Supplemental Materials and Results

to accompany

Modeling weather-driven long-distance dispersal of spruce budworm moths (*Choristoneura fumiferana*). Part 1: Model description.

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Contents

Note that all references cited here are also cited and listed in the main paper.

1. Regional maps

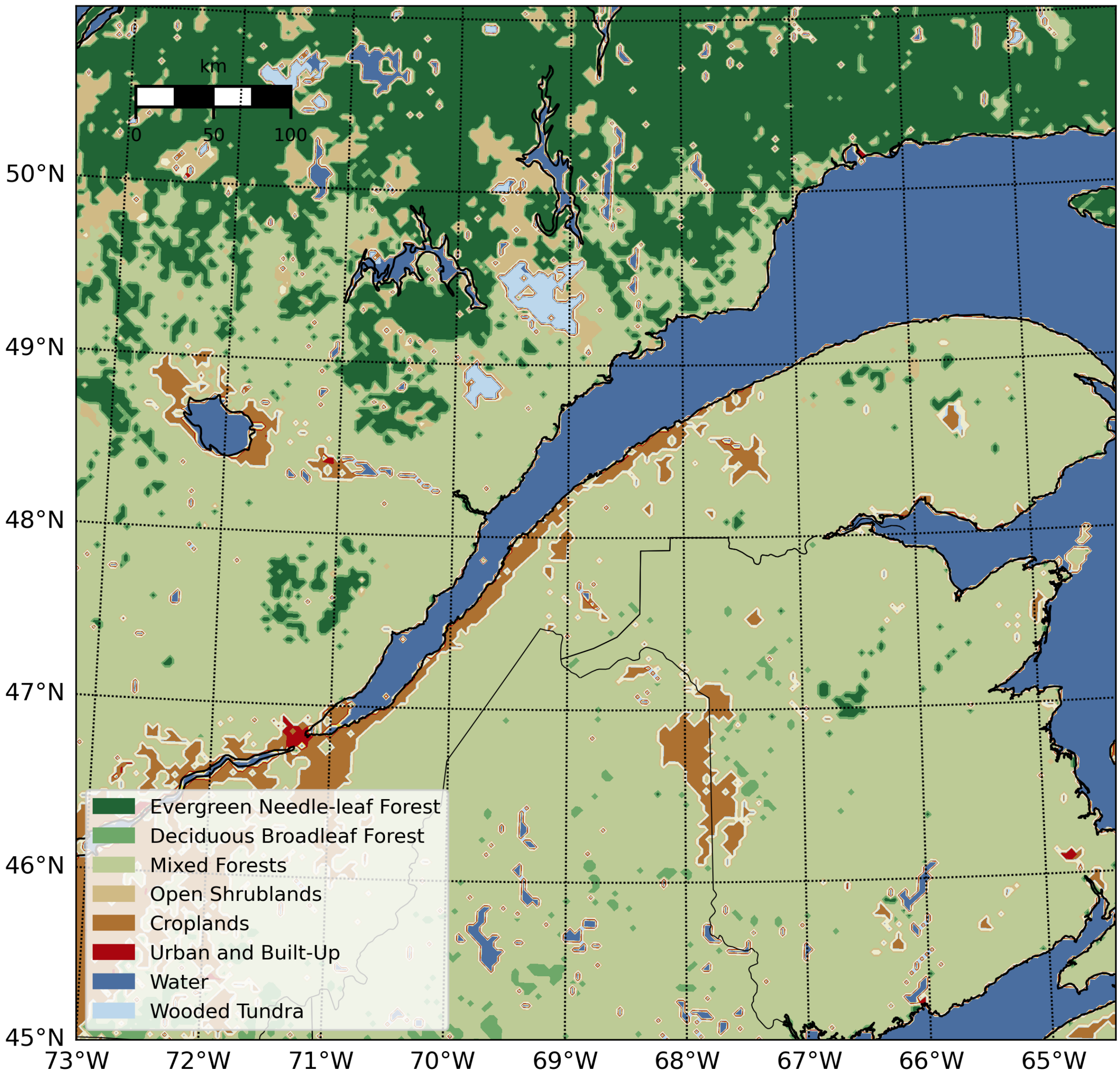


Figure S1: Regional landcover as represented at 3-km grid spacing (WRF Grid 3, see below) for the same area of eastern Canada and the northeastern United States as in Fig. 1. Colors are selected to match equivalent categories in the U.S. National Land Cover Database (NLCD; https://www.mrlc.gov/).

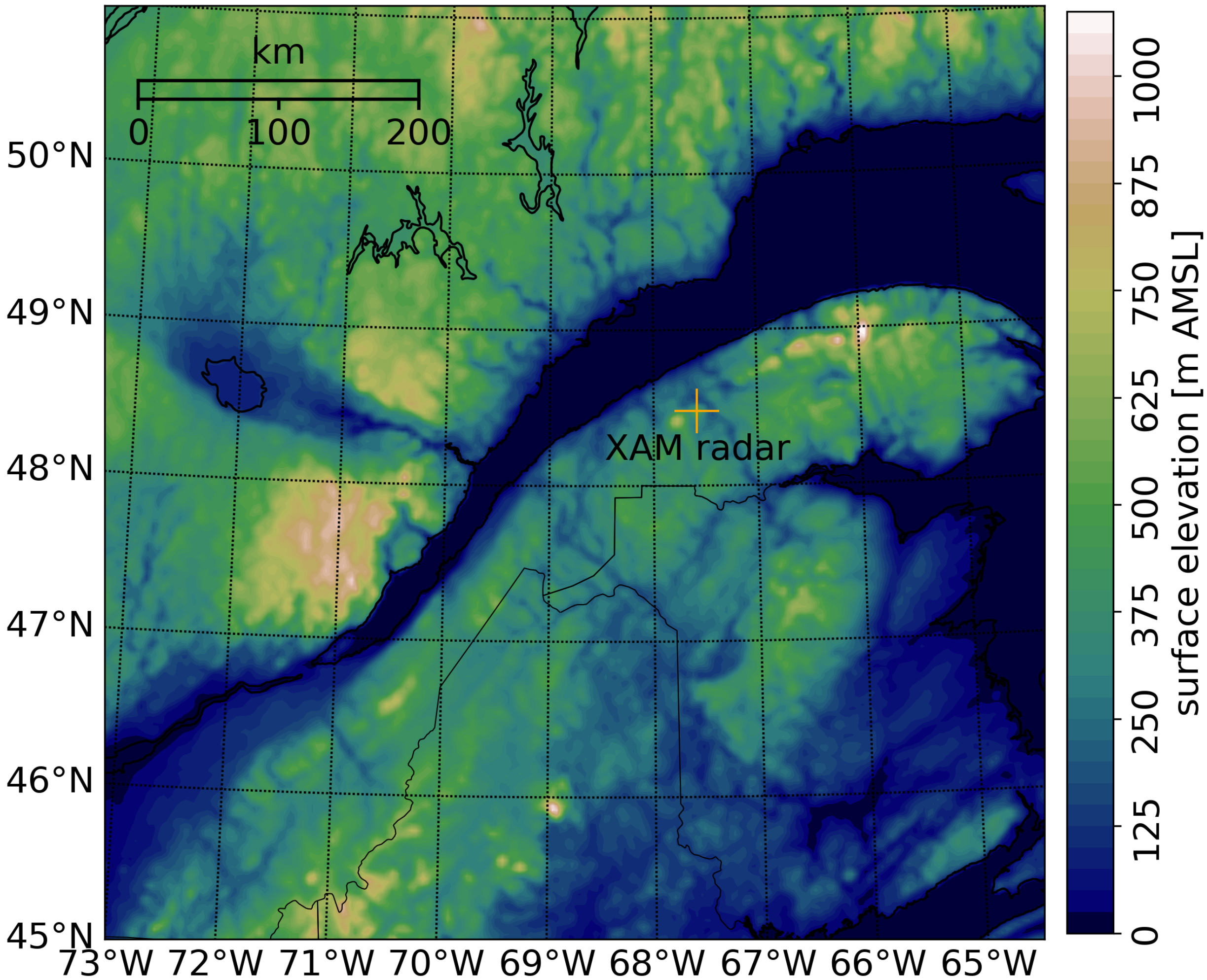


Figure S2: Regional topography as represented at 3-km grid spacing on WRF Grid 3 (see below) for the same area of eastern Canada and the northeastern United States as in Fig. 1, with the Val d'Irène weather surveillance radar (XAM) location marked.

2. BioSIM model output

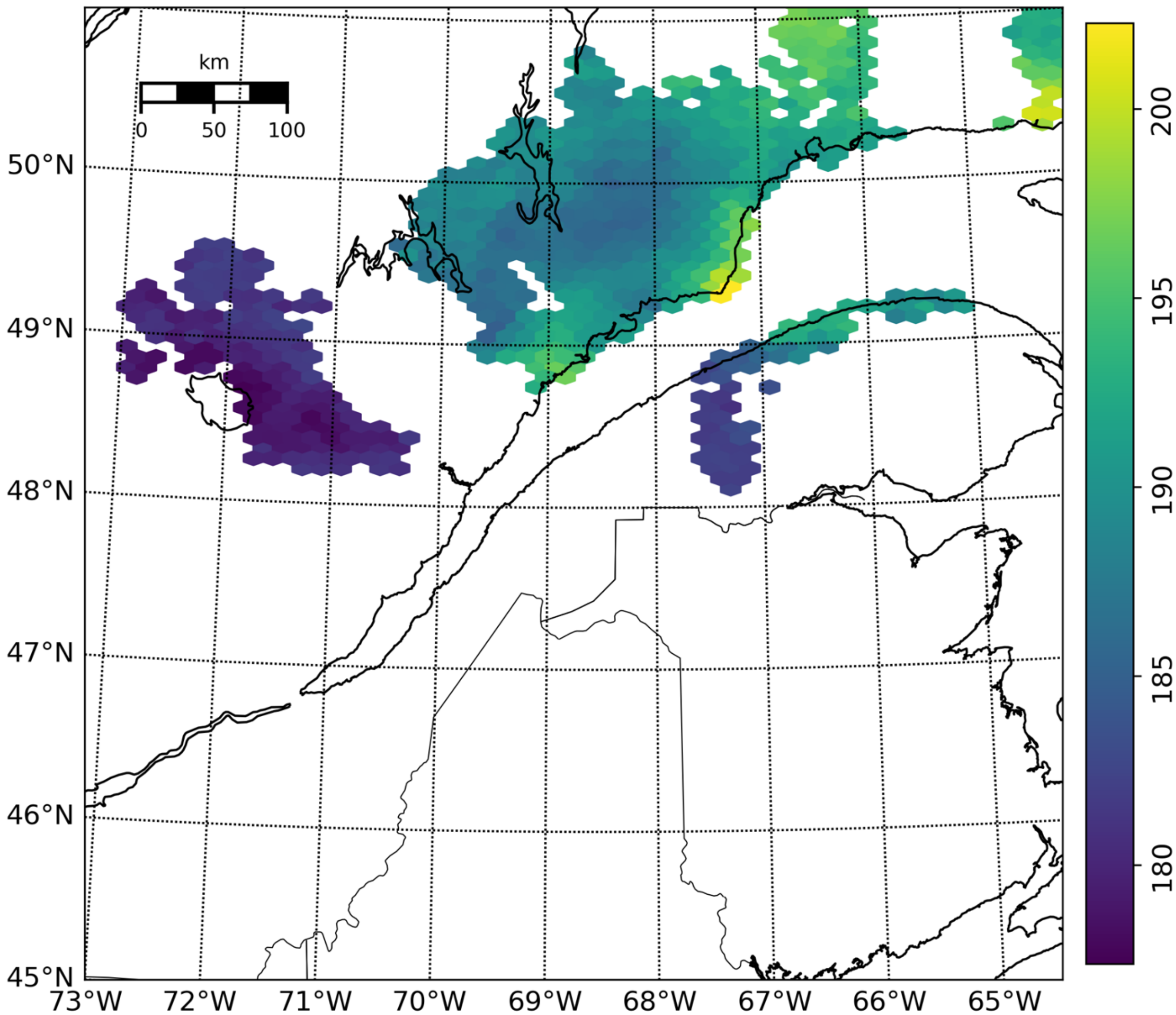


Figure S3: Regional SBW median adult eclosion dates (by day of year, DOY) as provided by BioSIM for the same area of eastern Canada and the northeastern United States as in Fig. 1. For reference, the simulations in this paper cover 14–16 July 2013 (DOY 195–197) and include SBW moths that emerged from pupation on or after 1 July 2013 (DOY 182).

3. WRF model configuration

For this work we used version 4.0.1 of the community-built Weather Research and Forecasting (WRF) model (Skamarock and Klemp, 2008; Skamarock et al., 2008; Powers et al., 2017). The Advanced Research WRF model is a widely used three-dimensional, non-hydrostatic, mesoscale atmospheric model. We applied WRF to the dynamically consistent reduction of large-scale meteorological data products from the NOAA–NCEP North American Regional Reanalysis (NARR: Mesinger et al., 2006; Luo et al., 2007) project. The NARR dataset is provided with a spatial grid resolution of Δx = ~32 km and temporal resolution of Δt = 3 h, which we reduced to Δx = 3 km at Δt = 60 min and Δx = 1 km at Δt = 15 min using four nested WRF grids in a telescoping configuration (see Fig. S5 and Table S1). Each WRF grid has a stretched vertical resolution ranging from Δz = 57 m at the surface to Δz = 310 m at z = ~2 km altitude, with 10 model levels within that span. Our WRF internal parameterization selections are listed in Table S2 for comparison with those used previously by Sturtevant et al. (2013). All WRF pre- and post-processing routines were run on the distributed high-throughput computing (HTC) resources at the UW–Madison Center for High Throughput Computing (CHTC). We performed our WRF model simulations using the parallelized high-performance computing (HPC) cluster resources at UW–Madison CHTC.

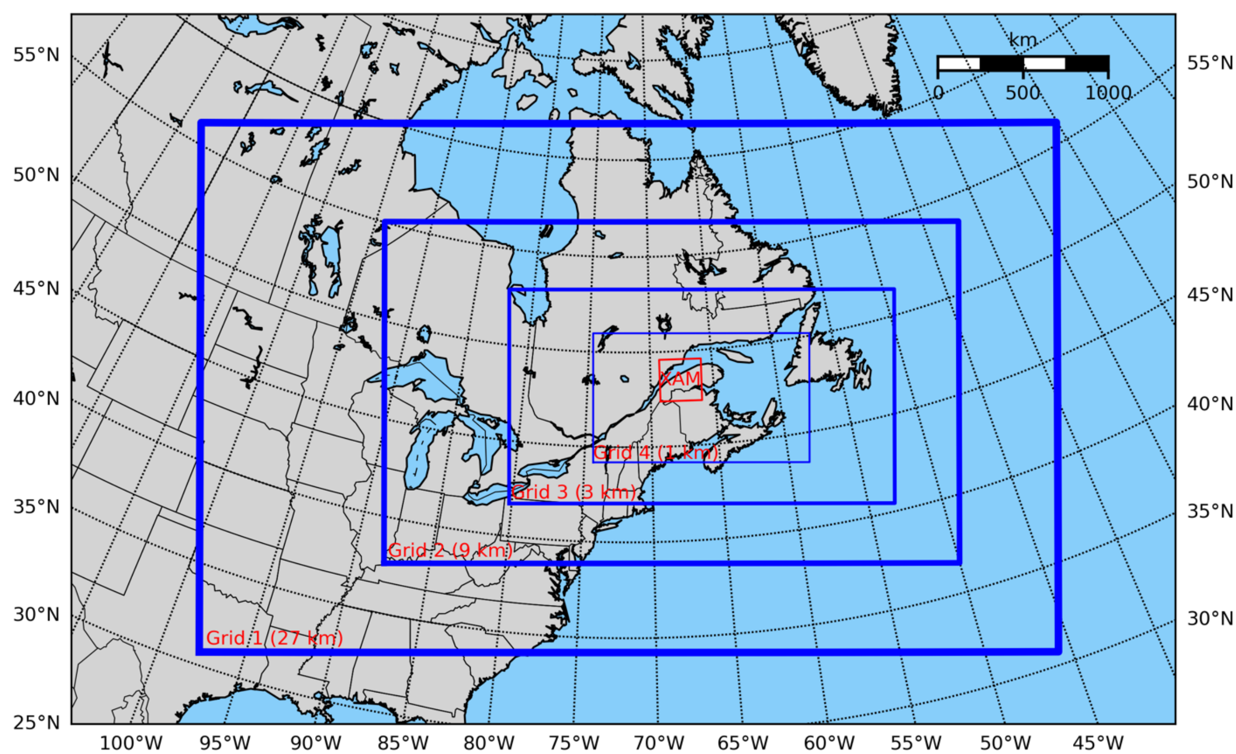


Figure S4: WRF model area and one-way nested grid configuration. The area of the Val d'Irène radar (XAM) coverage in southern Quebec is outlined in red.

Table S1: WRF model grid details for the 14–16 July 2013 simulations.

	Grid 1	**Grid 2**	**Grid 3**	**Grid 4**
Δx [km]	27	9	3	1
Δt [s]	108	36	12	4
Model Points (x, y)	182 x 113	364 x 217	730 x 406	1228 x 733
Distance (x, y) [km]	4914 x 3051	3276 x 1953	2190 x 1218	1228 x 733
Model Levels (z)	40, stretched	40, stretched	40, stretched	40, stretched
Cloud parameterization	Grell–Freitas	Grell–Freitas	Grell–Freitas	none
Simulation period	36 hours	36 hours	36 hours	36 hours
Output interval	6 hours	3 hours	1 hour	15 min

Table S2: WRF model configuration for the 14–16 July 2013 simulations.

Dynamical (physics) core	Advanced Research WRF v4.0.1
Longwave radiative transfer	RRTMG (“Goddard”)
Shortwave radiative transfer	RRTMG (“Goddard”)
Convective parameterization	Grell–Freitas (except on 1-km grid)
Cloud/precipitation microphysics	Thompson
Boundary layer	YSU non-local scheme
Surface layer	MM5 formulation
Horizontal diffusion	Simple, with K via 2-D deformation
Land surface model	Noah-MP
Topography	USGS GMTED2010
Land cover	Modified MODIS/IGBP categories
Vegetation (greenness, LAI, albedo)	NASA MODIS

4. SBW–pyATM flight model differences from Sturtevant et al. (2013)

Table S3: Summary of differences in configuration of moth behavior in the SBW–pyATM flight model from the sources and values used in Sturtevant et al. (2013).

SBW flight behavior	in Sturtevant et al. (2013)	in this work
Liftoff time	formulation from Greenbank et al. (1980)	based on Régnière et al. (2019d), subject to external conditions
Liftoff temperature	from Greenbank et al. (1980)	based on Régnière et al. (2019c)
Liftoff minimum wind speed	from Greenbank et al. (1980)	calibrated by sensitivity analysis using distribution of liftoff times
Liftoff maximum precipitation rate	from Greenbank et al. (1980)	same, but not a limitation for the dates explored in this work
Liftoff vertical velocity	from Greenbank et al. (1980) with random variation	by morphological parameterization (see Methods)
Level-off height	from Schaefer (1976)	emergent property based on Régnière et al. (2019c)
Flight speed	from Greenbank et al. (1980) with random variation	by morphological parameterization (see Methods)
Wingbeat conversion factor	none	calibrated by sensitivity analysis using radar observations
Energy conservation factor	none	calibrated by sensitivity analysis using radar observations
Landing behavior	host-seeking, derived from Greenbank (1980)	forced landing at sunrise
Max flight duration	from Greenbank et al. (1980)	sunrise (see Methods)
Descent velocity	from Greenbank et al. (1980)	same

5. SBW moth physiology: flight strength

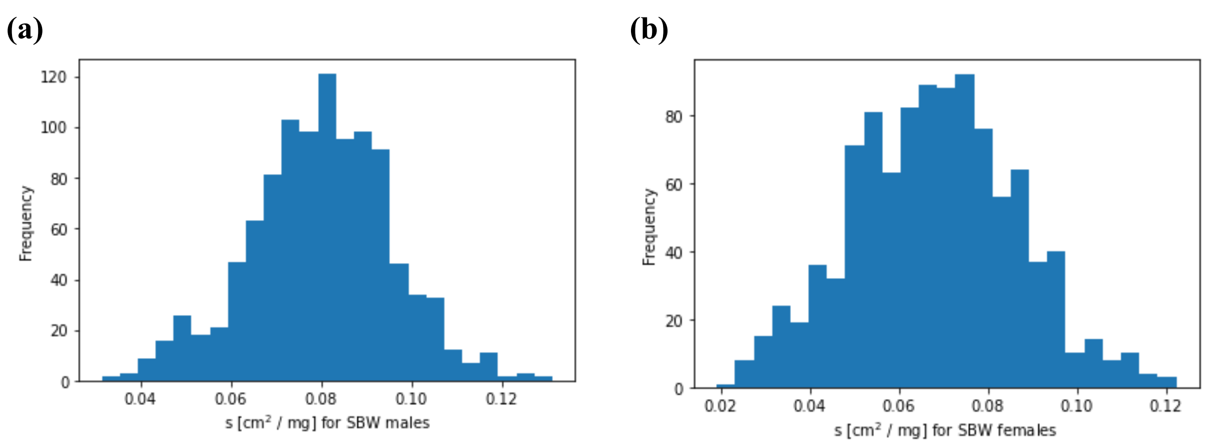


Figure S5: Frequency distributions of flight strength *s* for (a) SBW males and (b) SBW females as calculated by eq. (5) using moth mass and wing area data provided in Régnière et al. (2019c).

6. WRF-based weather conditions for 14–15 July 2013 flight simulation

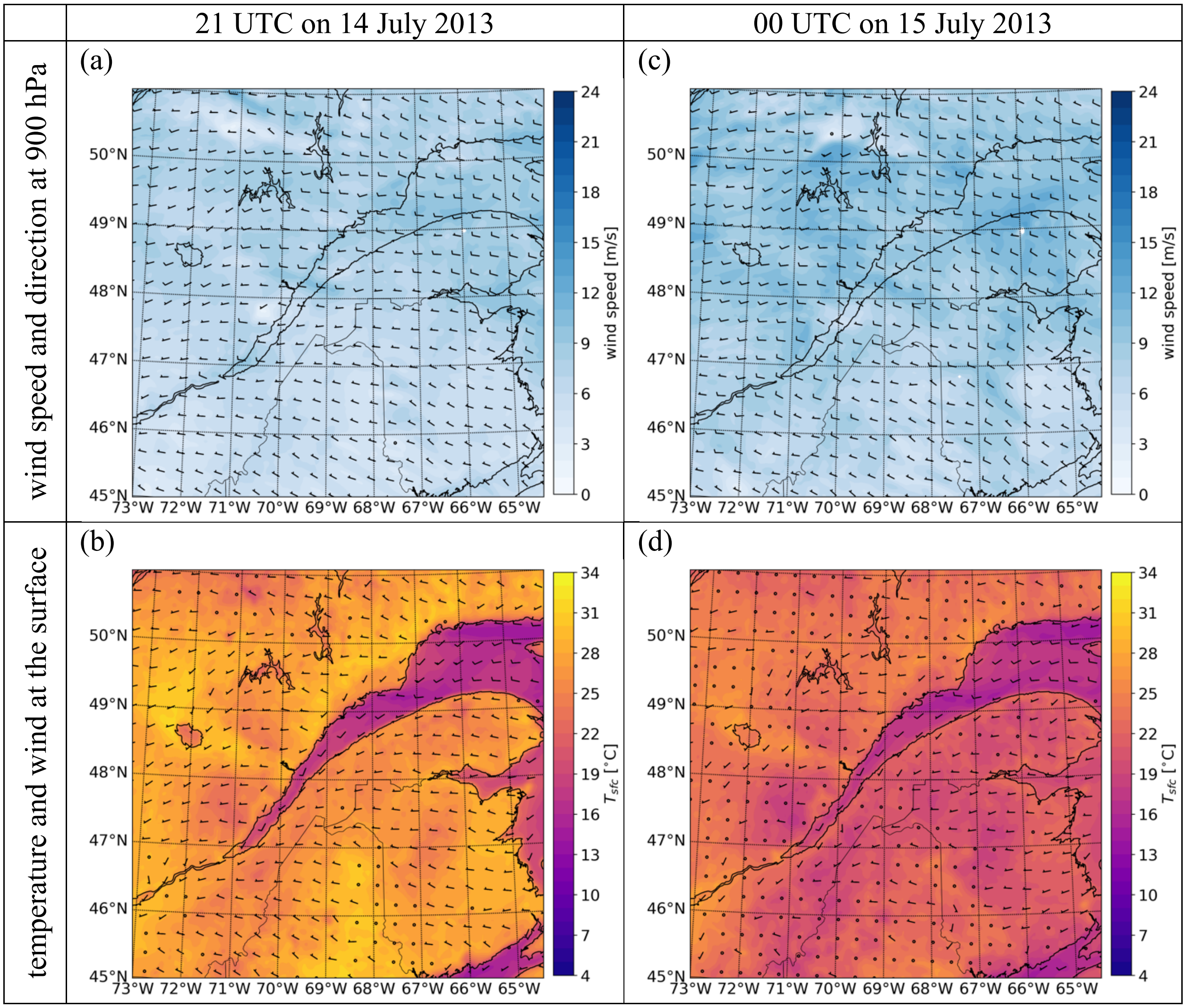


Figure S6: WRF-based regional weather maps for the 14–15 July 2013 simulation, as marked. Wind speed is given in [m/s], temperature is given in [ºC]. Figure parts (b) and (d) are also shown in Fig. 3 in the main paper. This figure is continued below.

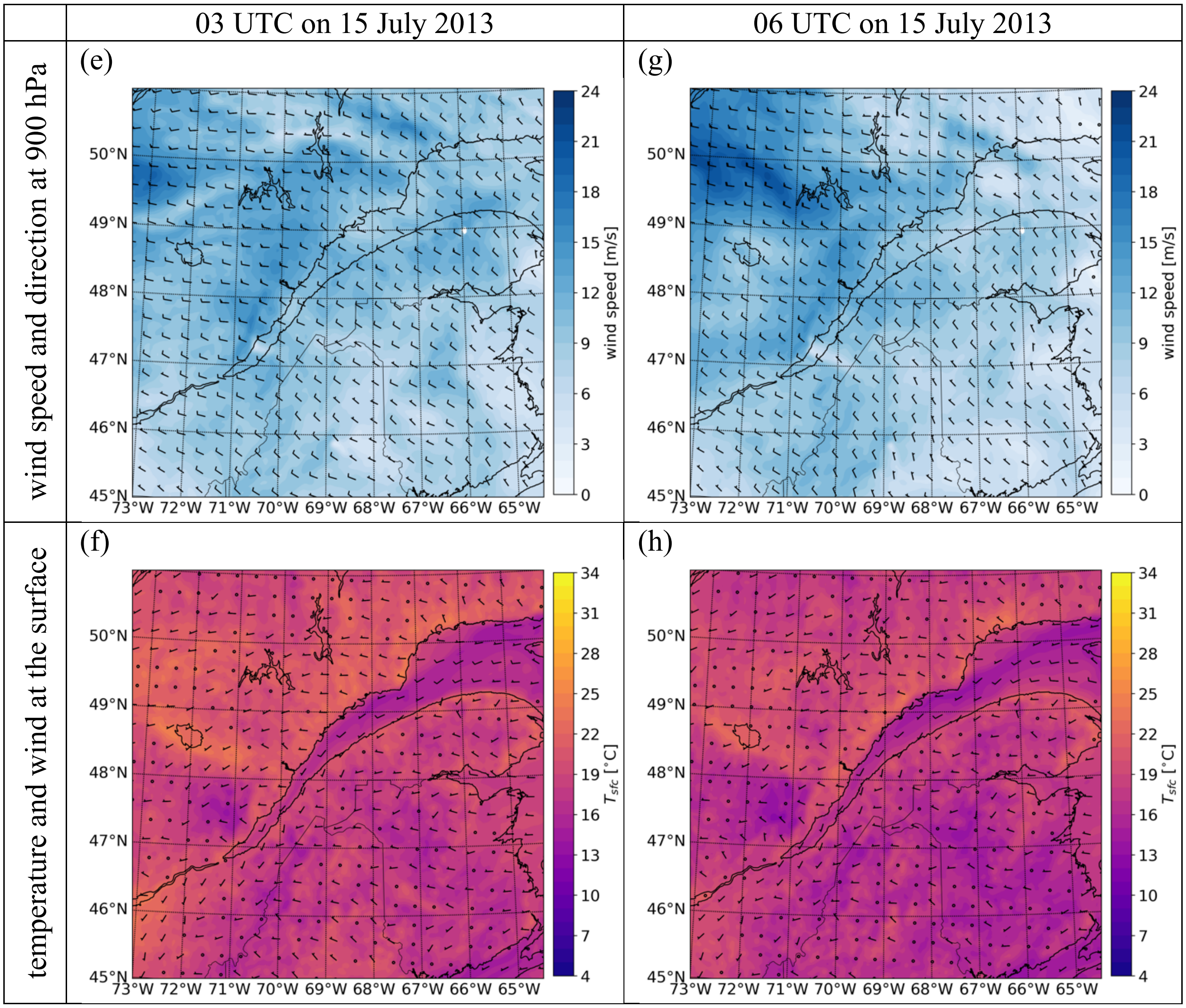


Figure S6 (continued): WRF-based regional weather maps for the 14–15 July 2013 simulation, as marked. Figure parts (g) and (h) are also shown in Fig. 3 in the main paper. This figure is continued below.

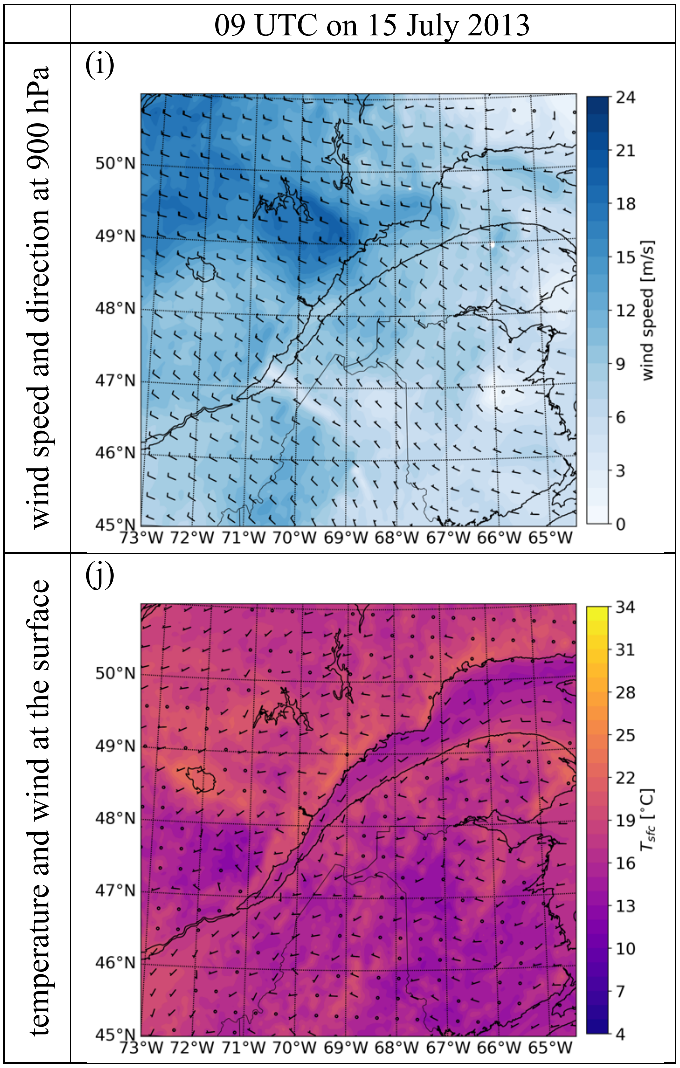


Figure S6 (continued): WRF-based regional weather maps for the 14–15 July 2013 simulation, as marked.

7. Additional SBW–pyATM results for 14–15 July 2013 flight simulation

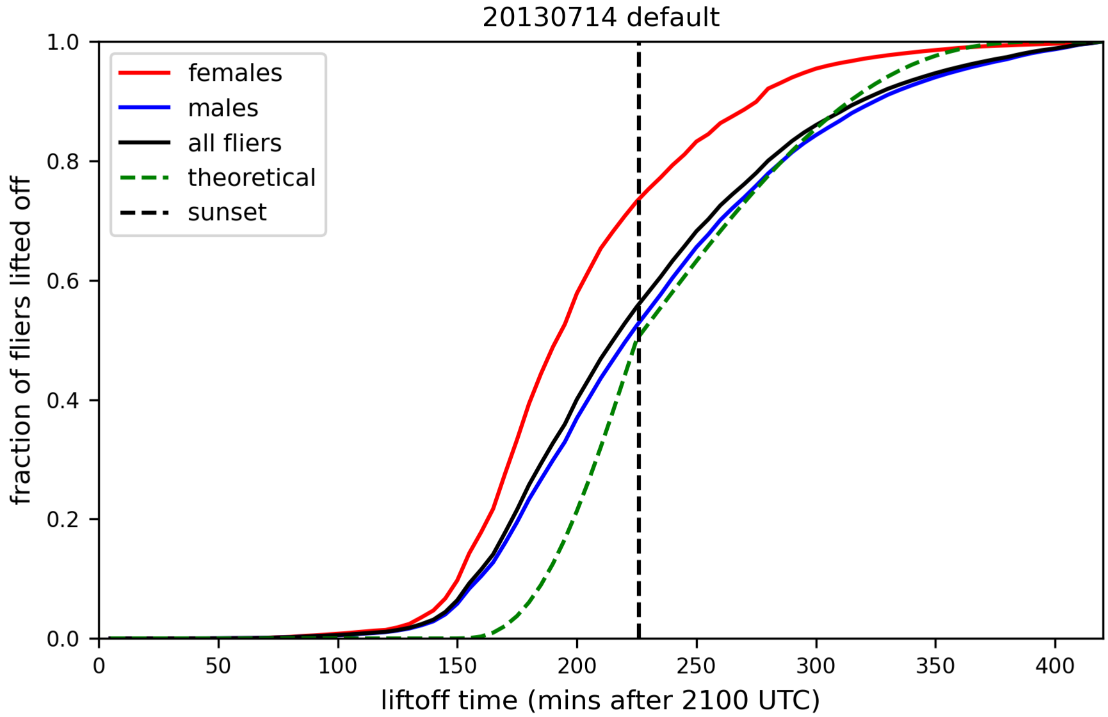


Figure S7: Simulated SBW moth liftoff times on 14–15 July 2013.

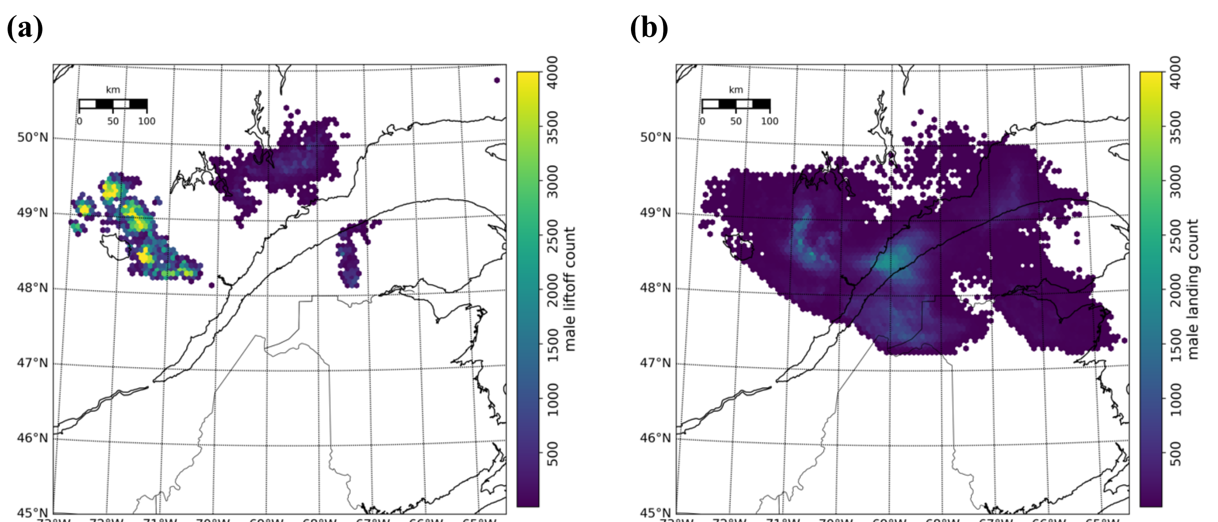


Figure S8: Simulated (a) liftoff and (b) landing count maps for SBW males on 14–15 July 2013.

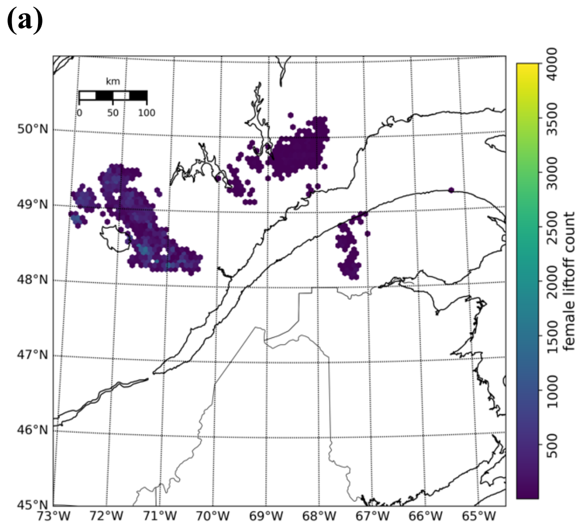


Figure S9: Simulated (a) liftoff and (b) landing count maps for SBW females on 14–15 July 2013.

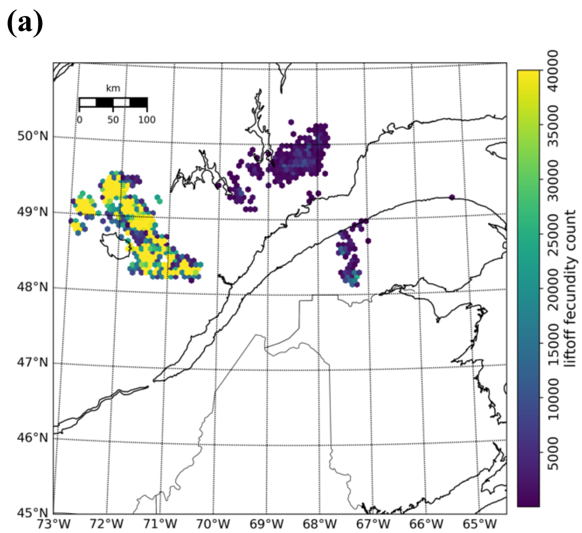


Figure S10: Simulated (a) fecundity export and (b) fecundity import by SBW females on 14–15 July 2013.

8. WRF-based weather conditions for 15–16 July 2013 flight simulation

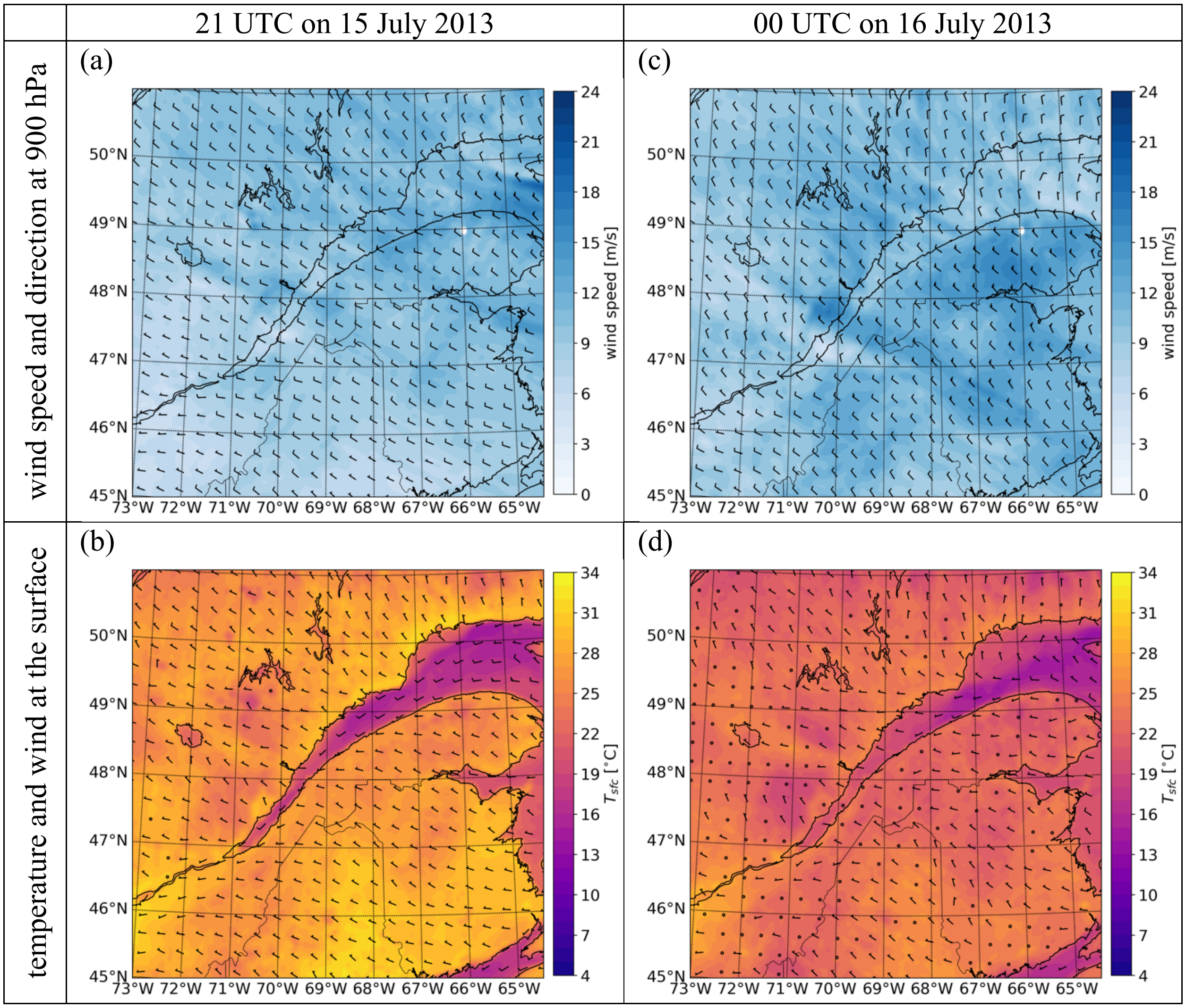


Figure S11: WRF-based regional weather maps for the 15–16 July 2013 simulation, as marked. Wind speed is given in [m/s], temperature is given in [ºC]. Figure parts (b) and (d) are also shown in Fig. 6 in the main paper. This figure is continued below.

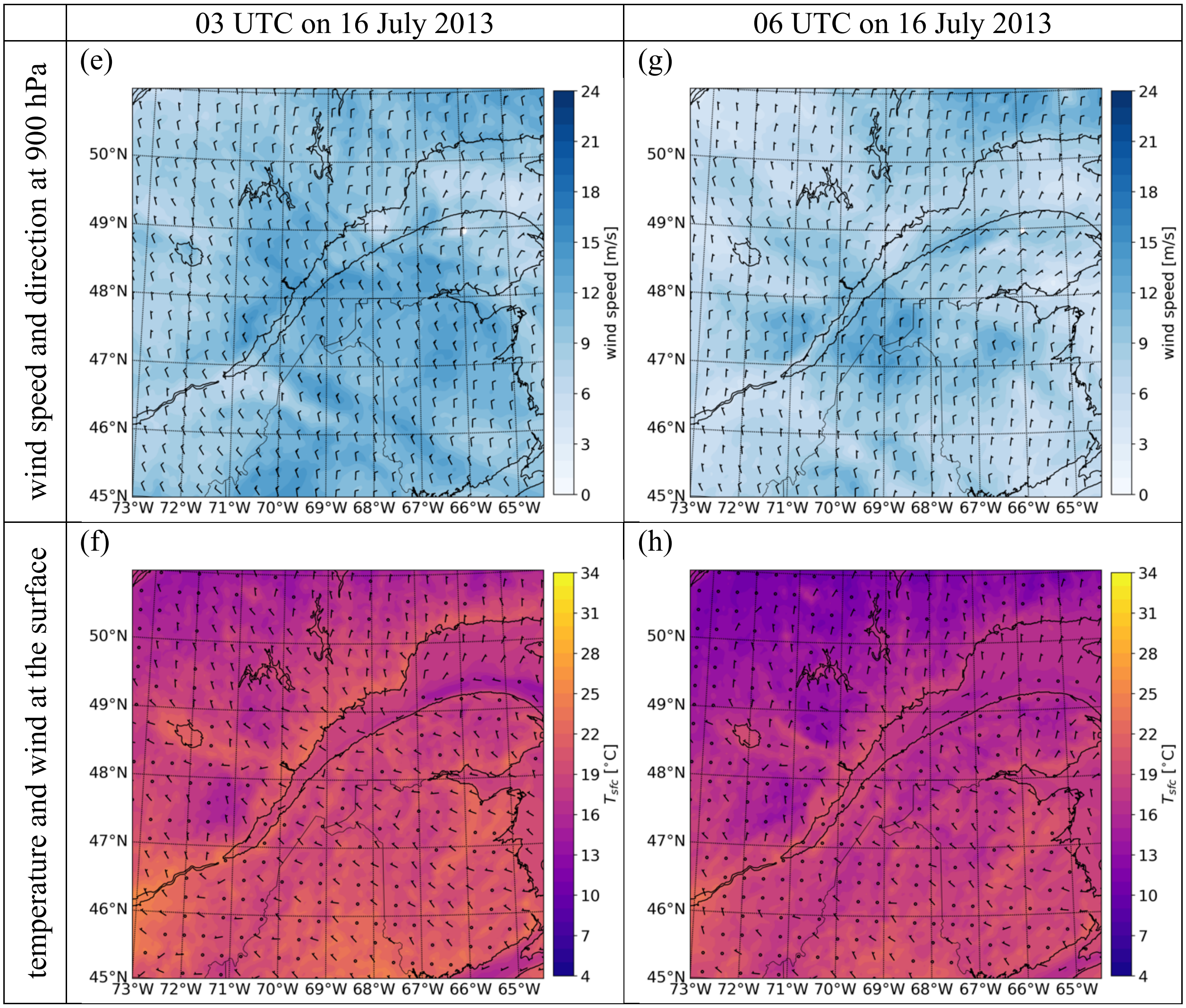


Figure S11 (continued): WRF-based regional weather maps for the 15–16 July 2013 simulation, as marked. Figure parts (g) and (h) are also shown in Fig. 6 in the main paper. This figure is continued below.

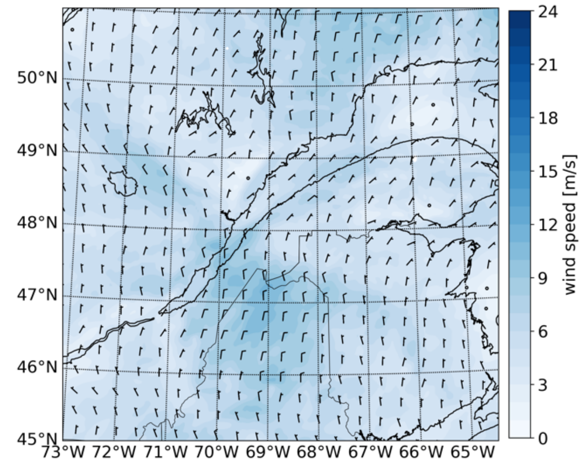
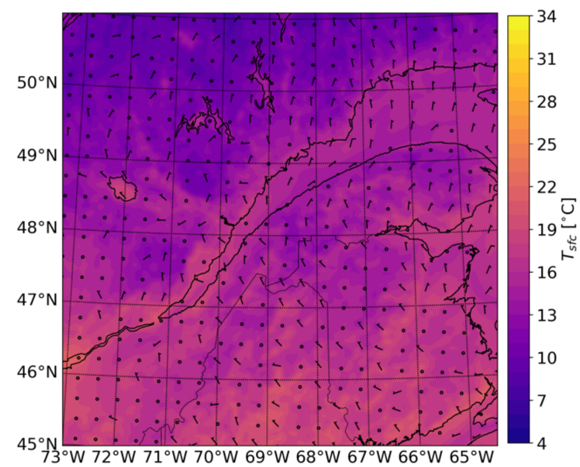
	09 UTC on 16 July 2013
wind speed and direction at 900 hPa	(i) 
temperature and wind at the surface	(j) 

Figure S11 (continued): WRF-based regional weather maps for the 15–16 July 2013 simulation, as marked.

9. Additional SBW–pyATM results for 15–16 July 2013 flight simulation

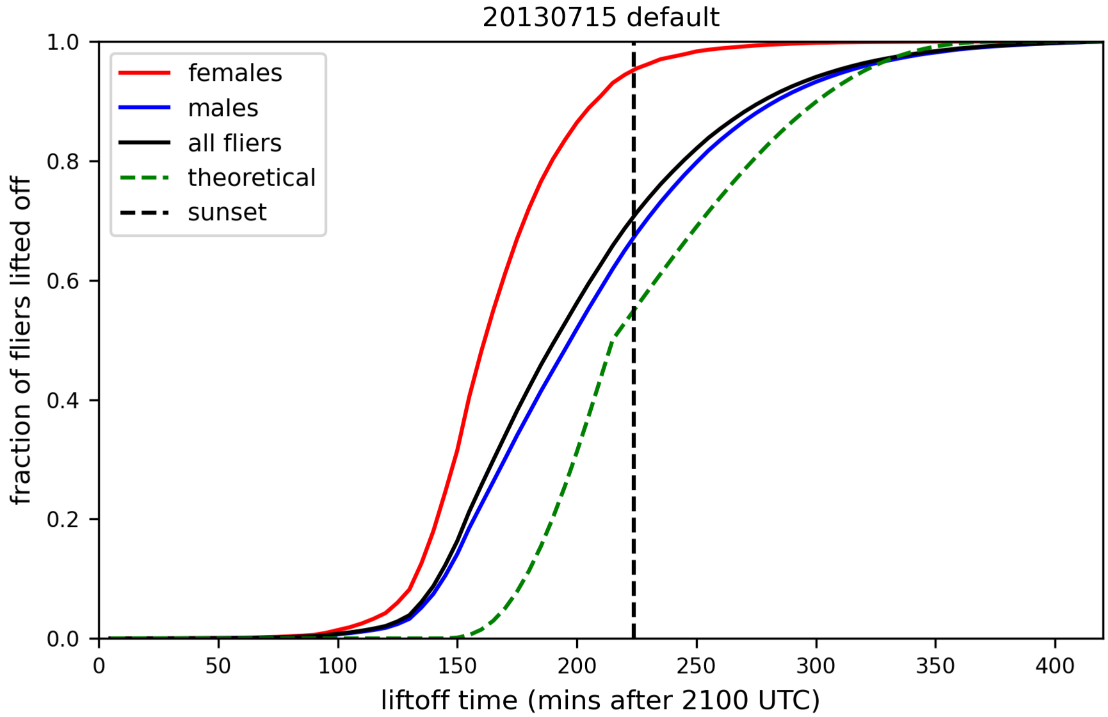


Figure S12: Simulated SBW moth liftoff times on 15–16 July 2013.

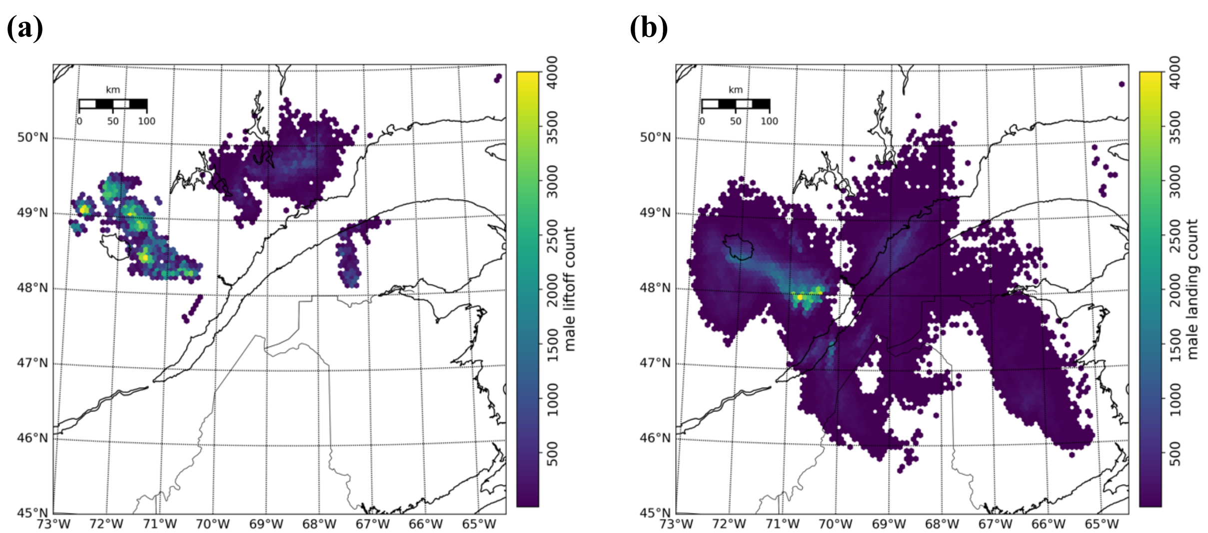


Figure S13: Simulated (a) liftoff and (b) landing count maps for SBW males on 15–16 July 2013.

(a) (b)

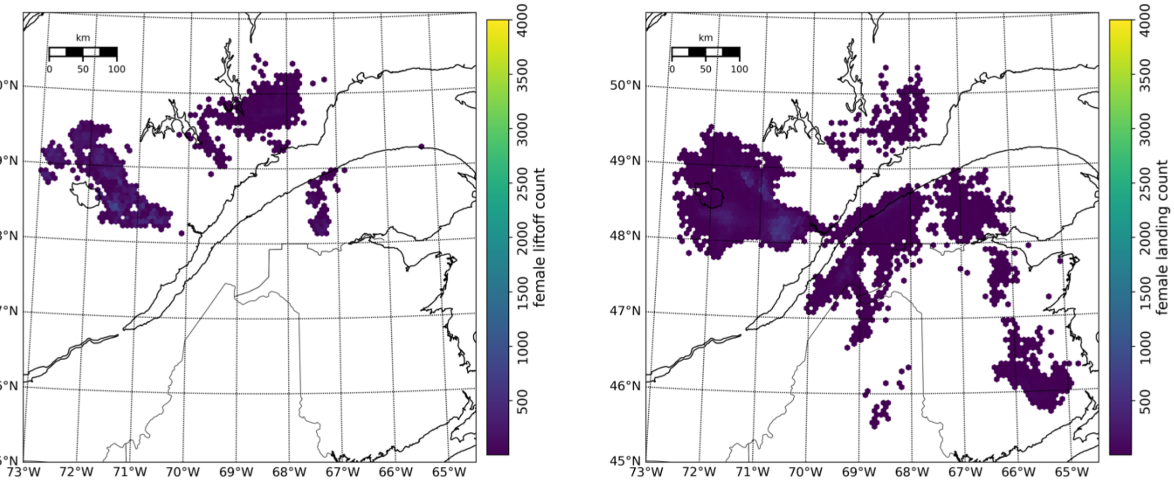


Figure S14: Simulated (a) liftoff and (b) landing count maps for SBW females on 15–16 July 2013.

(a) (b)

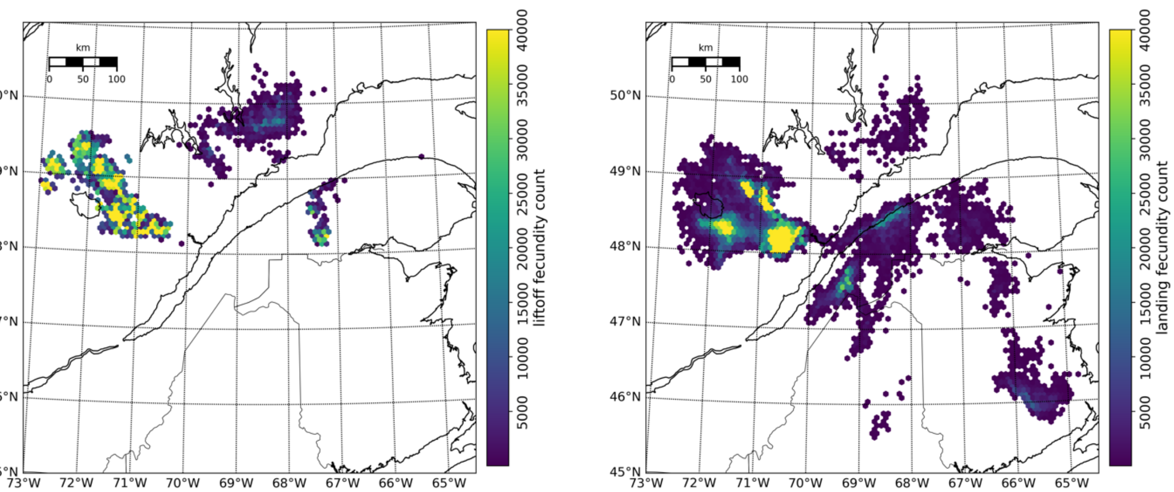


Figure S15: Simulated (a) fecundity export and (b) fecundity import by gravid SBW females on 15–16 July 2013.

10. Data and code sources

10.1 NOAA–NCEP North American Regional Reanalysis (NARR) product

- NCEP Research Data Archive at NCAR, Boulder, Colorado, USA
  https://rda.ucar.edu/data/ds608.0/

10.2 Community WRF model and postprocessing utilities

- Advanced Research WRF model code
  https://github.com/wrf-model
- *wrf-python* library
  https://github.com/NCAR/wrf-python
- *wrfcube* Python library
  https://github.com/mheikenfeld/wrfcube

10.3 Defoliation aerial survey geospatial data

- Quebec Ministère des Forêts, de la Faune et des Parcs
  https://mffp.gouv.qc.ca/

10.4 XAM Doppler radar

- Environment Canada
  https://climate.weather.gc.ca/
- Processing code developed at McGill University
  https://github.com/mcgillradar/bugtracker

10.5 This work

- SBW-pyATM code repository (via GitHub)
  https://github.com/megarcia/SBW-pyATM
- Python code for all figures in the main paper and Supplemental Materials (via GitHub)
  https://github.com/megarcia/Garcia_etal_2022a
- Model output data required for generating figures (via Dryad)
  https://doi.org/10.5061/dryad.mpg4f4r19
- Supplemental animations of input and results (via Zenodo) (see also next page)
  https://doi.org/10.5061/dryad.mpg4f4r19

11. Supplemental animations (SA) available on Zenodo (see link above)

SA1 file name: "20130714-15_WRF-NARR_900hPa_wind_sfc_T.gif"

- 14 frames @ 2 frames/sec = ~7 sec animation length.
- WRF model output at 1-hour intervals showing 900 hPa wind speed (top, at approximate flight level) and surface temperature and wind barbs (bottom) from 2100 UTC on 14 July through 1000 UTC on 15 July 2013 within the region of the flight simulations.
- WRF model output is at 3-km spatial resolution (Grid 3 shown above) and is based on low-resolution, large-scale NARR input as described above and in the main paper.

SA2 file name: "20130714-15_SBW-pyATM_flight_trajectories.gif"

- 149 frames @ 2 frames/sec = ~75 sec animation length.
- WRF-based topography (colored background) and SBW–pyATM simulated flight trajectories from a single simulation ensemble member at 5-minute intervals from 2100 UTC on 14 July through 0918 UTC on 15 July 2013.
- As in the main paper, SBW moth liftoff locations are marked "+" and landing locations are marked "×" with flight paths in orange.

SA3 file name: "20130714-15_XAM_flier_density_+_radar.gif"

- 72 frames @ 2 frames/sec = ~36 sec animation length.
- Simulated ensemble SBW airborne moth density (left) compared with XAM radar reflectivity (right) at 10-minute intervals from 2109 UTC on 14 July through 0859 UTC on 15 July 2013.
- The area shown corresponds to XAM radar coverage over southern Quebec, the St. Lawrence estuary, and northern New Brunswick.

SA4 file name: "20130715-16_WRF-NARR_900hPa_wind_sfc_T.gif"

- 14 frames @ 2 frames/sec = ~7 sec animation length.
- WRF model output at 1-hour intervals showing 900 hPa wind speed (top, at approximate flight level) and surface temperature and wind barbs (bottom) from 2100 UTC on 15 July through 1000 UTC on 16 July 2013 within the region of the flight simulations.
- WRF model output is at 3-km spatial resolution (Grid 3 shown above) and is based on low-resolution, large-scale NARR input as described above and in the main paper.

SA5 file name: "20130715-16_SBW-pyATM_flight_trajectories.gif"

- 149 frames @ 2 frames/sec = ~75 sec animation length.
- WRF-based topography (colored background) and SBW–pyATM simulated flight trajectories from a single simulation ensemble member at 5-minute intervals from 2100 UTC on 15 July through 0918 UTC on 16 July 2013.
- As in the main paper, SBW moth liftoff locations are marked "+" and landing locations are marked "×" with flight paths in orange.

SA6 file name: "20130715-16_XAM_flier_density_+_radar.gif"

- 71 frames @ 2 frames/sec = ~36 sec animation length.

- Simulated ensemble SBW airborne moth density (left) compared with XAM radar reflectivity (right) at 10-minute intervals from 2119 UTC on 15 July through 0859 UTC on 16 July 2013.
- The area shown corresponds to XAM radar coverage over southern Quebec, the St. Lawrence estuary, and northern New Brunswick.