Evaluation of Residence Time and Entrainment using a Particle Tracking Model for the Sacramento-San Joaquin Delta

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Abstract: We used a coupled hydrodynamic-particle tracking model to assess the recent trends (1990-2004) in residence time and entrainment risk for organisms in the San Francisco Estuary, California. Despite the fact the modeling tool has numerous limitations, we hoped that simulations of particles released into the Sacramento River at Freeport and the San Joaquin River at Vernalis would provide insight into potential mechanisms that could affect pelagic organisms. Our major hypotheses were that: 1) residence time in the delta has been reduced; 2) recent changes in operations have had a disproportional effect on inflow from the San Joaquin River and 3) entrainment of pelagic species has not increased.

Regarding the first hypothesis, the model runs did not provide evidence of major shift during the past 3-4 years, when we hypothesize that there has been a "step-change" in pelagic organisms. If anything, the model runs suggested that residence time may have increased slightly for the San Joaquin River. However, the Sacramento River runs provided evidence that residence time tended to be longer prior to the Bay-Delta Accord. This effect may have been strongly influenced by hydrology as residence time was typically longer in drier years.

The second hypothesis is related to the assumption that operations typically have a stronger effect on inflow from the San Joaquin River than the Sacramento River. This idea is supported by the model runs that showed that residence times tend to be shorter for particles released in the San Joaquin River than the Sacramento River. The second was at least partially supported for late-winter through early-spring (March-June), when

the model runs suggested that entrainment risk during the past 3-4 years has been somewhat higher than the long-term average. This observation is inconsistent with our third hypothesis, although additional analyses are needed (e.g. fish salvage data). The model results may partially be related to hydrology as entrainment risk appeared to be somewhat inversely correlated with hydrology for March-May. Moreover, the model suggested that entrainment risk tended to be lower during June-October before 1994, the drier period prior the Bay-Delta Accord.

In the last few years, the abundance indices calculated by the Interagency Ecological Program (IEP) show marked declines in numerous pelagic fishes in the upper San Francisco Estuary (the Delta and Suisun Bay) (IEP 2005). In addition to the declines in fish species, IEP monitoring also found declining abundance trends for zooplankton with a substantial drop in calanoid copepod abundance in 2004. While several of these declining species - including longfin smelt, juvenile striped bass and calanoid copepods have shown evidence of a long-term decline - there appears to have been a precipitous "step-change" to very low abundance during 2002-2004.

Based on the observations of recent trends, the IEP (2005) developed a study plan based on a conceptual model of the major likely factors in the Pelagic Organism Decline ("POD"). The plan proposes that there are at least three general factors that may be acting individually or in concert to lower pelagic productivity: 1) toxic effects; 2) exotic species effects; and 3) water project operations. The present report is one a suite of study components to examine whether recent changes in water project operations are likely to have had a substantial role in the pelagic organism decline. Kimmerer (2002) showed that water project operations have resulted in lower winter/spring inflow and higher summer inflow to the Delta. As noted in the IEP (2005) work plan, CBDA actions have restored some spring inflow, but have also increased summer inflows to meet increasing summer export demands. This shift was implemented based on the assumption that it would be more protective to sensitive early life stages of key estuarine fishes and invertebrates. However, it is possible that high export during summer-winter months has unanticipated food web effects by exporting biomass that would otherwise support the estuarine food web. Other possible mechanisms include increased entrainment of fishes during the summer-winter months, or a reduction in habitat quality downstream (e.g. less area of the appropriate salinity).

To help oversee these studies, a POD Water Project Operations Project Work Team (PWT) was formed conduct studies related to water project operations. As part of screening level studies in 2005, the team developed several hypotheses that might be relevant to the POD:

- Residence time in the delta has been reduced.
- Recent changes in operations have had a disproportional effect on inflow from the San Joaquin River.
- Entrainment of pelagic species has not increased.

Here, we use a coupled hydrodynamic-particle tracking model to assess the sensitivity of water source and timing on entrainment risk during the past 16 years. Model scenarios were based on neutrally buoyant particles that we hoped would provide insight into potential water project effects on phytoplankton, zooplankton and larval fish inputs from the Sacramento and San Joaquin rivers. We used the Delta Simulation Model-2 Particle Tracking Model (PTM) (CDWR 2002; Culberson et al. 2004) as the analysis tool. The analyses were based on actual flows and water project operations during 1990-2004.

Methods

DSM2 hydrodynamics and particle tracking model: The following description for the methods was largely taken from Culberson et a. (2004). The primary modeling tool used for this study is PTM (CDWR 2002: Culberson et al. 2004). The PTM simulates transport and fate of individual particles moving throughout Suisun Marsh and the Sacramento-San Joaquin Delta. The model uses velocity, flow, and stage output from a one-dimensional hydrodynamic model, DSM2 HYDRO. DSM2 HYDRO was adapted for the delta and marsh from the unsteady, open-channel flow USGS FourPt model (Delong et al. 1997). Time varying boundary conditions for the hydrodynamic model include river and stream inflows, State Water Project and Central Valley Project water diversions, agricultural water diversions, irrigation and leach water drainage flows, tide stage in Suisun Bay at Carquinez Strait (Figure 1), and delta water control operations. Fixed inputs include channel and flooded island geometry, and roughness coefficients. The system geometry is modeled as a network of channel segments and open-water areas connected by junctions (Figure 1; additional information on the model is available online at http://modeling.water.ca.gov/delta/models/dsm2/index.html).

The PTM uses the same system geometry as DSM2 HYDRO. The PTM was originally developed as a two-dimensional model, and subsequently modified to a quasi-3D model (CDWR 2002; Culberson et al. 2004). As modeled in these studies, particles were simply transported within the network under the influence of flows, tidal flows, and exports. The DSM2 PTM output data can be viewed as animations that display the movement of particles.

PTM Approach: The basic modeling approach was as follows:

Particle Release Locations: Vernalis (San Joaquin) and Freeport (Sacramento).

Boundaries (exit locations): Chipps Island, SWP/CVP pumps

Months: March-October

Timing of Releases: Daily

Model Runs: 90 days

Period to be Modeled: 1990-2004.

Analysis of Residence Time: To help address the first and second hypotheses, we calculated the time for 25, 50 and 75 percent of the particles to exit the system, either past Chipps Island, through the water projects, or onto Delta islands. We hoped that these variables would provide insight into trends in residence times of pelagic organisms that enter via the Sacramento and San Joaquin rivers.

Analysis of Entrainment Trends: To examine the third hypothesis, we assumed that the percentage of particles diverted into the SWP and CVP represented the likelihood of entrainment. Cumulative particle entrainment percentages after 90 days were used to compare the trends for particles released in the San Joaquin River at Vernalis. These results were intended to complement additional analyses of other measures of entrainment such as fish salvage.

Results

Detailed model results are provided in Figures 1-3. The model results include monthly summaries of means along with the anomalies (deviation from the long-term mean). The major observations include the following:

Residence Time (Sacramento River-Freeport Injections):

- Residence time tended to be longer before and including 1994, the drier period prior the Bay-Delta Accord.
- Residence time is typically longer in drier years such as 1990-1992, 1994 and 2001.
- There is no evidence of a major change in residence time during the past 3-4 years.

Residence Time (San Joaquin River-Vernalis Injections):

- Residence times tend to be much shorter for particles released in the San Joaquin River than the Sacramento River.
- Unlike the Sacramento River, water year type did not have as substantial an effect on residence time. Similarly, there was no obvious shift in residence times following the Bay-Delta accord.
- There is no evidence of a major change in residence time during the past 3-4 years. If anything, there has been a slight increase in residence time.

Entrainment (San Joaquin River-Vernalis Injections):

- Trends in entrainment risk appear to be somewhat inversely correlated with hydrology for March-May.
- In general, the model runs suggest that entrainment risk during June-October tended to be lower before 1994, a relatively dry period prior to the Bay-Delta Accord.
- In late-winter through early-spring (March-June), the model runs suggest that entrainment risk during the past 3-4 years has been somewhat higher than the long-term average.

Discussion

Our major hypotheses were that: 1) residence time in the delta has been reduced; 2) recent changes in operations have had a disproportional effect on inflow from the San Joaquin River and 3) entrainment of pelagic species has not increased.

Regarding the first hypothesis, there model runs did not provide evidence of major shift during the past 3-4 years, when we hypothesize that there has been a "step-change" in pelagic organisms. If anything, the model runs suggest that residence time may have increased slightly for the San Joaquin River. However, the Sacramento River runs provided evidence that residence time tended to be longer prior to the 1994 Bay-Delta Accord. This effect may strongly influenced by hydrology as residence time was typically longer in drier years such as 1990-1992, 1994 and 2001.

The second hypothesis is related to the assumption of many scientists that water project operations have a stronger effect on inflow from the San Joaquin River than the Sacramento River. This idea is supported by the model runs that showed that residence times tend to be shorter for particles released in the San Joaquin River than the Sacramento River. The second hypothesis was at least partially supported for late-winter through early-spring (March-June), when the model runs suggested that entrainment risk during the past 3-4 years has been somewhat higher than the long-term average. However, the model results were inconsistent with our third hypothesis. These conclusions may partially be related to hydrology as entrainment risk appeared to be somewhat inversely correlated with hydrology for March-May. Moreover, the model runs suggested that entrainment risk tended to be lower during June-October before 1994, the drier period prior the Bay-Delta Accord. This result seems fairly reasonable as the Bay-Delta Accord has tended to result in an increase in exports during summer and early autumn. Additional analyses on trends in fish salvage may help to address this issue (Brown et al. 1996).

Although the PTM provides an important tool for examining the effect of hydrodynamics on Delta organisms, the model has many limitations. As noted by Culberson et al. (2004), the PTM is not capable of modeling complex fish or zooplankton behaviors that may influence entrainment risk. For example, depending on hydrologic conditions, larval fish in the San Francisco Estuary have been shown to switch between vertical and horizontal migrations to maintain position within favorable habitats (Bennett et al. 2002). Further understanding of fish and zooplankton behaviors and continued model development can improve the applicability of PTM results. In addition, the model runs focused on <u>inputs</u> from the Sacramento and San Joaquin Rivers. They therefore are not necessarily relevant for organisms that are resident in the central or western Delta. They also may not be relevant for fishes that do not migrate upstream beyond the central or western Delta.

Acknowledgments

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References

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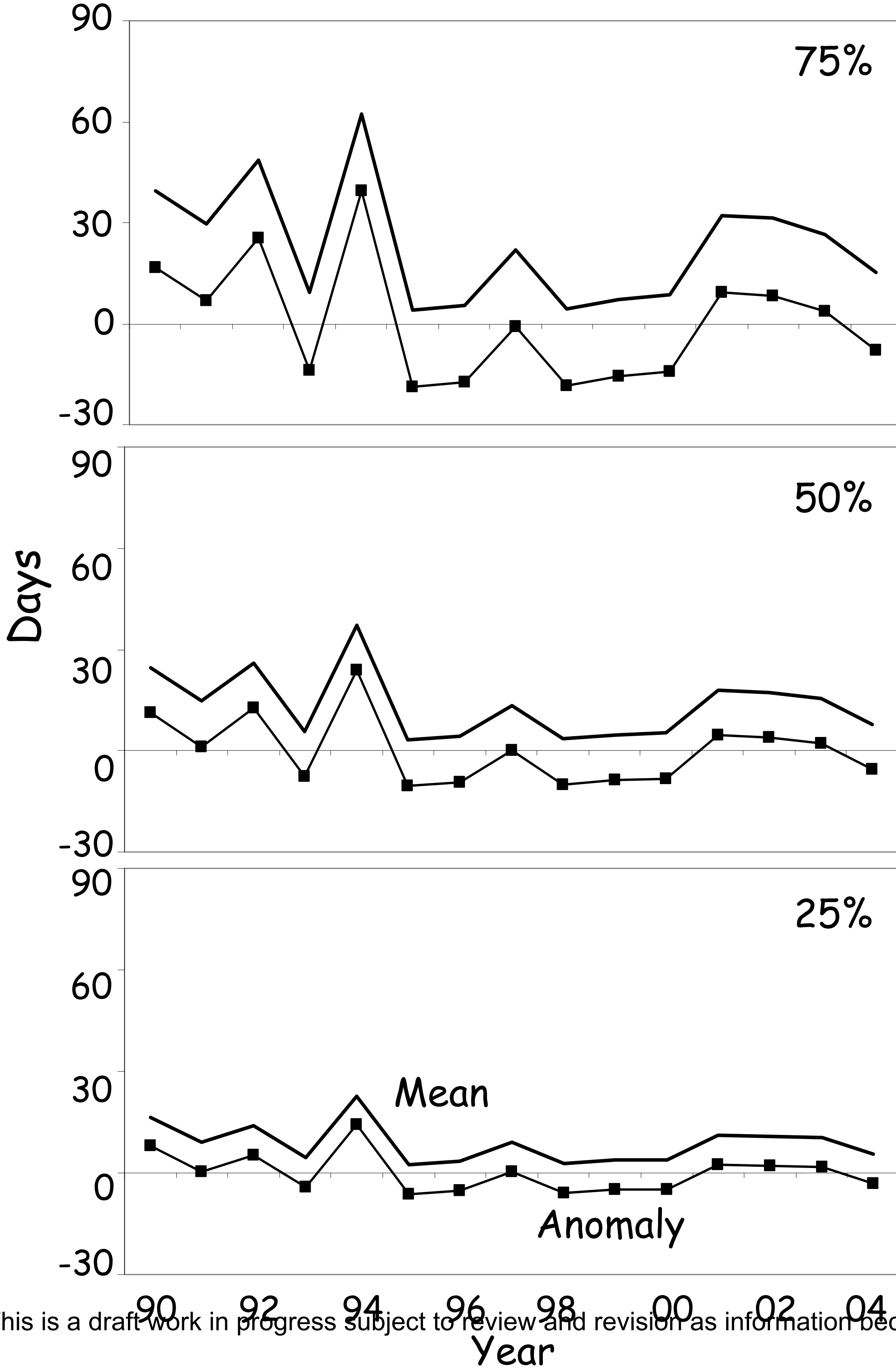
Figure captions

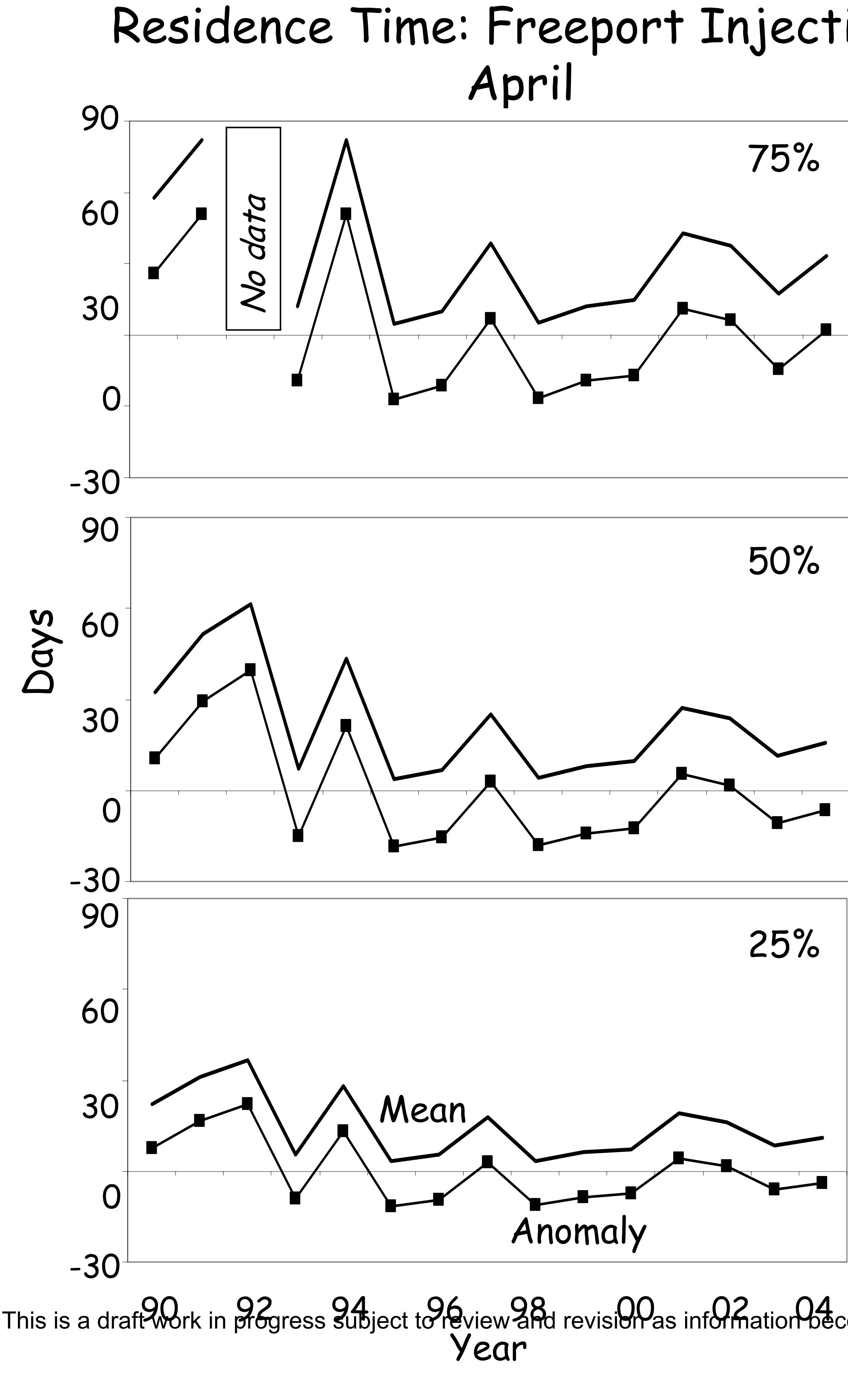
Figure 1 (a – h). Residence time (days) for particles injected in the Sacramento River at Freeport for 1990-2004. The monthly means and anomalies (deviation from the long-term mean for the entire period) are shown for March-October. The results for each month include estimates of the time for 75%, 50% or 25% of particles to exit the system (via the export pumps or in delta outflow past Chipps Island).

Figure 2 (a – h). Residence time (days) for particles injected in the San Joaquin River at Vernalis for 1990-2004. The monthly means and anomalies (deviation from the long-term mean for the entire period) are shown for March-October. The results for each month include estimates of the time for 75%, 50% or 25% of particles to exit the system (via the export pumps or in delta outflow past Chipps Island).

Figure 3 (a – c). The percentage of particles released in the San Joaquin River at Vernalis that were entrained in the SWP or CVP after 90 days. The monthly means and anomalies (deviation from the long-term mean for the entire period) are shown for March-October during 1990-2004.

Residence Time: Freeport Injections
March





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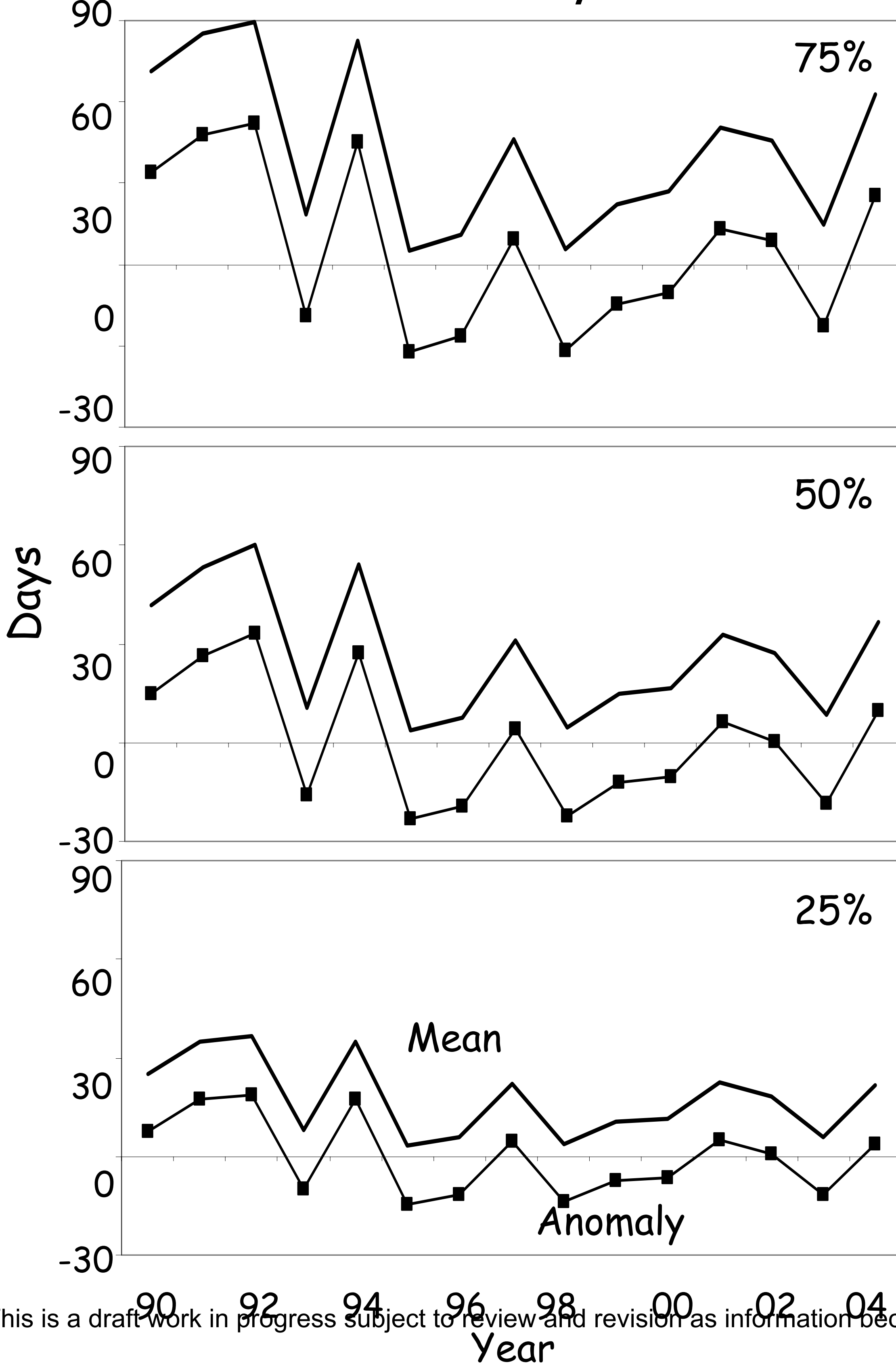
Residence Time: Freeport Injections
May



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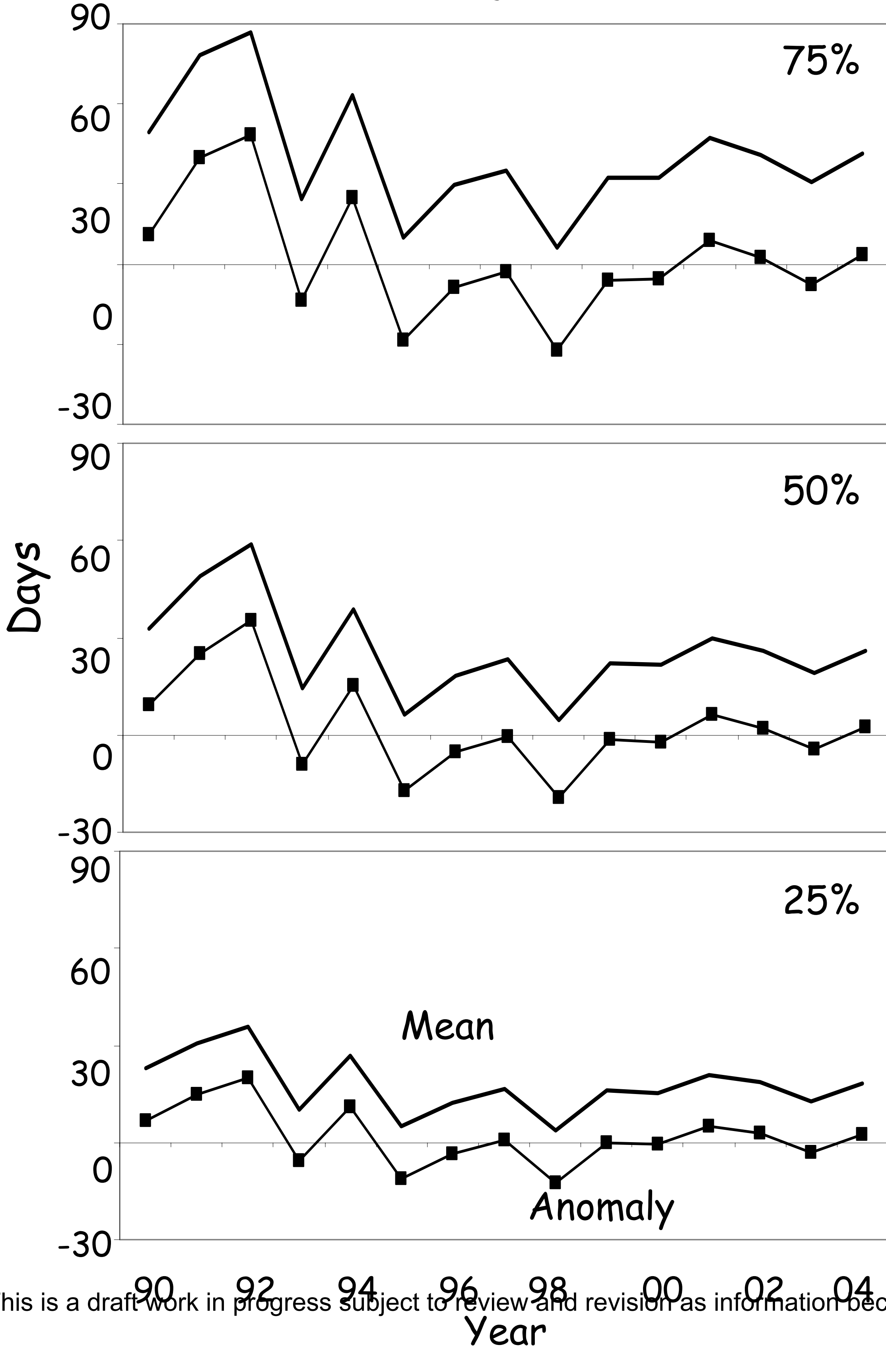
Residence Time: Freeport Injections
June



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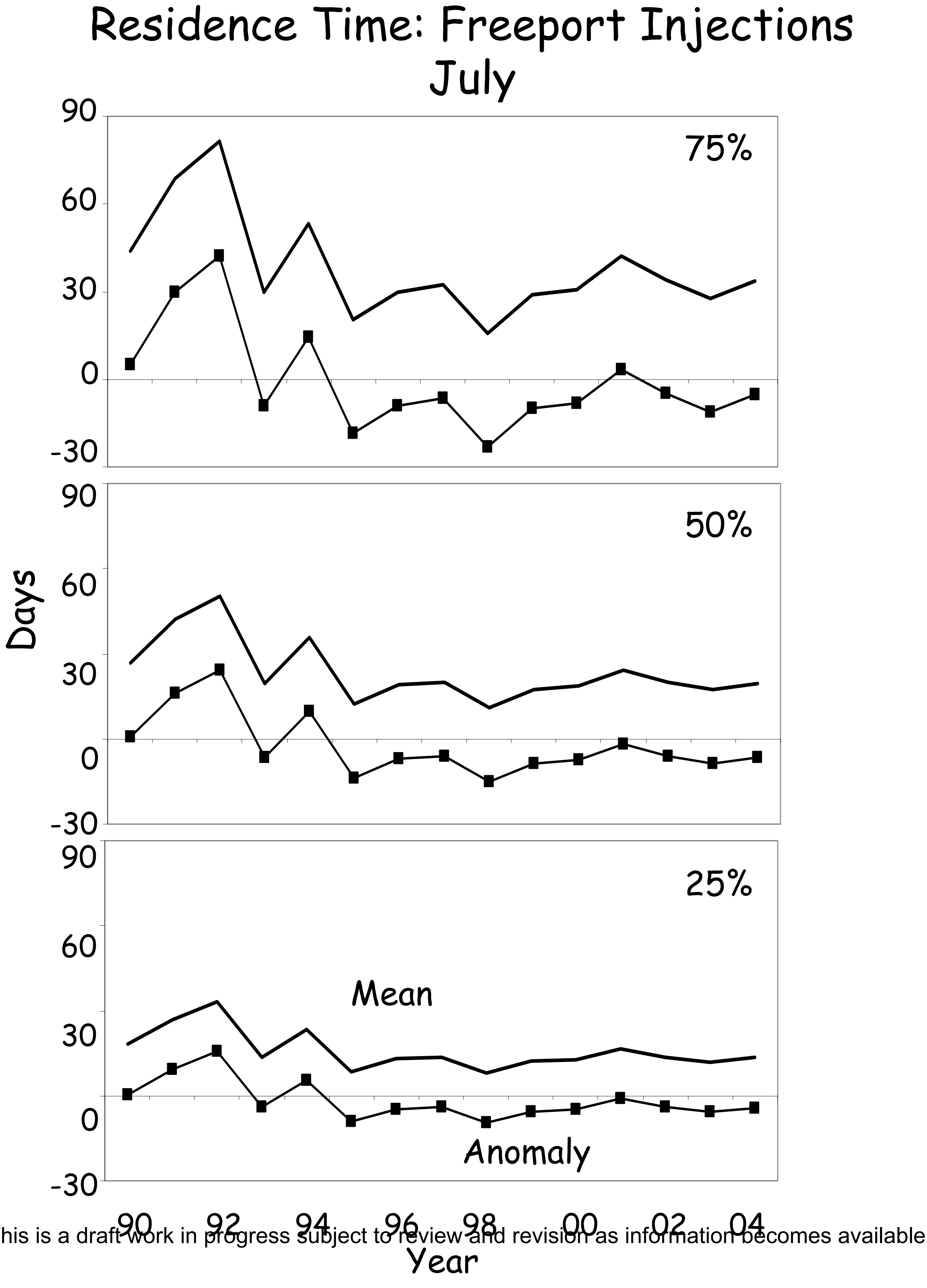
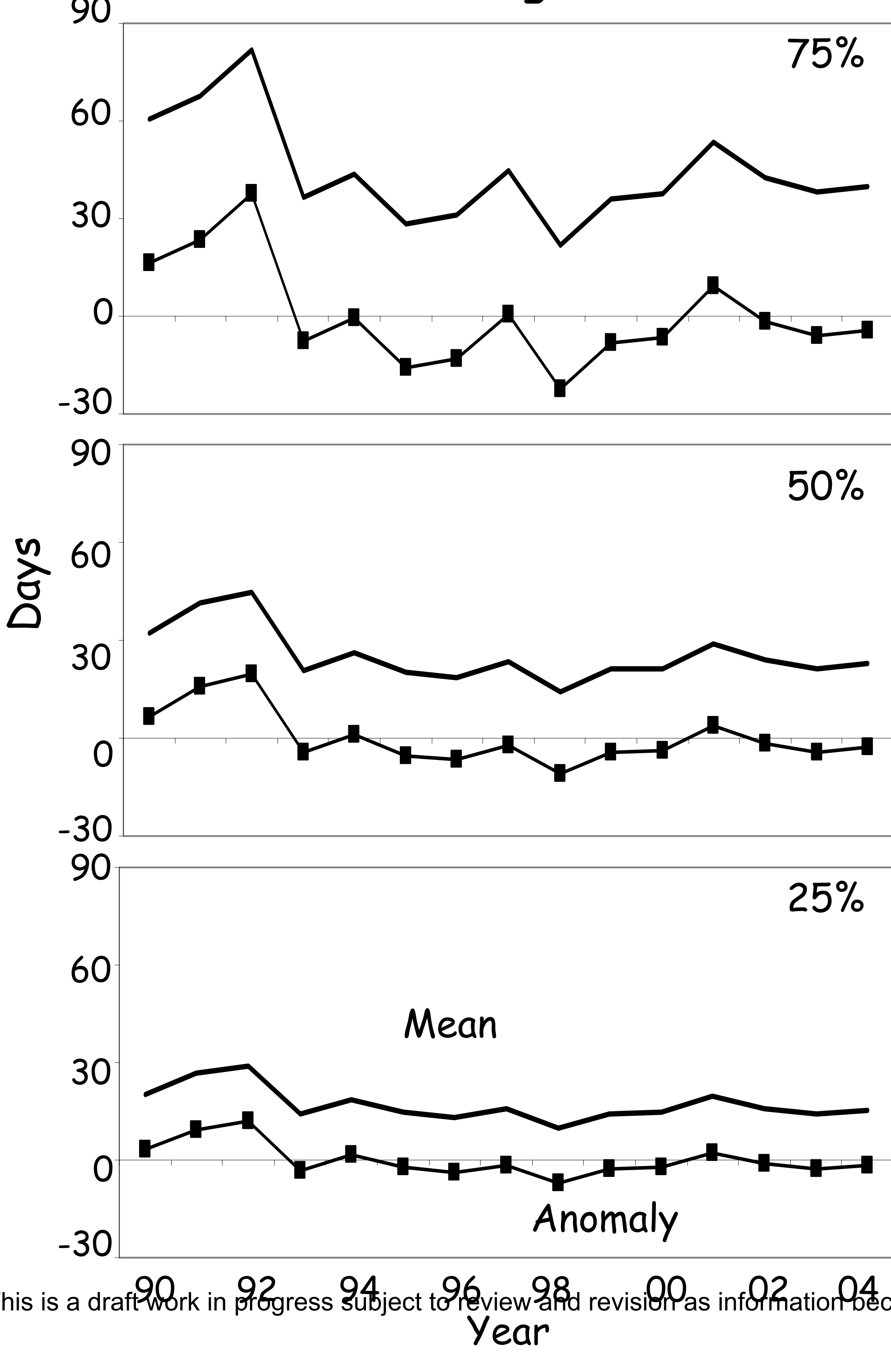

Residence Time: Freeport Injections
July
75%
50%
25%
Days
Mean
Anomaly
Year
90
60
30
0
-30
90
92
94
96
98
00
02
04

Residence Time: Freeport Injections August



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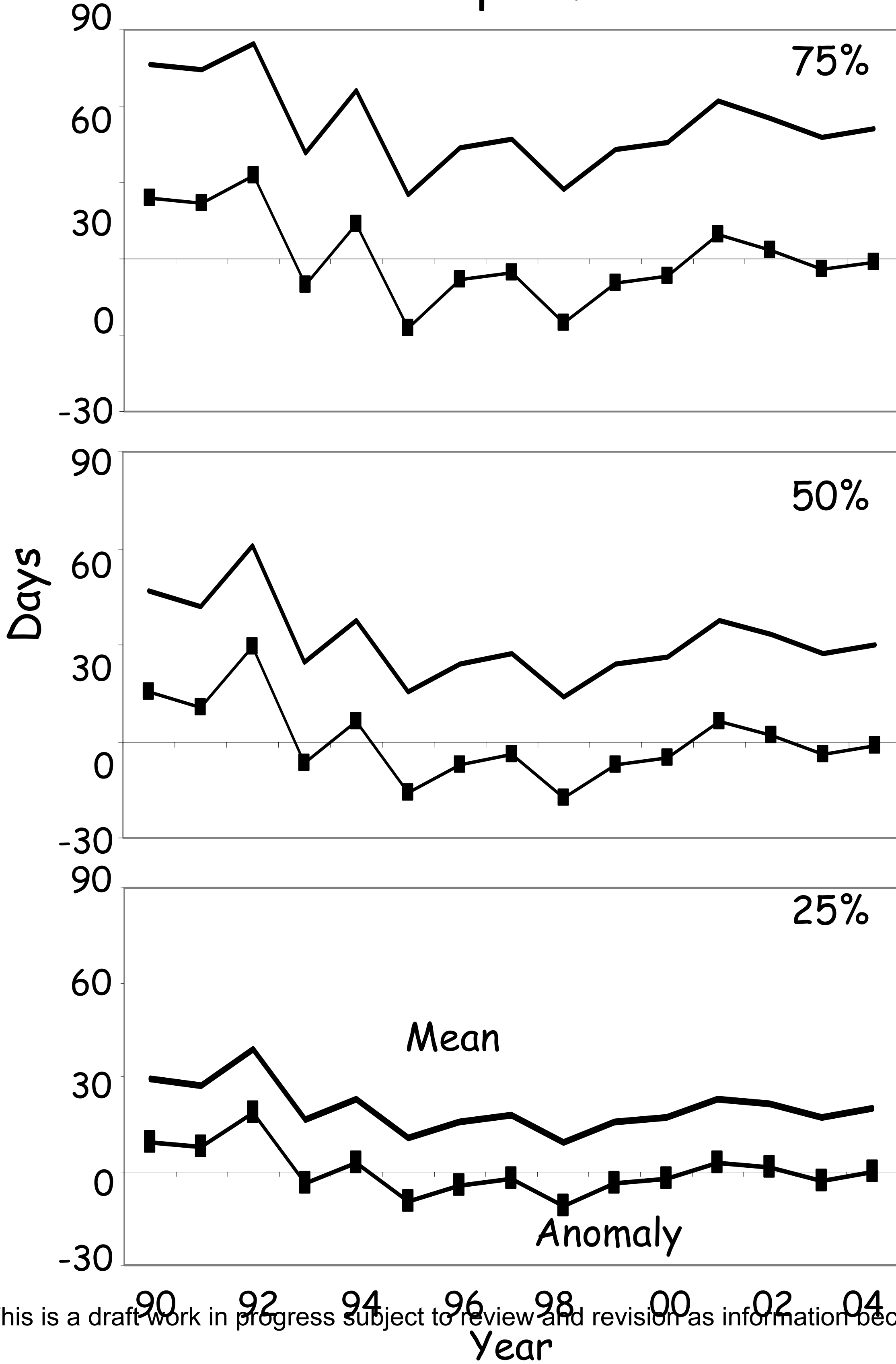
Residence Time: Freeport Injections
September



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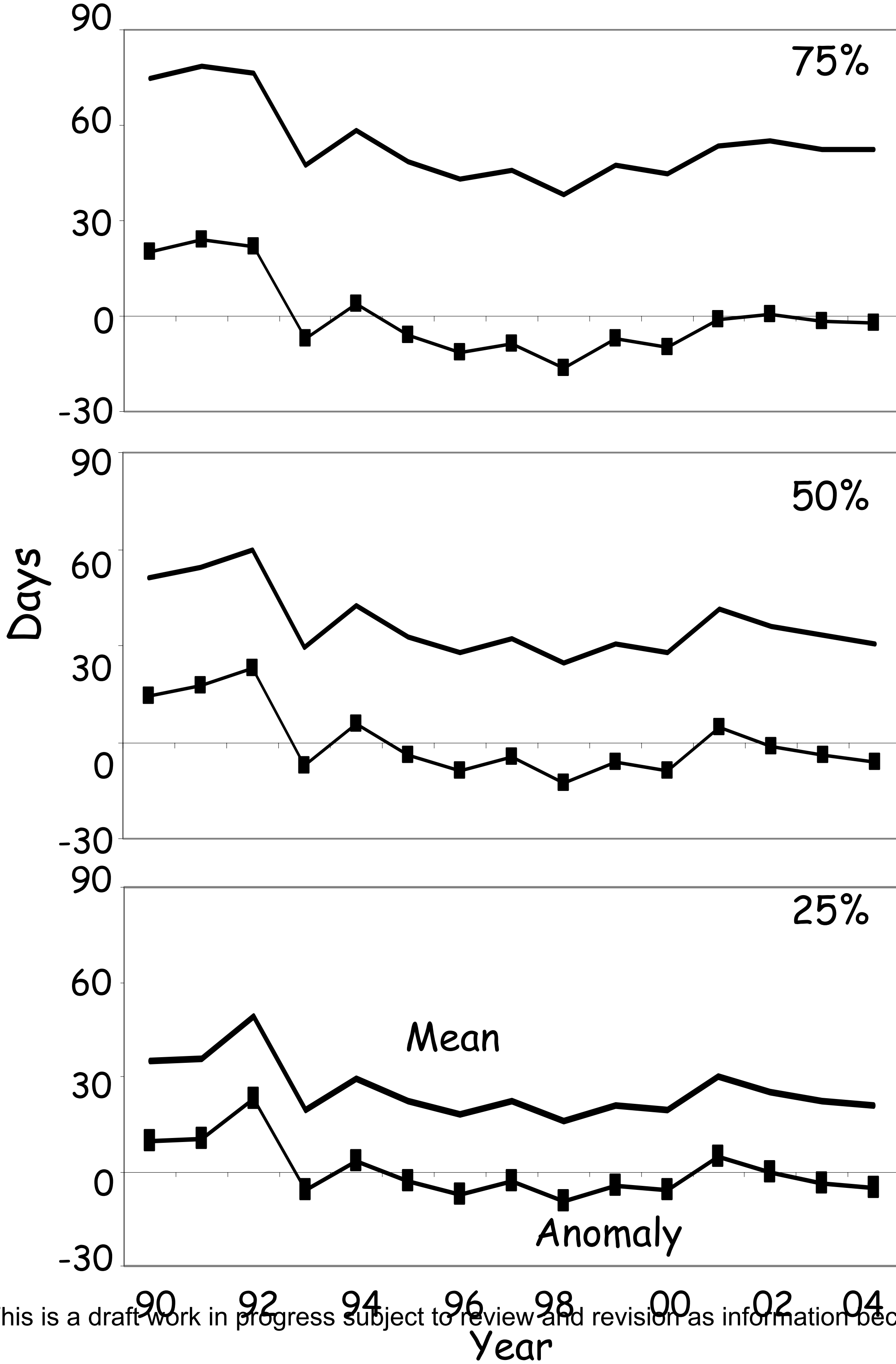
Residence Time: Freeport Injections
October



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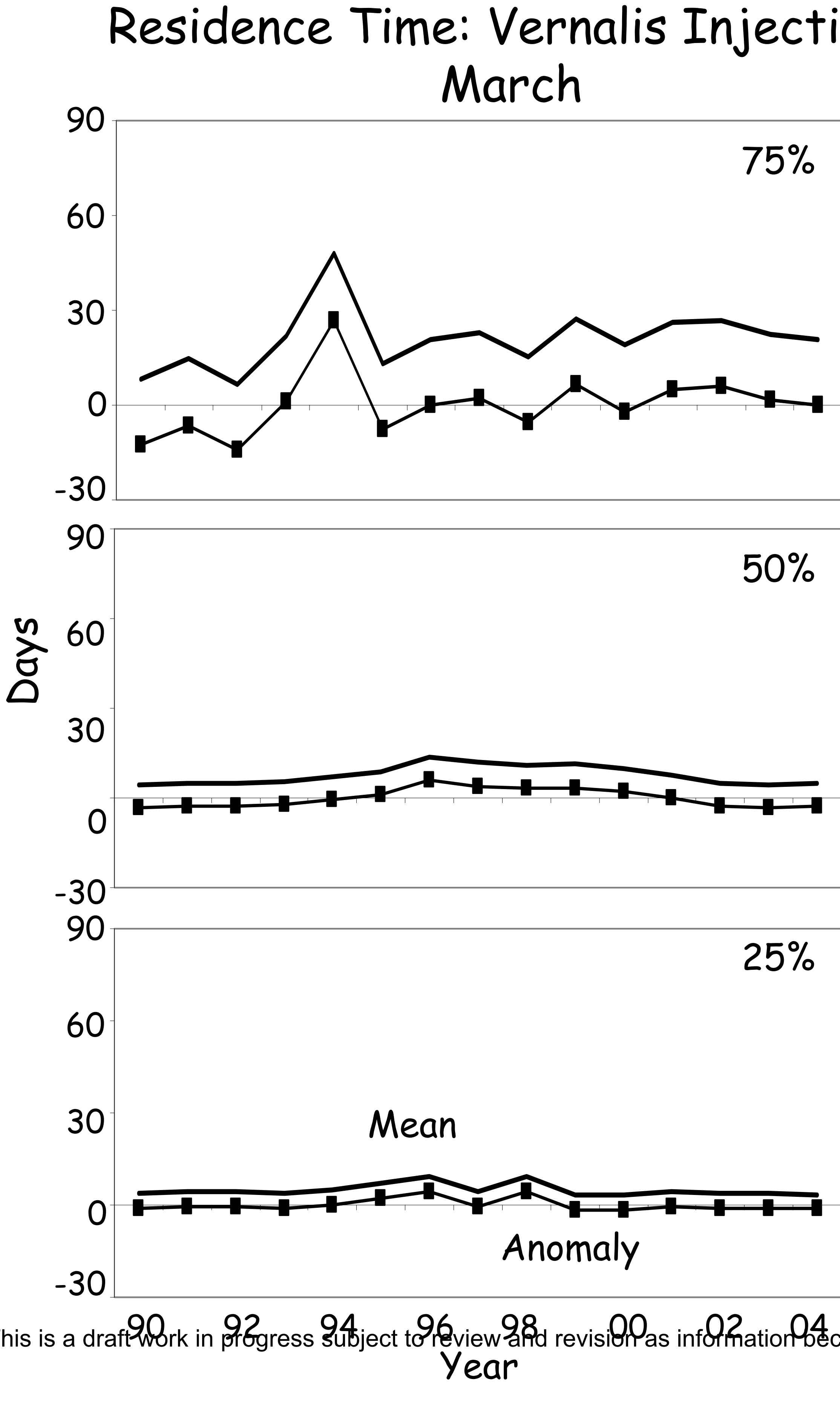
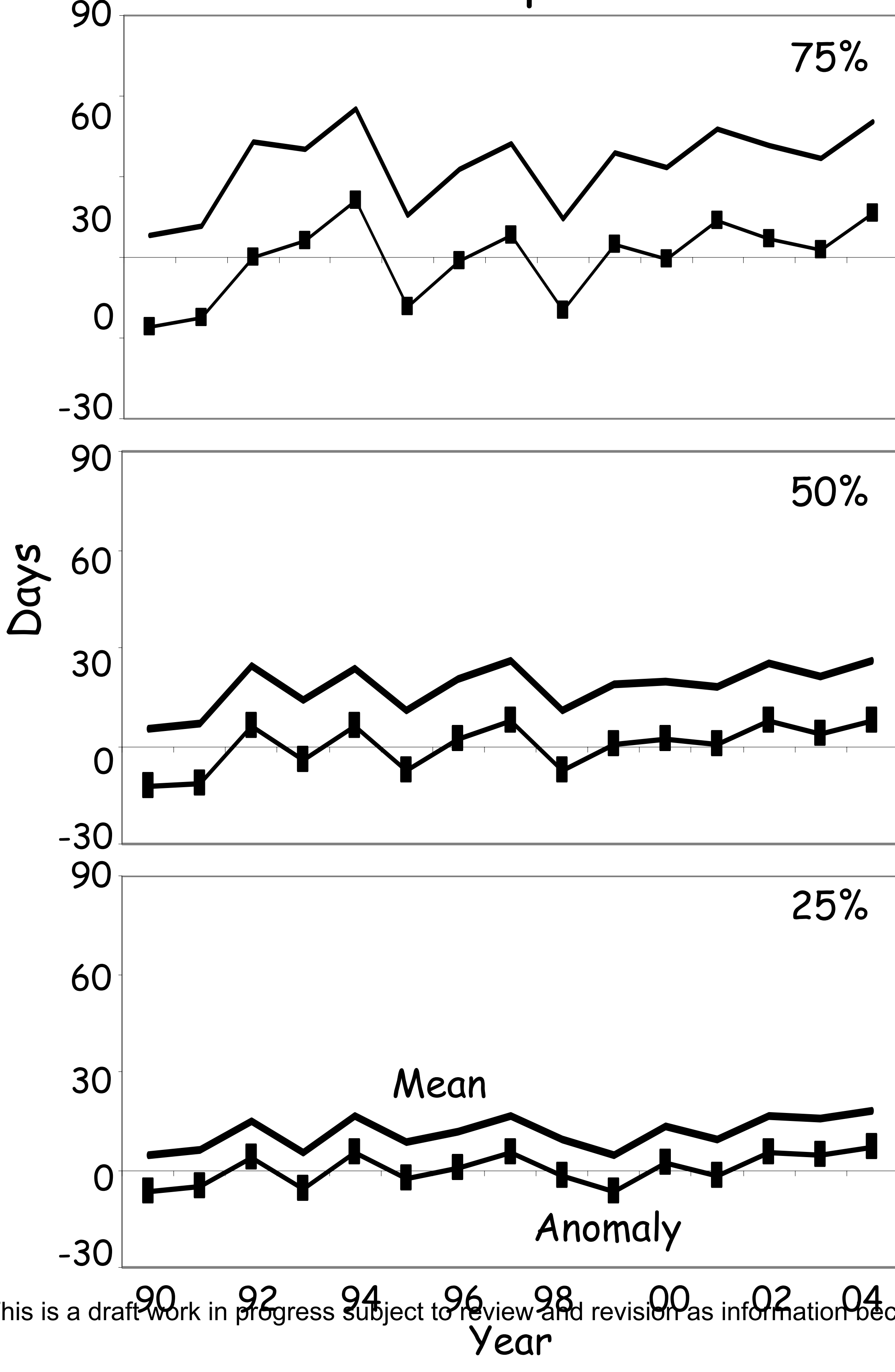
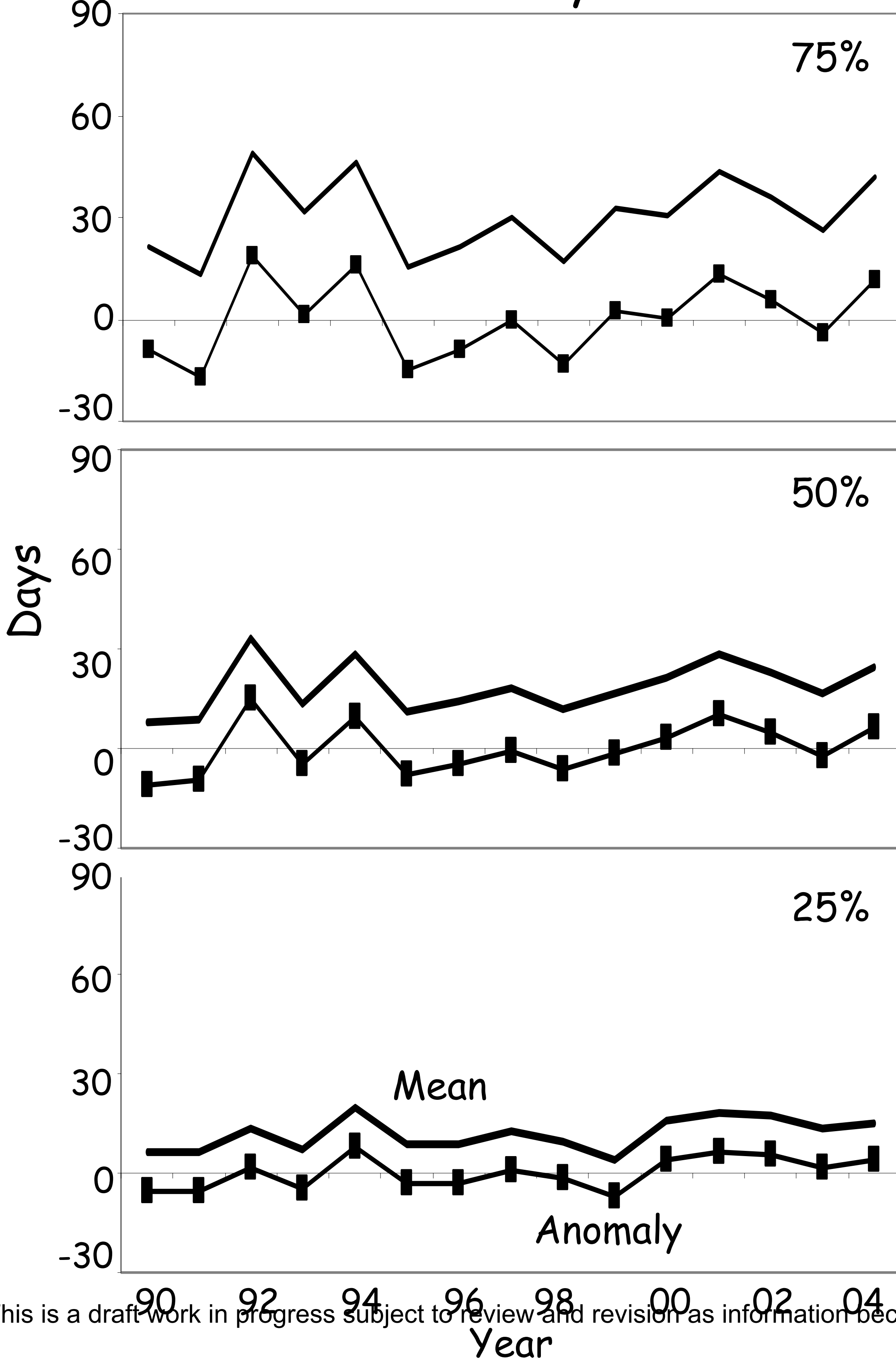


Residence Time: Vernalis Injections
March
Days
75%
50%
25%
Mean
Anomaly
90
60
30
0
-30
90
92
94
96
98
00
02
04
Year

Residence Time: Vernalis Injections
April



Residence Time: Vernalis Injections
May



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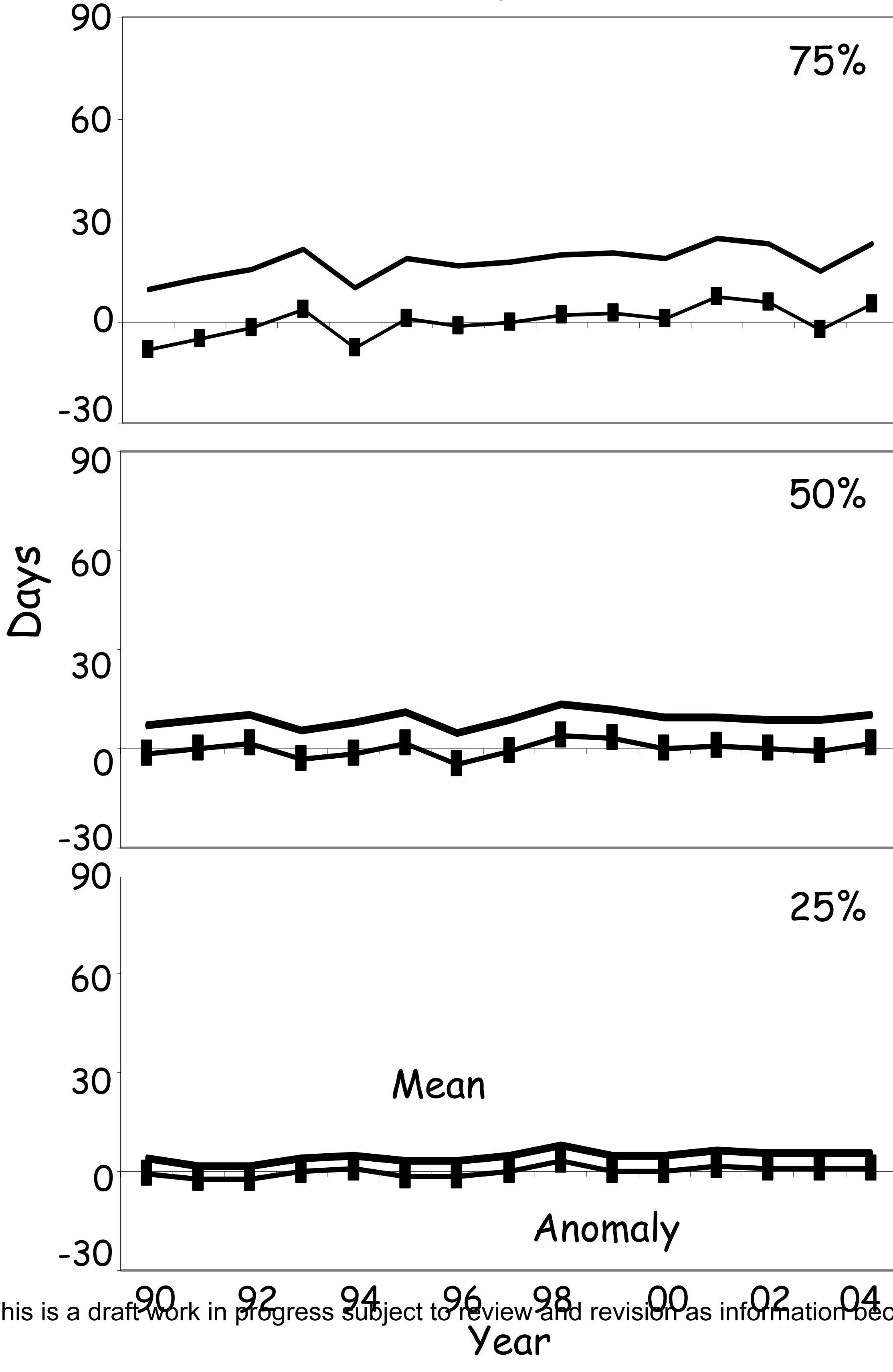
Residence Time: Vernalis Injections June



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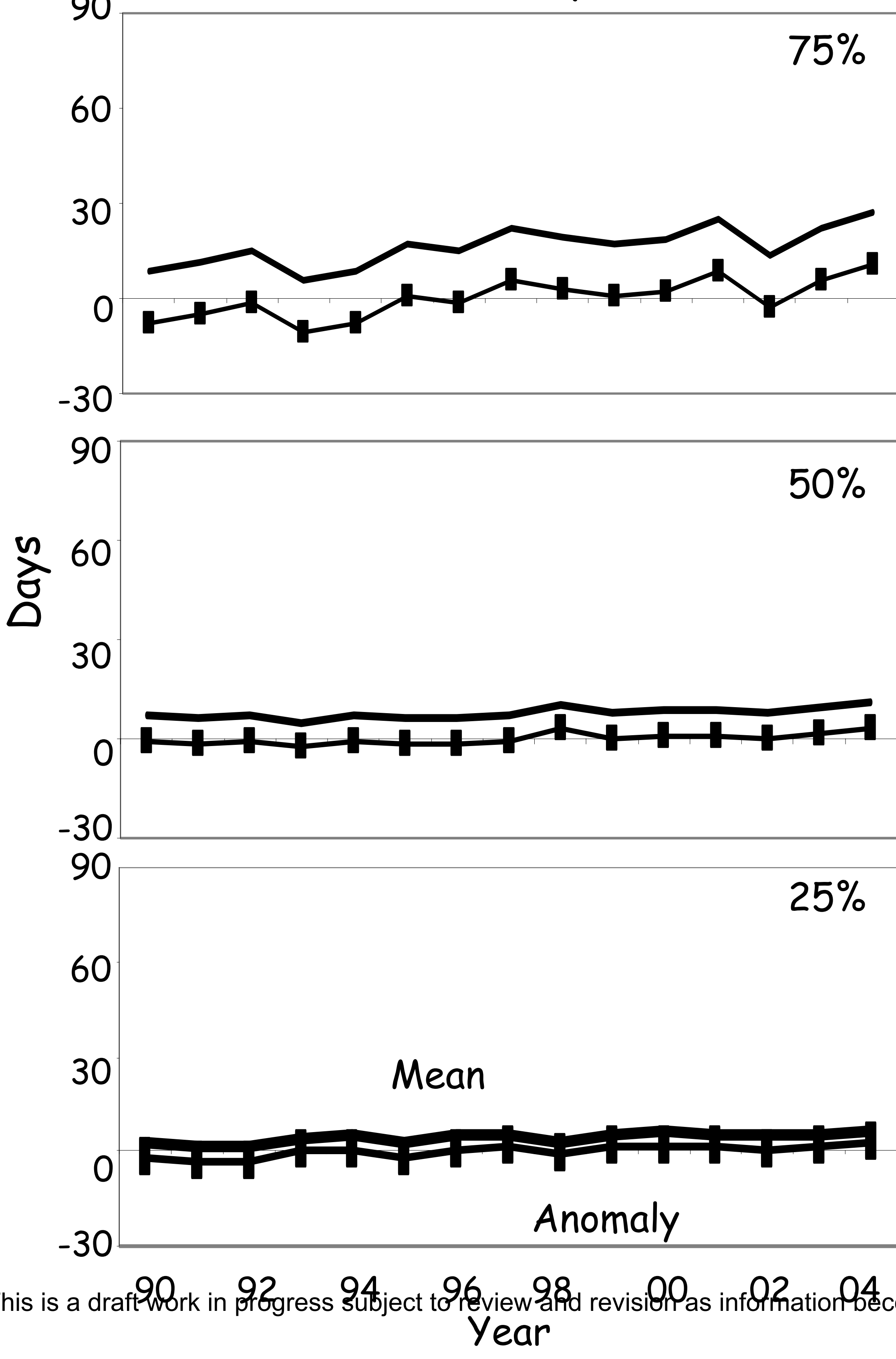
Residence Time: Vernalis Injections
July



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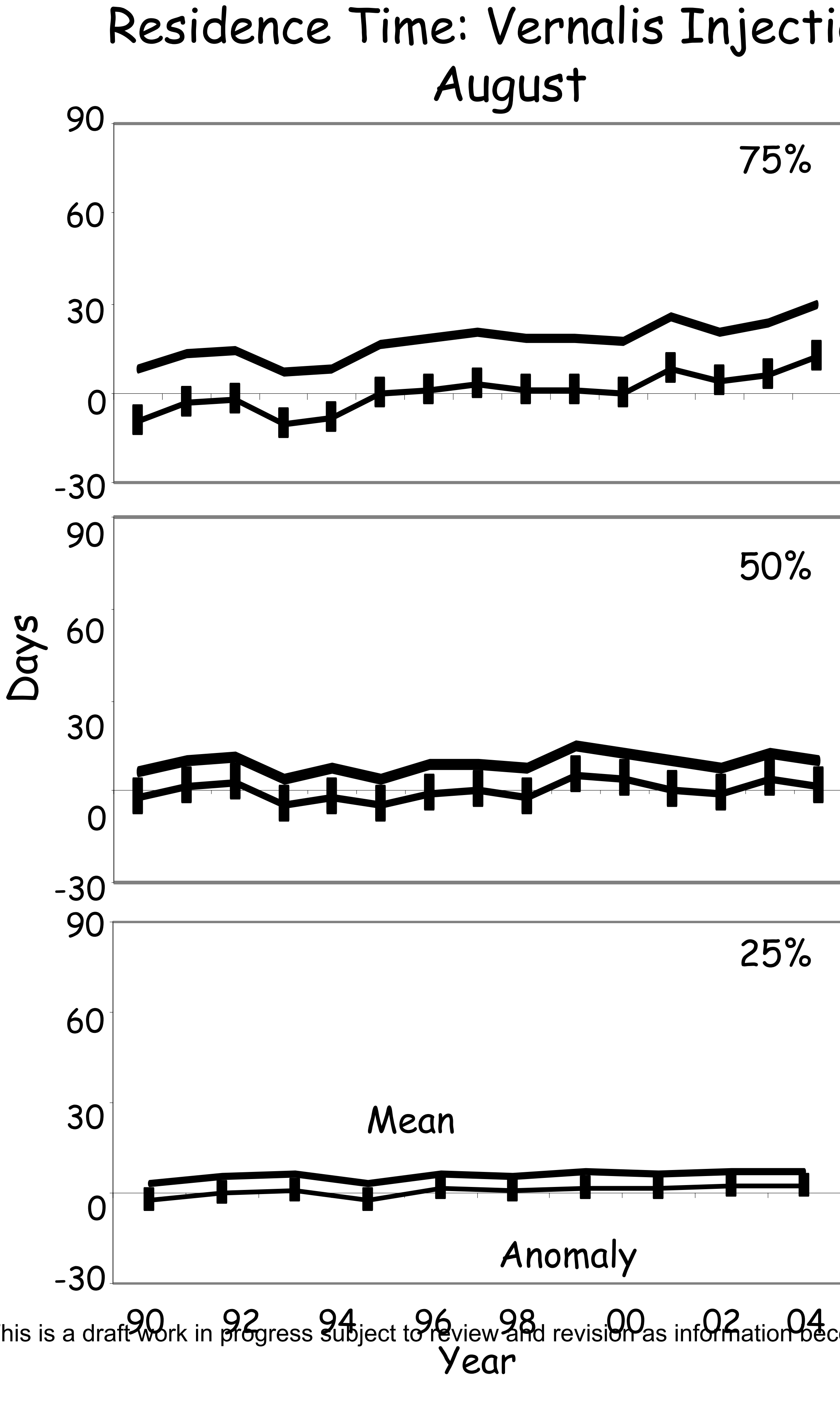

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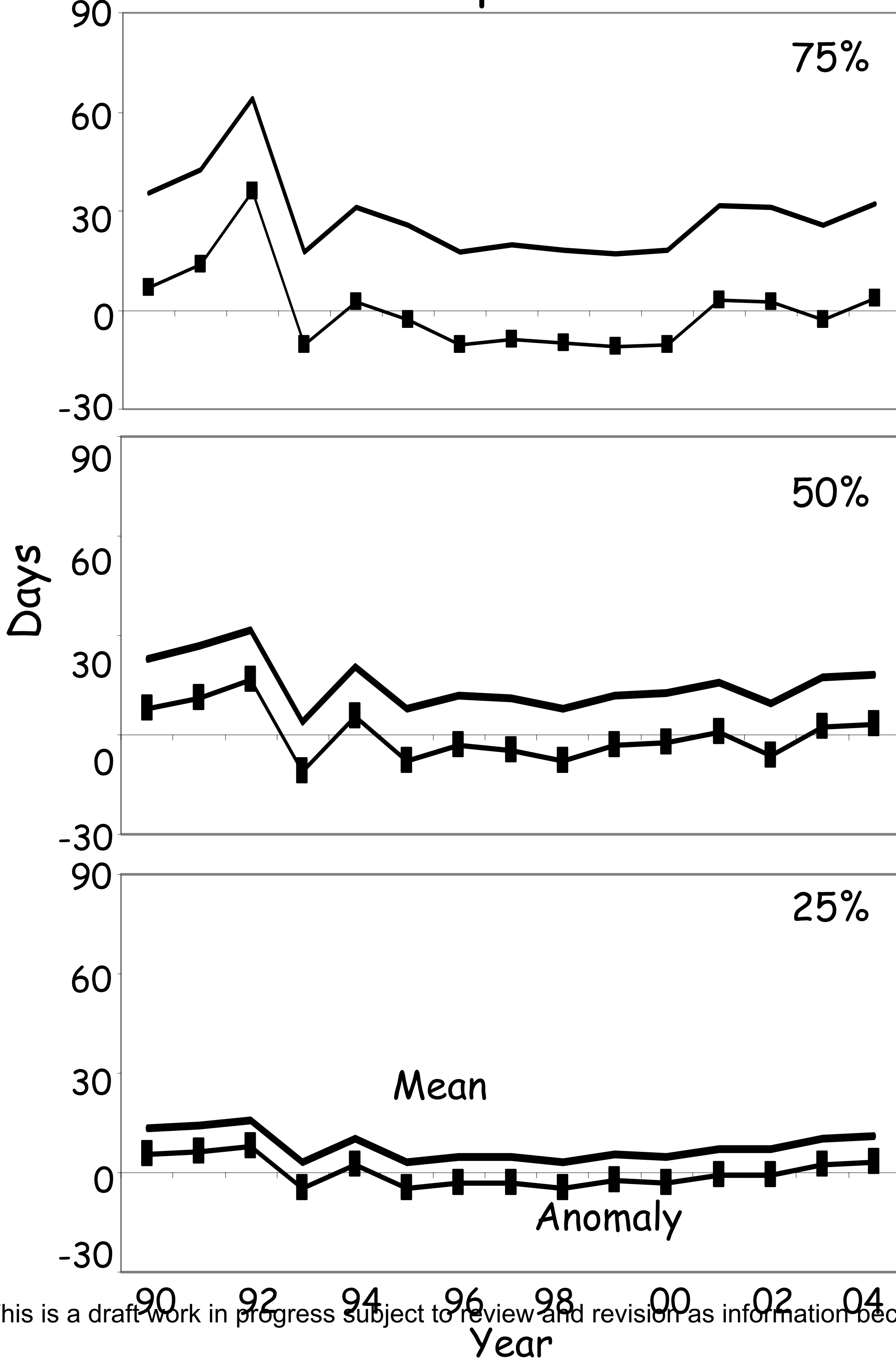
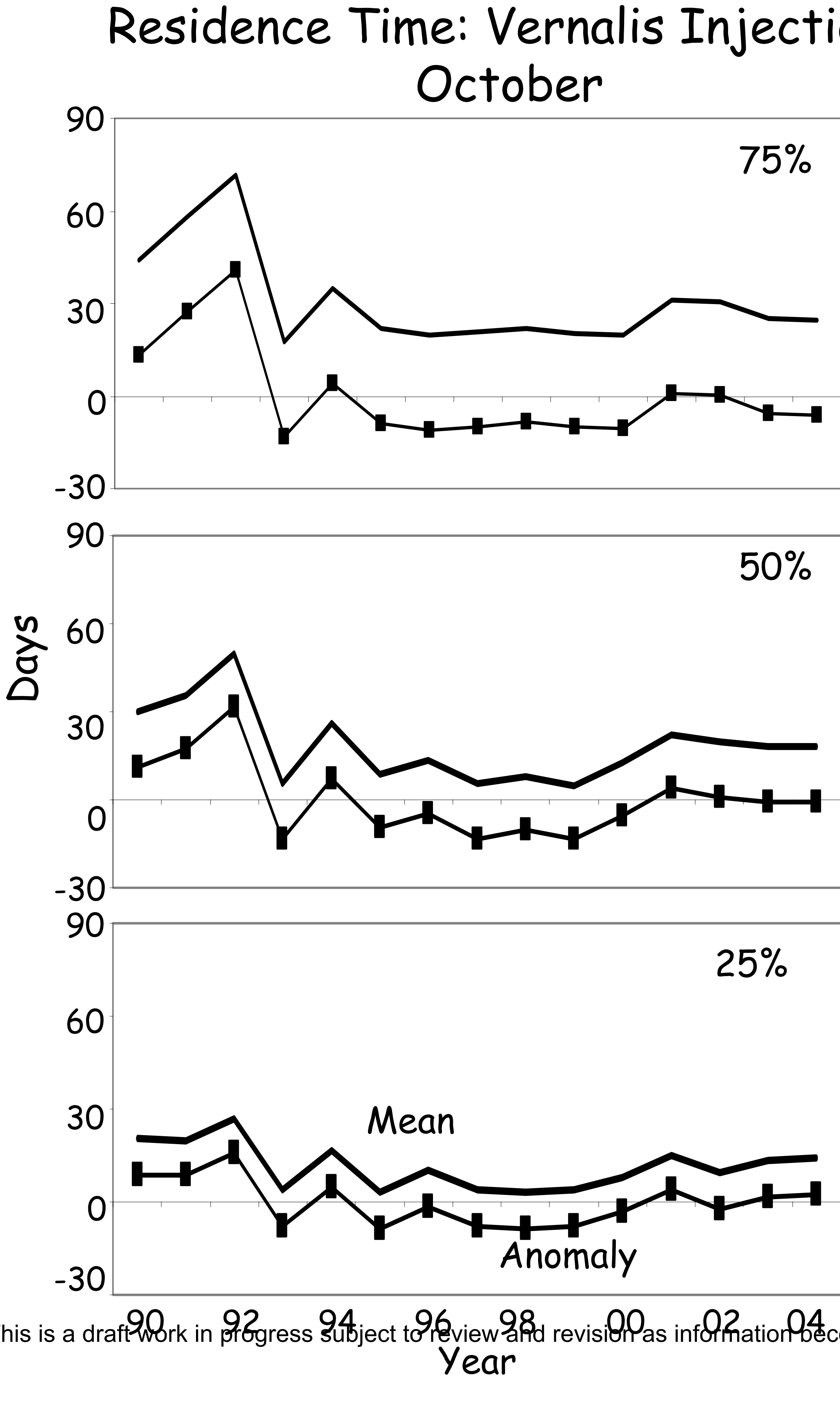
Residence Time: Vernalis Injections
September





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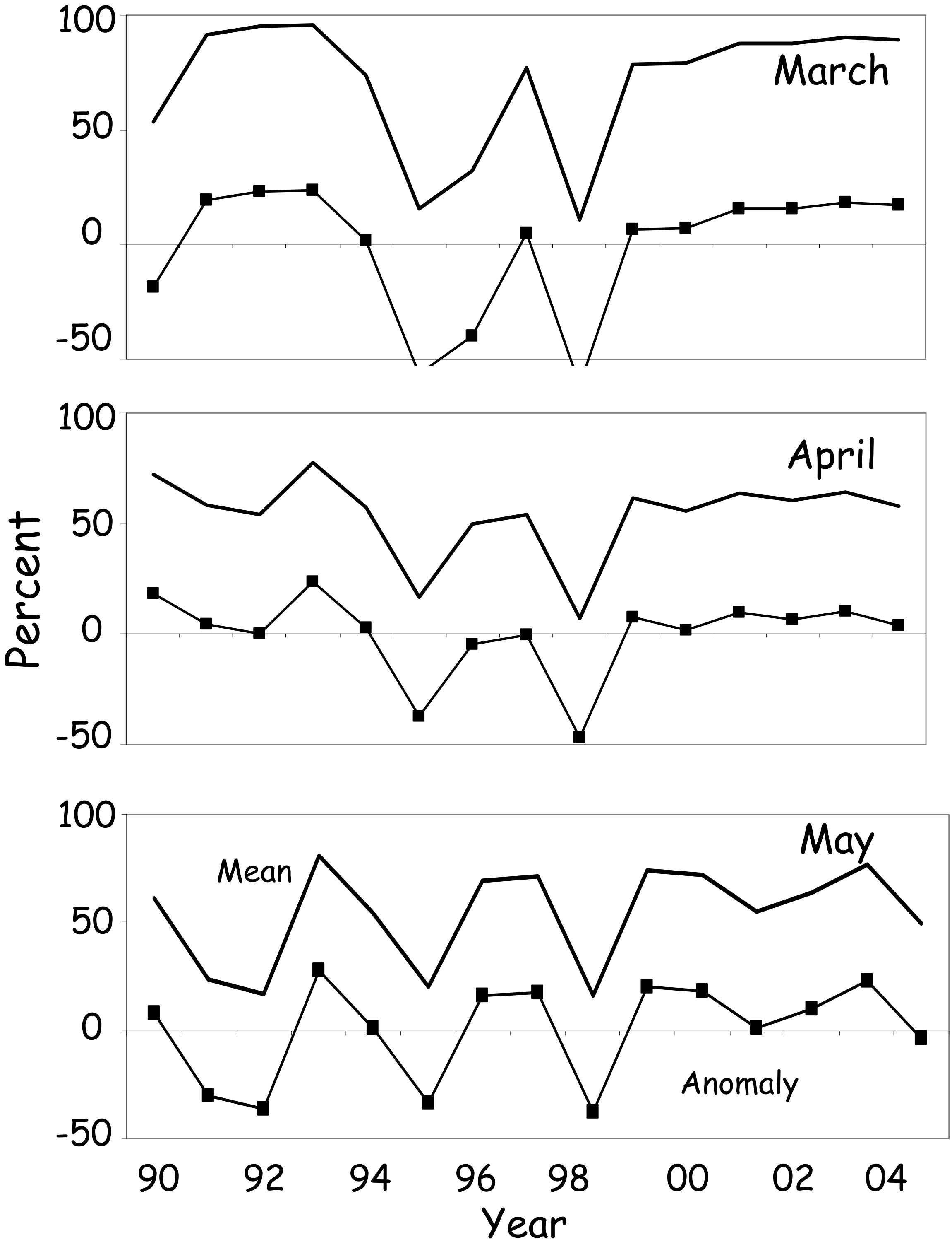
Entrainment: Vernalis Injections



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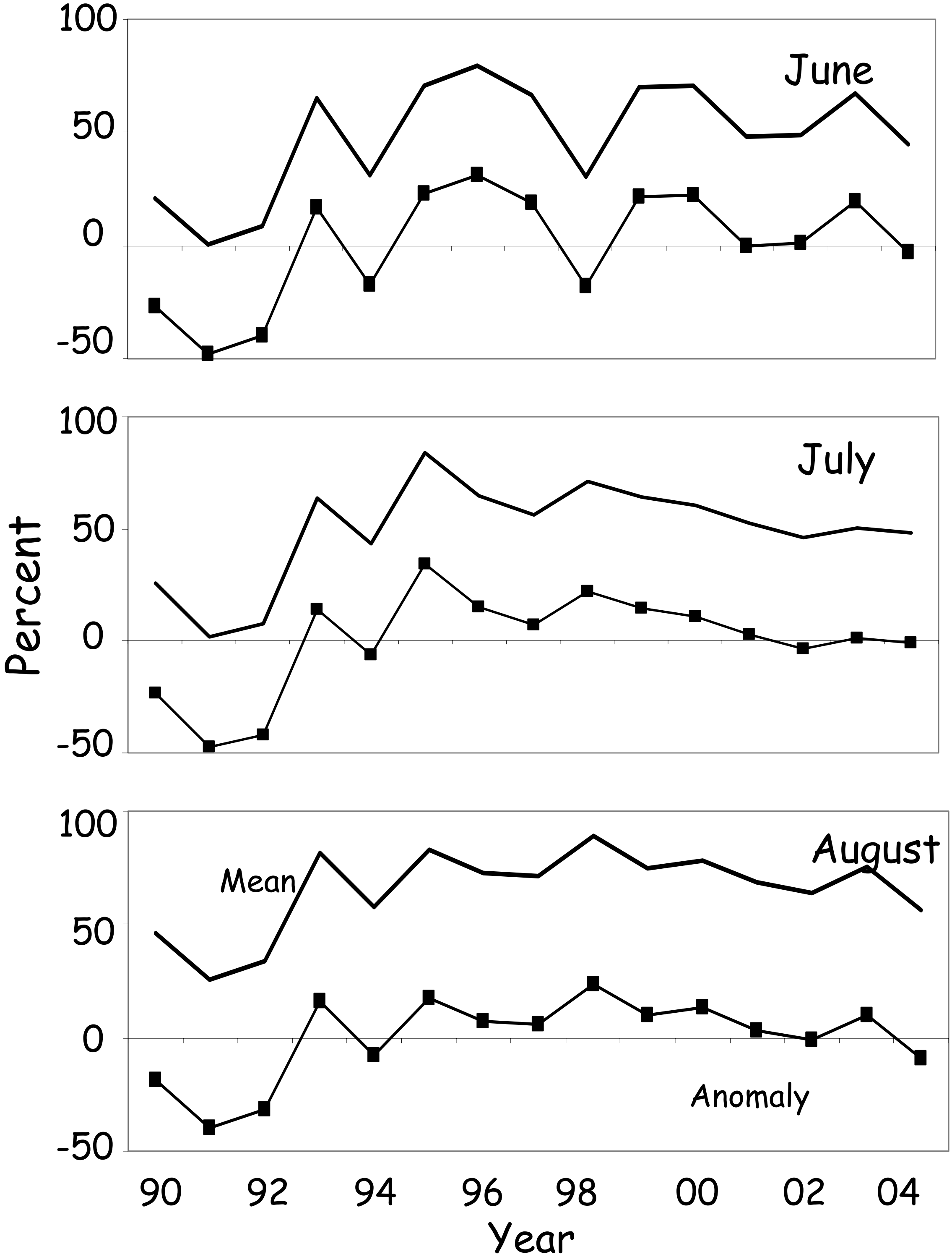
Entrainment: Vernalis Injections



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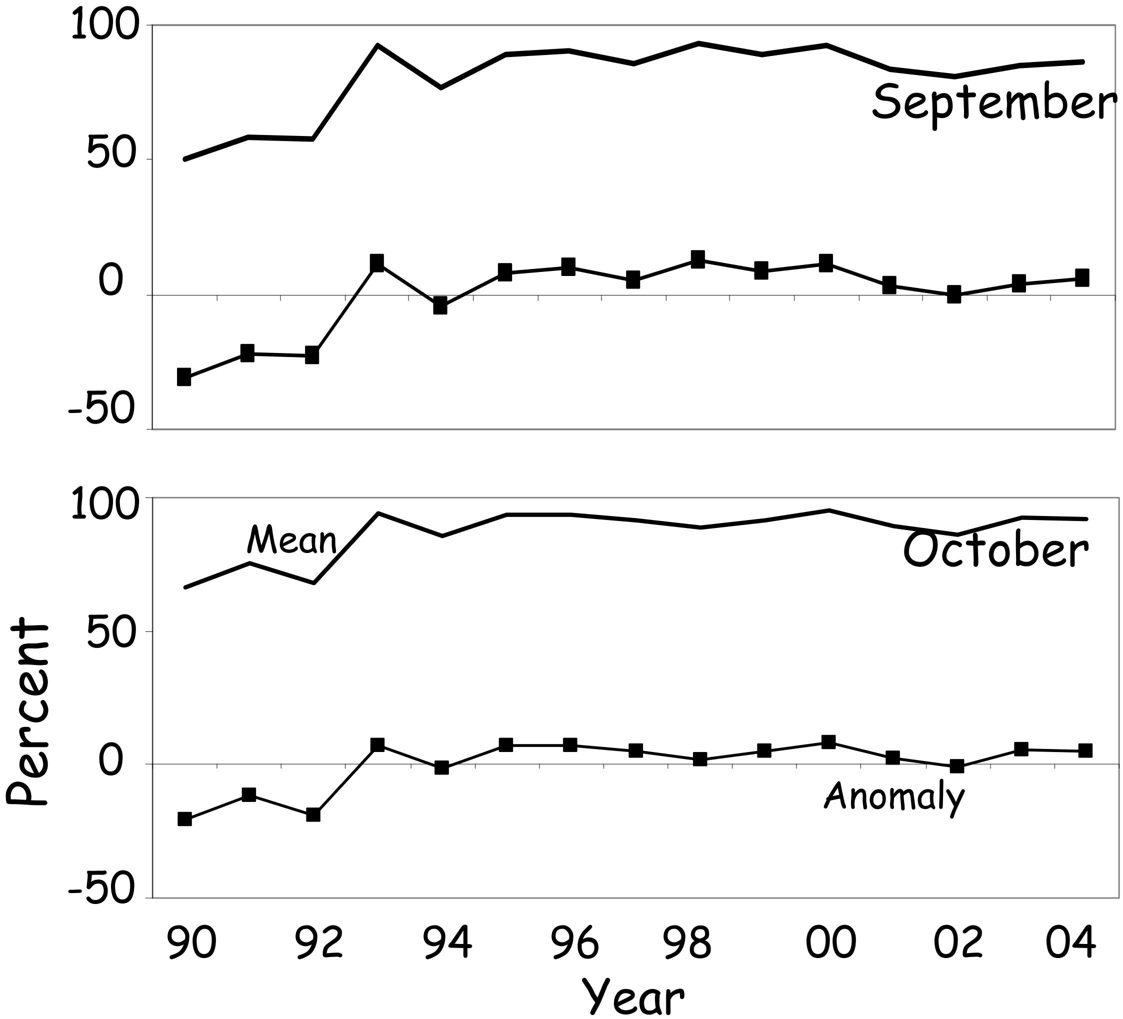
Entrainment: Vernalis Injections



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