Stochastic Modeling of Tropical Cyclone Track Data

Jonas Rumpf

Universität Ulm, Abteilung Stochastik

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Basic Concept

- Analyze historical cyclone tracks to extract important characteristics
- Create a stochastic model to simulate these characteristics

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Basic Concept

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- Create a stochastic model to simulate these characteristics
- Simulate a large number of synthetic storm tracks
- Estimate striking probabilities and possible damages from the synthetic storm tracks
- Not intended: weather forecasting

Available Data

- Historical cyclone track data from the western North Pacific
- Location and maximum wind speed of every known tropical cyclone from 1945–2004
- Recorded at intervals of 6 hours; compiled by Munich Reinsurance Company

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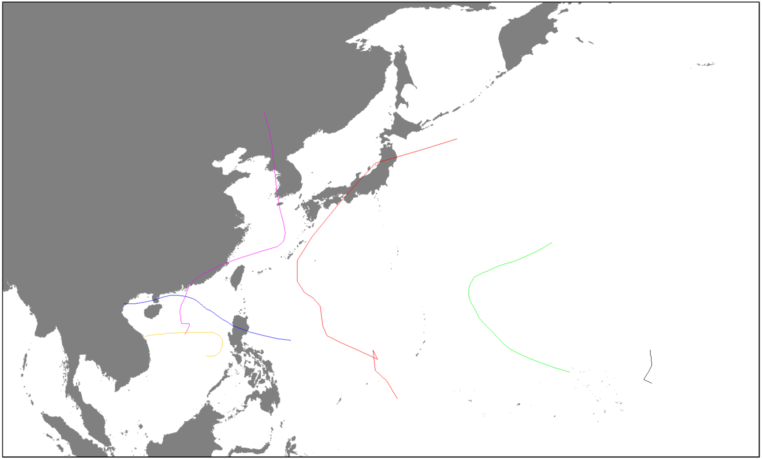
- Recorded at intervals of 6 hours; compiled by Munich Reinsurance Company
- Total: 1,519 storms; 37,377 locations

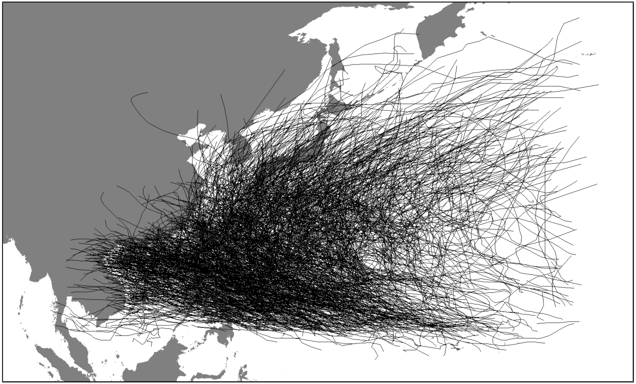
$\Rightarrow$ Cyclone tracks are given as polygonal trajectories

Example Tracks



All Tracks

Problem: Strong inhomogeneities in the data



Criteria for Classification

- Idea: Splitting the storms into more homogeneous classes

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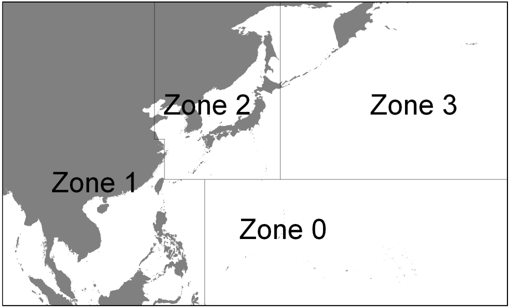
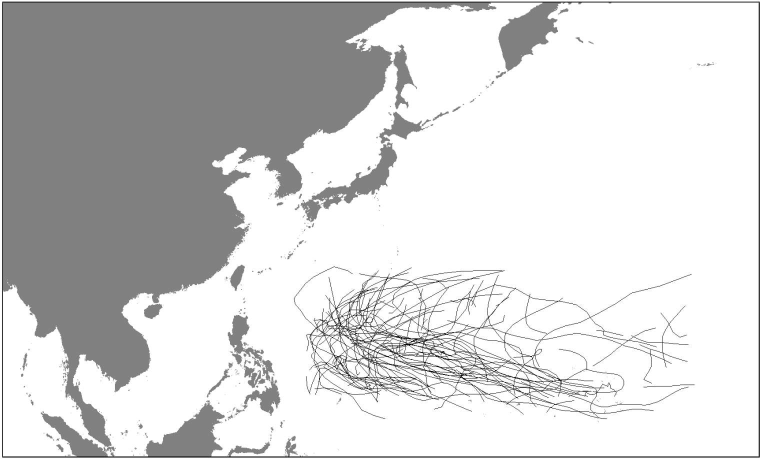
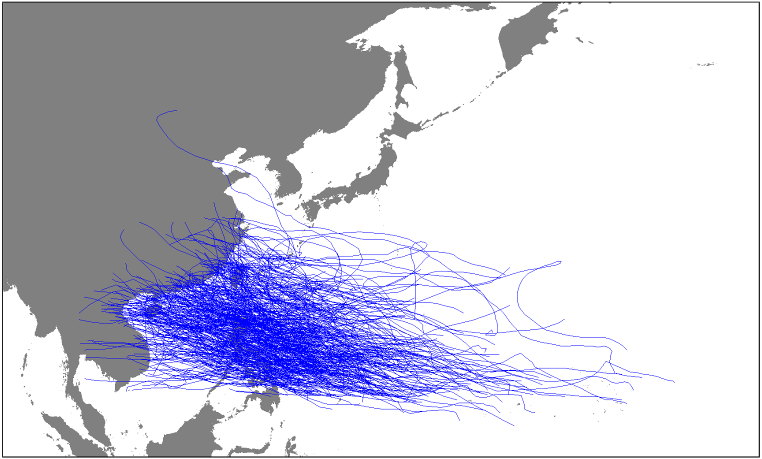
- Tracks are assigned to classes according to the areas of the observation window they move across



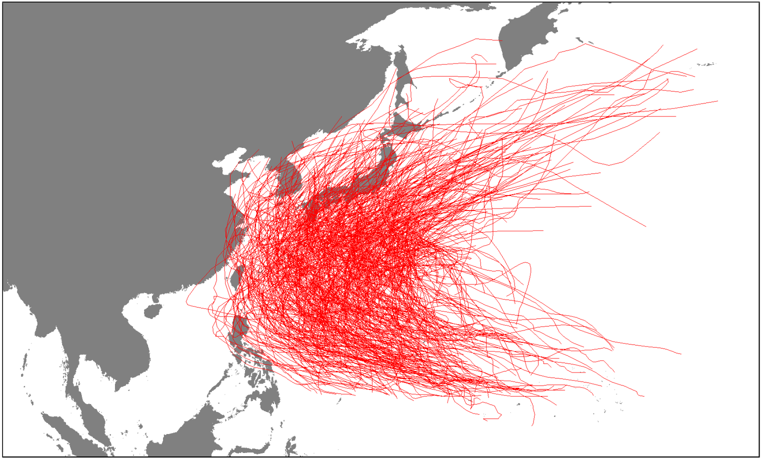
Storm Tracks, Class 0



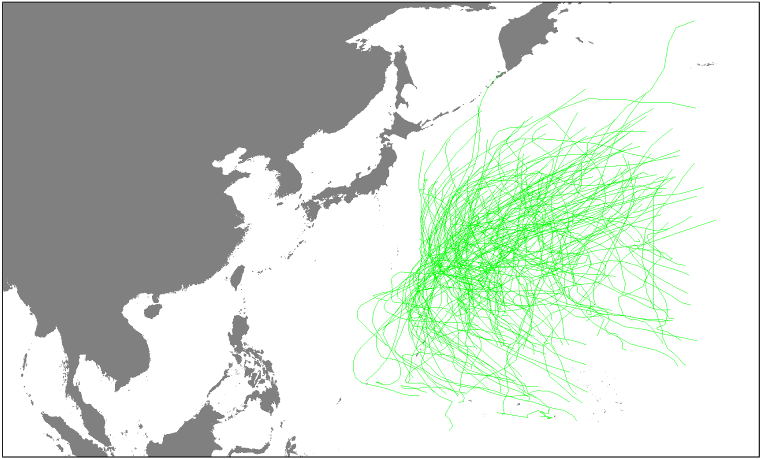
Storm Tracks, Class 1



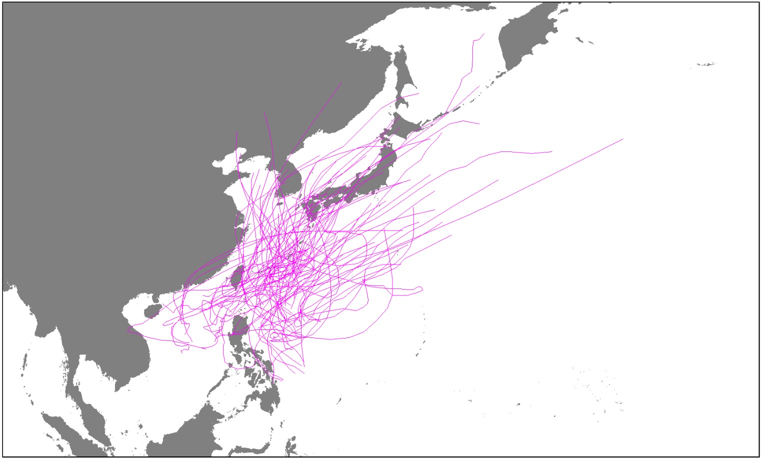
Storm Tracks, Class 2



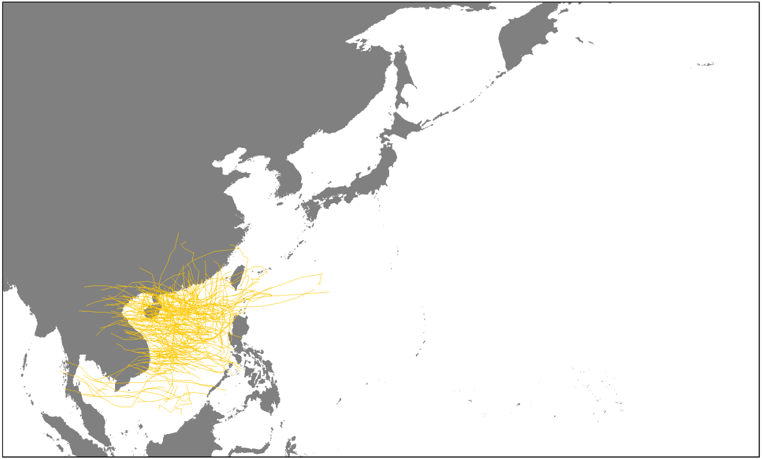
Storm Tracks, Class 3



Storm Tracks, Class 4



Storm Tracks, Class 5



Modeling the tracks

An appropriate model needs to include the following characteristics:

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- Points of genesis of storms
- Direction of storm movement
- Translation speeds

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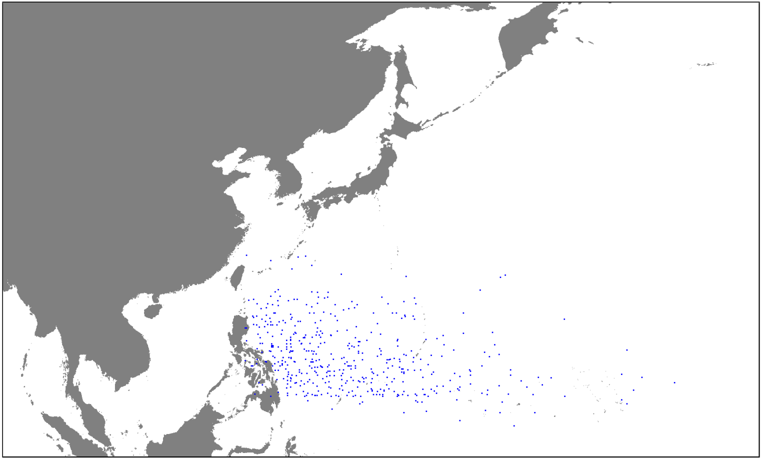
- Points of genesis of storms
- Direction of storm movement
- Translation speeds
- Also of interest: Maximum wind speeds along the tracks

Example: Points of Cyclone Genesis, Class 1



Modeling approach

- Intuitive approach: modeling points of cyclone genesis as a spatial point process
- From meteorology, no interactions between points of genesis are known

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- The locations of the points of genesis within the observation window are distributed inhomogenously

$\Rightarrow$ Estimation for the intensity field $f(\mathbf{t})$ of the inhomogeneous Poisson process is needed

- No parametric distribution immediately comes to mind

$\Rightarrow$ non-parametric estimation technique is needed

Intensity Field Estimation

Generalized nearest neighbor estimator for the intensity field $f(\mathbf{t})$:

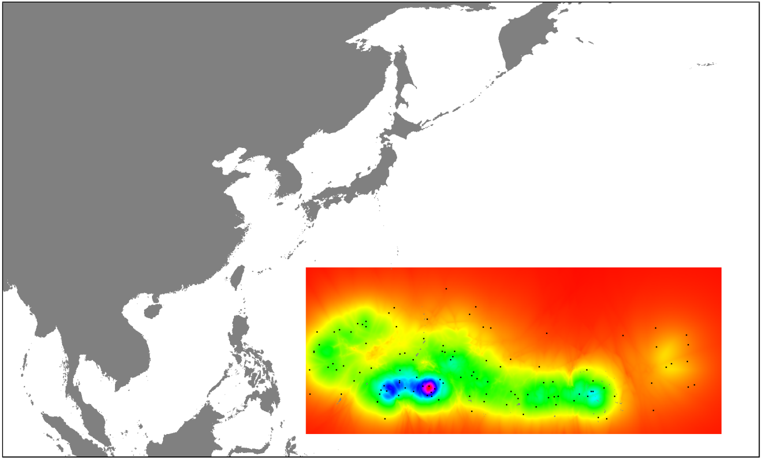
$$\widehat{f}(\mathbf{t}) = n^{-1} r_k(\mathbf{t})^{-2} \sum_{i=1}^{n} K_e \left\{ r_k(\mathbf{t})^{-1} (\mathbf{t} - \mathbf{X}_i) \right\} \ , \qquad (1)$$

where $r_k(\mathbf{t})$ is the distance of the k-th nearest neighbor of $\mathbf{t}$ from the point $\mathbf{t}$, $\mathbf{X}_i$ the i-th observation and K_e the Epanechnikov-Kernel:

$$K_e(\mathbf{x}) = \begin{cases} \frac{2}{\pi}(1 - \mathbf{x}^\top \mathbf{x}) & \text{if } \mathbf{x}^\top \mathbf{x} < 1, \\ 0 & \text{otherwise,} \end{cases} \qquad (2)$$

For details, see [Silverman, 1986].

Points of Cyclone Genesis, Class 0



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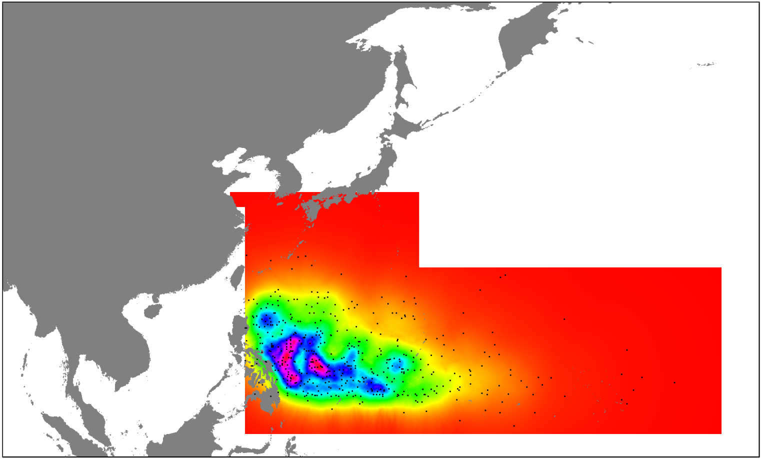
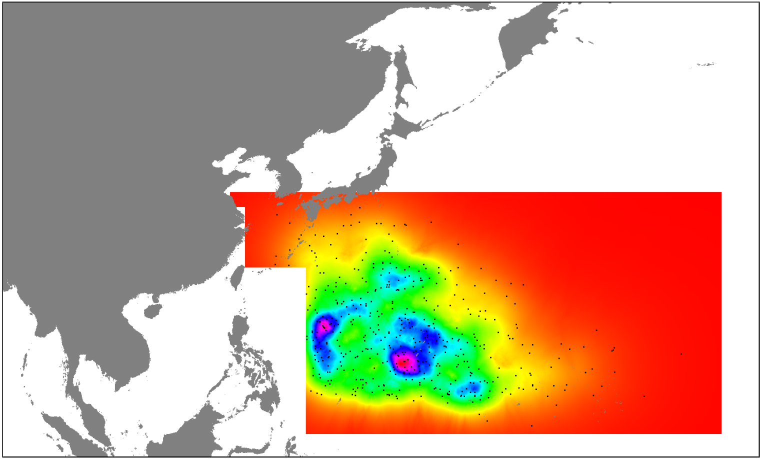
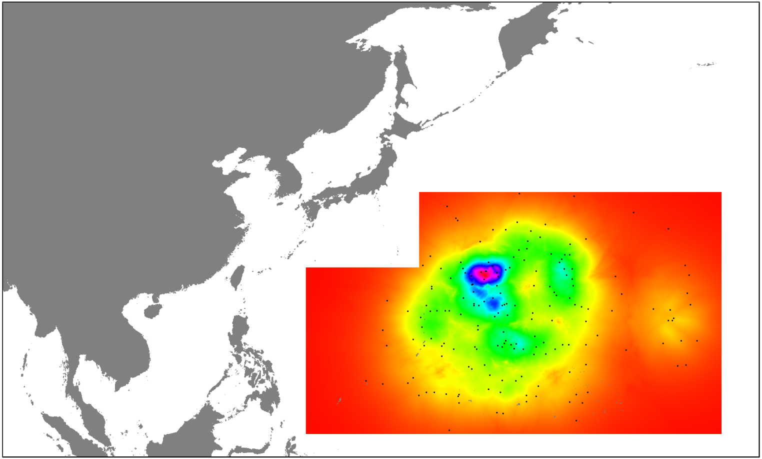


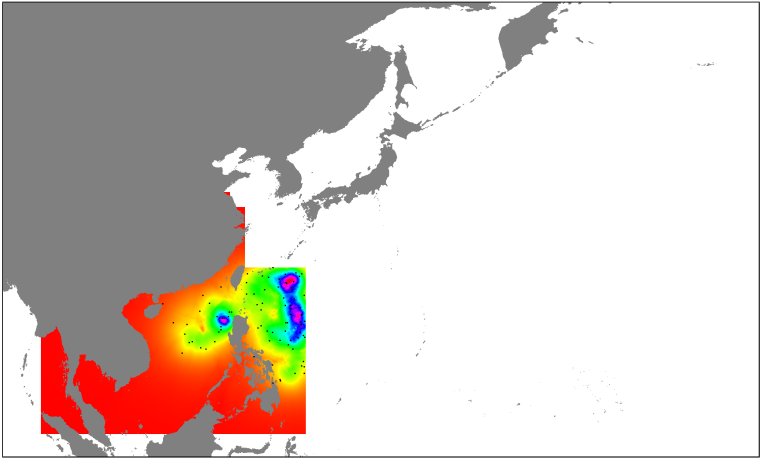
Points of Cyclone Genesis, Class 2



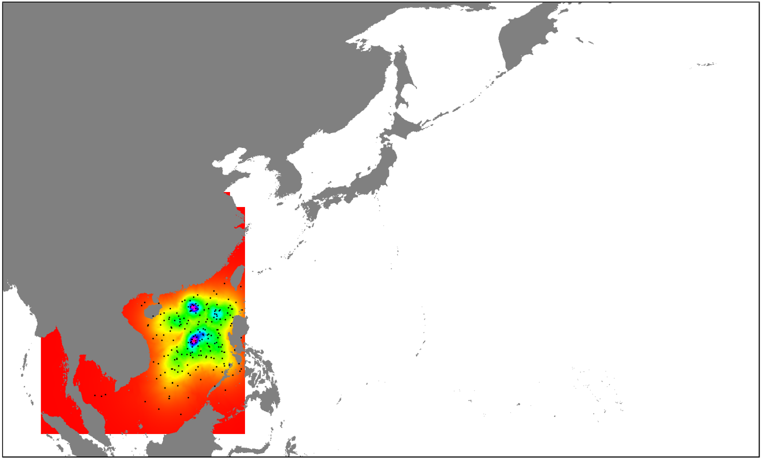
Points of Cyclone Genesis, Class 3



Points of Cyclone Genesis, Class 4



Points of Cyclone Genesis, Class 5



Modeling Approach: Direction

- Consider the direction of movement X as the sum of an initial direction X_0 and i.i.d. changes in direction X_i :

$$X = (X_0 + \sum_{i=1}^{n} X_i) \mod 360^\circ \qquad (3)$$

$\Rightarrow$ Direction of movement can be modeled as a generalized random walk

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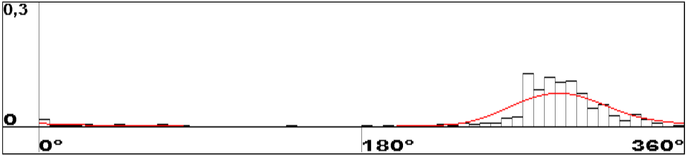
$\Rightarrow$ Direction of movement can be modeled as a generalized random walk

- Densities of X_0 and X_i need to be estimated from the historical data

$\Rightarrow$ Kernel techniques similar to those in the estimation of intensity fields can be used

Example Densities

- Density estimation: initial direction, class 1



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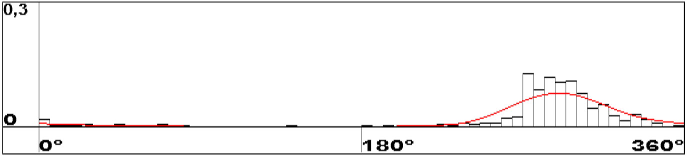
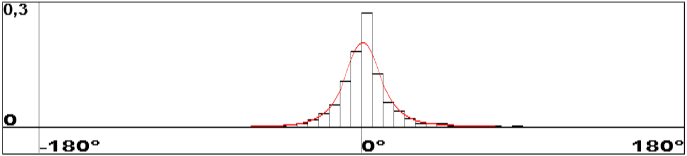


- Density estimation: change in direction, class 1



Modeling Approach: Translation Speed

- Consider the translation speed Y as the sum of an initial translation speed Y_0 and i.i.d. changes in translation speed Y_i :

$$Y = Y_0 + \sum_{i=1}^{n} Y_i \tag{4}$$

- Similar approach as for the direction, but certain boundary conditions have to be considered (e. g. $Y \geq 0$)

⇒ Translation speed can be modeled as a generalized random walk

- Densities of Y_0 and Y_i need to be estimated from the historical data

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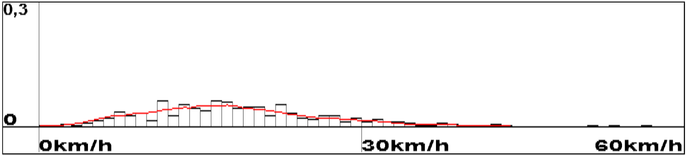
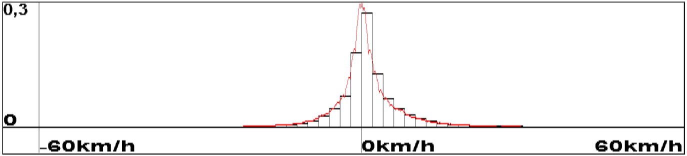
Example Densities

- Density estimation: initial translation speed, class 2



- Density estimation: change in translation speed, class 2



Modeling Approach: Wind Speed

- Consider the wind speed Z as the sum of an initial wind speed Z_0 and i.i.d. changes in wind speed Z_i :

$$Z = Z_0 + \sum_{i=1}^{n} Z_i \tag{5}$$

- Similar approach as for the direction, but certain boundary conditions have to be considered (e. g. $Z \geq 0$)

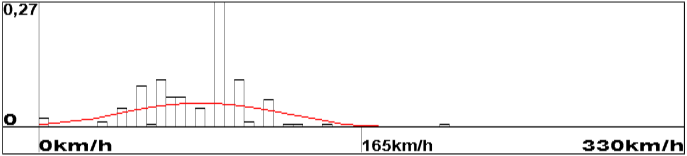
⇒ Translation speed can be modeled as a generalized random walk

- Densities of Z_0 and Z_i need to be estimated from the historical data

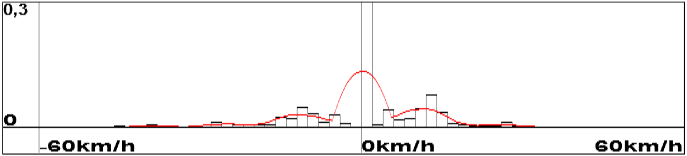
⇒ Kernel techniques similar to those used in the estimation of intensity fields can be used

Example Densities

- Density estimation: initial wind speed, class 5



- Density estimation: change in wind speed, class 5



Stopping Probability

- Basic meteorological knowledge: Storms will get weaker and end . . .
    - . . . when moving over land or
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- Basic meteorological knowledge: Storms will get weaker and end ...
  - ... when moving over land or
  - ... when moving over cold water or
  - ... when moving too close to the equator
- For every location in the observation window, the stopping probability of a storm is estimated depending on ...
  - ... geographical circumstances
  - ... meteorological circumstances

Model Algorithm (I)

1. Generate one realization of an inhomogeneous Poisson process according to the estimated intensity field
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1. Generate one realization of an inhomogeneous Poisson process according to the estimated intensity field
   $\Rightarrow$ points of genesis for a set of storms
2. Generate realizations of the random variables *initial direction*, *initial translation speed*, and *initial wind speed* according to the estimated densities
   $\Rightarrow$ initial segment for a storm
3. Determine the stopping probability of the storm according to the storm's current position
   $\Rightarrow$ decision whether the storm ends or not

Model Algorithm (II)

4. Generate realizations of the random variables *change in direction*, *change in translation speed*, and *change in wind speed* according to the estimated densities
   $\Rightarrow$ next track segment for a storm

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   $\Rightarrow$ complete storm track

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6. Determine, if the class of the storm track created in step 5 matches the class of the storm according to step 1
   $\Rightarrow$ accept or reject the storm

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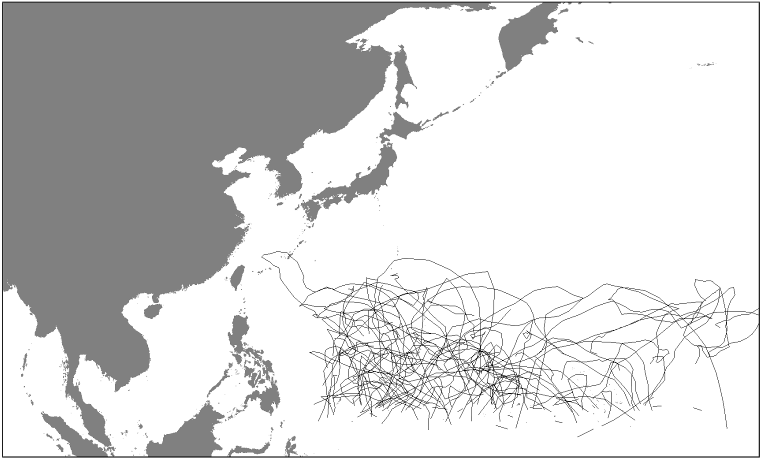
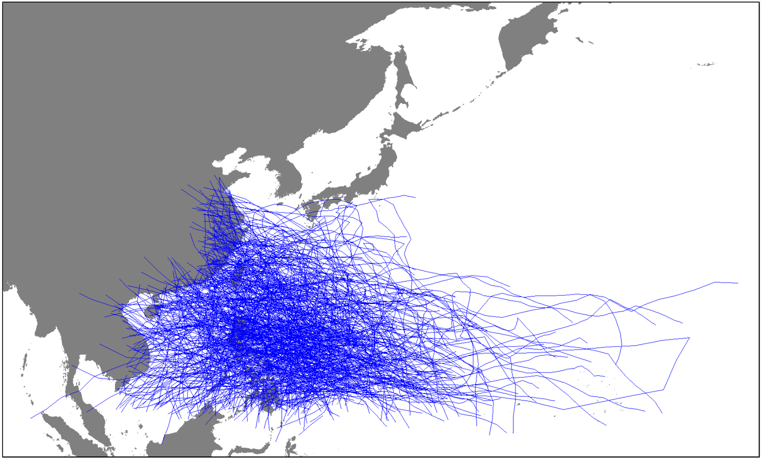
   $\Rightarrow$ complete storm track
6. Determine, if the class of the storm track created in step 5 matches the class of the storm according to step 1
   $\Rightarrow$ accept or reject the storm
7. Repeat steps 2 through 6 for every point generated in step 1 until for each point, an accepted track is generated
   $\Rightarrow$ complete set of storm tracks

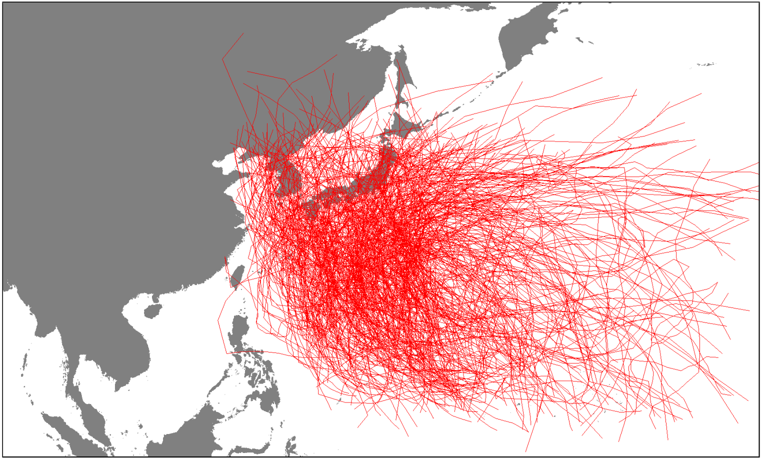
Synthetic Storm Tracks, Class 0



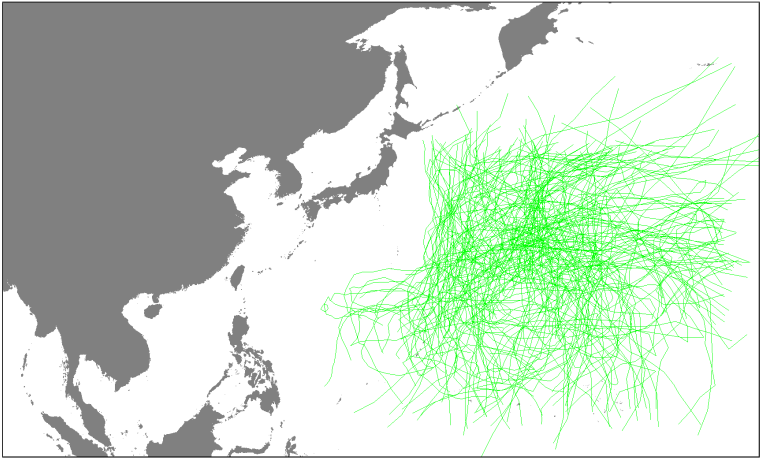
Synthetic Storm Tracks, Class 1



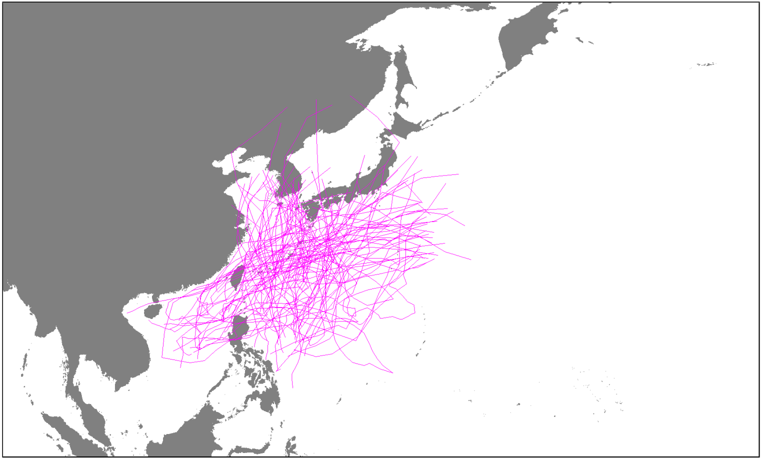
Synthetic Storm Tracks, Class 2



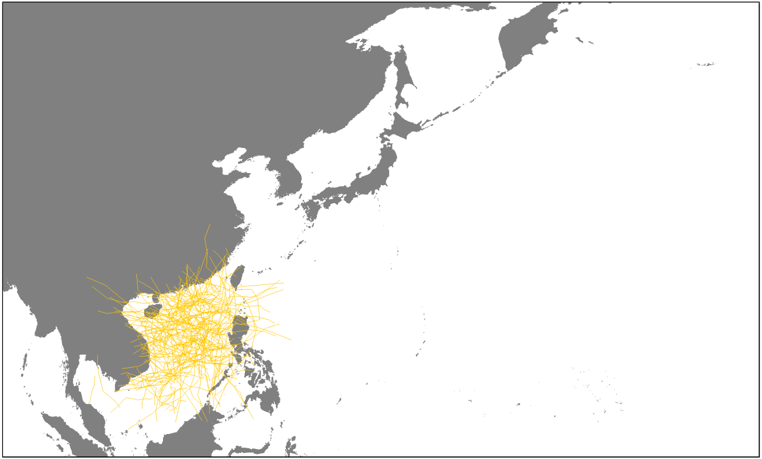
Synthetic Storm Tracks, Class 3



Synthetic Storm Tracks, Class 4

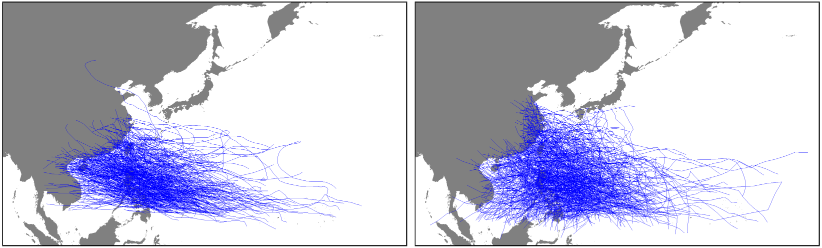


Synthetic Storm Tracks, Class 5



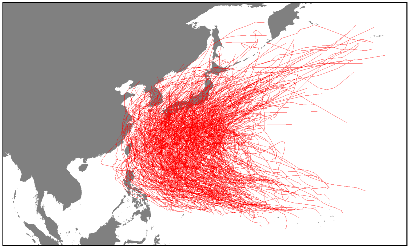
Evaluation (I)

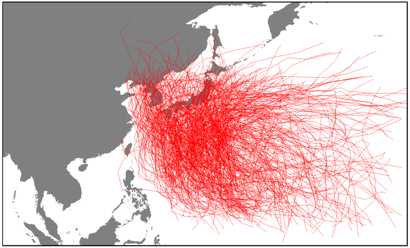
Comparison: Historical and Synthetic Cyclone Tracks, Class 1



Evaluation (II)

Comparison: Historical and Synthetic Cyclone Tracks, Class 2





Continued Research

- Project will be expanded with the continuing support of Munich Reinsurance Company
- Current Focus:
  - Making the distributions of X_i, Y_i, Z_i location-dependent
  - Making the distribution of Z_i (wind speed) dependent on Z_{i-1}
  - Readjusting the rules for calculating the stopping probability

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  - Readjusting the rules for calculating the stopping probability
- Plans for future model enhancements:
  - Modeling the points of cyclone genesis as more general point processes, e. g. Gibbs Processes
  - Modeling possible autocorrelation in X_i, Y_i, Z_i
  - Transfering the model to other ocean basins, e. g. the North Atlantic

Literature

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  Density Estimation for Statistics and Data Analysis
  Chapman & Hall, New York

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  Statistical modelling of tropical cyclone tracks, part 1-6
  arXiv:physics/0503231, 0505103, 0509024, 0510203, 0512091, 0512135

The End

Thank you for your attention!

jonas.rumpf@uni-ulm.de