Ecological Forecasting in the Coastal Zone

David S. Wethey PI
T. Jerry Hilbish, Brian S. Helmuth, Sarah A. Woodin, Venkat Lakshmi, Helen C. Power, Co-PIs
University of South Carolina
Columbia SC 29208 USA
wethey@biol.sc.edu
The zone between the tides as an indicator of climate change
Intertidal microclimate varies from temperate to tropical: tropical barnacles restricted to hot spots high on the shore.
Linking Biogeography to Climate

- Northern and southern geographic limits of species are likely influenced by climate.

- Factors that control local zonation on the shore may also control geographic distribution.
Interdisciplinary Team

- David Wethey – PI (Ecologist)
  - Field experiments, model development, rocky shores
- Brian Helmuth – Co PI (Biophysical Ecologist)
  - Biomimetic sensors, model development, rocky shores
- Jerry Hilbush – Co PI (Population Geneticist)
  - Sublethal stress measurement – heat shock, rocky shores
- Sally Woodin – Co PI (Sediment Ecologist)
  - Sublethal stress measurement – behavior, sediments
- Venkat Lakshmi – Co PI (Satellite Hydrologist)
  - Satellite image analysis
- Helen Power – Co PI (Climatologist)
  - Solar radiation modeling
General Goals

- Use NERRS observations and satellite (TOVS, AVHRR, MODIS, ASTER) to model body temperature of ecologically important intertidal species.
- Ground truth models with biomimetic sensors.
- Use validated models to produce maps of body temperature of ecologically important species on Atlantic and Pacific Coasts.
- Compare body temperature estimates to geographic limits.
- Hindcast using historical data to determine if range shifts can be explained by climate data.
- Identify intertidal “hot spots” where climate change should have large effects.
- Forecast effects of decadal and seasonal scale climate change on geographic distribution of ecosystem foundation species.
- Communicate results through NERRS Coastal Training Program.
Target Organisms
Ecosystem Foundation Species

• Sedimentary Shores
  – Sediment disruptors (shrimp, worms)
  – Tube and reef builders (worms, oysters)

• Rocky Shores
  – Dominant space occupiers (barnacles, mussels)
Tube Builders

Sediment disturbers
Mussels and Barnacles – Dominant Space Occupiers
Geographic Coverage

- Alaska to Mexico on Pacific Coast
- Maine to South Carolina on Atlantic Coast
- Five National Estuarine Research Reserves on each coast.
- Sites span the geographic limits of ecosystem foundation species
Ecological Forecasting of ecosystem engineers in the coastal zone.
How hot is it on the shore, and how do we measure and predict temperature?

• Measurements
  – Biomimetic sensors
  – Infrared Imagery

• Forecasting, Hindcasting, Nowcasting
  – Mechanistic simulation models
  – Based on ground and satellite climate data
Biomimetic Sensors
Satellite Data Sets

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sensor</th>
<th>Spatial Res</th>
<th>Temporal Res</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Air</td>
<td>TOVS</td>
<td>1°</td>
<td>2/day</td>
<td>1980-present</td>
</tr>
<tr>
<td>Temperature</td>
<td>AIRS</td>
<td>50 km</td>
<td>2/day</td>
<td>2002-present</td>
</tr>
<tr>
<td>SST /</td>
<td>ASTER</td>
<td>90 m</td>
<td>Request</td>
<td>2000-present</td>
</tr>
<tr>
<td>Ground</td>
<td>MODIS</td>
<td>0.5-1 km</td>
<td>2-4/day</td>
<td>2002-present</td>
</tr>
<tr>
<td>Surface</td>
<td>AVHRR</td>
<td>1 – 5 km</td>
<td>1-2/day</td>
<td>1980-present</td>
</tr>
<tr>
<td>Temperature</td>
<td>AMSR-E</td>
<td>10 km</td>
<td>1-2/day</td>
<td>2002-present</td>
</tr>
<tr>
<td></td>
<td>TOVS</td>
<td>1°</td>
<td>2/day</td>
<td>1980-present</td>
</tr>
<tr>
<td></td>
<td>AIRS</td>
<td>50 km</td>
<td>2/day</td>
<td>2002-present</td>
</tr>
<tr>
<td>Solar Rad</td>
<td>GOES</td>
<td>0.5 °</td>
<td>hourly</td>
<td>1996-present</td>
</tr>
<tr>
<td>Clouds</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Ground Based Datasets

• NCDC Integrated Surface Hourly (TD 3505)
  – Air T, Wind, Clouds, Precip, Dewpoint
  – Global coverage (online 1990s – present)
  – we would like to visit Asheville to do downloads of older data

• NERR System Wide Monitoring Program
  – Water quality, Meteorological, Solar Rad

• NDBC offshore buoy/CMAN
  – Air T, Wind, Wave height

• NOAA CO-OPS
  – Tide observations, some met, some SST
NERR Climate Data

• System Wide Monitoring Program
  – Meteorological stations
  – Water quality monitoring

• We are providing pyranometers to NERR sites to collect solar radiation data
Microclimate Model

Predict rock temperature from
- air temperature, humidity, wind, cloud cover
  - NOAA ground & buoy observations
  - NERR SWMP
  - Satellite observations
- water temperature
  - NOAA tide station, CMAN & buoy observations
  - NERR SWMP
  - Satellite observations
- Tides
  - NOAA model /observations or WxTide
  - Wave height adjustment (NOAA buoy observations)
  - NERR SWMP
  - http://tbone.geol.sc.edu/tide
- Solar radiation:
  - angle of incidence of direct sunlight - Jet Propulsion Lab ephemeris of the sun
  - NOAA GEWEX-GCIP Solar Radiation from GOES imagery
  - NERR SWMP Ground-based pyranometers
Tides Generate Geographic Complexity

Tides

SST
Model Cartoon

- \( Q_{\text{rad, sky}} \)
- \( Q_{\text{sol}} \)
- \( Q_{\text{conv}} \)
- \( Q_{\text{evap}} \)
- \( Q_{\text{stored}} \)
- \( Q_{\text{cond}} \)
- \( T_{\text{air}} \)
- \( T_{\text{ground}} \)
- \( T_{\text{body}} \)
- Wind (\( U \))
Model Components

• Low Tide:
  • Solve energy balance at rock/animal surface: convection + radiation + solar = conduction
  • Model heat conduction into rock/animal
  • repeat

• High Tide:
  • Model heat conduction to/from rock
Heat balance equations used to calculate body temperature of an intertidal animal, using climate data.

Major components $Q$ of the heat budget at low tide are:

$$Q_{\text{stored}} = Q_{\text{direct solar}} + Q_{\text{diffuse solar}} + Q_{\text{IR sky}} + Q_{\text{IR ground}} + Q_{\text{conduction}} + Q_{\text{convection}} + Q_{\text{evaporation}}$$

At low tide when animals are exposed to air, this is expanded as:

$$\Delta T_{\text{body}} \ m_{\text{body}} \ cp = \alpha A_{\text{solar}} S + A_{\text{diffuse}} S_{\text{diffuse}} + \sigma \varepsilon A_{\text{radiation}} (T_{\text{sky}}^4 - T_{\text{body}}^4) + \sigma \varepsilon A_{\text{ground}} (T_{\text{ground}}^4 - T_{\text{body}}^4) + 0.5KL^{-1} A_{\text{conduction}} (T_{\text{ground}} - T_{\text{body}}) + C A_{\text{convection}} (T_{\text{air}} - T_{\text{body}}) - \lambda m^*$$

At high tide when animals are immersed in the ocean, this is expanded as:

$$\Delta T_{\text{body}} \ m_{\text{body}} \ cp = 0.5KL^{-1} A_{\text{conduction}} (T_{\text{ground}} - T_{\text{body}}) + C A_{\text{convection}} (T_{\text{water}} - T_{\text{body}})$$
Ground Truth - Cape Cod Canal
Green = Model, Red = datalogger
Ground Truth

- Biomimetic loggers
  - Measure average daily maximum and average daily minimum temperature monthly per logger
  - Determine Mean and Std Deviation of these values at sites from California to Washington

- Model
  - Logger predictions are mostly within 2 SD of logger mean.
  - Indicates model predicts average daily maxima as well as loggers measure it.
Biogeography and climate - the Mediterranean mussel

Black = winter SST 8°C  Red = summer SST 30 °C
Comparing Body Temperatures to Geographic Distribution

Arctic vs Tropical Mussels

AMSR Cloud-Free SST
Geographic Model Predictions

Mussel species in Hokkaido

Combined Genotype Frequencies
US West Coast

Mytilus galloprovincialis
Strait of Georgia: Local *Mytilus galloprovincialis* populations
Geographic Statistics and Prediction
Preliminary Tests

• GARP
  – Genetic algorithms for statistical modeling
  – Dependent variable – species localities
  – Independent variables
    • Weather (Air T, SST, RH, Solar, Clouds, etc)
    • Model output (Avg Daily Max, Avg Daily Min)

• Mussel species in Hokkaido
  – 67% of the variance in species distribution is explained by independent variables
California-Oregon
Geographic Limits of Mussels

• Field Programs Underway
  – Sampling at 50 km intervals from Pt Sur to north of San Francisco – southern limit of arctic mussel – DNA fingerprinting analysis
  – Biomimetic sensors deployed from Santa Barbara to British Columbia

• Modeling Programs Underway
  – Ground Truth of Mussel Model
  – Sensitivity Analysis
Biogeography and Climate – the arctic barnacle

Fig. 3. Some records of the barnacle *Balanus balanoides*, showing particularly the apparent southern limits of the species. These limits are best fitted by the isotherm of the minimum monthly mean (winter) surface water temperature of 45° F.
Southern Geographic Limit of the arctic barnacle in BC – Washington State

Padilla Bay NERR
BC – Washington Border: Southern Limit of Arctic Barnacle Infaunal Analysis

• Field Programs Underway
  – Biomimetic loggers in San Juan Islands
  – Biomimetic loggers in Strait of Georgia

  – Sediment thermal conductivity measurements
    • San Juan Island
  – Preliminary infaunal activity measurement
    • Padilla Bay NERR, San Juan Island
Southern Limit of Arctic Barnacle and Arctic Mussel

- **Field Experiments underway**
  - Transplants beyond geographic limit
    - Growth, Mortality, Heat Shock Protein
  - Transplants within geographic range
    - Same measurements
  - Biomimetic temperature sensors deployed

- **Lab Programs**
  - Heat shock protein methods development

- **Modeling Programs**
  - Ground truth of barnacle model
Ground Truth of Barnacle Model
South Carolina Rock Temperatures

Measurement          Model Prediction

![Measurement Graph](image1)
![Model Prediction Graph](image2)
Modeled Barnacle Thermal Limits
North Carolina  South Carolina

Mid Shore Horiz

Lethal Coma

Mid Shore N face

Lethal Coma
Sedimentary Habitats

• Model development
  – Thermal conductivity vs grain size

• Depth-Time profiles of sediment temperature
  – Washington – Padilla Bay NERR
  – California - Elkhorn Slough NERR
  – South Carolina – North Inlet NERR
Sedimentary Habitats
Thermal conductivity of sediments

Temp Profiles (Thalassinid area top, Aerenicola on bottom)
Sublethal Effects on Populations

- Heat Shock Protein Expression

- Activity
  - Non invasive recordings of infaunal activity by porewater pressure sensors
  - Behavior specific waveforms
In situ behavior logging: pressure signals recorded in sediments

Clam
Nereid polychaete
Arenicolid polychaete
Bed of *Abarenicola*
Sediment Disruptor
Non-Invasive Activity Measures in Sedimentary Systems

Porewater Pressure

Water Flow and Behavior

Abernicola Defecation Signal

Time (min)

Porewater Pressure (cm of water)
NERR Sites Visited to Date

- Padilla Bay, Washington
- Elkhorn Slough, California
- Tijuana Slough, California
- Waquoit, Massachusetts
- Outer Banks, North Carolina
- North Inlet, South Carolina
NERR System Wide Monitoring Program

- Met with the weather station technicians from all NERR sites at their annual training session in January 2005.

- Central Data Management Office is on our campus at the University of South Carolina
Data Management and Modeling Software

• All Open Source Software
  – PostgreSQL relational database
    • www.postgresql.org
  – PostGIS georeferencing database modules
    • www.postgis.org
  – Mapserver / Generic Mapping Tools
    • mapserver.gis.umn.edu       gmt.soest.hawaii.edu
  – R statistics language
    – www.r-project.org
Model Application Example

• Resource Managers
  – Predict effects of El Nino or La Nina events when the ENSO indicators start changing.
  – Predict effects of hot or cool summers if the seasonal forecasts indicate an anomaly is coming.
  – If local die-offs or range shifts are predicted, the managers can plan a response in advance.
User Interface

• Year 3
  – Web-based front end to draw maps of
    • Forecasts
    • Hindcasts
    • Nowcasts

• We been getting advice from the programming team for CAROCOOPS, and SEACOOS who are on our campus.
Related Value Added Projects

• NASA Earth Science Enterprise
  – Biogeography and climate (W Pacific, E Atlantic)
    • PI Helmuth, Co PIs Wethey, Hilbish, Lakshmi
    • Barnacles and Mussels
    • Hong Kong to Hokkaido
    • Morocco to Scotland

• ONR Science & Technology
  – Real time measurement of behavior in infauna
    • PI Woodin, CoPIs Wethey, Marinelli
    • Worms and burrowing shrimp - pressure sensor development
The tropical atlantic barnacle
*Chthamalus fragilis* Darwin

- Caribbean to Cape Cod 1898
- Caribbean to Carolinas 1850
- Moving north with climatic warming?
Fig. 1. Minimum monthly mean temperatures for the months December to February in each winter, 1780–1980, at Boston, Massachusetts. Data are from Paine (1834), Blodgett (1857), Pickering (1889), and United States Weather Bureau (1936, 1931–1980). Temperatures below –5°C are associated with sea ice (see Methods: Climate Reconstructions).
Chthamalus refuge vs maximum rock temperature