Modelling the impacts of climate and land use change on the emission and transport of wheat rust spores

Marje Prank, Shawn C. Kenaley, Gary C. Bergstrom, Natalie M. Mahowald

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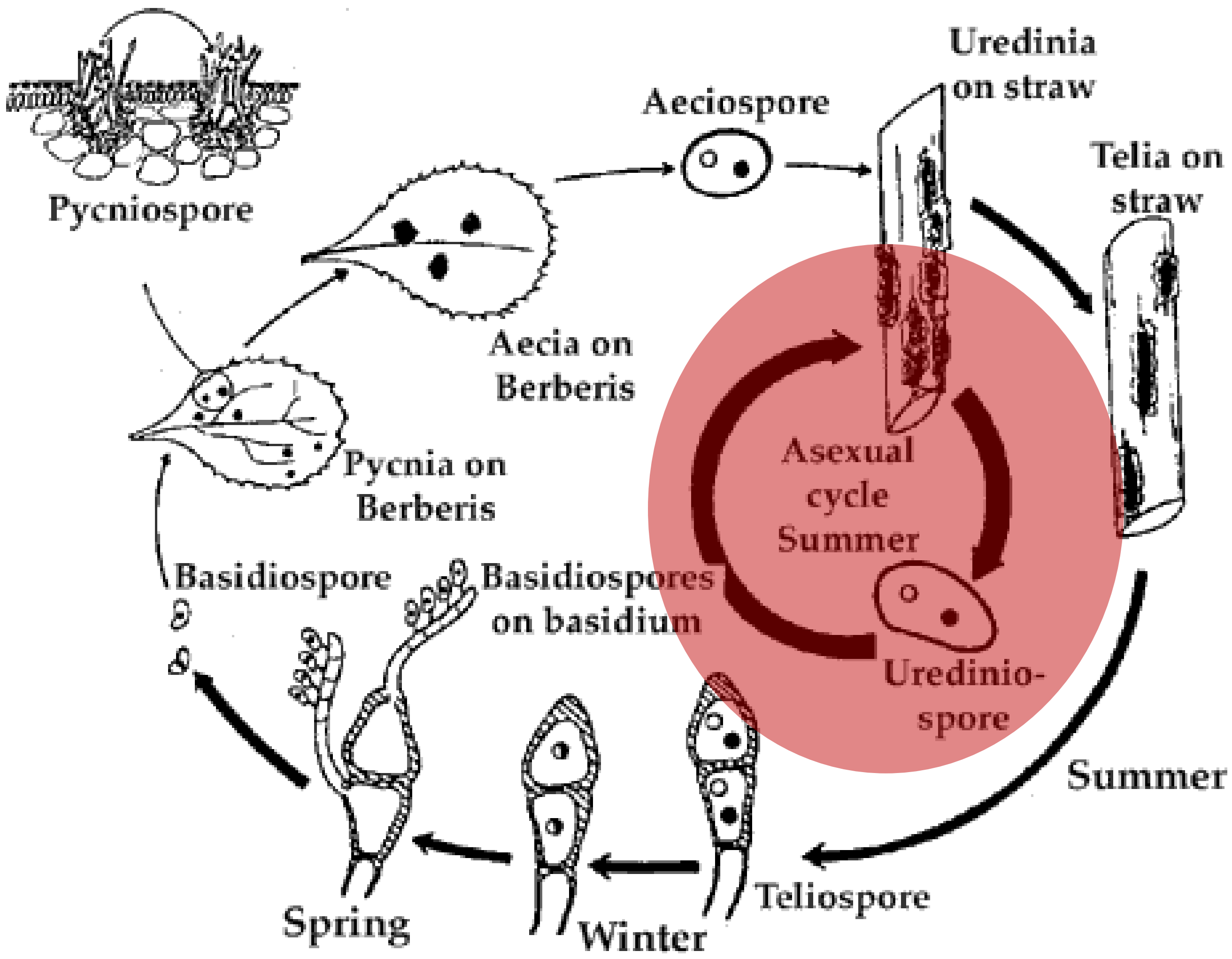
- Phytopathogenic microbes with explosive epidemic potential represent a major threat to agriculture, food security and sustainability
- Recent rise of hypervirulent races such as Ug99 of the **wheat stem rust fungus** (*Puccinia graminis* f. sp. *tritici*)
- Severe yield losses (50 to 70% over large areas, up to 100% on isolated fields) for susceptible wheat varieties

Life Cycle of *Puccina graminis*



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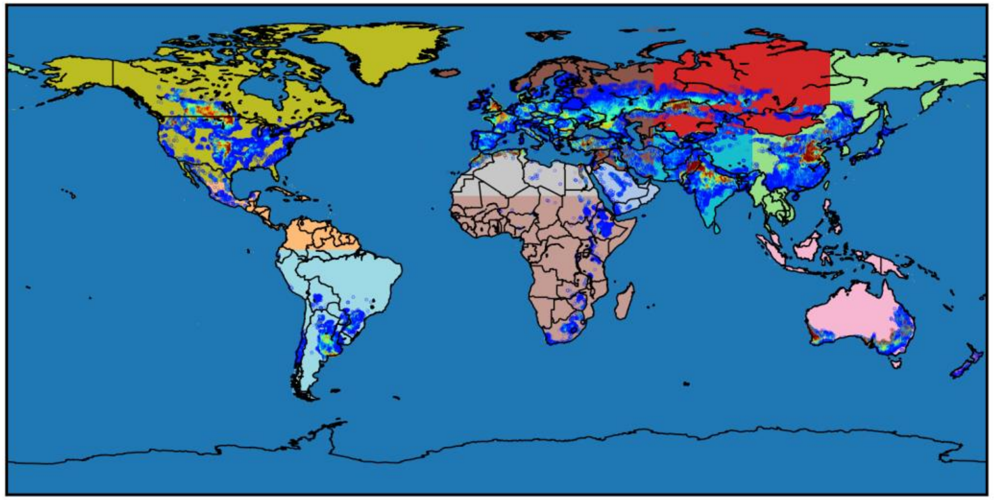
- Asexual repeating cycle
  - ~14 days in optimal conditions
  - In optimal temperature (~30 ℃) one uredinium produces 10 000 spores per day for 2-3 weeks
  - Up to ~1e6 urediniums/m2
    - Roughly estimated from 5% severity being ~50 pustules per tiller
  - Spores can be transported long distances (size ~20 micrometers)
  - Sensitive to UV and temperature
  - Require suitable temperatures, liquid water on leaves for 6 hours followed by >10000 Lux light intensity to germinate

Modelling with CESM 1.2.2

- Monthly wheat area from MIRCA 2000
  - Spring and winter wheat
- Emission flux from infected fields
- Tracers added to CAM5 for viable and dead spores or spore age
- Germination probability
- Infection development and spread

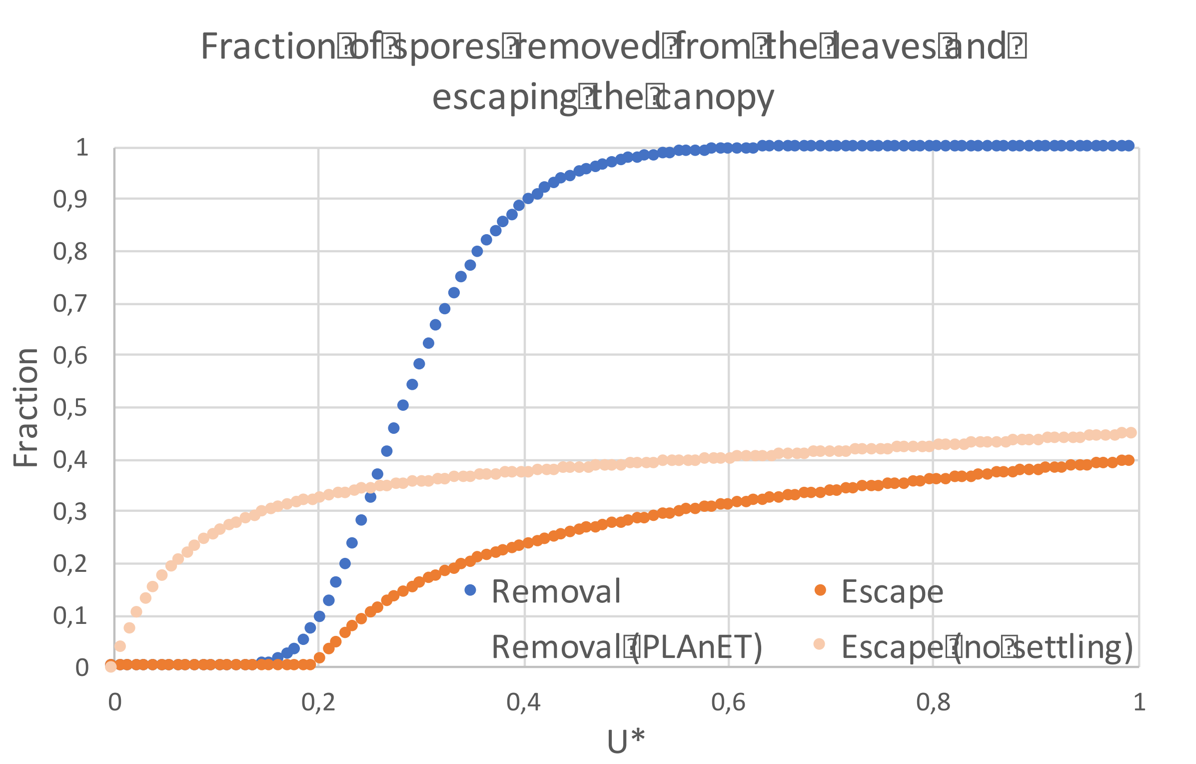
- Source-receptor relationships
  - Constant 20% infection severity on all wheat fields
  - 12 source/receptor regions
  - CESM simulations for 1850, 2000, 2100 (RCP8.5) + forced with MERRA2 reanalysis

MIRCA 2000 max wheat area %



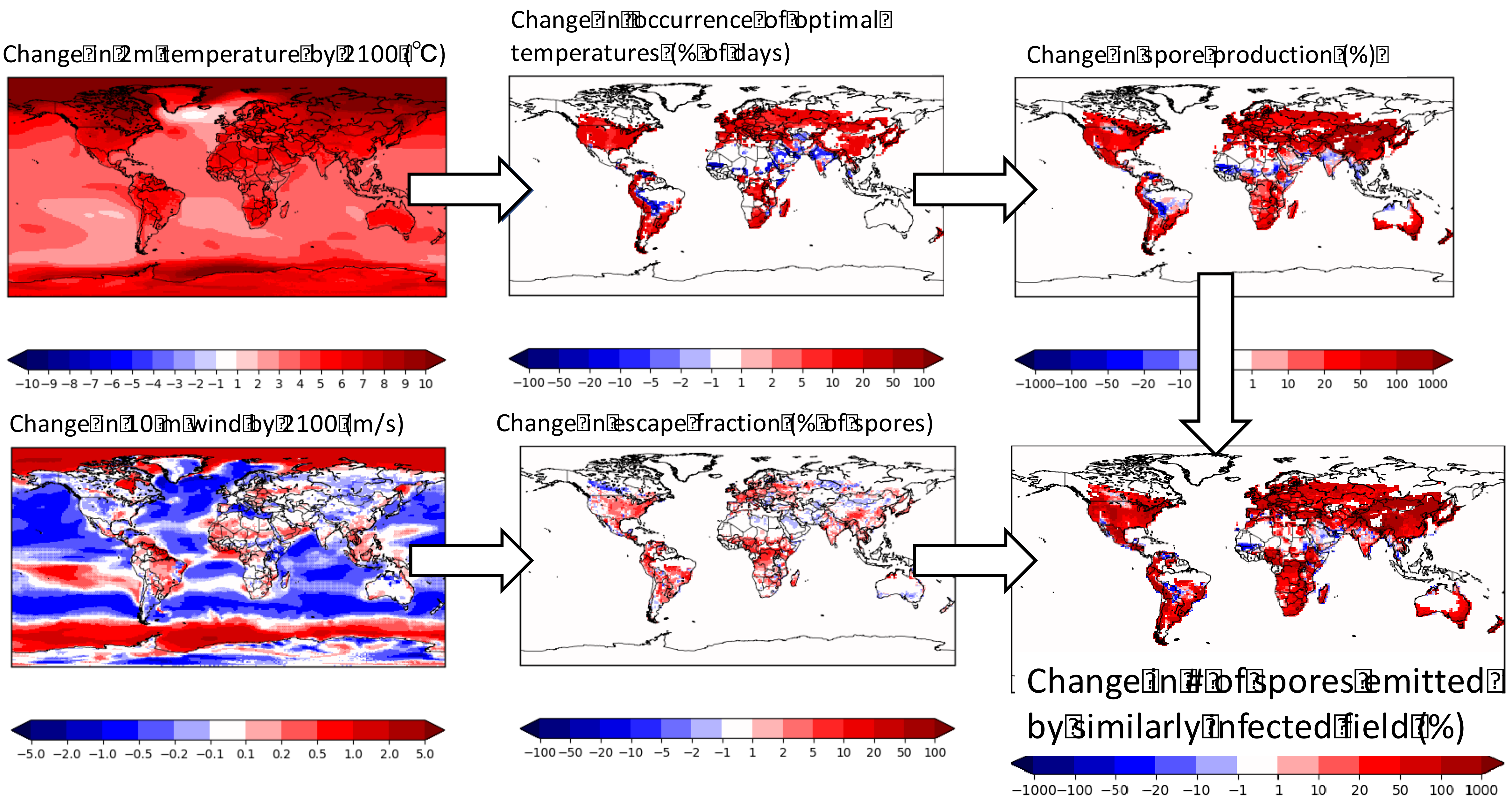
Spore emission

- Removal of spores from leaf surface (u_*, RH)
- Resistance analogy for local deposition and upwards flux



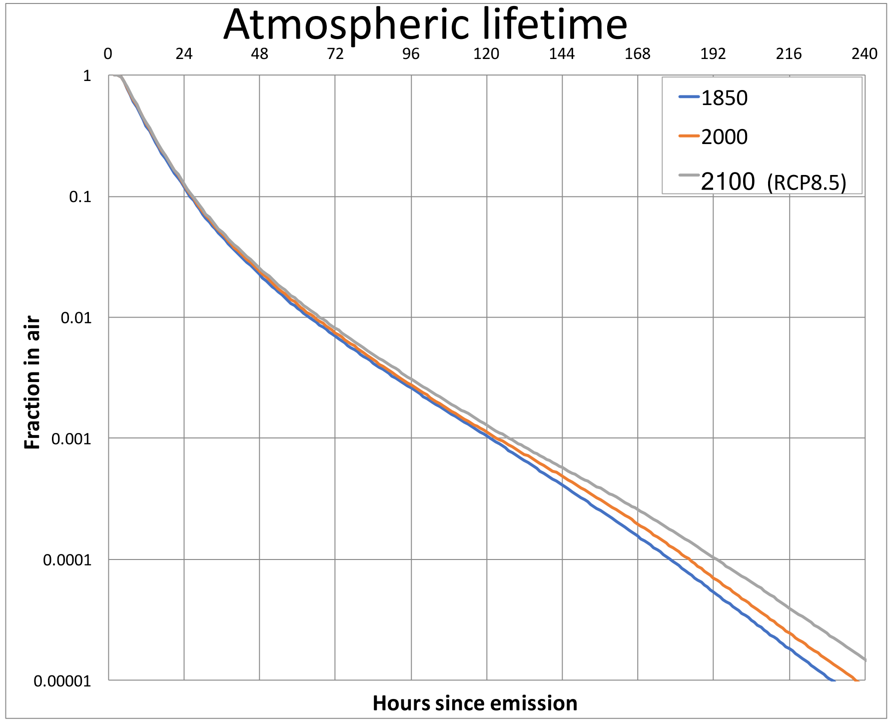
- It is often claimed that a very small fraction of spores escape the crop canopy (up to a few %)
- Annual average escape fraction of all wheat containing grid cells 1.6%
- Due to correlation between removal and escape, 17% of all produced spores escape
- Aylor & Ferrandino (1988) evaluated escape fraction 2 m downwind a line source of spores (d=32 um)
  - 22-57% and 56-64% for spores released at 0.4 m and 0.7 m height in wheat canopy
  - U* 0.3-0.5

Impact of climate change on spore emission



Intercontinental transport

- Frequent spore exchange between Africa, Asia and Europe
- Rare transport events across oceans
- Slightly longer atmospheric lifetimes in warmer climate

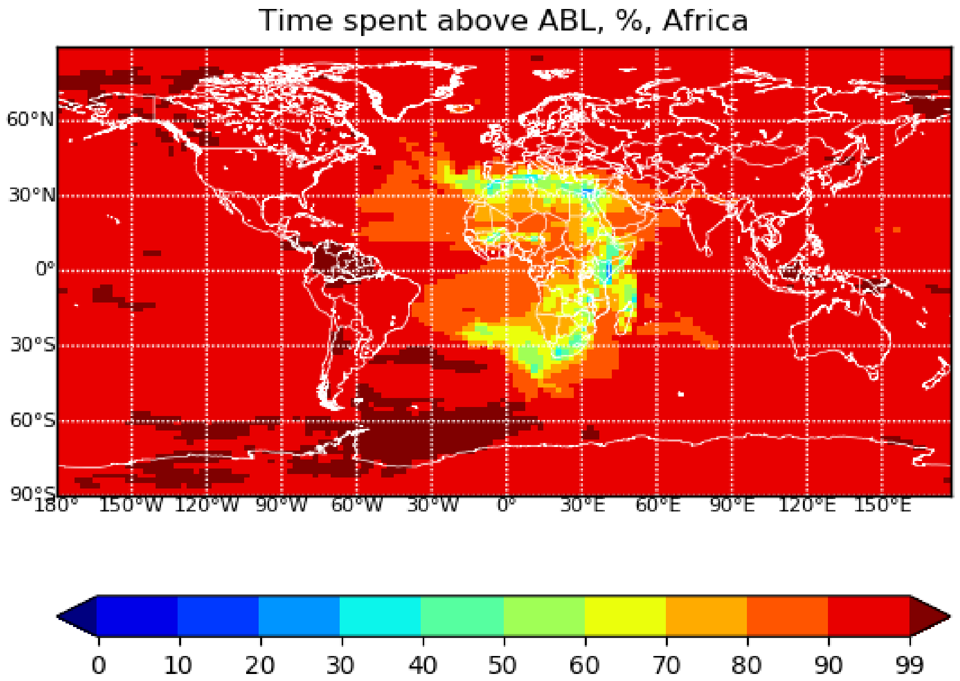


Receptor / Source	Africa	Asia	Europe	North America	South America	Oceania	Antarctica	Ocean
Africa	5.5E-01	1.2E-02	2.6E-02	8.0E-08	3.3E-07	1.5E-06	6.6E-09	4.1E-01
Asia	3.3E-04	8.0E-01	1.3E-01	8.0E-07	1.0E-09	2.2E-09	2.2E-13	7.6E-02
Europe	5.3E-04	6.9E-02	8.4E-01	2.6E-07	1.2E-11	5.1E-13	1.2E-15	8.8E-02
North America	1.3E-05	1.8E-06	2.8E-05	9.8E-01	4.6E-08	4.0E-13	2.8E-14	2.4E-02
South America	2.4E-06	3.2E-09	1.1E-08	1.8E-07	8.8E-01	2.5E-08	4.0E-08	1.2E-01
Oceania	2.2E-10	1.1E-06	5.0E-15	1.2E-13	2.3E-07	8.3E-01	2.3E-08	1.7E-01

Blue – low values, red – high values

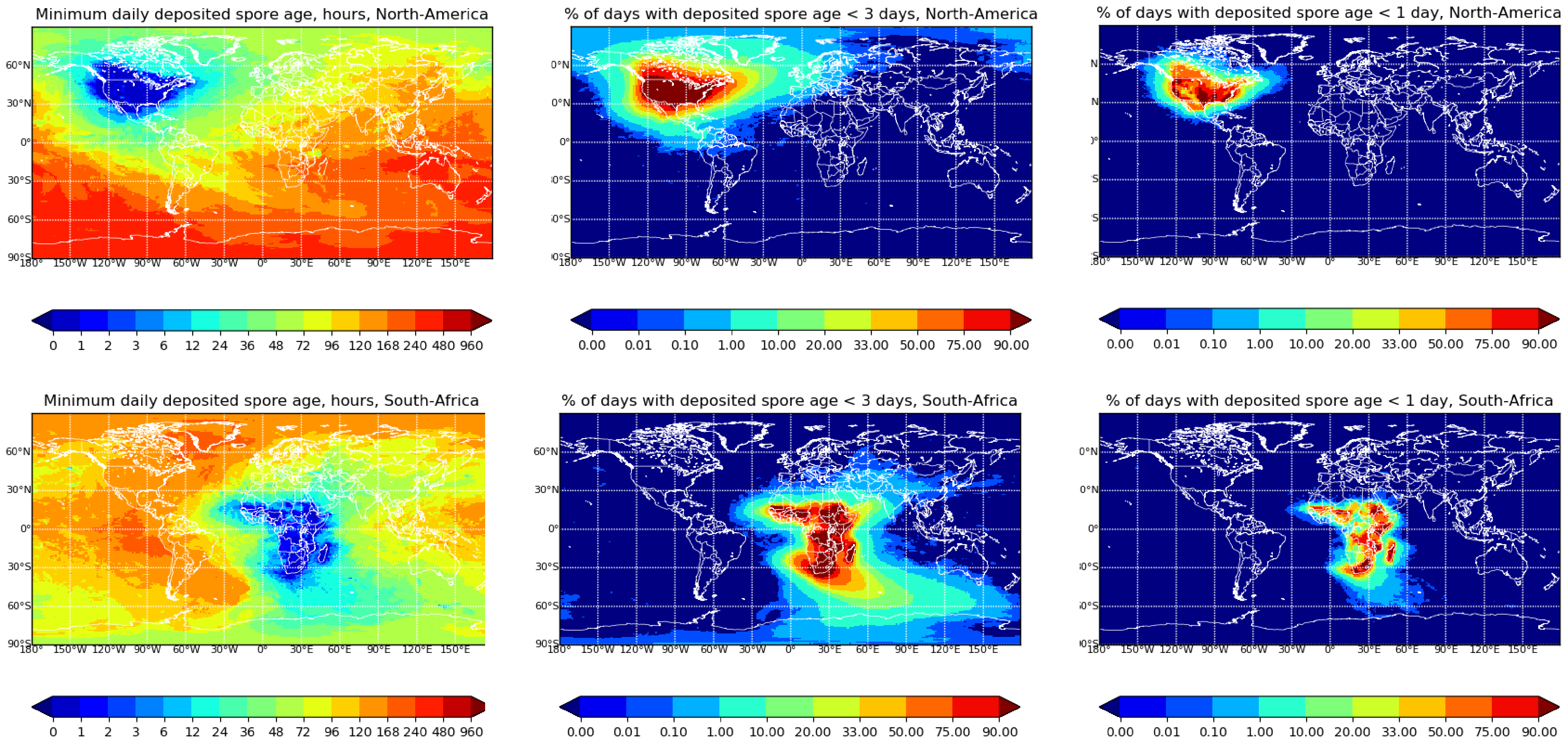
Spore viability during long range transport

- ~10% of spores germinate after 20 h of sunshine (Maddison and Manners, 1972), less than 0.1% after 35 hours
- Sensitivity higher at high relative humidity
- Germinability is not the same as infectivity
  - Infectivity 3-6 times more sensitive to UV
- Freezing kills in humid conditions

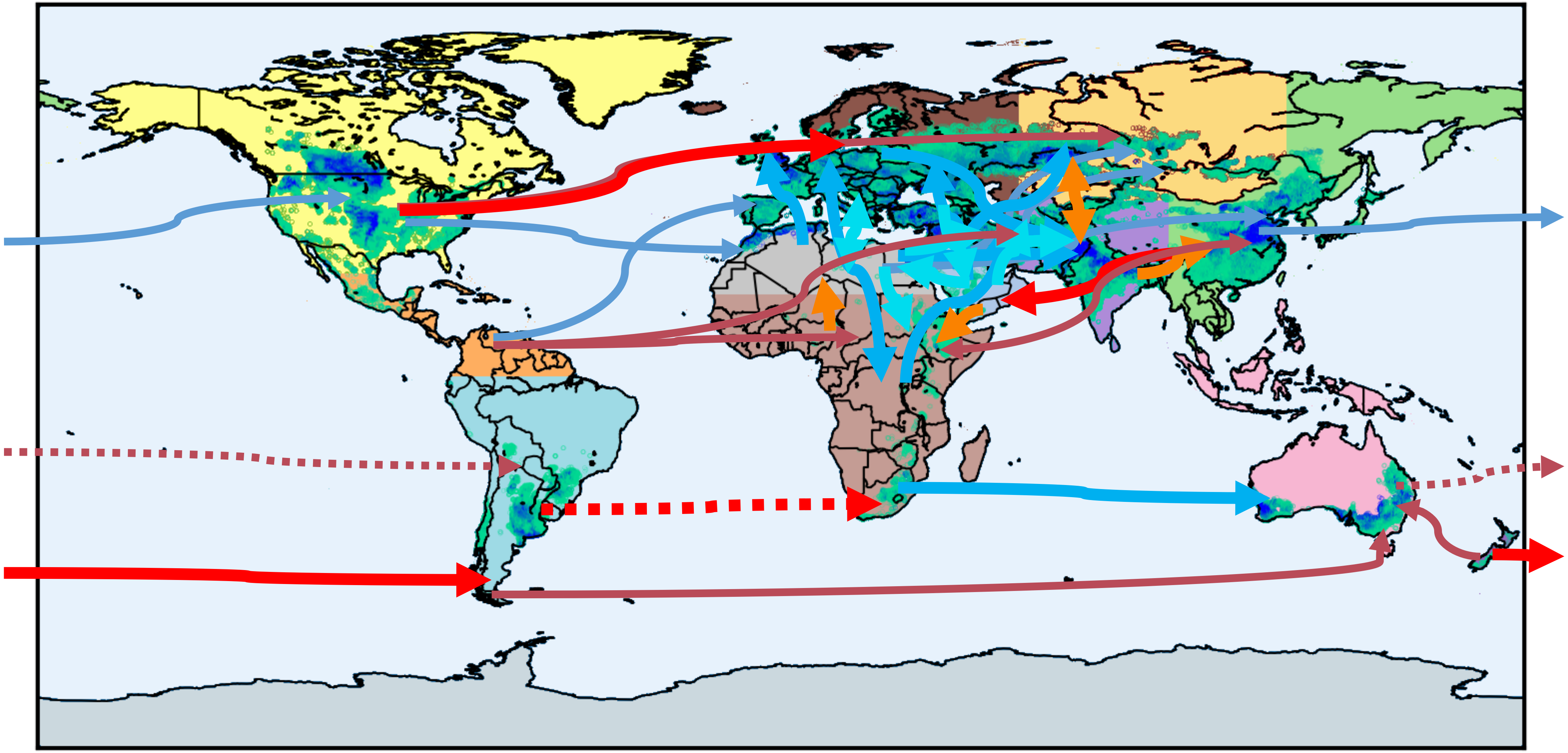


Long range transport happens above the boundary layer

Age of spores at deposition



Impact of climate change on spore transport

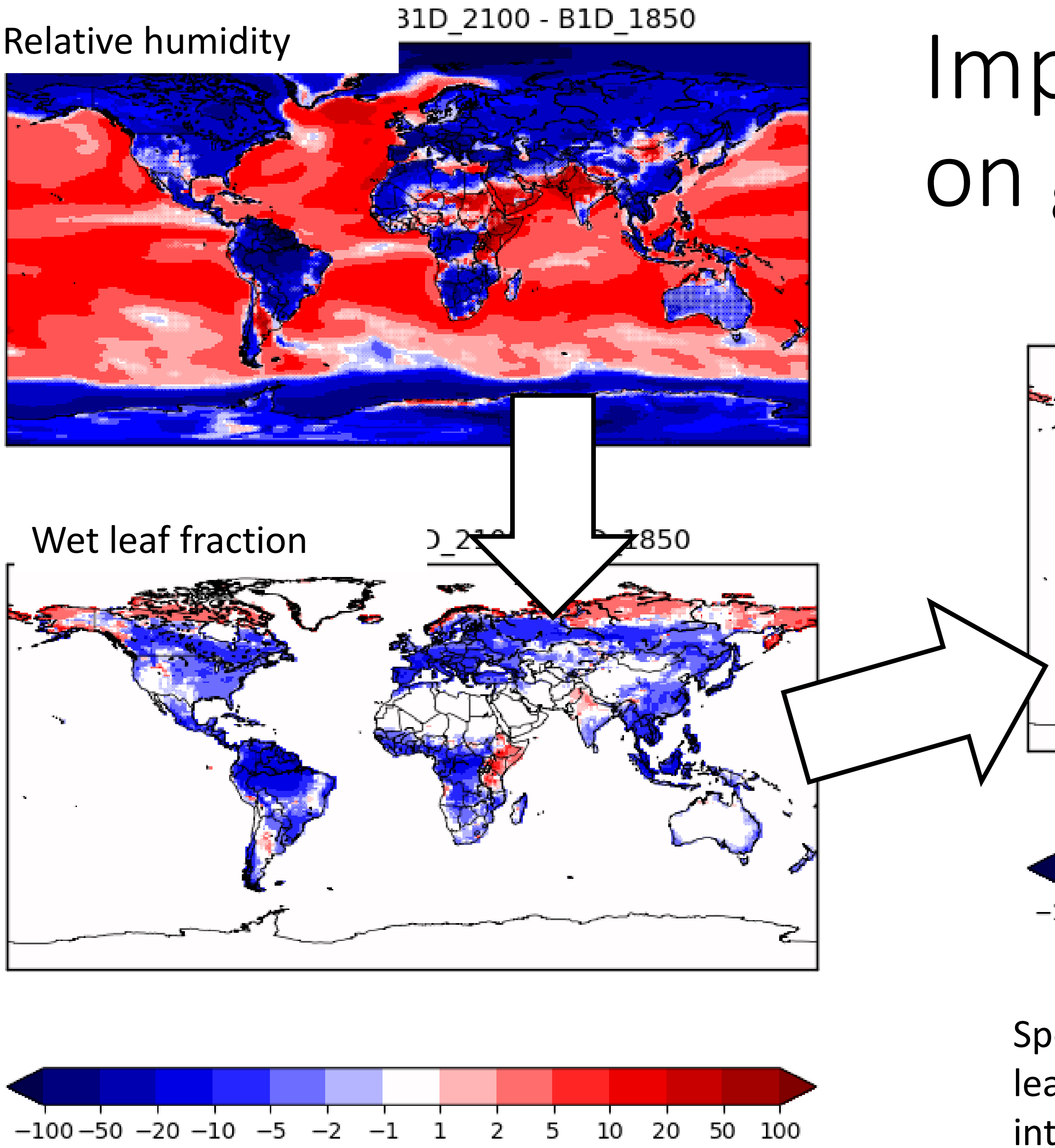


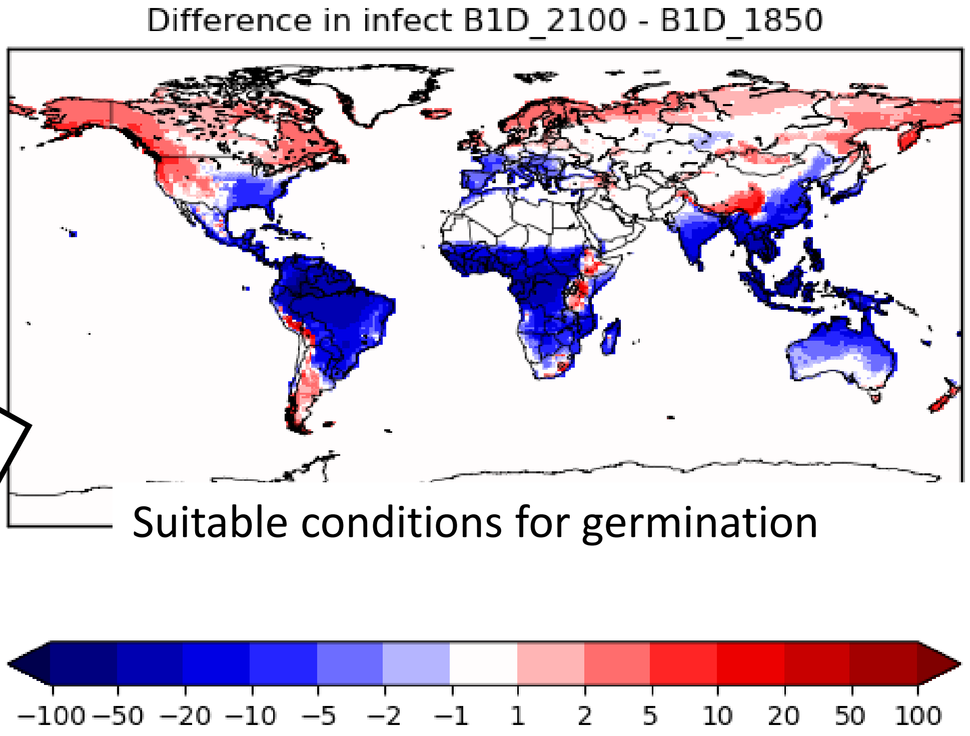
Changes in transport event frequency (fraction of days with deposition > 10 spore/ha). Arrows plotted for statistically significant changes of >5% of present value (FDR controlled at level 0.1).

significant change for future but not for the whole period

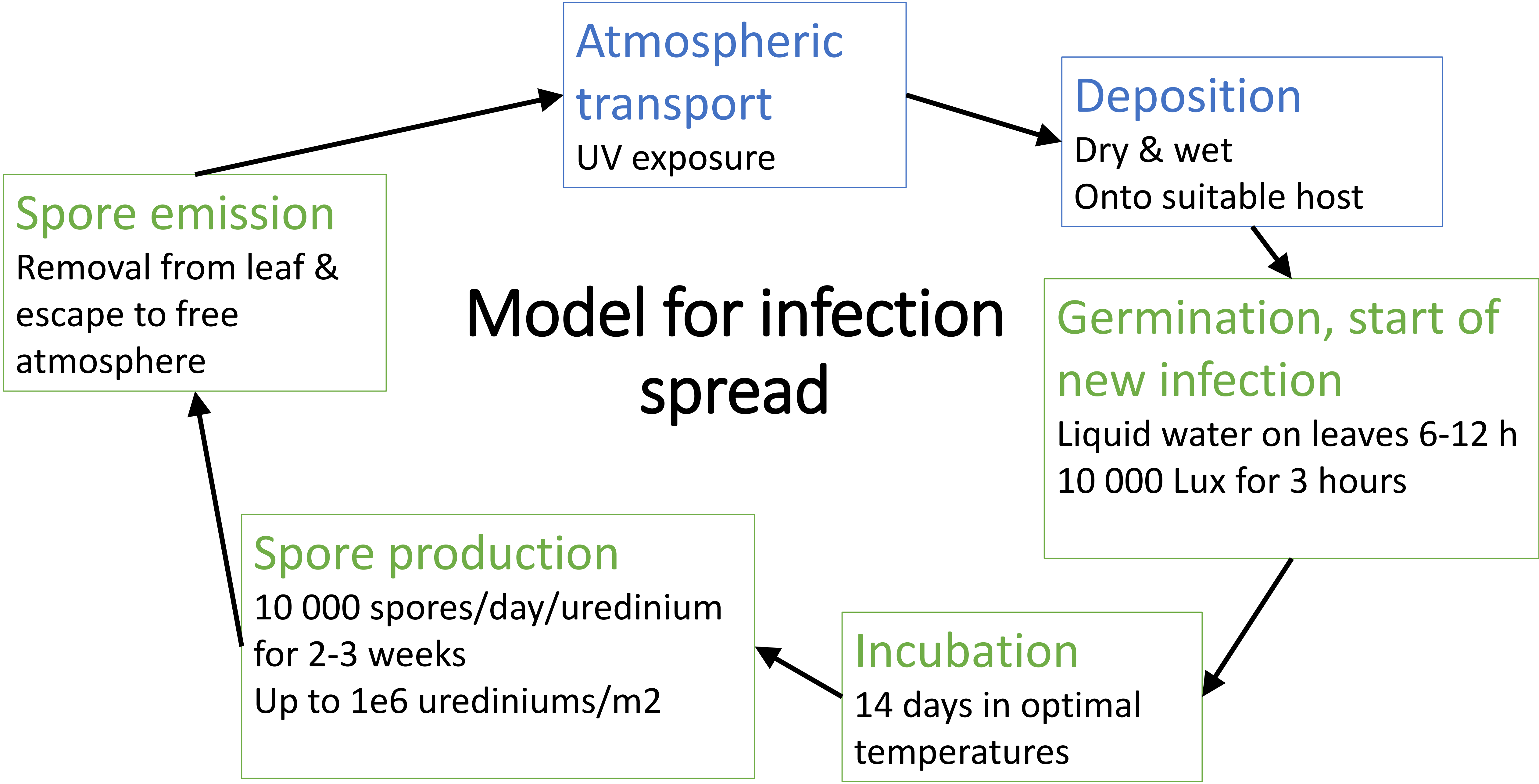
	Increase	Decrease
1 day		
3 days		
5 days		

Impact of climate change on germination probability





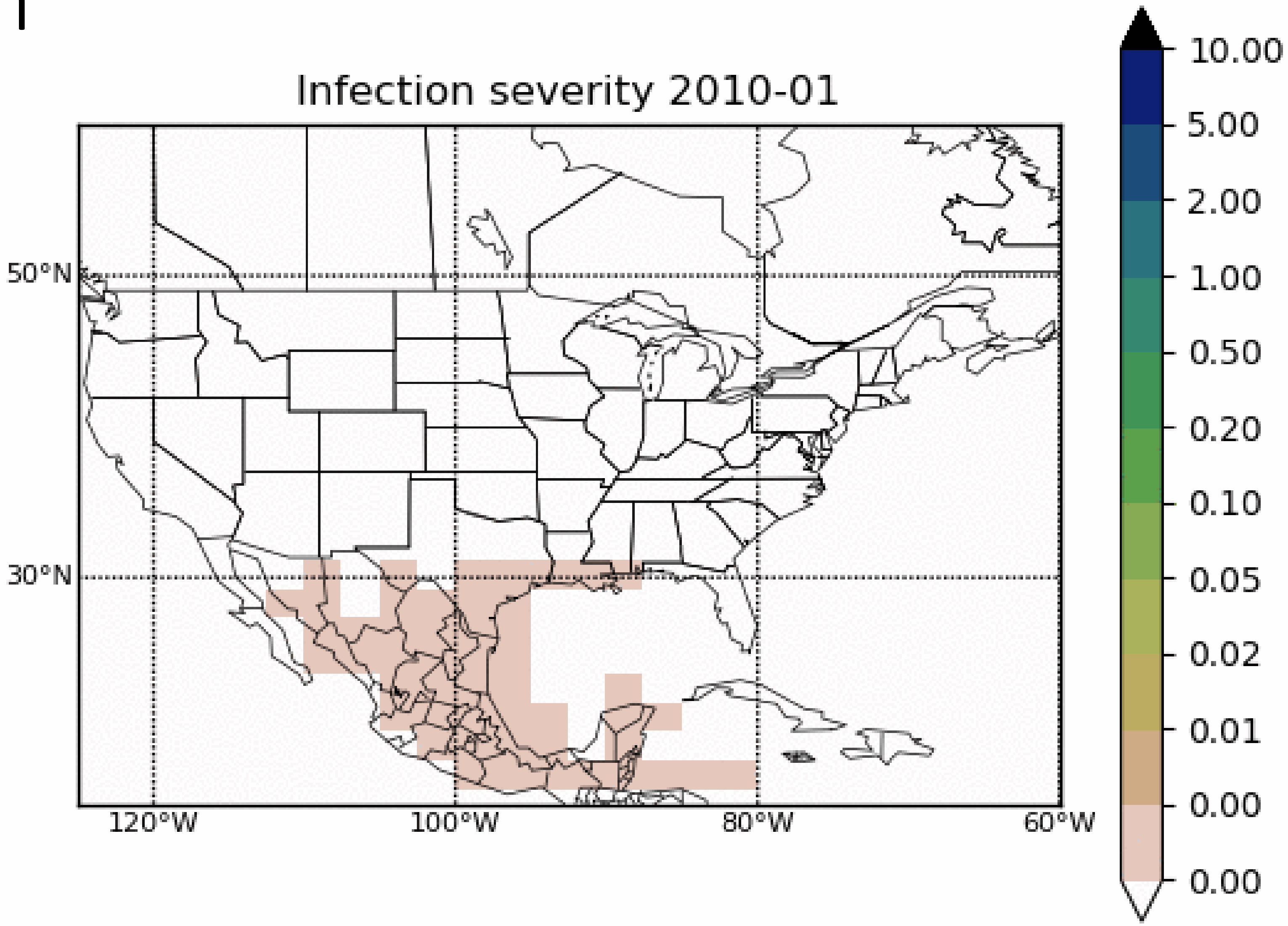
Spores require suitable temperatures, liquid water on leaves for at least 6 hours followed by >10000 Lux light intensity to germinate


Atmospheric transport
UV exposure
Deposition
Dry & wet
Onto suitable host
Germination, start of new infection
Liquid water on leaves 6-12 h
10 000 Lux for 3 hours
Incubation
14 days in optimal temperatures
Spore production
10 000 spores/day/uredinium
for 2-3 weeks
Up to 1e6 urediniums/m2
Spore emission
Removal from leaf &
escape to free atmosphere
Model for infection spread

Viable spore loss

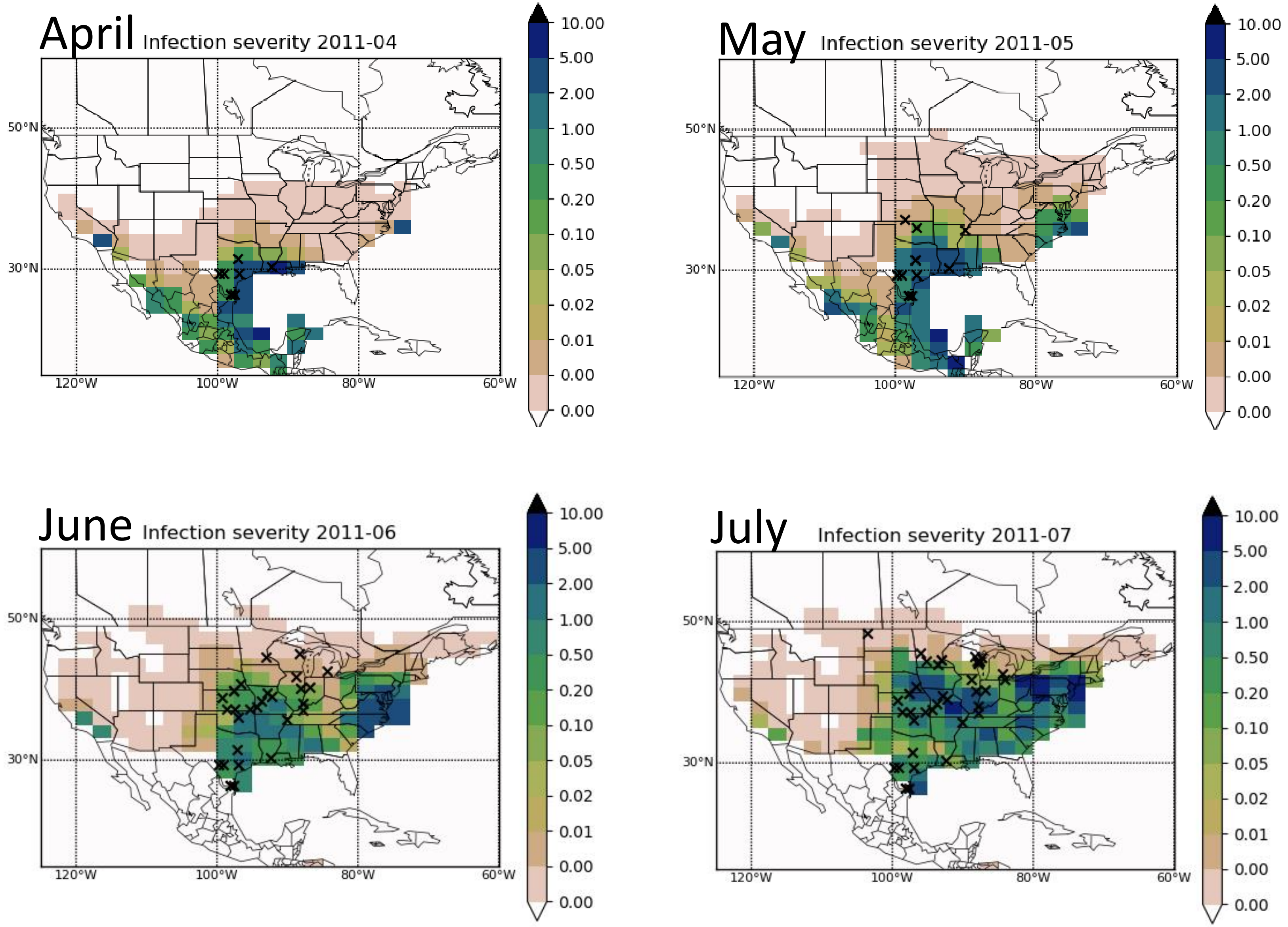
- UV acts on spores in air and also on fields
  - Half efficiency on field accounting for shadowing by leaves
- Rain
  - Spores washed off from plants with half atmospheric scavenging efficiency
- Frost kills
  - Incubating infection can survive in plants under thick snow cover
- Harvest
  - Ready spores emitted depending on humidity
- Spores that have started germinating can dry up before managing
- Spores deposited on a wheat field can fall on ground
  - LAI dependence currently missing

Evaluation



X – wheat stem rust seen on a field and reported to USDA

Evaluation

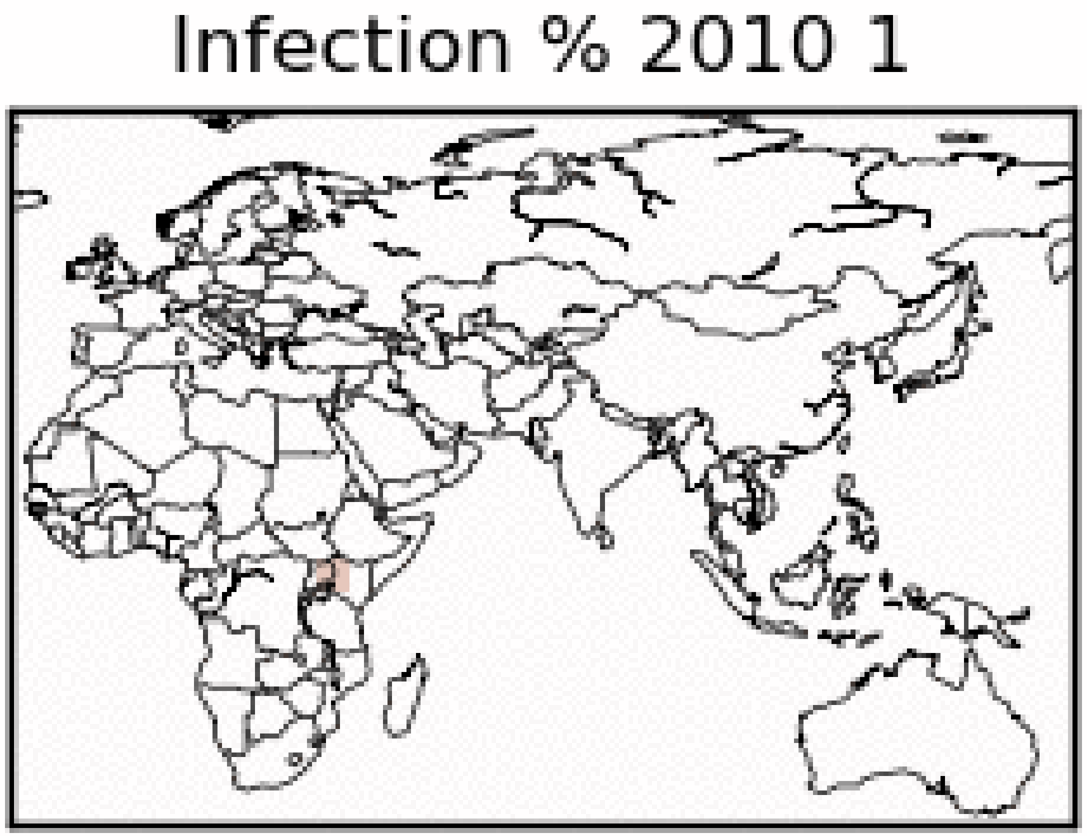


X – wheat stem rust seen on a field and reported to USDA

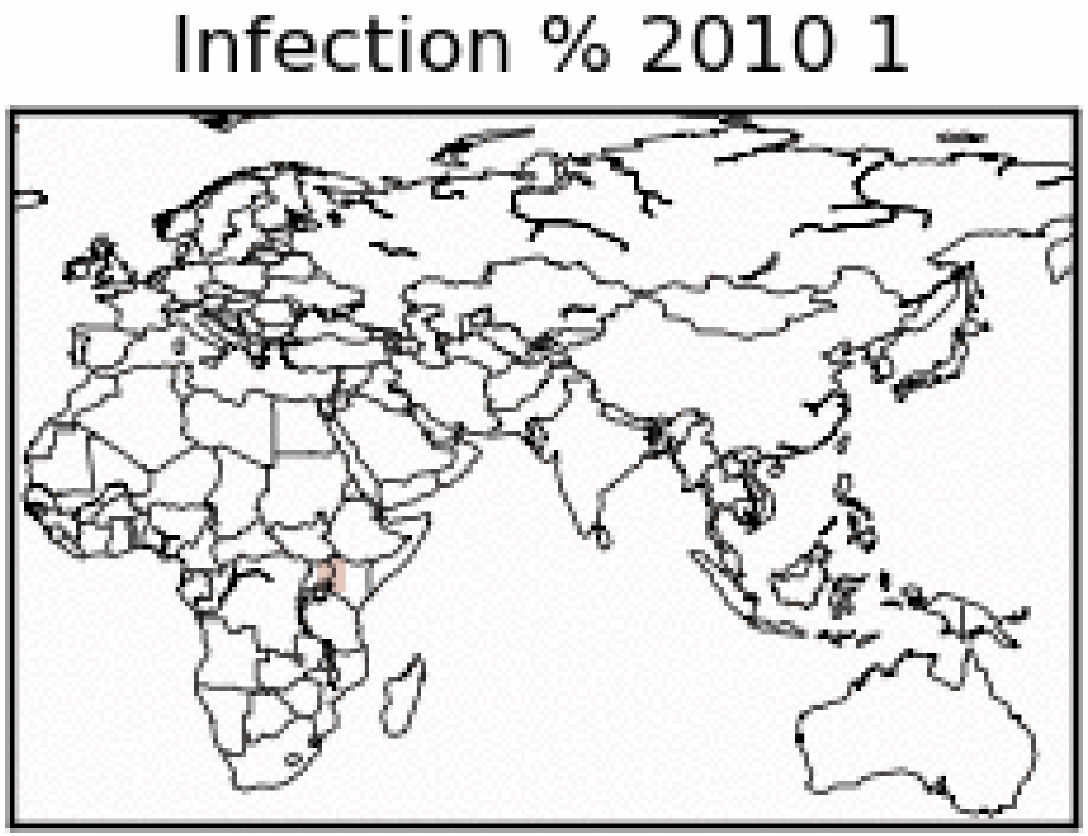
Impact of “green bridges”

- Growing both winter and spring wheat in the same area can form “green bridges” that allow the pathogen to overwinter
  - earlier initiation of epidemics in spring resulting in more severe disease
- Simulation of disease spread assuming maximum extent of wheat all year round

Impact of "green bridges"

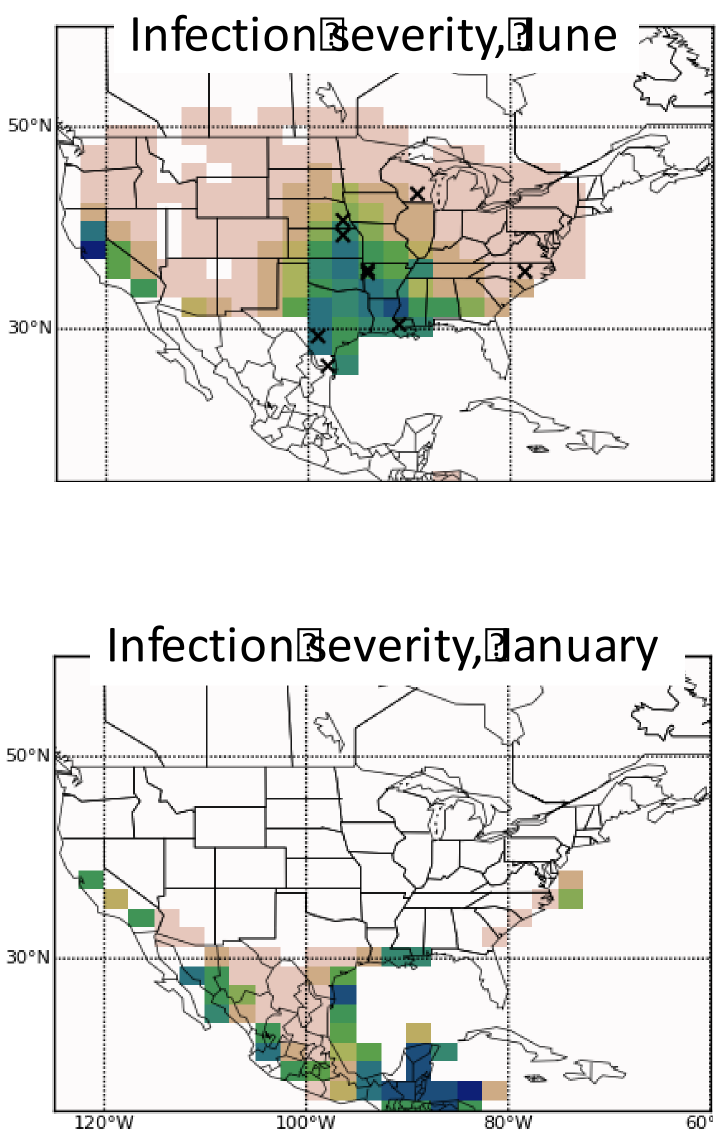


Monthly wheat area from MIRCA2000

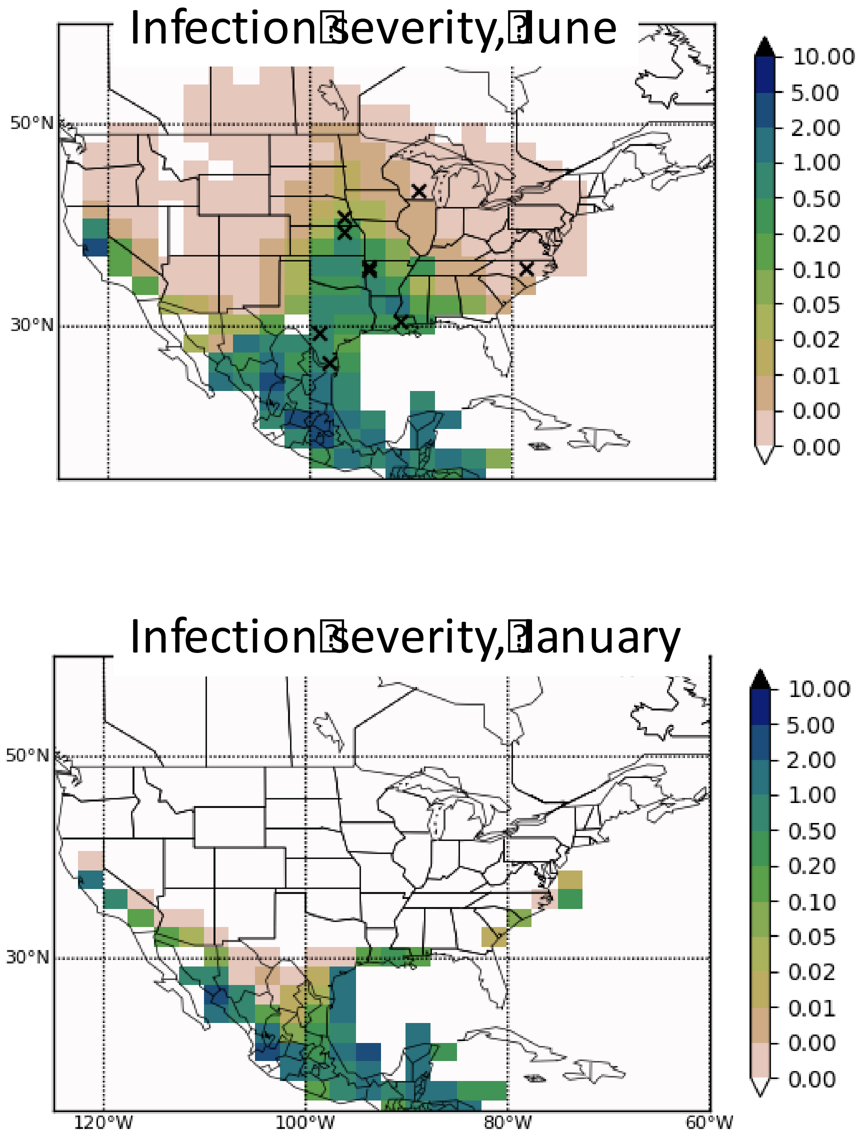


Maximum wheat area from MIRCA2000

Monthly wheat area from MIRCA2000



Maximum wheat area from MIRCA2000



Conclusions

- Warmer and dryer climate will lead to more spores being produced and larger fraction escaping to the free atmosphere
- Drier conditions reduce substantially the germination probability
- Slightly larger fraction of spores have longer atmospheric lifetimes and some changes in the source-receptor relationships are seen for warmer climate
- In North America the subfreezing temperatures keep the fungus from overwintering further than ~30 degrees north
- The spread eastwards from Sub-Saharan Africa is controlled by the different wheat growing seasons

Future work

- Evaluation of infection spread is challenging due to lack of observations
  - Existing observations:
    - Annual infection northwards spread in USA
    - Spread of Ug99
    - Frequent exchange between Australia and New Zealand, UK and Central Europe
- Missing processes
  - Host resistance
  - Fungicide use
  - Plant death
  - Irrigation
- Better integration with CLM
  - Land cover and crop distribution change
  - Changes in crop phenology, timing of sowing and harvest