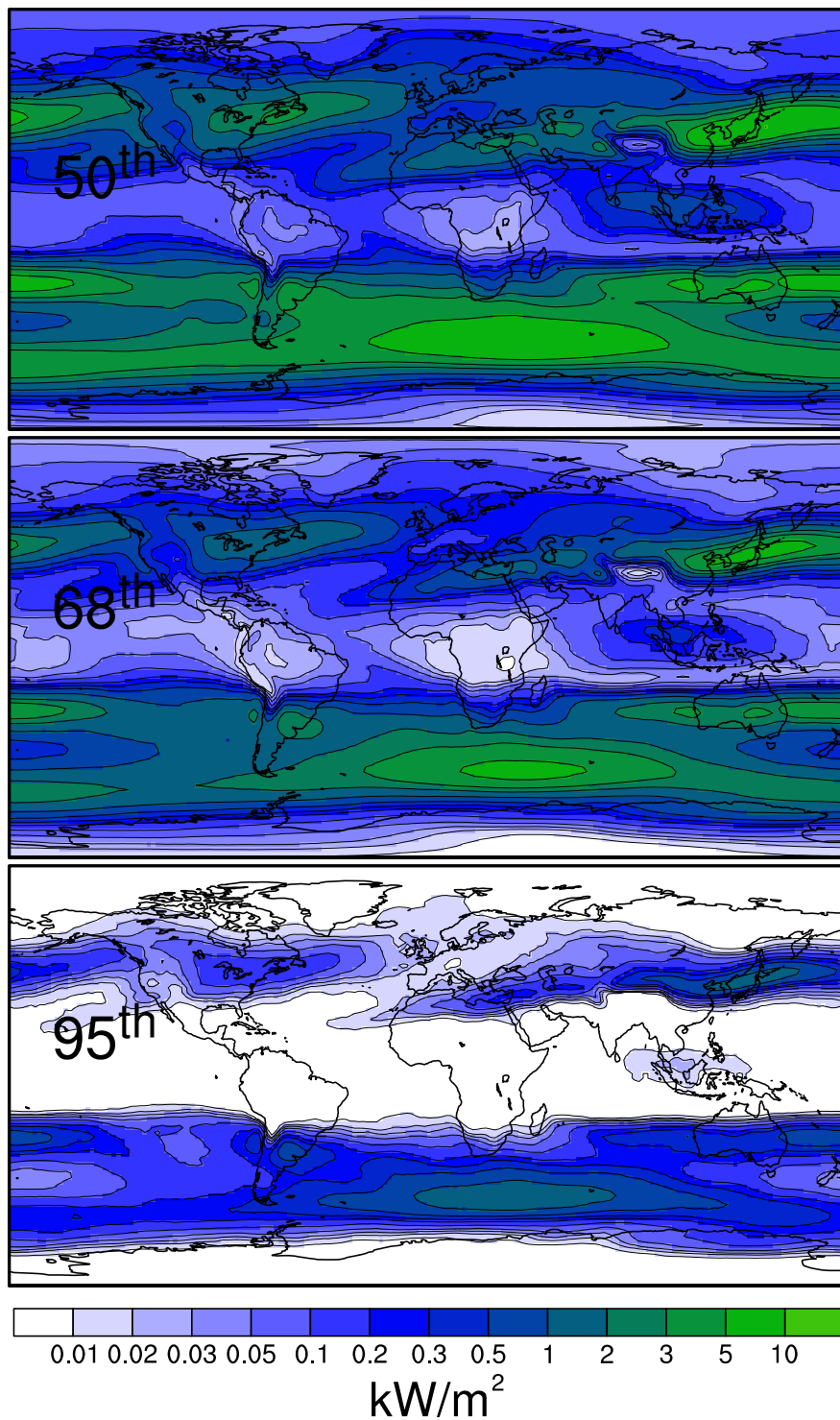


Figure 1.80: Wind power density (kW/m<sup>2</sup>) that was exceeded 50%, 68%, and 95% of the times at 12,000 m during September-October-November in 1979-2006 from the NCEP/DOE reanalyses.

## Chapter 2

# Optimal wind power density and optimal height distributions

This section contains annual and seasonal percentiles of optimal wind power density and optimal height calculated for the years 1979-2006 from the 6-hourly NCEP/DOE reanalyses. Optimal height is the height above the ground where the strongest winds are found at any given location and time. Similarly, optimal wind power density is the wind power density that is available at the optimal height. The idea is that the strongest winds are not necessarily always at the highest altitudes and therefore the best performance for high altitude technologies can be obtained by raising or lowering the kites to the height where the maximum potential exist.



## Optimal wind power and height - Annual

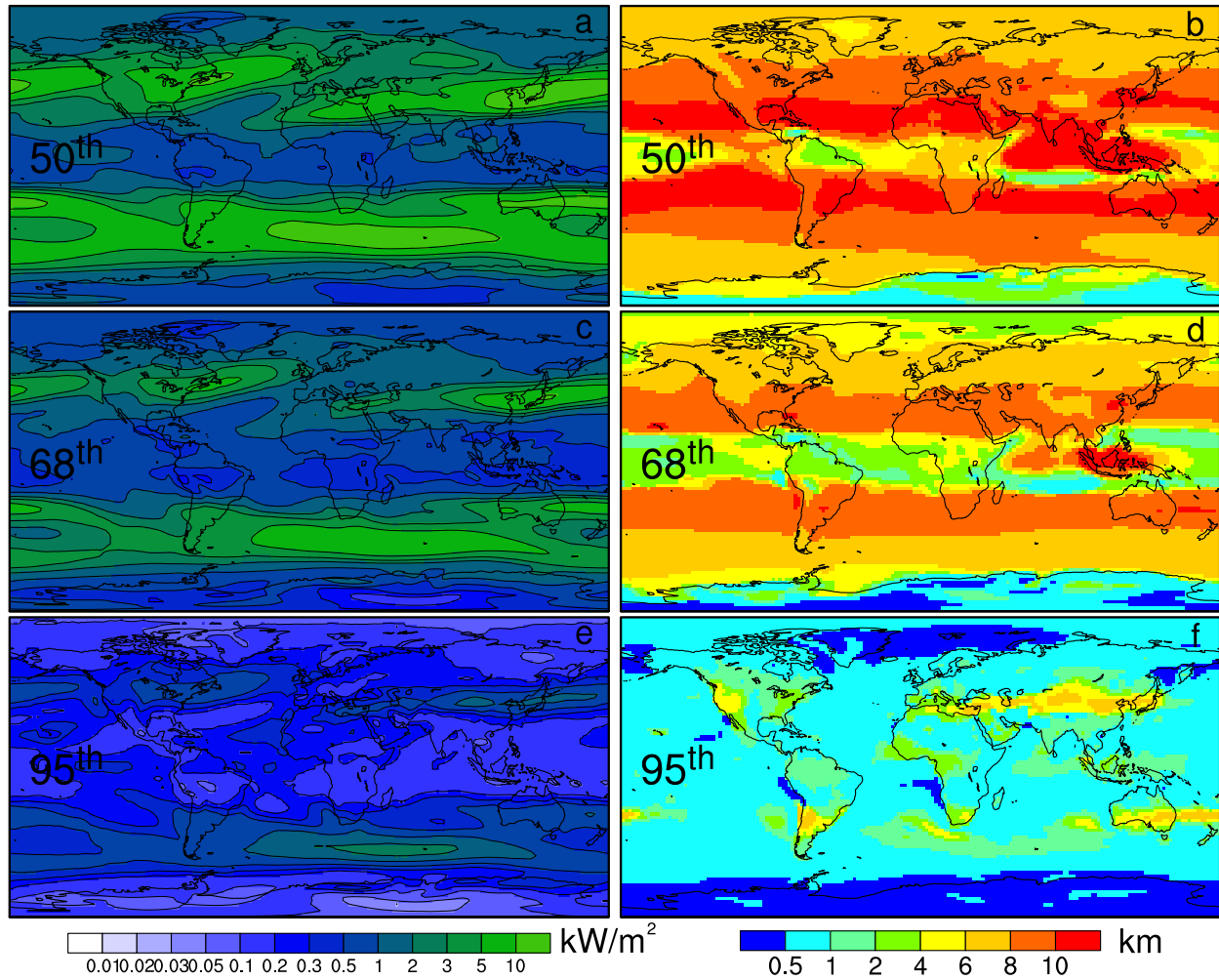


Figure 2.1: Optimal wind power density ( $\text{kW/m}^2$ , left panels) and optimal height (km, right panels) that was exceeded 50%, 68%, and 95% of the times during years in 1979-2006 from the NCEP/DOE reanalyses.

## Optimal wind power and height - DJF

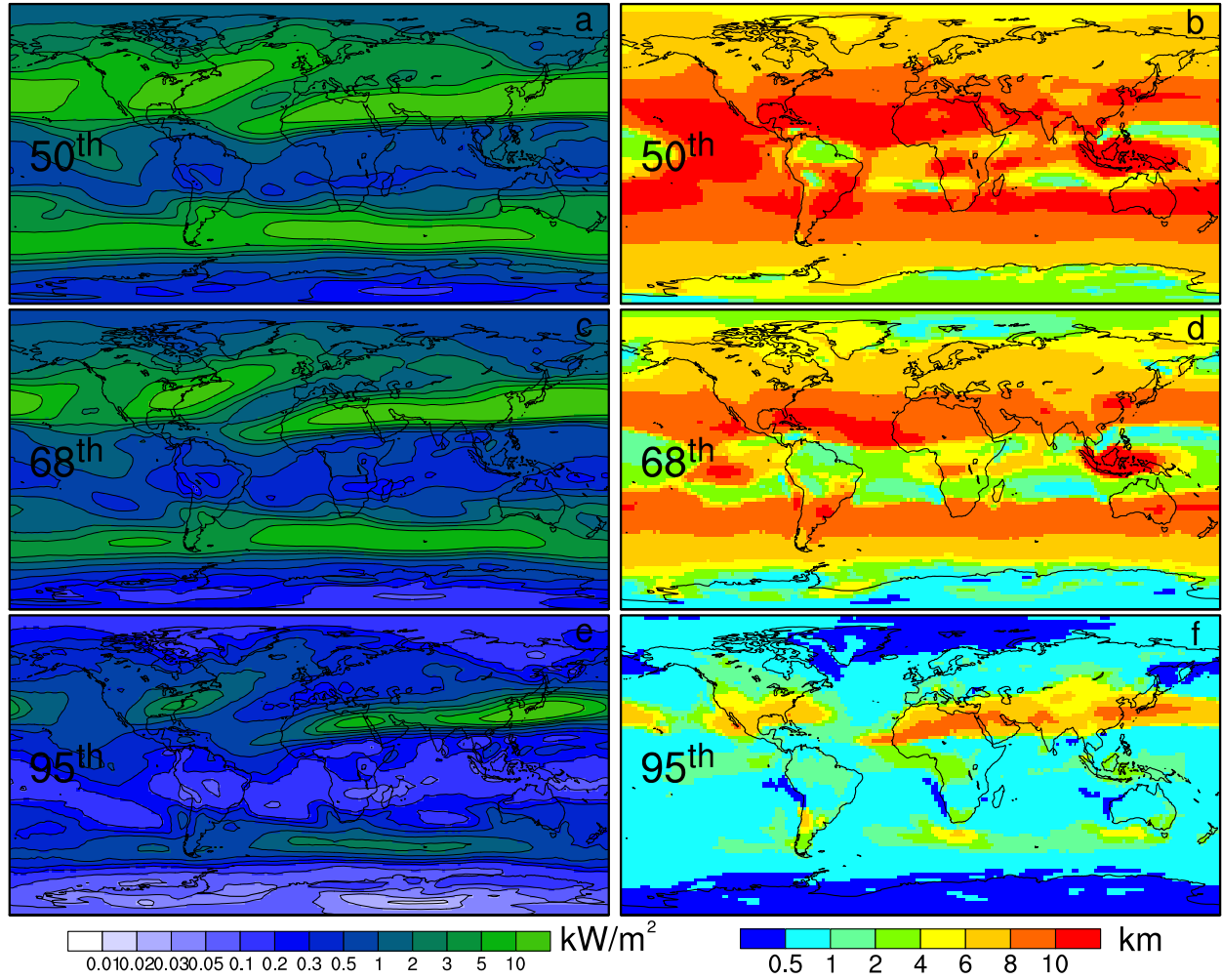


Figure 2.2: Optimal wind power density ( $\text{kW/m}^2$ , left panels) and optimal height (km, right panels) that was exceeded 50%, 68%, and 95% of the times during DJF in 1979-2006 from the NCEP/DOE reanalyses.

## Optimal wind power and height - MAM

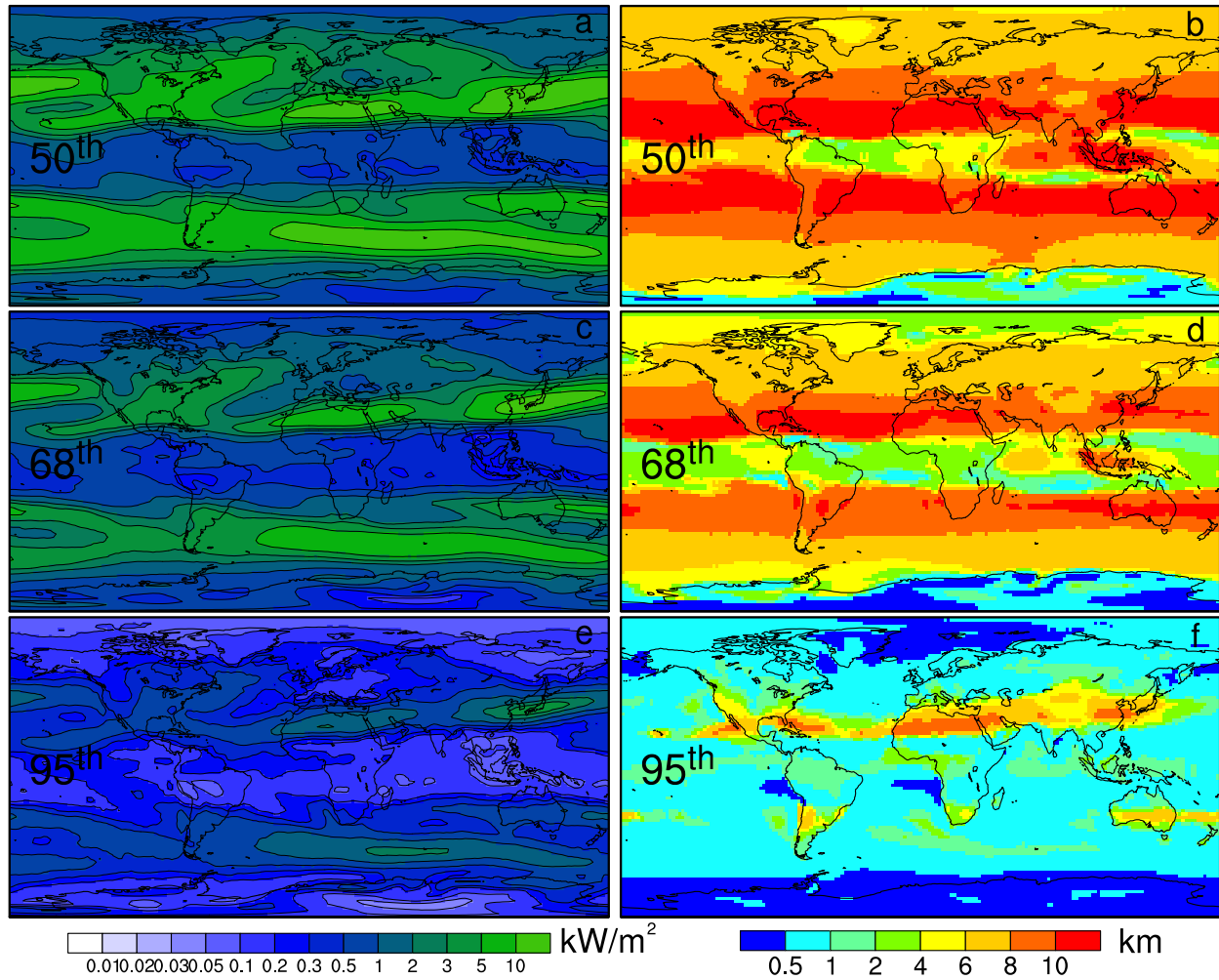


Figure 2.3: Optimal wind power density ( $\text{kW/m}^2$ , left panels) and optimal height (km, right panels) that was exceeded 50%, 68%, and 95% of the times during MAM in 1979-2006 from the NCEP/DOE reanalyses.

## Optimal wind power and height - JJA

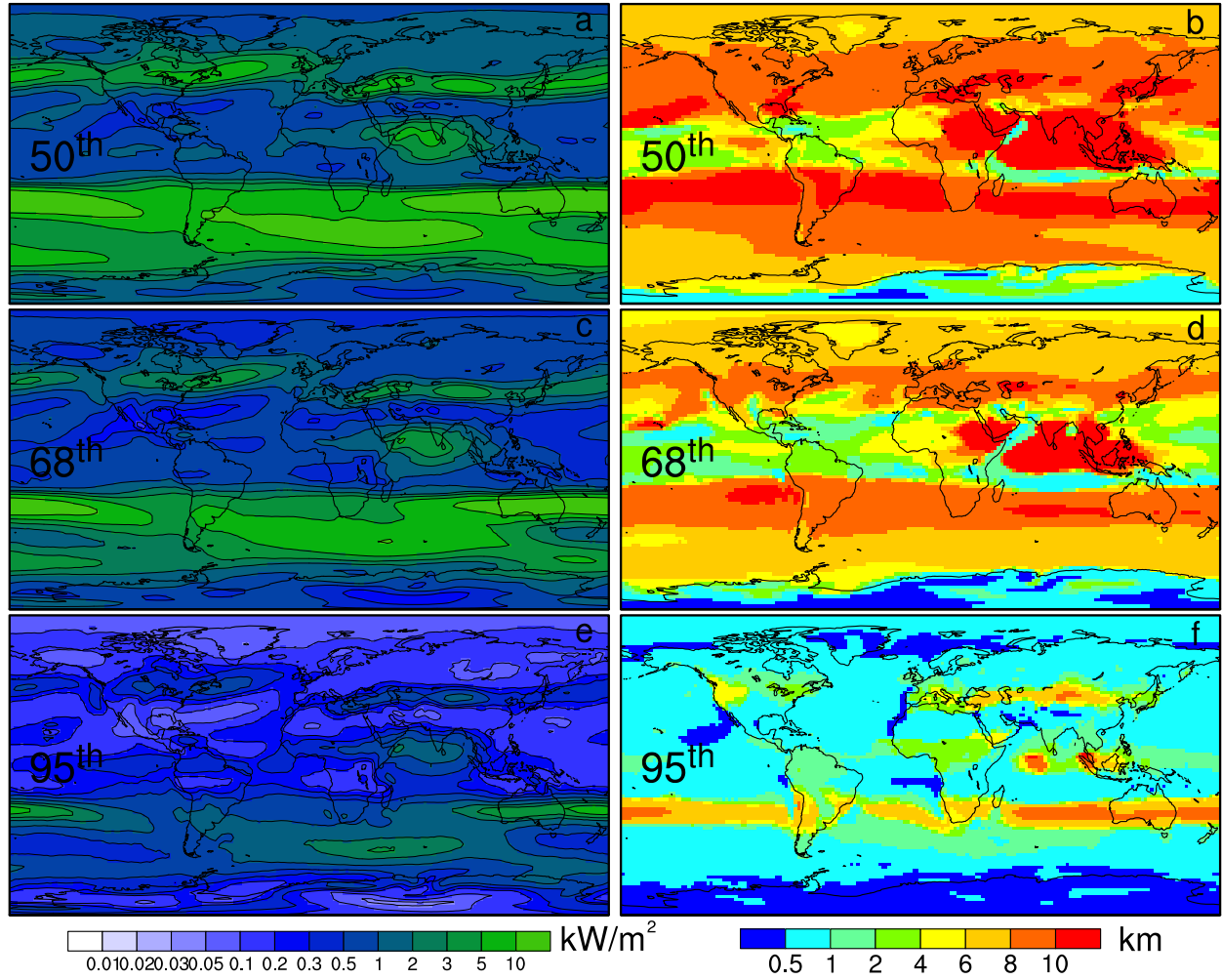


Figure 2.4: Optimal wind power density (kW/m<sup>2</sup>, left panels) and optimal height (km, right panels) that was exceeded 50%, 68%, and 95% of the times during JJA in 1979-2006 from the NCEP/DOE reanalyses.

## Optimal wind power and height - SON

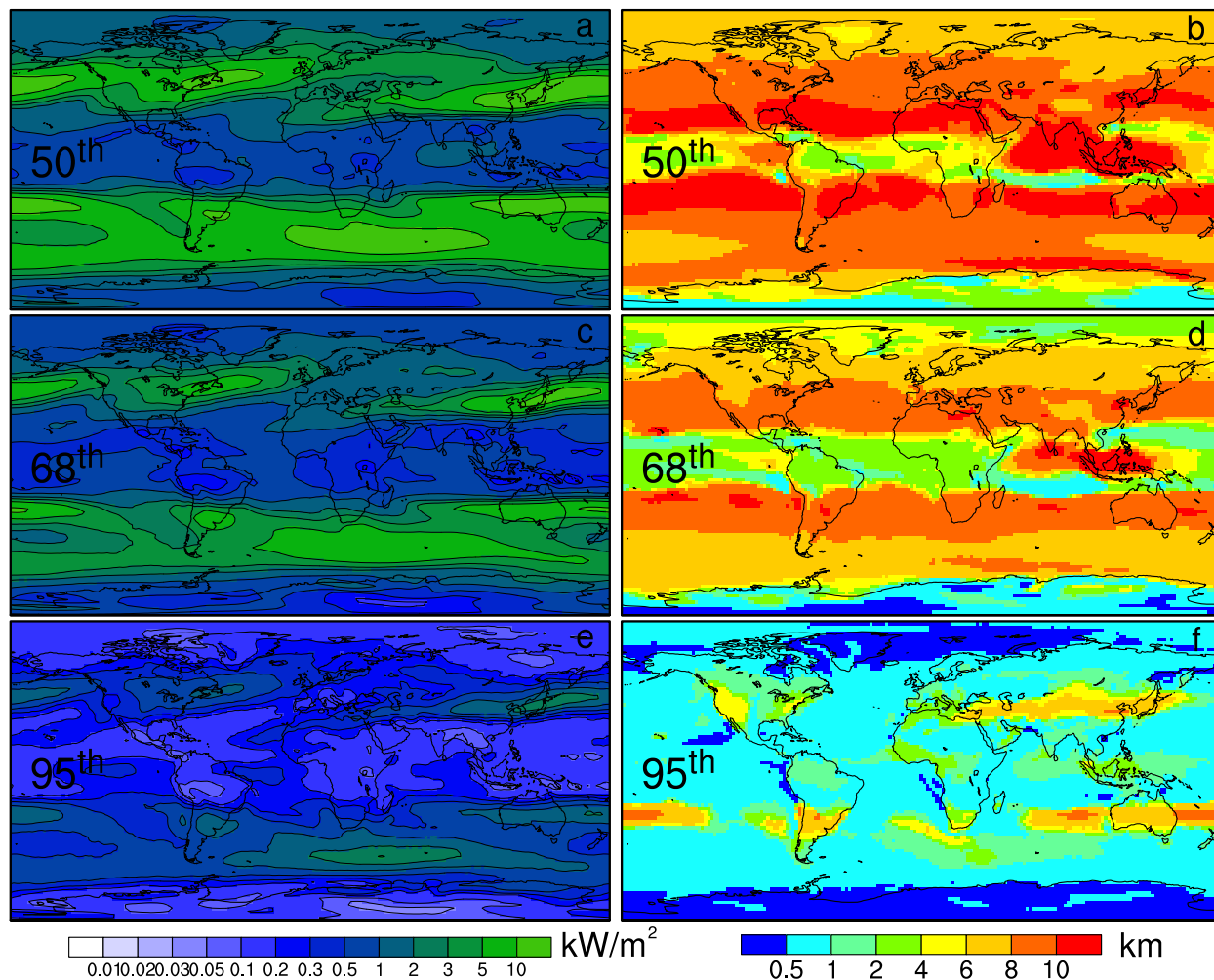


Figure 2.5: Optimal wind power density ( $\text{kW/m}^2$ , left panels) and optimal height (km, right panels) that was exceeded 50%, 68%, and 95% of the times during SON in 1979-2006 from the NCEP/DOE reanalyses.



# Chapter 3

## Dealing with intermittency

This section addresses the issue of intermittency of high altitude wind power. Three possible solutions are analyzed: increasing the area swept by the blades of the high altitude device (by either making larger devices or by adding more and more of them); utilizing storage devices, such as batteries or hydroelectric reservoirs, to store the excess energy and use it when needed; interconnecting several devices that are geographically farther and farther away. All solutions are addressed with the following plots, which show contours of wind power per square meter of area swept by the blades (i.e., wind power density) at different reliabilities (50% through 99.9%) that can be supplied by a combination of battery storage and increasingly larger transmission networks (as circular areas of given radius around a given city). The five largest cities in the world are shown, i.e., Tokyo, Seoul, Mexico City, New York, and Sao Paulo. Data were obtained from the optimal wind power density in the previous section.

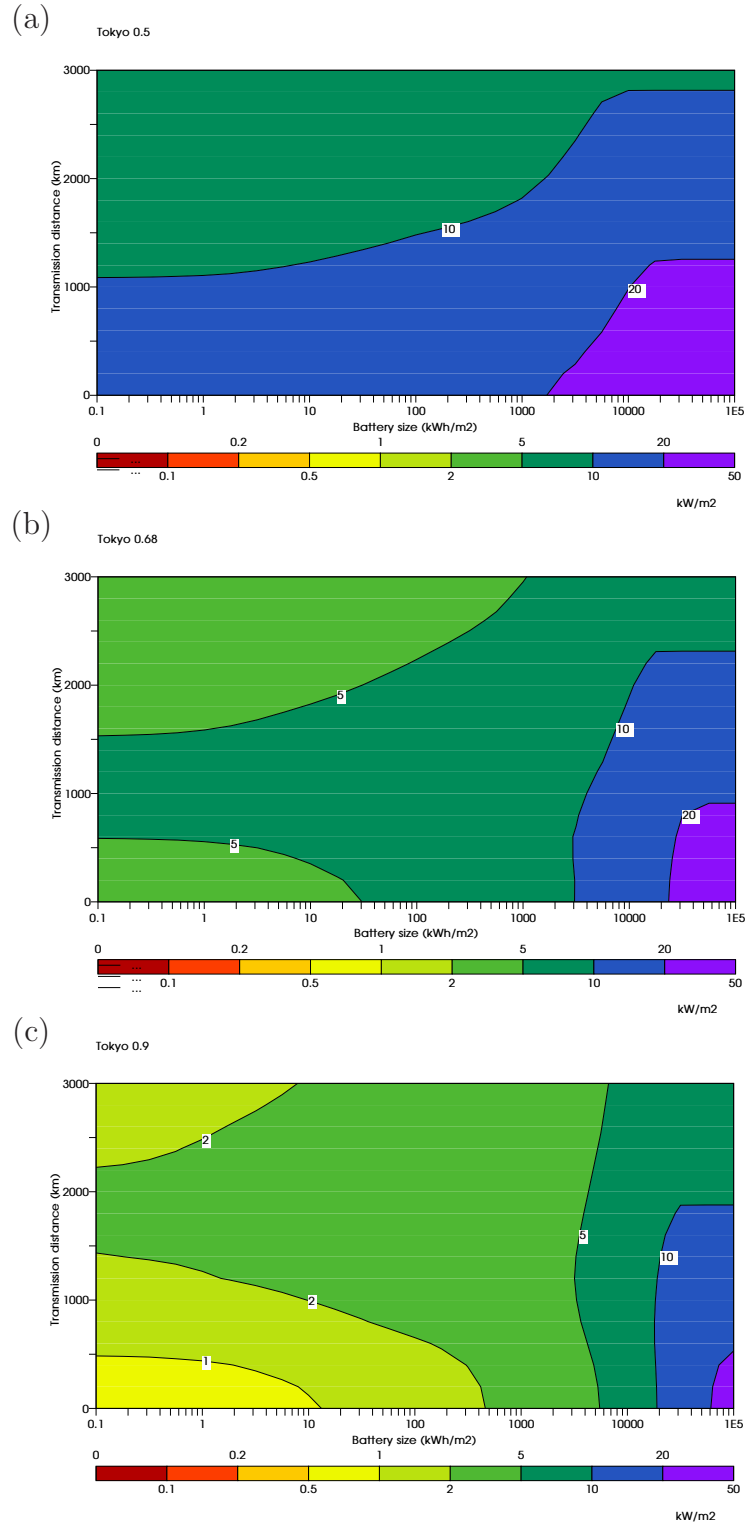


Figure 3.1: Contours of wind power density ( $\text{kW}/\text{m}^2$ ) that can be provided in Tokyo from optimal winds with 50% (a), 68% (b), and 90% (c) as a function of battery size ( $\text{kWh}/\text{m}^2$ ) and transmission distance (km), from the NCEP/DOE reanalyses.

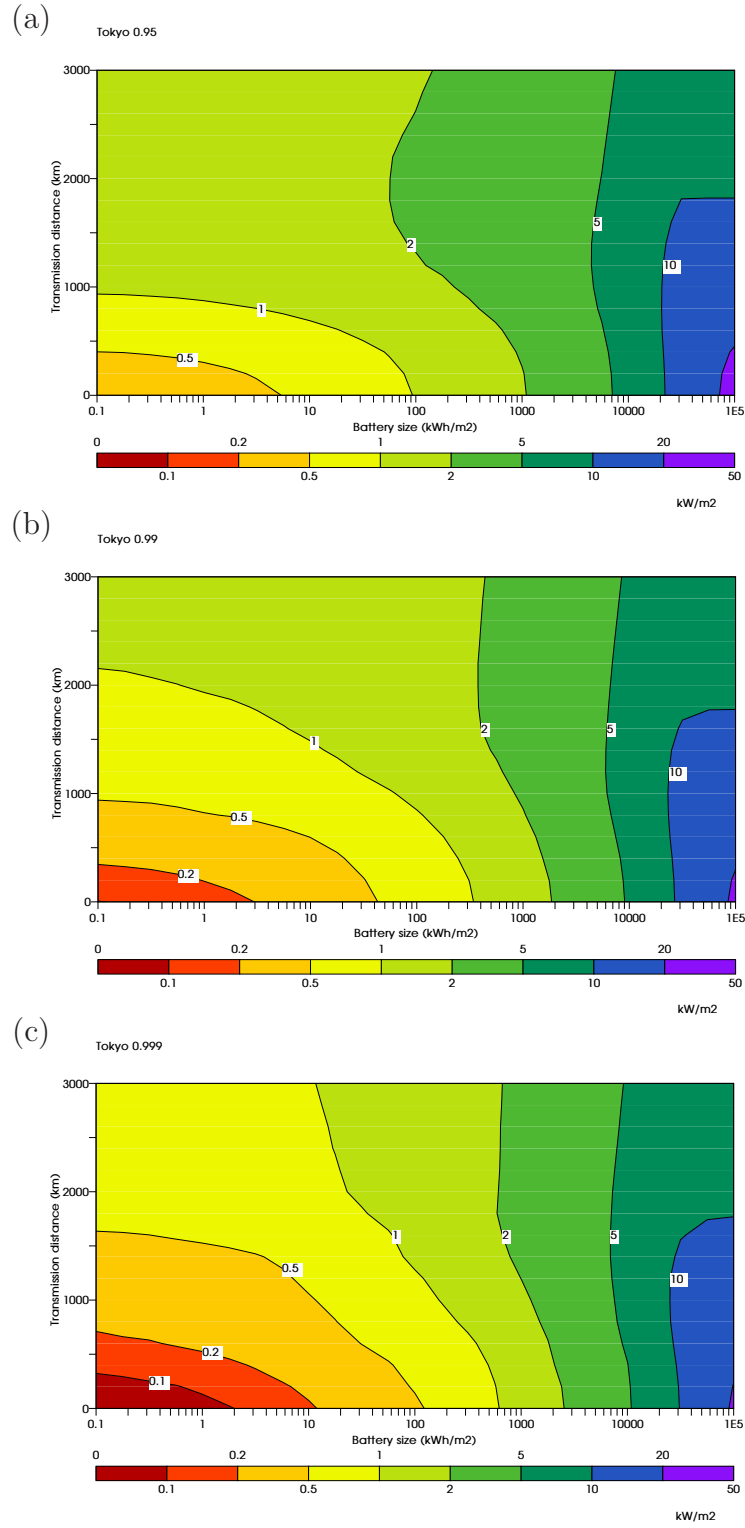


Figure 3.2: Contours of wind power density ( $\text{kW}/\text{m}^2$ ) that can be provided in Tokyo from optimal winds with 95% (a), 99% (b), and 99.9% (c) as a function of battery size ( $\text{kWh}/\text{m}^2$ ) and transmission distance (km), from the NCEP/DOE reanalyses.

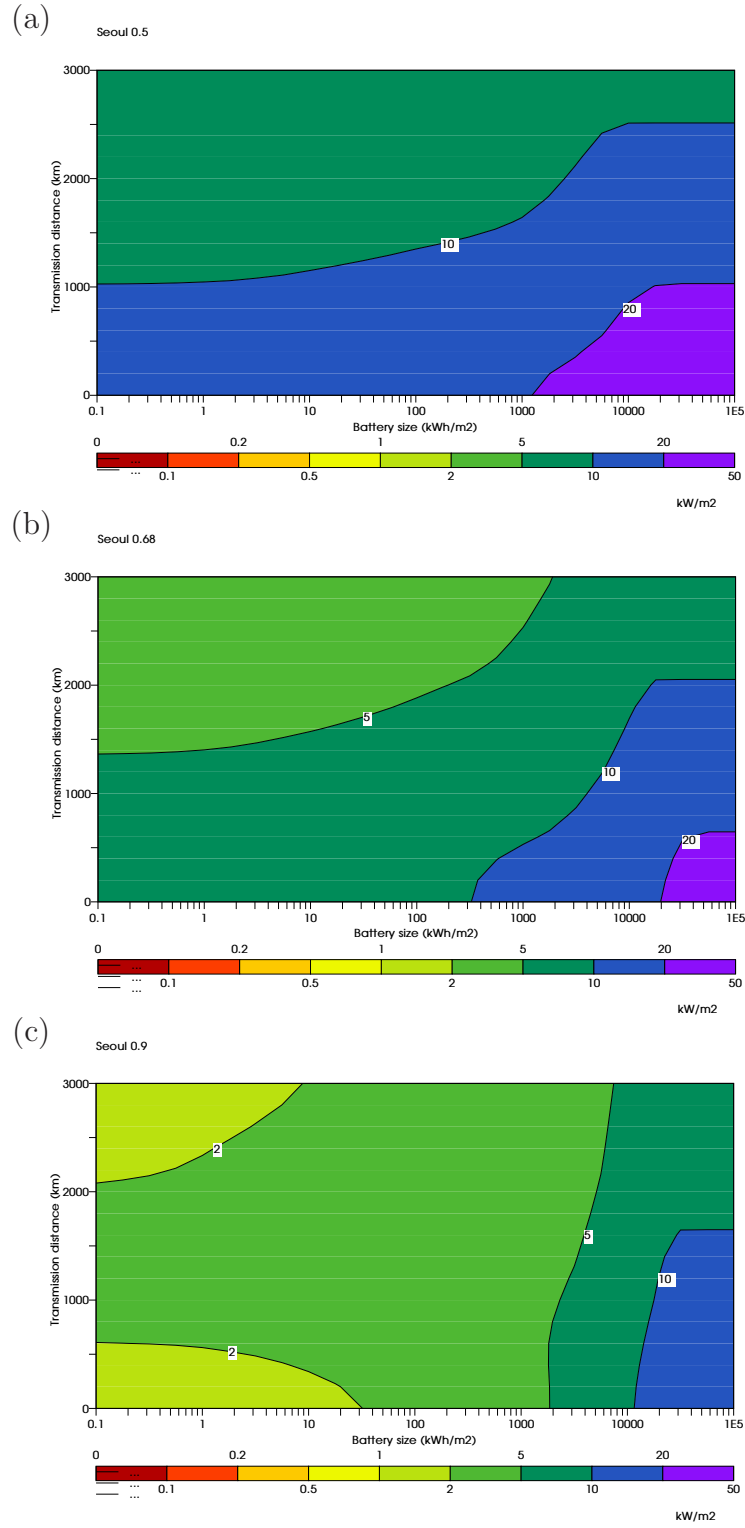


Figure 3.3: Contours of wind power density ( $\text{kW/m}^2$ ) that can be provided in Seoul from optimal winds with 50% (a), 68% (b), and 90% (c) as a function of battery size ( $\text{kWh/m}^2$ ) and transmission distance (km), from the NCEP/DOE reanalyses.

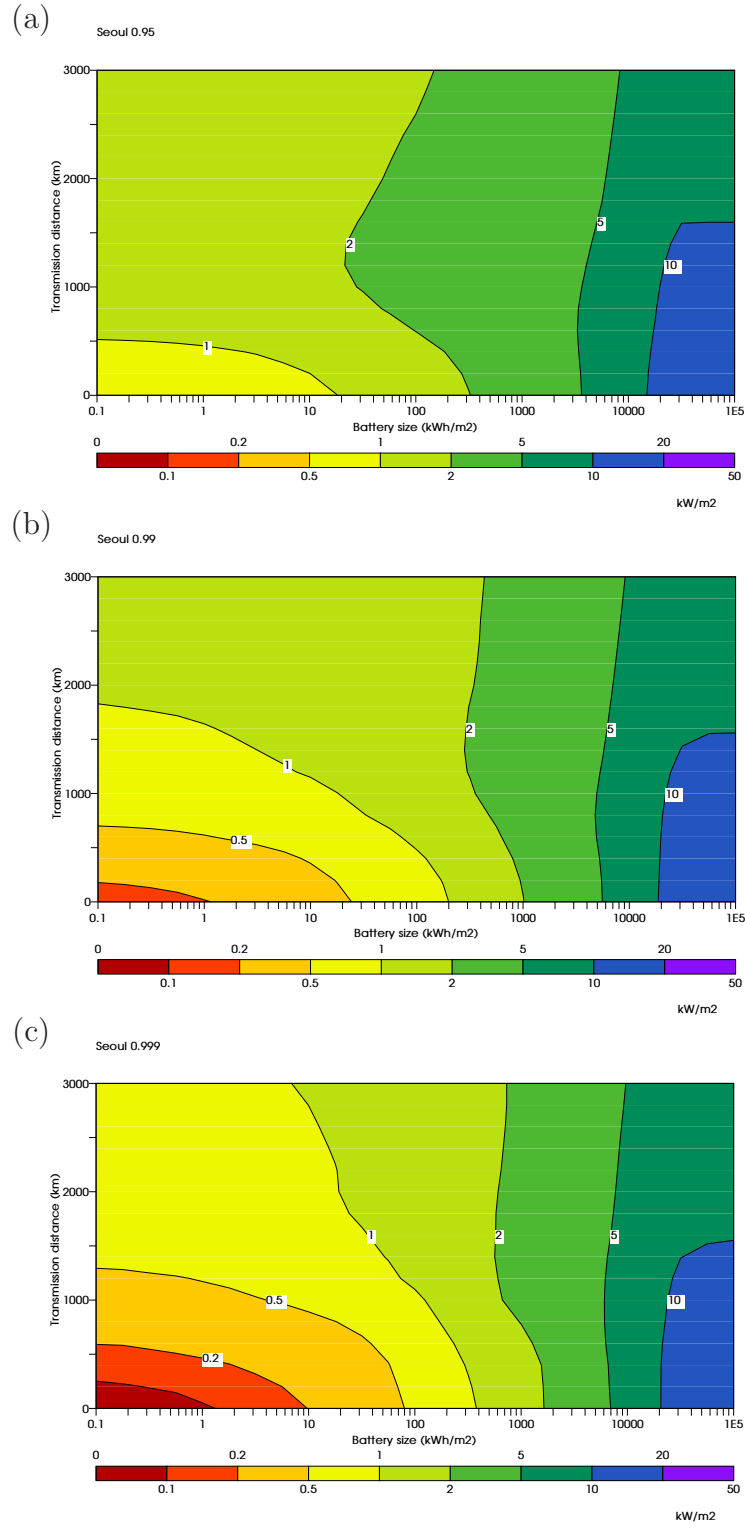


Figure 3.4: Contours of wind power density (kW/m<sup>2</sup>) that can be provided in Seoul from optimal winds with 95% (a), 99% (b), and 99.9% (c) as a function of battery size (kWh/m<sup>2</sup>) and transmission distance (km), from the NCEP/DOE reanalyses.



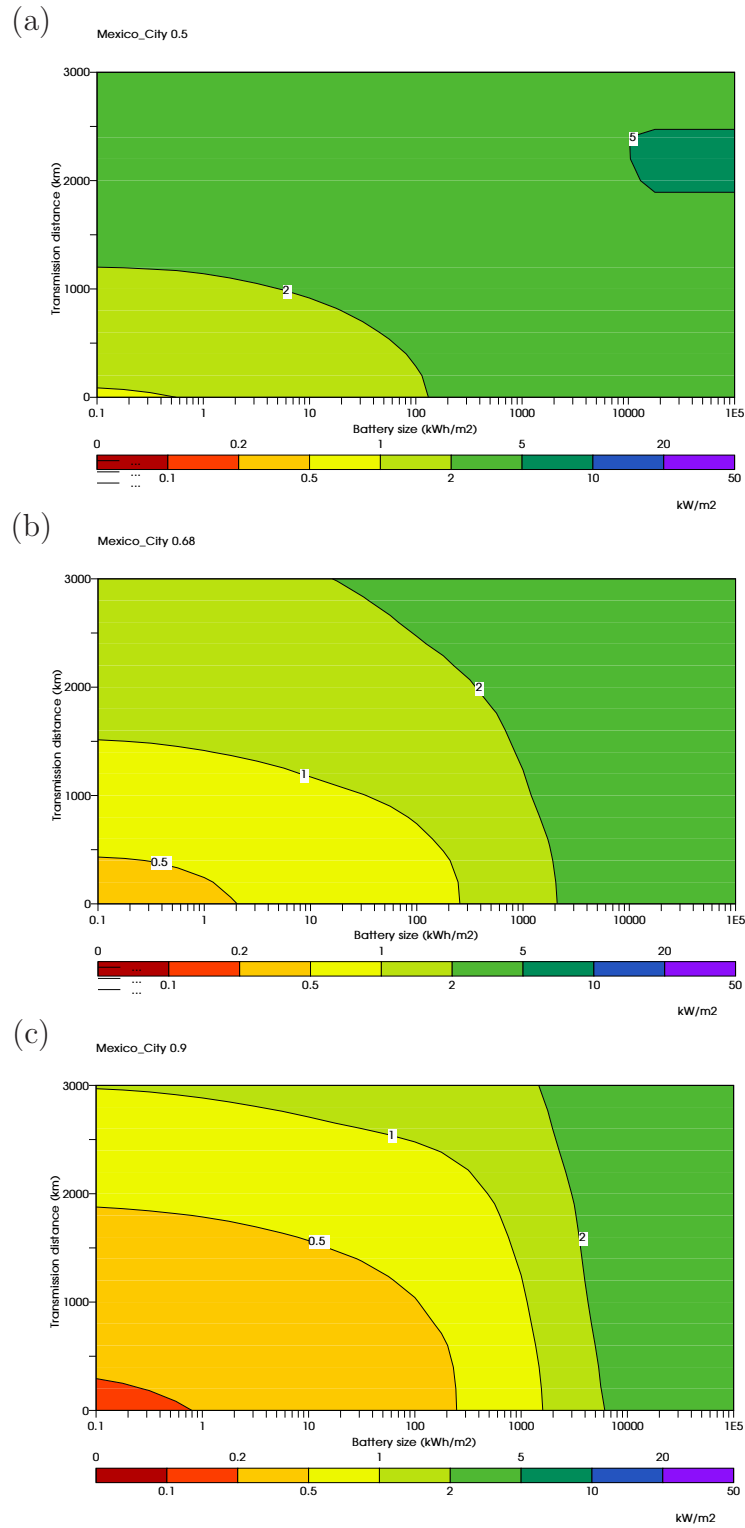


Figure 3.5: Contours of wind power density ( $\text{kW/m}^2$ ) that can be provided in Mexico City from optimal winds with 50% (a), 68% (b), and 90% (c) as a function of battery size ( $\text{kWh/m}^2$ ) and transmission distance (km), from the NCEP/DOE reanalyses.

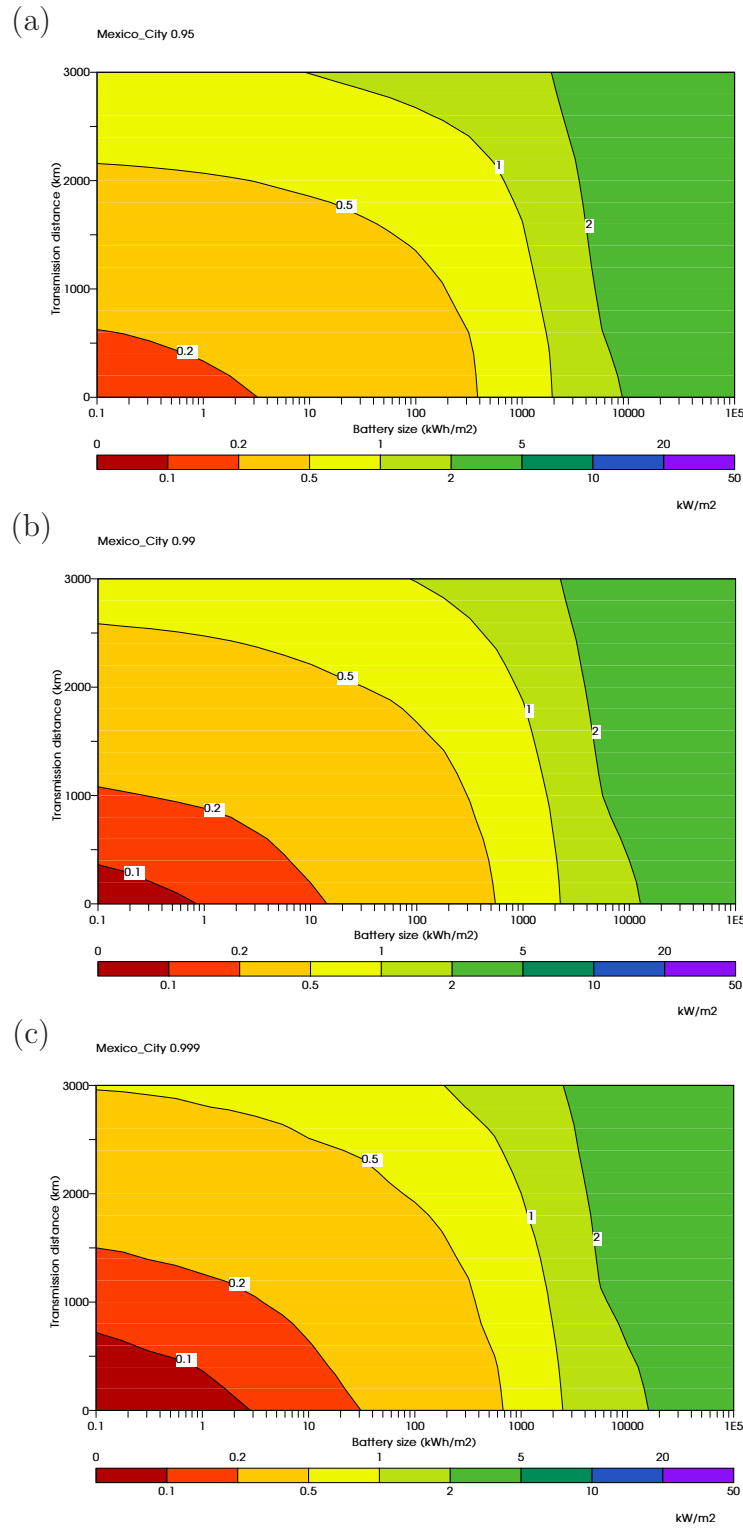


Figure 3.6: Contours of wind power density ( $\text{kW/m}^2$ ) that can be provided in Mexico City from optimal winds with 95% (a), 99% (b), and 99.9% (c) as a function of battery size ( $\text{kWh/m}^2$ ) and transmission distance (km), from the NCEP/DOE reanalyses.

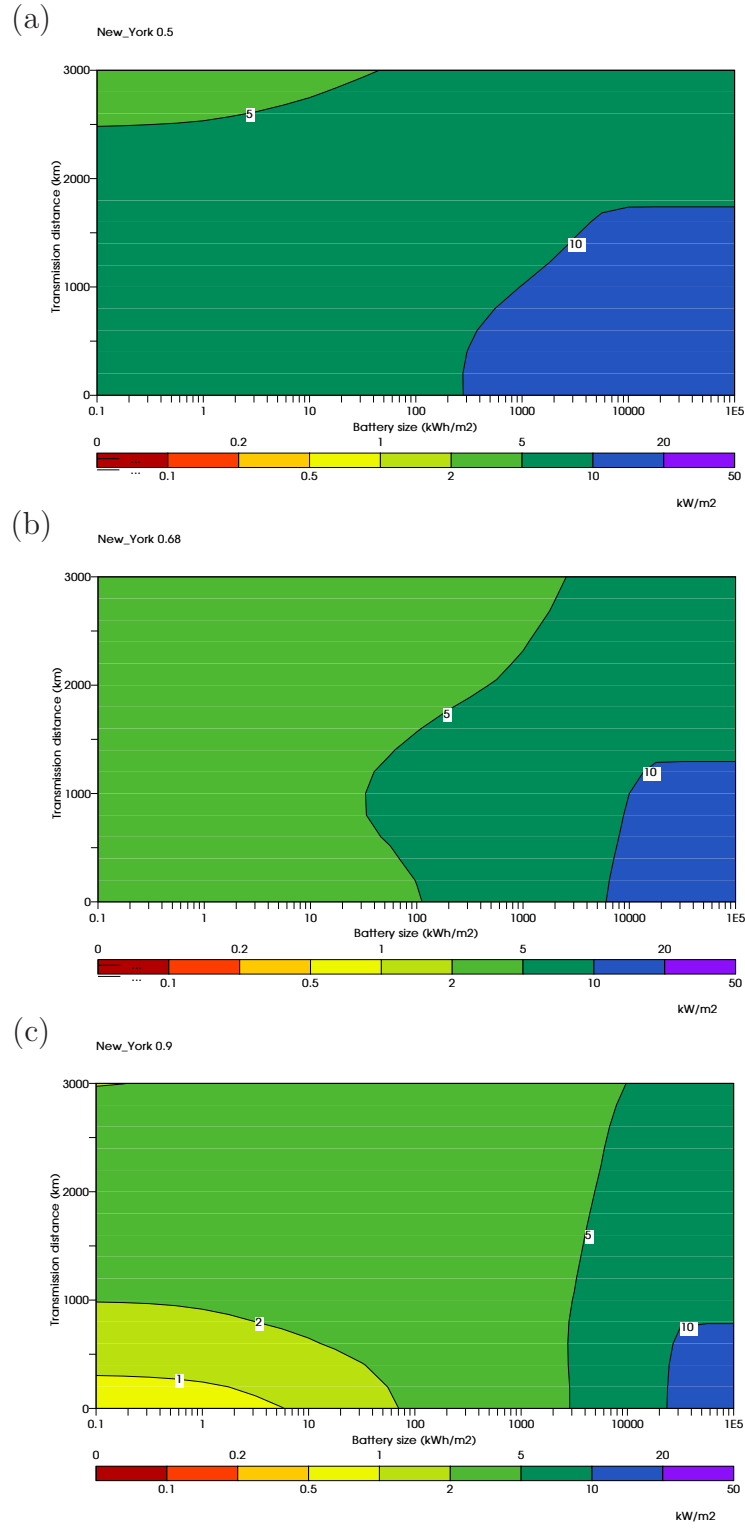


Figure 3.7: Contours of wind power density ( $\text{kW}/\text{m}^2$ ) that can be provided in New York from optimal winds with 50% (a), 68% (b), and 90% (c) as a function of battery size ( $\text{kWh}/\text{m}^2$ ) and transmission distance (km), from the NCEP/DOE reanalyses.

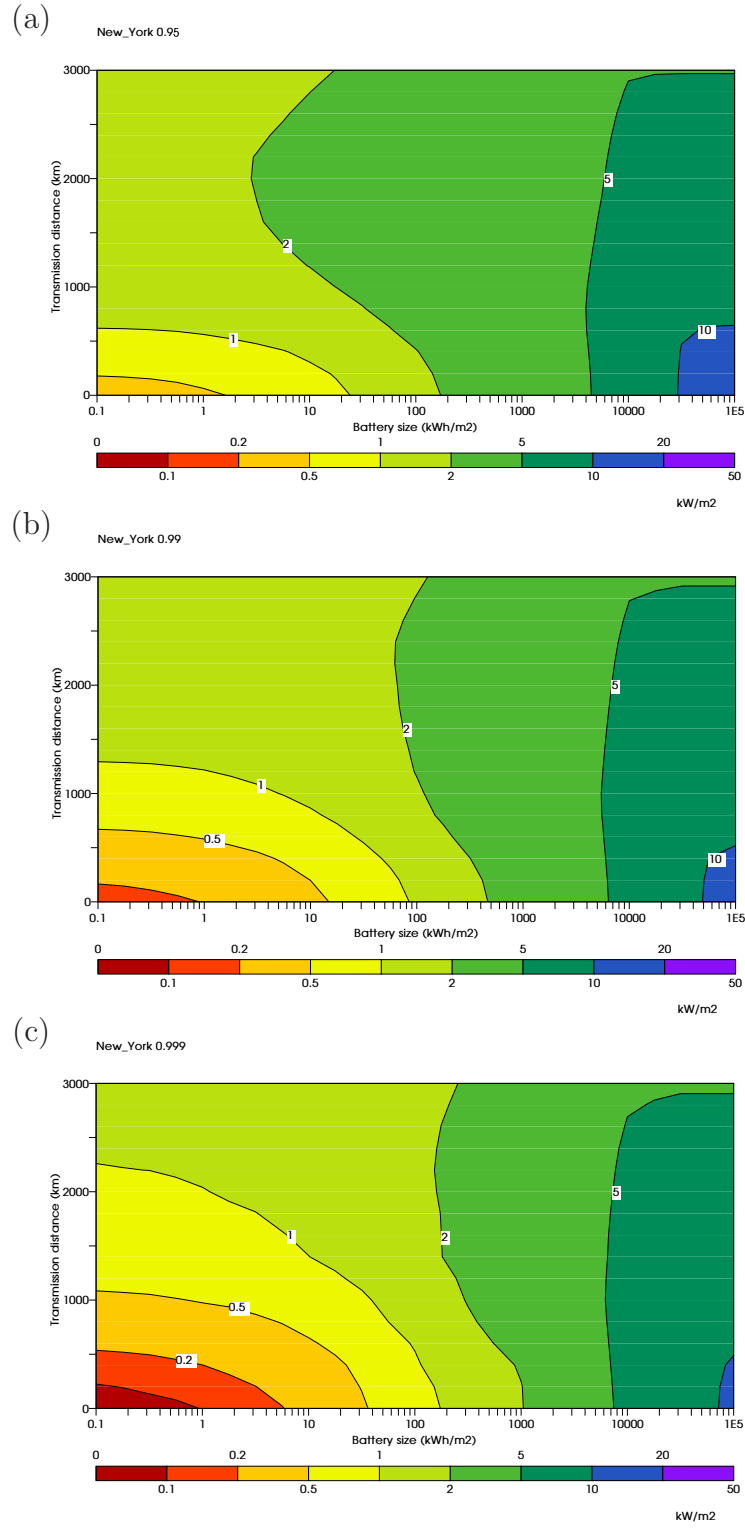


Figure 3.8: Contours of wind power density ( $\text{kW}/\text{m}^2$ ) that can be provided in New York from optimal winds with 95% (a), 99% (b), and 99.9% (c) as a function of battery size ( $\text{kWh}/\text{m}^2$ ) and transmission distance (km), from the NCEP/DOE reanalyses.

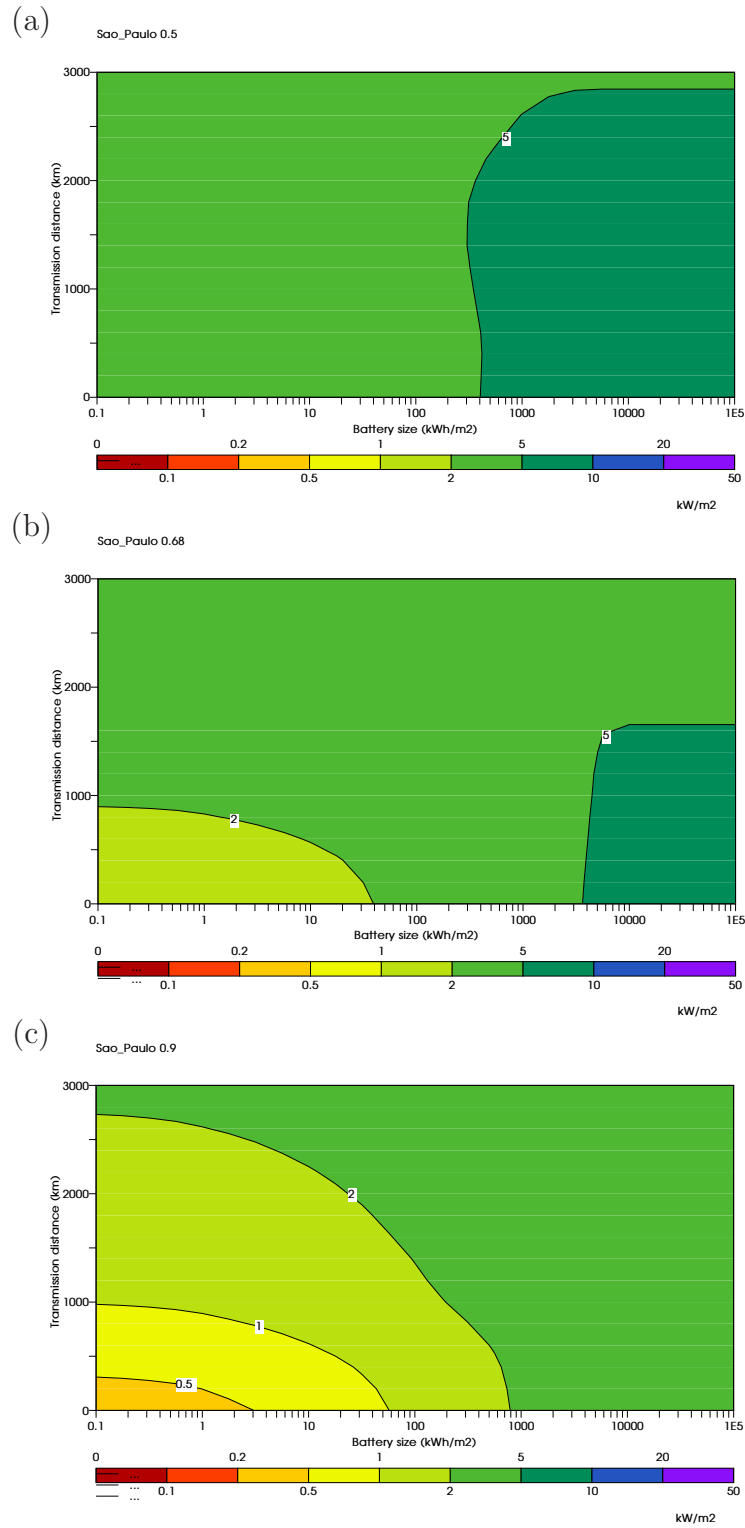


Figure 3.9: Contours of wind power density ( $\text{kW/m}^2$ ) that can be provided in Sao Paulo from optimal winds with 50% (a), 68% (b), and 90% (c) as a function of battery size ( $\text{kWh/m}^2$ ) and transmission distance (km), from the NCEP/DOE reanalyses.



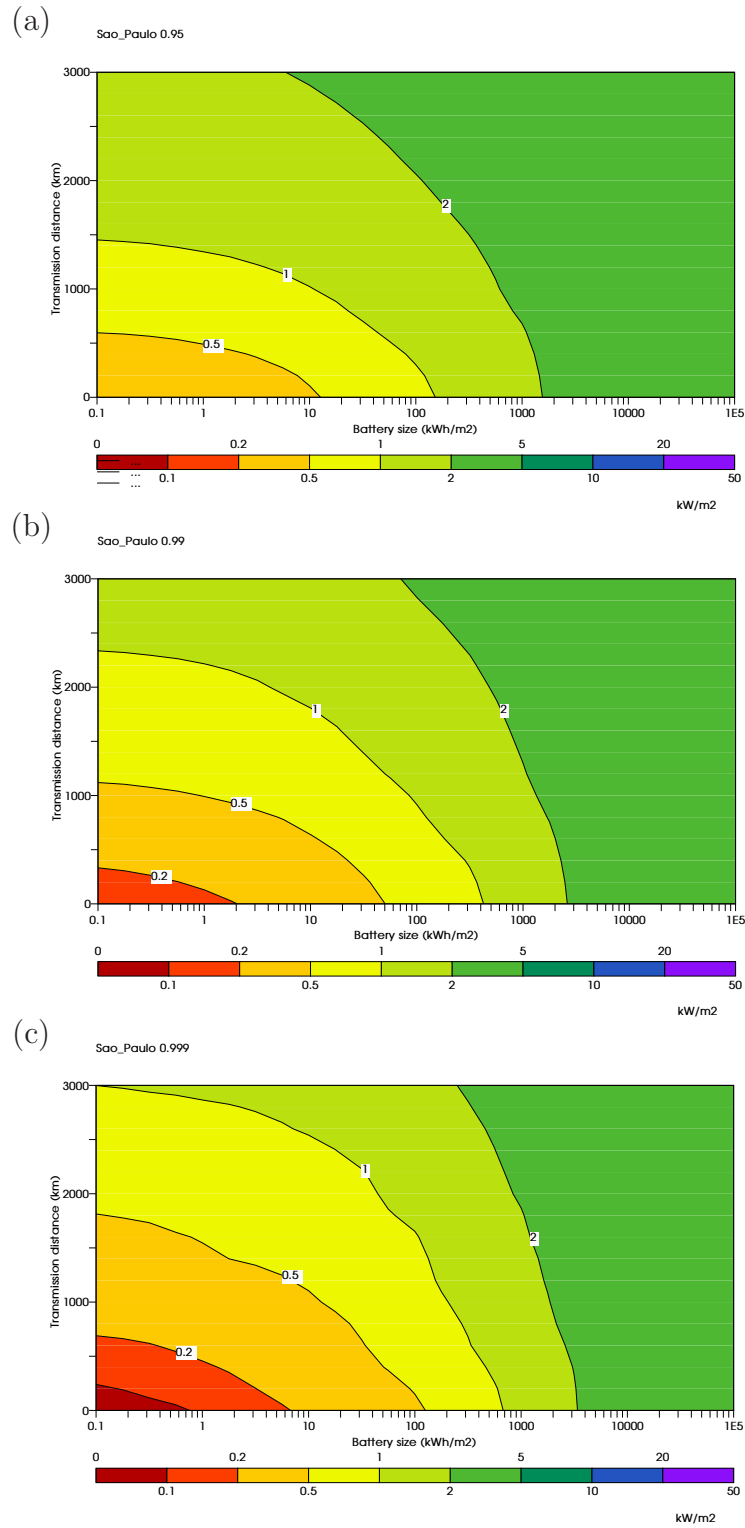


Figure 3.10: Contours of wind power density ( $\text{kW/m}^2$ ) that can be provided in Sao Paulo from optimal winds with 95% (a), 99% (b), and 99.9% (c) as a function of battery size ( $\text{kWh/m}^2$ ) and transmission distance (km), from the NCEP/DOE reanalyses.