National Park Service
U.S. Department of the Interior

South Florida Natural Resources Center
Everglades National Park

FLORIDA BAY ASSESMENT MODEL VERSION 1.0 April 18, 2016

User Manual

South Florida Natural Resources Center

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HYDROLOGIC MODEL MANUAL

SFNRC 2016:7-27

Cover picture shows false color satellite image of Florida Bay.

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South Florida Natural Resources Center
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Homestead, Florida

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EXECUTIVE SUMMARY

No estimate is more in danger of erroneous calculations
than those by which a man computes the force of his own genius.

– Samuel Johnson

Since all models are wrong the scientist cannot obtain a "correct" one by excessive elaboration. On the contrary following William of Occam he should seek an economical description of natural phenomena. Just as the ability to devise simple but evocative models is the signature of the great scientist so overelaboration and overparameterization is often the mark of mediocrity.

– George Box, (*Box*, 1976)

The Florida Bay Assessment Model (BAM) is a simple basins hydrological model specific to Florida Bay. The physical basis is exceedingly simple, conservation of mass, thereby the suggestion of Box may find some satisfaction. Nonetheless, simplification and reductionism have dangers of their own, particularly when attempting to comprehend complexity as abounds in the natural world.

BAM attempts to balance the dimensional reduction of the physical description valued by Box with fidelity to the underlying complexities through use of the best available observational data describing the environment. BAM leverages a rich set of high-fidelity observational data within Florida Bay administered by Everglades National Park: The Marine Monitoring Network, as well local tide predictions to address this need. BAM is also unique in that it is pure Python. Every aspect of the model is open, requiring no proprietary or special libraries or compilers. The source code is object-oriented, designed to be readable and extensible, fostering community involvement and empowering the user to mold the model to suit their own understanding of the underlying processes.

Dr. Johnson would no doubt question any claims of success and veracity regarding the usefulness of BAM, and as specifically observed by Box, the hope is that BAM will provide an economical description, albeit not a correct one, of natural phenomena in Florida Bay.

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1 Introduction

The Florida Bay Assessment Model (BAM) is a 'basins' hydrological model of Florida Bay. It is mass-conservative and explicitly designed to assess water levels and salinities in 54 idealized basins representing Florida Bay. Basins are separated and connected by shoals, thereby the model conforms to a linked-node network hierarchy with basins as nodes and shoals as links. Interbasin fluxes are driven by hydraulic gradients developed across the shoals in response to water level elevations and are modeled with depth integrated velocity based on frictional flow from Manning's equation.

Each basin is forced with rainfall and evaporation. Basins on the Gulf of Mexico and Atlantic Ocean boundaries are also forced across the appropriate shoals with sea levels consisting of tidal variations and sea level changes. Coastal basins along the Everglades are forced with water levels determined from the Everglades Depth Estimation Network (EDEN) (*Telis et al.*, 2014) with the shoal properties (length, width, depth) calibrated to match aggregate runoff from the FATHOM model (*Cosby et al.*, 2010).

BAM can be considered a derivative work from FATHOM since it employs the same basic physical and domain representations, however, it is significantly different in several aspects. First, BAM uses contemporary, high-quality, high-temporal density observational data to drive model inputs and boundaries. These environmental forcings leverage the wealth of meteorological and hydrographic observations available from the Marine Monitoring Network administered by Everglades National Park. Tidal data are computed from local NOAA subordinate tide stations within Florida Bay containing all astronomical forcings including intrannual variations. The reliance on high-quality, nearly continuous observational data to drive model inputs is a particular strength of BAM.

Second, BAM is pure Python. While this imposes an operational constraint since model runtimes are slower than a compiled binary image, it affords several advantages:

- Object oriented code facilitates clarity, scalability, extensibility and developer collaboration with modern programming language dictums.
- Adherence to modern programming standards and naming conventions results in code that is human readable and understandable, reducing the potential for software errors.
- Python dictionaries and native data containers simplify and clarify the processing of model data and objects.
- Cross-platform support. Any platform that runs Python can run BAM.
- No binaries and no dependence on special compilers or licensed third-party libraries.

Third, BAM outputs are not limited to specific time intervals, the output interval is user-controllable. Fourth, all BAM inputs/outputs are contained in ASCII comma delimited files imposing a uniform and accessible standard for model I/O enabling the evaluation of alternative scenarios in a straightforward manner. Fifth, the graphical user interface is designed to allow interaction and querying of model results and parameters. Each basin and shoal in the model is accessible with a mouse click on the map, or from a list box. Integrated plotting facilities allow the comparison of model outputs from different runs. Sixth, the GUI is not required. BAM can be run in text-mode inside a terminal and is therefore easily controlled in batch mode by shell or other scripts. Seventh, all model controls are exposed through the command line interface which applies whether the GUI is used or not.

Lastly, BAM is open-source. This fosters transparency, allows community development, and empowers the individual to adjust and change any aspect of the model to suit their needs or conceptualizations.

1.1 Limitations

The physical basis is interbasin Mannings flow over shoals with conservation of mass. The simplified physical basis imposes several restrictions:

1. No wave propagation, stage/volume changes are instantaneous.
2. No diffusion/mixing, concentration equilibriums are instantaneous.
3. Mannings flow over deep or narrow shoals is not justifiable.
4. Water levels are not geodetic, but anomalies with respect to zero shoal depth.
5. Geomorphic bank and shoal changes over time are ignored.

The representation of basins, shoals and forcings is incomplete:

1. There are shoals with missing channels. For example, the Florida Keys are largely considered flow barriers, ignoring many channels.
2. Evaporation is a single daily timeseries applied to the entire domain.
3. Rainfall is a sparse set of daily timeseries.

2 Model Domain

BAM decomposes Florida Bay into 54 basins based on the geomorphology of the mangroves, buttonwood banks, and shoals separating individual basins (figure 1). Basin bathymetry is partitioned into 10 depth classes in 0.305 m (1 ft) increments following *Cosby et al.* (2010). There are 410 shoals linking the basins each characterized with a shoal width, land length (zero depth), and submerged lengths partitioned into the same 10 depth classes as the basins. Each shoal also has a Manning's friction coefficient applied over the shoal width, so that the shoal width is parallel to the interbasin flow path while the shoal lengths are perpendicular to the flow path.

Shoal data are derived from the work of *Cosby et al.* (2010), however a review of the shoals bordering domain boundaries with the Florida Keys and Everglades identified numerous deficiencies ignoring well-established flow paths between the boundaries and model basins. These shoals were adjusted and calibrated to produce water level dynamics inside the appropriate basins consistent with observed water level data.

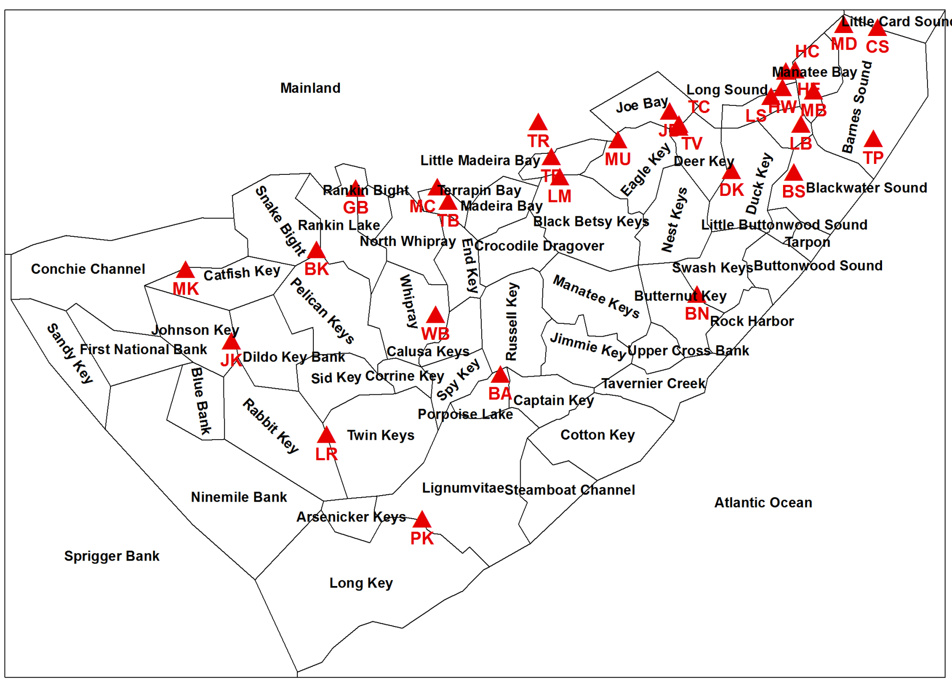

Figure 1.

BAM domain with basins and hydrographic stations (red).

3 Physical Representation

The physical basis of BAM is exceedingly simple. Mass-transport over shoals is governed by the transport velocity v integrated over the shoal depth and length

$$v = \sqrt{2g\,\frac{h_u - h_d}{1+f}} \tag{1}$$

where h_u and h_d are the upstream and downstream basin water levels, and f a friction factor

$$f = 2g\,n^2\,w\,\rho^{-4/3} \tag{2}$$

where n is the Mannings coefficient, w the shoal width, ρ the shoal hydraulic radius and g the vertical acceleration. The module `hydro.py` contains all hydraulic computations.

The mass flux of dissolved substances over each shoal M (g) is calculated as the product of the concentration of the substance in the water C ($\mathrm{g\,m^{-3}}$) and the water mass flux F ($\mathrm{m^3\,s^{-1}}$) on each shoal. The mass fluxes M are summed around the boundary of each basin, the net mass flux over the shoals is multiplied by the time step and, along with other inputs and outputs of mass during the time step, added to the mass in the basin at the beginning of the time step. The new mass is divided by the water volume to estimate the concentration at the end of the time step.

4 Input

BAM inputs are derived from a variety of sources, and with the exception of the Sea Level and Tide data are daily values specific to each basin in the domain. Sea Level is a monthly value applied to all Gulf and Ocean boundary basins, while Tides are interpolated to the model timestep from hourly tide data. The data files and their periods of record are listed in table 1.

Variable	File	Start	End	Option
Rain	DailyRainFilled_cm_1999-9-1_2015-12-8.csv	1999-09-01	2015-12-08	`-br`
ET	PET_1999-9-1_2015-12-8.csv	1999-09-01	2015-12-08	`-et`
Tide	HourlyTide1990_2020.tar.gz	1990-01-01	2021-01-01	`-bt`
Sea Level	MSL_Anomaly.csv	1999-08-15	2015-12-15	`-msl`
Runoff	EDEN_Stage_OffsetMSL.csv	1999-09-01	2015-12-31	`-bR`
Flow	S197_Flow_1999-9-1_2016-3-31.csv	1999-09-01	2016-03-31	`-bc`
Salinity	DailySalinityFilled_1999-9-1_2015-12-8.csv	1999-09-01	2015-12-08	`-sf`
Stage	DailyStage_1999-9-1_2016-3-1.csv	1999-09-01	2016-03-01	`-bs`

Table 1. Input data files, period of record and command line option. Note that Salinity and Stage inputs are used for model output comparison, not as explicit model inputs. However, salinity timeseries can be imposed on basins with the `--gaugeSalinity` command line option.

The input files listed in table 1 are created from the raw data with a series of R or Python scripts found in the `etc/` directory. These files include

1. `CreateRainData.R`
2. `CreateET.R`
3. `CreateTideData.py`
4. `CreateRegion.2.3.tide.R`
5. `EDEN_Stage.R`
6. `CreateSalinityData.R`
7. `Boundary.Salinity.R`
8. `CreateStageData.R`

4.1 Basins

Basins and their associated observational data stations are listed in table 2. Basins numbered 5 - 58 are the 54 basins representing Florida Bay, basins 1 - 4 are not used. Basins 59 - 68 are boundary basins representing Gulf of Mexico and ocean boundaries, and basins 69 - 82 are boundary basins of the Everglades. Each of the boundary basins has a one-to-one mapping to a basin in the model domain as described in the appropriate section (Tides section 4.6, or Runoff section 4.5).

Basin	Name	Gauge	Basin	Name	Gauge
5	Barnes Sound	MD	44	Dildo Key Bank	None
6	Manatee Bay	MB	45	Tavernier Creek	None
7	Long Sound	LS	46	Butternut Key	BN
8	Little Blackwater Sound	LB	47	Duck Key	DK
9	Blackwater Sound	BS	48	Manatee Keys	None
10	Tarpon	None	49	Swash Keys	BN
11	Little Buttonwood Sound	None	50	Deer Key	TC
12	Nest Keys	None	51	Eagle Key	None
13	Joe Bay	TC	52	Steamboat Channel	None
14	Little Madeira Bay	LM	53	Arsenicker Keys	None
15	Black Betsy Keys	LM	54	Sid Key	None
16	Upper Cross Bank	None	55	Pelican Keys	None
17	Rock Harbor	None	56	Blue Bank	None
18	Buttonwood Sound	None	57	First National Bank	None
19	Jimmie Key	None	58	Sandy Key	None
20	Cotton Key	None	59	Gulf Tide 1	Gulf_1
21	Captain Key	None	60	Gulf Tide 2	Gulf_1
22	Russell Key	None	61	Gulf Tide 3	Gulf_1
23	Crocodile Dragover	None	62	Gulf Tide 4	Gulf_1
24	Madeira Bay	None	63	Ocean Tide 5	Ocean_1
25	Terrapin Bay	None	64	Ocean Tide 6	Ocean_1
26	End Key	None	65	Ocean Tide 7	Ocean_1
27	Calusa Keys	None	66	Ocean Tide 8	Ocean_1
28	Spy Key	None	67	Ocean Tide 9	Ocean_1
29	Porpoise Lake	BA	68	Card Sound Tide 10	Ocean_1
30	Lignumvitae	PK	69	EVER to Snake Bight	S15
31	Long Key	None	70	EVER to Rankin Lake	S16
32	Twin Keys	LR	71	EVER to Rankin Bight	S16
33	Corrine Key	None	72	EVER to North Whipray	S16
34	Whipray	WB	73	EVER to Terrapin Bay	S17
35	North Whipray	None	74	EVER to Madeira Bay	S17
36	Rankin Bight	None	75	EVER to Little Madeira Bay	S18
37	Rankin Lake	GB	76	EVER to Eagle Key	S19
38	Rabbit Key	LR	77	EVER to Joe Bay	S20
39	Johnson Key	JK	78	EVER to Deer Key	S21
40	Catfish Key	MK	79	EVER to Long Sound	S22
41	Snake Bight	BK	80	EVER to Manatee Bay	S22
42	Conchie Channel	None	81	EVER to Conchie Channel	S15
43	Ninemile Bank	None	82	EVER to Barnes Sound	S22

Table 2. BAM basin numbers, names and observational data/boundary stations.

The basin parameter file defines mappings between basins and observational gauges, as well as boundary basins and their input timeseries. This file is specified with the `-bp [--basinParameter]` option (default: `Basin_Parameters.csv`).

The basin shapefile is specified with the `-bn [--basins]` option (default: `data/GIS/FLBayBasins`).

Bathymetry is described in the `-bd [--basinDepth]` file (default: `Basin_Area_Depth.csv`).

Initial values of basin variables are set from the `-bi [--basinInit]` file (default: `Basin_Initial_Values.csv`)

However, for basins where observations are available the `-si [--salinityInit]` option (default: `yes`) will override the initial salinity values set from `basinInit` with observed data.

4.2 Shoals

Shoals are links between basins, and the objects where mass transport is quantified. The structure of the model is dictated by the basin-shoal linkage in the `-sp [--shoalParameters]` file (default: `Shoal_Parameters.csv`).

The shoals shapefile is specified with the `-s [--shoals]` option (default: `data/GIS/FathomLines`).

Shoal bathymetry and width is defined in the `-sl [--shoalLength]` file (default: `Shoal_Length_Depth.` Mannings friction coefficients are also specified in the `shoalLength` file.

The user can override the Mannings coefficients specified in `shoalParameters` with the `-sm [--shoalManning]` option (default: `None`). Use of this option will set the Mannings coefficient for all shoals in the model to the single specified value.

4.3 Rain

Rain input is based on observational data from the Marine Monitoring stations show in figure 1. Since data coverage is not continuous, a resampling scheme is used to estimate surrogate values for missing data at each station. Data from each station is first partitioned into rain observations for each day of the year over the period of record. Data for a missing day is reconstructed by randomly sampling from the partitioned data for that day over all years. This preserves the seasonal distribution of rainfall while allowing for natural variability.

Observed and reconstructed rain at the stations in eastern Florida Bay is shown in figure 2, and for the western basins in figure 3.

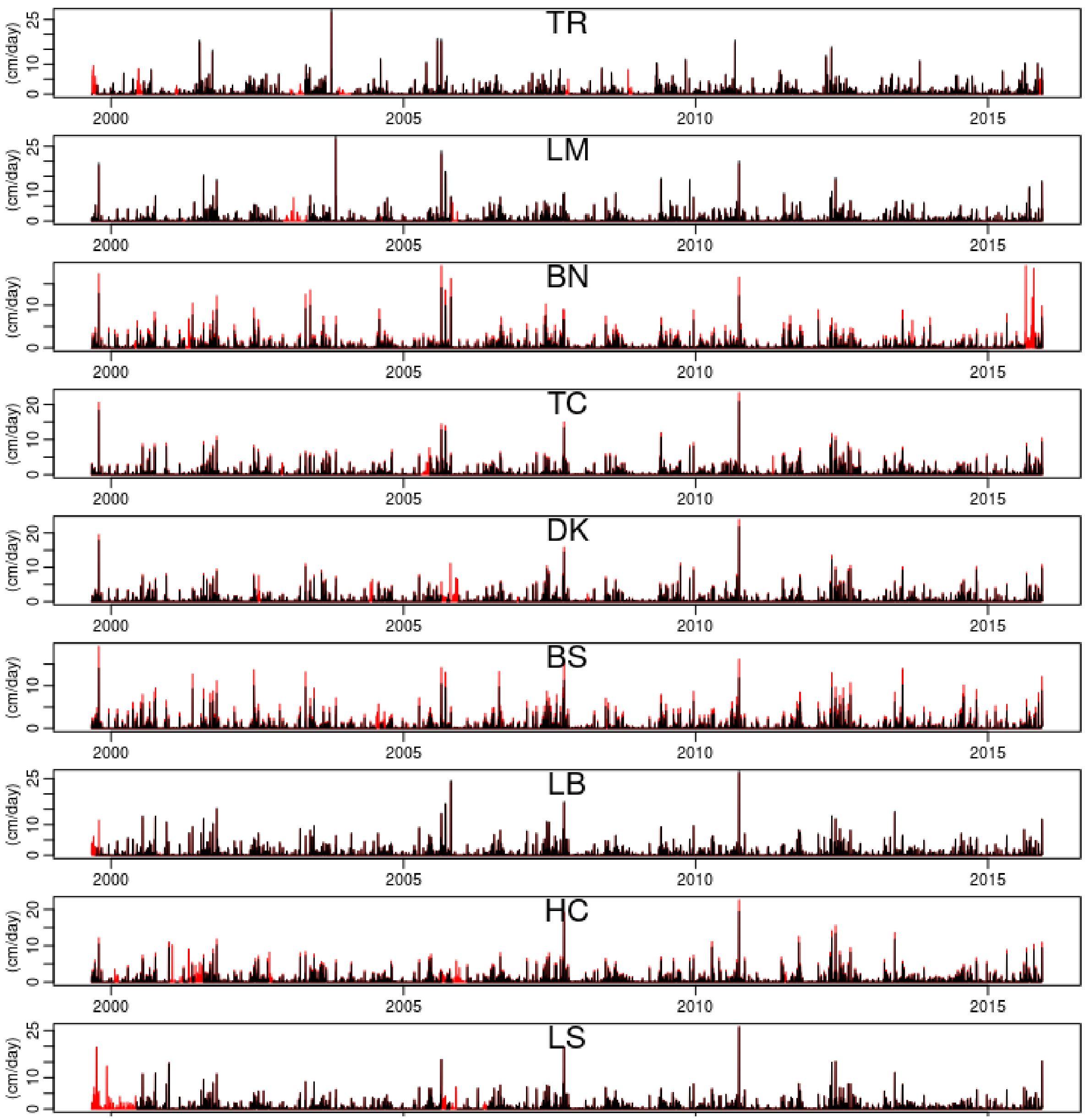

Figure 2. East Florida Bay observed rain (black) and reconstructed rain (red).

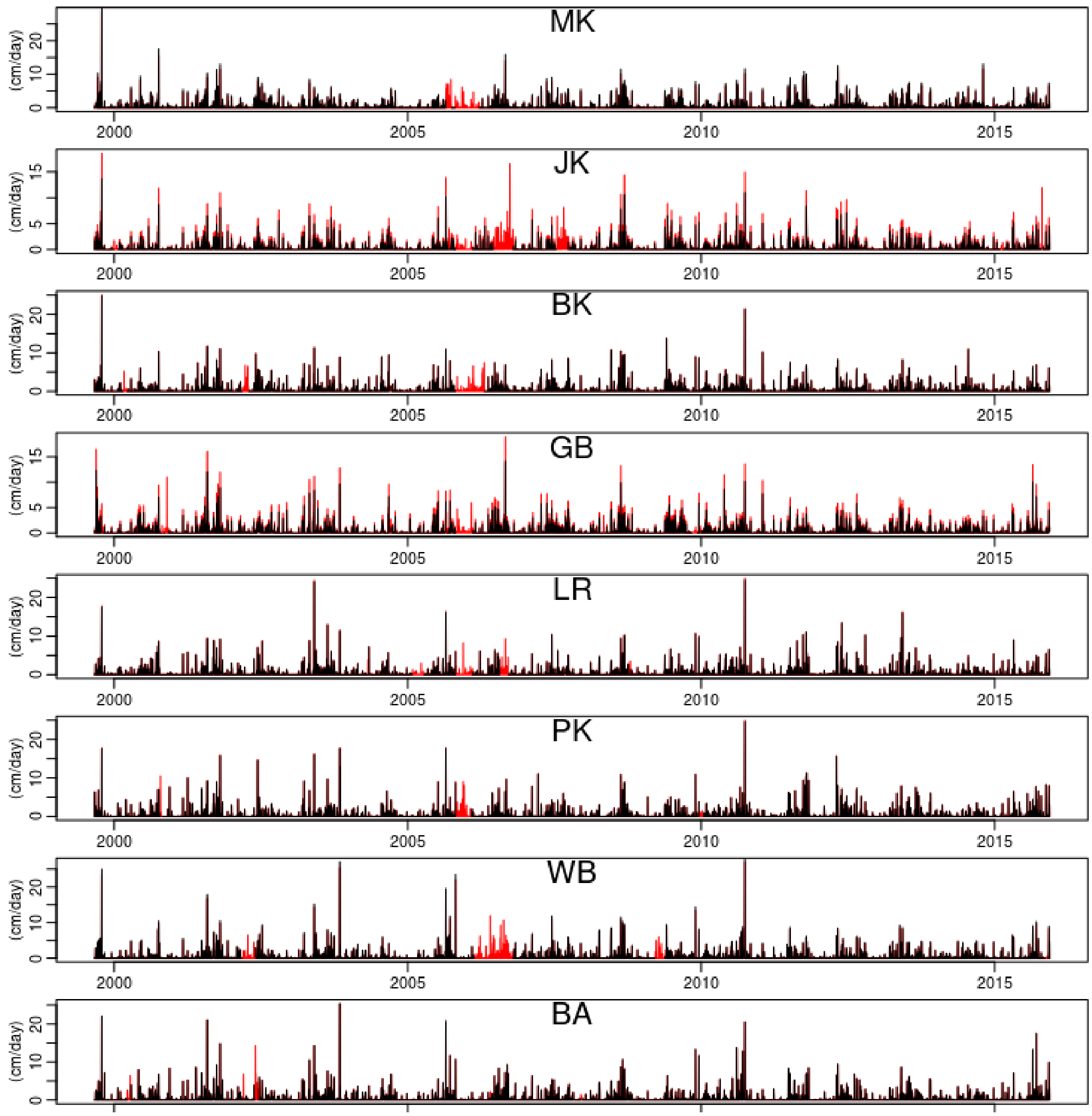

Figure 3. West Florida Bay observed rain (black) and reconstructed rain (red).

Estimation of total rain over basins tens to hundreds of square kilometers in area is notoriously challenging based on sparse, point measurements. To afford the user control over the selection and effective areal input of rain, a mapping of basin to rain gauge stations is specified in the basin parameters (`-bp, [--basinParameter]`) file. An excerpt of the basin parameter file is shown here:

```
Basin,      Name,            Rain Gauge,   Rain Scale, Gauge
8,    Little Blackwater Sound, [ LS LB BS ], [ 3 2 3 ],  LB
9,    Blackwater Sound,        [ DK BS LB ], [ 2 3 2 ],  BS
10,   Tarpon,                  [ BS BN DK ], [ 2 2 1 ],  None
11,   Little Buttonwood Sound, [ BS BN DK ], [ 1 2 2 ],  None
```

The `Rain Gauge` column defines a list of rain gauges aggregated to produce the input rainfall for a basin. The `Rain Scale` is a corresponding list of scale factors applied to each rain gauge data value in the gauge list. This allows complete control over the basin rain input, and has been found to give good spatial smoothing to compensate for the fact that point measurements of rain are often insufficient to represent total rain volumes over a large areal extents.

The rain input file is specified with the `-br [--basinRain]` option, and has a default value of `DailyRainFilled_cm_1999-9-1_2015-12-8.csv`. Rain inputs can be disabled by specifying the `-nr [--noRain]` option, which has a default value of `False`.

4.4 ET

Evapotranspiration (ET) data are obtained from the South Florida Water Management District (SFWMD) measuring stations at Joe Bay in the C-111 basin (JBTS_C111), structure S331 in the L31N basin (S331W_L31NS), and a three station average in water conservation area 3A of the WCA3A basin (3AS3WX_WCA3). Note that these basins are not in Florida Bay.

A single timeseries is created by taking the maximum value of the three data sets for any given day which covers most data gaps. The remaining gaps are reconstructed with a resampling scheme where the data are partitioned into samples for each day of the year over the period of record and missing data randomly drawn from the samples for a specific yearday. Figure 4 plots the resultant ET data which is applied to all basins in the model.

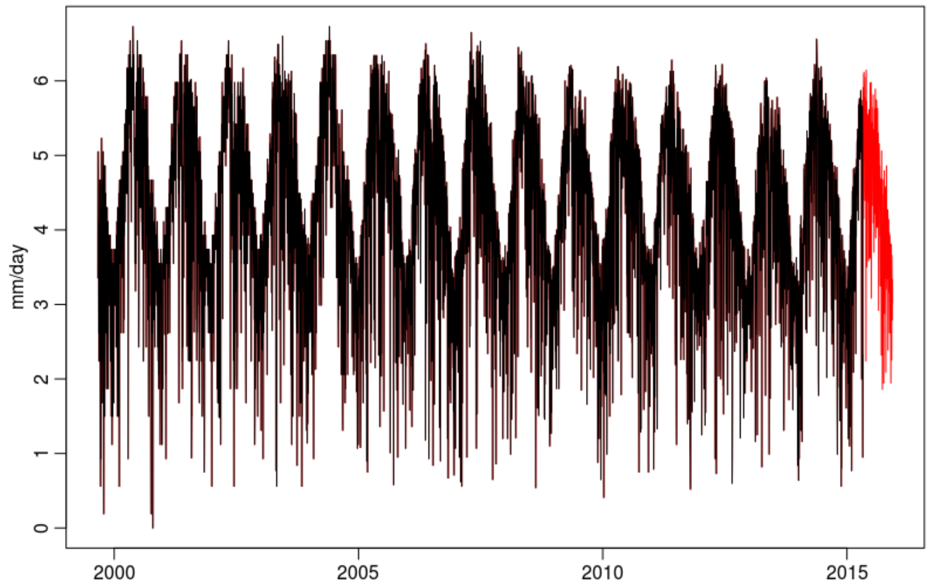

Figure 4.

SFWMD observed ET (black) and reconstructed ET (red).

To provide user control over the magnitude of ET, the `-es [--ET scale]` command line option applies a scale factor to the data shown in figure 4.

The ET input file is specified with the `-et [--ET]` option, and has a default value of `PET_1999-9-1_2015-12-8.csv`. ET inputs can be disabled by specifying the `-ne [--noET]` option, which has a default value of `False`.

4.5 Everglades Runoff

The BAM convention for basin runoff is that positive runoff corresponds to flow leaving the basin, while negative runoff quantifies flow entering the basin.

A hydraulic head relationship exists between water levels in the southern Everglades and freshwater runoff into the coastal basins as expressed in strong negative correlations between Everglades water level and coastal basin salinity (*Tabb*, 1967; *Kelble et al.*, 2007). BAM uses this relationship to estimate integrated Everglades runoff (streamflow, sheetflow and groundwater) into the coastal basins by the same shoal hydraulics as all other interbasin flows. Shoal parameters are calibrated to match runoff values determined by FATHOM (*Cosby et al.*, 2010) in section 10.

Upstream basins representing the Everglades have water levels determined by values extracted from the Everglades Depth Estimation Network (EDEN) at eight stations shown in figure 5 and table 3. These water levels are converted from NAVD to water level anomalies with respect to Florida Bay mean sea level over the period 2008 - 2015.

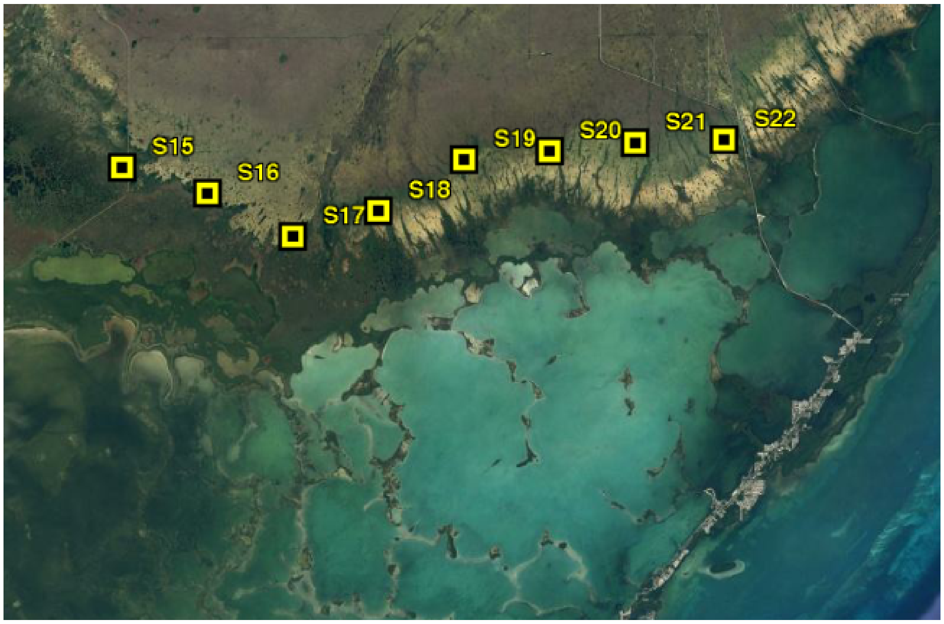

Figure 5.

Eight stations in the southern Everglades where EDEN stage is extracted to provide hydraulic forcings for runoff into the coastal basins.

Station	UTM North	UTM East	Zone	Longitude	Latitude
S15	2794000	520000	17	-80.801379	25.262235
S16	2792500	525000	17	-80.751752	25.248614
S17	2790000	530000	17	-80.702158	25.225945
S18	2791500	535000	17	-80.652480	25.239383
S19	2794500	540000	17	-80.602747	25.266350
S20	2795000	545000	17	-80.553075	25.270723
S21	2795500	550000	17	-80.503400	25.275079
S22	2795700	555200	17	-80.451747	25.276703

Table 3. Coordinates of EDEN stations providing Everglades stage to drive runoff.

Water levels at the EDEN stations are shown in figure 6 exhibiting the expected seasonal uniformity, as well as deeper dry-season minima along the western bay.

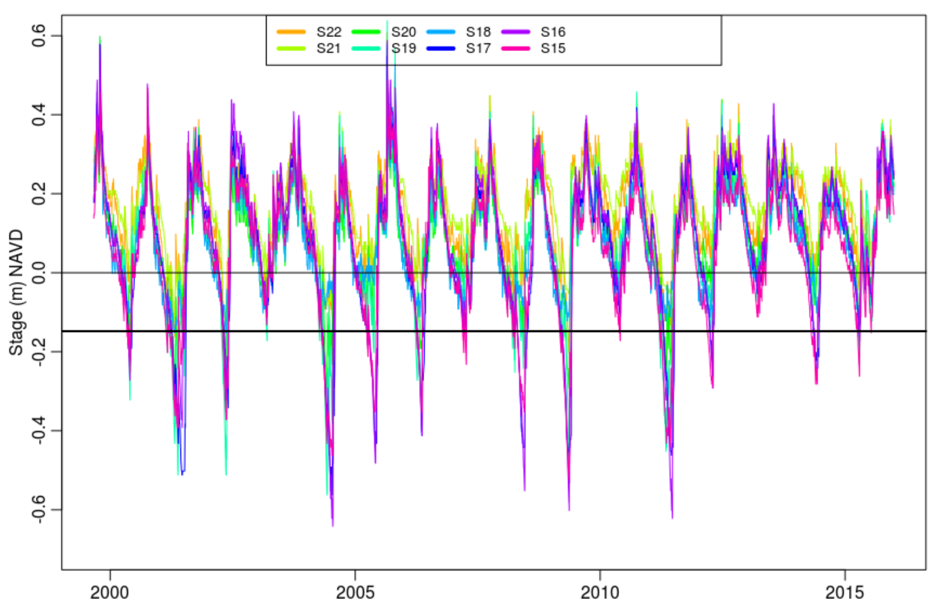

Figure 6.

EDEN stage at eight stations in the southern Everglades. Mean sea level (2008-2015) is shown by the line at -14.8 cm.

The EDEN stage file used to drive runoff is specified with the `-bR [--basinStageRunoff]` option with a default value of `EDEN_Stage_OffsetMSL.csv`. The mapping of EDEN stage values to coastal basins and the corresponding shoals is specified with the `-bS [--basinStageRunoffMap]` with a default of `Basin_Runoff_Boundary.csv`. Runoff from the hydraulic stage relationship can be disabled with the `-nR [--noStageRunoff]` option which has a default of `False`. An example of the EDEN stage to coastal basin runoff mapping file is shown below.

```
Source_Basin, EDEN, Dest_Basin, Dest_Name,         Shoals
82,           S22,  5,          Barnes Sound,      [ 373 ]
80,           S22,  6,          Manatee Bay,       [ 333 334 ]
79,           S22,  7,          Long Sound,        [ 336 337 338 339 340 341 342 343 ]
77,           S20,  13,         Joe Bay,           [ 348 358 359 360 ]
75,           S18,  14,         Little Madeira Bay,[ 168 169 170 171 172 173 174 ]
74,           S17,  24,         Madeira Bay,       [ 149 150 151 ]
73,           S17,  25,         Terrapin Bay,      [ 142 143 144 ]
72,           S16,  35,         North Whipray,     [ 126 127 ]
71,           S16,  36,         Rankin Bight,      [ 135 ]
70,           S16,  37,         Rankin Lake,       [ 136 137 138 139 140 141 ]
69,           S15,  41,         Snake Bight,       [ 24 25 26 ]
78,           S21,  50,         Deer Key,          [ 346 347 ]
76,           S19,  51,         Eagle Key,         [ 356 357 ]
81,           S15,  42,         Conchie Channel,   [ 6 7 8 9 10 ]
```

4.6 Tides

Tidal variations are a primary driver of hydraulic fluxes throughout Florida Bay. In order to accurately estimate basin water levels and thereby the associated mass transports between basins BAM uses local, hourly tidal estimates as the foundation for tidal boundary conditions. These estimates are computed from NOAA subordinate station harmonic constituents at the stations listed in table 4. The resultant tidal data contain all astronomical forcings, but do not include variations of secular sea level rise or annual and interannual cycles from ocean currents and atmospheric teleconnections. Those are accounted in section 4.7.

Name	Station ID
Cape Sable, East Cape, Florida	TEC4165
Long Key, western end, Florida	8723899
Lignumvitae Key, NE side, Florida Bay, Florida	8723824
Snake Creek, Hwy. 1 bridge, Windley Key, Florida	8723787
Tavernier Creek, Hwy. 1 bridge, Hawk Channel, Florida	8723748
Garden Cove, Key Largo, Florida	8723622
Little Card Sound bridge, Florida	8723534

Table 4. NOAA subordinate tide stations where tides are calculated along the gulf and ocean boundaries.

Timeseries for the stations in table 4 are generated by the `CreateTideData.py` and `CreateRegion.2.3.tide.R` programs.

Basins numbered 59 - 68 are tidal boundary basins, each one connected to a Florida Bay basin as specified in the `shoalParameters` file and shown in table 5.

Name	Basin	Name	Basin	Shoals
Conchie Channel	42	Gulf_1	59	23
Sandy Key	58	Gulf_2	60	22 370
Ninemile Bank	43	Gulf_3	61	45 371
Long Key	31	Gulf_4	62	70
Long Key	31	Ocean_5	63	64 65 66 67 68
Long Key	31	Ocean_6	64	61 62 63 239 237
Lignumvitae	30	Ocean_6	64	237
Steamboat Channel	52	Ocean_7	65	240
Cotton Key	20	Ocean_7	65	241 242
Tavanier Creek	45	Ocean_8	66	271 272 273 274
Rock Harbor	17	Ocean_8	66	288
Buttonwood Sound	18	Ocean_9	67	289 290
Tarpon	10	Ocean_9	67	309
Blackwater Sound	9	Ocean_9	67	310
Barnes Sound	5	Ocean_9	67	365 366
Barnes Sound	5	Ocean_10	68	362 363

Table 5. Tide boundary basin and shoal mapping. Boundary basin names corresponds to the basin Gauge listed in table 2.

There are no NOAA stations along western Florida Bay between Cape Sable and Long Key. Examination of tidal response at these two stations shows that tides at Long Key are delayed by 6 - 8 hours and attenuated by a factor of 2.7 - 3 in relation to Cape Sable. To estimate tidal responses between these two points it is assumed that the upper region tides are 2/3 the amplitude and 3 hours delayed from Cape Sable, while the lower region is 4/3 the amplitude and 3 hours prior to Long Key. These amplitude and phase modulations are performed in `CreateRegion.2.3.tide.R` producing the tidal forcings for the `Gulf_2` and `Gulf_3` boundaries. A graphical comparison shows that these assumptions give a reasonable transitional tidal response between Cape Sable and Long Key.

The mapping between boundary basin tidal heights and tidal timeseries is specified in the `-bt --basinTide` file (default: `Basin_Tide_Boundary_2010_2015.csv`). If the `-nt [--noTide]` option (default: `False`) is activated, no tidal data are applied at the boundaries.

BAM interpolates the hourly tidal timeseries to the model timestep at runtime based on cubic spline fits to the hourly data. The cubic splines are generated during model initialization and this process can be time consuming. Two approaches are used to minimize this process. First, the spline generations are parallel processed by up to 4 processors (if available). Second, subsets of hourly tidal data can be specified in the `basinTide` file that correspond to the model simulation period, say 2010-1-1 to 2015-12-31 instead of the entire model period of record.

An example of tidal boundary data and the corresponding basin response is depicted in figure 7.

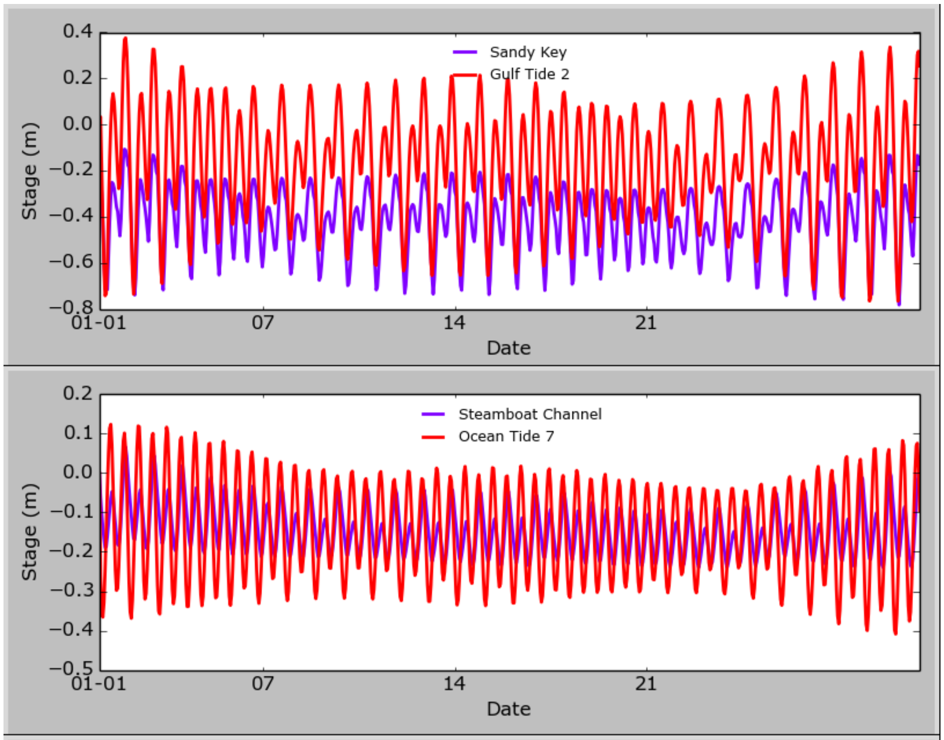

Figure 7.

Tidal boundary conditions (red) and corresponding basin water levels (blue) for the period 2010-1-1 through 2010-1-31.

4.7 Sea Level

Tidal data are local and derived from astronomically-forced harmonic constituents fit to water level observations. As such, they do not include sea level response to regional ocean currents, atmospheric teleconnections or secular sea level rise. To address this the `-msl [--seasonalMSL]` file (default: `MSL_Anomaly.csv`) specifies a regional mean sea level anomaly timeseries superimposed on the tidal boundary data. Regional sea levels are not applied if the `-nm [--noMeanSeaLevel]` option (default: `False`) is activated.

The default regional sea levels in `MSL_Anomaly.csv` are determined from monthly mean sea level data at the three long-term, primary NOAA tide stations listed in table 6. Monthly mean sea levels published by NOAA have the annual seasonal cycle removed, and are with respect to the current (1983 - 2001) National Tidal Datum Epoch (NTDE) determination of mean sea level at each station.

Station	CO-OPS ID	Verified Data	NAVD (m)	MSL (m)
Virginia Key	8723214	1994 - 2016	3.698	3.431
Vaca Key	8723970	1973 - 2016	1.182	0.931
Key West	8724580	1954 - 2016	1.928	1.662

Table 6. Long-term, primary NOAA tide gauges. MSL is the NTDE mean sea level datum elevation, and NAVD the North American Vertical Datum elevation.

To represent total mean sea level the annual seasonal cycle at each station is added to the published monthly sea levels and converted to the NAVD datum. The three stations are then averaged to estimate a regional mean sea level timeseries on a common datum (RMS deviation of 1.7 cm).

Finally, the mean sea level is converted from the NAVD datum to mean sea level in Florida Bay over the 2008-2015 period. Mean sea level in Florida Bay is determined from an average of daily mean data smoothed with a 30-day moving average at stations LM, PK and MK. This is necessary since BAM operates on water level anomalies rather than a geodetic reference. The resultant sea level signal is shown in figure 8.

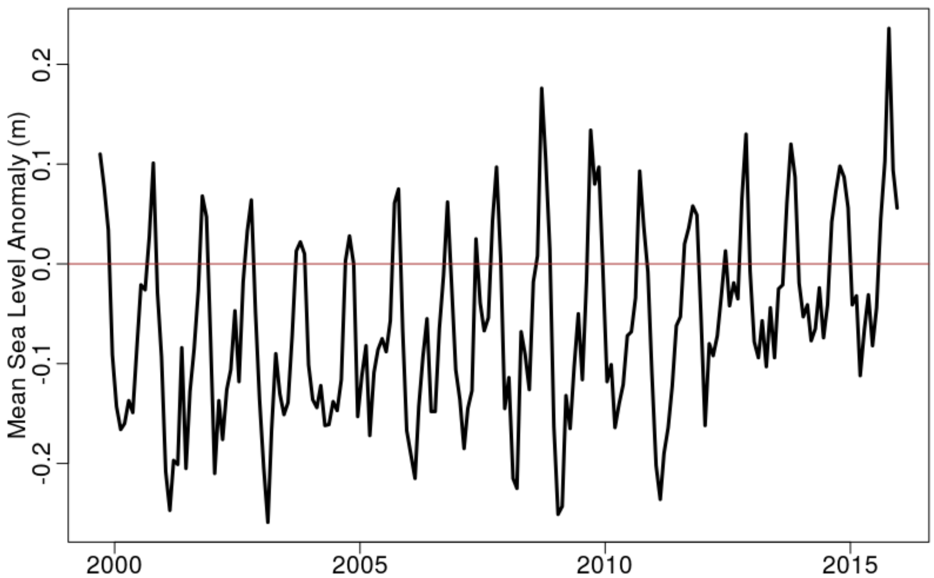

Figure 8.

Mean sea level anomaly with respect to the 2008 - 2015 mean sea level in Florida Bay (-14.8 cm NAVD).

4.8 Basin Boundary Conditions

Tidal and Everglades water levels constitute boundary conditions for the model imposing water levels on boundary basins which interact with basins of Florida Bay. There are also two methods to impose stage or flow boundaries onto interior basins: fixed boundary conditions impose a constant stage or flow, dynamic boundary conditions impose values from a timeseries.

Warning: Stage boundary conditions are imposed at the start of each timestep. Currently, the basin water level is then updated according to changes in volume from mass transport.

Warning: Dynamic timeseries flow values are assumed to be in units of $\mathrm{ft}^3\,\mathrm{s}^{-1}$. Fixed timeseries flow values are specified in units of $\mathrm{m}^3\,\mathrm{s}^{-1}$.

4.8.1 Fixed Boundary Conditions

Fixed boundary conditions are enabled with the `-fb [--fixedBoundaryConditions]` option (default: `False`). When enabled, the forcings are specified in the `-bf [--basinFixedBCFile]`

file (default: `Basin_Fixed_Boundary_Condition.csv`). An example of a `basinFixedBCFile` is shown below:

```
Basin, Name,      Type, Value
56,    Blue Bank, flow, 1000
```

`Type` can have the value `stage` or `flow`. If `Type` is `flow` then at each model timestep the flow `Value` ($\mathrm{m^3\,s^{-1}}$) is multiplied by the model timestep interval converting the flow into a volume ($\mathrm{m^3}$). This volume is added to the basin at the beginning of the timestep.

If `Type` is `stage` then at each model timestep the basin water level is set to the stage `Value` at the beginning of the timestep. This does not prevent the basin water level from being updated at the end of the timestep in response to mass transport.

4.8.2 Dynamic Boundary Conditions

Dynamic boundary conditions are enabled with the `-nb [--noDynamicBoundaryConditions]` option (default: `False`). When enabled forcings are specified in the `-bc [--basinBCFile]` file (default: `Basin_Boundary_Condition.csv`). An example of a `basinBCFile` is shown below:

```
Basin, Name,        Type, File
6,     Manatee Bay, flow, data/Boundary/S197_Flow_1999-9-1_2016-3-31.csv
```

`Type` can have the value `stage` or `flow`. If `Type` is `flow` then at each model timestep the flow value obtained from `File` is multiplied by 0.028317 to convert it from $\mathrm{ft^3\,s^{-1}}$ to $\mathrm{m^3\,s^{-1}}$. The resulting value is multiplied by the model timestep interval to convert the flow to a volume ($\mathrm{m^3}$). This volume is added to the basin at the beginning of the timestep.

If `Type` is `stage` then at each model timestep the basin water level is set to the stage value obtained from the `File` at the beginning of the timestep. This does not prevent the basin water level from being updated at the end of the timestep in response to mass transport.

4.9 Salinity

Salinity is a primary output of the model and is not required as input to estimate basin salinities. However, high-quality, long-period salinity available from marine monitoring stations affords several advantages to model operation and evaluation. First, salinity in the gulf and ocean boundary basins has an important influence on salinities inside the bay. Boundary salinity and runoff may be the most important exogenous variables for coastal basin salinity and good model results require accurate boundary salinities.

Second, observed data can be used to initialize basin salinities with the `-si [--salinityInit]` option. Third, basin salinities can be imposed from observed timeseries with the `-gs [--gaugeSalinity]` option. If `-gs` is specified then all basins with salinity gauges listed in the `basinParameter -bp` file will have observed salinities imposed. Finally, the database of observed salinities allows the user to plot observed data against model data for evaluation and comparison purposes.

Salinity on the Gulf of Mexico boundary has significant variability in comparison to open ocean seawater. Here, the Florida Shelf has a wide, flat and shallow bathymetry, with a generally weak, northerly countercurrent to the Loop current. This allows hypersaline conditions to develop during times of high evaporation and weak circulation. The shelf also receives freshwater runoff from the Shark River and Everglades distributaries, and significant subtropical rain events can also contribute to hyposaline conditions. Boundary salinity for this domain is computed from a 4-gauge average of daily mean salinity at the stations MK, JK, LR, PK, which has an overall standard deviation of 1.7 g/kg over the period September 1, 1999 to December 31, 2015 (N = 5943).

On the Atlantic side salinity is less variable than the Florida Shelf, but still ranges considerably in comparison to open ocean values. The Lignumvitae basin (station PK) in southern Florida Bay is a predominantly marine environment with significant exchange with the Atlantic, and we use a six-month lowpass filter applied to the PK station salinity to represent Atlantic boundary salinities.

Observed salinities are specified in the `-sf [--salinityFile]` file (default: `DailySalinityFilled_1999-9-1_2015-12-8.csv`). Boundary salinties are also included in this file with boundary data 'gauges' specified in the `basinParameter` file (for example: `Ocean_1` and `Gulf_1`).

Salinity observations are not continuous thereby a resampling scheme is used to estimate values of missing data at each station. Data from each station is first partitioned into observations for each day of the year over the period of record. Data for a missing day is reconstructed by randomly sampling from the partitioned data for that day over all years.

4.10 Basin Water Level

Basins water levels are computed according to mass conservation of water across the shoals along with contributions from rainfall, ET, runoff and fixed boundary conditions. Exceptions are the gulf and ocean boundary basins where water levels are imposed from tidal and sea level data.

Since basin water levels provide the hydraulic potential for interbasin mass transfer, the availability of high-quality, long-period observational water levels is useful in the evaluation of model development and performance. The graphical user interface provides graphical comparison of observed and modeled water levels.

The water level data file is defined with the `-bs [--basinStage]` option (default: `DailyStage_1999-9-1_2016-3-1.csv`).

4.11 Wind

Wind is currently not used.

5 Output

Model output is exclusively in UTF-8 encoded comma-delimited variable (`.csv`) files. Each basin in the model has a file created based on the basin name, for example `Long Sound.csv`.

Basin output variables can be selected in the graphical user interface, default variables are `Salinity, Stage, Flow, Volume, Rain, Evaporation, Runoff`.

The output directory is defined by the `-bo [--basinOutput]` option with default: `home_dir/BAM.out` where `home_dir` is the value of the `HOME` environment variable if it is defined, otherwise the current working directory.

Messages generated during a model run are written to the `RunInfo.txt` file in the model output directory.

Currently, no shoal output is created.

6 Model Execution

BAM is a Python 3 application. The model entry-point is the function `main()` in `bam.py` which is invoked by simply executing `bam.py` as a shell command. To execute the model without the graphical user interface specify the `-ng [--noGUI]` option.

6.1 Installation

In addition to Python 3, several community modules such as SciPy are needed. Installation notes can be found in the docstring of the Notes.py module and can be accessed from the Python console:

```
>>> import Notes
>>> help( Notes.InstallationNotes )
```

returns:

```
InstallationNotes()
      Installation:

    sudo apt-get install python3
    sudo apt-get install python3-tk
    sudo apt-get install tk-dev
    sudo apt-get install libffi-dev  # for cairocffi/matplotlib.backends
    sudo apt-get install python3-pip
    sudo pip3    install cairocffi   # for matplotlib.backends
    sudo pip3    install numpy
    sudo pip3    install scipy
    sudo pip3    install matplotlib
    sudo pip3    install pyshp       # https://github.com/GeospatialPython/pyshp
    sudo pip3 install git+https://github.com/uqfoundation/dill.git@master
    sudo pip3 install git+https://github.com/uqfoundation/multiprocess.git@master

    Editor: gedit
    sudo apt-get install gedit
```

6.2 Command line options

All model control parameters can be set with command line arguments. Important options for run control:

```
  -p PATH, --path PATH    : Top level path of BAM: -p /opt/hydro/models/PyBAM/
  -t TIMESTEP, --timestep : TIMESTEP timestep (s): -t 360
  -S START, --start START : Start date time: -S "2010-01-01 00:00"
  -E END, --end END       : End date time:   -E "2010-01-01 08:00"
  -oi OUTPUTINTERVAL, --outputInterval OUTPUTINTERVAL :
                      Time interval (hr) of output data: -oi 1
  -bo BASINOUTPUTDIR, --basinOutput BASINOUTPUTDIR :
                      Directory to write basin outputs: -bo /home/jpark/BAM.out
```

6.2.1 All options

Issuing the command `./bam.py -h` will list all arguments.

```
> ./bam.py --help
usage: bam.py [-h] [-p PATH] [-t TIMESTEP] [-S START] [-E END]
              [-vt VELOCITY_TOL] [-it MAX_ITERATION] [-bn BASINSHAPEFILE]
              [-bd BASINDEPTH] [-bp BASINPARAMETERS] [-bi BASININIT]
              [-bt BASINTIDE] [-br BASINRAIN] [-bc BASINBCFILE]
              [-bf BASINFIXEDBCFILE] [-bo BASINOUTPUTDIR]
              [-bR BASINSTAGERUNOFF] [-bS BASINSTAGERUNOFFMAP]
              [-bs BASINSTAGE] [-et ET] [-es ET_SCALE] [-s SHOALSHAPEFILE]
              [-sp SHOALPARAMETERS] [-sl SHOALLENGTH] [-sm SHOALMANNING]
              [-sf SALINITYFILE] [-msl SEASONALMSL] [-si SALINITYINIT] [-gs]
              [-e EDITOR] [-r RUNID] [-rf RUNINFOFILE] [-oi OUTPUTINTERVAL]
              [-mi [MAPINTERVAL [MAPINTERVAL ...]]] [-L STAGELEGENDBOUND]
              [-P SALINITYLEGENDBOUND] [-fb] [-nb] [-nr] [-ne] [-nR] [-nt]
              [-nm] [-ng] [-D] [-DA]

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optional arguments:
  -h, --help            show this help message and exit
  -p PATH, --path PATH  Top level path of BAM: -p /opt/hydro/models/PyBAM/
  -t TIMESTEP, --timestep TIMESTEP
                        timestep (s): -t 360
  -S START, --start START
                        start date time: -S "2010-01-01"
  -E END, --end END     End date time: -E "2010-01-02"
  -vt VELOCITY_TOL, --velocity_tolerance VELOCITY_TOL
                        velocity iteration tolerance (m/s): -vt 0.0001
  -it MAX_ITERATION, --max_iteration MAX_ITERATION
                        velocity iteration limit: -it 3000
  -bn BASINSHAPEFILE, --basins BASINSHAPEFILE
                        Basins shape file: -bn data/GIS/FLBayBasins
  -bd BASINDEPTH, --basinDepth BASINDEPTH
                        Basin area depth input file: -bd
                        data/init/Basin_Area_Depth.csv
  -bp BASINPARAMETERS, --basinParameter BASINPARAMETERS
                        Basin parameters input file: -bp
                        data/init/Basin_Parameters.csv
  -bi BASININIT, --basinInit BASININIT
                        Basin initial state variable input file:-bi
                        data/init/Basin_Initial_Values.csv
  -bt BASINTIDE, --basinTide BASINTIDE
                        Basin tide boundary data files: -bt
                        data/Boundary/Basin_Tide_Boundary_2010_2015.csv
  -br BASINRAIN, --basinRain BASINRAIN
                        Daily rain data file: -br
                        data/Rain/DailyRainFilled_cm_1999-9-1_2015-12-8.csv
  -bc BASINBCFILE, --basinBCFile BASINBCFILE
                        Basin boundary condition data files: -bc
                        data/Boundary/Basin_Boundary_Condition.csv
  -bf BASINFIXEDBCFILE, --basinFixedBCFile BASINFIXEDBCFILE
                        Basin fixed boundary condition data files: -bf
                        data/Boundary/Basin_Fixed_Boundary_Condition.csv
  -bo BASINOUTPUTDIR, --basinOutput BASINOUTPUTDIR
                        Directory to write basin outputs: -bo
                        /home/jpark/BAM.out
```

```
-bR BASINSTAGERUNOFF, --basinStageRunoff BASINSTAGERUNOFF
                      Daily runoff EDEN stage data file: -bR
                      data/Runoff/EDEN_Stage_OffsetMSL.csv
-bS BASINSTAGERUNOFFMAP, --basinStageRunoffMap BASINSTAGERUNOFFMAP
                      Mapping of EDEN stage to basin: -bS
                      data/Boundary/Basin_Runoff_Boundary.csv
-bs BASINSTAGE, --basinStage BASINSTAGE
                      Daily stage data file: -bs
                      data/Stage/DailyStage_1999-9-1_2016-3-1.csv
-et ET, --ET ET       PET data file: -et data/ET/PET_1999-9-1_2015-12-8.csv
-es ET_SCALE, --ET scale ET_SCALE
                      Scale factor on global ET: -es 2
-s SHOALSHAPEFILE, --shoals SHOALSHAPEFILE
                      Shoals shape file: -s data/GIS/FathomLines
-sp SHOALPARAMETERS, --shoalParameters SHOALPARAMETERS
                      Shoal to basin mapping file:-sp
                      data/init/Shoal_Parameters.csv
-sl SHOALLENGTH, --shoalLength SHOALLENGTH
                      Shoal width and length depth input file:-sl
                      data/init/Shoal_Length_Depth.csv
-sm SHOALMANNING, --shoalManning SHOALMANNING
                      Manning friction for all shoals: -sm 0.1
-sf SALINITYFILE, --salinityFile SALINITYFILE
                      Daily salinity data file: -sf data/Salinity/DailySalin
                      ityFilled_1999-9-1_2015-12-8.csv
-msl SEASONALMSL, --seasonalMSL SEASONALMSL
                      Seasonal MSL: -msl data/Tide/MSL_Anomaly.csv
-si SALINITYINIT, --salinityInit SALINITYINIT
                      Initialize basin salinity from gauge data.
-gs, --gaugeSalinity  Impose basin gauge salinity where available.
-e EDITOR, --editor EDITOR
                      Editor: -e gedit
-r RUNID, --runID RUNID
                      Run ID for output files: -r RunID
-rf RUNINFOFILE, --runInfoFile RUNINFOFILE
                      File for model run messages: -rf RunInfo.txt
-oi OUTPUTINTERVAL, --outputInterval OUTPUTINTERVAL
                      Time interval (hr) of output data: -oi 1
-mi [MAPINTERVAL [MAPINTERVAL ...]], --mapInterval [MAPINTERVAL [MAPINTERVAL ...]]
                      Time interval of display refresh in (days) and [(hr)]:
                      -mi 1 [0]
-L STAGELEGENDBOUND, --stageLegend STAGELEGENDBOUND
                      Stage legend bound on map: -L 0.5
-P SALINITYLEGENDBOUND, --salinityLegend SALINITYLEGENDBOUND
                      Salinity legend bound on map: -P 50
-fb, --fixedBoundaryConditions
                      Enable fixed boundary conditions for basins.
-nb, --noDynamicBoundaryConditions
                      Disable basin dynamic boundary conditions.
-nr, --noRain         Disable rain inputs.
-ne, --noET           Disable ET inputs.
-nR, --noStageRunoff  Disable EDEN stage runoff inputs.
-nt, --noTide         Disable tidal boundary inputs.
-nm, --noMeanSeaLevel Disable mean sea level inputs.
-ng, --noGUI          Disable GUI.
-D, --DEBUG
-DA, --DEBUG_ALL
```

7 Graphical User Interface

The graphical user interface (GUI) is enabled by default (figure 9). The GUI can be disabled with the `-ng --noGUI` option. The GUI Map updates a color-coded representation of basin stage or salinity during a run at intervals specified by the `-mi [--mapInterval]` option (default: 1 day, 0 hours). Since the function which executes a model run (`Model.Run()`) is not exposed to the GUI main loop, there is currently no user interaction processed during a model run. This may change in future versions.

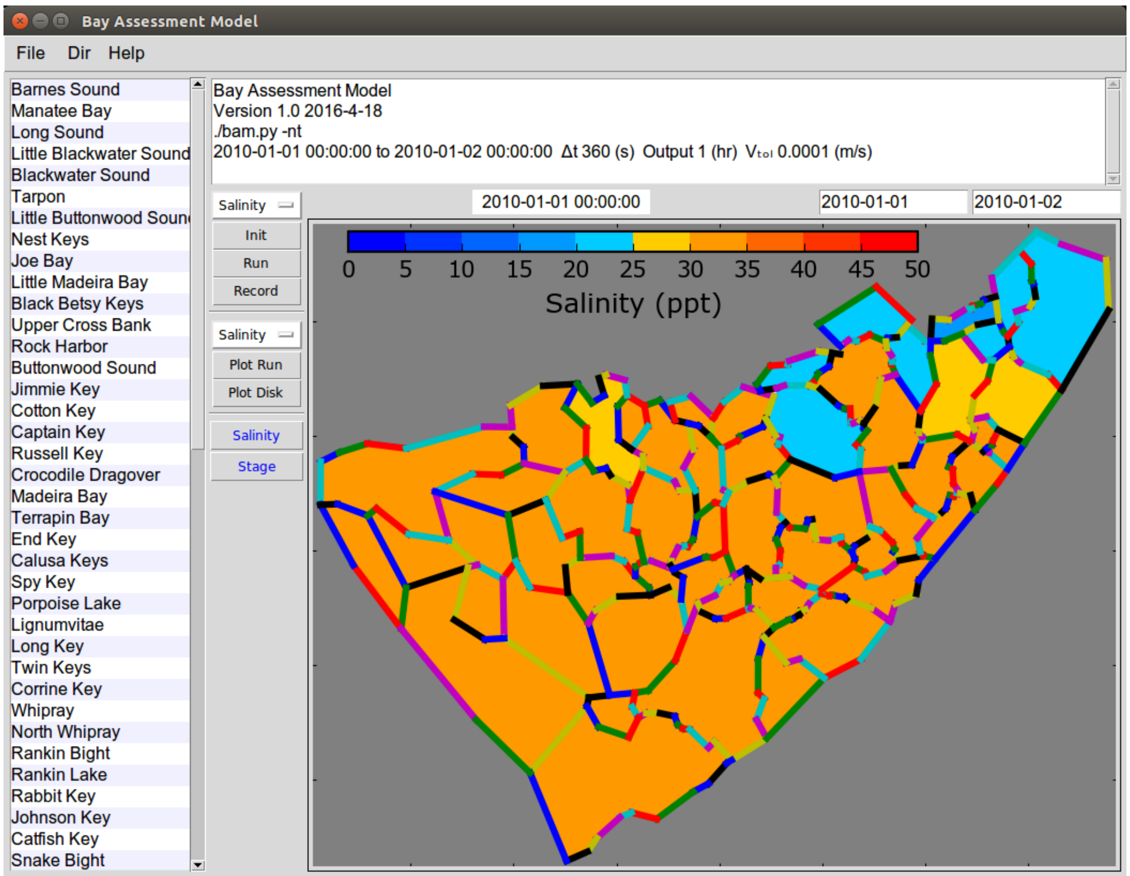


Figure 9. BAM graphical user interface.

The main window is divided into 6 sections:

1. Menu bar
2. Basin listbox
3. Message window
4. Run and Plot controls
5. Time display and entry boxes
6. Map

each described below.

7.1 Menu

7.1.1 File : Init

The `File : Init` menu opens a dialogue box allowing the user to select a file to initialize basin variables. The default is `Basin_Initial_Values.csv`.

7.1.2 File : Edit

`File : Edit` opens a dialogue box allowing the user to specify a file to be edited. The editor which is invoked is specified with the `-e [--editor]` option (default: `gedit`).

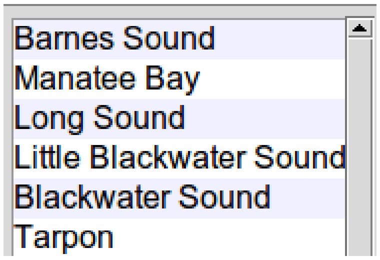
7.1.3 Dir : Plot Disk

The `Dir : Plot Disk` menu opens a dialogue box specifying the directory location of ouput data files to be plotted when the `Plot Disk` button is pressed. The default is either the previous value of this dialogue selection, or the value of the `HOME` environment variable if defined, or the current working directory.

7.1.4 Dir : Output

`Dir : Output` opens a dialogue box specifying the directory location to write output data files. The default is either the previous value of this dialogue selection, or the value of the `HOME` environment variable if defined, or the current working directory.

7.2 Basin listbox



The basin listbox allows the user to select any combination of basin objects with the mouse. Single basins are also selected if clicked on the map. When a basin is selected its current information is printed in the message window. The basin listbox is also used to select basins for plot commands.

7.3 Run and Plot

These selectors and buttons control the map display and plotting options.

The top selector allows for either salinity or stage color graduations to be displayed on the map.

The `Init` button calls the model initialization function for the current model start, stop times and run options.

`Run` initiates model execution.

`Record` raises a pop-up window of check button selectors to specify which basin variables will be written to output.

The middle selector specifies the basin variable to be plotted.

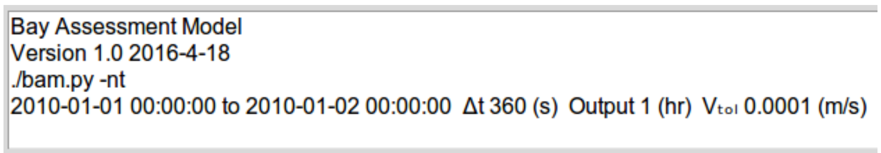
`PlotRun` plots the currently selected variable from the model run for all basins selected in the basin list box.

`Plot Disk` plots the currently selected variable from the archive directory specified in the `Dir : Plot Disk` menu for all basins selected in the basin list box.

`Salinity` plots observed salinity data for basins selected in the basin list box where data is available.

`Stage` plots observed water level data for basins selected in the basin list box where data is available.

7.4 Message window



The message window is a text box displaying messages and information on model objects. Messages generated during a model run are written to the `RunInfo.txt` file in the model output directory.

7.5 Time

Current model time is displayed above the map in a message box. Two text entry boxes are located on the right above the map. The text entry on the left can be used to set the model simulation start time, the text entry on the right to set the model simulation end time.

Simulation start and stop times can also be set with the `-S [--start]` and `-E [--end]` command line options.

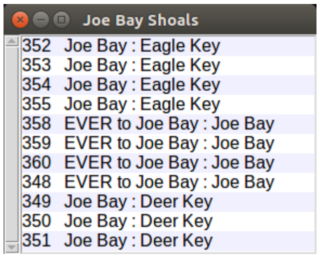
Two formats are supported for time entry: `YYYY-MM-DD` and `YYYY-MM-DD HH:MM`.

7.6 Map

The map is an interactive display of two GIS shapefiles, the basins shapefile (`-bn [--basins]` default: `FLBayBasins`) and the shoals shapefile (`-s [--shoals]` default: `FathomLines`).

The map will display color graduations of basin state variables salinity or stage as specified with the selector (section 7.3). Shoals are shown with a random color assignment to allow easy visualization.

Left-mouse-click on a basin will select the basin in the basin list box and will display current basin state variables in the message box. Left-mouse-click on a shoal will display current shoal state variables in the message box.



Right-mouse-click on a basin will present a list box with all shoals associated with the basin. Selecting a shoal in the list box will display current shoal state variables in the message box.

8 Mass Balance Check

To check mass balance turn off all normal inputs and specify a fixed flow (`-fb [--fixedBoundaryConditions]`) into Blue Bank with 1000 m^3/s, t = 1 s timestep and all shoal Mannings coefficients of 0.1. The `-bf [--basinFixedBCFile]` file would be:

```
Basin, Name,      Type, Value
56,    Blue Bank, flow, 1000
```

The command line:

```
./bam.py -t 1 -E "2010-1-1 08:00" -nt -nm -ne -nr -nR -nb -fb -si 'n' -sm 0.1
```

Blue Bank should then equilibriate at 8 hours to:

```
    Blue Bank : dt = 1 s
      Stage: 0.01 (m)
      Salinity: 17.77 (g/kg)
      Volume: 0.0425 (km^3)
      Shoal Flux: 1000.0 (m^3/s)
```

Independent mass balance calculations and verification are detailed in `etc/Notes.txt`.

9 Salinity Check

```
-------------------------------------------------------------------
Salinity Check: over 8:00 hours
Constant addition of V = 1000 m^3 to Blue Bank at dt = 60 s Manning 0.1
./bam.py -t 60 -nt -nm -ne -nr -nR -nb -fb -si 'n' -sm 0.1
Initial salinity in Blue Bank and surrounding basins is 35
-------------------------------------------------------------------
Time      Salinity (ppt) Stage(m) Volume(m^3)  Flow(m^3/dt) Salt mass     Computed
2010-01-01 00    35.00  0        42277037     NA         1475257188737   35.00
2010-01-01 01    32.15  0.01     42501455     60275      1349060380152   31.84
2010-01-01 02    29.54  0.01     42501891     60293      1234233094273   29.13
2010-01-01 03    27.14  0.01     42501966     60294      1129178205339   26.65
2010-01-01 04    24.94  0.01     42501989     60295      1033064976498   24.38
2010-01-01 05    22.91  0.01     42501995     60295       945132604037   22.30
2010-01-01 06    21.05  0.01     42501998     60295       864684834211   20.41
2010-01-01 07    19.34  0.01     42501999     60295       791084610753   18.67
2010-01-01 08    17.77  0.01     42501999     60295       723749088579   17.08

Timesteps per Interval (hour) 60
```

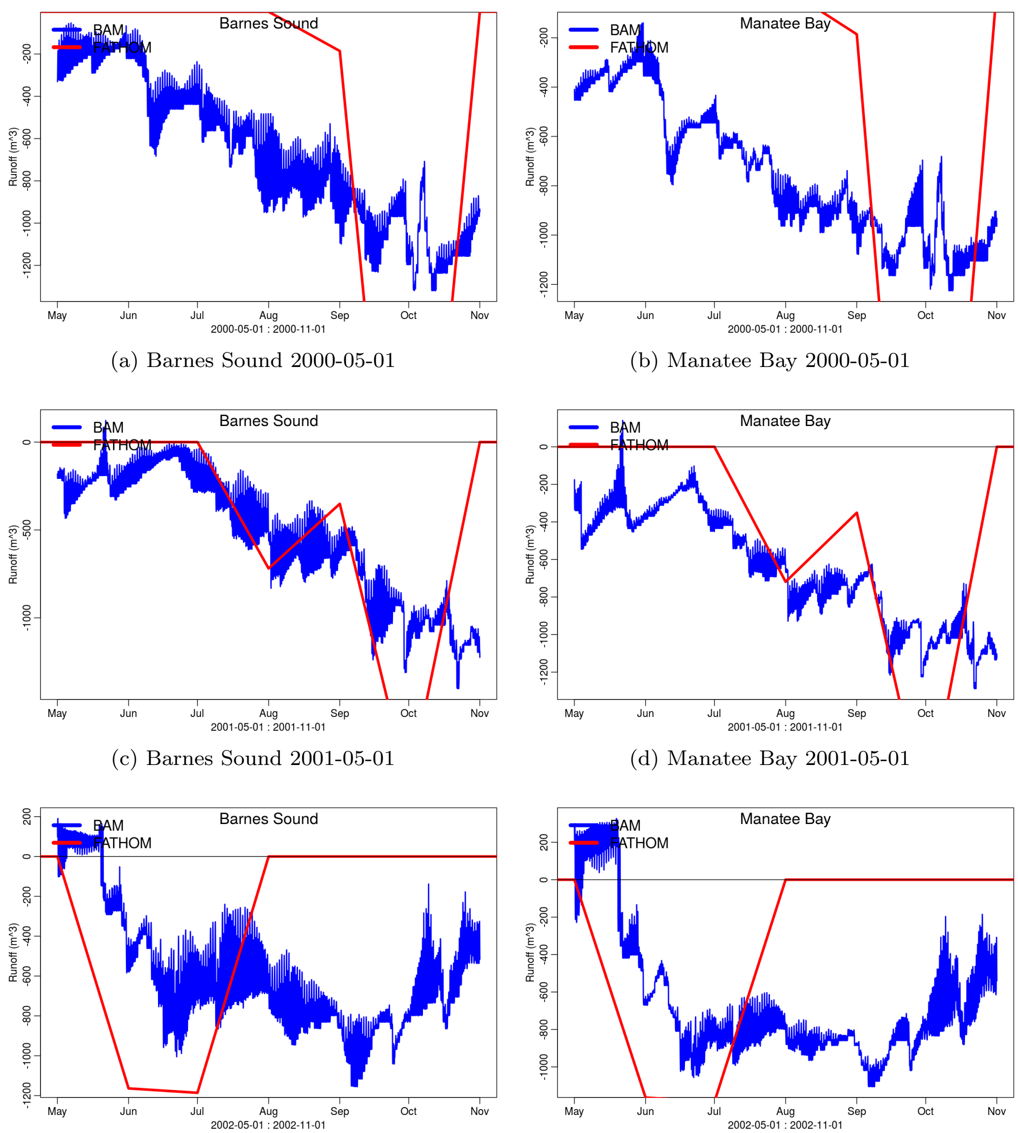
The above BAM reported values are correct, the Salt mass and Computed salinity are from a spreadsheet. The Computed salinity is inaccurate due to inaccurate volume and salt mass computations at a timestep of 60 seconds.

Salinity verification at t = 1s can be found in `etc/BlueBankSalinity-Q+1000cms_dt1.ods`, and is reproduced below:

```
Time                 Salinity(ppt) Stage(m) Volume(m^3)  Flow(m^3/dt)  Salt mass  Computed
2010-01-01 00:00:00     35            0  42277036.502    NA       1475257188737  35.00
2010-01-01 00:00:01     34.999        0  42278036.502    0        1475257188737  35.00
2010-01-01 00:00:02     34.998        0  42278968.321    68.182   1475254809583  35.00
2010-01-01 00:00:03     34.998        0  42279873.768    94.553   1475251510312  35.00
2010-01-01 00:00:04     34.997        0  42280759.225    114.543  1475247513617  35.00
...
2010-01-01 07:59:56     17.774     0.01  42500628.472    1000      753148504363  17.77
2010-01-01 07:59:57     17.774     0.01  42500628.472    1000      753130783484  17.77
2010-01-01 07:59:58     17.773     0.01  42500628.472    1000      753113063021  17.77
2010-01-01 07:59:59     17.773     0.01  42500628.472    1000      753095342976  17.77
2010-01-01 08:00:00     17.773     0.01  42500628.472    1000      753077623348  17.77
```

10 Runoff Calibration

Runoff from the Everglades to coastal basins is determined by the relative water level elevation between the Everglades and coastal basins. This allows for both positive and negative runoff between the Everglades and coastal basins. Shoal properties of the coastal basins (length, width, depth) have been calibrated to match aggregate runoff from the FATHOM model (*Cosby et al.*, 2010) over the rainy seasons of 2001, 2002 and 2003, the three years of overlap between BAM and FATHOM. Plots shown below compare the calibrated basin runoff and FATHOM values. It should be noted that FATHOM values are strictly negative (no flow is allowed from the coastal basins into the Everglades) and are available at only 1 point per month.



(a) Barnes Sound 2000-05-01

(b) Manatee Bay 2000-05-01

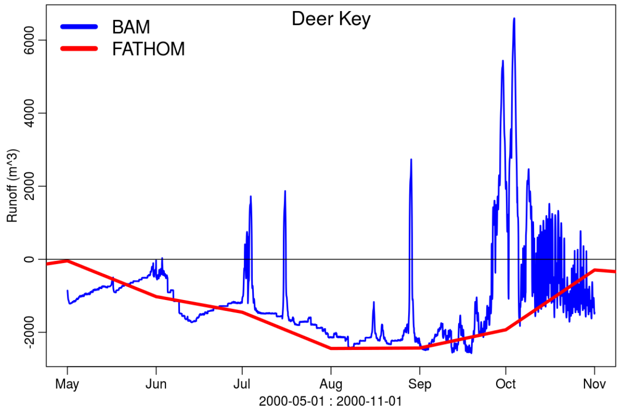
(c) Barnes Sound 2001-05-01

(d) Manatee Bay 2001-05-01

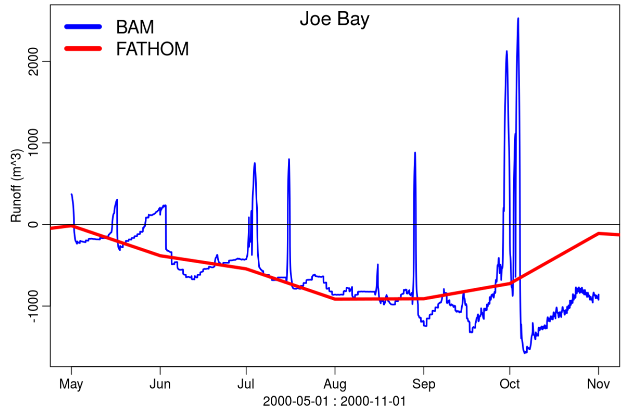
(e) Barnes Sound 2002-05-01

(f) Manatee Bay 2002-05-01

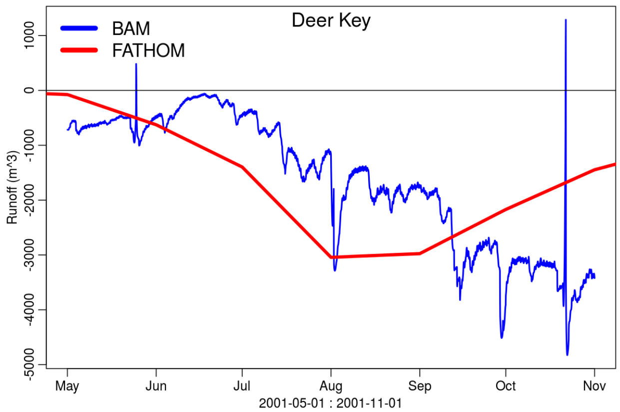
Figure 10. Barnes Sound and Manatee Bay Runoff



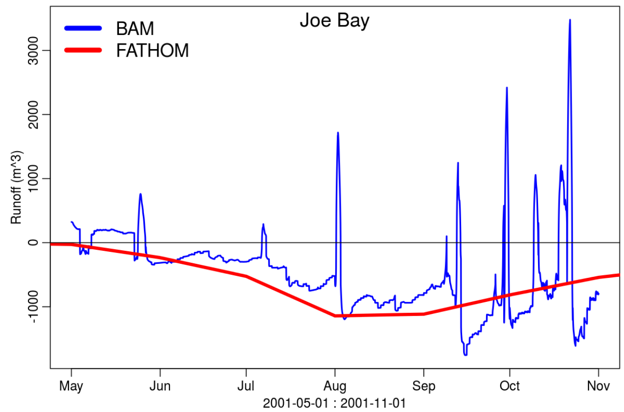
(a) 2000-05-01



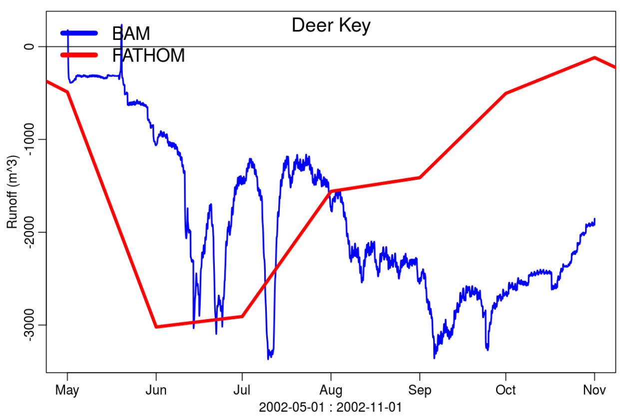
(b) 2000-05-01



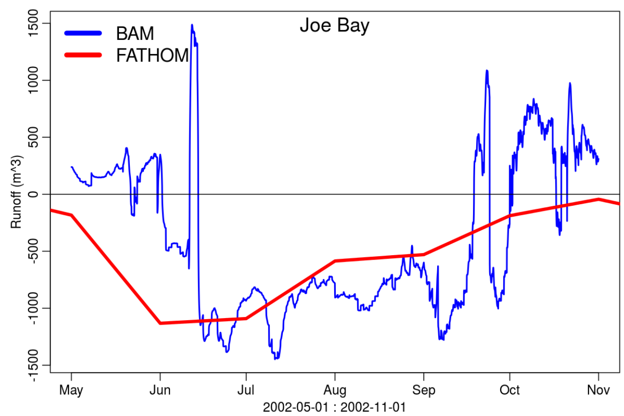
(c) 2001-05-01



(d) 2001-05-01



(e) 2002-05-01



(f) 2002-05-01

Figure 11. Deer Key and Joe Bay Runoff

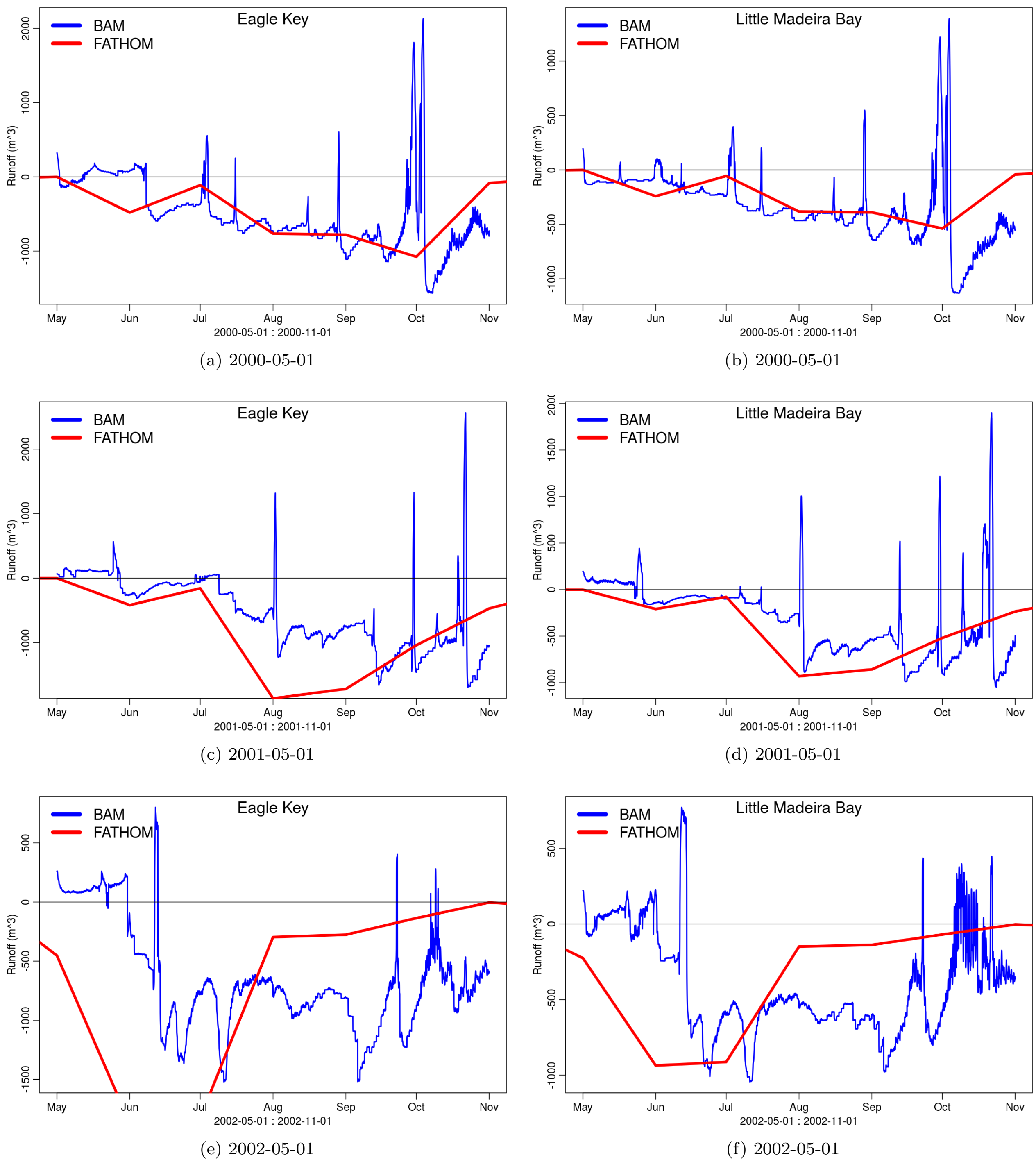
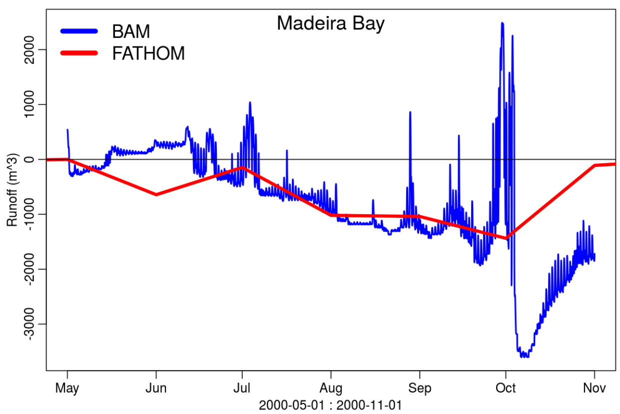
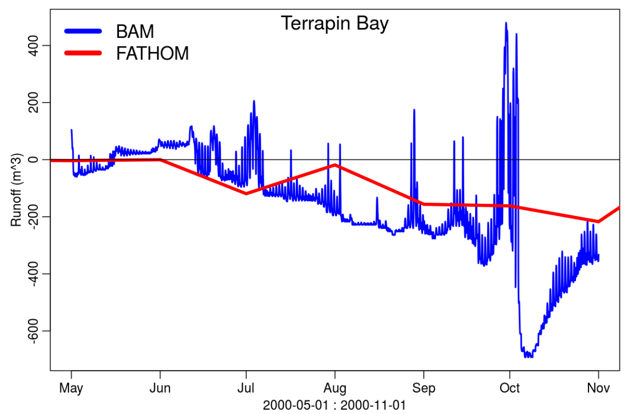


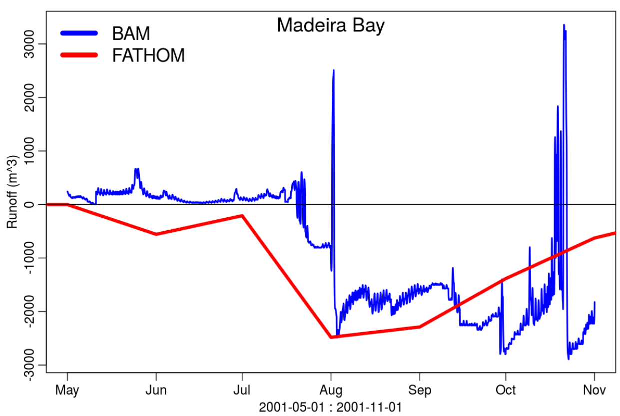
Figure 12. Eagle Key and Little Madeira Bay Runoff



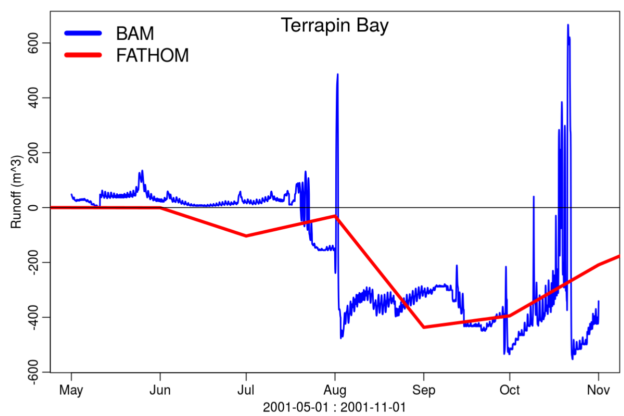
(a) 2000-05-01



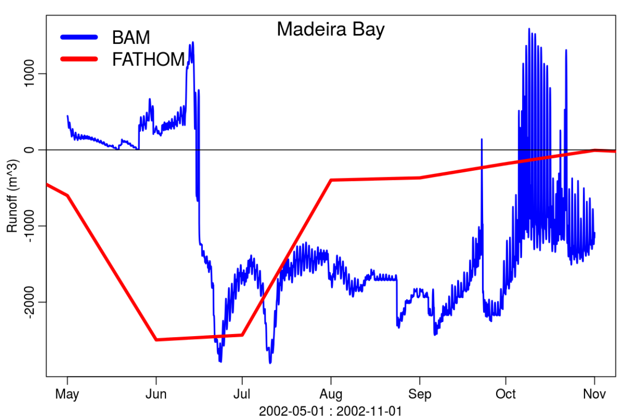
(b) 2000-05-01



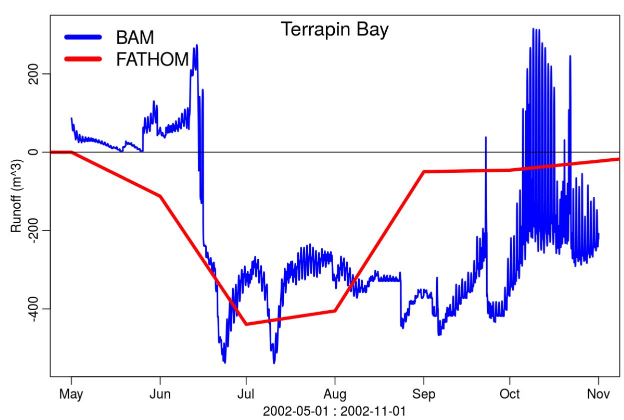
(c) 2001-05-01



(d) 2001-05-01

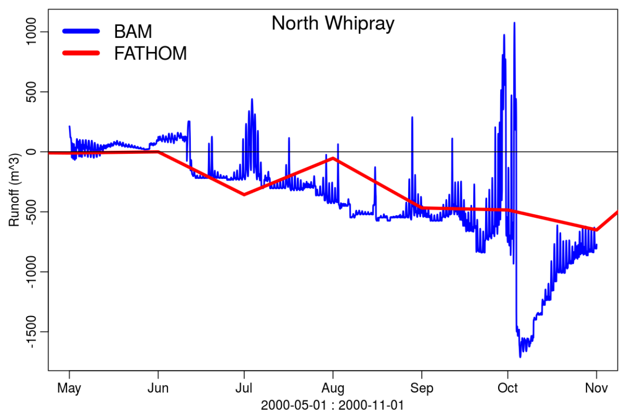


(e) 2002-05-01

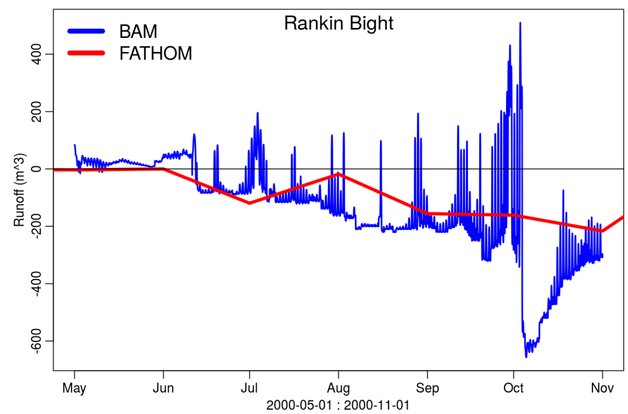


(f) 2002-05-01

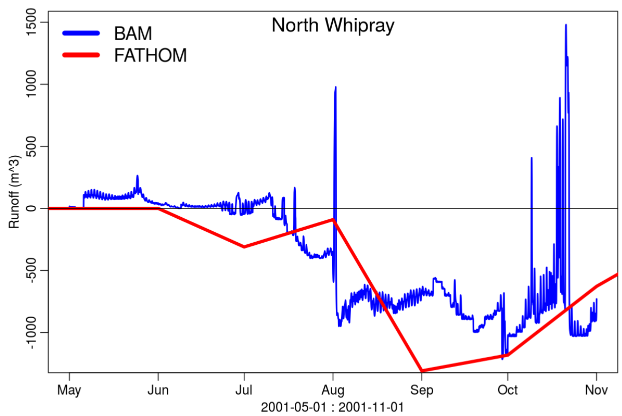
Figure 13. Madeira Bay and Terrapin Bay Runoff



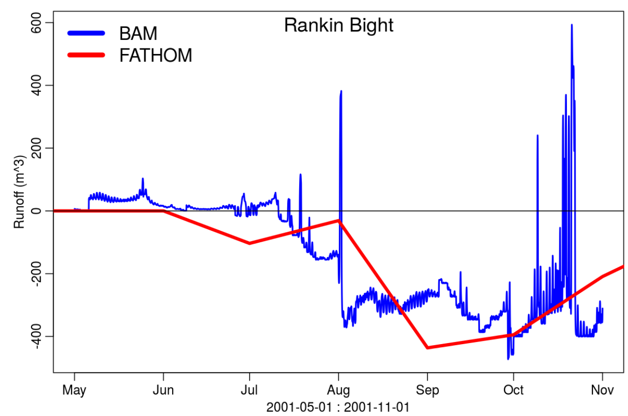
(a) 2000-05-01



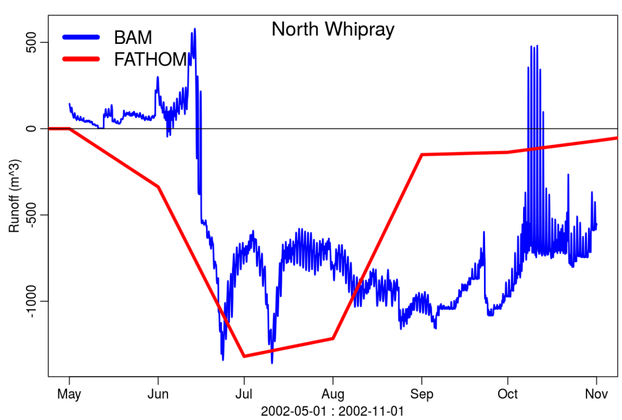
(b) 2000-05-01



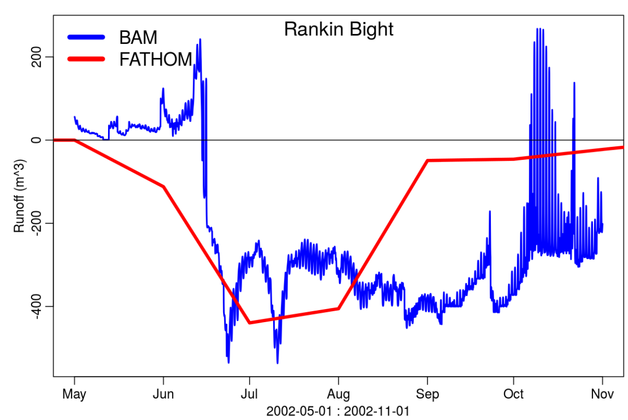
(c) 2001-05-01



(d) 2001-05-01

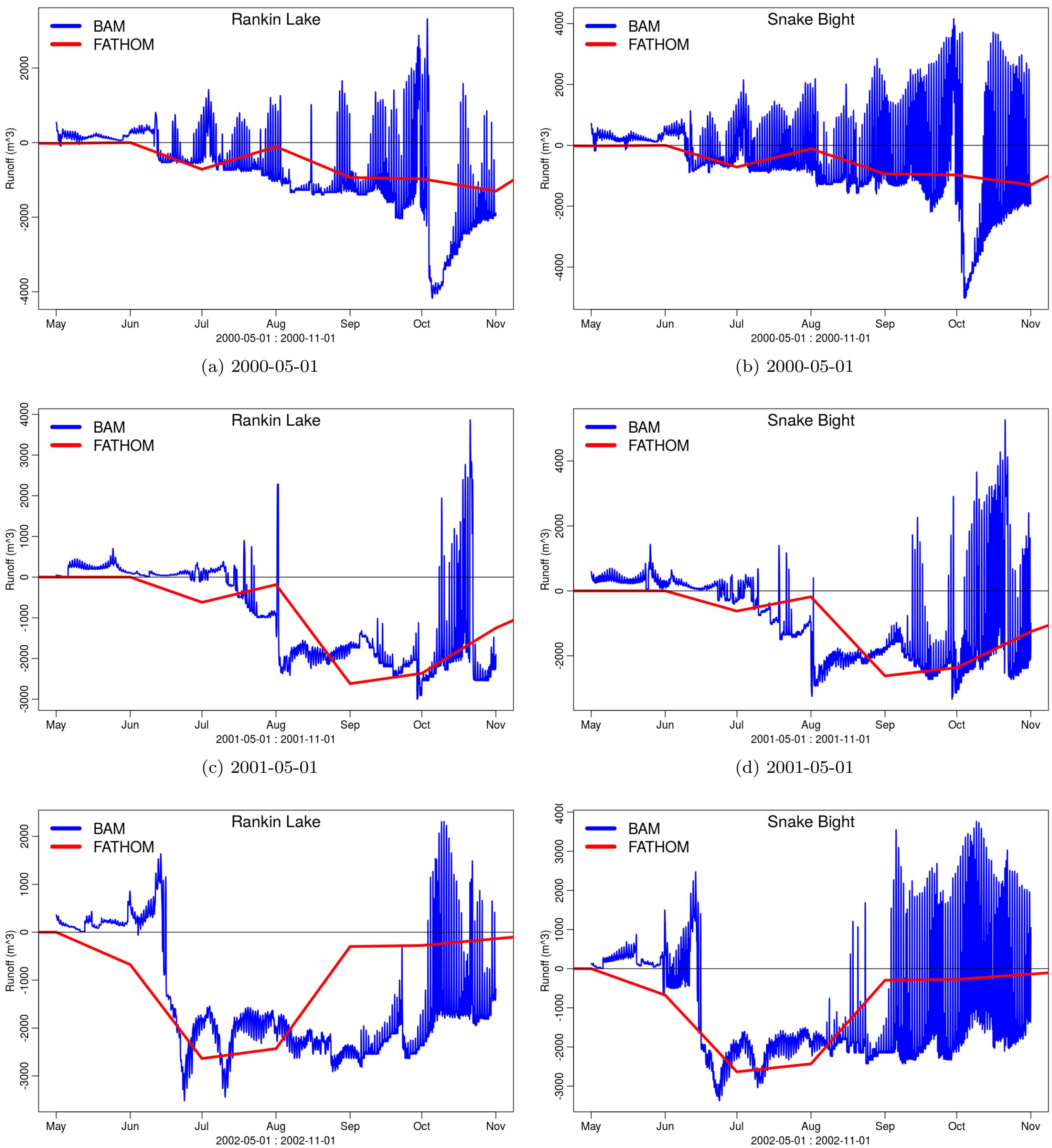


(e) 2002-05-01



(f) 2002-05-01

Figure 14. North Whipray and Rankin Bight Runoff



(a) 2000-05-01

(b) 2000-05-01

(c) 2001-05-01

(d) 2001-05-01

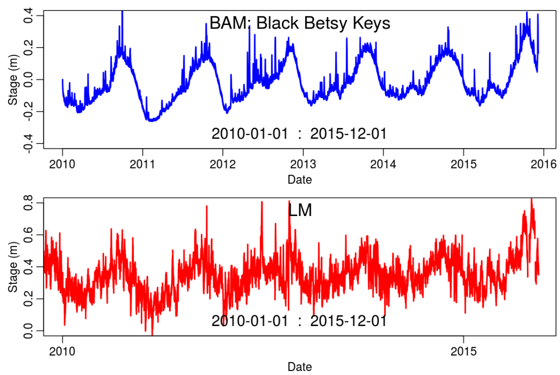
(e) 2002-05-01

(f) 2002-05-01

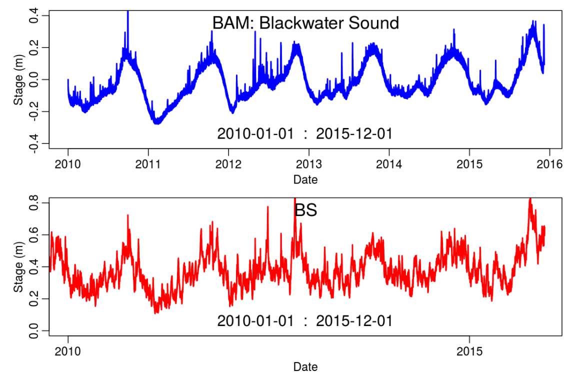
Figure 15. Rankin Lake and Snake Bight Runoff

11 Stage Comparison

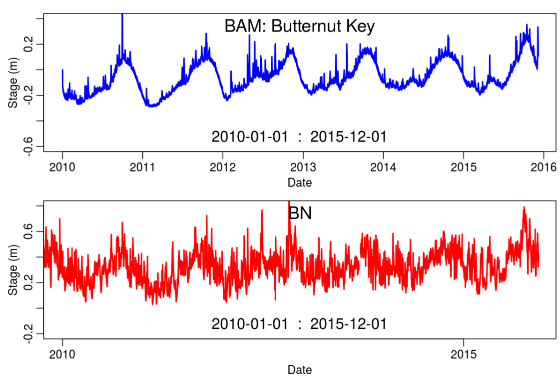
Interbasin mass transport is driven by hydraulic potential between basins. Accurate water level simulation is a core competency for good model performance. This section presents comparisons of basin water levels computed by BAM (blue) and the associated marine monitoring station point-observations (red) over the period 2010-1-1 to 2015-12-1.



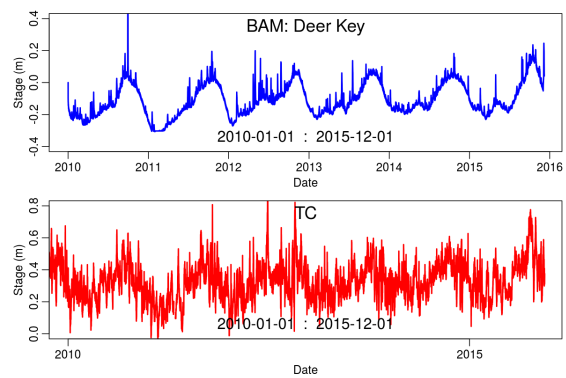
(a) Black Betsy Keys



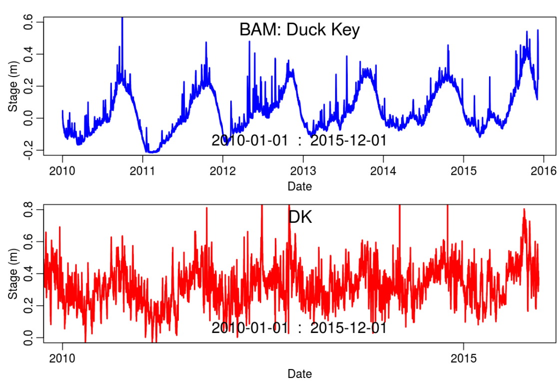
(b) Blackwater Sound



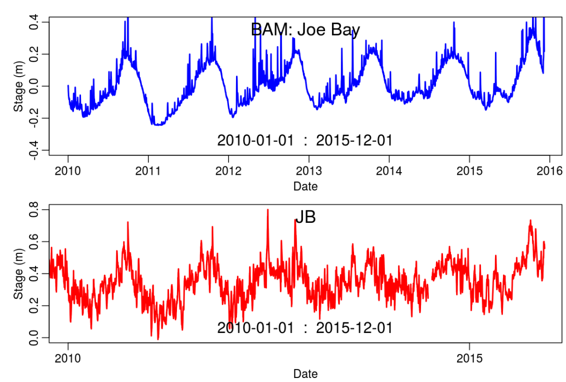
(c) Butternut Key



(d) Deer Key

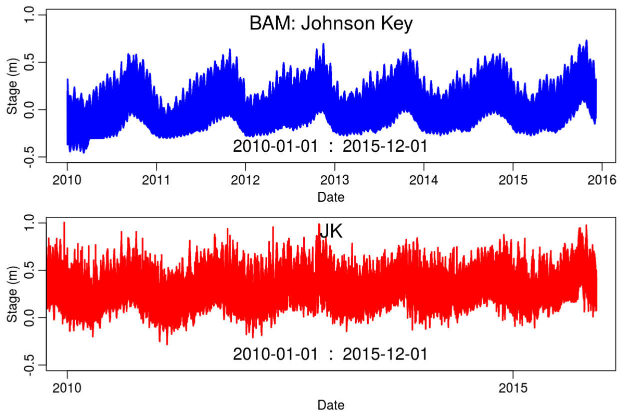


(e) Duck Key

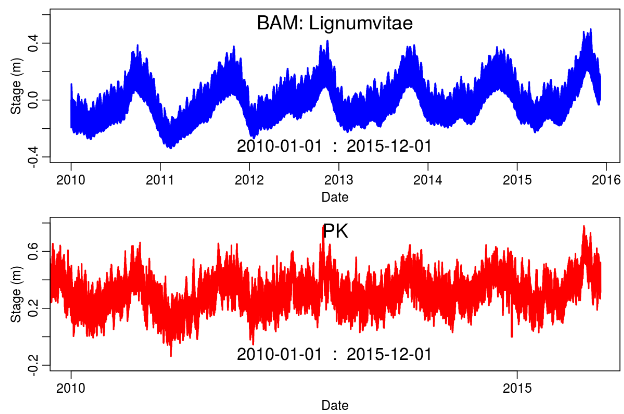


(f) Joe Bay

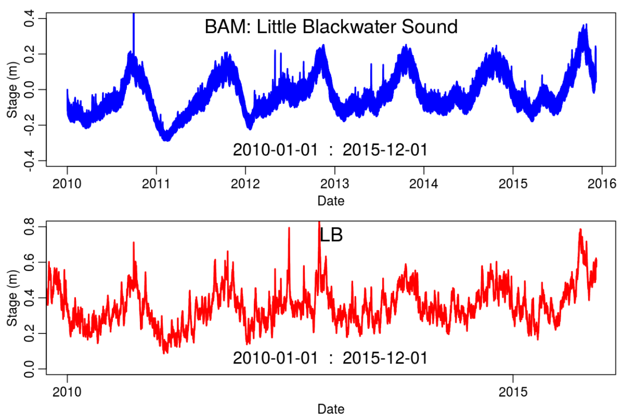
Figure 16. Water level comparisons: Black Betsy Keys, Blackwater Sound, Butternut Key, Deer Key, Duck Key and Joe Bay.



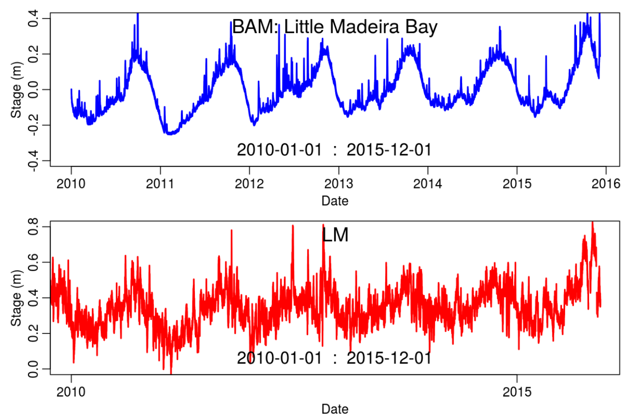
(a) Johnson Key



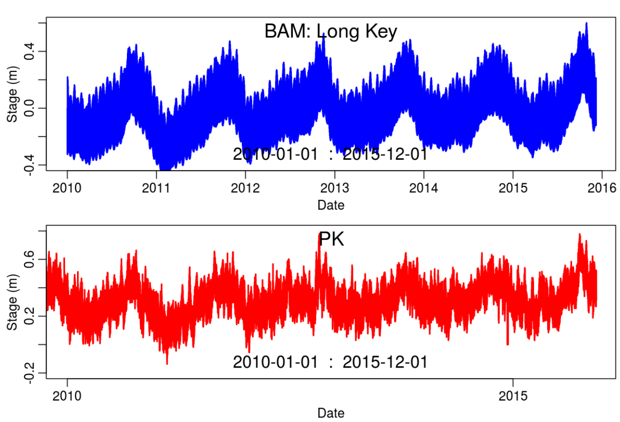
(b) Lignumvitae



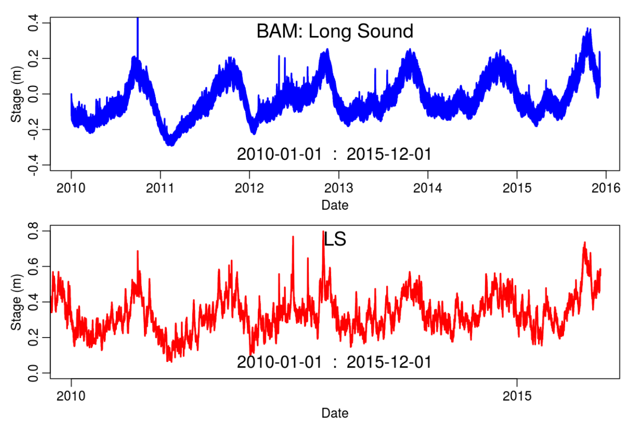
(c) Little Blackwater Sound



(d) Little Madeira Bay

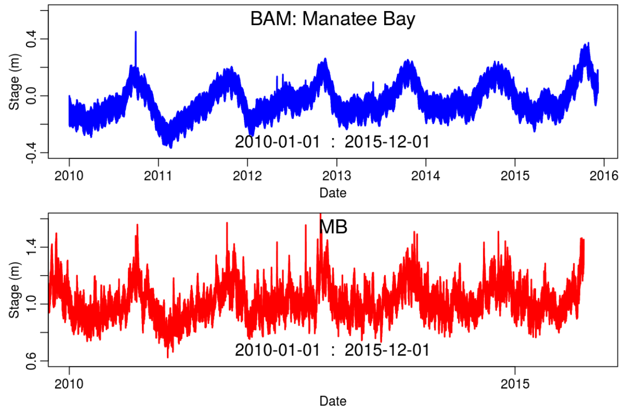


(e) Long Key

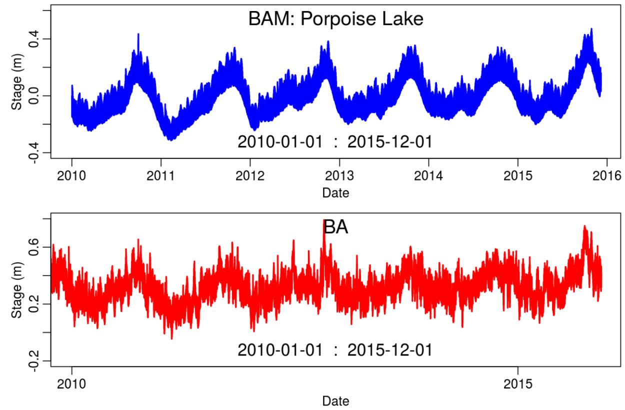


(f) Long Sound

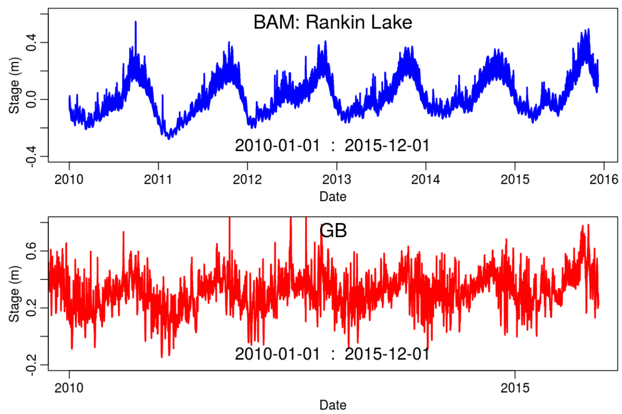
Figure 17. Water level comparisons: Johnson Key, Lignumvitae, Little Blackwater Sound, Little Madeira Bay, Long Key and Long Sound.



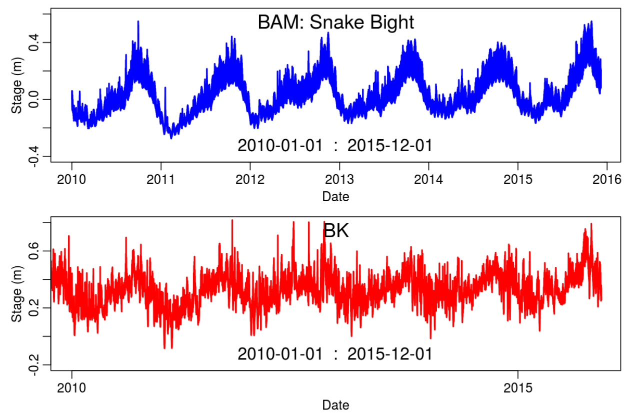
(a) Manatee Bay



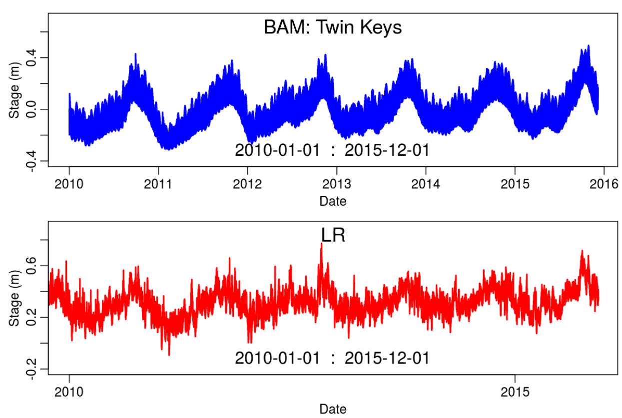
(b) Porpoise Lake



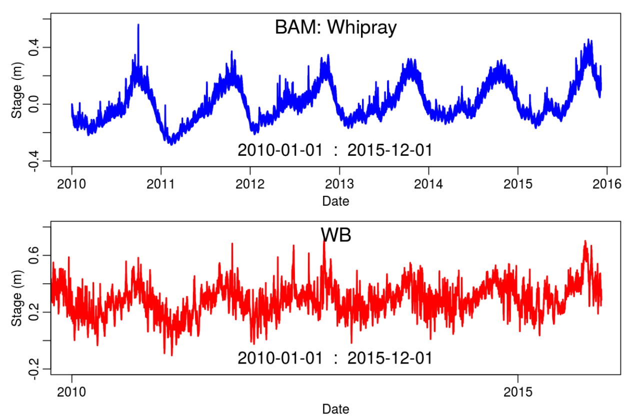
(c) Rankin Lake



(d) Snake Bight



(e) Twin Keys

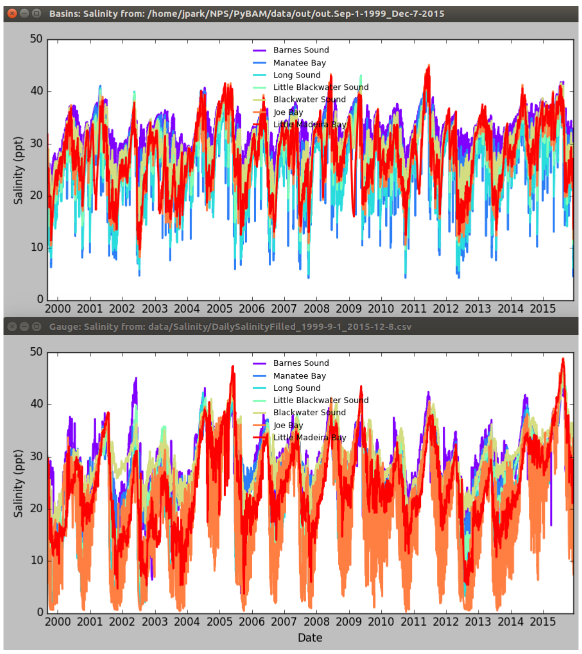


(f) Whipray

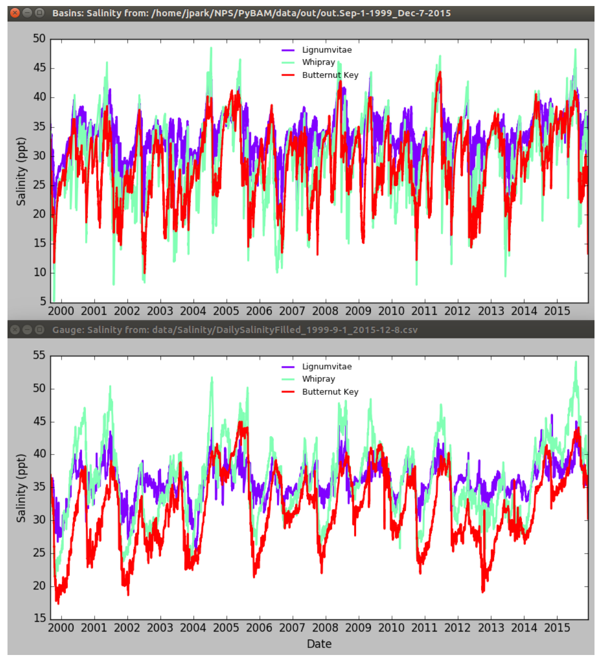
Figure 18. Water level comparisons: Manatee Bay, Porpoise Lake, Rankin Lake, Snake Bight, Twin Keys and Whipray.

12 Salinity Comparison

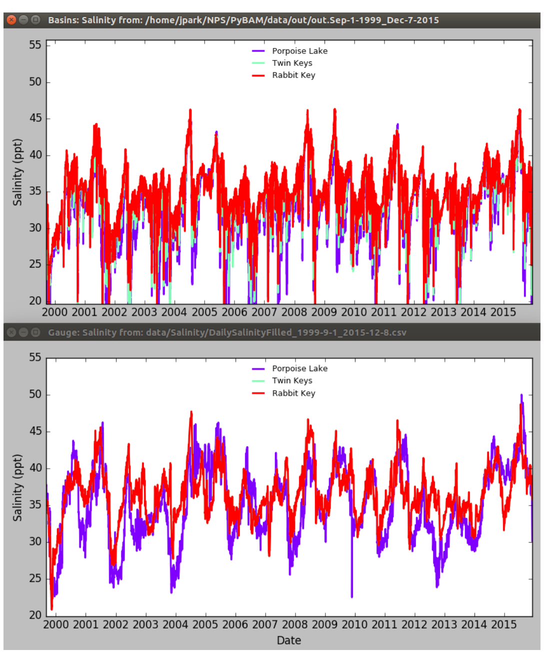
Salinity comparisons for the period 1999-9-1 to 2015-12-7 are shown in figure 19. Top panel is BAM output, bottom panel observed data.



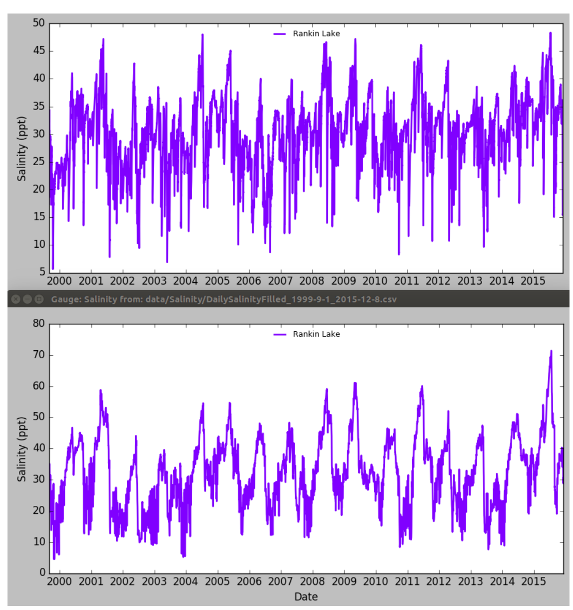
(a) NE Basins



(b) Central Basins



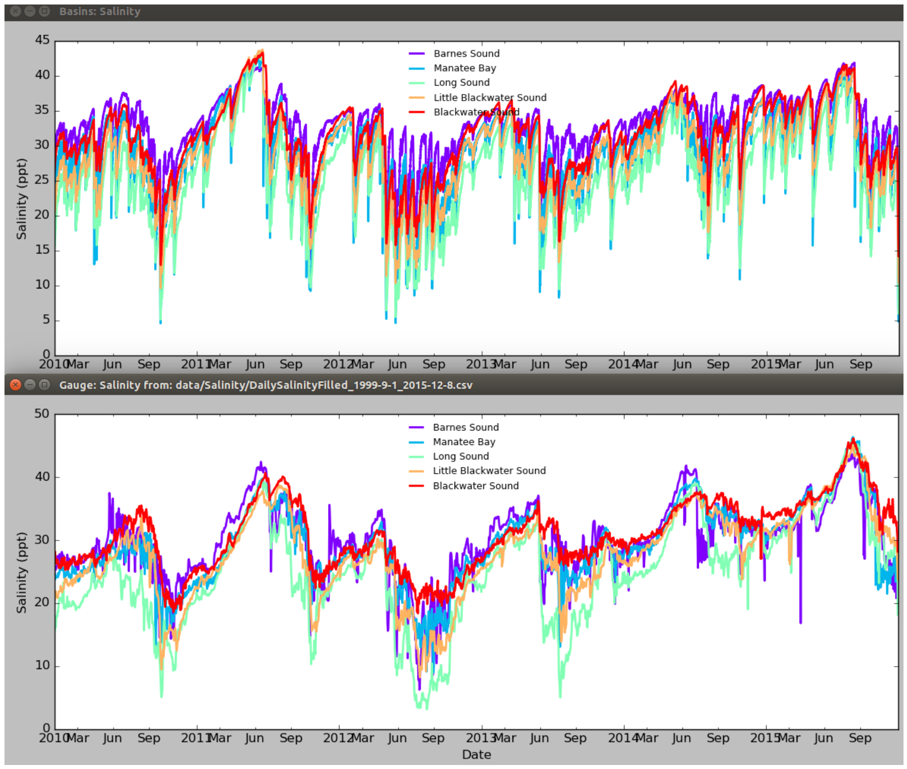
(c) Central SE Basins



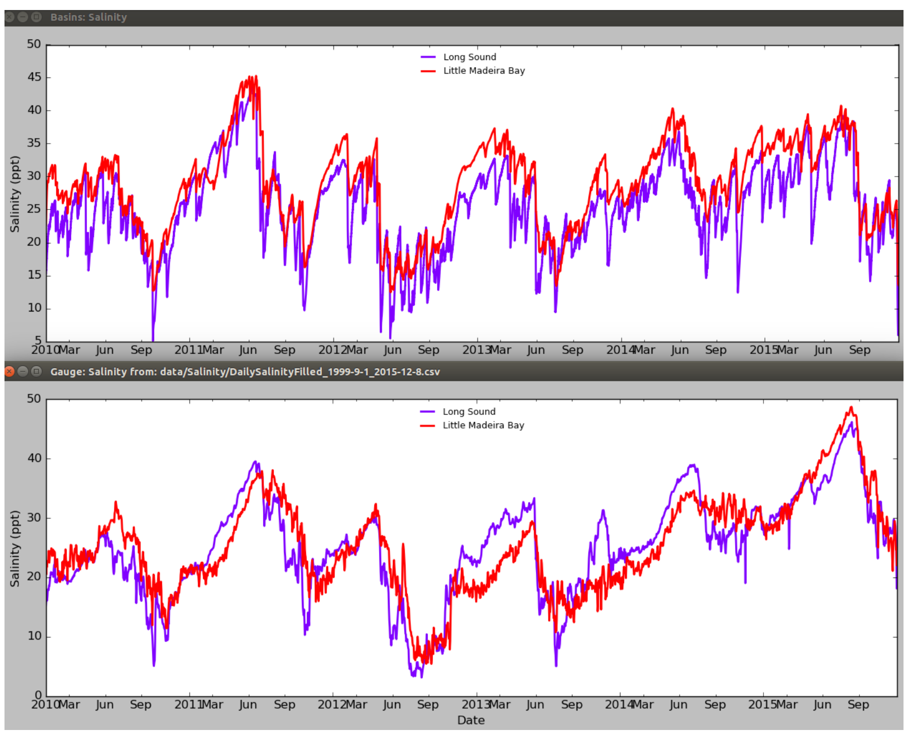
(d) Rankin Lake

Figure 19. Salinity comparisons 1999-9-1 to 2015-12-7.

Salinity comparisons for the period 2010-1-1 to 2015-12-7 are shown in figure 19. Top panel is BAM output, bottom panel observed data.

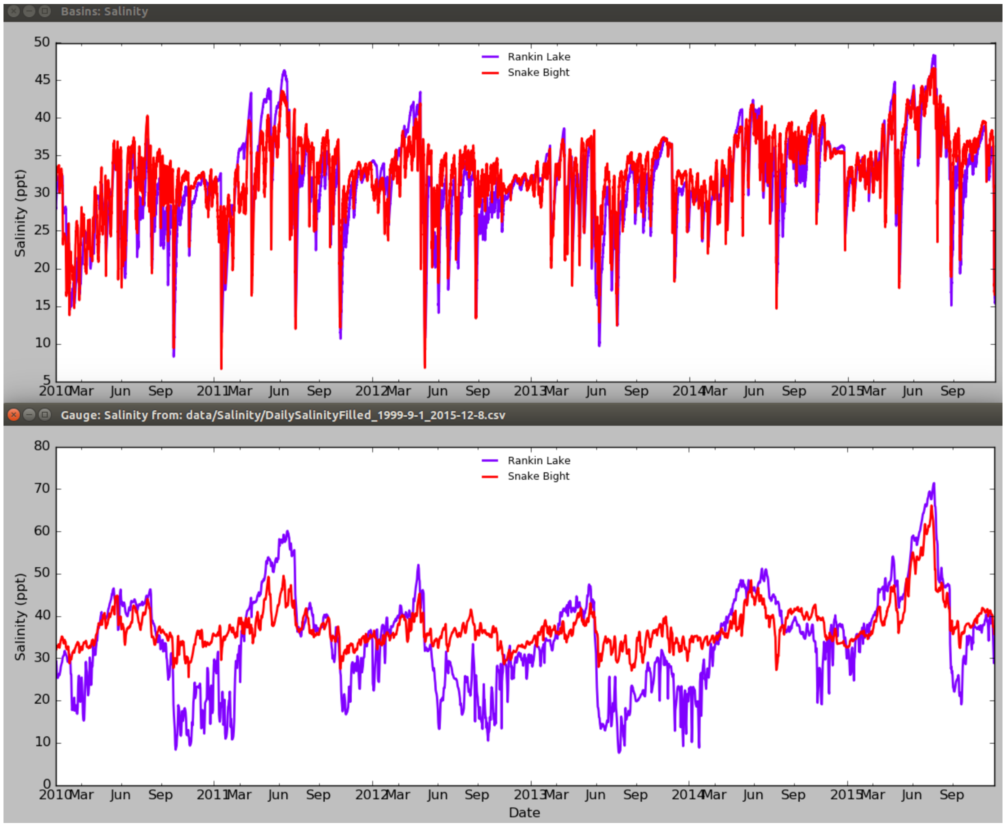


(a) NE Basins



(b) N Basins

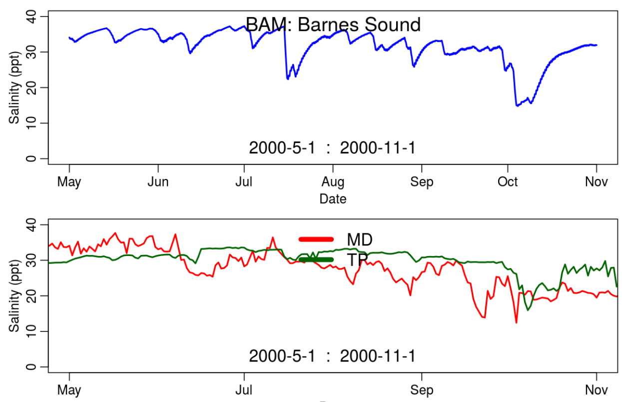
Figure 20. Salinity comparisons 2010-1-1 to 2015-12-7.



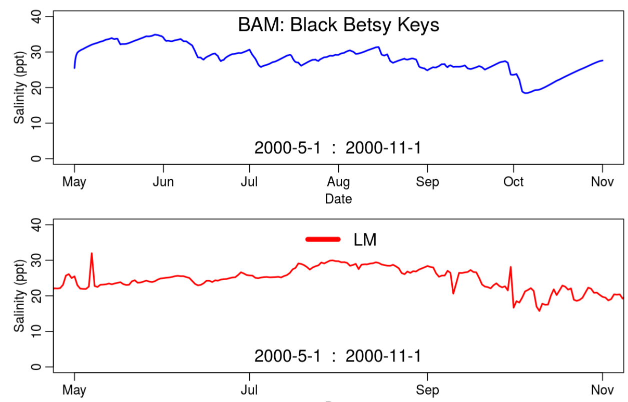
(a) NW Basins

Figure 21. Salinity comparisons 2010-1-1 to 2015-12-7.

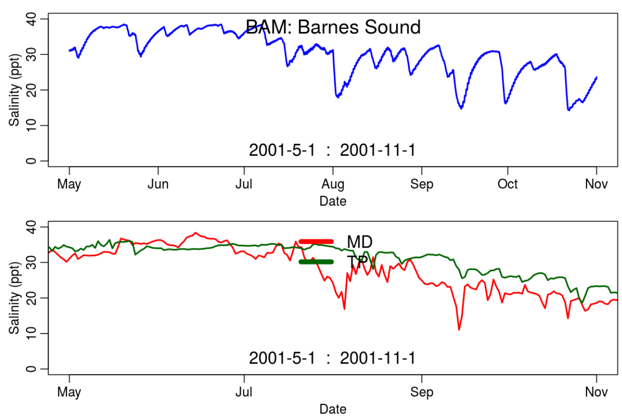
Salinity comparisons over the rainy seasons of 2000, 2001, and 2002 are shown below. Top panels are BAM output, bottom panels observed salinity. BAM values are basin-wide, observations are point measurements, and not necessarily in the same basin as the BAM output. In some cases multiple observations from adjacent basins are shown.



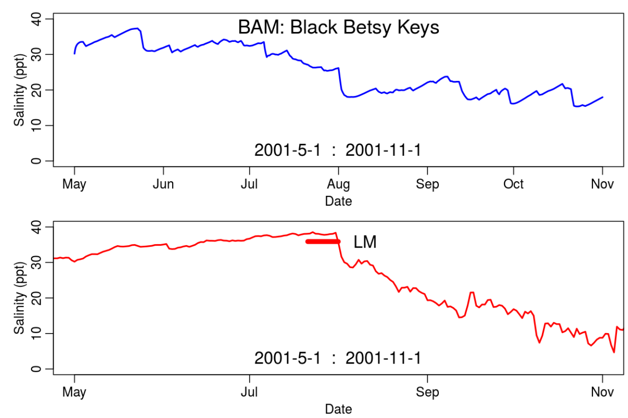
(a) Barnes Sound 2000



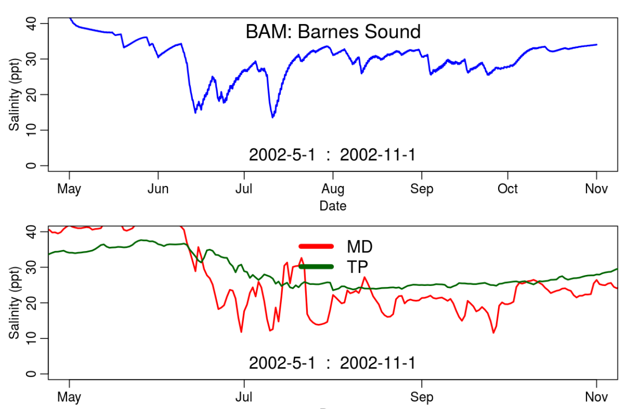
(b) Black Betsy Key 2000



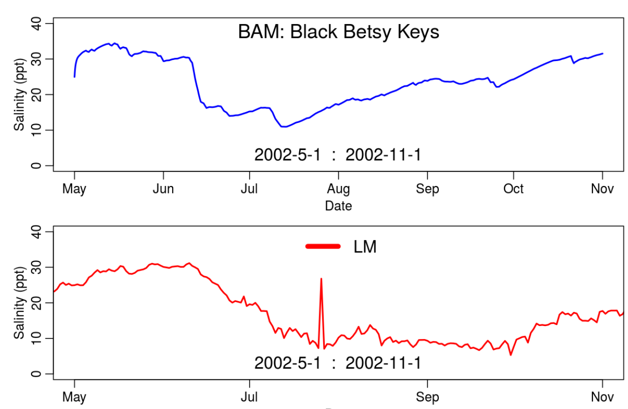
(c) Barnes Sound 2001



(d) Black Betsy Key 2001

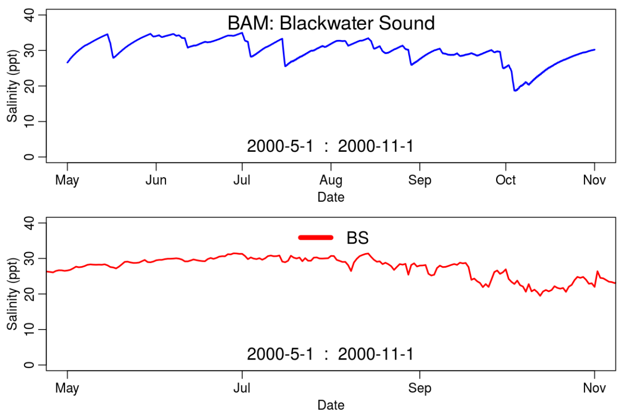


(e) Barnes Sound 2001

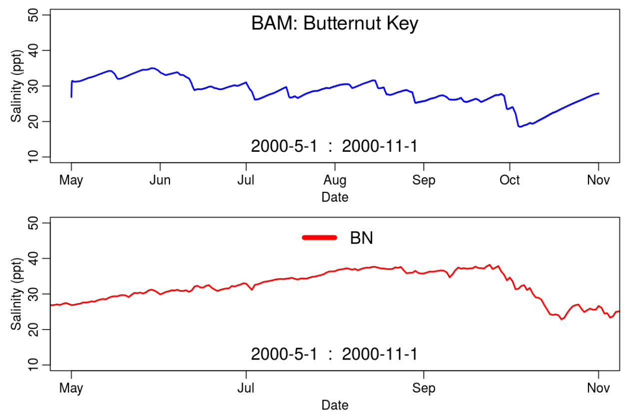


(f) Black Betsy Key 2002

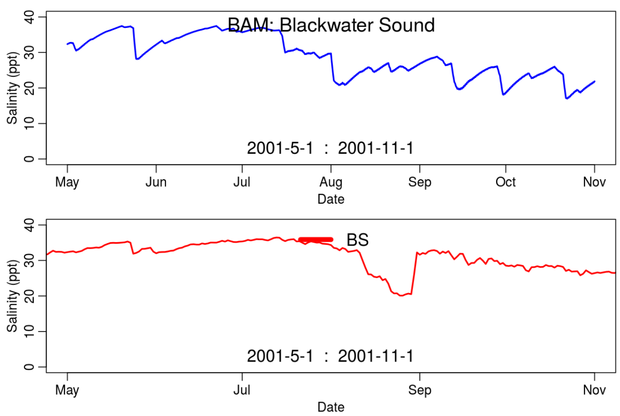
Figure 22. Salinity comparisons at Barnes Sound and Black Betsy Key 2000-2002.



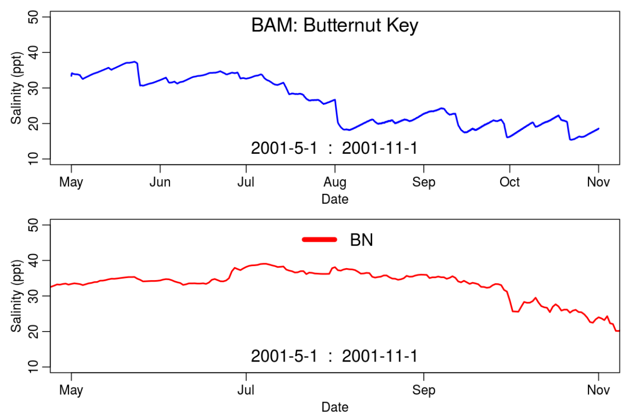
(a) Blackwater Sound 2000



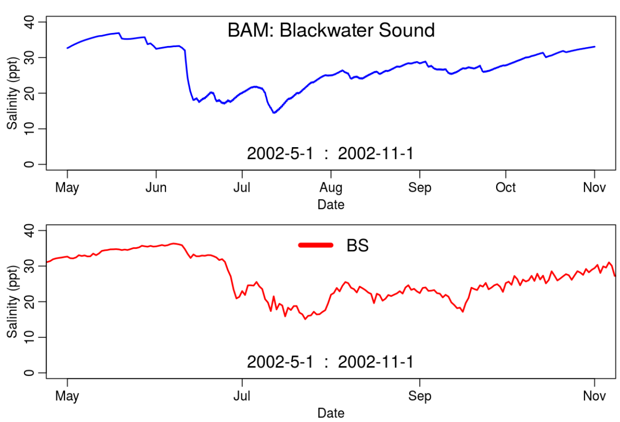
(b) Butternut Key 2000



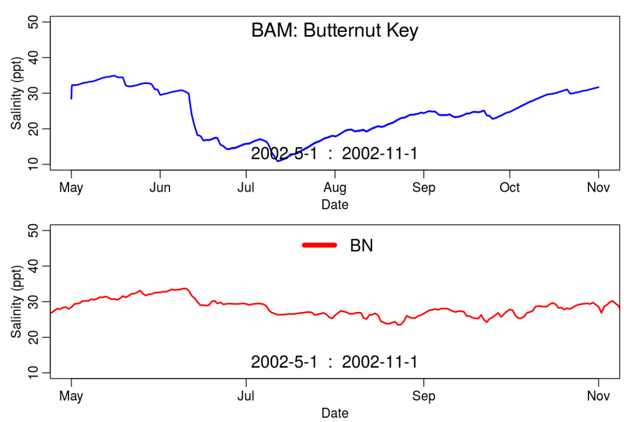
(c) Blackwater Sound 2001



(d) Butternut Key 2001

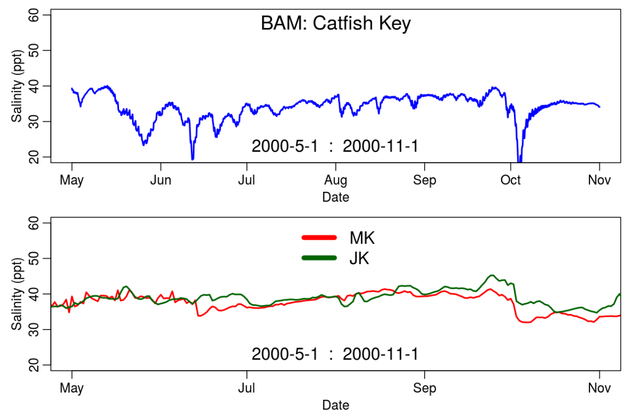


(e) Blackwater Sound 2002

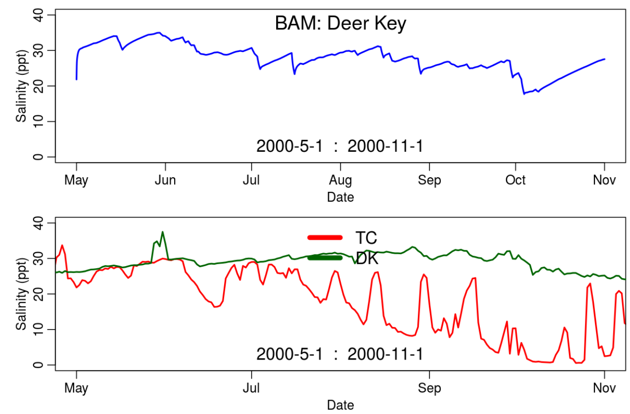


(f) Butternut Key 2002

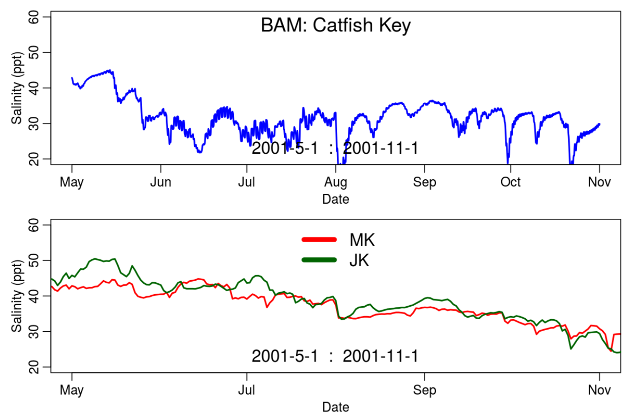
Figure 23. Salinity comparisons at Blackwater Sound, and Butternut Key 2000-2002.



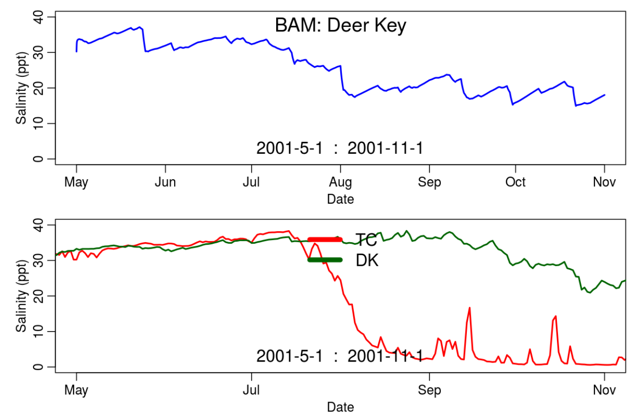
(a) Catfish Key 2000



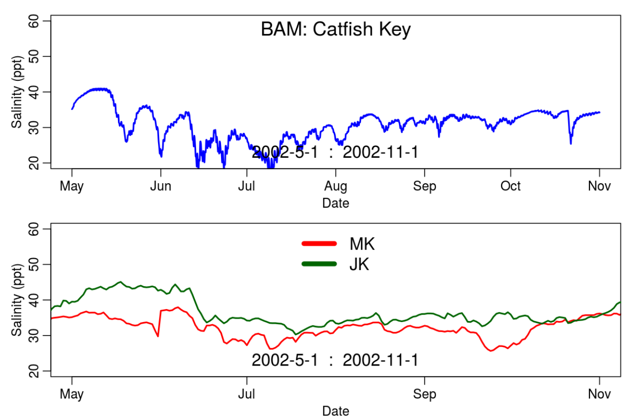
(b) Deer Key 2000



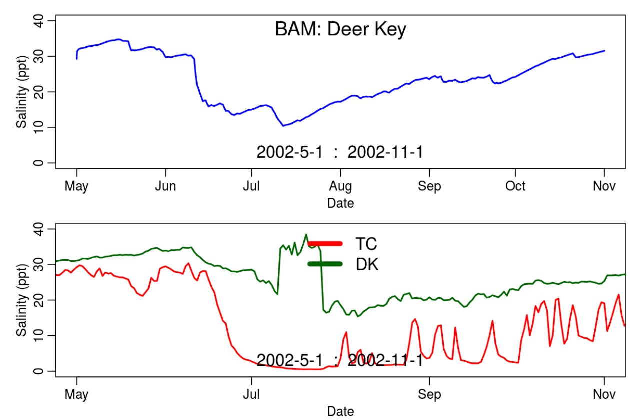
(c) Catfish Key 2001



(d) Deer Key 2001

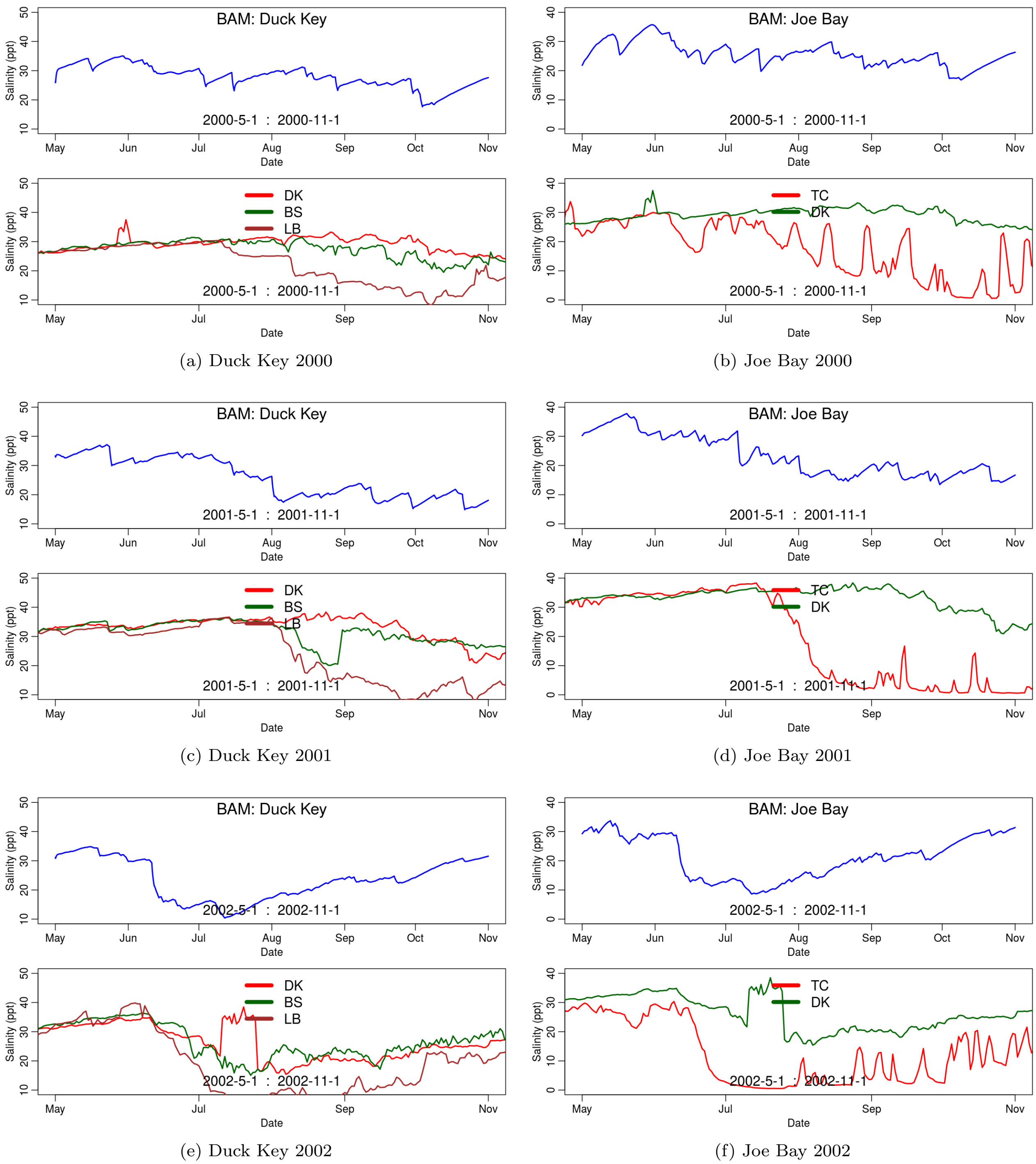


(e) Catfish Key 2002



(f) Deer Key 2002

Figure 24. Salinity comparisons at Catfish Key and Deer Key 2000-2002.

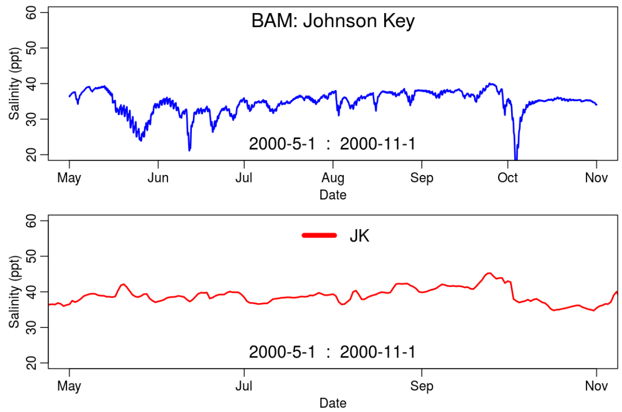


(a) Duck Key 2000 (b) Joe Bay 2000

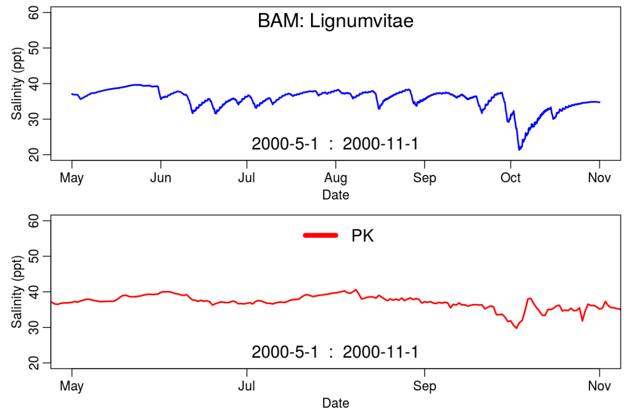
(c) Duck Key 2001 (d) Joe Bay 2001

(e) Duck Key 2002 (f) Joe Bay 2002

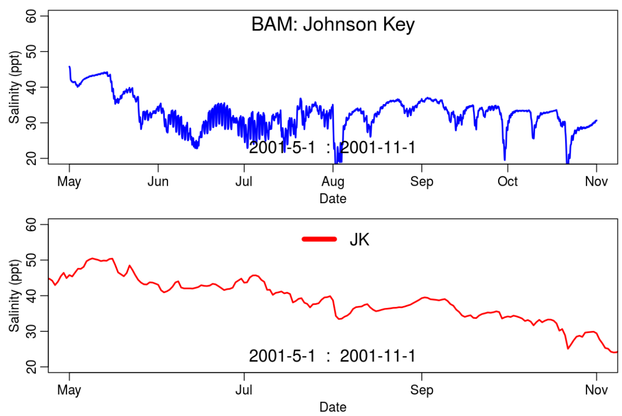
Figure 25. Salinity comparisons at Duck Key and Joe Bay 2000-2002.



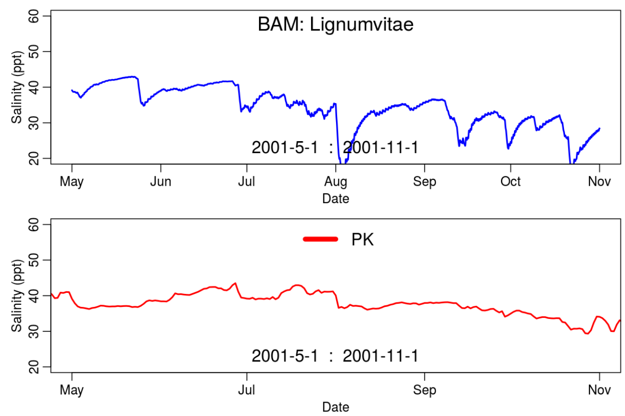
(a) Johnson Key 2000



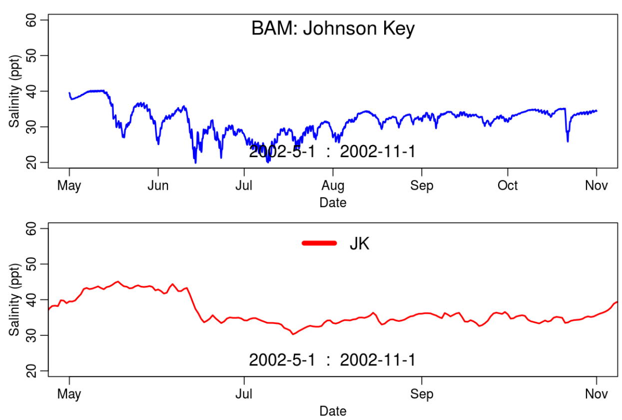
(b) Lignumvitae 2000



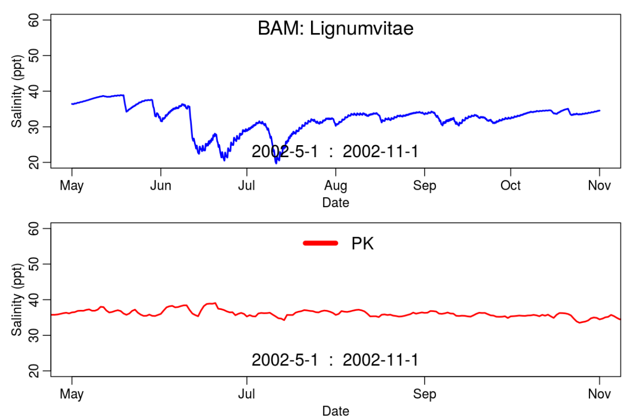
(c) Johnson Key 2001



(d) Lignumvitae 2001

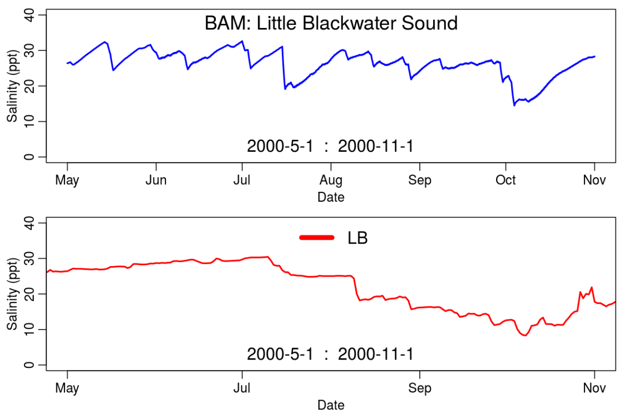


(e) Johnson Key 2002

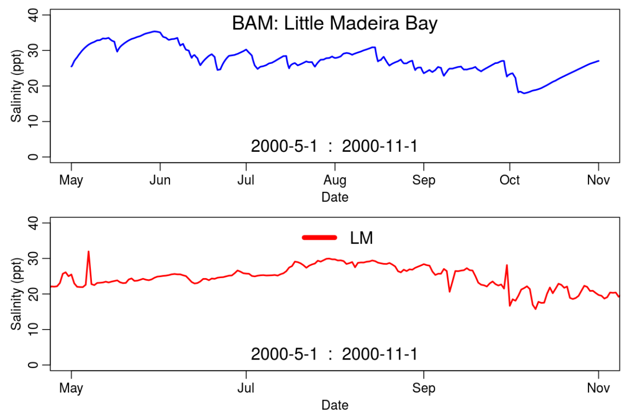


(f) Lignumvitae 2002

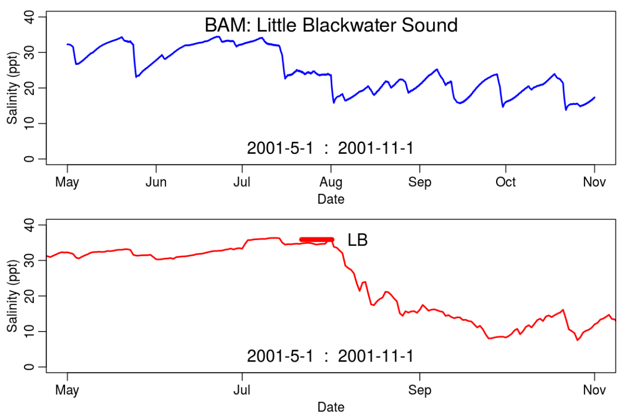
Figure 26. Salinity comparisons at Johnson Key and Lignumvitae 2000-2002.



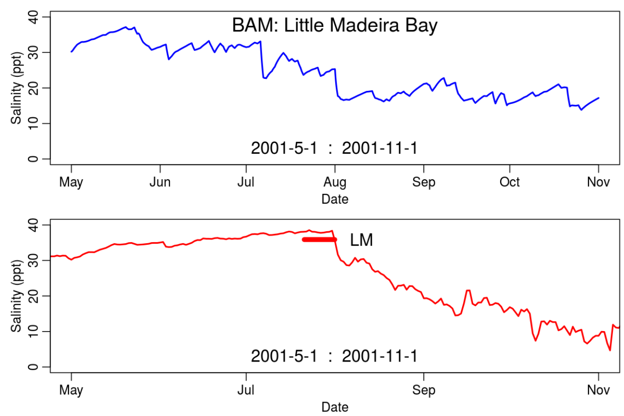
(a) Little Blackwater Sound 2000



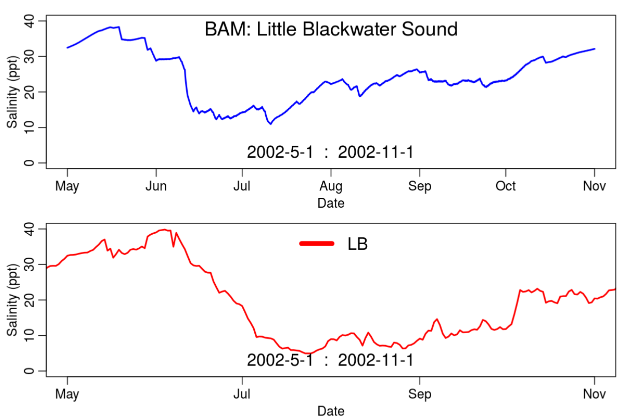
(b) Little Madeira Bay 2000



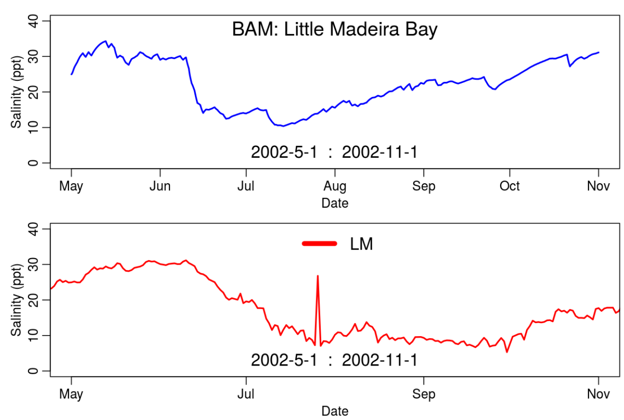
(c) Little Blackwater Sound 2001



(d) Little Madeira Bay 2001

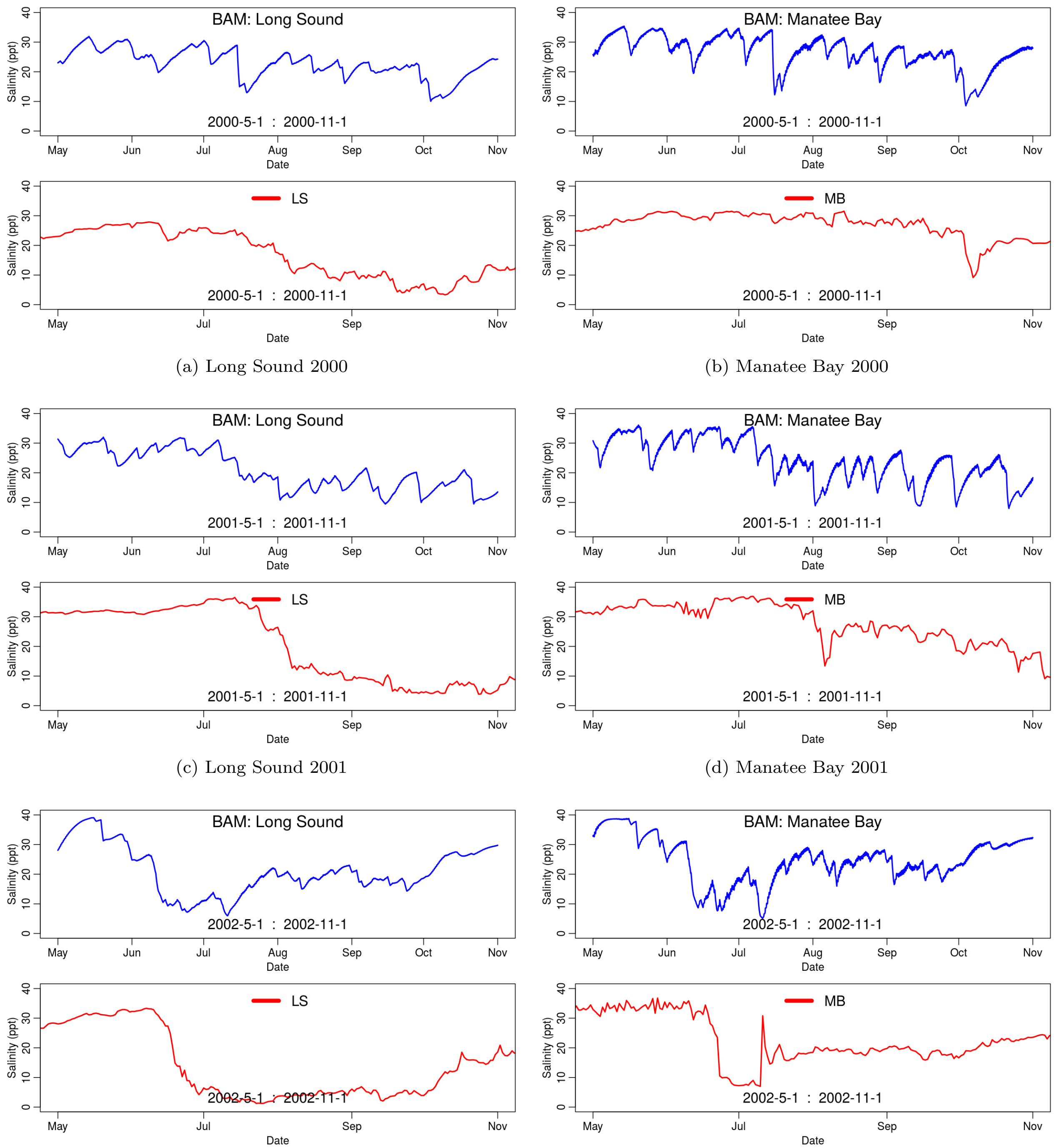


(e) Little Blackwater Sound 2002



(f) Little Madeira Bay 2002

Figure 27. Salinity comparisons at Little Blackwater Sound and Little Madeira Bay 2000-2002.



(a) Long Sound 2000

(b) Manatee Bay 2000

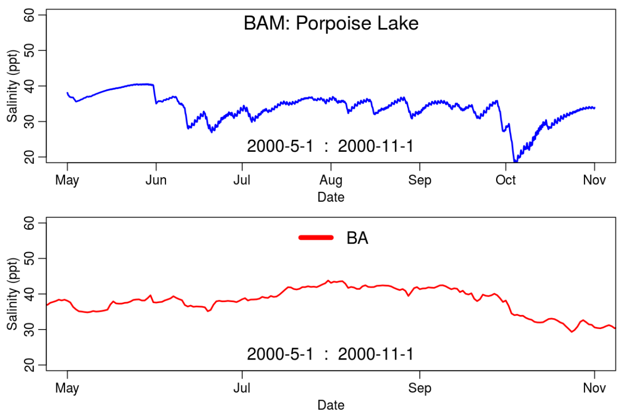
(c) Long Sound 2001

(d) Manatee Bay 2001

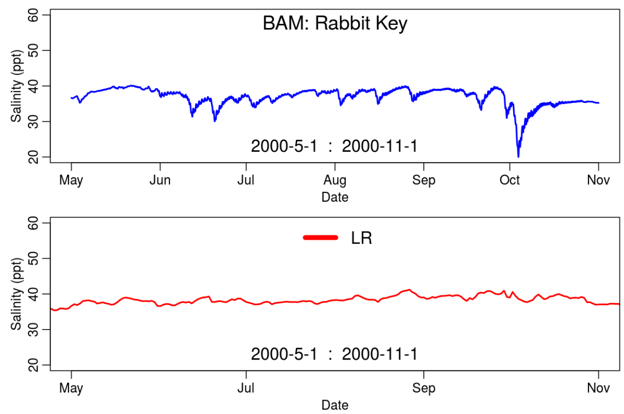
(e) Long Sound 2002

(f) Manatee Bay 2002

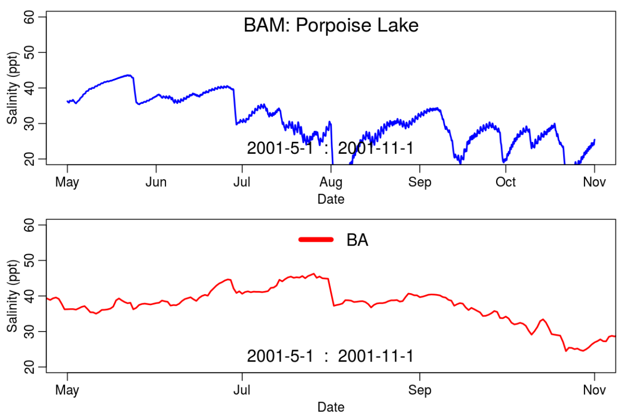
Figure 28. Salinity comparisons at Long Sound and Manatee Bay 2000-2002.



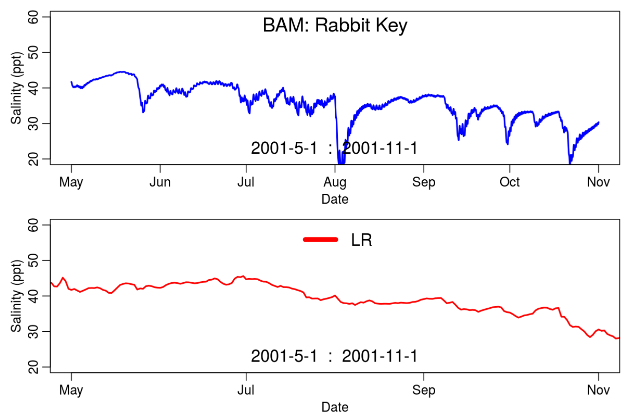
(a) Porpoise Lake 2000



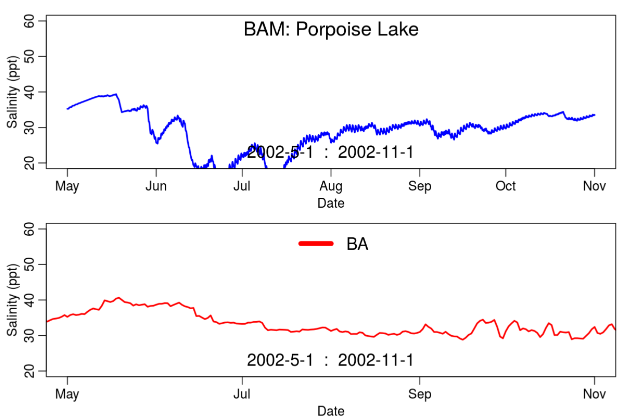
(b) Rabbit Key 2000



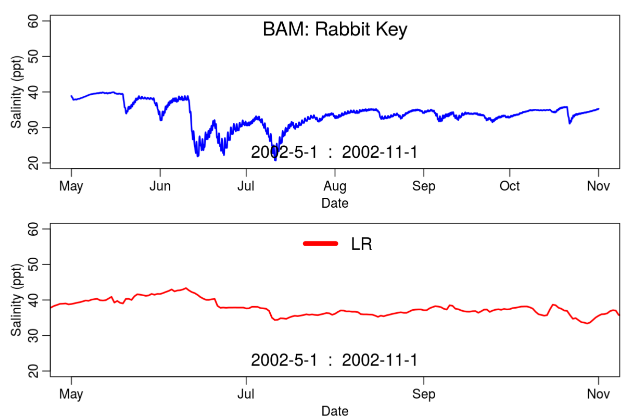
(c) Porpoise Lake 2001



(d) Rabbit Key 2001

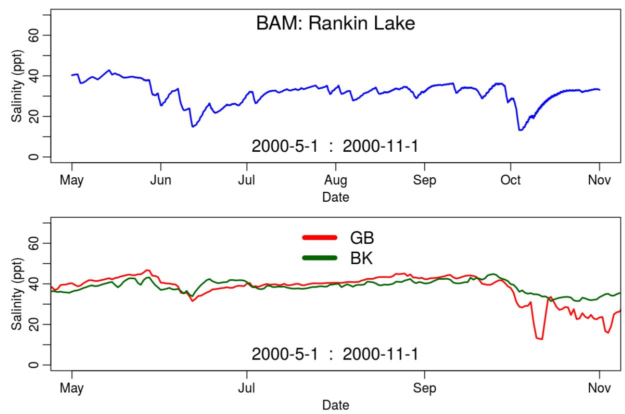


(e) Porpoise Lake 2002

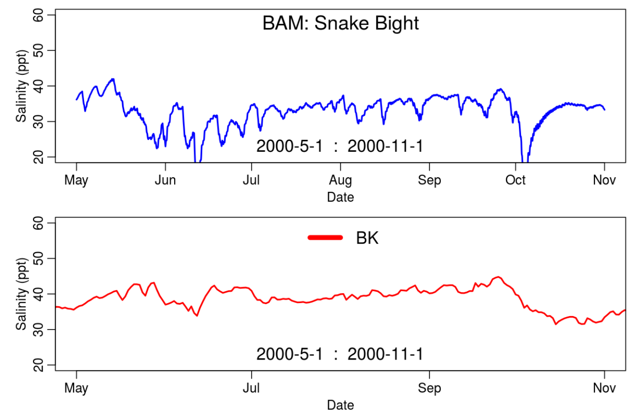


(f) Rabbit Key 2002

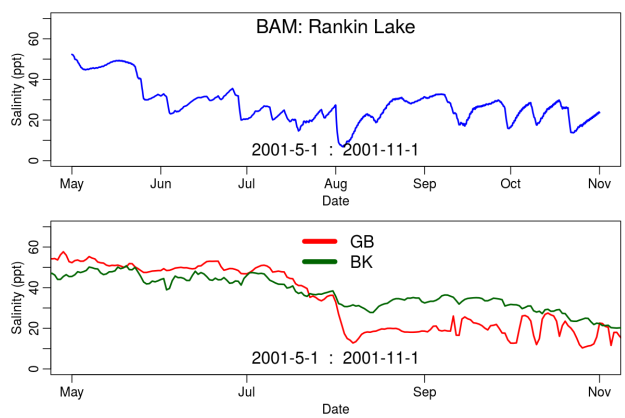
Figure 29. Salinity comparisons at Porpoise Lake and Rabbit Key 2000-2002.



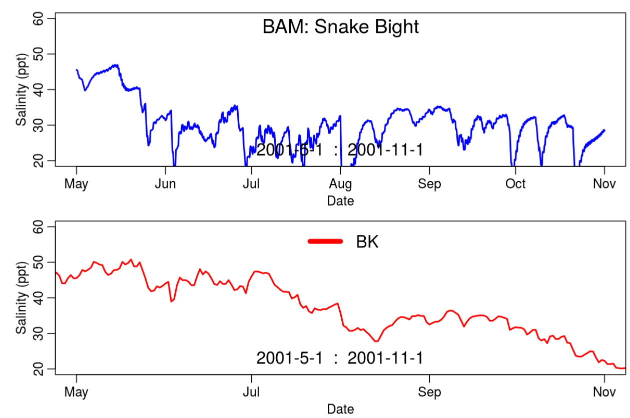
(a) Rankin Lake 2000



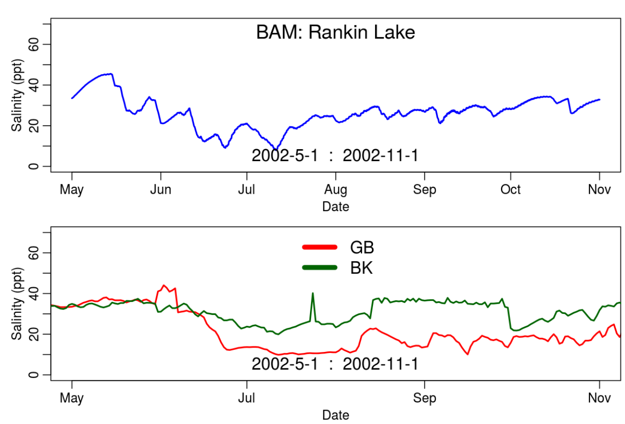
(b) Snake Bight 2000



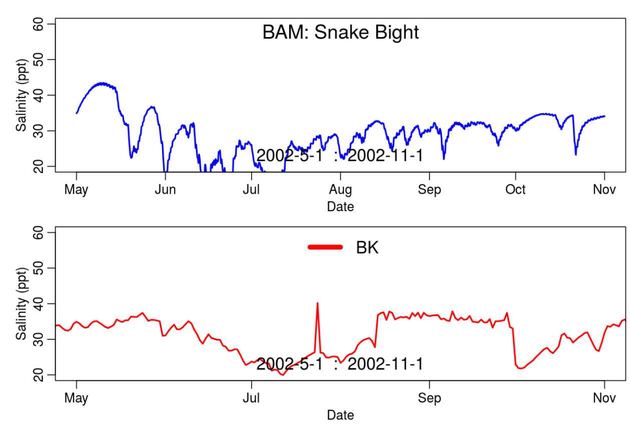
(c) Rankin Lake 2001



(d) Snake Bight 2001

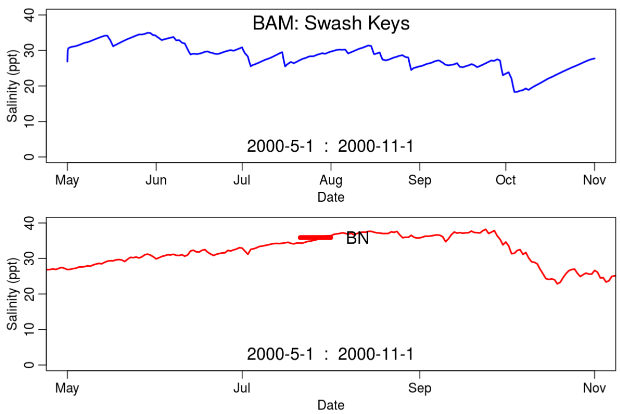


(e) Rankin Lake 2002

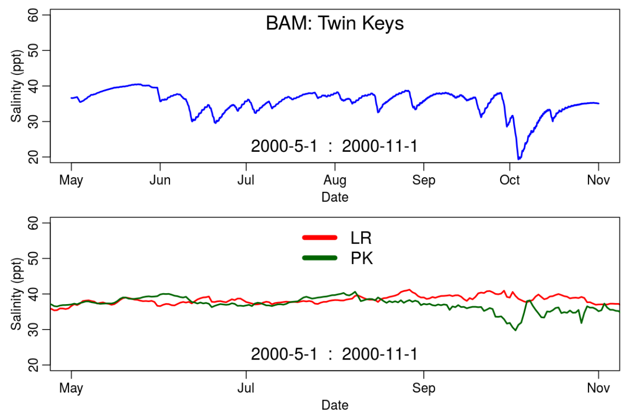


(f) Snake Bight 2002

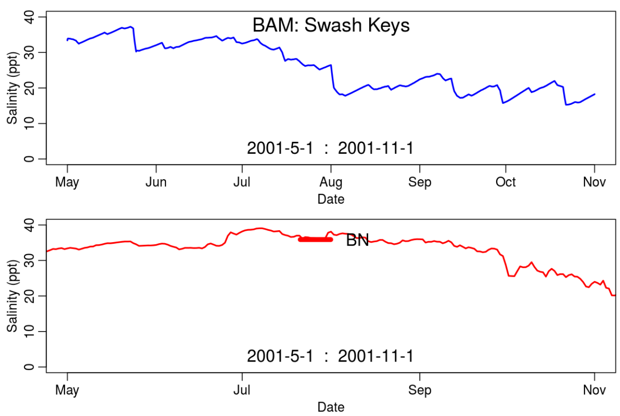
Figure 30. Salinity comparisons at Rankin Lake and Snake Bight 2000-2002.



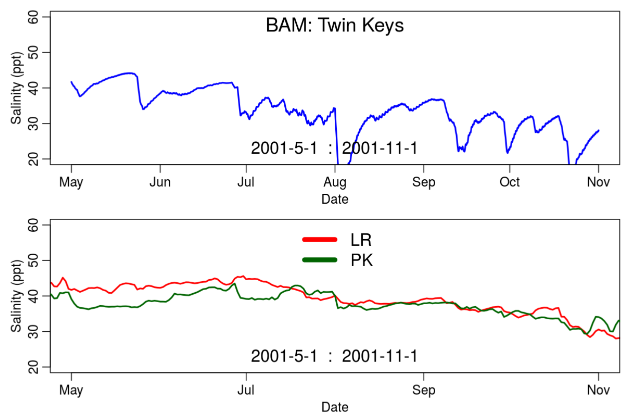
(a) Swash Keys 2000



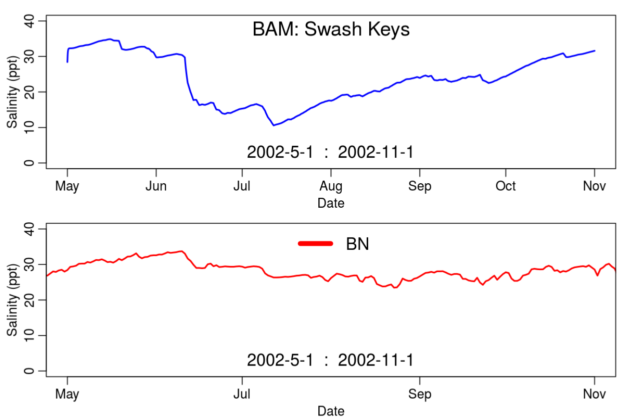
(b) Twin Keys 2000



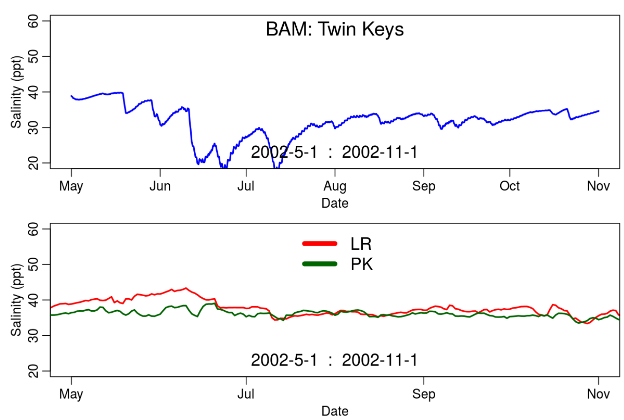
(c) Swash Keys 2001



(d) Twin Keys 2001

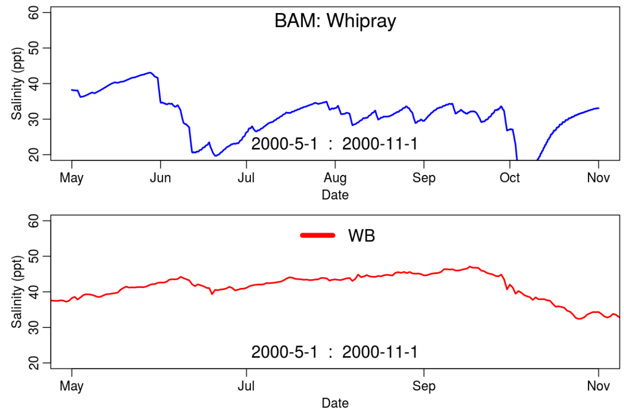


(e) Swash Keys 2002

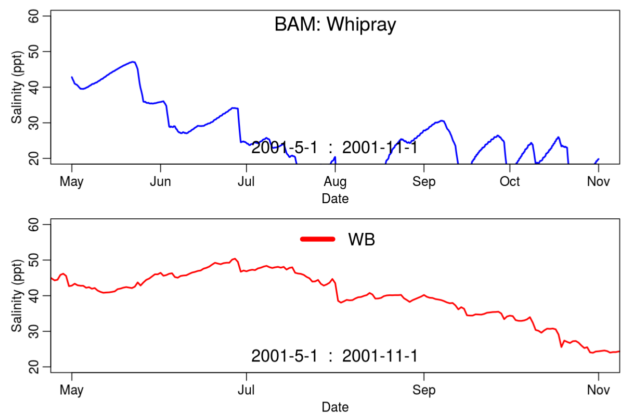


(f) Twin Keys 2002

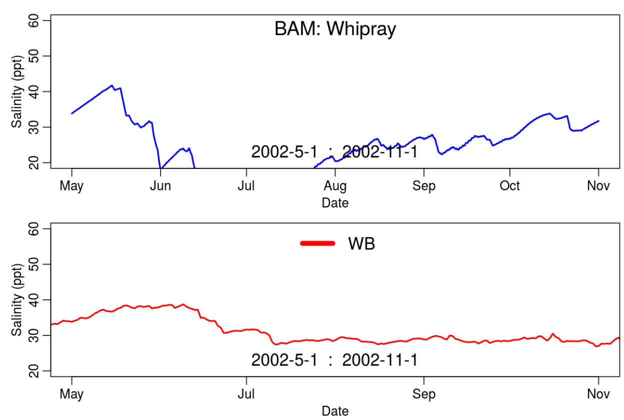
Figure 31. Salinity comparisons at Swash Keys and Twin Keys 2000-2002.



(a) Whipray 2000



(b) Whipray 2001



(c) Whipray 2002

Figure 32. Salinity comparisons at Whipray 2000-2002.

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Appendix A License

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                       TERMS AND CONDITIONS

  0. Definitions.

  "This License" refers to version 3 of the GNU General Public License.

  "Copyright" also means copyright-like laws that apply to other kinds of
works, such as semiconductor masks.

  "The Program" refers to any copyrightable work licensed under this
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"recipients" may be individuals or organizations.

  To "modify" a work means to copy from or adapt all or part of the work
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exact copy.  The resulting work is called a "modified version" of the
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  A "covered work" means either the unmodified Program or a work based
on the Program.

  To "propagate" a work means to do anything with it that, without
permission, would make you directly or secondarily liable for
infringement under applicable copyright law, except executing it on a
computer or modifying a private copy.  Propagation includes copying,
distribution (with or without modification), making available to the
public, and in some countries other activities as well.

  To "convey" a work means any kind of propagation that enables other
parties to make or receive copies.  Mere interaction with a user through
a computer network, with no transfer of a copy, is not conveying.

  An interactive user interface displays "Appropriate Legal Notices"
to the extent that it includes a convenient and prominently visible
feature that (1) displays an appropriate copyright notice, and (2)
tells the user that there is no warranty for the work (except to the
extent that warranties are provided), that licensees may convey the
work under this License, and how to view a copy of this License.  If
the interface presents a list of user commands or options, such as a
menu, a prominent item in the list meets this criterion.

  1. Source Code.

  The "source code" for a work means the preferred form of the work
for making modifications to it.  "Object code" means any non-source
form of a work.

  A "Standard Interface" means an interface that either is an official
standard defined by a recognized standards body, or, in the case of
interfaces specified for a particular programming language, one that
is widely used among developers working in that language.

  The "System Libraries" of an executable work include anything, other
than the work as a whole, that (a) is included in the normal form of
packaging a Major Component, but which is not part of that Major
Component, and (b) serves only to enable use of the work with that
Major Component, or to implement a Standard Interface for which an
implementation is available to the public in source code form.  A
"Major Component", in this context, means a major essential component
(kernel, window system, and so on) of the specific operating system
(if any) on which the executable work runs, or a compiler used to
produce the work, or an object code interpreter used to run it.

  The "Corresponding Source" for a work in object code form means all
the source code needed to generate, install, and (for an executable
work) run the object code and to modify the work, including scripts to
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control those activities.  However, it does not include the work's
System Libraries, or general-purpose tools or generally available free
programs which are used unmodified in performing those activities but
which are not part of the work.  For example, Corresponding Source
includes interface definition files associated with source files for
the work, and the source code for shared libraries and dynamically
linked subprograms that the work is specifically designed to require,
such as by intimate data communication or control flow between those
subprograms and other parts of the work.

  The Corresponding Source need not include anything that users
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  The Corresponding Source for a work in source code form is that
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b) Convey the object code in, or embodied in, a physical product (including a physical distribution medium), accompanied by a written offer, valid for at least three years and valid for as long as you offer spare parts or customer support for that product model, to give anyone who possesses the object code either (1) a copy of the Corresponding Source for all the software in the product that is covered by this License, on a durable physical medium customarily used for software interchange, for a price no more than your reasonable cost of physically performing this conveying of source, or (2) access to copy the Corresponding Source from a network server at no charge.

c) Convey individual copies of the object code with a copy of the written offer to provide the Corresponding Source. This alternative is allowed only occasionally and noncommercially, and only if you received the object code with such an offer, in accord with subsection 6b.

d) Convey the object code by offering access from a designated place (gratis or for a charge), and offer equivalent access to the

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