Climate Change and Vector-Borne/Zoonotic Diseases

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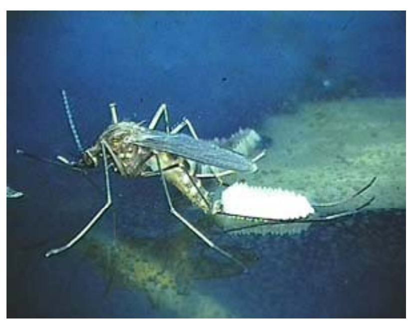
Effects of Climatic Factors on Hosts and Vectors*

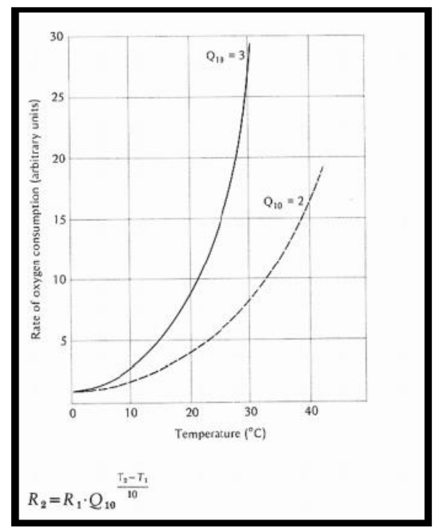
- Growth, development and reproduction
  - Q_{10} effects (approximate doubling of metabolic rates in poikliothermic organisms with 10°C rise in temperatures)
  - Rate of reproduction/Number of generations per season
  - Example: *Anopheles gambiae* gonotrophic cycles significantly shorter in open treeless sites (warmer) than forested sites (cooler)
- Activity patterns
  - Feeding
  - Host seeking
  - Mate seeking etc.
- Availability of breeding sites
- Survival
  - Severe weather events
  - Tolerance limits for vectors and hosts
  - Food or water availability
  - Freezing or heat stress

Vector	Disease agents	Threshold for Biological Activity
Anopheles mosquitoes	*Plasmodium sp.*	8-10° C
Triatomine bugs	*Trypanosoma cruzi*	20° C (2-6° C for survival)
Aedes mosquitoes	Dengue virus	6-10° C
Ixodes ticks	*Borrelia burdgdorferi, Anaplasma phagocytophilum*, *Babesia microti*	5-8° C
Bulinus and other snails	*Schistosoma sp.*	5° C (25±2° C optimal)

Source: Patz and Olson 2006



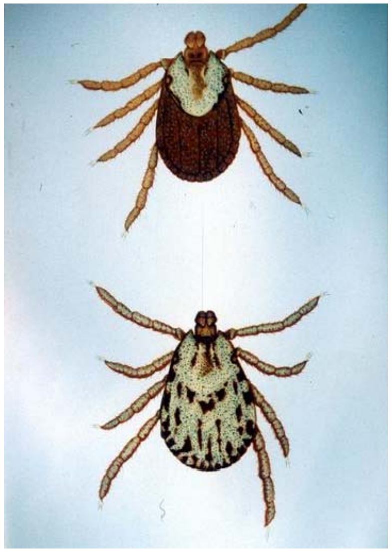
Effect of Temperature on Oxygen Consumption



* See Gubler et al. 2001 for citations and additional examples

Climate Effects on Hosts and Vectors
- Distribution and Abundance -

- "Weather school" (Andrewartha and Birch 1954)
  - Changing conditions make areas more or less suitable for survival and reproduction, which affects abundance of different species
  - Changing conditions often related to climatic variables (temperature, precipitation, humidity, etc.)
  - Most extreme effects seen for insects and other arthropods
- Host or vector populations can increase during favorable conditions and later crash as conditions deteriorate
- Many examples with epidemiologic significance
  - Mosquito vectors
    - Rift valley fever (arbovirus)(Linthicum et al. 1999)
    - Malaria (protozoal)
  - Small mammal hosts
    - Deer mice and SNV (Yates et al. 2002)
    - Gerbils and plague (Kausrud et al. 2007)
  - Ticks
    - *Ixodes ricinus* (Sweden)(Lindgren, Talleklint and Polfeldt 2002, Talleklint and Jaenson 1998)
    - *Dermacentor variabilis* (Colorado) (Eisen, Meyer and Eisen 2007)



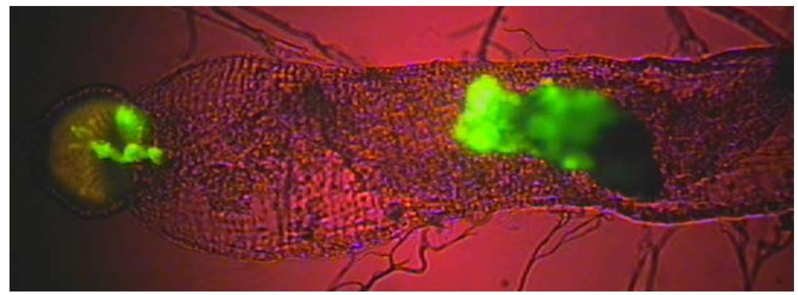
Climatic Effects on Pathogen Development

- Extrinsic incubation periods
- Infectivity
- Ability to maintain development in vector

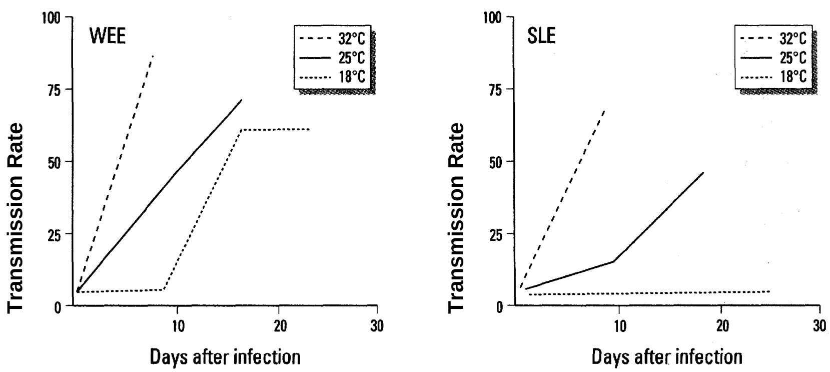
Effect of Temperature on Blocking of Fleas by *Yersinia pestis* and Mortality among Infected Fleas

Yersinia pestis Strain	Percent of fleas blocked at given temperature			Percent flea mortality at given temperature		
	20°C	25°C	30°C	20°C	25°C	30°C
195-P-wt	32	13	0	42	41	70

Source: Hinnebusch, Fischer and Schwan 1998

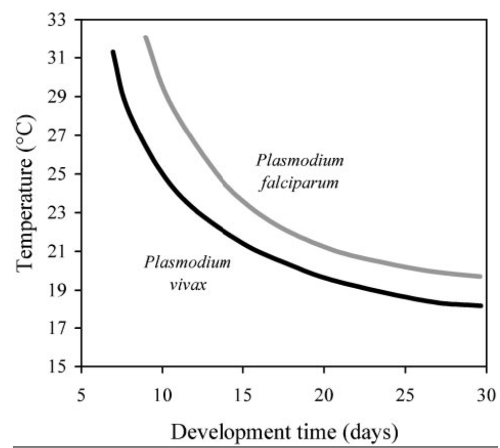


Effect of Temperature on Viral Transmission by *Culex tarsalis*



Source: Reeves et al. 1994

Effect of Temperature on Extrinsic Incubation Period of *Plasmodium sp.* in *Anopheles* mosquitoes



Source: McDonald 1957

Climate and Vector-Borne Diseases - Malaria -

- African malaria epidemics triggered by climate anomalies that follow periods of drought (DeSilva et al. 2004)
- Dec-Feb rainfall totals explain > two-thirds of variation in Botswana cases
- Sea surface temperatures linked to rainfall and El Nino-La Nina cycles (Thomson et al. 2005, 2006)
- Other climatic anomolies linked to malaria epidemics in
  - Columbia (Poveda et al. 2001)
  - Indian subcontinent (Bouma and van der Kaay 1994)
  - Southern Africa - Incidence correlated with pos. SOI (La Nina periods) (Mabaso et al. 2006, 2007a, b)
  - Uganda – Incidence linked to El Nino cycles (Lindblade et al. 1999)
  - South Africa – Maximum daily temperatures from preceding season correlated with malaria cases (Craig et al. 2004)
  - Ethiopia – Minimum temperatures (< 12^{o}C) in cold region correlated with cases
  - Kenya and Ethiopia – Heavy rainfall associated with outbreaks (Lindsay and Martens 1998)
  - Burkina Faso – Temperature best predictor of clinical malaria in children under 5 years (Ye et al. 2007)
  - Pascual et al. (2006) – Significant warming trend in East African highlands associated with increased malaria risk. Models of mosquito population dynamics suggest temperature effect on the biological response of the mosquitoes will be amplified by at least 1 order of magnitude

Projected Effects of Climage Change
- Malaria -

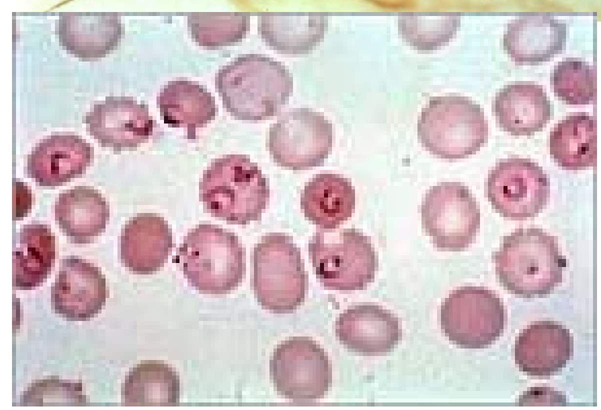
- Many have suggested that global warming will result in a northward shift of vectors and increased malaria risks for those in temperate regions

- Small, Goetz and Hay (2003)
  - Incidence in Africa would increase in some areas and decrease in others

- Tanser, Sharp and le Sueur (2003)
  - 16-28% increase in person-months of exposure
  - Little latitudinal change in risk – most change occurs in existing areas or with altitude

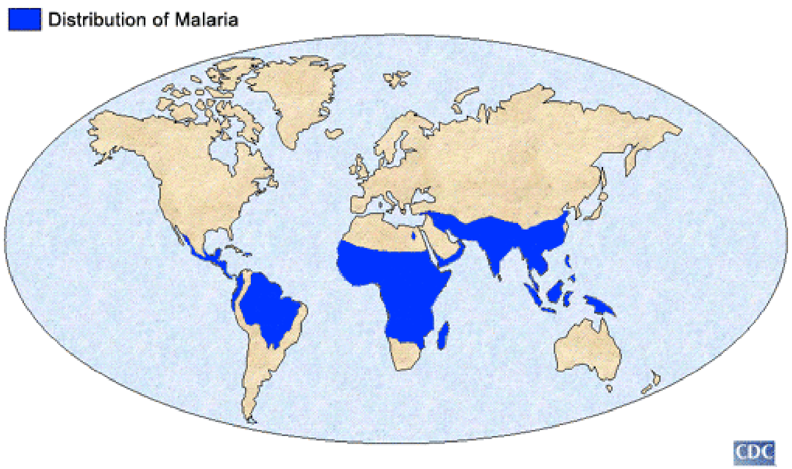
- Deforestation in Kenya associated with
  - Higher temperatures and relative humidities in *Anopheles gambiae* breeding sites
  - Higher mosquito infection rates and decreased parasite development times (Afrane et al. 2008). Similar effects elsewhere?

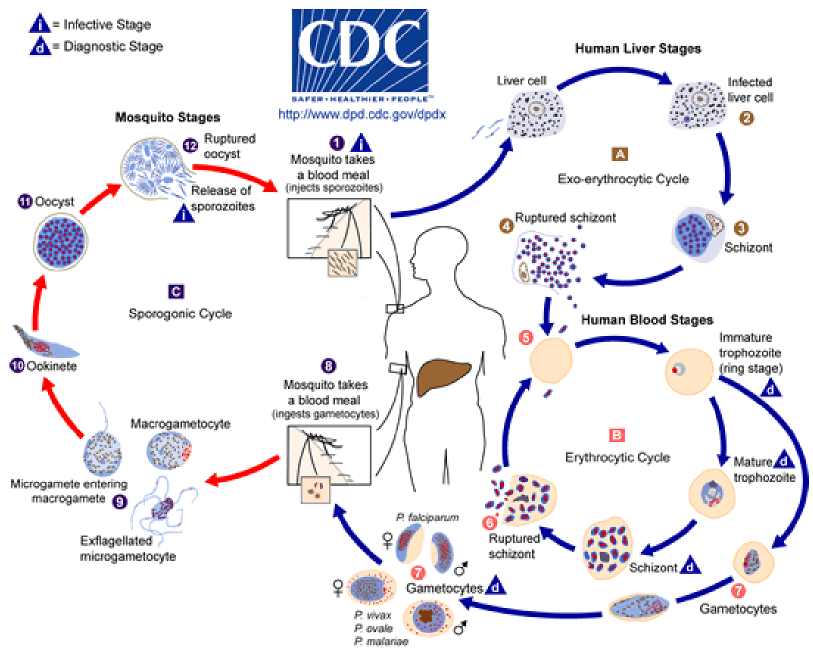
- Many have proposed using remote sensing and GIS-based modeling to predict outbreaks and sites of likely range expansion for malaria (Abeku 2007, Malone et al. 2006, Guerra et al. 2006,



Climate and Vector-Borne Diseases
- Malaria -

- Others failed to find links between climate and malaria incidence/outbreaks
- Reiter et al. (2004)
  - Stressed local effects and other factors that could be confounded with climate effects.
  - Felt Tanser et al. (2003) used too few points were used to draw continent-wide conclusions on future transmission risks
  - Disagreed with how Tanser et al. (2003) used the term stable and its implication for where outbreaks would occur
- Hay et al. (2002) – Africa
- Dev (2007) – India
- Haile (1989) – Possible US transmission
  - *Anopheles quadrimaculatus* still abundant in former malaria-affected regions of US but no current malaria foci in this country
  - Would climate change lead to reestablishment of malaria in U.S.?





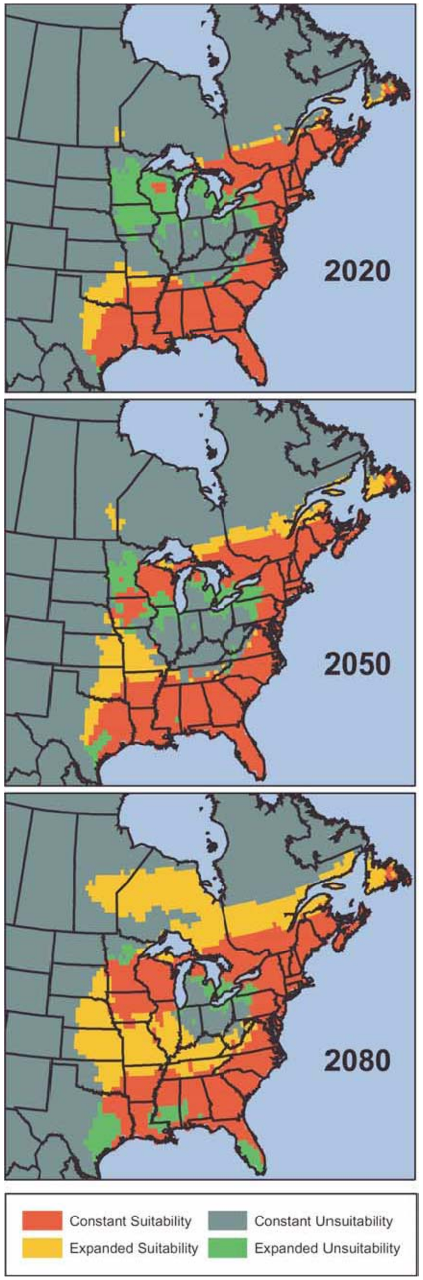
Climate and Vector-Borne Diseases
- Lyme Disease -

- Water stress and temperature regulate off-host mortality for *I. scapularis* (Needham and Teel 1991, Bertrand and Wilson 1996)

- 98% of *I. scapularis* life cycle occurs in off-host environments (Brownstein, Holford and Fish 2005) – High likelihood for climate factors to effect survival and reproduction

Climate and Vector-Borne Diseases
- Lyme Disease -

- *Ixodes* tick life cycles and activity patterns known to be affected by temperature, humidity and rainfall
- Brownstein, Holford and Fish (2005) used climate-based logistic regression models to explain current distribution of *I. scapularis* in North America
- Used above model to extrapolate changes in distribution based on climate change predictions
- Expanded habitat suitability in Canada
- Decreased suitability in southern U.S.



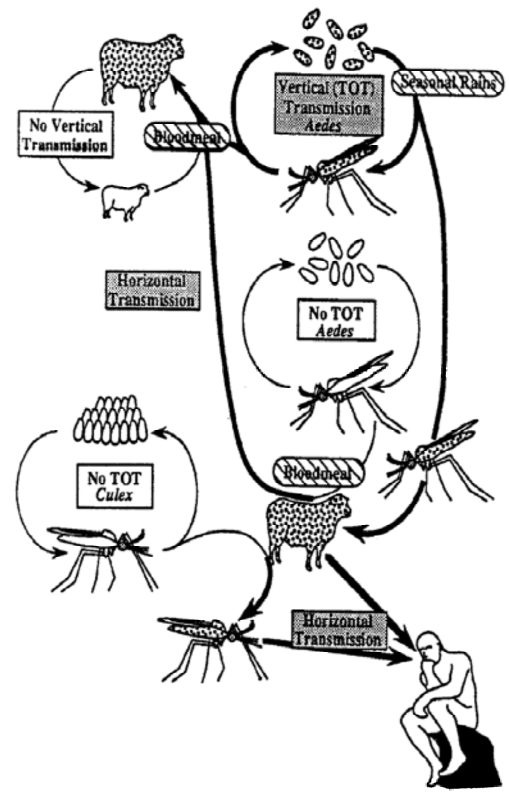
Brownstein, Holford and Fish. Ixodes scapularis hability suitability and projected future Lyme risks – EcoHealth 2, 38-46, 2005

Climate and Zoonotic Diseases
- Tick-Borne Encephalitis -

- Randolph and Rogers (2000) modeled TBE distribution in Europe
- Used above model and GCMs to project future distribution of TBE
- Summer temperature rises and decreases in moisture should drive TBE into higher latitude or higher altitude sites
- Eventually TBE might occur only in a small part of Scandinavia with new foci in southern Finland
- Changes likely to be due to disruptions in tick seasonal dynamics
- Sumilio et al. (2007)
  - Spring-time daily max temperatures have increased since 1989
  - But other factors likely to be more important in occurrence of TBE

Climate and Vector-Borne Diseases
- Rift Valley Fever -

- RVF outbreaks associated with periods of heavy rainfall in enzootic regions (Meegan and Bailey 1988, Wilson et al. 1994, Digoutte and Peters 1989, Linthicum et al. 1999)
- Linthicum et al. (1999) – Remote sensing can be used to observe flooding of dambos and forecast outbreaks
- Climate change could create suitable conditions for RVF transmission in southern Europe, southwestern Asia, or southern USA (Gould and Higgs 2008; Martin et al. 2008)

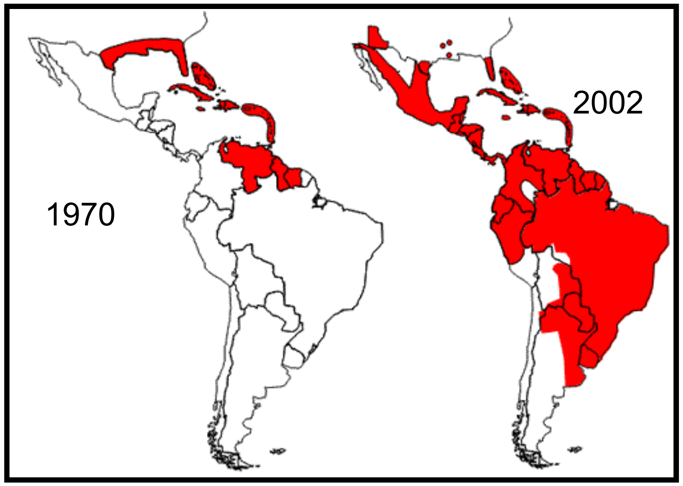


Source: Wilson 1994 Ann NY Acad Sci.

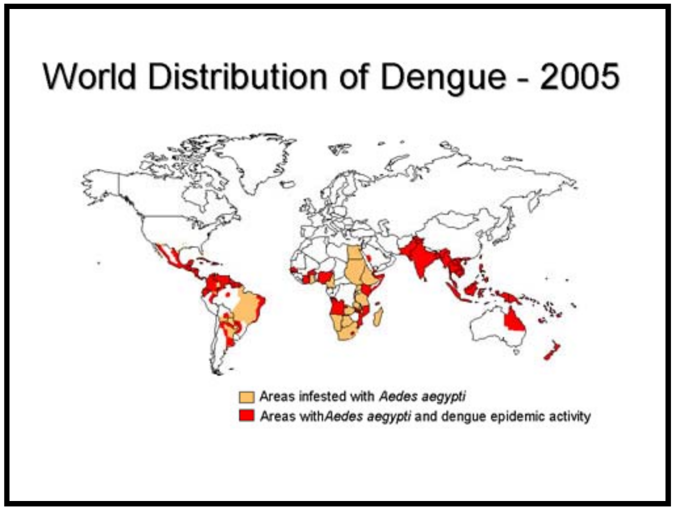
Climate and Zoonotic Diseases
- Dengue -

Transmission and distribution influenced by climatic factors

- Freezing temperatures kill overwintering eggs and larvae of *Aedes aegypti* (Chandler 1945)
- Temperature affects pathogen replication, maturation and length of infectivity in vector (Reiter 1988, Watts et al. 1987)
- Dengue epidemics correlated with rainfall in Trinidad (Chadee et al. 2006)
- Wu (2007) dengue incidence in Taiwan negatively correlated with monthly temperature deviation and relative humidity
- Dengue rates remained relatively constant in Puerto Rico despite reduced rainfall and other climatic changes. Other factors thought to be important. (Jury 2008)

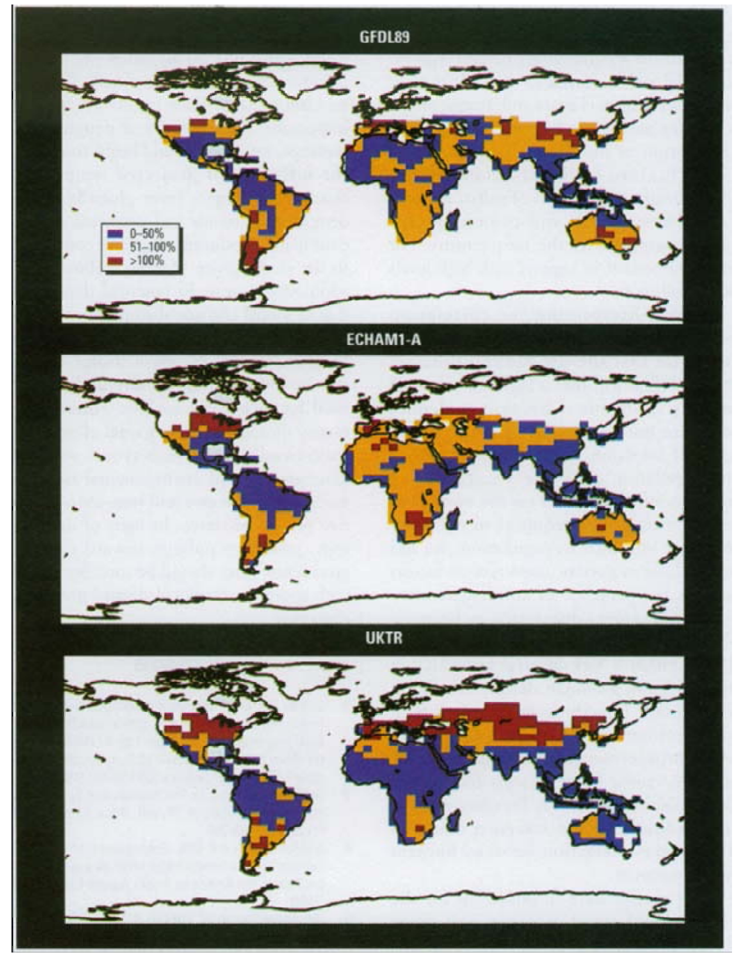


Aedes aegypti distribution in 1970 and 2002



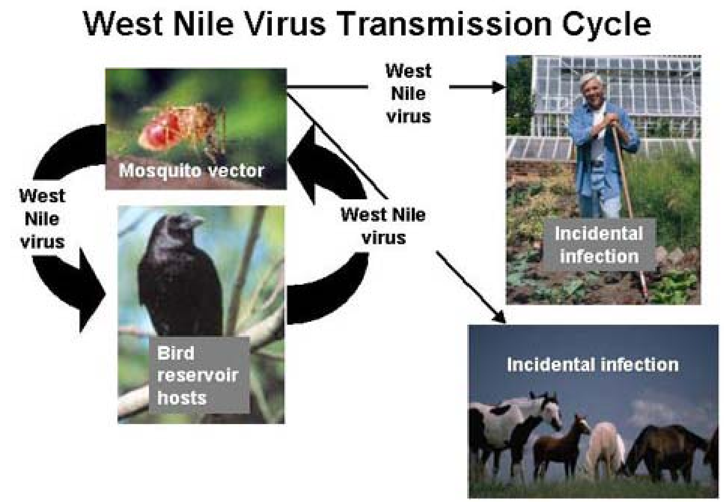
Climate and Zoonotic Diseases
- Dengue -

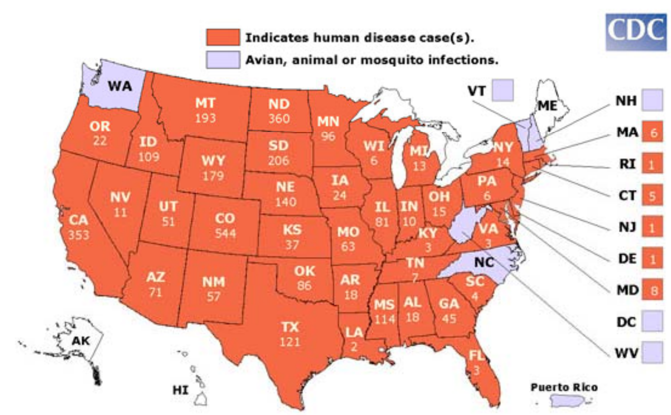
- Jetten and Focks (1997) – Increasing temperatures will increase length of transmission season in temperate regions
- Patz et al. (1998) used simulation analyses to link temperature outputs from three general circulation models (GCM) to a dengue vectorial capacity equation
  - Models with all three GCMs predicted temperature-related increases (averages of 31-47%) in potential seasonal transmission
  - Predicted risks would initially increase near edges of current distribution
  - Also predicted that endemic areas would be at more risk of DHF as transmission intensity increases
- Will dengue spread in continental US?
- Possible lessons from outbreaks along US-Mexico border



Climate and West Nile Virus

- Climatic factors can limit the distributions of WNV vectors (Eisen et al. 2008 and others)
- Minimum temperature and warming tendency were major climatic factors favoring earlier appearance of disease in affected areas (Paz 2006; Paz and Albersheim 2008)
- Cases more closely correlated with extreme heat than high humidity
- Proposed early extreme rise in summer temperatures is a good indicator of increased vector populations
- Outbreaks in Romania (1996) and New York City (1999) also occurred after summer heat waves
- Abundance of potential West Nile vectors in Washington state correlated with temperature (Pecoraro et al. 2007)
- Drier conditions associated with increased WNV-associated illness in Iowa (DeGroote et al. 2008)



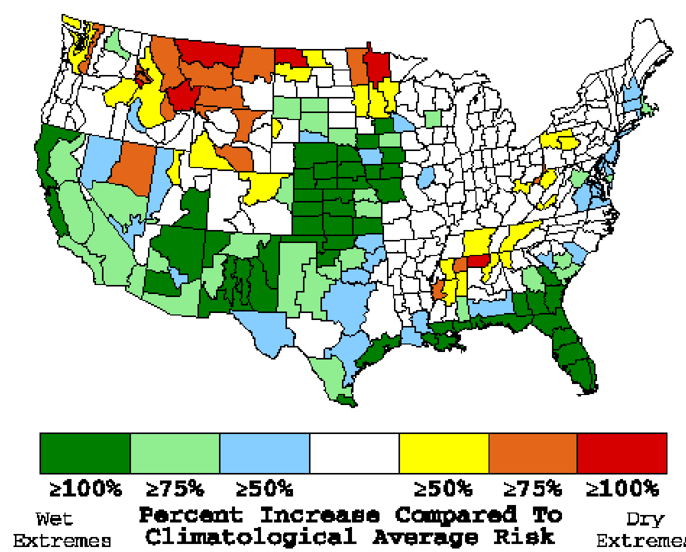


2007 West Nile Virus Activity as of 10/23/07

Climate and Zoonotic Diseases
- Hantavirus -

- High rodent densities should increase
  - hantavirus transmission
  - likely human contact (invasion of homes, etc.)
- Trophic cascade hypothesis (Yates et al. 2002)
- El Nino events result in high precipitation that might lead to
  - Increased availability of rodent food sources
  - Increased rodent reproduction and survival
  - Increase in human HPS cases
- Relationships between climatic variables, deer mouse numbers, hantavirus prevalence in mice and the occurrence of increased human cases are complex (Mills 2005)

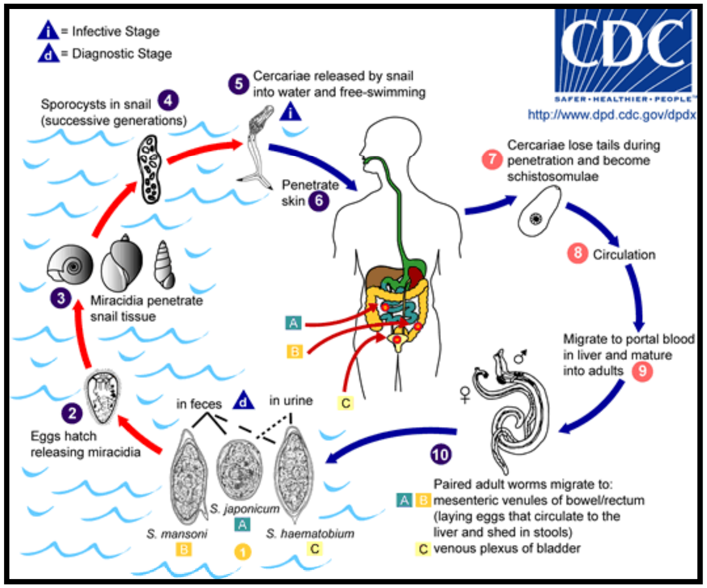
DJF Precipitation Extremes During El Nino
Risk of Extreme Wet and Dry Years

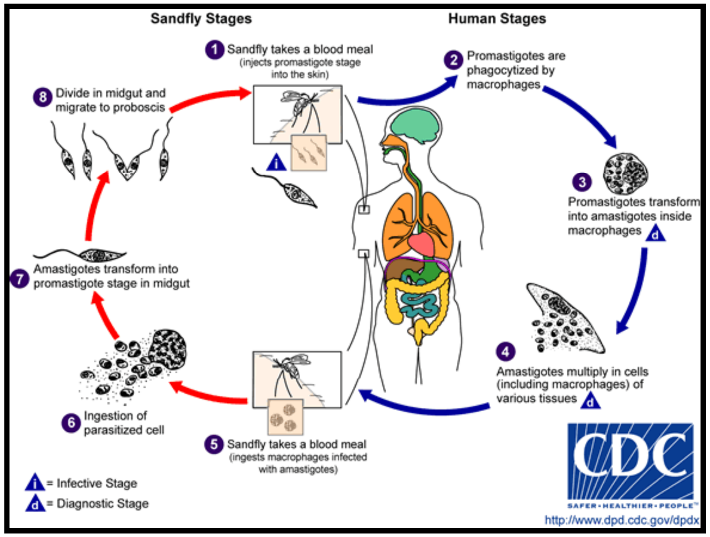


Climate Change
- Parasites other than Malaria -

- Development of *Schistosoma* in *Oncomelania* snails linked to temperature (Yang et al. 2007)
  - No development at < 15.3° C
  - Development increased up to 30°C
  - Proposed to be important factor if China experiences warming

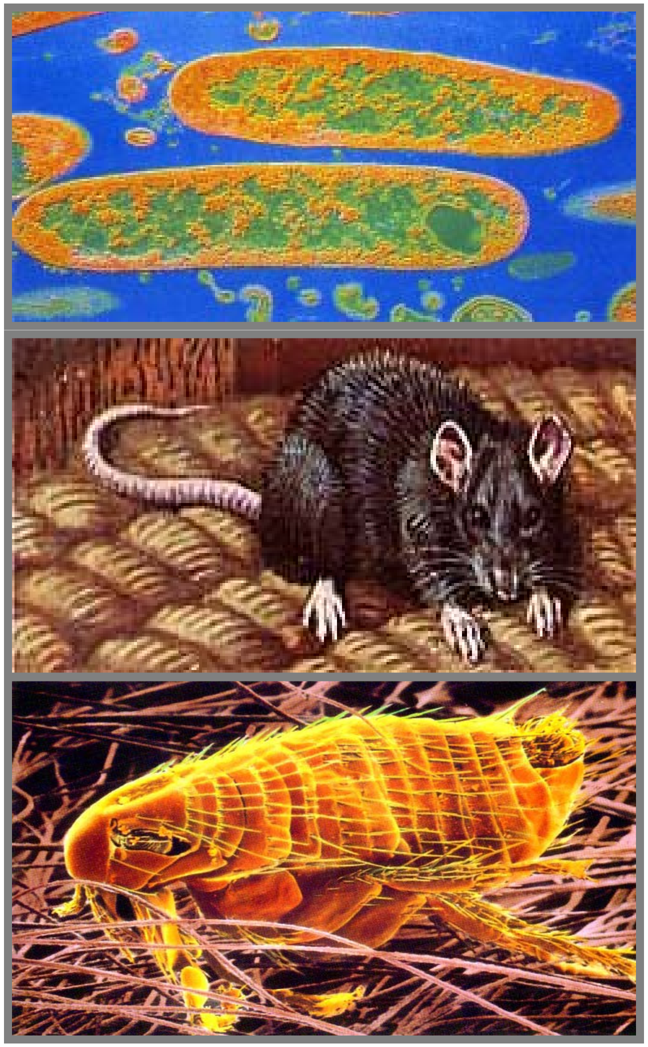
- Cases of cutaneous leishmaniasis correlated with temperature and multivariate ENSO index (Cardenas and Pascual. 2006)





Climate and Plague Transmission

- Major Pandemics (Justinian's Plague and the Black Death) were associated with major climatic fluctuations
- India – Temperature, humidity and rainfall effects (Greenwood 1911, Brooks 1915-1917, Rogers 1928)
- Vietnam – Decreased transmission at temperatures above 27º C (Cavanaugh and Marshall 1972)
- Southern Africa – Severe drought forces bush rodents into peridomestic environments (Isaacson 1983)
- Peru – Outbreaks after El Ninos
- Kazakhstan – Cases occurred 1-2 years after higher than normal rainfall years (Dubyansky et al. 1992)



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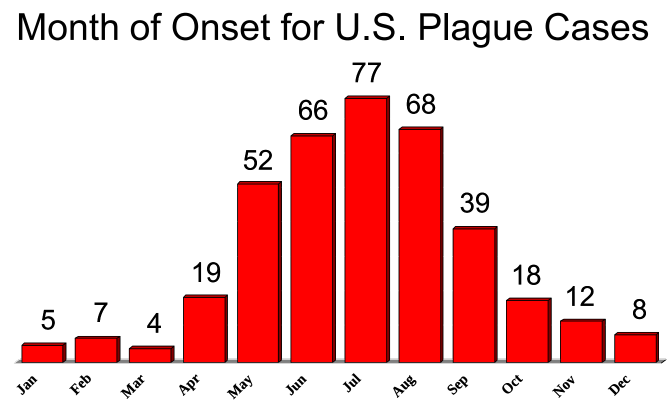
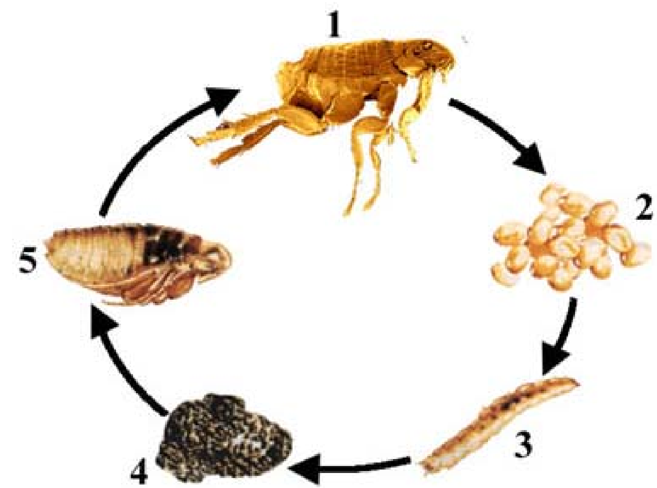
How Could Climate Influence Plague Activity?

- Seasonality of transmission
- Survival of fleas
- Ability of fleas to transmit and retain infection
- Rodent host and flea vector population dynamics





Climatic Effects on Pathogen Development and Flea Survival

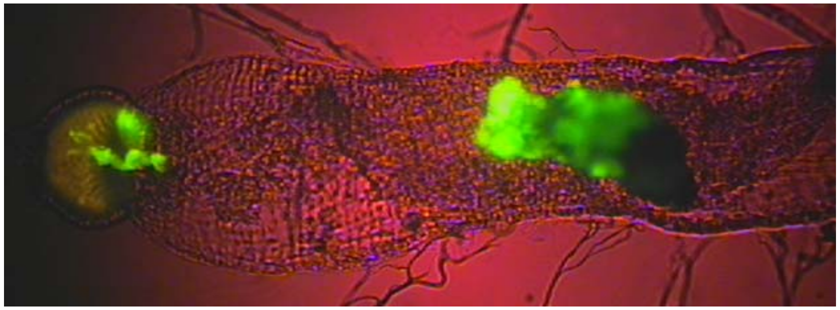
- **Transmission and blockage**

  (Martin 1911, 1913; Goyle 1928; Eskey and Haas 1940; Kartman 1969; Cavanaugh 1971; Hinnebusch, Fischer and Schwan 1998)
  - ***Y. pestis b*iofilm development occurs at temperatures below 28º C**
  - **Can result in formation of proventricular blockage**
  - **Block formation increases transmission efficiency**
  - **Blocks begin to break down at temperatures above 27º C**
- **Ability to maintain infection in vector**
  - **Biofilm might help prevent clearance**
- **Flea survival**
  - **Hot, dry conditions decrease survival**

Effect of Temperature on Blocking of Fleas by *Yersinia pestis* and Mortality among Infected Fleas

Yersinia pestis Strain	Percent of fleas blocked at given temperature			Percent flea mortality at given temperature		
	20ºC	25ºC	30ºC	20ºC	25ºC	30ºC
195-P-wt	32	13	0	42	41	70

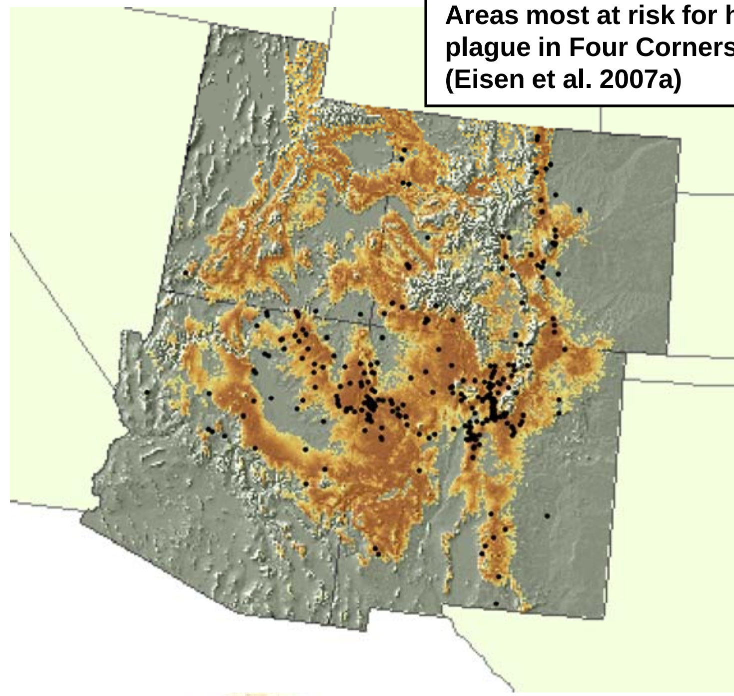
Source: Hinnebusch, Fischer and Schwan 1998



CDC
Centers for Disease Control and Prevention

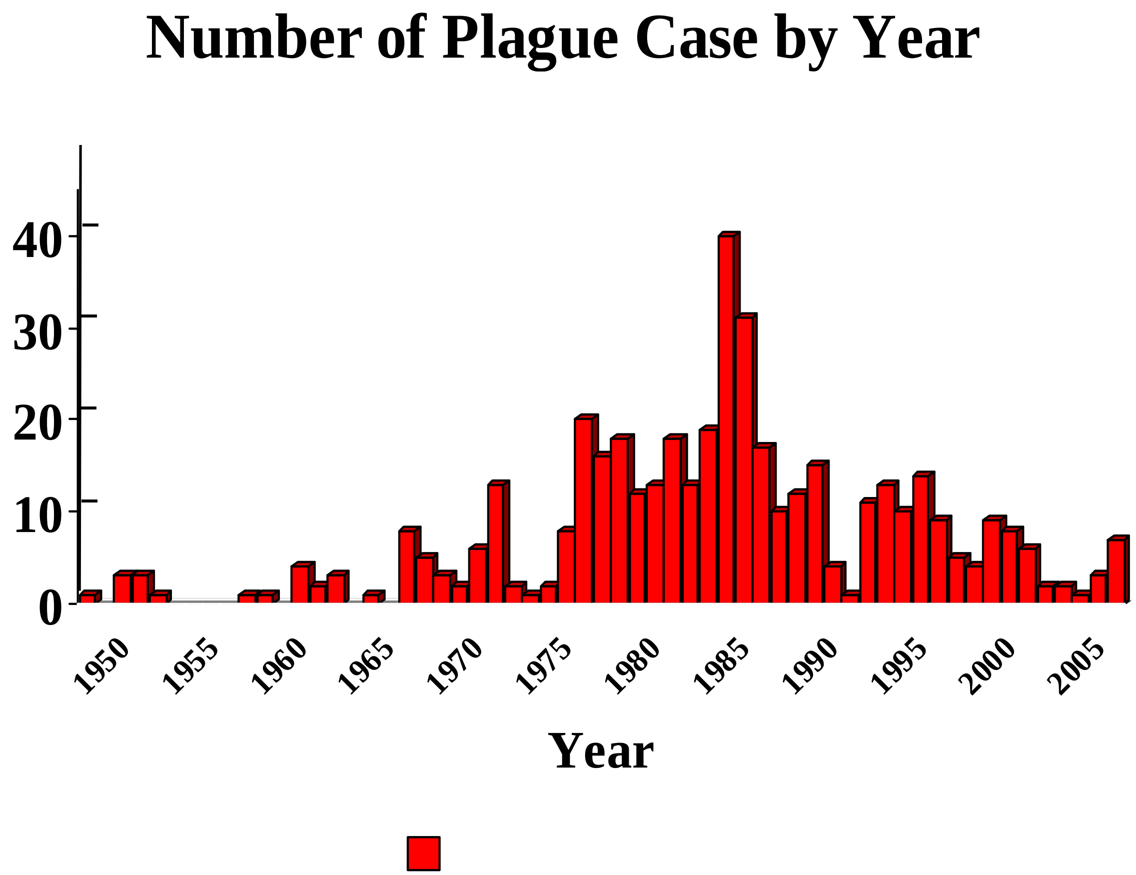
Plague in the Southwest

- Site of about 80% of U.S. cases
- High risk areas well-defined (Eisen et al. 2007a)
- Peridomestic exposures
  - Rodent food and shelter
  - Pets
- Rock squirrels, other ground squirrels, prairie dogs, wood rats, deer mice and their relatives
- Acquired via:
  - Flea bite (~ 80%)
  - Direct contact (~20%)
  - Inhalation (rare – cats)
- Most cases acquired during epizootics



Areas most at risk for human plague in Four Corners states (Eisen et al. 2007a)

Reported Human Plague Cases By Year-U.S.A., 1947-2005



N = 420

Precipitation and Plague in New Mexico (Parmenter et al. 1999)

Am. J. Trop. Med. Hyg., 61(5), 1999, pp. 814–821

INCIDENCE OF PLAGUE ASSOCIATED WITH INCREASED WINTER-SPRING PRECIPITATION IN NEW MEXICO

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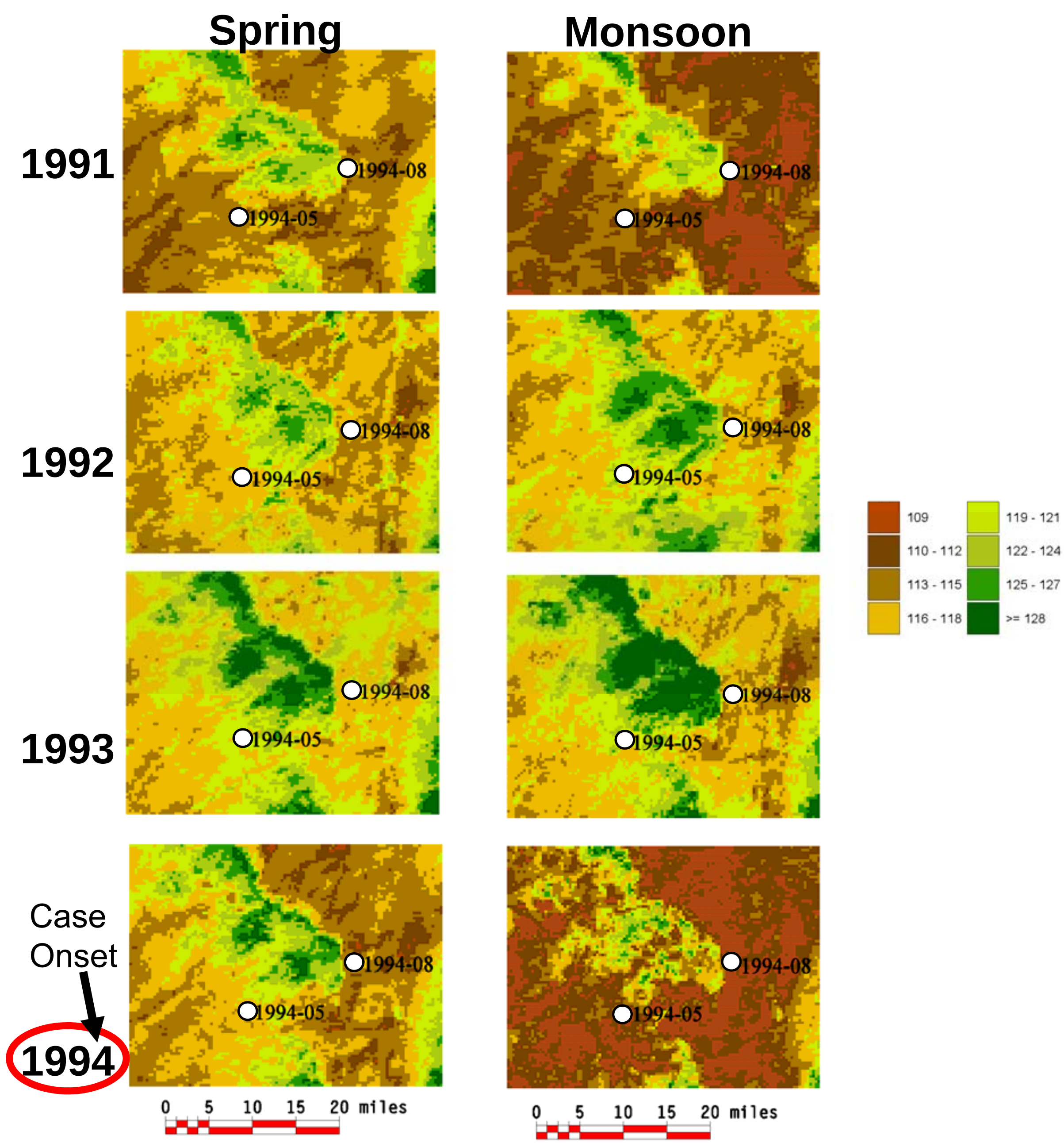
- Parmenter et al. (1999) – Positive correlation between local winter-spring precipitation and occurrence of human cases (218 cases reported 1948-1996)
- Proposed trophic cascade model - Increased precipitation enhances small mammal food resource productivity, which leads to increases in host populations and plague risk.
- Human case numbers did not correlate well with El Nino-Southern Oscillation Index

NDVI Changes Around Two Arizona Case Sites (Onset May 1994)

Note:

- **"Green" peak in Spring 1993 (1993 hantavirus outbreak)**
- **Prolonged "greenness" in summer 1992 and 1993**
- **Prolonged favorable conditions for rodents and fleas**
- **"Brown-down" in summer 1994**
- **Hot, dry conditions bring epizootics to a halt (summer 1994)**



Shared Risk for Plague and HPS in Four Corners Region (Eisen et al. 2007b)
- Precipitation and Plague -

- Identified environmental predictors for plague and HPS in Four Corners region
- Plague predictors were
  - Distance to pinon-juniper ecotones
  - Amount of precipitation
- HPS predictors were
  - Elevation
  - Amount of precipitation
- Logistic regression models accurately identified case locations as suitable for
  - Plague (93%) and
  - HPS (96%)
- Half of coverage area suitable for plague or HPS
- Suitability of site for plague highly correlated with its suitability for HPS (ρ_s = 0.88)
- Amount of precipitation important for both diseases

Am. J. Trop. Med. Hyg., 77(6), 2007, pp. 999-1004

A Spatial Model of Shared Risk for Plague and Hantavirus Pulmonary Syndrome in the Southwestern United States

Rebecca J. Eisen,* Gregory E. Glass, Lars Eisen, James Cheek, Russell E. Enscore, Paul Ettestad, and Kenneth L. Gage

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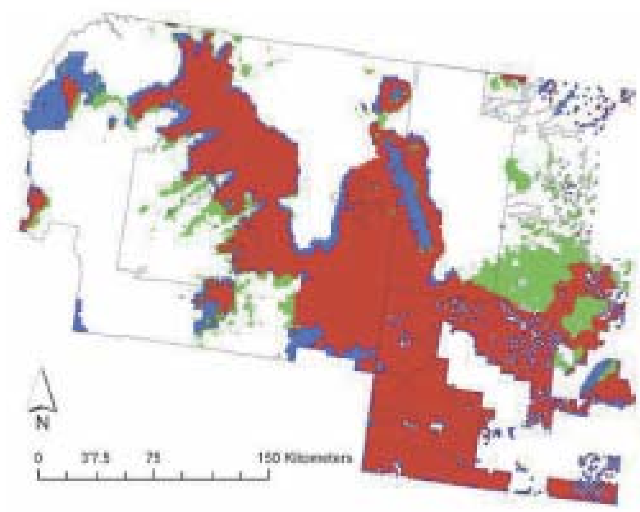
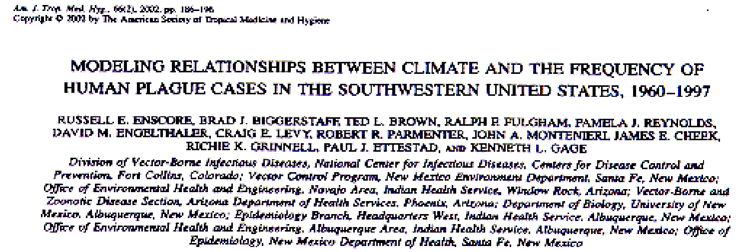


Plague and HPS Risk
HPS Risk
Plague Risk

Impact of Late Winter Precipitation and Threshold Temperatures on Human Plague in the Four Corners Region (Enscore et al. 2002)


Am. J. Trop. Med. Hyg., 66(2), 2002, pp. 186–196

MODELING RELATIONSHIPS BETWEEN CLIMATE AND THE FREQUENCY OF HUMAN PLAGUE CASES IN THE SOUTHWESTERN UNITED STATES, 1960–1997

RUSSELL E. ENSCORE, BRAD J. BIGGERSTAFF, TED L. BROWN, RALPH F. FULGHAM, PAMELA J. REYNOLDS, DAVID M. ENGELTHALER, CRAIG E. LEVY, ROBERT R. PARMENTER, JOHN A. MONTENIERI, JAMES E. CHEEK, RICHIE K. GRINNELL, PAUL J. ETTESTAD, AND KENNETH L. GAGE

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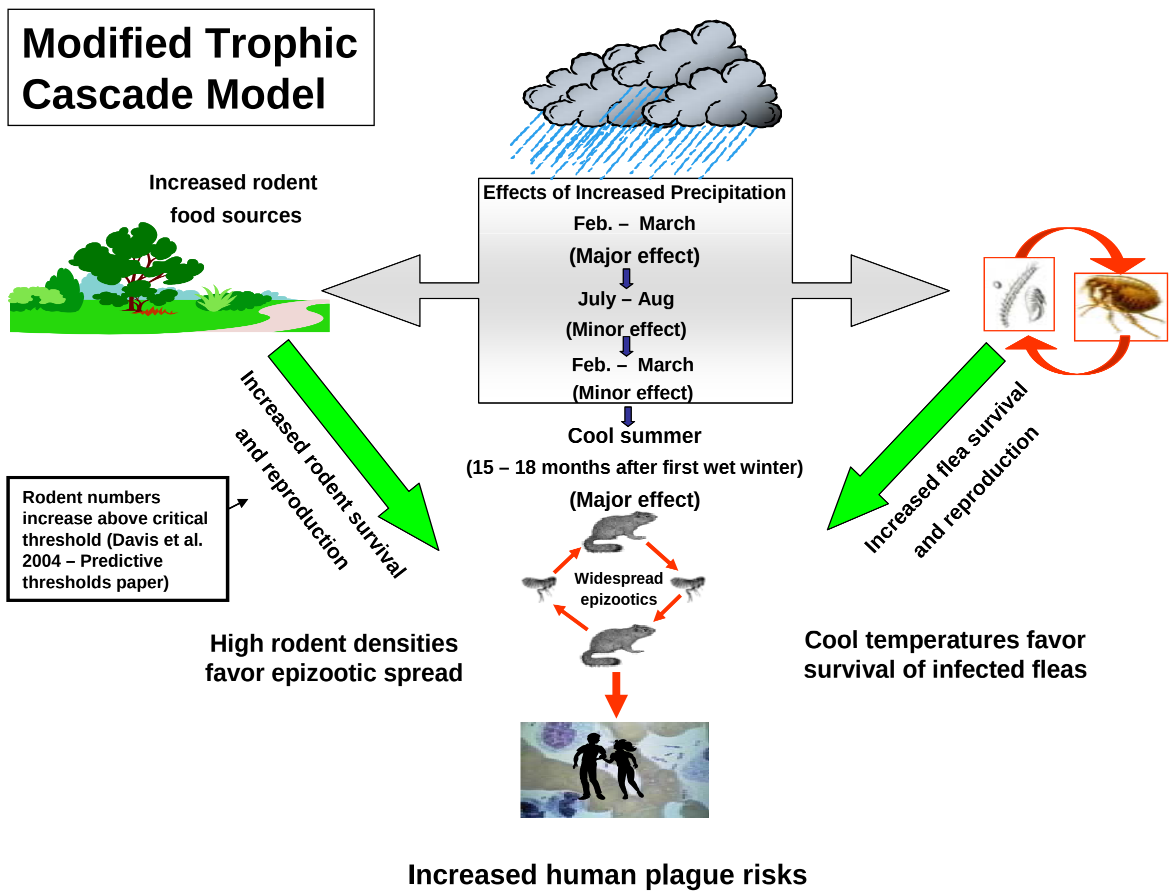

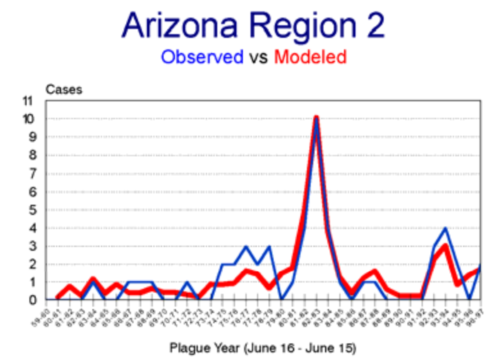

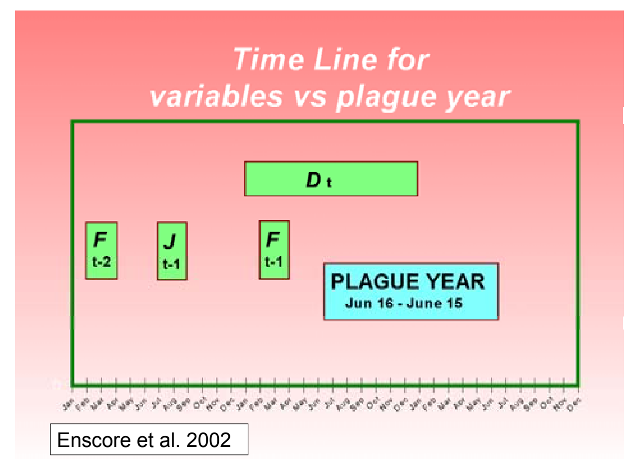

Similar results observed for plague in prairie dogs in Montana (Collinge et al. 2005)

Regional and Local Climate Influences
Ben Ari et al. (2008)

- Enscore et al. 2002 model worked well only regionally
- Parmenter et al. 1999 did not see correlation with El Nino-Southern Oscillation Index but only with local winter-spring precipitation
- Ben Ari et al. (2008) analyzed 56 year time series of human cases
- Variability in human plague activity across western U.S. could be explained largely by interactions between
  - Previous plague levels
  - Above normal temperatures
  - Pacific Decadal Oscillation
- Warmer and wetter climate led to increased human cases

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Human plague in the USA: the importance of regional and local climate

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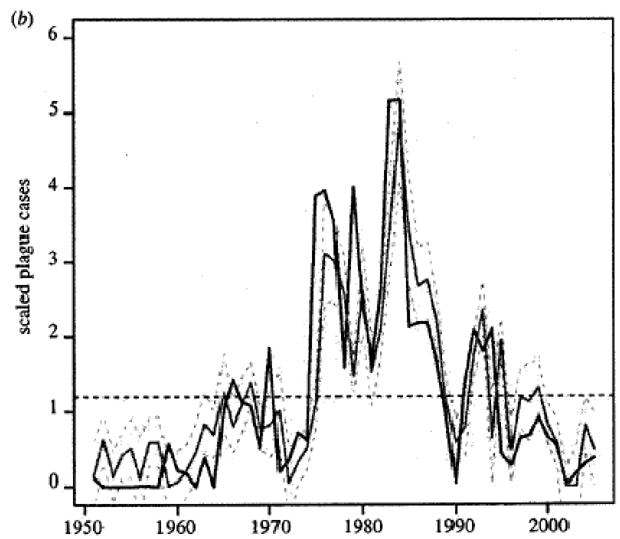
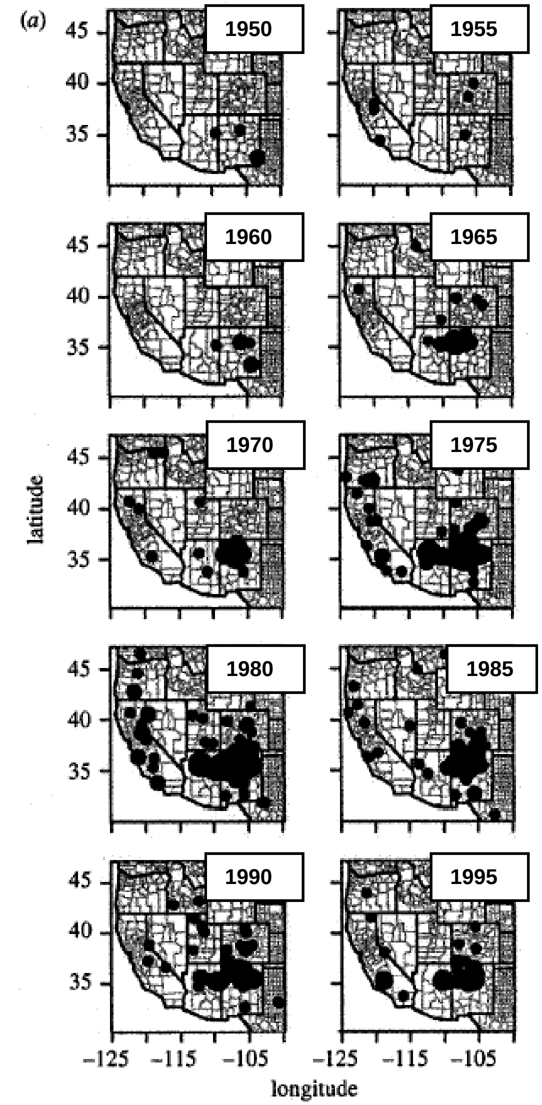
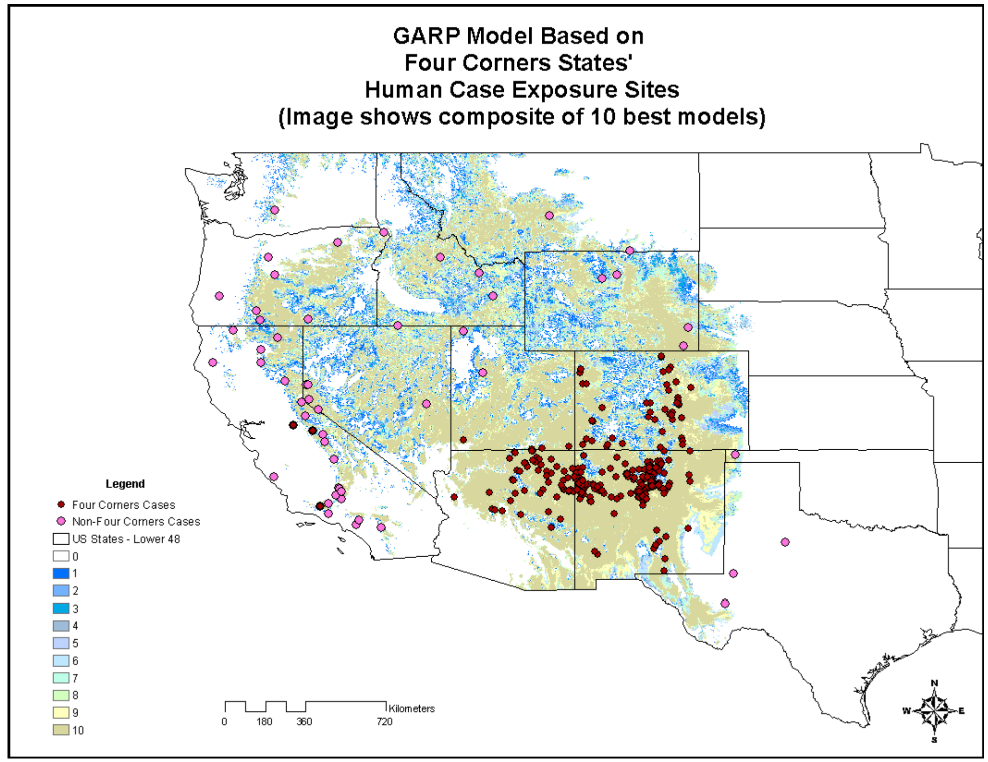


Black solid line – Observed plague
Black dashed line – Mean plague value
Grey solid line – Predicted plague
Grey dashed lines – 95% Confidence intervals



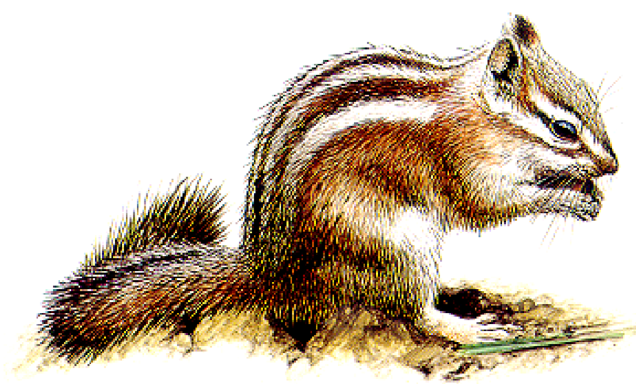
Plague and Climate Change

- Nakazawa et al. (in press, VBZD) evaluated spatial patterns of plague transmission using four different general circulation models of project climate change
- Concluded that some shifting of transmission sites would occur but changes will be subtle with general northward movement of areas of high transmission



Plague and Climate
-Summary-

- Annual and seasonal variations in precipitation and temperature affect rodent and flea population dynamics
- High rodent and flea densities will increase the likelihood of epizootics
- Epizootics increase the risk of human cases
- Human cases and epizootics can be expected to increase following
  - Increased rainfall during critical periods (periods might vary from region to region)
  - Moderate to cool summers
- Large scale and local climatic factors affect human plague occurrence (for example, PDO and local precipitation)
- Ecological and human behavioral factors both contribute to level of human plague risk (80 percent of U.S. cases are peridomestic)
- Likely effects of climate change might include slight northward shift of foci or shifts to higher altitudes
- Could plague shift to major metropolitan area? (Denver, Los Angeles as examples)
- Effects of climate only one of many changing factors in U.S. plague foci (human behaviors, cultural factors, land usage, urbanization, etc.)



Climate Change and Vector-Borne or Zoonotic Diseases

Source: Gubler et al. 2001

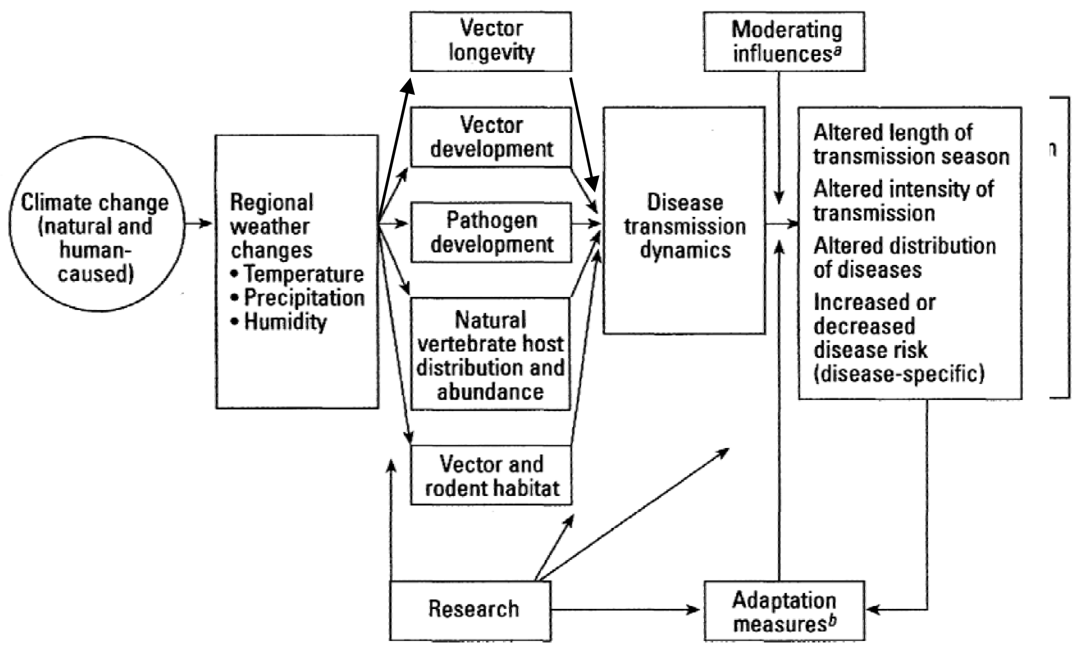


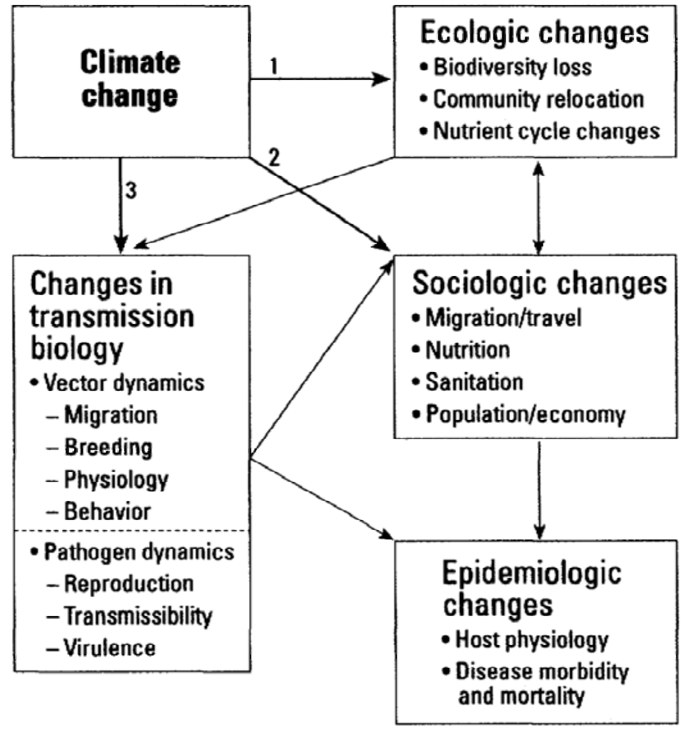
Figure 1. Potential vector- and rodent-borne diseases. [a]Moderating influences include nonclimate factors that affect climate-related health outcomes, such as standards of living, access to health care, international travel, and public health infrastructure. [b]Adaptation measures include actions to reduce risks of adverse health outcomes, such as medical technology (e.g., vaccine development) or use of climate forecasts for early warning of favorable conditions for disease transmission.

Predicting the Effects of Climate Change on Vector-Borne or Zoonotic Diseases

- Incomplete knowledge and few long-term studies
- Ecological cycles are complex and vary between regions
- Many confounding factors of human origin
  - landuse patterns
  - agricultural and industrial development
  - water management
  - cultural and behavioral factors, etc.

- Many global changes appear to be occurring (Sutherst 2004 and others)
  - Climate
  - Atmospheric composition
  - Urbanization
  - Land use, landcover, and biodiversity
  - Trade and travel
  - Civil unrest and unstable governments
  - Other factors

- Global climate change likely to present emerging disease threats



Assessing effects of climate change on vector-borne diseases

Source: Data from Chan et al. 1999; Figure in Gubler et al. 2001

Responding to Possible Climate Change

- Long-term ecological and epidemiological research on how environmental changes influence disease cycles
- Enhanced surveillance
  - Appearance of human cases in previously disease-free areas
  - Introduction of new vectors, hosts, or pathogens
  - Changing transmission patterns in existing foci
- Strengthen public health infrastructure to improve recognition and response
- Identify potentially vulnerable populations
- Maintain awareness of other changes that could interact with climate changes to result in emerging disease risks
- Measures to reduce the spread of disease or disease vectors and hosts
- Review, evaluate and prepare countermeasures (vaccines, therapeutic agents, insecticides, etc.)